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Energy Levels of Light Nuclei. III*

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RECENT years have seen the accumulation of a considerable amount of new information, both experimental and theoretical, pertaining to the location and character of the excited states in the light nuclei. We have attempted in the following sections to summarize the pertinent facts appearing in the literature and to present this material in a systematic way. To a large extent the organization of the present article follows the pattern of the two previous papers on this subject.[1,2] The present article contains a summary of the most important information appearing in the earlier papers and is intended to supersede them entirely.

The range of the survey has been increased to include a discussion of all the light nuclei up to and including neon. The order in which the nuclei are discussed has been changed to follow the order of increasing mass number rather than the order of increasing atomic number. This arrangement permits a more direct comparison of the mirror nuclei and those nuclear species which may be expected to have similar or corresponding properties. In general, only a cursory treatment has been given to the high energy disintegration experiments (bombarding energies exceeding 30 Mev), since at present it is not clear how these experiments bear on the discrete nuclear level structure.

With the exception of the nuclei with $A \leqslant 4$ and a few cases with larger A, each nucleus discussed in this report is represented in a separate diagram on which the known levels are plotted, located according to excitation energy on a vertical scale. On each diagram and plotted to the same energy scale are the various nuclear transitions by which the levels are identified, both as to method of formation and mode of decay. Thus, each diagram contains a representation of the nuclear reactions in which the nucleus in question occurs as either the compound or the residual member. In the case of levels characterizing compound states in a given reaction, some information concerning the lifetimes and the relative probabilities of various modes of decay is given by the measurement of the yields of various products as a function of bombarding energy. These excitation functions, where they are known, are indicated schematically with the pertinent reactions at the side of the diagrams. The curves refer to thin target yields except where otherwise noted. The bombarding energies indicated at characteristic points on the excitation curves are the laboratory energies, but the scale of the curves has been reduced to the excitation energies in the center-of-mass system. Where the excitation function is not known we have indicated either the bombarding voltage or the range of bombarding voltages used in a typical experiment. It is important to note that because many reaction products are not emitted isotropically, the yields quoted at a specified angle of observation may not be directly interpreted to give the total yield.

The existence of levels in the nucleus residual to a reaction is ordinarily revealed through the observation of particle groups or by measurement of the gamma-radiation from the subsequent decay to the ground state. Such groups or transitions are represented by arrows connecting the indicated reactions with the level in question. The vertical projection of any arrow gives directly the energy change and can be used to determine the particle energy by application of the appropriate momentum relations. To facilitate identification of gamma-ray transitions and associated reactions, the measured energy values are indicated on some diagrams and in some instances reference is made to the figure caption. Since the excited levels to which the gamma-ray transitions correspond may in some instances be more

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[1] W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. 20, 191 (1948).

[2] T. Lauritsen, N.R.C. Preliminary Report No. 5 (1949).

accurately located by other means, there will be discrepancies between the indicated gamma-ray energy and the value calculated from the level differences. The same type of discrepancy will occur in that section of the text relating to various determinations of level locations. The values plotted represent the weighted mean of all valid determinations.

Since most experiments permit the location of only the relatively sharply defined levels, the diagrams give little information concerning the broad, continuous states which exist to some extent throughout the entire energy range. Locations in this continuum are in general indicated by short lines leading part way into the well, as opposed to sharp levels which are given by lines extending the full width of the well. It is also important to emphasize that the various regions of excitation of a given nucleus have not been uniformly investigated and that the experimental information available on some nuclei is much more abundant than on others. Although a considerable variety of techniques is available for the identification of nuclear levels, the application of any particular method may be limited by the amount of excitation attainable, by the availability of a suitable target nucleus, and by the probability of occurrence of a reaction. Thus, for example, the methods of non-capture excitation and photo-disintegration are applicable only to the stable isotopes or to radioisotopes of relatively long life. The observation of resonances in the compound nucleus is again restricted to those nuclei which can be formed from available target nuclei and is further limited by the energy interval which can be surveyed. The bombardment of Be^9 with protons, for example, leads to excitation in B^{10} from 6.49 Mev to an upper limit depending on the proton energy available. Even the region immediately above 6.49 Mev is poorly covered because of the small probability of penetrating the Coulomb barrier with low energy protons. The detection of levels from disintegration particle groups depends on the existence of an appropriate combination of target and bombarding particle and on a sufficient probability for the particular mode of decay involved. All of these restrictions vary in a more or less random manner from one nucleus to another with the consequence that some regions have been fairly completely mapped and others not at all. The nucleus C^{10} is in a particularly ill-favored position; it cannot be formed as a compound nucleus by α-particle, proton, neutron, or deuteron bombardment and is observed as a residual nucleus in only one reaction, $B^{10}(p\ n)C^{10}$. It is thus clear that inferences concerning level density can be derived from the material here presented only in a very general and approximate way and conclusions concerning a lack of levels for a given nucleus or a lack of levels in a given region of excitation can be drawn only with due regard to the availability of techniques applicable in the particular case. On the other hand, when a region is accessible in several experiments, it can be assumed with some confidence that a reasonable approximation to the true level structure is indicated in the diagrams.

As support for the representations of the diagrams a brief discussion—largely in the form of an annotated bibliography—of each pertinent reaction is included. Since a particular reaction usually gives information concerning two nuclei, most reactions are discussed twice, leading inevitably to some duplications. The same sort of redundancy also applies to the diagrams: in a sense each must be regarded as a portion of a single master diagram in which all the nuclei are represented side by side with all nuclear reactions represented by cross connections between levels of neighboring systems —that the excerpted portions should overlap is then only natural and reasonable. In a number of cases, where the decay of the nucleus under consideration leads to transitions to several states in a neighboring nucleus this fact has been indicated on the diagram. More detailed information for such cases will be found on the diagram of the residual nucleus. Where possible the discussion is divided in such a way as to place the emphasis on the appropriate nucleus in each case. Energy change (Q) values, γ-ray transitions, and particle groups are discussed under the residual nucleus, while excitation energies (E_x), excitation functions, resonances, cross sections and angular distributions are discussed under the compound nucleus. Similarly, the radioactivity of a particular nucleus is discussed twice. Questions relating to the complexity of the beta-decay are considered under the daughter nucleus, while the remainder of the radioactivity constants are given under the parent nucleus. A table containing the "best values" for the radioactivity constants and the corresponding "ft" values[3] is to be found at the end of this compilation.

A very tentative theoretical discussion of certain reactions and nuclear properties will be found throughout the text. Since these discussions are intended for guidance only, no attempt has been made at completeness either in the references cited or in the extent of the theoretical discussion. Several excellent books have recently appeared to which the reader may profitably refer for a more detailed survey of these considerations; notable among these is the book by Devons.[4]

In particular, a paragraph of comment is appended at the close of the material given for each nucleus. The measured properties of the ground state, whenever available, are included here. These are followed by the more tentative conclusions on the ground state character arising from various nuclear models. In these discussions the word *shell* indicates the usual notation for configuration. The alpha-particle or O^{16} closed-shell core is indicated, followed by the usual symbols for principal quantum number and l value with an exponent for the number of nucleons in the given orbital state. To these

[3] The "ft" functions used were those calculated by G. L. Trigg at Washington University.

[4] S. Devons, *The Excited States of Nuclei* (Cambridge University Press, London, 1949).

orbital values are suffixed the expected total angular momentum I value for the *single particle*. Following this configuration symbol (from which the $j-j$ coupling model result for the ground state can almost always be immediately deduced[5]) there is a statement of the ground state character from the quasi-atomic Hartree-type calculations without strong spin-orbit coupling, or a conclusion from the alpha particle model.[6] Additional notations used in these sections are: μ = magnetic dipole moment in nuclear magnetons, with the last figure quoted possessing an error of approximately unity. Q = electric quadrupole moment, in units of $e\times 10^{-24}$ e.s.u.-cm^2.

No attempt has been made to present the evidence for particular levels in historical order. On the contrary, we have in many cases relegated original discoveries to the undiscussed bibliography in favor of more recent or more definitive measurements. References discussed in the classical work of Livingston and Bethe[7] are generally omitted here, except where no later work exists.

Inasmuch as the energy change values indicated on the diagrams and in the reaction headings are intended only for a general guide without claim to great accuracy, we have continued to use the 1947 mass table[8] in the interests of uniformity. Despite the fact that better values are now known for most of the masses of the light elements (principally for the neutron mass), it would seem that the adoption of a new table should await further work on the exceptions—notably He^4. In a few cases of radioactive nuclei, where only rough estimates were given in the 1947 table, we have adopted masses based on recent experiments; the mass actually used for each nucleus is given with the heading for that nucleus.

As in the two previous compilations all the references are collected together at the end; in addition those references specifically discussed under a particular reaction are also given explicitly at the end of that discussion. This procedure has enabled us to eliminate to a large extent the use of names in the text material while still making them readily accessible to the reader. The principal original sources are indicated at the end of each statement in the text by including the short hand designation for the references. The coding used in the designation of the references follows the scheme used in the two previous publications. The entire bibliography of the previous papers has been included.

The nominal values for the energy release in a given reaction are designated as Q_m and are listed on the same line as the symbolic representation of the reaction. Experimental determinations are described in the text and are designated simply as Q. In addition to listing the Q_m value for a reaction we also now list E_x, the excitation energy of the compound nucleus resulting from the mass excess of the incident particle and target nucleus relative to the compound nucleus. This is a considerable aid in locating a reaction on the nuclear diagrams. The values given for E_x are nominal ones calculated from mass values.

Where it was necessary to refer to the magnetic or electric moments of a nucleus or its spin, these values were taken from the compilations of Poss[9] and Mack.[10]

Both because it is felt that the concept of a compound nucleus becomes less useful and because the diagrammatic representation becomes less instructive when the combined mass number of the reacting particles becomes smaller, two separate methods of approach have been used in the present survey. Reactions involving a combined mass number greater than or equal to five are treated from the point of view of the compound nucleus concept, as before. Reactions involving a combined mass number less than five are discussed in a separate section. These reactions are discussed in the order given below:

A.	$n(\beta^-)H^1$	I.	$H^2(p\ \gamma)He^3$
B.	$H^1(p\ \beta^+)H^2$	J.	$H^2(d\ p)H^3$
C.	$H^1(\gamma\ n)\beta^+$	K.	$H^2(d\ n)He^3$
D.	$H^1(n\ \gamma)H^2$	L.	$H^2(d\ \gamma)He^4$
E.	$H^2(\gamma\ n)H^1$	M.	$H^3(\beta^-)He^3$
F.	$H^2(n\ 2n)p$	N.	$H^3(p\ n)He^3$
G.	$H^2(n\ \gamma)H^3$	O.	$H^3(p\ \gamma)He^4$
H.	$H^2(p\ n)2p$	P.	$He^3(n\ p)H^3$.

As is evident from this list the fundamental scattering problems are not included (nor are the $d\ t$ and d He^3 scattering experiments included in the following section). It is felt that the data and the analysis of the data on the scattering experiments are much too extensive to be included in this report.

It might be pointed out at this time that several independent compilations covering the range of reactions presented here are available in the literature. Among these may be mentioned the surveys by Volz,[11] Mattauch and Flammersfeld,[12] and Kondratiev.[13] The range $11\leq Z\leq 20$ has been investigated and systematized by Alburger and Hafner.[14]

It is realized that errors and misinterpretations of published results are inevitable in a compilation of this type. We welcome corrections and addenda from authors and readers. These should be addressed to the first named author at the Brookhaven National Laboratory.

[5] M. Mayer, Phys. Rev. **78**, 16 (1950).
[6] L. Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1949), pp. 203, 281 ff.
[7] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 245 (1937).
[8] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).
[9] H. Poss, BNL Report 26(T-10) (October 1, 1949).
[10] J. Mack, Rev. Mod. Phys. **22**, 64 (1950).
[11] H. Volz, Ergeb. d. exakt. Naturwiss. **21**, 208 (1945).
[12] J. Mattauch and A. Flammersfeld, special issue, Zeits. f. Naturforschung (1949).
[13] V. N. Kondratiev, Prog. Phys. Sci. U.S.S.R. **38**, No. 2, 153 (1949).
[14] D. E. Alburger and E. M. Hafner, BNL Report T-9 (July 1, 1949) and also Rev. Mod. Phys. **22**, 370 (1950).

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Note added in proof: To the Editorial and Publication staffs of the *Reviews of Modern Physics* we owe a particular debt of gratitude: their patience and cooperative spirit, well known to authors whose works have appeared in this Journal, have been much imposed upon by the many post-deadline changes which have been made and by the difficult typographical problems associated with the unconventional arrangement of the article.

Fundamental Reactions

A. $n(\beta^-)H^1$

The decay of the neutron has been detected and the half-life established $10<T_{\frac{1}{2}}<30$ min. (Ro 50a, Sn 50a).

The β-spectrum of the neutron decay has been observed using a lens spectrometer in coincidence with the decay protons. The Kurie plot for this preliminary experiment is straight from an end point of ~780 kev (Au^{198} calibration) down to ~200 kev (Robson, private communication).

Ro 50a Robson, Phys. Rev. **78**, 311 (1950).
Sn 50a Snell, Pleasonton, and McCord, Phys. Rev. **78**, 310 (1950).

Experiments on the $n-H^1$ mass difference have been recently summarized (To 50), see also St 47a. The nuclear reaction cycles involved and the computed mass difference are given in Table I.

The direct determination of the deuteron binding energy has been made by a number of investigators:

$H^1(n\ \gamma)H^2$:	$Q=2.230\pm0.007$ Mev	(Be 48a, Be50g) [a]
$H^2(p\ n)2p$:	$=-2.225\pm0.010$	(Sm 50, Sm 50b) [b]
$H^2(\gamma\ n)H^1$:	$=-2.226\pm0.003$	
Mean value	$E_b=2.226\pm0.003$ Mev	

[a] Mean of earlier and more recent work based on Th C'' γ-ray energy = 2.615.
[b] $E_{thr}=3.339\pm0.015$ Mev, based on $Li^7(p\ n)$ threshold 1.882 Mev.
[c] (Mobley and Laubenstein, private communication), based on $Li^7(p\ n)$ threshold 1.882 Mev.

This value combined with the mass spectroscopic value $2H^1-H^2=1.442\pm0.005$ Mev (Ro 50b) (estimated error from quoted internal consistency of a few parts in 10^6 of the mass number measured) gives a $(n-H^1)$ difference of 0.784 ± 0.006 Mev.

B. $H^1(p\ \beta^+)H^2$

The cross section for this reaction has been calculated theoretically and its importance in stellar energy evolution discussed (Be 38c, Be 39b, Ga 49). Recent theoretical values of the cross section used in calculations of the energy evolution in the sun are calculated from

$$\sigma(E)=2.6E^{-1}\exp(-0.99E^{-\frac{1}{2}})\times10^{-49}\ \text{cm}^2$$

for E in Mev, and are as follows (Salpeter, private communication):

E	1 kev	10 kev	100 kev	1 Mev
σ (cm²)	6×10^{-60}	1.2×10^{-51}	1.1×10^{-49}	9.4×10^{-50}

Be 38c Bethe and Critchfield, Phys. Rev. **54**, 248, 862 (1938).
Be 39b Bethe, Phys. Rev. **55**, 434 (1939).
Ga 49 Gamow and Critchfield, *Theory of Atomic Nucleus and Nuclear Energy Sources* (Oxford University Press, London, 1949).
See also: Al 50e, Te 50a.

TABLE I.

Reaction	Q (Mev)	$n-H^1$ (Mev)	Reference
$H^2(d\ p)H^3$	$4.036\ \pm0.022$		To 49a
$H^2(d\ n)He^3$	$3.265\ \pm0.018$	$0.789\ \pm0.006$	To 49a
$H^3(\beta^-)He^3$	0.0185 ± 0.0005		Ha 49b, Cu 49b
$H^3(p\ n)He^3$	-0.7637 ± 0.001	0.7822 ± 0.001	Ta 49c
$H^3(\beta^-)He^3$	0.0185 ± 0.0005		Ha 49b, Cu 49b
$He^3(n\ p)H^3$	$0.765\ \pm0.007$	$0.783\ \pm0.007$	Hu 48b, Je 49b, Fr 50
$H^3(\beta^-)He^3$	0.0185 ± 0.005		Ha 49b, Cu 49b
$C^{12}(d\ p)C^{13}$	$2.729\ \pm0.009$		Bu 49
$C^{12}(d\ n)N^{13}$	$-0.281\ \pm0.003$	$0.788\ \pm0.010$	Bo 49c
$N^{13}(\beta^+)C^{13}$	$2.222\ \pm0.003$		See N^{13}
$C^{13}(p\ n)N^{13}$	$-3.003\ \pm0.003$	$0.781\ \pm0.004$	Ri 50
$N^{13}(\beta^+)C^{13}$	$2.222\ \pm0.003$		See N^{13}
$B^{11}(p\ n)C^{11}$	$-2.762\ \pm0.002$	$0.759\ \pm0.005$ [a]	Ri 50
$C^{11}(\beta^+)B^{11}$	$2.003\ \pm0.005$		To 40
$C^{14}(p\ n)N^{14}$	$-0.620\ \pm0.009$	$0.776\ \pm0.009$	Sh 49a
$C^{14}(\beta^-)N^{14}$	$0.156\ \pm0.001$		See C^{14}
$N^{14}(n\ p)C^{14}$	$0.626\ \pm0.006$	$0.782\ \pm0.006$	Fr 50, Hu 48b, Je 49b
$C^{14}(\beta^-)N^{14}$	$0.156\ \pm0.001$		See C^{14}
Weighted mean from nuclear cycles:		0.782 ± 0.001	

[a] Omitted in calculation of mean value.

C. $H^1(\gamma\ n)\beta^+$

An upper limit for the photo-disintegration of the proton has been reported at $\lesssim4\times10^{-32}$ cm² by comparison with the cross section for the reactions $Be^9(\gamma\ n)$ and $H^2(\gamma\ n)$ for mixed γ-rays 1.8–2.7 Mev (Bu 48a). A theoretical calculation by Primakoff (Pr 48) based on

TABLE II.

σ (barns)	Remarks	Reference
0.31	n diffusion in paraffin, $\tau=170$ μsec.	Am 36
0.3	n diffusion in hydrogeneous materials	We 37
$0.33\ \pm0.01$	Mean life in H_2O, $\tau=205\pm10$ μsec.	Ma 42
$0.37\ \pm0.02$	$\sigma_B/\sigma_H=1940\pm100$ ($\sigma_B=710$ b) [a]	Fr 38
0.329 ± 0.005	$\sigma_B/\sigma_H=2160\pm30$ ($\sigma_B=710$ b) [a]	Fe 43
0.298 ± 0.011	$\sigma_B/\sigma_H=2380\pm70$ ($\sigma_B=710$ b) [a]	Ku 44
0.363 ± 0.005	$\sigma_B/\sigma_H=1954\pm24$ ($\sigma_B=710$ b) [a]	Sc 45
0.313 ± 0.005	$\sigma_B/\sigma_H=2270\pm30$ ($\sigma_B=710$ b) [a]	Wh 47
0.326 ± 0.010	$\sigma_B/\sigma_H=2180\pm60$ ($\sigma_B=710$ b) [a]	Re 48
0.25	$\sigma_{Cd}/\sigma_H=10{,}000$ ($\sigma_{Cd}=2500$ b) [a]	Sp 38
0.18	$\sigma_{Cd}/\sigma_H=14{,}100$ ($\sigma_{Cd}=2500$ b) [a]	Ha 43
0.338 ± 0.014	$\sigma_{Mn}/\sigma_H=42\pm1.5$ ($\sigma_{Mn}=14.2$ b) [a]	Ba 47a
Weighted mean: 0.328 ± 0.005		

[a] Estimated absorption cross sections used: B $\sigma_a=\sigma_t-4$ b, Cd $\sigma_a\approx\sigma_t$ Mn $\sigma_a=\sigma_t-2.2$ b.

the Fermi theory of β-decay places the cross section at $\sim 10^{-46}$ cm^2 for γ-rays of the energy used above.

Bu 48a Burling and Kurie, Phys. Rev. **74**, 109 (1948).
Pr 48 Primakoff, Phys. Rev. **74**, 110 (1948).

D. $H^1(n\ \gamma)H^2$

The absorption of slow neutrons in hydrogen is entirely by the capture process. The theoretically predicted variation of the cross section with velocity follows the "$1/v$ law" for magnetic dipole capture, this being the most prominent mode of capture for slow neutrons.

The absorption cross section for thermal neutrons $\sim 1/40$ ev (C-neutrons, $\bar{v}=2.2\times 10^5$ cm/sec.) has been determined by numerous investigators; their results are given in Table II.

The above mean experimental value of 0.328 b is to be compared with the theoretically predicted values of 0.30 to 0.33 b (Ra 41, Ro 49a), where the singlet ($^1S_0$) state of the deuteron at $\sim$100 kev is taken as a virtual state. A capture cross section of approximately one-half these values would be predicted if the singlet state is taken as real rather than virtual.

The most recent determinations of the diffusion length of neutrons in H_2O are: 3.0±0.3 cm for thermal neutrons (Ga 46), 2.77±0.04 cm for Cd absorbable neutrons and 2.88±0.07 cm for B absorbable neutrons (Be 47d). These values are consistent with a capture cross section of the order of 0.3 b (Ro 49a).

Early investigators (Li 37), notably Fleischmann (Fl 36) and Kikuchi, Aoki, and Husimi (Ki 36) have determined the energy of the capture γ-ray by absorption techniques: the reported values are $E_\gamma=2.26$ Mev (2.23 using E_γ of Th C'' as 2.62) and 2.2 Mev, respectively. Nakagawa (Na 43, Na 49a) reports the observation of three γ-rays of equal intensity for slow neutron capture in paraffin. The reported energies are 2.24, 1.4_0, and 0.8_0 Mev. The evaluation of these experimental results is difficult. Theoretical considerations are given (Na 48).

A recent spectrometer measurement by Bell and Elliott (Be 48a, Be 50g) gives a reaction energy of Th $C''-0.385\pm 0.005$ Mev, including recoil correction. If one takes the energy of the Th C'' γ-ray as 2.615 ±0.003 Mev (Ho 49a, Wo 50b), the capture energy change is found to be 2.230±0.007 Mev.

Ra 41 Rarita and Schwinger, Phys. Rev. **59**, 436 (1941).
Ro 49a Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1949).
Ga 46 Gammertsfelder and Goldhaber, Phys. Rev. **62**, 556 (1946).
Be 47d Berthelot, Cohen, and Reel, Comptes Rendus **225**, 406 (1947).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Fl 36 Fleischmann, Zeits. f. Physik **103**, 113 (1936).
Ki 36 Kikuchi, Aoki, and Husimi, Nature **137**, 186 (1936).
Na 43 Nakagawa, Sumoto, and Arai, Proc. Imp. Acad. Japan **19**, 373 (1943).
Na 49a Nakagawa, J. Sci. Res. Inst. Tokyo **43**, No. 1196 (1949).
Na 48 Nakagawa, J. Sci. Res. Inst. Tokyo **43**, No. 1185 (1948).

TABLE III.

E_B (Mev)	Remarks[b]	Reference
2.14 ±0.08	Th $C''-\gamma$, ion. chbr.	Ch 35
2.25 ±0.05	Th $C''-\gamma$, cl. chbr. range	Ch 37a
2.16 ±0.04	Correction of Ch 37a	Be 38b
2.18_1 ±0.03[a]	Th $C''-\gamma$, ion. chbr.	St 38b
2.17 ±0.05	Th $C''-\gamma$, cl. chbr. ($B\rho$)	Ro 39
2.22_5 ±0.010	Th $C''-\gamma$, BF^3 pulse height	Ha 45
2.18_1 ±(0.005?)	Th $C''-\gamma$, proportional counter	Me 49a
1.95 ±(0.04?)	$Na^{24}-\gamma$, cl. chbr. range	Ri 38
2.01 ±(0.04?)	Correction of Ri 38	St 47a
2.08 ±0.06	$Na^{24}-\gamma$, ion. chbr.	Go 44
2.18_9 ±0.007	Ra C$-\gamma$, n-slowing in paraffin	Ki 39d
2.18_3 ±0.02[a]	X-rays, $H^2/Be^9=1.342\pm 0.006$	My 42
2.18_5 ±0.02[a]	X-rays, $H^2/Be^9=1.340\pm 0.003$	Wi 45
—	e^-, $H^2/Be^9=1.338\pm 0.004$	Wa 48a
—	Betatron, $H^2/Be^9=1.35\pm 0.03$	Mc 49
2.226±0.003	X-rays	[c]

[a] The errors have been raised over those quoted by the authors, following Bethe (Be 47c) and Stephens (St 47a).
[b] Gamma-ray energies used: Th C'' $E\gamma=2.615\pm 0.003$ (Ho 49a, Wo 50b); Na^{24} $E\gamma=2.75_5\pm 0.005$ (Ro 49b, Wo 50b).
[c] (Mobley and Laubenstein, private communication); based on $Li^7(p\ n)$ threshold 1.882 Mev.

Be 48a Bell and Elliott, Phys. Rev. **74**, 1552 (1948).
Be 50g Bell and Elliott, Phys. Rev. **79**, 282 (1950).
Ho 49a Hornyak, Lauritsen, and Rasmussen, Phys. Rev. **76**, 731 (1949).
Wo 50b Wolfson, Phys. Rev. **78**, 176 (1950).
See also: Am 36, We 37, Fr 38, Sp 38, Ma 42, Fe 43, Ha 43, Ku 44, Sc 45, Ba 47a, Wh 47, Re 48. (Theory) Bu 48b.

E. $H^2(\gamma\ n)p$

The reaction energy in the photo-disintegration of the deuteron has been determined by numerous experimenters. A detailed discussion is given by Stephens of the determination through the year 1946 (St 47a). Table III gives the results of the experiments to date.

The measurements involving the determination of the comparatively low energy of the photo-neutrons or photo-protons, when Th C'' or Na^{24} γ-ray sources are used, with the possible exception of Hansen's work, require difficult corrections and calibrations (i.e., stopping power corrections, multiple scattering corrections, low energy proton range-energy relationship, etc.) which in general are not very accurately known. The photo-disintegration of deuterium by Ra C γ-rays reported by Kimura and others is probably caused, as suggested by Mitchell *et al.* (Mi 36), by harder γ-ray components than the γ-ray γW (2.208 Mev). Evidence exists for such harder components: See the work of Ellis (El 34), Gray (Gr 37), Mann and Ozeroff (Ma 49b), and Wolfson (Wo 50b). Bishop *et al.* (Bi 49) have shown that the 2.21-Mev γ-ray component of Ga^{72} does not produce photo-disintegration in H^2; this gives a binding energy not less than 2.207 Mev. While the ratio of thresholds for the photo-disintegration of H^2 to Be^9 by x-rays and electrons has been accurately determined some years ago, an absolute voltage calibration which could be compared with the $Li^7(p\ n)$ or $F^{19}(p\ \alpha)$ standards was not available until the recent

TABLE IV.

$E_\gamma - E_B$[a] (Mev)	$\tau = 3a/2b$[c]	Reference
0.22	0.67 ± 0.27	Wo 49b
0.27	0.71 ± 0.27	Wo 49b
0.35	0.77 ± 0.22	Wo 49b
0.39 (Th C'')	0.39 ± 0.12	Gr 45
0.48	0.49 ± 0.07	Wo 49b
0.53 (Na^{24})	0.295 ± 0.036	Ge 49
0.53 (Na^{24})	0.26 ± 0.05	La 49
0.53 (Na^{24})	0.317 ± 0.012	Me 49
0.53 (Na^{24})	$0.30_8 \pm 0.08$	Ha 49e
0.66	0.27 ± 0.06	Wo 49b
$\sim$4.0[b]	$\sim$0.15	Go 50

[a] E_B taken as 2.23 Mev.
[b] $F+p$, γ-rays $\sim$80 percent 6.2 Mev; $\sim$20 percent 6.9–7.2 Mev.
[c] Some values do not include a small Doppler correction to convert from lab. system to c.m. system. See Ha 49d.

TABLE V.

$E_\gamma - E_B$ (Mev)[a]	$\sigma \times 10^4$ (barns)	Reference
0.39 (Th C'')	10 ± 0.8	Ha 38b
0.39 (Th C'')	14 ± 1.0	Wi 49
0.39 (Th C'')	13.9 ± 0.6	[b]
0.39 (Th C'')	$\sim$15.5	Elliott[c]
0.53 (Na^{24})	15.6 ± 1.0	Wi 49
0.53 (Na^{24})	15.9 ± 0.6	[b]
0.53 (Na^{24})	16 ± 4	Ru 48
0.53 (Na^{24})	$\sim$15	Segrè[c]
0.53 (Na^{24})	14.5 ± 1.5	Sn 49
2.22 [d]	24.3 ± 1.7[e]	[f]
3.91 [d]	21.9 ± 1.0[e]	[f]
3.91 [d]	26.9 ± 3.8	[g]
3.91 [d]	11.6 ± 1.5	Va 41a
3.91 [d]	21.5 ± 1.2	Ba 50d
5.16 [d]	18.4 ± 1.5[e]	[f]
5.91 [d]	16.4 ± 1.2[e]	[f]
10.3 [d]	10.4 ± 1.0[e]	[f]
15.4 [d]	7.7 ± 0.9[e]	[f]
15.4 [d]	8.5 ± 1.2	Ba 50d
15.4 [d]	8 ± 3	Wa 49h
15.4 [d]	7.8 ± 1.2	[h]

[a] E_B taken as 2.23 Mev.
[b] Halban, Harwell Conference 1950.
[c] Unpublished, see Wa 49e.
[d] γ-ray sources: 4.45 $N^{15}+p$, 6.14 $F^{19}+p$, 7.39 Be^9+p, 8.14 $C^{13}+p$, 12.5 $F^{19}+p$, 17.6 Li^7+p. All corrected for inhomogeneity in energy.
[e] Corrected to give electric dipole transition only.
[f] Wilkinson, private communication.
[g] Kruger, Harwell Conference 1950.
[h] Wäffler, Harwell Conference 1950.

work of Mobley and Laubenstein. For the best determination of the H^2 binding energy and the $n-H^1$ difference, see $n(\beta^-)H^1$ discussion of $n-H^1$ difference.

At low energies (up to several Mev above threshold) the photo-disintegration of deuterium is principally through electric and magnetic dipole capture (Ra 41, Be 47c, Ro 49a), higher multipole transitions being important only at much higher energies ($\sim$50 Mev) (Ro 47). At energies just above the threshold the magnetic dipole capture ($^3S_1$ ground state to $^1S_0$ virtual state) predominates, while at energies $\sim$1 Mev above threshold and higher the electric dipole capture ($^3S_1$ ground state to P-state continuum) becomes the predominant mode. On this model the photo-neutrons and -protons have an angular distribution in the center-of-mass system (virtually the same as in the laboratory system) $F(\theta)=a+b\sin^2\theta$, where the isotropic component is provided by the magnetic dipole transition and the $\sin^2\theta$ term arises from the electric dipole transition. The ratio $\tau=3a/2b=\sigma_m/\sigma_e$ has been determined by several observers and is given in Table IV.

Fuller (Fu 49, Fu 50)* finds the photo-protons for $E_\gamma \gtrsim 10$ Mev to have a slight asymmetry about $\theta_{c.m.}=90°$, there being more forward protons.

The photoelectric cross section at various energies has also been determined. Table V gives the results to date.

The earlier attempts to compare theoretical and observed cross sections and angular distributions were hampered by the low value used for the deuteron binding energy E_B (2.18_6 Mev), since these properties are a sensitive function of $E_\gamma - E_B$. Using simple rectangular well potentials Woodward and Halpern (Wo 49b) find that the angular distribution observed is consistent with the $n-p$ scattering parameters. See below.

State	Well depth (Mev)	Well width $\times 10^{13}$ (cm)
$^3S_1$ (ground)	-2.24	1.9
$^1S_0$	0.06_4	2.6

The effective triplet range determined by Wilkinson, private communication, is $(1.73 \pm 0.09)\times 10^{-13}$ cm.

Hansson and Hulthén (Ha 49d) have made a detailed comparison of various theoretical models and experiments; while no definite conclusions are arrived at, a meson mass of $\sim 300\,m_0$ seems to be indicated. For example, at $E_\gamma - E_B = 0.53$ (Na^{24}) the predicted values for a meson of mass 300 m_0 are $14.3<\sigma<14.8\times 10^{-4}$ b and $0.28_4<\tau<0.30_3$, these values compare favorably with the corresponding experimental values. See previous tables.*

St 47a Stephens, Rev. Mod. Phys. **19**, 19 (1947).
Be 47c Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).
Ho 49a Hornyak, Lauritsen, and Rasmussen, Phys. Rev. **76**, 731 (1949).
Wo 50b Wolfson, Phys. Rev. **78**, 176 (1950).
Ro 49b Robinson, Ter-Pogossian, and Cook, Phys. Rev. **75**, 1099 (1949).
Mi 36 Mitchell, Rasetti, Fink, and Pegram, Phys. Rev. **50**, 189 (1936).
El 34 Ellis, Proc. Roy. Soc. **143**, 350 (1934).
Gr 37 Gray, Proc. Roy. Soc. **159**, 263 (1937).
Ma 49b Mann and Ozeroff, Can. J. Research **27**, 164 (1949).
Bi 49 Bishop, Collie, Halban, and Wilson, Phys. Rev. **76**, 683 (1949).
Ra 41 Rarita and Schwinger, Phys. Rev. **59**, 436 (1941).
Ro 49a Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1949).
Ro 47 Rose and Goertzel, Phys. Rev. **72**, 749 (1947).
Ha 49d Hansson and Hulthén, Phys. Rev. **76**, 1163 (1949).
Fu 49 Fuller, Phys. Rev. **76**, 576 (1949).
Fu 50 Fuller, Phys. Rev. **77**, 752 (1950).
Gr 45 Graham and Halban, Rev. Mod. Phys. **17**, 297 (1945).
Wa 49e Wattenburg, N.R.C. No. 6 (1949).
Wo 49b Woodward and Halpern, Phys. Rev. **76**, 107 (1949).

* *Note added in proof:* For a more complete report on relative cross sections and angular distribution in the range $E_\gamma = 4.5-20.3$ Mev see Fuller, Phys. Rev. **79**, 303 (1950).

See also Ch 35, Ch 37a, Be 38b, Ha 38b, Ri 38, St 38b, Ki 39d, Ro 39, No 40, Va 41a, My 42, Go 44, Ha 45, Wi 45, Gi 47, Al 48b, La 48a, Ru 48, Wa 48a, Wi 48, Ge 49, La 49, Mc 49, Me 49, Me 49a, Pa 49, Sn 49, Wa 49h, Wi 49, Ha 49e, Ba 50d, Go 50. (Theory, representative selection only) Be 36, Le 49b, Ma 49c, Ro 49a, Be 50c, Le 50a.

E_1. $H^2(e, e'n)H^1$

A theoretical discussion of this reaction is given by Schlögl (Sc 49) who predicts a total cross section of the order of 10^{-31} cm^2 at $\sim$3 Mev above threshold.

Sc 49 Schlögl, Zeits. f. Naturforschung **4A**, 664 (1949).

F. $H^2(n\ 2n)p$

Bagge (Ba 42a) using a Ra—Be neutron source found evidence for a comparatively narrow group of proton tracks having a range of 10.0 to 11.5 cm (N.T.P.) in a cloud chamber filled with H^2, which he ascribed to this reaction. The cross section is estimated to be 0.3 b. (The exact interpretation of this experiment is not clear.)

Experiments by Halban *et al.* (Ha 41a) and Fenning and Knowles (Fe 44) designed to detect the $n\ 2n$ reaction in H^2 by surrounding a Ra—Be neutron source with heavy water were subject to corrections overlooked by these authors. See El 48a. Elliott, Hincks, and May (El 48a), using a Po—Be neutron source immersed in a spherical tank of heavy water, find the fraction of neutrons giving the $n\ 2n$ reaction to be 0.1 ± 2.7 percent. This result is lower ($\gtrsim\frac{1}{3}$) than the value of 2 b at 10 Mev predicted by Höcker (Ho 42) based on theoretical considerations. Other theoretical results give cross sections of 0.3 b at 30 Mev and 2 b at 17 Mev (Is 42, Is 42a).

Ageno *et al.* (Ag 47) estimate the $n\ 2n$ cross section to be $\sim$0.05 b at $E_n=14$ Mev (Li+d neutrons). Coon and Taschek (Co 49d) using $H^3(d\ n)$ 14-Mev neutrons give $\sim$0.05 b/sterad. as the upper limit for the differential cross section at $\theta_{c.m.}=0°$. (Both of these observations give cross sections smaller than that predicted by Höcker.)

Ba 42a Bagge, Physik. Zeits. **43**, 226 (1942).
Ha 41a Halban *et al*, British Atomic Energy Proj. Br-3 (1941).
Fe 44 Fenning and Knowles, Nat. Research Coun. Canada MP-41 (1944).
El 48a Elliott, Hincks, and May, Can. J. Research **26**, 386 (1948).
Ho 42 Höcker, Physik. Zeits. **43**, 236 (1942).
Ag 47 Ageno, Amaldi, Bocciarelli, and Trabacchi, Phys. Rev. **71**, 20 (1947).
Co 49d Coon and Taschek, Phys. Rev. **76**, 710 (1949).
See also: Is 42, Is 42a.

G. $H^2(n\ \gamma)H^3$

Early attempts at irradiating heavy water with slow neutrons (Bo 40) failed to produce a detectable amount of H^3. An upper limit of $\sim2\times10^{-4}$ b has been thus set for the cross section. This reaction has been recently detected for pile neutrons (Zi 43).

A theoretical estimate places the cross section at $\sim3\times10^{-3}$ b (Sc 37).

$Q=6.244\pm0.009$ Mev (Kinsey, private communication).

Bo 40 Borst and Harkins, Phys. Rev. **57**, 659 (1940).
Zi 43 Zinn, Wattenberg, and West, Plut. Proj. Report CP-781 (July, 1943).
Sc 37 Schiff, Phys. Rev. **52**, 242 (1937).

H. $H^2(p\ n)2p$

$\sigma\sim10^{-6}$ b $E_p=3.4$ Mev (Sm 48a)
$\sigma=14$ mb $E_p=5.1$ Mev (Ba 39)

A threshold determination gives $Q=-2.231\pm0.010$ Mev (using $Li^7(p\ n)E_{thr}=1.882$ Mev) (Sm 50, Sm 50b). There is some evidence (Je 50c) that neutrons are produced below the threshold through the double process of $p\ d$ scattering and $H^2(d\ n)He^3$.

Sm 48a Smith and Richards, Phys. Rev. **74**, 1871 (1948).
Ba 39 Barkas and White, Phys. Rev. **56**, 288 (1939).
Sm 50 Smith and Martin, Phys. Rev. **77**, 752 (1950).
Sm 50b Smith, Ph.D. thesis, University of Wisconsin (1950).
Je 50c Jennings, Leiter, and Sun, Tech. Report 1497, Westinghouse (March 20, 1950).

I. $H^2(p\ \gamma)He^3$

A weak non-resonant yield of γ-rays ($\sim10^{-11}$ γ per p) was observed for a thick D_2O target $0.5<E_p<1$ Mev (Cu 39). More recent work indicates that in the energy range 0.5 to 1.5 Mev the cross section follows the empirical expression

$$\sigma=0.74E^{0.72}\times10^{-29}\ \text{cm}^2.$$

The angular distribution is proportional to $\sin^2\theta$, where θ is in the laboratory system. The γ-ray energy is found to be 6.3 ± 0.3 Mev, indicating a transition directly to the ground state of He^3(Fo 49c).

Cu 39 Curran and Strothers, Proc. Roy. Soc. **172**, 72 (1939).
Fo 49c Fowler, Lauritsen, and Tollestrup, Phys. Rev. **76**, 1767 (1949).

J. $H^2(d\ p)H^3$

Early experiments indicated a reaction energy of 3.98 ± 0.02 Mev, a yield of 1 p per 10^6 d at $E_d=0.1$ Mev, and an asymmetrical angular distribution (Li 37).

A recent determination gives $Q=4.03_6\pm0.02_2$ Mev using a magnetic spectrometer (To 49a, To 49c) and the voltage scale of Herb *et al.* (He 49).

The cross section is found to increase rapidly from 15 kev ($\sigma=1.3\times10^{-4}$ b) to 300 kev ($\sigma=0.052$b) (Gr 46a, Br 48, Fr 48b, Sa 50). Numerous observations at low energies $E_d<400$ kev have shown that the angular distribution of protons in the center-of-mass system approximately follows the law $F(\theta)=a+b\cos^2\theta$ the ratio $A=b/a$ being an increasing function of the bombarding energy (Ha 39, Hu 40c, Ma 41b, Ma 42a, Br 48, Sa 50). See below.

E_d Kev	A
→0	→0.18
50	0.35
250	1.0
390	1.5

In the energy range $1<E_d<3.5$ Mev the reactions $H^2(d\ n)$ and $H^2(d\ p)$ behave similarly. The $d\ p$ total cross section reaches a broad maximum of 0.09 b at 2 Mev and remains almost constant to 3.5 Mev. The angular distribution in the center-of-mass system follows the law $F(\theta)=K(1+A\cos^2\theta+B\cos^4\theta)$. The coefficients are functions of energy, A going through zero at 1.5 Mev and being negative at higher energies, B being positive and increasing smoothly with energy (Bl 48). Differential cross sections of 16.2, 2.6, and 4.5 mb/sterad. at $\theta_{c.m.}=21°$, 49°, and 89°, respectively, are reported at $E_d=10$ Mev (Le 49a).*

Only one proton group is reported at $E_d=10$ Mev, thus indicating the absence of excited states in H^3 below 5 Mev (Ro 49c).

Flügge (Fl 38) has been able to show that the Hartree-Fock approximation for $l=0$ (S wave) gives about the right order of magnitude for the cross section at 150 kev ($\sim 10^{-2}$ b). Konopinski and Teller (Ko 48) analyzed the $H^2(d\ p)$ and $H^2(d\ n)$ data on angular distribution and find that an admixture of S and P waves with large spin orbit coupling is required to account for the observations at the lower energies. Nakamo (Na 49) has extended the analysis of Konopinski and Teller to include D wave effects in accounting for the higher energy experimental results which involve terms higher than $\cos^2\theta$. An extensive theoretical discussion of the centrifugal barrier penetration and spin orbit coupling is given by Beiduk, Pruett, and Konopinski (Be 50b).

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
To 49a Tollestrup *et al.*, Phys. Rev. **75**, 1947 (1949).
To 49c Tollestrup *et al.*, Phys. Rev. **76**, 181 (1949).
He 49 Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).
Gr 46a Graves, Graves, Coon, and Manley, Phys. Rev. **70**, 101 (1946).
Br 48 Bretscher, French, and Seidl, Phys. Rev. **73**, 815 (1948).
Fr 48b French, Phys. Rev. **73**, 1474 (1948).
Sa 50 Sanders, Moffatt, and Roaf, Phys. Rev. **77**, 754 (1950).
Ha 39 Haxby, Allen, and Williams, Phys. Rev. **55**, 140 (1939).
Hu 40c Huntoon, Ellett, Bayley, and Van Allen, Phys. Rev. **58**, 97 (1940).
Ma 41b Manning, Crenshaw, and Young, Phys. Rev. **59**, 941 (1941).
Ma 42a Manning, Huntoon, Myers, and Young, Phys. Rev. **61**, 371 (1942).
Bl 48 Blair *et al.*, Phys. Rev. **74**, 1599 (1948).
Le 49a Leiter, Meagher, Rodgers, and Kruger, Phys. Rev. **76**, 167 (1949).
Ro 49c Rosen, Tallmadge, and Williams, Phys. Rev. **76**, 1283 (1949).
Fl 38 Flügge, Zeits. f. Physik **108**, 545 (1938).
Ko 48 Konopinski and Teller, Phys. Rev. **73**, 822 (1948).
Na 49 Nakamo, Phys. Rev. **76**, 981 (1949).
Be 50b Beiduk, Pruett, and Konopinski, Phys. Rev. **77**, 622, 628 (1950).
See also: Pe 49a, Br 48, Sa 50.

TABLE VI.

Q (Mev)	Remarks	Reference
3.1	He^3 recoils, ion. chbr.	Ba 38
3.29 ±0.08	$n-p$ recoils, cl. chbr.	Bo 38a
3.31 ±0.03	$n-p$ recoils, cl. chbr.	Bo 41
3.30 ±0.01	Electrostatic analysis of He^3	Ar 48, Al 48a
3.23 ±0.02	Photo-plate $n-p$ recoils	Li 48
3.27 ±0.03	Correction of Bo 41	Li 48
3.256±0.018	Mag. spectrometer	To 49a, To 49c

* *Note added in proof:* For a more complete discussion see Leiter, Rodgers, and Kruger, Phys. Rev. **78**, 663 (1950).

TABLE VII.

$E_{\beta\ max}$ (kev)	Remarks	Reference
12 ±5	Magnetic field cut-off	Li 39
15 ±3	0.48±0.06 mg/cm² Al abs.	On 40a
(16 ±3)	Cl. chbr. 13±1 mm He^4; corrected by On 41a	Br 41
11 ±2	Accelerated betas through thin window	Wa 46
17.0	Cl. chbr.	By 48, By 49
17.9 ±0.3[a]	Proportional counter	Cu 48, Cu 49
18.0 ±0.5	Al abs. of brehmsstrahlung	Gr 49
18.9_5±0.5	Proportional counters	Ha 49b

[a] Visual limit 17.9 kev, Kurie plot extrapolation 18.1 kev.

K. $H^2(d\ n)He^3$

Early experiments (Li 37) notably by Amaldi, Hafstad, and Tuve showed a smooth increase in the neutron yield $0.2<E_d<1.0$ Mev ($\sigma=0.13$ b at 700 kev). Reaction energies ranging from 3.0 to 3.2 Mev were reported. Table VI summarizes the more recent determinations.

The yield of protons from the $H^2(d\ p)$ reaction to the yield of neutrons is 1.15±0.15, $E_d=26$–65 kev (Pe 49a).

$$\sigma=25\text{ mb},\quad E_d=119\text{ kev}\quad(\text{Ma 46c})$$
$$\sigma=84\text{ mb},\quad E_d=294\text{ kev}\quad(\text{Ma 46c}).$$

The cross section is essentially constant in the range $1<E_d<4$ Mev ($\sigma\sim 0.1$ b) (Hu 49d, Ha 49s)

$$\sigma=70\text{ mb},\quad E_d=10.3\text{ Mev}\quad(\text{Er 49}).$$

The forward yield of neutrons increases smoothly from 0.5 to 1.8 Mev while the 80° yield is almost constant. An angular distribution in the center-of-mass system of the form $F(\theta)=a+b\cos^2\theta$ is found to fit the neutron yield data well with $A=b/a$ varying from 1.8 at 0.5 Mev to 3.4 at 1.8 Mev (Be 46, Ha 49s). In the energy range 1 to 3.5 Mev there are more forward neutrons than predicted by the above expression and anomalies appear at 90° for the higher energies. The representation of the angular distribution becomes $F(\theta)=K(1+A\cos^2\theta+B\cos^4\theta)$ (Bl 48, Ha 49s)—see also $H^2(d\ p)$. A better empirical fit is obtained by including $\cos^6\theta$-terms, with A negative above 1.4 Mev (Hu 49d, Ha 49s). At $E_d=10.3$ Mev the differential cross section is $\sim$24, 2, and 5 mb/sterad. at $\theta_{c.m.}=0°$, 45°, and 90°, respectively (Er 49).

For theoretical considerations see $H^2(d\ p)$.

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Pe 49a Pepper, Can. J. Research **27**, 143 (1949).
Ma 46c Manley, Coon, and Graves, Phys. Rev. **70**, 101 (1946).
Hu 49d Hunter and Richards, Phys. Rev. **76**, 1445 (1949).
Ha 49s Hanson, Taschek, and Williams, Rev. Mod. Phys. **21**, 635 (1949).
Er 49 Erickson, Fowler, and Stovall, Phys. Rev. **76**, 1141 (1949).
Be 46 Bennett, Mandeville, and Richards, Phys. Rev. **69**, 418 (1946).
Bl 48 Blair, Freier, Lampi, Sleator, and Williams, Phys. Rev. **74**, 1599 (1948).
See also: La 37a, Ba 38, Bo 38a, Bo 41, Ri 41a, Al 48a, Ar 48, Li 48, Sm 48, To 49a, To 49c, St 50d.

L. $H^2(d\ \gamma)He^4$

An upper limit of $\sim 10^{-31}$ cm^2 was determined for this reaction near $E_d \sim 1$ Mev by Fowler, Lauritsen, and Tollestrup (Fo 49c). An explanation of this low cross section as compared to the $H^3(p\ \gamma)$ cross section of $\sim 2\times 10^{-28}$ cm^2 at 1 Mev is suggested. The state in He^4 responsible for the $H^3(p\ \gamma)$ reaction is presumed to be a ^1P state which cannot be produced by any combination of two deuterons.

Fo 49c Fowler, Lauritsen, and Tollestrup, Phys. Rev. **76**, 1767 (1949).

M. $H^3(\beta^-)He^3$

The end point of the β-spectrum has been determined by numerous investigators. Their results are given in Table VII.

The Kurie plot has been found to be straight from ~ 1 kev to the end point, indicating that the decay is simple and allowed. The neutrino mass is estimated to be $0 \leqslant \nu < 1$ kev (Cu 49, Ha 49b). A search for $\beta-\gamma$-coincidences indicates that less than one percent of the transitions are accompanied by γ-radiations (Cu 49).

The mean energy released in the β-decay by a calorimetric determination gives 5.69 ± 0.06 kev (Je 49). This value is in fair agreement with 6.5 kev determined from a droplet count in a cloud chamber (Ni 41) and with ~ 10 kev given by the number of ion pairs produced in a gas (Al 40d). The mean energy determined by (Je 49) gives an end point of 18.6 ± 0.2 kev using a Fermi "allowed" shape with the Coulomb correction (Sl 49).

Sherk (Sh 49c) has made a theoretical estimate of the probability of K-creation to normal β-decay. He finds that K, the ratio of K-creation to normal β-decay, is given by $K=0.24\ E_\beta^{-\frac{3}{2}}$ ($K=0.0030$, $E_\beta=18.5$ kev) for molecular H^3 and $K=0.45\ E_\beta^{-\frac{3}{2}}$ ($K=0.0056$, $E_\beta=18.5$ kev) for atomic H^3.

The half-life determinations are given below.

$T_{\frac{1}{2}}$ (yr.)	Reference
$31\ \pm 8$	On 40a
$10.7\ \pm 2.0$	Go 47, Sp 47
$12.1\ \pm 0.5$	No 47
12.46 ± 0.2	Je 49

Cu 49 Curran, Angus, and Cockroft, Phil. Mag. **40**, 53 (1949).
Ha 49b Hanna and Pontecorvo, Phys. Rev. **75**, 983 (1949).
Je 49 Jenks, Ghormley, and Sweeton, Phys. Rev. **75**, 701 (1949).
Ni 41 Nielsen, Phys. Rev. **60**, 160 (1941).
Al 40d Alvarez and Cornog, Phys. Rev. **57**, 248 (1940).
Sl 49 Slack, Owen, and Primakoff, Phys. Rev. **75**, 1448 (1949).
Sh 49c Sherk, Phys. Rev. **75**, 789 (1949).
See also: Li 39, On 40a, Br 41, On 41a, Wa 46, Go 47, No 47, Sp 47, By 48, Cu 48, Ma 48, By 49, Cu 49b, Gr 49.

N. $H^3(p\ n)He^3$

$Q=-763.7\pm 1$ Kev, using the $Al(p\ \gamma)$ resonance as 993.3 kev (Ta 49, Ta 49c).

The angular distribution of neutrons is found to be approximately isotropic in the center-of-mass system for $1.2<E_p<2$ Mev (Ta 49a), although there is an indication that terms as high as $\cos^3$ might be required (Ja 49). A differential cross section of $\sigma_{0°}=0.029$ b/sterad. and $\sigma_{117°}=0.035$ b/sterad. is found at $E_p=2$ Mev giving a total cross section of ~ 0.4 b (He 49a). The neutron yield is found to increase smoothly from the threshold to $E_p=2.5$ Mev ($\sigma=0.55$ b) (Ja 49, Ha 49s).

Ta 49 Taschek *et al.*, Phys. Rev. **75**, 1268 (1949).
Ta 49c Taschek *et al.*, Phys. Rev. **76**, 325 (1949).
Ta 49a Taschek *et al.*, Phys. Rev. **75**, 1361 (1949).
Ja 49 Jarvis *et al.*, Phys. Rev. **76**, 168 (1949).
He 49a Hemmendinger, Jarvis, and Taschek, Phys. Rev. **75**, 1291 (1949).
Ha 49s Hanson, Taschek, and Williams, Rev. Mod. Phys. **21**, 635 (1949).
See also: Go 49.

O. $H^3(p\ \gamma)He^4$

This reaction has been observed by the Los Alamos group (Ar 49). The γ-ray has an energy of ~ 20 Mev, the radiation thus being to the ground state. The angular distribution is anisotropic ($\sim\sin^2\theta$). The cross section is $\sim 3\times 10^{-28}$ cm^2 at 1.24 Mev rising to $\sim 10^{-27}$ cm^2 at 2.6 Mev (Ta 49e).

Ar 49 Argo *et al.*, Phys. Rev. **76**, 182 (1949).
Ta 49e Taschek, Phys. Rev. **76**, 584 (1949).

P. $He^3(n\ p)H^3$

The reported Q value of 736 ± 25 kev based on a cloud-chamber determination of the proton range (Hu 48b) has been corrected to 764 kev (Je 49b) using a newer range-energy relationship for the proton. This value compares favorably with 766 ± 10 kev from an ionization chamber measurement (Fr 50).

Pure He^3 exposed to thermal column neutrons follows the "$1/v$ law" for the cross section in the range 0.001–0.03 ev; $\sigma v=(11.2\pm 0.5)\times 10^6$ b$\times$meters$\times$sec.$^{-1}$ (~ 5100 b at 1/40 ev, i.e., thermal neutrons). The estimated thermal neutron scattering cross section is ~ 1 b (Ki 49).

The thermal neutron cross section is reported as 5040 ± 200 b, using pure He^3($\sigma_B=703$ b, thermal neutrons) (Co 49b).

Hu 48b Hughes and Eggler, Phys. Rev. **73**, 1242, 809 (1948).
Je 49b Jesse and Sadaukis, Phys. Rev. **75**, 1110 (1949).
Fr 50 Franzen, Halpern, and Stephens, Phys. Rev. **77**, 641 (1950).
Ki 49 King and Goldstein, Phys. Rev. **75**, 1366 (1949).
Co 49b Coon and Nobles, Phys. Rev. **75**, 1358 (1949).
See also: Co 47, Ba 49, Fr 49e, Go 49.

He^5

(Mass: 5.0137 amu)

I. (*a*) $H^2(t\ n)He^4$
(*b*) $H^3(d\ n)He^4$ $\Big\}\ Q_m=17.60\quad E_x=16.80$

(*a*) The excitation function from $15<E_t<125$ kev has been observed. It is found that in addition to the Gamow factor a resonance at $E_t=120$ to 340 kev, $\Gamma\sim 75$ kev is required to account for the observed data. The cross section at 75 kev is 1.1 b. The angular distribution of α-particles is essentially isotropic at 35 kev while at 75 kev there is a slight forward preference (Br 49a). The excitation function has been carried to 200 kev, showing a pronounced resonance at 155 ± 15 kev (Al 49b). Using the data of Bretscher and French (Br 49a) for the cross section at lower energies as a calibration, this work gives $\sigma_r\sim6$ b. A peak in the excitation function at ~0.32 Mev (for a 0.2-Mev thick target) is reported (Ba 48d). Hanson, Taschek, and Williams (Ha 49s) find that a good empirical fit is given to all the above data by taking the resonance at 96 kev, $\Gamma=174$ kev, and including a Gamow factor.

(*b*) This reaction has been studied in the range $1.0<E_d<2.5$ Mev and $45°<\theta_{\text{lab}}<135°$. The angular distribution shows strong asymmetry. The differential cross section is 23 mb/sterad. at 0° and 2 Mev (Ta 49b, Ta 49d, Ha 49s).

Br 49a Bretscher and French, Phys. Rev. **75**, 1154 (1949).
Al 49b Allan and Poole, Nature **164**, 102 (1949).
Ba 48d Baker, Holloway, King, and Schreiber, AECD 2226 (August 1948).
Ha 49s Hanson, Taschek, and Williams, Rev. Mod. Phys. **21**, 635 (1949).
Ta 49b Taschek, Hemmendinger, and Jarvis, Phys. Rev. **75**, 1464 (1949).
Ta 49d Taschek *et al.*, AECD 2250 (1949).

II. $H^3(t\ n)He^5$ $Q_m=10.6$ (not illustrated)

There is evidence that this reaction takes place—see He^6:$H^3(t\ n)$.

III. $He^4(n\ n)He^4$

An anomalous backward scattering of ~1-Mev neutrons in He^4 was observed, no other striking anomalies appearing up to $E_n\sim6$ Mev (St 39b, Ga 39a).

A more detailed study by Staub and Tatel (St 40) was reported to resolve this broad anomaly into a doublet at $E_n=0.95$ and 1.35 Mev. These experimenters conclude that S wave potential and resonance scattering can account for only one-fourth of the observed cross section which for backward scattering they give as ~0.65 b and ~0.4 b at 0.95 and 1.35 Mev, respectively. Rosenfeld (Ro 49a) states that Wenzel's criterion (We 34) for the maximum backward scattering cross section indicates nearly a pure $^2P_{3/2}$ resonance level. Bloch (St 39b) points out that an S wave resonance would be expected to have a larger width than a P wave resonance, being of the order of several Mev which is not in agreement with observation.

A detailed analysis based on the theory of resonance scattering developed by Bloch (Bl 40) and carried out by Staub and Tatel gives as the best fit to their experimental data either of the following alternatives:

Sign of δ_0	σ_0 (barns)	$E_{3/2}$ (Mev)	$E_{1/2}$ (Mev)	$\Gamma_{1/2,3/2}$ (kev)	Order of levels
+	0.7	0.76	1.08	320	Inverted
−	1.5	1.08	0.84	320	Regular

where the excitation energies are in the $(\alpha+n)$ complex center-of-mass system and $4\pi\lambda^2\sin^2\delta_0=\sigma_0$ is the pure potential scattering cross section. Carroll and Dunning (Ca 38) observe a thermal neutron cross section $\sigma_0=1.51$ b, the sign of δ_0 remaining undetermined, however. The value of Γ given here is in good agreement with the determination of $[(9/5)\times140=250\text{ kev}]$ given by Williams, Shepherd, and Haxby—see He^5:$Li^7(d\ \alpha)$.

Barschall and Kanner (Ba 40) have observed the angular distribution of the recoil α-particles (through their energy distribution) using $d+d$ neutrons ($E_n\sim2.5$ Mev). They find the alphas to be predominantly forward and estimate $\sigma\sim3$ b. Wheeler and Barschall (Wh 40) find that an analysis of this data requires strong outgoing S and $P_{1/2,3/2}$ waves, the difference in phase shifts for the P waves being of the order of 60°. Rosenfeld (Ro 49a) suggests that this difference is much larger than could be accounted for by the assumption by Staub and Tatel of a narrow resonance doublet at ~1 Mev. The analysis also gives some indication of weak $D_{3/2,5/2}$ waves.

Hall and Koontz (Ha 47) have studied the angular distribution of the recoil α-particles (through their energy distribution) for $0.6<E_n<1.6$ Mev. They find a total cross section of 6.8 b at ~1 Mev and find their data consistent with P scattering and the parameters given by Staub and Tatel; the sign of the splitting is not established, nor is the double peak ~1 Mev clearly resolved. In this experiment $Li^7(p\ n)$ neutrons were used. In view of the doublet structure of Be^7 any indicated splitting of the resonance in $He^4(n\ n)$ could be due to the slower neutron group (Ha 50a). Baskin *et al.* (Ba 50a) also fail to resolve the double peak $0.95<E_n<1.32$ Mev. Their investigation covered the range $E_n=40$ kev ($\sigma=0.8$ b) to $E_n=6.4$ Mev ($\sigma=2.3$ b), they find the scattering peak to occur at ~1.1 Mev ($\sigma=6.7$ b).

Goldstein (Go 50c) suggests an inverted P-doublet with the $P_{1/2}$ level 2–5 Mev higher than the ground state of He^5 as consistent with all the above experimental results and the $p-He^4$ scattering data concerning the mirror nucleus Li^5.

A detailed discussion of the P-doublet splitting is given by Dancoff (Da 40a) and Rosenfeld (Ro 49a). Dancoff estimates the splitting to be 3 to 4 kev with an inverted doublet for the Thomas relativistic spin-orbit coupling while he estimates the meson tensor spin-orbit coupling to give a "normal" doublet with a splitting of ~100 kev (Bethe's neutral meson theory). Since a larger spin-orbit coupling of another origin seems to be required for a ~300-kev splitting, Rosenfeld was lead to suggest the existence of a meson of spin one—the mixed meson theory could then provide the required coupling. (To date, however, it is not at all clear that the experimental results require such a large splitting, if indeed the doublet structure is real at all.)

St 39b Staub and Stephens, Phys. Rev. **55**, 131 (1939).
Ga 39a Gaerttner, Pardue, and Streib, Phys. Rev. **56**, 856 (1939).
St 40 Staub and Tatel, Phys. Rev. **58**, 820 (1940).

Ro 49a Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1949).
We 34 Wenzel, Zeits. f. Physik **90**, 754 (1934).
Bl 40 Bloch, Phys. Rev. **58**, 829 (1940).
Ca 38 Carroll and Dunning, Phys. Rev. **54**, 541 (1938).
Ba 40 Barschall and Kanner, Phys. Rev. **58**, 590 (1940).
Wh 40 Wheeler and Barschall, Phys. Rev. **58**, 682 (1940).
Ha 47 Hall and Koontz, Phys. Rev. **72**, 196 (1947).
Ha 50a Hall, Phys. Rev. **77**, 411 (1950).
Ba 50a Bashkin *et al.*, Phys. Rev. **77**, 748 (1950).
Go 50c Goldstein, Phys. Rev. **79**, 740 (1950).
Da 40a Dancoff, Phys. Rev. **58**, 326 (1940).
See also: (Theory) Ty 39, Ki 42, No 46a.

IV. (*a*) $He^4(d\,p)He^5$ $Q_m=-3.0$
(*b*) $He^4(d\,pn)He^4$ $Q_m=-2.18$

(*a*) Guggenheimer, Heitler, and Powell (Gu 47) report a homogeneous proton group for $E_d=6.5$ Mev and give $Q=-2.9$ Mev.

(*b*) This reaction has also been observed—see Li^6.

Gu 47 Guggenheimer, Heitler, and Powell, Proc. Roy. Soc. **190**, 196 (1947).

V. (*a*) $Li^7(d\,n)Be^8$ $Q_m=15.03$
(*b*) $Li^7(d\,\alpha)He^5$ $Q_m=14.3$
(*c*) $Li^7(d\,n)2He^4$ $Q_m=15.15$

Reactions (*a*) and (*c*) are discussed under the compound nucleus Be^9, in addition, reaction (*a*) is further discussed under Be^8.

(*b*) Williams, Shepherd, and Haxby (Wi 37) (Wi 37c) observed a homogeneous α-particle group of 7.10-cm range ($E_d=0.2$ Mev) and conclude that the He^5 formed is unstable by 0.93 Mev [$Q=14.3$ Mev and instability 0.78 Mev (Li 37)]. The α-group was observed to have a width of 0.14 Mev.

Staub and Stephens (St 39a) confirm the presence of the 7-cm α-particle group and find a plateau in the neutron spectrum which they interpreted as caused by neutrons from the He^5 breakup. Richards (Ri 41) observed the neutron spectrum by a photographic plate technique but could not confirm the plateau reported by Staub and Stephens. He does not, however, consider that his data excludes the existence of reaction (*b*).* Lattes, Fowler, and Cuer (La 47b) give $Q=13.43$ for the homogeneous α-group, observed in a photographic emulsion.

Buechner (Oak Ridge Symposium, June 8–9, 1950) tentatively reports a broad α-group indicating a possible excited state $\sim$2 Mev above the virtual ground state.

Wi 37 Williams, Shepherd, and Haxby, Phys. Rev. **51**, 888 (1937).
Wi 37c Williams, Shepherd, and Haxby, Phys. Rev. **52**, 390 (1937).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
St 39a Staub and Stephens, Phys. Rev. **55**, 845 (1939).
Ri 41 Richards, Phys. Rev. **59**, 796 (1941).
La 47b Lattes, Fowler, and Cuer, Proc. Phys. Soc. London **59**, 883 (1947).

* *Note added in proof:* The continuum of neutrons from $Li^7(d\,\alpha)He^5 \rightarrow He^4+n$ has been verified by Whitehead (Phys. Rev. **79**, 393, 1950.) With enriched Li^7 and using nuclear emulsion recoils.

TABLE VIII

Reaction	Q (Mev)	(Mev)	Γ_{obs} (kev)	Γ_{true} (kev)
$He^4(n\,n)He^4$	—	0.80	$\sim$400.	320.
$He^4(d\,p)He^5$	-2.9	0.68	200.	240.
$Li^7(d\,\alpha)He^5$	14.3	0.75	140.	250.
$Li^7(d\,\alpha)He^5$	13.43	1.62	—	—
Weighted mean		0.87		270.

VI. $Be^9(\alpha\,\alpha')Be^8+n$ $Q_m=-1.63$
$Be^9(\alpha\,\alpha')He^5+\alpha$ $Q_m=-2.4$
$Be(\alpha\,\alpha')2He^4+n$ $Q_m=-1.58$

See Be^9 and C^{13}.

General

The main experimental facts concerning the virtual ground state of He^5 are summarized in Table VIII. Thus the instability to decay into an α-particle and a neutron is $\sim$0.87 Mev, while the width $\sim$0.27 Mev gives a mean life of 2.4×10^{-21} sec.

He^5 Theory

Unstable. Shell: $\alpha+1p_{\frac{3}{2}}^1$ (neutron). Expected state $^2P_{\frac{3}{2}}$, odd.

The proved instability of this nucleus is the most direct evidence for the saturated character of the α-particle. The mean life of the "ground state" is seen in the width of the scattering resonance discussed in Section III. It is about 2.4×10^{-21} sec., a few score vibrations of the compound system. The character of the state is of importance. From the general arguments about the closed shell configuration of the α-particle, with all four of its nucleons in the same space state, we expect the ground state here to be at least a P state, and the tensor forces presumably mix in $D_{\frac{3}{2}}$ and $S_{\frac{1}{2}}$ states with the predominant $^2P_{\frac{1}{2}}$ and $^2P_{\frac{3}{2}}$. The originally apparent resolution of the doublet states now seems experimentally uncertain. It is not unlikely that the main contribution comes from the $I=\frac{3}{2}$ state, with its higher statistical weight, arguing from the strong backscattering at the resonance peak. (Ro 49a, p. 362).

Ro 49a Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1949).

Li^5

(Mass: 5.0136)

I. (*a*) $He^3(d\,p)He^4$ $Q_m=18.34$
(*b*) $H^2(He^3\,\alpha)p$

(*a*) Allred (Al 50b) using 10.2-Mev deuterons reports that no excited states in He^4 below 21 Mev are formed with differential cross sections $\geqslant0.2$ mb. Wyly, Sailor, and Ott (Wy 49b) using absorption measurements find a value of $Q=18.5\pm0.1$ Mev. The angular distribution of the protons $0<\theta<120°$ at $E_d=3.17$ Mev is of the form $1.22+0.60\,P_2+0.23\,P_4$ where P_2 and P_4 are the respective Legendre polynomials.

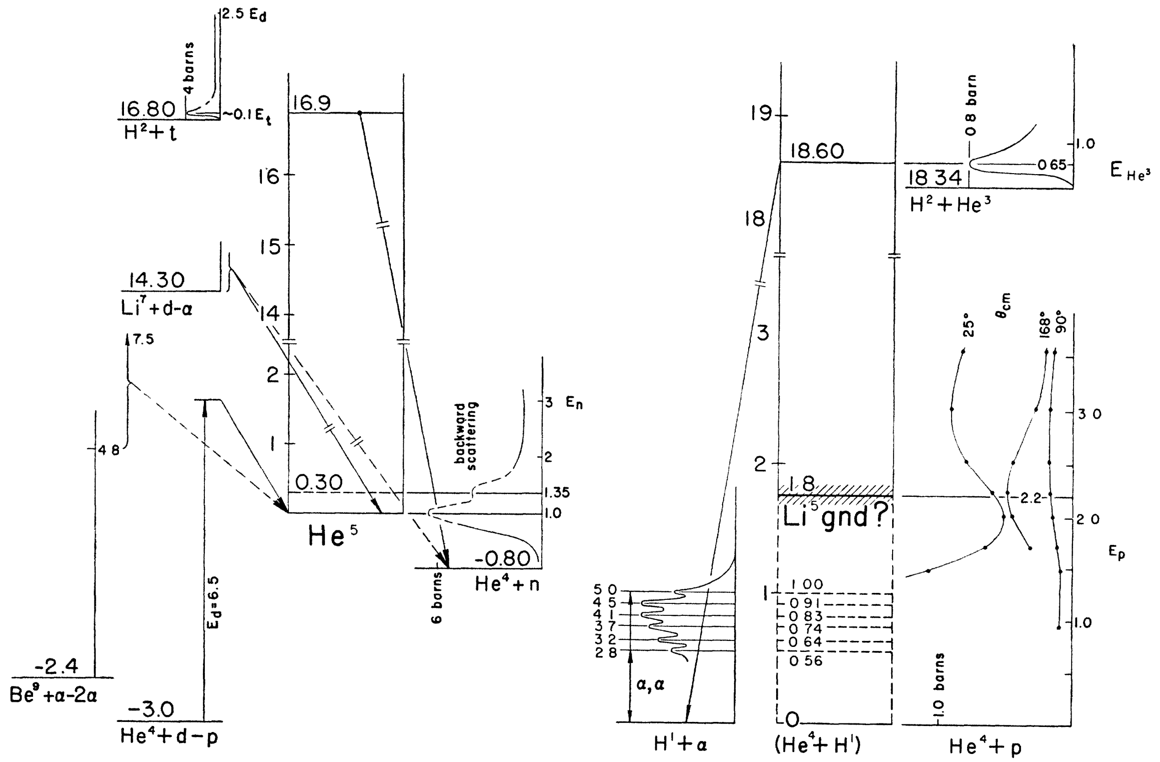

FIG. 1. Energy levels in He^5 and Li^5. In these diagrams energy values are plotted vertically in Mev, based on the ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Total energy change in positron decay is $E_{\beta\max}+2m_0c^2$.

(*b*) The yield of long-range protons has been observed by Hatton and Preston (Ha 49h) in the range $80<E_d<180$ kev. The yield is found to follow a Gamow function increase, an extrapolation to 1 Mev gives 10^7 protons/min./μa He^3 ions. Baker, Holloway, King, and Schreiber (Ba 48c) bombarded heavy hydrogen with He^3 up to 1.04 Mev in energy. They observed a broad (~0.6 Mev wide) resonance at 0.65 Mev, indicating an excited state in Li^5 at 18.60 Mev above the $(p+\alpha)$ complex. Observation of the yield at 90° and 0° showed that at energies below 0.45 Mev there is a larger yield at 90° while above this energy the reverse is true.

Al 50b Allred, Phys. Rev. **77**, 753 (1950).
Wy 49b Wyly, Sailor, and Ott, Phys. Rev. **76**, 1532 (1949).
Ha 49h Hatton and Preston, Nature **164**, 143 (1949).
Ba 48c Baker *et. al.*, AECD 2189 (August, 1948).

II. (*a*) He^4(p p)He^4
(*b*) H^1(α α)H^1

(*a*) The scattering of protons by He^4 has been investigated for $0.9<E_p<4$ Mev and $10°<\theta<170°$ (He 41, He 47, Fr 49c). A broad maximum (width ~1 Mev) in the cross section for backward scattered protons at $E_p\sim 2.2$ Mev is found; the differential resonant cross section being 0.475 b/sterad. ($\theta=168°$, Fr 49c).

Stephens (St 40a) using the central model of Bethe (Be 38a) normalized for the N$^{13}-$C^{13} Coulomb difference (2.97±0.05 Mev) calculates a Li$^5-$He^5 Coulomb difference of 0.86 Mev. This value agrees well with the observed difference of $\frac{4}{5}\times(2.2-1.0)=0.96$ Mev, assuming the excitation in the $(p+\alpha)$ complex at $E_{\text{c.m.}}=\frac{4}{5}\times 2.2=1.8$ Mev represents the virtual ground state of Li^5, see also He^5, He^4(n n).

Tsien (Ts 44) (Ro 49a) finds by comparing the data on backward scattering ($\theta=140°$) of (He 41) with the maximum backward cross section predicted by theory (We 34) that the data is compatible with a resonance level ($E_{\text{c.m.}}\sim 1.7$ Mev) which is nearly a pure ${}^2P_{\frac{3}{2}}$ state. Landau and Smorodinsky (La 44) (Ro 49a) report that a more complete analysis requires three states: (S_0?), ${}^2S_{\frac{1}{2}}$, ${}^2P_{\frac{1}{2}}$, and ${}^2P_{\frac{3}{2}}$. These conclusions are also arrived at by Critchfield and Dodder (Cr 49a) who require a small S wave phase shift and ${}^2P_{\frac{1}{2},\frac{3}{2}}$ phase shifts to account for the angular distribution.

(*b*) Tsien (Ts 40) reports six narrow resonances in the cloud-chamber study of the scattering of Po-α-particles in hydrogenous materials: the resonances are at $E_\alpha=2.78$, 3.20, 3.70, 4.14, 4.54, and 5.02 Mev (all ±0.10 Mev). Excitations in the $(p+\alpha)$ complex at $E_{\text{c.m.}}=0.556$, 0.640, 0.740, 0.828, 0.908, and 1.004 Mev (all ±0.020 Mev) are indicated. These virtual states are all *below* the resonance at $E_{\text{c.m.}}=1.6-1.8$ Mev observed by Heydenburg and Ramsey (He 41), and Frier *et al.* (Fr 49c). To date these results have not been confirmed.

Beck and Tsien (Be 42a) (Ts 44) using the theory developed by Wenzel (We 34) (Ro 49a) find the data (Ts 40) to be consistent with $I=\frac{1}{2}$ for all six levels. A mixture of $S_{\frac{1}{2}}$ and $P_{\frac{1}{2}}$ waves with $14 \leqslant |S_{\frac{1}{2}}/P_{\frac{1}{2}}| \leqslant 86$ percent is required for these levels.

He 41 Heydenburg and Ramsey, Phys. Rev. **60**, 42 (1941).
He 47 Heitler, May, and Powell, Proc. Roy. Soc. **190**, 180 (1947).
Fr 49c Frier, Lampi, Sleator, and Williams, Phys. Rev. **75**, 1345 (1949).
St 40a Stephens, Phys. Rev. **57**, 938 (1940).
Be 38a Bethe, Phys. Rev. **54**, 436 (1938).
Ts 44 Tsien, Comptes Rendus **218**, 996 (1944).
Ro 49a Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1949).
We 34 Wenzel, Zeits. f. Physik **90**, 754 (1934).
La 44 Landau and Smorodinsky, J. Phys. USSR **8**, 154 (1944).
Cr 49a Critchfield and Dodder, Phys. Rev. **76**, 602 (1949).
Ts 40 Tsien, J. de phys. et rad **1**, 1 (1940).
Be 42a Beck and Tsien, Phys. Rev. **61**, 379 (1942).
See also: Mo 37, He 39, Ba 50. (Theory) Do 49.

Li^5 Theory

Unstable. Shell: $\alpha+1p_{\frac{3}{2}}{}^1$ (proton). State expected $^2P_{\frac{3}{2}}$, odd.

Plainly less stable than the already unstable He^5 by the Coulomb repulsion of the odd proton. The level which was studied in the α-particle-neutron scattering shows up here in the α-proton scattering, but with similar uncertainties. The width of around 1 Mev is confirmed, and the greater accuracy available for proton-scattering measurements makes a little stronger the assignment of the doublet P character to the five-nucleon ground state, mainly with $I=\frac{3}{2}$, but certainly unresolved into separated components. The other states claimed below 18.6 Mev have no theoretical support.

He^6

(Mass: 6.0209)

I. $He^6(\beta^-)Li^6$ $Q_m=3.6$

The determinations of the β-spectrum end point are summarized in Table IX.

The half-life determinations are: 0.85±0.05 sec. (So 46), 0.82±0.06 sec. (Kn 48a, Kn 48b), 0.87±0.06 sec. (Ca 47), 0.89±0.03 sec. (Hu 46b), 0.823±0.013 sec. (Ho 49b), 0.84±0.02 sec. (Ru 50).

The shape of the spectrum is of the simple allowed type down to ~200 kev (Pe 50). No evidence has been found for γ-radiation other than that due to bremsstrahlung (So 46, Kn 48a, Kn 48b).

Allen, Paneth, and Morrish (Al 49) observe β-recoil ion coincidences at 162° and 180° and found the $1-(v/3c)\cos\theta$ correlation (axial vector-interaction) to fit the data best (although an isotropic distribution could not be ruled out).

Pe 50 Perez-Mendez and Brown, Phys. Rev. **77**, 404 (1950).
So 46 Sommers and Sherr, Phys. Rev. **69**, 21 (1946).
Kn 48a Knox, Phys. Rev. **74**, 1192 (1948).
Kn 48b Knox, University of California Rad. Lab. Report UCRL-159 (August 1948).

TABLE IX.

$E_{\beta\,max}$ (Mev)	Comments	Reference
3.7 ±0.2	Feather analysis, Al abs. 1.8_{5-8} mg/cm²	Kn 48a, Kn 48b
3.7 ±0.5	Cl chbr.	Bj 36, Bj 38b
3.5 ±0.6	Al abs.	So 46
3.2 ±0.2		Ru 50
3.215±0.015	Semicircular spectrometer	Pe 50

Al 49 Allen, Paneth, and Morrish, Phys. Rev. **75**, 570 (1949).
See also: Bj 36, Bj 38b, Hu 46b, Ca 47, Ho 49b.

II. (*a*) $H^3(t\,\alpha)2n$ $Q_m=11.44$ $E_x=12.2$
(*b*) $H^3(t\,\alpha)n^2$ $Q_m=11.44$*
(*c*) $H^3(t\,n)He^5$ $Q_m=10.6$

The above reactions have been observed at the Los Alamos and Chalk River Laboratories (Lo 50, Sa 50a, Al 50a, Oak Ridge Symposium June 8–9, 1950).

The energy distribution of neutrons (recoil protons in a photographic plate) shows the continuum from below 1 Mev to an upper limit of 9.5 Mev ($E_t=0.22$ Mev) to be expected from reaction (*a*). There is some evidence (total intensity <10 percent) for a small peak (8.5 to 9 Mev) which might be attributed to reaction (*c*).

The total neutron yield varies from 0.011 b/sterad. at 0° (lab. angle) to 0.0075 b/sterad. at 100° (lab. angle) with $0.6<E_t<0.8$ Mev. The total cross section as a function of energy $0.4<E_t<1.4$ Mev has been observed.

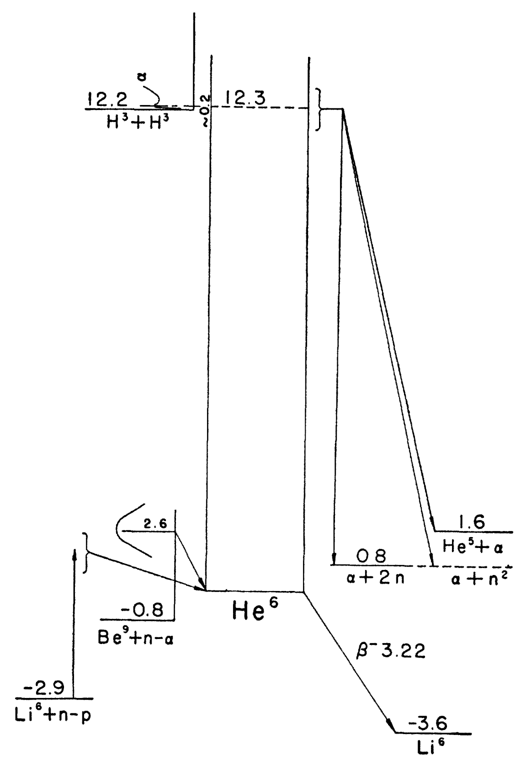

FIG. 2. Energy levels in He^6: for notation see Fig. 1. *Note added in proof:* At 1.6 Mev excitation $He^5+\alpha$ should read He^5+n.

A magnetic analysis of the α-particles shows the continuum expected from reaction (a).

There is preliminary evidence from Los Alamos (not confirmed at Chalk River) for a discrete α-group corresponding to the formation of the dineutron n^2 indicated in reaction (b). The thin target α-particle yield exhibits a resonance at ~200 kev, corresponding to a level in He^6 at ~12.3 Mev. H^2 contamination might affect both the above results (Hemmendinger, private communication).

* Assuming the virtual state of n^2 has near zero binding.

Lo 50 Los Alamos Scientific Laboratory, Phys. Rev. **79**, 238 (1950).
Sa 50a Sanders *et al.*, Phys. Rev. **79**, 238 (1950).
Al 50a Allen *et al.*, Phys. Rev. **79**, 238 (1950).

III. $Li^6(n\ p)He^6$ $Q_m=-2.9$

See Li^7.

IV. $Li^7(\gamma\ p)He^6$ $Q_m=-10.1$ (not illustrated)

See Li^7.

V. $Be^9(n\ \alpha)He^6$ $Q_m=-0.8$

See Be^{10}.

He^6 Theory

Beta$^{(-)}$-active; no measured ground state properties. Shell: $\alpha+1p_{\frac{3}{2}}^2$ (neutrons); $^1S_0$, even.

The value of the product $\langle|\sigma|^2\rangle ft_{\frac{1}{2}}$ of β-decay theory is 3500 sec., taking the matrix element $\langle|\sigma|^2\rangle=6$, expected for the mainly $^1S_0\rightarrow{}^3S_1$ transition (confirmed by the more general supermultiplet formulation) (Ko 43c). This is only about 20 percent higher than the value for the transition $H^3\rightarrow He^3$ which takes place without the necessity of spin change. The spatial wave functions for this nucleus and the daughter Li^6 thus seem to overlap surprisingly well when the nearly 3-Mev spin-produced difference in binding (after Coulomb correction) is recalled. The expected dominant part of the ground state wave function is $^1S_0$; the singlet state of the deuteron plus an α-core.

Ko 43c Konopinski, Rev. Mod. Phys. **15**, 209 (1943).

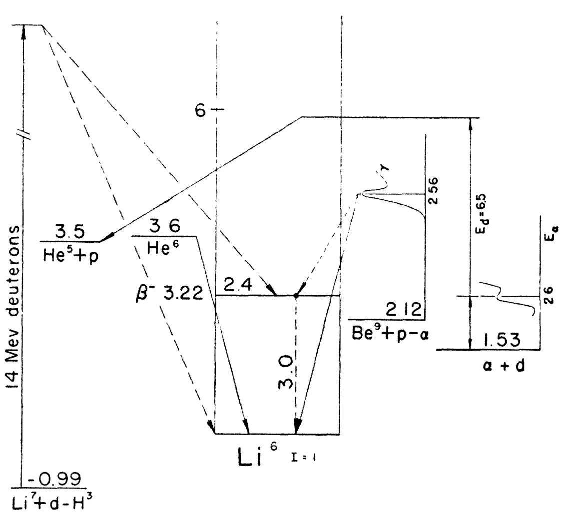

FIG. 3. Energy levels in Li^6: for notation see Fig. 1.

Li^6

(Mass: 6.01697)

I. $He^4(d\ d)He^4$ $E_x=1.53$
$H^2(\alpha\ \alpha)H^2$

The scattering of deuterons in He^4 has been observed for $E_d=0.9$ to 6.5 Mev and for scattering angles from 15° to 160° (He 39, Bl 49, Gu 47). The scattering at 6.5 Mev requires S, P, and D waves to account for the angular distribution observed (Gu 47).

Pollard and Margenau (Po 35a, Po 35b) find a resonance yield in the recoil deuterons when α-particles of ~2.6 Mev energy are scattered in heavy hydrogen. A level in Li^6 at ~2.4 Mev is thus indicated; the corresponding anomaly in the scattering of deuterons in helium would be expected to occur at $E_d\sim1.3$ Mev. The scattering of α-particles in the range 1 to 3 cm by Mohr and Pringle (Mo 37) does not show any well-defined resonance at 1.4 cm (~2.6 Mev).

He 39 Heydenburg and Roberts, Phys. Rev. **56**, 1092 (1939).
Bl 49 Blair, Freier, Lampi, and Sleator, Phys. Rev. **75**, 1678 (1949).
Gu 47 Guggenheimer, Heitler, and Powell, Proc. Roy. Soc. **190**, 196 (1947).
Po 35a Pollard and Margenau, Phys. Rev. **47**, 571 (1935).
Po 35b Pollard and Margenau, Phys. Rev. **47**, 833 (1935).
Mo 37 Mohr and Pringle, Proc. Roy. Soc. **160**, 190 (1937).

II. (a) $He^4(d\ p)He^5$ $Q_m=-3.0$ $E_x=1.53$
(b) $He^4(d\ pn)He^4$ $Q_m=-2.18$

(not illustrated)

Both the homogeneous energy protons from reaction (a) and the continuum from reaction (b) were observed at $E_d=6.5$ Mev (Gu 47). See also He^5: $He^4(d\ p)$.

Gu 47 Guggenheimer, Heitler, and Powell, Proc. Roy. Soc. **190**, 196 (1947).

III. $He^6(\beta^-)Li^6$

See He^6

IV. $Li^7(d\ t)Li^6$ $Q_m=-0.99$

There is evidence from this reaction for a level in Li^6 at ~2.3 Mev (Boyer, private communication).

V. $Be^9(p\ \alpha)Li^6$ $Q_m=2.12$

The resonant yield of 3.0-Mev γ-radiation observed by Hushley (Hu 45) when Be^9 is bombarded with 2.56-Mev (Herb's voltage scale) protons may be caused by this reaction, indicating a possible level in Li^6 at ~3.0 Mev.

Summary of Q Determinations

2.115±0.04	Al 40a (correction to Al 38a)
2.078±0.04	Ma 40 (correction to Al 38a)
2.074±0.03	Ro 48b
2.121±0.012	To 49b
2.142±0.006	(Strait *et al.*, private communication)

See also B^{10}: $Be^9(p\ \alpha)$

Hu 45 Hushley, Phys. Rev. **67**, 34 (1945).
Al 40a Allison, Skaggs, and Smith, Phys. Rev. **57**, 550 (1940).
Al 38a Allison, Skaggs, and Smith, Phys. Rev. **54**, 171 (1938).
Ma 40 Mattauch, Phys. Rev. **57**, 550 (1940).
Ro 48b Rosario, Phys. Rev. **74**, 304 (1948).
To 49b Tollestrup, Fowler, and Lauritsen, Phys. Rev. **76**, 428 (1949).

Li^6 Theory

$\mu=0.822$; $|Q|<10^{-3}$; $I=1$. A one-particle model predicts the α-core $+1p_{\frac{3}{2}}{}^1$ (proton) $+1p_{\frac{3}{2}}{}^1$ (neutron), with the lowest state $^3S_1$, even.

This nucleus is the homologue of the deuteron, admitting that the triplet-singlet spacing is about 3 Mev here (from the He^6 singlet state) instead of some 2.3 Mev. The magnetic moments are very close, though the quadrupole moments are not. The tensor forces here can mix in not only the $^3D_1$ state as in the deuteron, but also the $^3P_1$ and $^1P_1$; spin is no longer a strict constant of the motion as it is for the two-body system. The "singlet" state at about 2.4 Mev may have been observed. The β-transition to this state is infrequent even if allowed, perhaps one part in a few thousand from the available energy alone; it is unobserved. This stable nucleus is well described by any reasonable model which does not insist on rigid $L-S$ coupling.

Li^7

(Mass: 7.018 22)

I. $Li^6(n\ p)He^6$ $Q_m=-2.9$ $E_x=7.15$

He^6 identified by β-spectrum (Po 46).

Po 46 Poole and Paul, Nature **158**, 482 (1946).
See also: Na 37, Ve 37, Bj 38a, Bj 38b.

II. $Li^6(n\ \alpha)H^3$ $Q_m=4.64$ $E_x=7.15$

Resonance at $E_n=0.27$ Mev, $\sigma_R=3$ b (Li^6) (Go 47a).
$\sigma(n\ \alpha)$ thermal $=870$ b (Li^6) (Wa 48d).
$\sigma(Li)/\sigma(B)$ thermal $=0.095$ (Fe 47a).

TABLE X. Q determinations.

Q (Mev)	Method	Reference
4.86	Range of $H^3=5.90\pm0.06$ cm	Li 38
4.97	Range of α	Ru 38
4.70±0.3	Photo-plate	Fa 48b
4.66	Photo-plate	Ch 49g
4.69±0.1	Photo-plate	Na 49b
4.56	Range of $\alpha=1.04\pm0.02$ cm[a]	Bo 49
4.92	Range of $H^3=6.00\pm0.06$ cm[a]	Bo 49

[a] Range of α and H^3 in this reaction now used as a fixed point on range-energy curves (Be 50d, Je 50). Quoted Q's from old range-energy curves.

An absolute cross-section curve is given in Go 47a. There is some possibility that the 0.27-Mev resonance in the α-particle yield from $Li+n$ may actually be due to the sequence of reactions $Li^7(n\ \gamma)Li^8(\beta^-)Be^8\rightarrow 2\alpha$, since $Li^7(n\ n)$ shows a resonance at 0.27 Mev. See Li^8: $Li^7(n\ n)$. However, Keepin and Roberts (Ke 50) have observed the resonance in the distribution of α-particle plus triton tracks in Li^6 loaded emulsions exposed to scattered neutrons. (See Table X.)

Q from Q of $Li^6(p\ \alpha)He^3+Q$ of $He^3(n\ p)H^3=4.785\pm0.03$ (To 50).

Go 47a Goldsmith, Ibser, and Feld, Rev. Mod. Phys. **19**, 259 (1947).
Wa 48d Way and Haines, AECD 2138 (1948).
Fe 47a Fenning, Graham, and Seligman, Can. J. Research **25**, 77 (1947).
Ke 50 Keepin and Roberts, Rev. Sci. Instr. **21**, 167 (1950).
To 50 Tollestrup, Fowler, and Lauritsen, Phys. Rev. **78**, 372 (1950).
See also: Li 38, Ru 38, Ha 46, Fa 48b, Ch 49g, Na 49b, Ho 49g, Bo 49, Sh 49b, Ad 50, Be 50d, Je 50.

III. $Li^6(d\ p)Li^7$ $Q_m=4.97$

$Q=5.019\pm0.005$ Mev (spectrometer) (St 49b, Strait *et al.*, private communication).

ΔQ from proton groups: 483±6 kev (spectrometer) (Bu 48c).

ΔQ from γ-ray: 478±3 kev (spectrometer) (La 50).

The relative yield of short-range protons depends on bombarding energy: see Be^8.

St 49b Strait and Buechner, Phys. Rev. **76**, 1766 (1949).
Bu 48c Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).
La 50 Lauritsen and Thomas, Phys. Rev. **78**, 88 (1950).
See also: Wi 37c, Ru 38, Po 42, La 47b, Cu 50a.

IV. $Li^7(p\ p')Li^{7*}$

ΔQ from proton groups: 479.0±1.0 kev (Fo 49b).
ΔQ from γ-ray: 476.7±1 kev (Ho 49a).[a]

[a] Includes a 1.6 kev Doppler correction.

The angular distribution of γ-radiation is isotropic for $E_p=0.8$ to 1.08 Mev, implying $I=\frac{1}{2}$ for the excited state (Li 50a).

Fo 49b Fowler and Lauritsen, Phys. Rev. **76**, 314 (1949).
Ho 49a Hornyak, Lauritsen, and Rasmussen, Phys. Rev. **76**, 731 (1949).
Li 50a Littauer, Proc. Phys. Soc. **63**, 294 (1950).
See also: Fo 39, Hu 40, Ru 48a, Fo 49a.

V. $Li^7(\alpha\ \alpha')Li^{7*}$

Gamma-ray energy $=462$ kev (Si 46a).

The yield of γ-rays rises smoothly from $E_\alpha=2.3$ to 5.3 Mev (Sl 48b).

Si 46a Siegbahn and Slätis, Arkiv. f. Ast. Math. Fys. **34A**, No. 15 (1946).
Sl 48b Slätis, Nature **161**, 899 (1948).
See also: Bo 36a, Sp 36, Si 47.

VI. $Li^7(\gamma\ p)He^6$ $Q_m=-10.1$

Threshold 9.8±0.5 Mev (Mc 49).

TABLE XI. Range of α-groups.[a]

α_0	α_1	I_0/I_1	Reference
0.94	0.64		Ha 37
0.80	0.66		Li 38
0.89	0.715		Oc 38
(0.88)	(0.74)		Ku 38
	0.735	8.6/91.4	Bo 38, Gi 48a, Je 50
(0.835)	0.70	7/93	Bo 45
	(0.720—best mean: Je 50)		

[a] The range of α_1 is used as a fixed point in the range-energy relation (Be 50d, Je 50).

Note added in proof: Observation of $Li^7(\gamma\ \alpha)H^3$ has been reported, Titterton, Proc. Phys. Soc. London **63**, 915 (1950).

Mc 49 McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).

VII. $Be^7(K)Li^7$ $Q_m = 0.88$

Q from $n-p$ difference $-Q$ of $Li^7(p\ n) = 0.863 \pm 0.003$.

ΔQ from γ-ray: 474±4 kev (Za 48), 485±5 kev (Ku 48), 476.7±0.8 kev (Ho 49a, Ra 49a), 478.5±0.5 kev (Te 49b).

Fraction of transitions to Li^{7*}: 0.107±0.02 (Wi 49b); 0.1 to 0.13 (Tu 49a).

Za 48 Zaffarano, Kern, and Mitchell, Phys. Rev. **74**, 105 (1948).
Ku 48 Kurie and Ter-Pogossian, Phys. Rev. **74**, 677 (1948).
Ho 49a Hornyak, Lauritsen, Lauritsen, and Rasmussen, Phys. Rev. **76**, 731 (1949).
Ra 49a Rasmussen, Lauritsen, and Lauritsen, Phys. Rev. **75**, 199 (1949).
Te 49b Ter-Pogossian, Robinson, and Goddard, Phys. Rev. **76**, 1407 (1949).
Wi 49b Williamson and Richards, Phys. Rev. **76**, 614 (1949).
Tu 49a Turner, Phys. Rev. **76**, 148 (1949).
See also: Ma 38, Ru 38, Ma 39, Hi 39a, Ru 41a, Zl 42, Ru 46, Si 46, Ra 49b.

VIII. $Be^9(d\ \alpha)Li^7$ $Q_m = 7.09$

$Q = 7.093 \pm 0.022$ Mev (range) (Gr 40).

$Q = 7.150 \pm 0.008$ Mev (spectrometer) (Bu 49e; Strait *et al.*, private communication).

$Q = 7.151 \pm 0.010$ Mev (spectrometer) (Wh 50e).

ΔQ from alphas = 482±3 kev (Bu 48c).

ΔQ from γ-ray ~474 kev (broad) (Ra 49a).

Fraction of transitions leading to excited state ($\theta = 90°$):

at $E_d \sim 0.3$ Mev:	0.64	(Gr 40, In 50a)
0.6 Mev:	0.47	(In 50a)
1.38 Mev:	0.36	(Bu 48c, In 50a)

No other states of Li^7 are observed >5 percent in range 0 to 2.5 Mev, >10 percent to 3.6 Mev (In 50a, Bu 49e).

Study of the Doppler broadening indicates a lifetime $<10^{-12}$ sec.: the asymmetry of the broadening observed with thin targets suggests that either the Li^{7*} particles or the subsequent γ-rays are anisotropically emitted (Ra 49a, Ra 50a).

Gr 40 Graves, Phys. Rev. **57**, 855 (1940).
Bu 49e Buechner and Strait, Phys. Rev. **76**, 1547 (1949).
Wh 50e Whaling and Li, Phys. Rev. (to appear).
Bu 48c Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).
In 50a Inglis, Phys. Rev. **78**, 104 (1950).
Ra 49a Rasmussen, Lauritsen, and Lauritsen, Phys. Rev. **75**, 199 (1949).
Ra 50a Rasmussen, Ph.D. thesis, California Institute of Technology (1950).
See also: Ha 37a, Wi 37d, Al 40, Sk 40, La 47b, Bu 50f, In 50.

IX. $B^{10}(n\ \alpha)Li^7$ $Q_m = 2.78$

See Table XI.

Q values: 2.80±0.05, 2.31±0.04 (Bu 50: mag. spect.) 2.310±0.010 (Je 50: ionization in argon).

Q values: 2.795±0.004, 2.317±0.004 from $B^{10}(p\ \alpha)Be^7$ and $Li^7(p\ n)Be^7$ (Va 50, Br 50a, He 49, Sh 49d).

ΔQ from γ-ray: 478.5±1.5 kev (El 48); study of the Doppler broadening in various stopping materials gives a lifetime of $0.75 \pm 0.25 \times 10^{-13}$ sec. (El 49).

The angular distribution of γ-emission with respect to the direction of the α-particles is spherically symmetrical, suggesting that the excited state has $I = \frac{1}{2}$ (Ro 50).

Je 50 Jesse, Forstat, and Sadauskis, Phys. Rev. **77**, 782 (1950).
Be 50d Bethe, Rev. Mod. Phys. **22**, 213 (1950).
Bu 50 Burcham and Freeman, Phil. Mag. **41**, 337 (1950).
El 48 Elliott and Bell, Phys. Rev. **74**, 1869 (1948).
El 49 Elliott and Bell, Phys. Rev. **76**, 168 (1949).
Ro 50 Rose and Wilson, Phys. Rev. **78**, 68 (1950).
See also: Ku 35, Ta 35a, Ha 37, Ku 38, Li 38, Oc 38, Bo 38, Ma 39a, Wi 40, Ch 44, Bo 45, Gi 48a, In 48b, Ro 48d, De 49a, Fa 49a, Fe 49a, He 49, Ho 49g, Sh 49d, St 49e, Wa 49b, Br 50a, Va 50.

Li^7 Theory

$\mu = 3.257$; $Q = 0.02$, $I = \frac{3}{2}$. Shell: $\alpha + 1p_{\frac{3}{2}}^1$ (proton) $+1p_{\frac{3}{2}}^2$ (neutrons). Expect $^2P_{\frac{3}{2}}$, odd.

This and its mirror nucleus constitute the pair of best-studied nuclei. The Hartree theory has assigned the ground state to a ^2P doublet, for which assignment the presence of the nearby state at 480 kev was taken as some confirmation. That the quadrupole moment of the ground state is probably positive is difficult to understand on the basis of any such theory, but can be explained, together with the magnetic moment (which is not far from that expected for the odd p wave proton) by including either other configurations, or giving up the central-force idea that L and S are even approximate quantum numbers. See also Fe 50a and Av 50.

The spin of the excited state is still in some doubt, though the emitted gammas after the α-emission [$B^{10}(n\ \alpha)$], are spherically symmetric (Ro 50), implying very probably $I = \frac{1}{2}$, unless there are quite special circumstances. The β-transition lifetime (Be^7: K-capture) however might suggest a higher value under rather restrictive assumptions; see also Fe 50a and Av 50. The absence of other normally excited levels to a high energy is striking, and would appear to imply that one is dealing with a pure Hartree scheme with one odd particle but

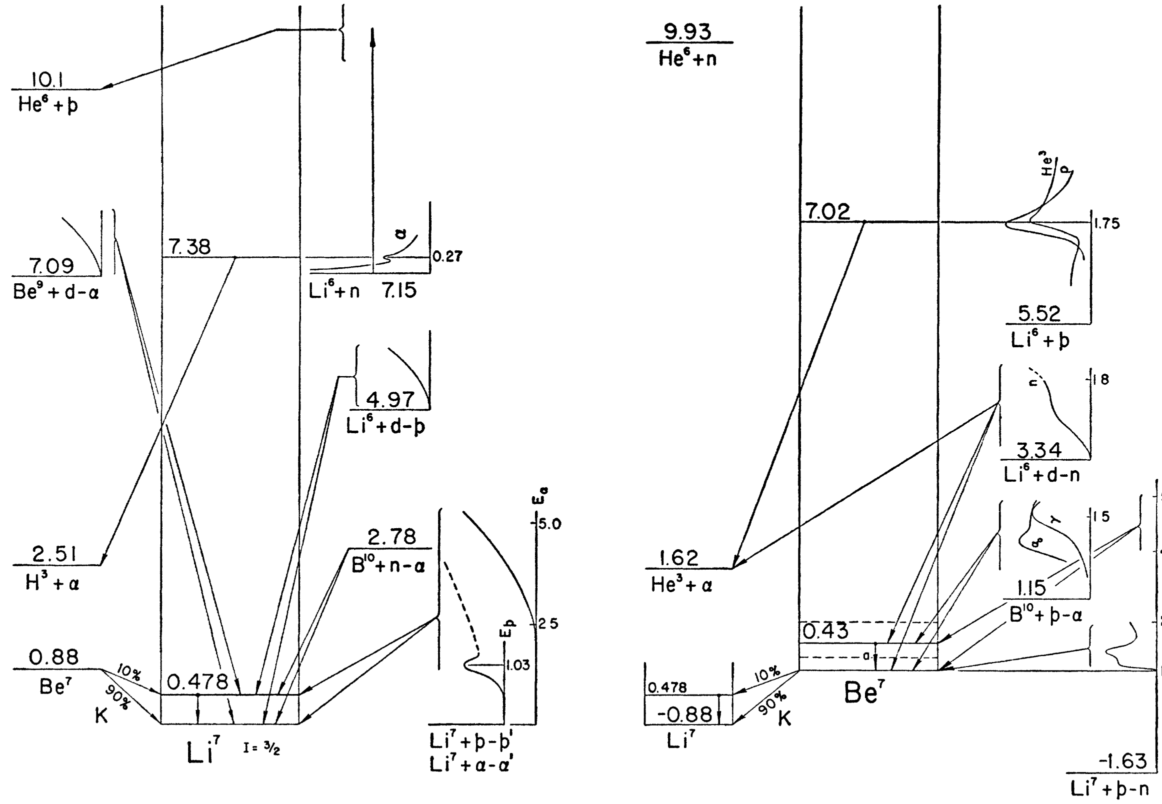

FIG. 4. Energy levels in Li^7 and Be^7: for notation see Fig. 1. (*a*) 0.429-Mev γ-ray from $Li^6(d\ n)$ and $B^{10}(p\ \alpha)$.

with strong $L-S$ coupling present, splitting the next level, a member of the distant ^2F set. Obviously this is an unsafe conclusion; but the facts are clear (In 50a). The γ-ray lifetime of the excited state has been directly measured by Doppler methods. It is probably a quadripole γ-ray.

The literature on this nucleus is by now voluminous and specialized; what appears here is hardly more than a sketch of present ideas.

Fe 50a Feenberg, Phys. Rev. **78**, 328 (1950).
Av 50 Avery and Blanchard, Phys. Rev. **78**, 704 (1950).
Ro 50 Rose and Wilson, Phys. Rev. **78**, 68 (1950).
In 50a Inglis, Phys. Rev. **78**, 104 (1950).

Be^7

(Mass: 7.019 16)

I. $Be^7(K)Li^7$ $Q_m=0.88$

Half-life $=52.93\pm0.22$ days (Se 49). The decay is complex: see Li^7.

Se 49 Segrè and Wiegand, Phys. Rev. **75**, 39 (1949).
See also: Br 38, Br 38b, Hi 40, Al 42, Se 47a, Bo 48e, Bo 49g, Be 49d, Le 49d, Sm 50a.

II. $Li^6(p\ \gamma)Be^7$ $Q_m=5.52$

Not observed: yield $<2.5\times10^{-10}$ at $E_p=0.95$ Mev (Cu 39: thick target).

Cu 39 Curran and Strothers, Proc. Roy. Soc. **172**, 72 (1939).

III. $Li^6(p\ \alpha)He^3$ $Q_m=3.90$ $E_x=5.52$
$Li^6(p\ p)Li^6$

Q from α-ranges: 3.94 ± 0.08 (Mi 40).

Q from α-ranges: 3.945 ± 0.06 (Pe 40).

Q from spectrometer: 4.017 ± 0.022 (To 49b). 3.97 ±0.03 (Bu 50e). 4.021 ± 0.006 (Strait *et al.*, private communication).

The yield of α-particles rises smoothly from $E_p=0.2$ to 0.9 Mev (Ru 38, Bo 39b, Mi 40, Bu 50e): absolute yields are reported in these references. He^3 particles and elastically scattered protons ($\theta_{lab}=164°$) show maxima at $E_p=1.82$ and 1.75 Mev, respectively (both 0.45 Mev wide), indicating a level in Be^7 at 7.0 Mev: (Ba 50c, Richards, private communication).

The angular distribution of α-particles is isotropic at $E_p=0.2$ Mev (Ne 37a).

Mi 40 Miller, Phys. Rev. **58**, 935 (1940).
Pe 40 Perlow, Phys. Rev. **58**, 218 (1940).
To 49b Tollestrup, Fowler, and Lauritsen, Phys. Rev. **76**, 428 (1949).
Bu 50e Burcham and Freeman, Phil. Mag. **41**, 921 (1950).
Ru 38 Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).
Bo 39b Bowersox, Phys. Rev. **55**, 323 (1939).
Ba 50c Bashkin, Ajzenberg, Browne, Goldhaber, Laubenstein, and Richards, Phys. Rev. **79**, 238 (1950).
Ne 37a Neuert, Physik. Zeits. **38**, 618 (1937).
See also: Al 40b.

TABLE XII. Threshold determinations.

Threshold, Mev	Reference	Method
1.856 ±0.02	Ha 40a	Gen. voltmeter—based on $F(p\ \alpha)\gamma=862$
1.883 ±0.006	Ha 44	Absolute electrostatic deflector
1.85 ±0.01	Sh 48e	Gen. voltmeter—based on $F(p\ \alpha)\gamma=862$
1.882 ±0.002	He 49	Absolute electrostatic deflector
1.8812±0.002	Sh 49d	Radiofrequency velocity measurements

TABLE XIII. Q values.

Q_1	Q_2	ΔQ	Reference
1.148±0.006	0.714±0.008	0.434±0.004	Br 50a
1.152±0.004	0.721±0.006	0.431±0.005	Va 50
		0.429±0.005	La 50
1.147±0.01			Bu 50

IV. (*a*) $Li^6(d\ n)Be^7$ $Q_m=3.34$
(*b*) $Li^6(d\ n)He^3+He^4$ $Q_m=1.72$

$Q_a=3.27$ Mev (Wh 50b: cloud chamber). 3.30 Mev (Ma 49d: photo-plates). 3.40±0.05, 2.95±0.06 (Gi 50: photo-plate).

The neutron spectra of Mandeville *et al.* (Ma 49d) indicate relative yields for a/b in ratio 2:1 ($E_d=0.9$ Mev, 100-kev target, $\theta=90°$) and show no groups >10 percent corresponding to levels in Be^7 between 0.5 and 1.0 Mev, and none >2 percent for levels between 1 and 2 Mev. Whaling and Butler (Wh 50b) find $a/b\sim1$ ($E_d=0.595$ Mev, 150-kev target, $\theta=0°$), Gibson and Green (Gi 50) ($E_d=0.93$, 50-kev target, $\theta=0°$ and 120°) have resolved the lower energy group (reaction (*a*): 430-kev level). All three works are consistent with ~30 percent transitions to the excited state.

A γ-ray at 429±3 kev is observed (La 50); at $E_d=1.4$ Mev the intensity is roughly equal to that of the 429-kev line from $Li^6(d\ p)$. No other lines are observed <850 kev.

Wh 50b Whaling and Butler, Phys. Rev. **78**, 72 (1950).
Ma 49d Mandeville, Swann, and Snowden, Phys. Rev. **76**, 980 (1949).
Gi 50 Gibson and Green, Proc. Phys. Soc. London **63**, 494 (1950).
La 50 Lauritsen and Thomas, Phys. Rev. **78**, 88 (1950).
See also: Ro 38a, Ru 38, St 39a.

V. $Li^7(p\ n)Be^7$ $Q_m=-1.63$

[In view of the general agreement that the $F^{19}(p\ \alpha)\gamma$ resonance on which the first and third measurements in Table XII are based should be raised to 873.5 kev, it would seem that all measurements are consistent with a value of 1.882 Mev.]

At $E_p=5.1$ Mev, three (incompletely resolved) neutron groups are reported, in addition to the ground state neutrons, corresponding to levels in Be^7 at 0.205 ±0.07, 0.470±0.07, and 0.745±0.07 Mev (Gr 50). For $E_p=2.7$ to 3.9 Mev, only two groups appear, giving a single level at 435±15 kev (Jo 50: $E_p=3.36$, 3.91 Mev); 428±15 kev (Fr 50a: $E_p=3.49$); 428±20 kev (Ha 50b: $E_p=2.7$, 3.12 Mev). The lower energy group comprises 8 to 17 percent of the total, depending on angle of observation and bombarding energy (Jo 50, Fr 50a, Ha 50b). At $\theta_{lab}=30°$, the intensity of the lower energy group relative to the main group is 9±1.5, 10.5±1, and 12±1 percent at $E_p=2.75$, 2.89, and 3.66 Mev, respectively (Johnson and Barschall, private communication).

Gr 50 Grosskreutz and Mather, Phys. Rev. **77**, 580 (1950).
Jo 50 Johnson, Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).
Fr 50a Freier, Rosen, and Stratton, Phys. Rev. **79**, 721 (1950).
Ha 50b Hamermesh and Hummel, Phys. Rev. **78**, 73 (1950).
See also: Hi 39a, Ha 40a, Hi 40, Ha 44, Ko 46, Sh 48e, Fr 49a, Ha 49s, He 49, Sh 49d, St 49c, Ha 50a.

VI. $B^{10}(p\ \alpha)Be^7$ $Q_m=1.15$

(See Table XIII.) At $E_p=1.5$ Mev, about one-half of the disintegrations result in the excited state (Br 50a). At $E_p=1.79$ Mev, no group corresponding to a possible level at 745±70 kev appears >1 percent of the ground state group. At $E_p=1.60$ Mev, the upper limits for groups corresponding to levels at ~745, ~205 kev are two and three percent, respectively, of the ground state group (Va 50).

At $E_p=1.79$ Mev, observed relative intensities at $\theta=90$ are (Va 50):

$B^{10}(p\ \alpha)Be^7$ 1.00, $B^{10}(p\ \alpha)Be^{7*}$ 0.44, $B^{10}(p\ p)B^{10}$ 10.1.

Br 50a Brown, Chao, Fowler, and Lauritsen, Phys. Rev. **78**, 88 (1950). Brown, Ph.D. thesis, California Institute of Technology (1950).
Va 50 Van Patter, Sperduto, Strait, and Buechner, Phys. Rev. **79**, 900 (1950).
La 50 Lauritsen and Thomas, Phys. Rev. **78**, 88 (1950).
Bu 50 Burcham and Freeman, Phil. Mag. **41**, 337 (1950).
See also: Ro 38a, Cu 39a, Bu 49b, Bu 49f, Ch 49e.

Be^7 Theory

Beta-active (*K*-electron capture). Shell: $\alpha+1p_{\frac{3}{2}}{}^2$ (protons) $+1p_{\frac{3}{2}}{}^1$ (neutron); ${}^2P_{\frac{3}{2}}$ odd.

It is very gratifying that this nucleus, after a long experimental search, finally has been demonstrated to have a level structure like its mirror nucleus Li^7. The *K*-capture of the ground state, going as it does primarily but not wholly to the ground state of Li^7, is allowed in both cases, probably $\Delta I=1$, or 0, no. It is noteworthy that this nucleus exhibits a measured variation in lifetime with chemical combination (Se 49, Bo 49g) (due to differences in atomic electron density) and that it may play a quite unexpected role in such a cosmic phenomenon as supernovae (Bo 50d).

Se 49 Segrè and Wiegand, Phys. Rev. **75**, 39 (1949).
Bo 49g Bouchez *et al.*, J. de phys. et rad. **10**, 201 (1949).
Bo 50d Borst, Phys. Rev. **78**, 807 (1950).

Li^8

(Mass: 8.025 02)

I. $Li^8(\beta^-)Be^8$ $Q_m=15.98$

The decay is complex, proceeding to broad states in Be^8 which decay by α-particle emission: the β-spectrum extends to ~15 Mev (see Be^8). Half-life $=0.89\pm0.02$ sec. (Hu 47a).

Hu 47a Hughes, Hall, Eggler, and Goldfarb, Phys. Rev. **72**, 646 (1947).
See also: Fo 36, Br 37, Ru 38, Ki 39b, At 43, Ch 47.

II. $Li^7(n\ \gamma)Li^8$ $Q_m=1.98$ $E_x=1.98$

Isotopic cross section for production of Li^8 by thermal neutrons $=0.033\pm0.005$ b (Hu 47a).

Hu 47a Hughes, Hall, Eggler, and Goldfarb, Phys. Rev. **72**, 646 (1947).
See also: Ve 37, Bj 38a, Ru 38, Po 46.

III. $Li^7(n\ n)Li^7$ $E_x=1.98$

Resonances in the total cross section appear at $E_n=0.27$ Mev ($\sigma_t=7.8$ b, p wave) and 1.15 Mev ($\sigma_t=1.6$ b, s wave), indicating levels at 2.2 and 3.0 Mev, both of spin 2 (Adair, private communication).

IV. $Li^7(d\ p)Li^8$ $Q_m=-0.20$

Q from excitation function: -0.20 ± 0.03 Mev (Ru 38).

Q from protons (angular thresh.): -0.187 ± 0.010 (Pa 50).

Q from protons (spectrometer): -0.188 ± 0.007 (Bu 50f).

Ru 38 Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).

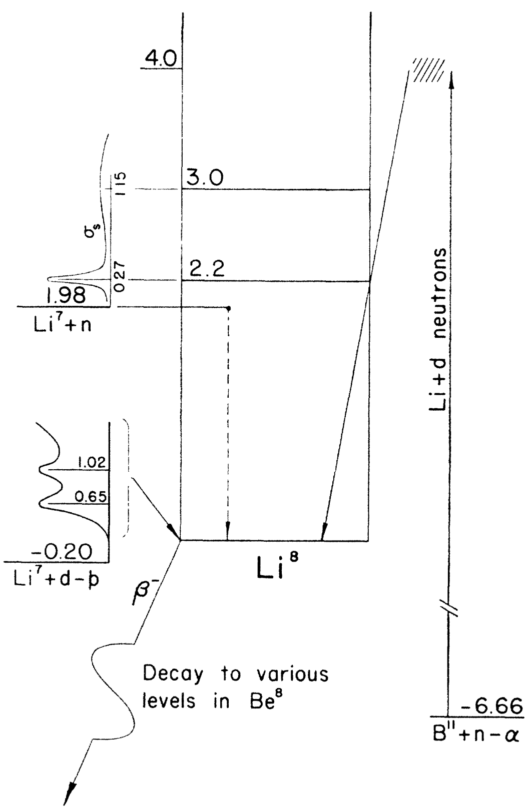

FIG. 5. Energy levels in Li^8: for notation see Fig. 1.

Pa 50 Paul, Phil. Mag. **41**, 942 (1950).
Bu 50f Buechner *et al.*, M.I.T. Progress Report (July 1, 1950).
See also: Fo 37, Ru 38, St 48c.

V. $Be^9(\gamma\ p)Li^8$ $Q_m=-16.86$ (not illustrated)

Threshold: 18 ± 1 Mev (Og 47).

Og 47 Ogle, Brown, and Conklin, Phys. Rev. **71**, 378 (1947).
See also: Co 48d.

VI. $B^{11}(n\ \alpha)Li^8$ $Q_m=-6.66$

Production of Li^8 is observed with $Li-d$ neutrons (La 39). This reaction is occasionally observed in boron-loaded photographic plates from cosmic-ray neutrons.

La 39 Lawrance, Proc. Camb. Phil. Soc. **35**, 304 (1939).
See also: Pi 48, Fr 48d, Pi 49.

Li^8 Theory

Beta$^{(-)}$-active; properties of ground state unmeasured. Shell: $\alpha+1p_{3/2}^1$ (proton) $+1p_{3/2}^3$ (neutrons), with ground state $^3P_2$, even.

The complex decay proceeds mainly by a once-forbidden transition to the wide state in Be^8 at about 3 Mev. The matrix element for decay to the ground state of Be^8 is less by a factor of 20 or more. Recalling that the parameter $R/\lambda\!\!\!^{-}_\beta$, which measures the effect of emitted orbital momentum in delaying β-decay (Ko 43c), is here only ~0.5, it seems likely that the transition to the ground state is at least twice forbidden, with angular momentum and parity change $\Delta I=2$, no, or perhaps $\Delta I=3$, yes. It is not hard to fit this with the evidence that the Be^8 ground state is $I=0$ (cf. Be^8). There is weak evidence from the estimated energy distribution of the alphas arising from the breakup of Be^8 that the angular momentum of the 3-Mev state in Be^8 is actually $I=4$, and that Li^8 has $I=3$ (Bo 47). The slowness of β-decay to the ground state might be related to the change in nuclear L expected for the transition (cf. N^{14}).

Ko 43c Konopinski, Rev. Mod. Phys. **15**, 209 (1943).
Bo 47 Bonner *et al.*, Phys. Rev. **72**, 163 (1947).

Be^8

(Mass: 8.007 85)

I. $Be^8\rightarrow 2He^4$ $Q_m=0.05$

Wheeler (Wh 41) obtained $Q=0.125$ from analysis of $B^{11}(p\ \alpha)$ experiments.

Hemmendinger (He 49b) gives $Q=0.103\pm0.01$ from observations of the α-particles from $Be^9(\gamma\ n)$.

Tollestrup *et al.* (To 49b) obtain $Q=0.089\pm0.005$ from $Be^9(p\ d)$.

Wh 41 Wheeler, Phys. Rev. **59**, 27 (1941).
He 49b Hemmendinger, Phys. Rev. **75**, 1267 (1949).
To 49b Tollestrup, Fowler, and Lauritsen, Phys. Rev. **76**, 428 (1949).
See also: Bo 37a, Kr 37b, Gl 38, He 48c.

II. $He^4(\alpha\ \alpha)He^4$

Scattering data indicate the existence of state at 3 Mev, 0.8 Mev wide, with spin zero (Wh 41a).

Wh 41a Wheeler, Phys. Rev. **59**, 16 (1941).
See also: Mo 37, De 39b.

III. (*a*) $Li^6(d\ n)Be^7$ $Q_m = 3.34$ $E_x = 22.18$
(*b*) $Li^6(d\ n)He^4 + He^3$ $Q_m = 1.72$

A broad resonance for neutron production occurs at $E_d \sim 0.4$ Mev (corrected for barrier factor: Wh 49). The observed increase at $E_d = 1.8$ Mev in number of neutrons >1 Mev may be due to neutrons from reaction (*b*). The relative probability of reactions (*a*) and (*b*) is ~ 1 (see Be^7).

The thick $Li^6{}_2SO_4$ target yield of 430-kev γ-radiation (from Be^{7*}) at $E_d = 1.49$ Mev is $1 \times 10^{-6}\ \gamma/d$ (La 50). From γ and n yields it may be estimated that ~ 0.1 to 0.5 of disintegrations in reaction (*a*) produce Be^7 in the excited state (see Be^7).

The angular distribution of neutrons is anisotropic (Wh 49).

Wh 49 Whaling, Evans, and Bonner, Phys. Rev. **75**, 688 (1949).
La 50 Lauritsen and Thomas, Phys. Rev. **78**, 88 (1950).
See also: Wi 37c, Am 37, Ru 38.

IV. $Li^6(d\ p)Li^7$ $Q_m = 4.97$ $E_x = 22.18$

A broad resonance at $E_d = 0.4$ Mev (corrected for barrier factor) appears for long-range protons. The observed cross section, for the two proton groups together, is nearly constant above $E_d = 0.8$ at 0.1 b (Wh 50d). The relative yield of short-range protons increases with bombarding energy from about 20 percent of the total yield at $E_d = 0.3$ Mev to about 40 percent at $E_d = 1.85$ Mev (Wh 50d: $\theta = 0°$; Ru 38: $\theta = 90°$). The angular distribution is roughly similar for the two groups, with pronounced asymmetries appearing for $E_d > 1.0$ Mev. There may be some disagreement in the experiments at low energies: Whaling (Wh 50d) finds the two groups

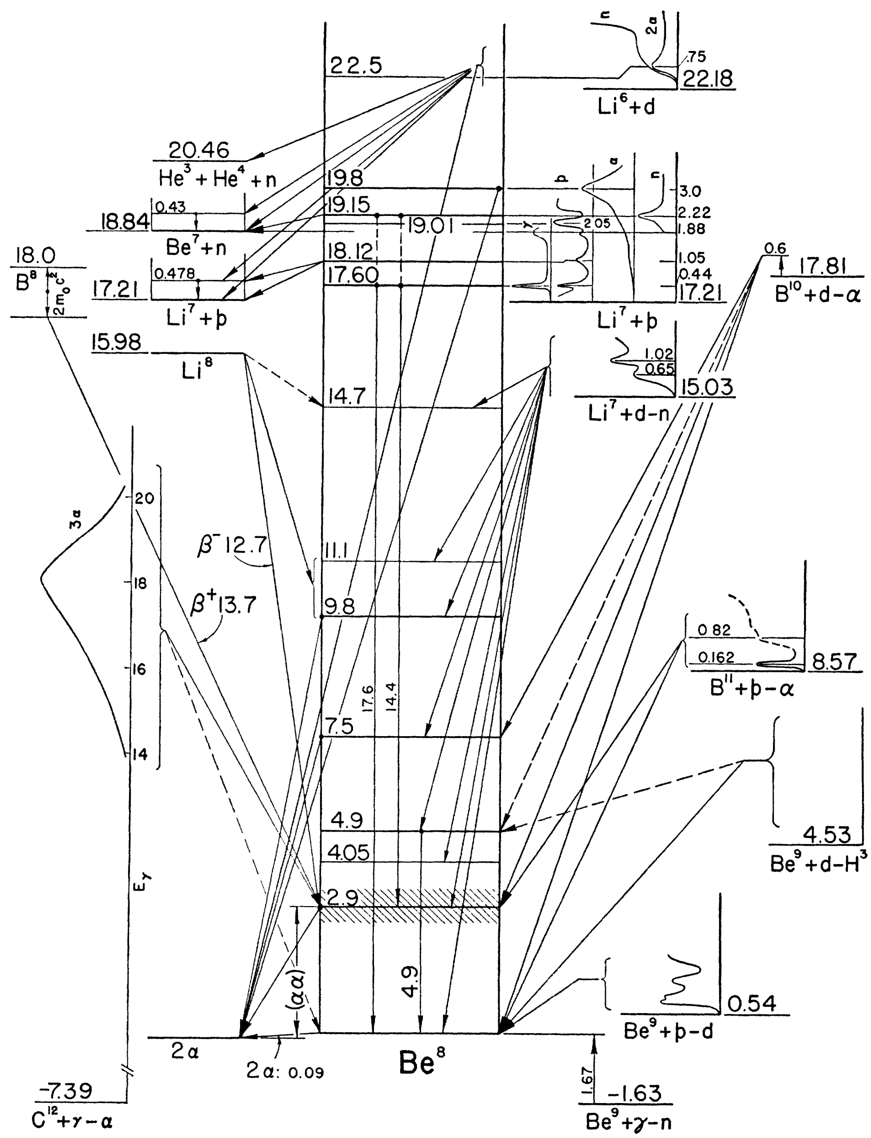

FIG. 6. Energy levels in Be^8: for notation see Fig. 1.

similar and symmetric within about five percent at $E_d=0.4$ Mev, while Inglis *et al.* (Kr 49, Ha 49f, Ha 49k, and Inglis, private communication) find a term as high as $\cos^4\theta$ in the short-range group, but not in the long at $E_d=0.4$ Mev.

Thick $Li^6{}_2SO_4$ target yield of 478-kev radiation from Li^{7*} at $E_d=1.49$ Mev: 1×10^{-6} γ/d (La 50).

Wh 50d Whaling and Bonner, Phys. Rev. **79**, 258 (1950).
Ru 38 Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).
Kr 49 Krone, Hanna, and Inglis, Phys. Rev. **75**, 335 (1949).
Ha 49f Hanna and Inglis, Phys. Rev. **75**, 1767 (1949).
Ha 49k Hanna, Phys. Rev. **76**, 686 (1949).
La 50 Lauritsen and Thomas, Phys. Rev. **78**, 88 (1950).
See also: Ne 37, Ru 38, Ne 39, Wh 49.

V. $Li^6(d\ \alpha)He^4$ $Q=22.23$ $E_x=22.18$

$Q=22.20\pm0.04$ Mev from α-particle range (Sm 39a).

The yield curve shows a broad maximum at $E_d=0.75$ Mev (He 48e).

At $\theta=90°$, the maximum occurs at 0.6 Mev; $\sigma=0.03$ b; correction for Coulomb barrier penetration indicates $E_d=0.38$ Mev for the resonance (Wh 50d). There is indication of another resonance $\sim$3.5 Mev (He 48e). For angular distributions see He 48e, Re 49, Re 49b.

Sm 39a Smith, Phys. Rev. **56**, 548 (1939).
He 48e Heydenburg, Hudson, Inglis, and Whitehead, Phys. Rev. **74**, 405 (1948).
Wh 50d Whaling and Bonner, Phys. Rev. **79**, 258 (1950).
Re 49 Resnick and Inglis, Phys. Rev. **75**, 1291 (1949).
Re 49b Resnick and Inglis, Phys. Rev. **76**, 1318 (1949).
See also: Wi 37c, Ru 38, Al 39a, Ha 39, Ne 39, St 39a, La 47b, In 48, Wh 49.

VI. $Li^7(p\ \gamma)Be^8$ $Q_m=17.21$

A strong resonance exists at 0.441 Mev (see Table XIV); there is evidence (Hi 48a, Hu 40) for an additional increase in yield at 1.9 Mev (near $p\ n$ threshold).

Thick (Li metal) target yield at $E_p=0.85$ Mev: 2.6×10^{-8} γ/p (Fo 49b). Resonance cross section: 6×10^{-27} cm^2 (Fo 49b), 7.2×10^{-27} cm^2 (Bo 48c).

The γ-radiation comprises two components: $Q=17.2\pm0.2$ Mev (sharp) and $Q=14.4\pm0.3$ Mev (broad). The relative intensity of the lower energy line is about 0.5 for 0.46-Mev protons and 1.5 for 1.15-Mev protons (thick target), but both lines appear in both the resonant and the non-resonant radiation (Wa 48). Devons and Hine (De 49d) find the radiation anisotropic above and below resonance: they interpret their results in terms of interference between radiation from the 440-kev (E_p) level formed by *s* wave protons ($I=1$, odd), and a broad level of opposite parity, at $\sim$3 Mev.

TABLE XIV. Summary of measurements on $Li^7(p\ \gamma)$ resonances.

Voltage (kev)	Half-width (kev)	Reference	Method
440 ±8	11	Ha 36	Resistance voltmeter
440		Pa 38a	—
440 ±4		He 39a	Proton scatt. in argon
446.5±1.5		Ha 44	Elec. deflection, absolute
440 ±2	11±2	Ta 46	Resistance voltmeter
	14	Bo 48c	
441.4±0.5	12	Fo 49b	Rel. to $F^{19}(p\ \alpha)$ res. at 873.5
442.3±1.5		Hu 49c	Rel. to $F^{19}(p\ \alpha)$ res. at 873.5
440.8±0.5		Mo 49a	

The α-particles associated with the lower energy γ-ray have been reported, giving a level energy in Be^8 of 3.03 ± 0.1 Mev and a width of $\sim$2 Mev. (Bu 49a, Bu 50b, Bu 50e.) The great width observed suggests that this level may not be the same as that observed in other reactions [$B^{11}(p\ \alpha)$, $Li^8(\beta^-)$, $Li^7(d\ n)$].

Hi 48a Hill and Shoupp, Phys. Rev. **73**, 931 (1948).
Hu 40 Hudson, Herb, and Plain, Phys. Rev. **57**, 587 (1940).
Fo 49b Fowler and Lauritsen, Phys. Rev. **76**, 314 (1949).
Bo 48c Bonner and Evans, Phys. Rev. **73**, 666 (1948).
Wa 48 Walker and McDaniel, Phys. Rev. **74**, 315 (1948).
De 49d Devons and Hine, Proc. Roy. Soc. **199**, 56, 73 (1949).
Bu 49a Burcham and Freeman, Phys. Rev. **75**, 1756 (1949).
Bu 50b Burcham and Freeman, Phys. Rev. **77**, 287 (1950).
See also: Bo 37e, De 37, Ga 37, Ge 37, Ka 38, Ru 38, Cu 39, Fo 39, Ag 41, Ho 41, Ha 44, Ta 46, Mc 47b, De 48, Bo 48c, Fo 48, Fo 48b, Ch 49, Fo 49a, Hu 49c, Mo 49a, Bu 50e.

VII. (*a*) $Li^7(p\ p)Li^7$ $E_x=17.21$
(*b*) $Li^7(p\ p')Li^{7*}$

(*a*) Elastically scattered protons show pronounced peaks at 0.44 Mev (width 12 kev) and 1.05 Mev (1.030 ± 0.005 Mev, width 168 kev, corrected for penetration factors). σ_s at 0.440 Mev, 137.8°=2.4 times, at 81.1°=1.6 times Rutherford scattering. σ_s at 1.05 Mev, 81.1° lab. angle=1.41 b (per 4π-sterad.); σ_s at 1.05 Mev, 137.8°=1.22 b. (Fo 49, Fo 49b.) A further weak maximum (half-width=30 kev) occurs at $E_p=1.87$ Mev, possibly associated with the onset of the $p\ n$ reaction. An intense, broad maximum is observed at $E_p\sim2.05$ Mev; after a minimum at $E_p\sim2.25$ Mev, the yield rises until 2.5 Mev, after which the yield is constant to 3.5 Mev (Ri 50a: $\theta=164°$). Analysis of the lower energy data suggests assignment of $I=1$ (*p* wave protons) to the 0.440-Mev state (17.60 Mev in Be^8) and $I=1$ (*s* wave) to the 1.03-Mev state (17.57 and 18.13 Mev in Be^8) (Co 49). [This conclusion for the 0.44-Mev state is incompatible with the evidence from $Li^7(p\ \gamma)$.]

(*b*) Inelastically scattered protons indicate a resonance at 1.030 ± 0.005 Mev when corrected for penetration factors. Cross section at $E_p=1.240$ Mev (above resonance): 0.036 b at 81.1° (lab.) 0.065 b at 137.8° (lab.) 0.057 b from γ-rays.

The resonance cross section, corrected for non-resonant background, for γ-radiation is 0.047 b: the thick target yield at $E_p=1.35$ Mev is 1.2×10^{-5} γ's per proton (Fo 49b; note errors in reference: angles were interchanged, and γ-yield was given as 1.2×10^{-4}). No further structure is observed to $E_p=3.5$ Mev (Ri 50a).

Fo 49 Fowler, Lauritsen, and Rubin, Phys. Rev. **75**, 1463 (1949).
Fo 49b Fowler and Lauritsen, Phys. Rev. **76**, 314 (1949).
Ri 50a Richards, Bashkin, Craig, Donahue, Johnson, and Martin, Phys. Rev. **79**, 239 (1950).
Co 49 Cohen, Phys. Rev. **75**, 1463 (1949); Ph.D. thesis, California Institute of Technology (1949).
See also: Cr 39, Fo 39, Hu 40.

VIII. $Li^7(p\ \alpha)He^4$ $Q_m=17.27$ $E_x=17.21$

$Q=17.28\pm0.03$ from α-particle range (Sm 39a).

$Q=17.340\pm0.014$, spectrometer (Strait *et al.*, private communication).

$Q=17.338\pm0.011$, spectrometer (Wh 50e).

The yield has a broad maximum at $E_p=3$ Mev (He 48e, g).

Theoretical fits to angular distribution curves indicate a level ($\sim$1 Mev broad) at $E_p=3$ Mev ($I=2$, even) and a (several Mev) broad level ($I=0$, even) in the same general region, produced by both p and f wave protons (In 48, He 48e).

Sm 39a Smith, Phys. Rev. **56**, 548 (1939).
Wh 50e Whaling and Li, Phys. Rev. (to appear).
He 48e Heydenburg, Hudson, Inglis, and Whitehead, Phys. Rev. **74**, 405 (1948).
He 48g Heydenburg, Hudson, Inglis, and Whitehead, Phys. Rev. **73**, 241 (1948).
In 48 Inglis, Phys. Rev. **74**, 21 (1948).
See also: Al 35, Ha 38, Ka 38, Ru 38, Ne 39, Yo 40, Cr 41, Ei 44, Sw 44, Ch 47a, Ru 47, Ru 47c, Ma 49e, Bu 50f, Ta 50.

IX. $Li^7(p\ n)Be^7$ $Q_m=-1.63$ $E_x=17.21$

Threshold: $E_p=1.882$ Mev (see Be^7).

Resonance: $E_p=2.22$ Mev; $\sigma_{res}=0.50$ b (Ta 48).

No further resonances appear <3.66 Mev (Fr 49a).

The angular distribution of neutrons is anisotropic (see Ta 48, Ha 49s). An analysis by Breit and Bloch (Br 48a) suggests that the behavior of the yield and angular distribution implies the existence of a quasi-stationary state at 2.2 Mev and possibly one below the threshold energy, both of odd parity.

Ta 48 Taschek and Hemmendinger, Phys. Rev. **74**, 373 (1948).
Fr 49a Freier, Lampi, and Williams, Phys. Rev. **75**, 901 (1949).
Ha 49s Hanson, Taschek, and Williams, Rev. Mod. Phys. **21**, 635 (1949).
Br 48a Breit and Bloch, Phys. Rev. **74**, 397 (1948).
See also: Du 39, Hi 39a, Ar 46, Hi 48a, Ki 49b.

X. $Li^7(d\ n)Be^8$ $Q_m=15.03$

Q from neutrons$=15.0\pm0.15$ Mev (Gr 49e).

TABLE XV. Levels in Be^8 from neutron groups.

	A		B		C	
E_n	Width	Be^{8*}	Be^{8*}	Width	Q	Be^{8*}
14	$\sim$0.5	0	0			
10.8	2.0	3.0 and 4.8	2.8	0.8		
			4.05			
			4.9			
7.5	1.5	7.5	7.5	1.7		
5.0	$\sim$1.5	10.				
					3.9	11.1
					0.3	14.7

A: $E_d=0.7$ Mev (Ri 41).
B: $E_d=1$ Mev; 4.05 and 4.9 levels only partially resolved (Gr 49e).
C: $E_d=1.1$ Mev; $\theta=0°$ (Wh 50c).

Gamma-radiation at 4.9 ± 0.3 Mev, with a yield $\sim$3.3 percent of the neutron yield, is observed (Be 41a, Be 47).

Ri 41 Richards, Phys. Rev. **59**, 796 (1941).
Gr 49e Green and Gibson, Proc. Phys. Soc. London **62**, 407 (1949).
Wh 50c Whitehead, Phys. Rev. **79**, 393 (1950).
Be 41a Bennett, Bonner, Richards, and Watt, Phys. Rev. **59**, 904 (1941).
Be 47 Bennett, Bonner, Richards, and Watt, Phys. Rev. **71**, 11 (1947).
See also: Wi 37, Ru 38, St 38, St 39a, Bo 41b, La 47b.

XI. $Li^8(\beta^-)Be^8$ $Q_m=15.98$

The α-particle distribution indicates a state in Be^8 at 3.1 to 3.2 Mev, 0.8 Mev wide, and possibly a broad state at 7 to 9 Mev (Bo 48). Magnetic analysis gives the level at 3.13 ± 0.05 Mev, (Baxter *et al.*, private communication). The β-spectrum (Ho 50) fits reasonably well with such a scheme, indicating about 90 percent of transitions to the 3-Mev state, 10 percent to states at $\sim$10 and $\sim$13 Mev; less than two percent to the ground state and less than five percent to the 4.8-Mev state.

Bo 48 Bonner, Evans, Malich, and Risser, Phys. Rev. **73**, 885 (1948).
Ho 50 Hornyak and Lauritsen, Phys. Rev. **77**, 160 (1950).
See also: Fo 36, Ba 37, Br 37, Fo 37, Ru 38, Sm 38, Wh 41, Bo 47, Ho 48f.

XII. $Be^9(p\ d)Be^8$ $Q_m=0.54$

$Q=0.547\pm0.006$ Mev (elect. defl.) (Al 40a); 0.541 ± 0.003 Mev (elect. defl.) (Ro 48b); 0.558 ± 0.003 Mev (spectrometer) (To 49b); 0.562 ± 0.004 Mev (spectrometer) (Strait *et al.*, private communication).

Q for $Be^8\rightarrow2He^4=89\pm5$ kev (To 49b).

Al 40a Allison, Skaggs, and Smith, Phys. Rev. **57**, 550 (1940).
Ro 48b Rosario, Phys. Rev. **74**, 304 (1948).
To 49b Tollestrup, Fowler, and Lauritsen, Phys. Rev. **76**, 428 (1949).
See also: Al 37, Ha 37a, Wi 37d, Al 38a, Ha 38a, Al 39, Sk 39, Ma 40.

XIII. $Be^9(\gamma\ n)Be^8$ $Q_m=-1.63$

TABLE XVI. Threshold determinations.

E_γ (Mev)	Reference
1.63 $\pm$0.05	Co 39a
1.627$\pm$0.010	My 42[a]
1.630$\pm$0.006	Wi 45[a]
1.681$\pm$0.013	Ha 49g
1.666$\pm$0.002	[b]

[a] If the $H^2(\gamma\ n)$ threshold, determined in these experiments is increased to 2.230 Mev, these values become $\sim$1.66 Mev. If the ratio 1.338 ± 0.004 (Wa 48a) is used, $Be(\gamma\ n)=-1.667$ (To 50).
[b] Mobley and Laubenstein (private communication) based on $Li^7(p\ n)$ threshold 1.882 Mev.

The neutrons are monoergic (Go 41, Ha 49g).

Q for $Be^8\rightarrow2He^4=103\pm10$ kev (He 49b).

Wa 48a Waldman and Miller, Phys. Rev. **74**, 1225 (1948).
To 50 Tollestrup, Fowler, and Lauritsen, Phys. Rev. **78**, 372 (1950).
Go 41 Goloborodko, J. Phys. U.S.S.R. **5**, 15, 19 (1941).
Ha 49g Hanson, Phys. Rev. **75**, 1794 (1949).
He 49b Hemmendinger, Phys. Rev. **75**, 1267 (1949).
See also: Gl 38, Co 39a, My 42, Wi 45, He 48c, Wa 49e.

XIV. $Be^9(d\ t)Be^8$ $Q_m=4.53$

$Q=4.32$ Mev, from range of tritons (Wi 37d).

$Q=4.595\pm0.013$ Mev (spectrometer): there is evidence for a group at $Q=-0.025$, corresponding to a level energy of 4.62 (W. W. Buechner, private communication; Boyer, private communication, also reports this lower energy group).

Wi 37d Williams, Haxby, and Shepherd, Phys. Rev. **52**, 1031 (1937).
See also: On 40, La 47b.

XV. $B^8(\beta^+)Be^8$ $Q=16.2\pm1.02=17.2$†

B^8 is produced in the reactions $Be^9(p\ 2n)$, $B^{10}(p\ t)$, and $C^{12}(p,\ n\ \alpha)$. The half-life is 0.65 ± 0.1 sec.; $E_{\beta(\max)}$ $\sim$13.7 Mev. Delayed α-particles from the 3-Mev state of Be^8 are observed. B^8 appears to be just stable to proton emission (Alvarez, private communication).

XVI. $B^{10}(d\ \alpha)Be^8$ $Q_m=17.81$

$Q=17.76\pm0.08$ (Co 36a, Li 37).

TABLE XVII. Alpha-particle groups (Sm 39: $E_d=0.6$ Mev).

Range (cm)	Be^{8*}
14.75	0
10.8	3.0
8.6[a]	4.8[a]
6.2	7.0

[a] Possibly Li contamination.

A continuous distribution at lower energies is also observed (Sm 39, Li 37).

Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Sm 39 Smith and Murrell, Proc. Camb. Phil. Soc. **35**, 298 (1939).

XVII. $B^{10}(n\ t)Be^8$ $Q_m=0.22$ (not illustrated)

H^3 observed from B+high energy neutrons (Co 41a).

Co 41a Cornog and Libby, Phys. Rev. **59**, 1046 (1941).
See also: Po 47a.

XVIII. $B^{11}(p\ \alpha)Be^8$ $Q_m=8.57$

Alpha-particles exhibit a 4.4-cm group (ground state transition) and a continuum at lower ranges corresponding to transitions to a state at 2.8 Mev with width 0.8 Mev (Be 37, Wh 41). $Q=8.567\pm0.011$ Mev (spectrometer: Strait *et al.*, private communication).

Be 37 Bethe, Rev. Mod. Phys. **9**, 216 (1937).
Wh 41 Wheeler, Phys. Rev. **59**, 27 (1941).
See also: Ki 37, La 38, Fi 39, Bu 50f.

XIX. $C^{12}(\gamma\ \alpha)Be^8$ $Q_m=-7.39$

For $E_\gamma\sim14$ to 25 Mev, the reaction proceeds predominately to the 3-Mev state of Be^8; about five percent of disintegrations yield the ground state (Go 50b).

Go 50b Goward, Telegdi, and Wilkins, Proc. Phys. Soc. London **63**, 402 (1950).
See also: Ha 48c, Te 49c, Mi 50b, We 50.

† From this reaction.

XX. $B^{10}(\gamma\ d)Be^8$, $B^{10}(\gamma\ n\ p)Be^8$, $B^{11}(\gamma\ t)Be^8$ (not illustrated)

See: Go 50a.

Be^8 Theory

Unstable; no measured parameters of ground state except disintegration energy. Either a shell model or an α-particle model would predict a $^1S_0$, even parity ground state, with a shell configuration like $\alpha+1p_{\frac{3}{2}}^2$ (protons) $+1p_{\frac{3}{2}}^2$ (neutrons).

The wide state at 3 Mev is reached through several reactions, and the Li^8 decay suggests that this state differs from ground by one or perhaps two units of angular momentum. The ground state seems to differ from all of the three or four next-occurring excited states. The complex of γ-transitions from the famous state at 17.60 Mev (Li^7+440-kev protons) does not confirm in detail the expected value of ground state spin, though any other value would be an exception to the famous rule that even-even nuclei are spherically symmetric in the ground state. The sharp γ-resonance implies a strong selection rule against the very rapid disintegration into two alphas, which is held generally to be either (1) the strict rule from parity, that the state is odd and cannot decay into two Bose particles or (2) the equally rigid requirement that the total angular momentum of the level, and hence the orbital momentum of the residual alphas cannot be odd, even if the parity is even.

There is a wide level at this excitation energy, whose coherent interference with the sharp level has been observed, in confirmation of the nuclear dispersion theory, and by the change in angular distribution of the γ-rays as the proton energy is varied through the resonant value (De 49d). This experiment demonstrates directly that the wide and sharp states have opposite parities. Both the wide and the sharp level appear to combine with both the ground state and the 3-Mev state. The angular distribution of both γ-rays confirms the simple assumption that the sharp level corresponds to the capture of s wave protons, to a Be^8 level with $I=1$, odd, while the wide level is formed by p wave proton capture with character $I=2$, even. The ground state of Be^8 then has $I=0$, even, as expected, and the radiations are of the reasonable electric dipole and quadripole types. High γ-yield from the wide state or states, and the apparent p wave nature of the elastic scattered protons from the sharp level are observations not explained by the simple description taken from the γ-ray work. The lifetime of the Be^8 ground state should be unmeasurably short, $<10^{-19}$ sec., if the $I=0$ assignment is correct (Be 36).

De 49d Devons and Hine, Proc. Roy. Soc. **199**, 56, 73 (1949).
Be 36 Bethe and Bacher, Rev. Mod. Phys. **9**, 69 (1937).
See also: Wh 41a, Ch 49.

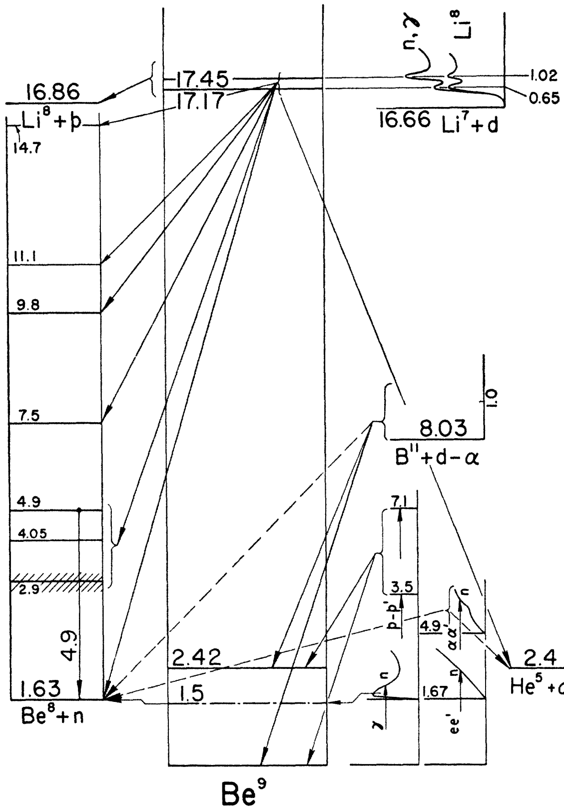

FIG. 7. Energy levels in Be^9: for notation see Fig. 1.

B^8

(not illustrated)

[Mass: $Be^8+18.5$ mmu (17.2 Mev) = 8.0264 amu]

I. $B^8(\beta^+)Be^8$ $\quad Q_m=16.2+1.02=17.2$

B^8 is produced in the reactions $Be^9(p, 2n)$, $B^{10}(p\ t)$, and $C^{12}(p, n\alpha)$. The decay is complex, see Be^8.

Be^9

(Mass: 9.015 03)

I. $Li^6(\alpha\ p)Be^9$ $\quad Q_m=-2.12$

Not observed: see B^{10}.

II. $Li^7(d\ p)Li^8$ $\quad Q_m=-0.20$ $\quad E_x=16.66$

Resonances occur at $E_d=0.65$ and 1.02 Mev (Be 47); a third peak, reported at 1.35 Mev, is in some doubt (Bonner, private communication).

Be 47 Bennett, Bonner, Richards, and Watt, Phys. Rev. **71**, 11 (1947).
See also: Fo 37, Ru 38, Be 41b.

III. (*a*) $Li^7(d\ n)Be^8$ $\quad Q_m=15.03$ $\quad E_x=16.66$
(*b*) $Li^7(d\ \alpha)He^5$ $\quad Q_m=14.3$
(*c*) $Li^7(d\ n)He^4+He^4$ $\quad Q_m=15.15$
(*d*) $Li^7(d\ t)Li^6$ $\quad Q_m=-0.99$

Resonances for production of neutrons and γ-rays (from Be^{8*}, 4.9 Mev) occur at $E_d=0.65$ and 1.02 Mev (Be 47, Wh 49). The angular distribution of neutrons is isotropic at $E_d=0.605$, 0.700, 0.820, and 1.34 Mev; at 1.02 Mev the neutrons are predominately forward.

The observation of a homogeneous α-particle group [$Q=14.3$ (Wi 37c, Li 37); 13.43 (La 47b)] indicates the formation of He^5 nuclei [reaction (*b*)] which subsequently break up into neutrons and α-particles having, because of the recoil energy, a continuous energy distribution (α-particles from 3 to 7 Mev, neutrons from 0.1 to $\sim$4 Mev). Reaction (*a*) leads to neutron groups corresponding to broad but resolvable states of Be^8 at 2.9, 4.0, 4.9, 7.5, 10 (?), 11.1, and 14.7 Mev (see Be^8:Li^7, *d n*). The α-particles resulting from the breakup of the Be^8 will again have a continuous distribution (from 0 to $\sim$7 Mev) because of the breadth of the states and recoil from the neutrons. It appears, from estimates of the relative yield of the homogeneous α-particle group, that reaction (*b*) accounts for about 20 percent of the disintegrations and most of the neutrons <4 Mev (St 39a).

Whether the three-body reaction (*c*) occurs is not clear (Gr 49e). For reaction (*d*) see Li^6.

Be 47 Bennett, Bonner, Richards, and Watt, Phys. Rev. **71**, 11 (1947).
Wh 49 Whaling, Evans, and Bonner, Phys. Rev. **75**, 688 (1949).
Wi 37c Williams, Shepherd, and Haxby, Phys. Rev. **52**, 390 (1937).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
La 47b Lattes, Fowler, and Cuer, Proc. Phys. Soc. London **59**, 883 (1947).
St 39a Staub and Stephens, Phys. Rev. **55**, 845 (1939).
Gr 49e Green and Gibson, Proc. Phys. Soc. London **62**, 407 (1949).
See also: Ru 38, St 38, Fa 49.

IV. (*a*) $Be^9(\gamma\ n)Be^8$ $\quad Q_m=-1.63$
(*b*) $Be^9(e, e'n)Be^8$

(*a*) Measurements of the (γ *n*) cross section have been summarized by Guth and Mullin (Gu 49a). A pronounced maximum ($\sigma=1\times10^{-27}$ cm^2) appears $\sim$100 kev above threshold. A theoretical treatment assuming a *P* ground state indicates that the observed variations can be accounted for by a bound *S* level $\sim$110 kev below threshold and a *D* state >2.5 Mev above threshold (Gu 49a).

Hammermesh *et al.* (Ha 49j) find the neutrons isotropic for $E_\gamma=1.70$ and 1.81 Mev. At $E_\gamma=2.76$ Mev, the distribution is of the form $a+b\sin^2\theta$ with $a/b=1.2$. Mullin and Guth (Mu 49) obtain good agreement with this value by assuming that the transitions responsible are $P_{\frac{3}{2}}\rightarrow S_{\frac{1}{2}}$ and $P_{\frac{3}{2}}\rightarrow D_{\frac{3}{2}}$. (See also Be^9, *p p'*).

On photo-neutron sources, see (Wa 49e, Ha 49g).

(*b*) The cross section for electrodisintegration is much smaller ($\sim$1/137) than that for direct photo-disintegration and shows only a continuous rise (Gu 49a).

Gu 49a Guth and Mullin, Phys. Rev. **76**, 234 (1949).
Ha 49j Hamermesh, Hamermesh, and Wattenberg, Phys. Rev. **76**, 611 (1949).
Mu 49 Mullin and Guth, Phys. Rev. **76**, 682 (1949).

Wa 49e Wattenburg, N.R.C. No. 6 (1949).
Ha 49g Hanson, Phys. Rev. **75**, 1794 (1949).
See also: (Experimental): Ha 38b, Ol 38a, Co 39, Co 39a, Ko 39, Go 40, Ho 43, Wi 46, Al 48b, Ru 48, Sn 49. (Theoretical) Gu 39, Wi 40a, Ca 47a, Ca 47b, Je 47a, Bo 48l, Gu 48, Gu 48a, Gu 48b, Sc 48a, Sa 49, Se 49a.

V. $Be^9(\gamma\ p)Li^8$ $Q_m = -16.86$

Alpha-particles (from Li^8 decay) identified (Co 48d). Yield has a broad maximum $E_\gamma \sim 32$ Mev (Ba 49b).

Co 48d Conklin and Ogle, Phys. Rev. **73**, 648 (1948).
Ba 49b Baldwin, Phys. Rev. **76**, 182 (1949).
See also: Og 47, Ti 50.

VI. $Be^9(p\ p')Be^{9*}$

Observation of scattered protons indicates a level in Be^9 at 2.41 Mev with a half-width of <100 kev (Da 48a); 2.39±0.05 Mev (Rh 50). The differential cross section for excitation at $E_p = 4.5$ and 7.1 Mev is about 3×10^{-27} cm^2. No other levels appear in this work <5.2 Mev. Longmire (Lo 48) suggests that the state involved is $D_{\frac{5}{2}}$, but it is not clear why such a state should not appear in the $\gamma\ n$ process (see Gu 49a).

Da 48a Davis and Hafner, Phys. Rev. **73**, 1473 (1948).
Lo 48 Longmire, Phys. Rev. **74**, 1773 (1948).
See also: Gu 49a.

VII. $Be^9(\alpha\ \alpha')Be^8 + n$ $Q_m = -1.63$
$Be^9(\alpha\ \alpha')He^5 + \alpha$ $Q_m = -2.4$
$Be^9(\alpha\ \alpha')2He^4 + n$ $Q_m = -1.58$

Bjerge (Bj 38) observed a threshold for slow neutron production at $E_\alpha = 4.9$ Mev for which one of the above processes may be responsible. There is some disagreement as to the existence of the slow neutrons (Ya 46, An 48a).

Bj 38 Bjerge, Proc. Roy. Soc. **164**, 243 (1938).
Ya 46 Yalow, Yalow, and Goldhaber, Phys. Rev. **69**, 253 (1946).
An 48a Anderson, N.R.C. Nuclear Science Series, No. 3 (December, 1948).
See also: Am 37a, Sz 40, Ri 46.

VIII. $Be^9(d\ d')Be^{9*}$

Inelastically scattered deuterons indicate a level in Be^9 at 2.6 Mev (Boyer, private communication).

IX. $B^{11}(d\ \alpha)Be^9$ $Q_m = 8.03$

Q from α-particle range = 8.13±0.12 Mev (Co 36a, Li 37).

Q from spectrometer = 8.018±0.007 Mev, 5.997 ±0.005. $\Delta Q = 2.421 \pm 0.005$ (Van Patter and Buechner, private communication).

No other groups appear $>\frac{1}{6}$ of intensity of 2.4-Mev transition from 0 to 4.9 Mev excitation in Be^9, at $E_d = 1.51$ Mev.

Relative intensities ($E_d = 1.51$ Mev, $\theta = 90°$):

$B^{11}(d\ d)B^{11}$ 10, $B^{11}(d\ \alpha)Be^9$ 0.8, $B^{11}(d\ \alpha)Be^{9*}$ 0.5.

The term width of the 2.42-Mev level appears to be <5 kev (Van Patter and Buechner, private communication).

Disintegration into $3\alpha + n$ may occur (Li 37).

Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
See also: Sm 39.

X. $C^{12}(n\ \alpha)Be^9$ $Q_m = -5.75$ (not illustrated)

Has been observed (Li 37). See also C^{13}.

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).

XI. $B^{11}(n\ t)Be^9$ $Q_m = -9.57$

See B^{12}.

Be^9 Theory

$\mu = -1.178$; $I = \frac{3}{2}$ (probable). Shell configuration: $\alpha + 1p_{\frac{3}{2}}^2$ (protons) $+ 1p_{\frac{3}{2}}^3$ (neutrons). Mainly $^2P_{\frac{3}{2}}$, odd, on either an α-particle or Hartree model.

The paucity of levels is not likely to remain. The identification of the lowest states by interpretation of the angular distribution and energy variation of the photo-neutrons is very plausible, even though it is made on the basis of a much-simplified two-body model, in which the odd neutron is imagined moving in the potential field of the Be^8 core. For the low states this model seems quite good, giving best agreement for a ground state which is $^2P_{\frac{3}{2}}$ with an unresolved neighbor of $^2P_{\frac{1}{2}}$, making transitions to a wider state, also an unresolved doublet ^2D at about 2.4 Mev (Mu 49). All such results depend only on a few parameters, and the fact of agreement with this simple model should not lead one to rash extrapolation of the picture to more remote levels.

Mu 49 Mullin and Guth, Phys. Rev. **76**, 682 (1949).

B^9

(not illustrated)

(Mass: 9.01620)

I. $Be^9(p\ n)B^9$ $Q_m = -1.84$

Haxby, Shoupp, Stephens, and Wells (Ha 40a) give 2.03 Mev as the threshold for the production of neutrons by the proton bombardment of Be^9; based on the $F^{19}(p\ \alpha)$ resonance as 862 kev.

Hanson and Benedict (Ha 44) give 2.058±0.006 Mev and Richards and Smith (Ri 50) give 2.059±0.002 Mev as the threshold, both based on $Li^7(p\ n)E_{thr} = 1.882$ Mev, see Be^8:$Li^7(p\ n)$. Using $Q = -1.852 \pm 0.002$ Mev as the reaction energy, B^9 is unstable to disintegration into $(Be^8 + p)$ by $1.852 - 1.666 = 0.186 \pm 0.003$ Mev.

The neutron spectrum at $E_p = 3.8$ shows a group corresponding to the ground state transition, of half-width 0.12 Mev, in addition to a continuous distribution attributed to either $Be^9(p,\ p'\ n)Be^8$ or a very broad level in B^9. No evidence is found for any narrow levels in B^9 up to ~1.8 Mev (Jo 50a, and Johnson *et al.*, private communication).

The mean life is estimated to be greater than 5×10^{-21} sec. $[\Gamma < (10/9)\times0.12 = 0.13$ Mev$]$.

Ha 40a Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **58**, 1035 (1940).

Ha 44 Hanson and Benedict, Phys. Rev. **65**, 33 (1944).
Ri 50 Richards and Smith, Phys. Rev. **77**, 752 (1950).
Jo 50a Johnson, Laubenstein, and Ajzenberg, Phys. Rev. **79**, 239 (1950).
See also: Do 37, Ha 40, Hi 40, Hu 45.

B^9 Theory

Unstable. Shell: $\alpha+1p_{\frac{3}{2}}^3$ (protons) $+1p_{\frac{3}{2}}^2$ (neutrons). Expected ground state like the mirror nucleus Be^9: $^2P_{\frac{3}{2}}$, odd.

This nucleus is unstable against disintegration into a proton, and Be^8 or two α-particles. Since Be^9 is bound, the Coulomb energy is apparently the source of the instability for binding a proton to the two-α-particle core. This is confirmed by the quantitative calculation of the Coulomb energy, which is about 2 Mev here, and outweighs the observed binding energy of the neutron in Be^9 by several hundred kilovolts. The width of the "ground" state here is expected to be like that for Li^5, reduced however by the smaller energy available (as $E^{\frac{3}{2}}$) and by the higher Coulomb barrier. Thus one expects a width of only some 10 kev; while experiment indicates about 10 times this width (Jo 50a).

Jo 50a Johnson, Laubenstein, and Ajzenberg, Phys. Rev. **79**, 239 (1950).

Be^{10}

(Mass: 10.016 77)

I. $Be^{10}(\beta^-)B^{10}$ $Q_m=0.55$

TABLE XVIII. Q values.

β_{max} (Mev)	Method	Reference
0.58 ±0.03	(Absorption)	Hu 47
0.56 ±0.01	(Absorption)	Mc 47
0.57 ±0.01	(Absorption)	Hu 49a
0.545±0.01	(Scint. ctr.)	Be 50
0.550±0.005	(Spectrometer)	Fe 50
0.560±0.005	(Spectrometer)	Hu 50b

Half-life: $2.5\pm0.5\times10^6$ yr. (Mc 47); 2.9×10^6 yr. (Hu 47).

Mean: $2.7\pm0.4\times10^6$ yr. (Hu 49a).

The spectrum appears to fit the D_2 shape (Ma 49) for energies >100 kev (Be 50, Fe 50, Hu 50b, Fu 49b).

No transitions occur to other than the ground state of B^{10} (<1 percent $\beta-\gamma$-coincidences: W. E. Stephens, private communication). [The existence of a level at 0.41 Mev in B^{10}, to which transitions might occur, is now in doubt (see B^{10}: Be^9, d n).]

Mc 47 McMillan, Phys. Rev. **72**, 591 (1947).
Hu 47 Hughes, Eggler, and Huddleston, Phys. Rev. **71**, 269 (1947).
Hu 49a Hughes, Eggler, and Huddleston, Phys. Rev. **75**, 515 (1949).
Ma 49 Marhsak, Phys. Rev. **75**, 513 (1949).
Be 50 Bell and Cassidy, Phys. Rev. **77**, 301 (1950).
Fe 50 Feldman and Wu, Phys. Rev. **78**, 318 (1950).
Hu 50b Hughes, Eggler, and Alburger, Phys. Rev. **77**, 726 (1950).
Fu 49b Fulbright and Milton, Phys. Rev. **76**, 1271 (1949).
See also: Po 40, Co 41, Br 46, Pi 46, Le 47, Eg 48, Hu 48d, St 48, Hu 49, Wu 49.

II. $Be^9(n\ \gamma)Be^{10}$ $Q_m=6.69$

$E_\gamma=6.797\pm0.008$ Mev (Ki 50a).
$\sigma_{th}=0.01$ b (Wa 48d).

Ki 50a Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950).
Wa 48d Way and Haines, AECD 2138 (1948).
See also: Hu 47, Le 47, Ki 50.

III. $Be^9(n\ \alpha)He^6$ $Q_m=-0.8$ $E_x=6.69$

A resonance for production of α-particles occur at $E_n=2.6$ Mev, ~1 Mev wide; $\sigma_\alpha\sim0.05$ b (Al 47b).

Al 47b Allen, Burcham, and Wilkinson, Proc. Roy. Soc. **192**, 114 (1947).
See also: Bj 36, Po 37b, Fu 44, Al 47, Ca 47, Go 47a, Sc 48a, Te 49d.

IV. $Be^9(n\ n)Be^9$ $E_x=6.69$

Adair, Barschall, Bockelman, and Sala (Ad 49) observe a resonance at $E_n=625$ kev: $\sigma_t=7$ b, which they attribute to a level of spin 3, formed by p neutrons. An additional resonance at 810 kev ($\sigma_t=4.5$ b) is reported (Bockelman, private communication). [Levels in Be^{10} at 7.25, 7.42.]

Cross-section curves: see (Go 47a, Ad 50).

Ad 49 Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949).
Ad 50 Adair, Rev. Mod. Phys. **22**, 249 (1950).
Go 47a Goldsmith, Ibser, and Feld, Rev. Mod. Phys. **19**, 259 (1947).
See also: Ma 46b, Ba 47, Fi 47, Şc 48a.

V. $Be^9(n\ 2n)Be^8$ $Q_m=-1.63$ $E_x=6.69$

$\sigma\sim0.3$ b, Ra α+Be neutrons (Fu 44).
$\sigma\sim3.6$ b, Rn α+Be neutrons (Ol 38b).
$\sigma=3.6$ b, Po α+Be neutrons (Ho 46).
$\sigma>0.4$ b, Ra α+Be neutrons (Te 49d).

Fu 44 Fünfer and Bothe, Zeits. f. Physik **122**, 769 (1944).
Ol 38b Ollano, Nuovo Cimento **15**, 604 (1938).
Ho 46 Houtermans, Göttingen Nechrichten 52 (1946).
Te 49d Teucher, Zeits. f. Physik **126**, 410 (1949).
See also: Ru 36, Sc 48a.

VI. $Be^9(d\ p)Be^{10}$ $Q_m=4.52$

$Q=4.585\pm0.008$ (spectrometer) (Bu 49e; Strait, *et al.*, private communication); 4.59 ± 0.05 (range) (Al 48f).

At $E_d=1$ Mev, only one additional proton group is observed (La 47b, Bu 49e). The level energy from this group is 3.375 ± 0.01 Mev; ~0.6 of the disintegrations lead to the excited state (Bu 49e). A γ-ray of 3.38 Mev energy has been observed: correction for Doppler shift yields 3.36 ± 0.015 for the transition energy (Ra 49b). At $E_d=14$ Mev, proton groups corresponding to the following levels appear: 3.3, 6.3, 7.6, and 8.3 Mev (Bo 50, and Boyer, private communication).

Bu 49e Buechner and Strait, Phys. Rev. **76**, 1547 (1949).
Al 48f Allan and Wilkinson, Proc. Roy. Soc. **194**, 131 (1948).
La 47b Lattes, Fowler, and Cuer, Proc. Phys. Soc. London **59**, 883 (1947).

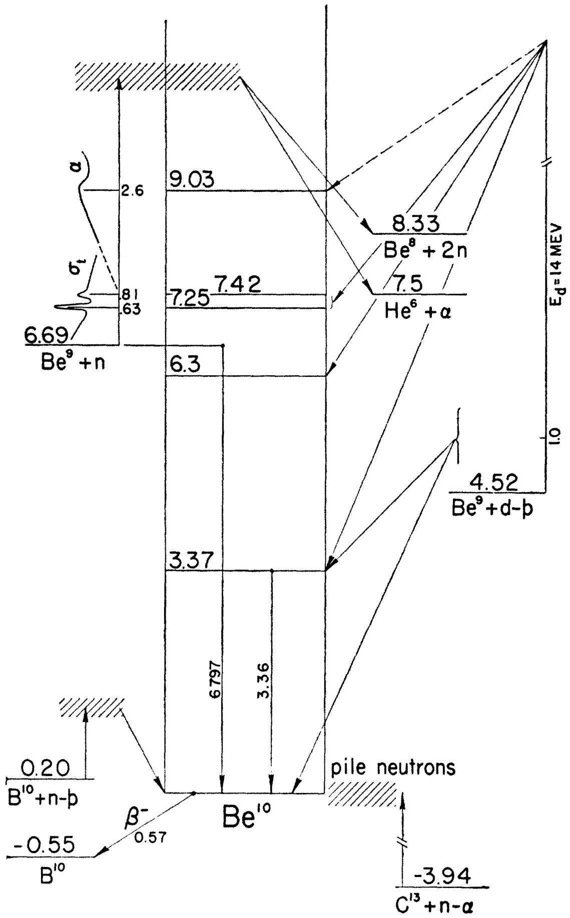

FIG. 8. Energy levels in Be^{10}: for notation see Fig. 1.

Ra 49b Rasmussen, Hornyak, and Lauritsen, Phys. Rev. **76**, 581 (1949).
Bo 50 Boyer, M.I.T. Progress Reports (October 1, 1949; January 1, 1950); Phys. Rev. **78**, 345 (1950).
See also: Wi 37d, Po 40, Mc 46, La 47c, Mc 47, Re 49c, Ra 50a.

VII. $B^{10}(n\ p)Be^{10}$ $Q_m=0.20$

Production of Be^{10} has been observed (Eg 48): see B^{11}.

Eg 48 Eggler, Hughes, and Huddleston, Phys. Rev. **74**, 1238 (1948).

Be^{10} Theory

Beta$^{(-)}$-radioactive. Configuration: $\alpha+1p_{\frac{3}{2}}^2$ (protons) $+1p_{\frac{3}{2}}^4$ (neutrons), and predicted ground state $^1S_0$, even.

The long-standing mystery of the great difference between the very slow β-decay of this nucleus and the allowed transition of its mirror nucleus C^{10} was completely resolved by the discovery that the ground state of B^{10} had $I=3$. (Cf. B^{10}.) This means that if both even-even nuclei have the expected value $I=0$, decay to the ground state of B^{10} is strongly forbidden. The low energy Be^{10} decay has only the ground state energetically available, while C^{10}, with its higher Coulomb energy can take advantage of the first excited level in the product nucleus. The shape of the β-spectrum is almost certainly of the so-called D_2 type (Ma 49), consistent with Gamow-Teller coupling types in the β-decay theory.

Numerous excited levels have been observed; little can be said of their character.

Ma 49 Marshak, Phys. Rev. **75**, 513 (1949).

B^{10}

(Mass: 10.016 18)

I. $Li^6(\alpha\ p)Be^9$ $Q_m=-2.12$ $E_x=4.36$

Not observed: $\sigma<0.01$ b for Ra C′ α-particles (Sh 37).

Sh 37 Shepherd, Haxby, and Hill, Phys. Rev. **52**, 674 (1937).

II. $Li^7(\alpha\ n)B^{10}$ $Q_m=-2.78$

Steps in the slow neutron yield are observed for $E_\alpha\sim5.0$, 6.3, 7.2, and 8.5 Mev (Ha 39a). [Levels in B^{10}: 0.8, 1.3, 2.1 Mev.]

Ha 39a Haxel and Stuhlinger, Zeits. f. Physik **114**, 178 (1939).

III. $Be^9(p\ \gamma)B^{10}$ $Q_m=6.49$

At $E_p=1.15$ Mev (thick target: predominantly from the 998-kev resonance) the γ-ray energy is 7.38±0.07 Mev (R. L. Walker, private communication). With a thin target at $E_p=1.21$ Mev (1087-kev resonance) three lines appear, at 7.50±0.10, 6.84±0.10 (Walker), and 0.72±0.1 Mev (La 48). (See Table XIX.)

The radiation from the 988-kev resonance is nearly isotropic $(1+0.09\sin^2\theta)$ (De 49d); theoretical analysis suggests contribution of *d* wave terms to the predominant *s* wave component, forming a state in B^{10} with $I=2$, odd (see also Be^9, *p p*).

The radiation is isotropic at $E_p=340$ kev (Ja 48).

The weak resonance at ~870 kev found by many experimenters and usually attributed to fluorine contamination may in fact be a real effect in beryllium.

Ta 46 Tangen, Kgl. Nord. Vid. Selsk. Skr. No. 1 (1946).
Cu 39a Curran, Dee, and Petrzilka, Proc. Roy. Soc. **169**, 269 (1939).
Fo 49b Fowler and Lauritsen, Phys. Rev. **76**, 314 (1949).
Hu 45 Hushley, Phys. Rev. **67**, 34 (1945).
La 48 Lauritsen, Fowler, Lauritsen, and Rasmussen, Phys. Rev. **73**, 636 (1948).
De 49d Devons and Hine, Proc. Roy. Soc. **199**, 56, 73 (1949).
Ja 48 Jacobs, Malmberg, and Wahl, Phys. Rev. **73**, 1130 (1948).
See also: He 37, Ho 40d, Co 48g, Fo 48, Fo 48b, Th 49, Wa 50a.

TABLE XIX. Resonances reported.

E_p (kev)	Width (kev)	Radiation (Mev)	Yield[b]	σ_R (cm²)	Reference
(150)?					Ta 46
310	140	6.8			Ta 46, Cu 39a
670		7.1			Cu 39a
998±4	94	7.4	1.78×10^{-8}	4.0×10^{-28}	Fo 49b
1087±2	4	6.8, 0.72	1.01×10^{-9}	5.3×10^{-28}	Fo 49b
2560[a]		3.			Hu 45

[a] The soft radiation at the highest resonance is probably due to $Be^9(p\ \alpha)Li^{8*}$.
[b] Thick target yield: disintegrations per proton.

IV. $Be^9(p\ p)Be^9$ $E_x=6.49$
$Be^9(p\ \alpha)Li^6$ $Q_m=2.12$
$Be^9(p\ d)Be^8$ $Q_m=0.54$

The yield of elastically scattered protons, observed at 138°, exhibits pronounced interference effects at the 0.330-, 0.998-, and 1.087-Mev resonances (see Be^9, $p\ \gamma$, above). The α-particles and deuterons similarly show anomalous effects, peaks occurring at $E_p=0.33$, 0.93 for α-particles and at $E_p=0.33$, 0.44, and 0.93 for deuterons (Th 49). Analysis of the proton scattering data suggests assignment of $I=2$ to the 0.988-Mev level (7.38 Mev in B^{10}, s wave protons, electric dipole radiation) and $I=0$ (d wave) to the 1.087-Mev level (Co 49).

The angular distributions of deuterons and α-particles have a $1+a\cos\theta$ dependence for $E_p=0.6$ to 1.0 Mev, with the coefficient a increasing with energy. Analysis suggests that s-wave protons are responsible for the 0.33-Mev resonance and p wave for the higher [0.988?] resonance (Ne 50a).

Inelastic scattering of protons has been studied: see Be^9.

Th 49 Thomas, Rubin, Fowler, and Lauritsen, Phys. Rev. **75**, 1612 (1949).
Co 49 Cohen, Phys. Rev. **75**, 1463 (1949); Ph.D. thesis, California Institute of Technology (1949).
Ne 50a Neuendorffer, Inglis, and Hanna, Phys. Rev. **79**, 239 (1950).
See also: Al 37, Ha 37a, Wi 37d, Al 40a, Cr 39, Ru 47c, Ke 48, Gu 49a.

V. $Be^9(p\ n)B^9$ $Q_m=-1.84$ $E_x=6.49$

Threshold: 2.058±0.006 Mev (Ha 44); 2.059±0.002 Mev (Ri 50).

A resonance for neutron and γ-ray (~3 Mev: see Be^9, $p\ \gamma$) production occurs at 2.56 Mev (Hu 45). No others appear <3.5 Mev (Br 50b).

See also B^9.

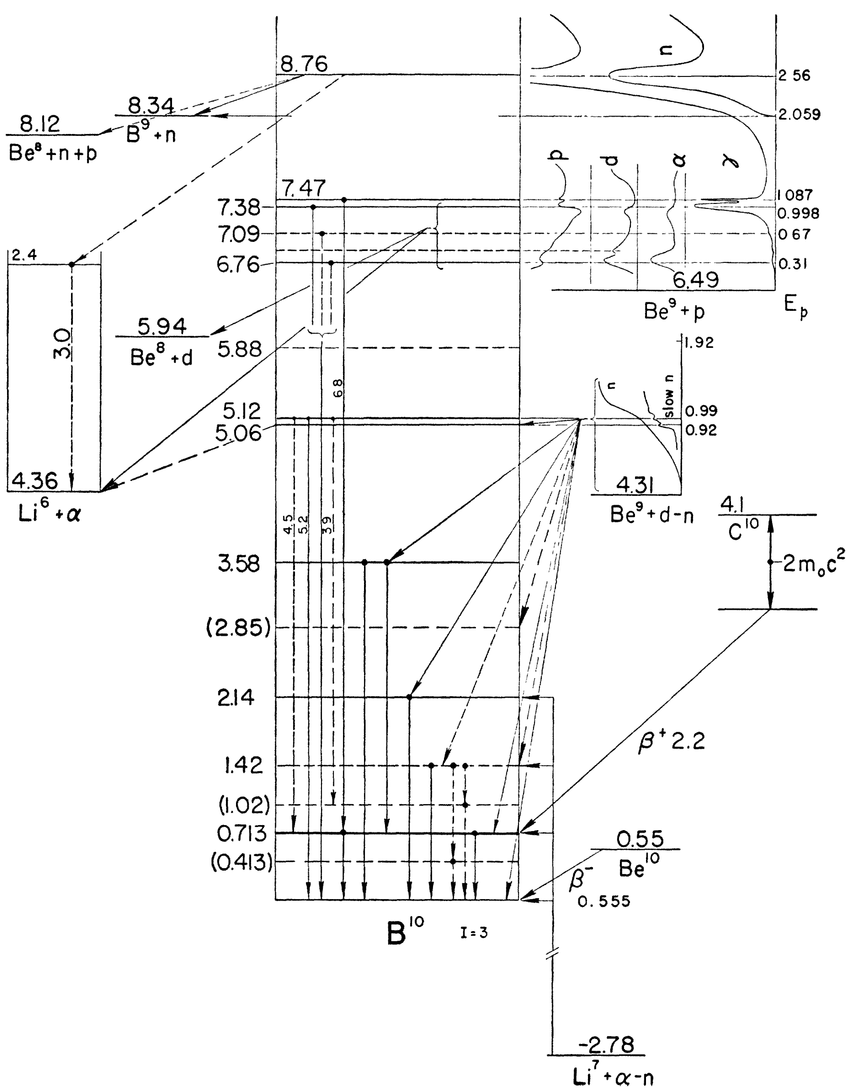

FIG. 9. Energy levels in B^{10}: for notation see Fig. 1. *Note added in proof:* For most recent work on the $Be^9(d\ n)$ reaction refer to text.

Ha 44 Hanson and Benedict, Phys. Rev. **65**, 33 (1944).
Ri 50 Richards and Smith, Phys. Rev. **77**, 752 (1950).
Hu 45 Hushley, Phys. Rev. **67**, 34 (1945).
Br 50b Browne, Smith, and Richards, Phys. Rev. **77**, 754 (1950).
See also: Do 37, Ha 40, Ha 40a, Hi 40, Gu 49, Je 50c.

VI. $Be^9(d\ n)B^{10}$ $Q_m=4.31$

TABLE XX. Neutron groups.

A Level	A Intens.	B Level	C Q	D Q	D Level	E Intens.	F Intens.
0	31	0		4.39	0	38.6	39
0.55	37	0.63		3.70	0.69±0.10	35.6	39
(1.2)		(1.2)					
2.15	15	1.93		2.19	2.20±0.10	9.4	15
3.45	17	3.52		0.73	3.66±0.10	1.9	7
			−0.74	−0.74	5.13±0.08	14.5	

A: Thick target; E_d=0.9-Mev peak: the group corresponding to a possible level at 1.2 Mev is attributed to $H^2(d\ n)$ (Bo 36b, Ev 49).
B: Thick target; E_d=0.6- and 0.88-Mev peak (St 39b).
C: From threshold for slow neutrons (Ev 49).
D: 100-kev target; E_d=1.62 Mev (Wh 50).
E: E_d=1.62; θ=0° (Wh 50).
F: E_d=1.15; θ=0° (Wh 50).

Three thresholds for slow neutron production occur, at E_d=0.92, 0.99, and 1.92 Mev, indicating levels in B^{10} at 5.06, 5.12, and 5.88 Mev [Bo 50b; Bonner, Oak Ridge Symposium (June, 1950)].

Gamma-ray lines No. 2, 5, 7, and 10 are assigned to B^{10*} because of their correspondence with the neutron groups [No. 2 also occurs in $Be^9(p\ \gamma)$]. Line No. 6 is probably a cascade (7→2). Lines 1 and 3 appear to be related to line 4, suggesting a level in B^{10} at 1.42 Mev and another at 0.41 or 1.02 Mev [such levels are not indicated in the neutron work, although they are not completely excluded; there is, in fact some indication of a level at 1.4 Mev in $Li^7(\alpha\ n)$]. Lines 8 and 9 may be cascades from the complex levels at 5.1 and 5.2 Mev.

The low intensity of lines 8, 9, and 10 suggests that this level decays mainly by α-particle emission. Lines 11 and 12 are from excited states of Li^7 and Be^{10}, respectively.

Note added in proof: Recent work by Ajzenberg (private communication) at E_d=3.41 Mev, using photographic plates at 0° and 80° shows strong groups corresponding to the following levels in B^{10}: 0, 0.73, 2.0, 3.61, 4.78, 5.1 (unresolved doublet) 5.91 and 6.1 Mev (unresolved doublet). The great width of the group corresponding to the 2.0 Mev level suggests that two levels exist, at 2.24 and 1.85. Weaker groups, corresponding to levels at 5.57, 5.68, 6.33, 6.57 and 6.80 Mev are also observed. Levels at 0.4 and 1.0 Mev are uncertain, and no neutrons corresponding to possible levels at 1.4 or 2.8 Mev are observed. It is pointed out that levels at 0.71, 1.73, 2.14 and 3.58 Mev would account for all the gamma-rays <3.6 Mev (see table: gamma-radiation).

Bo 36b Bonner and Brubaker, Phys. Rev. **50**, 308 (1936).
Ev 49 Evans, Malich, and Risser, Phys. Rev. **75**, 1161 (1949).
St 39b Staub and Stephens, Phys. Rev. **55**, 131 (1939).
Wh 50 Whitehead and Mandeville, Phys. Rev. **77**, 732 (1950).
Bo 50b Bonner, Butler, and Risser, Phys. Rev. **79**, 240 (1950).
Ra 49b Rasmussen, Hornyak, and Lauritsen, Phys. Rev. **76**, 581 (1949).
Ra 50a Rasmussen, Ph.D. thesis, California Institute of Technology (1950).
Ch 49c Chao, Lauritsen, and Rasmussen, Phys. Rev. **76**, 582 (1949).
See also: Kr 37, Kr 39, Po 39b, Po 42, La 48, Ho 49a.

VII. $Be^{10}(\beta^-)B^{10}$ $Q_m=0.55$

No transitions observed other than to the ground state: see Be^{10}.

VIII. $B^{10}(\gamma\ d)Be^8$ $Q_m=-5.94$
$B^{10}(\gamma,\ n\ p)Be^8$ $Q_m=-8.12$

See: Go 50a.

IX. $B^{10}(p\ p')B^{10*}$

The 0.42-Mev radiation formerly attributed to this reaction (La 48) is due to $B^{10}(p\ \alpha)Be^{7*}$ (La 50). An upper limit of $\sim 10^{-7}\ \gamma/p$ can be placed on the thick target yield of γ-radiation at E_d=1.5 Mev from the present reaction.

La 48 Lauritsen, Fowler, Lauritsen, and Rasmussen, Phys. Rev. **73**, 636 (1948).
La 50 Lauritsen and Thomas, Phys. Rev. **78**, 88 (1950).

X. $C^{10}(\beta^+)B^{10}$ $Q_m=3.1+1.02=4.1$

Sherr, Muether, and White (Sh 49) report production of C^{10} with a half-life of 19.1±0.8 sec., in the reaction $B^{10}(p\ n)$. The earlier reported 8.8-sec. activity is thought to be a contamination. The decay appears to take place with the emission of 2.2±0.1-Mev positrons, followed by 0.96±0.2-Mev γ-radiation (presumably from the 0.71-Mev level in B^{10}). Calculation of the Coulomb energy difference between Be^{10} and C^{10} leads to an expected mass for C^{10} 4.080 Mev above B^{10}, which is in reasonable agreement with the decay energy. A similar calculation suggests a state of B^{10} of spin zero at 2.04 Mev.

Sh 49 Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).
See also: De 40, Co 41.

Gamma-radiation:[a]

No.	E_γ, kev	Yield[b] $\gamma/d\times10^6$	$E_{transition}$, kev[d]
1	413.5±1	1.2	412± 1.5
2	716.6±1	13.7	713± 1.5
3	1022 ±2	3.9	1017± 2
4	1433 ±5	2.5	1424± 5
5	2151 ±16	1.2	2140± 15
6	2871 ±15	2.4	2856± 15
7	3604 ±30	0.9	3584± 30
8	3970 ±80	c	3940± 80
9	4470 ±70	c	4440± 70
10	5200 ±100	c	5160±100
11	472 (broad)	1.6	$Be^9(d\ \alpha)Li^{7*}$
12	3380 ±15	2.1	$Be^9(d\ p)Be^{10*}$

[a] E_d=1.2 Mev, thick target (Ra 49b, Ra 50a).
[b] Probable error=25 percent.
[c] At E_d=1.5 Mev, 300-kev target: relative intensities=1:1.4:0.4, sum less than two percent of total γ-radiation (Ch 49c).
[d] Corrected for Doppler shift; there is some evidence that the 717-kev line is not shifted (Ra 50a).

XI. $C^{12}(d\ \alpha)B^{10}$ $Q_m=-1.44$

See N^{14}.

B^{10} Theory

$\mu=1.800$; $Q=0.06$; $I=3$. Shell: $\alpha+1p_{\frac{3}{2}}^3$ (protons) $+1p_{\frac{3}{2}}^3$ (neutrons); the Hartree models predict a $^3S_1$ ground state, even, while spin-orbit allows $^3D_3$ as well.

The measurement of the high spin of this nucleus demonstrates that its ground state is somewhat exceptional among the few odd-odd nuclei. The magnetic moment is consistent with a ground state mainly $^3D_3$, with some admixture from ^3F, ^1F, and even ^3G. The combining state at 7.38 Mev [$Be^9(p\ \gamma)$] can be given a tentative assignment on the basis of angular distributions and computed particle and γ-ray widths; this state is very likely $I=2$, odd, decaying to the ground state by an electric dipole γ-ray. This assignment is borne out by the proton scattering data which gives in addition $I=0$, odd, character for the 7.47-Mev level. The spin zero state which is the homologue of the C^{10} ground state is not certain. The several states more or less equally combining with the ground state by radiation below about 5 Mev are presumably states of angular momentum between 1 and 5; they are especially interesting because there are here possibly five levels whose energies are integeral multiples of 713 kev to an accuracy distinctly better than one percent.* Only a true simple harmonic motion can quantum-mechanically have a Fourier analysis containing only integeral harmonics. There seems to be such a tendency, not so well marked, in a few other heavier nuclei. Whether these cases are significant for the force law, or merely chance curiosities, is still entirely unclear. From the C^{10} decay one concludes that the lowest of these states, at 0.713 Mev, has $I=1$ and radiates a quadrupole γ-ray.

C^{10}

(not illustrated)

[Mass $=B^{10}+4.4$ mmu (4.1 Mev) $=10.020\ 6$]

I. $C^{10}(\beta^+)B^{10}$ $Q_m=3.1+1.02=4.1$

Half-life $=19.1\pm0.8$ sec. (Sh 49). The decay is complex: see B^{10}.

Sh 49 Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).

II. $B^{10}(p\ n)C^{10}$ $Q_m=-4.9$

C^{10} observed with 16- to 18-Mev protons (Sh 49). The earlier reported 8.8-sec. activity (De 40) is apparently spurious.

Sh 49 Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).
De 40 Delsasso, White, Barkas, and Creutz, Phys. Rev. **58**, 586 (1940).

C^{10} Theory

Beta$^{(+)}$-active; shell: $\alpha+1p_{\frac{3}{2}}^4$ (protons) $+1p_{\frac{3}{2}}^2$ (neutrons): expected state: $^1S_0$, even.

There is no reason to doubt that this nucleus fulfills the rule that even-even nuclei have ground states $I=0$, probably even. The available excited state in B^{10} to which it decays then has spin 1. From the value of $ft=2100$ sec., the transition is allowed.

* See, however, note added in proof under reaction VI, above.

B^{11}

(Mass: 11.012 84)

I. $Li^7(\alpha\ \alpha')Li^{7*}$

See Li^7.

II. $Li^7(\alpha\ n)B^{10}$ $Q_m=-2.78$ $E_x=8.64$

Resonances for production of neutrons indicate levels at 13.0, 13.5, 13.8, and 14.2 Mev (Ha 39a).

Thick target yield with Po alphas (5.3 Mev): 2.6×10^{-6} n/α (Ro 44a); 4.7×10^{-6} n/α (Se 44a).

Ha 39a Haxel and Stuhlinger, Zeits. f. Physik **114**, 178 (1939).
Ro 44a Roberts, MDDC 731 (1944).
Se 44a Segrè and Wiegand, MDDC 185 (1944).

III. $Li^7(\alpha\ p)Be^{10}$ $Q_m=-2.58$ $E_x=8.64$

See: Ec 37.

IV. $Be^9(d\ \alpha)Li^7$ $Q_m=7.09$ $E_x=15.73$

Thick target yield at $E_d=390$ kev: 25×10^{-9} α/d (Gr 40).

The angular distribution of (unresolved) α-groups is isotropic at $E_d\sim700$ kev (Re 49c). The relative number of short-range alphas depends on bombarding voltage: see Li^7.

Gr 40 Graves, Phys. Rev. **57**, 855 (1940).
Re 49c Resnick and Hanna, Phys. Rev. **76**, 168 (1949).
See also: Ha 37a, Al 40, In 50.

V. $Be^9(d\ p)Be^{10}$ $Q_m=4.52$ $E_x=15.73$

The yield has a maximum between $E_d=6$ and 9 Mev (Mc 47).

Thick target yield at $E_d=212$ kev: 2×10^{-11} p/d (Wi 37d).

From $E_d=0.3$ to 0.7 Mev, the short-range protons are roughly spherically symmetric, while the long-range protons exhibit a strong $(-\cos\theta)$ dependence (Re 49c).

Mc 47 McMillan, Phys. Rev. **72**, 591 (1947).
Wi 37d Williams, Haxby, and Shepherd, Phys. Rev. **52**, 1031 (1937).
Re 49c Resnick and Hanna, Phys. Rev. **76**, 168 (1949).
See Also: Mc 46.

VI. $Be^9(d\ t)Be^8$ $Q_m=4.53$ $E_x=15.73$

Thick target yield at $E_d=212$ kev: 2×10^{-10} t/d (Wi 37d).

Angular distribution: see Re 49c.

Wi 37d Williams, Haxby, and Shepherd, Phys. Rev. **52**, 1031 (1937).
Re 49c Resnick and Hanna, Phys. Rev. **76**, 168 (1949).
See also: On 40.

VII. $Be^9(d\ n)B^{10}$ $Q_m=4.31$ $E_x=15.73$

The fast neutron and γ-ray yields rise smoothly to $E_d=1.8$ Mev, with some indication of a broad resonance at 1 Mev. At $E_d=0.88$ Mev the γ-ray and neutron cross sections are 0.43 and 0.4 b, respectively (Ev 49). At $E_d=1.2$ Mev the thick target yield is 3×10^{-5} γ/d (Ra 50a). At $E_d=10$ Mev the thick target yield is $5.9\pm0.6\times10^{-2}$ n/d (Sm 48). An absolute thick target yield curve is given for $E_d<1.$ Mev (Am 37).

Between $E_d=0.92$ and 1.92 Mev, three thresholds for production of slow neutrons appear, attributed to excitation of new levels in B^{10}(Bo 50b: see B^{10}).

Angular distribution of neutrons: see Ev 49, Fa 49.

Ev 49 Evans, Malich, and Risser, Phys. Rev. **75**, 1161 (1949).
Ra 50a Rasmussen, Ph.D. thesis, California Institute of Technology (1950).
Sm 48 Smith and Kruger, Phys. Rev. **74**, 1258 (1948).
Am 37 Amaldi, Hafstad, and Tube, Phys. Rev. **51**, 896 (1937).
Bo 50b Bonner, Butler, and Risser, Phys. Rev. **79**, 240 (1950).
Fa 49 Falk, Creutz, and Seitz, Phys. Rev. **76**, 322 (1949).
See also: Be 37a, Do 37, Ag 40, Sw 48, Am 49, Al 50f.

VIII. $B^{10}(n\ \alpha)Li^7$ $Q_m=2.78$ $E_x=11.42$

Cross-section curves indicate a resonance for 1.85-Mev neutrons, and possibly one for 0.1-Mev neutrons. $\sigma\sim1/v$ for slow neutrons. Isotopic cross section = 3800 b for thermal neutrons (Go 47a, Wa 48d, Ad 50). Angular distribution of main α-particle group (to Li^{7*}) is isotropic (Gi 48a, Go 39a).

Go 47a Goldsmith, Ibser, and Feld, Rev. Mod. Phys. **19**, 259 (1947).
Wa 48d Way and Haines, AECD 2138 (1948).
Ad 50 Adair, Rev. Mod. Phys. **22**, 249 (1950).
Gi 48a Gilbert, Proc. Camb. Phil. Soc. **44**, 447 (1948).
Go 39a Good and Hill, Phys. Rev. **56**, 288 (1939).
See also: Ro 36, Go 39, Go 39a, Hi 39b, Ba 46b, Ma 46a, Ma 46b, Ra 46, Ba 47, Fe 47, Fe 47a, Su 47, Wh 47, St 50d.

IX. $B^{10}(n\ t)Be^8$ $Q_m=0.22$ $E_x=11.42$

See: Li 37, Co 41a, Po 47a.

X. $B^{10}(n\ p)Be^{10}$ $Q_m=0.20$ $E_x=11.42$

$\sigma=3\times10^{-3}$ b for fast pile neutrons (Eg 48).

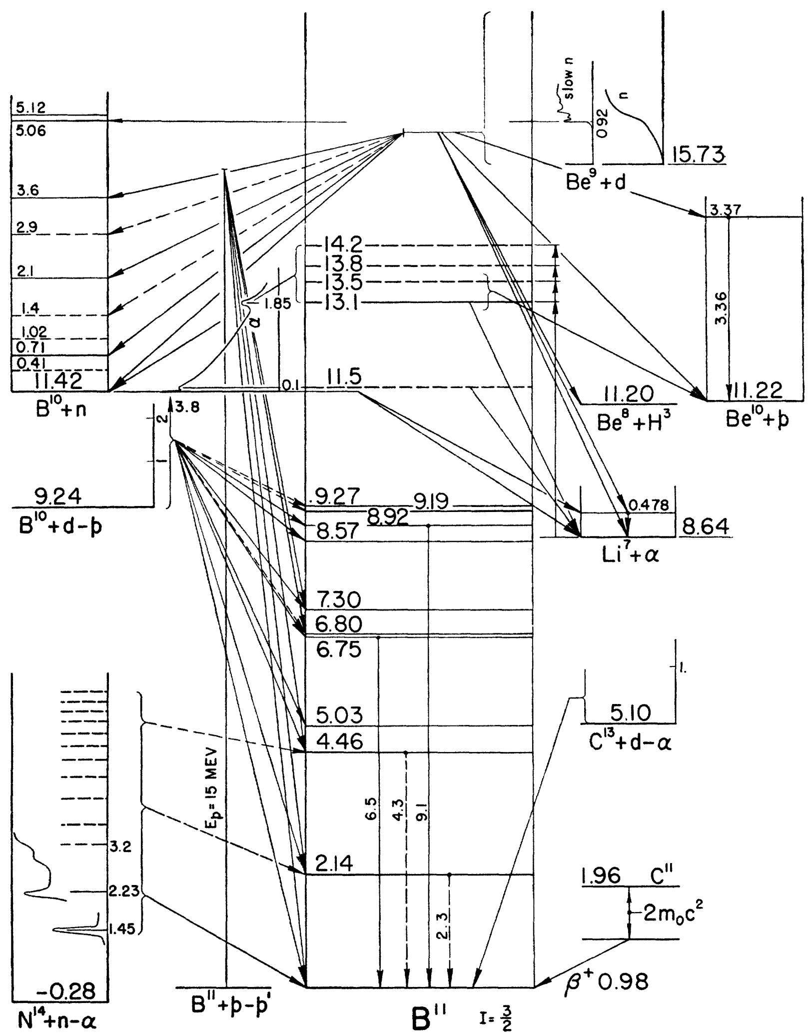

FIG. 10. Energy levels in B^{11}: for notation see Fig. 1.

Eg 48 Eggler, Hughes, and Huddleston, Phys. Rev. **74**, 1238 (1948).
See also: Ku 35, Ku 38, Ma 39a, Br 40, Bo 45, Br 46.

XI. $B^{10}(d\ p)B^{11}$ $Q_m=9.24$

TABLE XXI. Proton groups.

A		B		C	D	
Q	Intens.	Q	Intens.	Q	Q	B^{11*}
9.14±0.06	0.43	9.22±0.2	1	9.18±0.06	9.232	0
7.00	0.14	7.30±0.2	1.5	7.03	7.091	2.141
4.71	0.5	5.00±0.2	0.6	4.70	4.775	4.457
			28	4.15	4.199	5.033
		2.39±0.1		2.26	2.480	6.752
					2.430	6.802
				1.36	1.935	7.297
				0.70	0.667	8.565
					0.311	8.921
					0.047	9.185
					−0.039	9.271

A: E_d = 0.5 Mev, θ=90° (Co 36a, Li 37).
B: E_d = 3.1 Mev, θ=90° (Po 39a).
C: E_d=3.8 Mev, θ=90° (Ba 50b).
D: E_d=1.5 Mev, θ=90° (Bu 50a, Bu 50c, and W. W. Buechner, private communication: doublet spacing at 6.8 Mev =50±2 kev).

TABLE XXII. Gamma-radiation from $B+d$

	A		B	
No.	Energy	Intens.	Energy	Intens.
1	1.5	>2.5	1.4	1
2	2.2±0.3	2.5	2.4	1
3	4.4±0.3	1	4.2	6
4	6.9±0.4	0.3	6.0	2
5	9.1±0.4	0.1	8.6	1

A: E_d 0.5 to 0.85 Mev, (peak) (Ga 39).
B: E_d 0.7 Mev, (peak) (Ha 39b).

Hudspeth and Swann (Hu 49j) report that most of the radiation >2 Mev is from B^{10} rather than B^{11}. Lines 4 and 5 must then be from the present reaction, while 2 and 3 can be ascribed either to $B^{10}(d\ p)$ or $B^{10}(d\ n)$. The lack of $\gamma-\alpha$-coincidences (Th 49d) suggests that $B^{10}(d\ \alpha)$ is not involved. Line 1 is attributed to $B^{11}(d\ p)$: see B^{12}. Work with a pair spectrometer (Terrell and Phillips, private communication) gives γ-ray energies of 4.5, 6.7, and 9.1 Mev from $B^{10}+d$ (E_d=1.5 Mev) and only 4.5 Mev from $B^{11}+d$. Curling and Newton (Cu 50a) have observed $p-\gamma$-coincidences between 4.5- and 2.1-Mev radiation and the appropriate proton groups from $B^{10}+d$.

Note added in proof: Rutherglen reports γ-ray lines at 4.5, 6.5, 6.7, and 8.94 Mev from $B^{10}+d$, and 4.45 Mev from $B^{11}+d$ (Harwell conference, 1950).

Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Po 39a Pollard, Davidson, and Schultz, Phys. Rev. **57**, 1117 (1939).
Ba 50b Bateson, Phys. Rev. **78**, 337 (1950).
Bu 50a Buechner and Van Patter, Phys. Rev. **79**, 240 (1950).
Bu 50c Buechner *et al.*, M.I.T. Progress Report (April 1, 1950).
Ga 39 Gaerttner, Fowler, and Lauritsen, Phys. Rev. **55**, 27 (1939).
Ha 39b Halpern and Crane, Phys. Rev. **55**, 415 (1939).
Hu 49j Hudspeth and Swann, Phys. Rev. **76**, 1150 (1949).
Th 49d Thirion, Comptes Rendus **229**, 1007 (1949).
Cu 50a Curling and Newton, Nature **166**, 339 (1950).
See also: Po 42, La 47b.

XII. $B^{11}(\gamma\ t)Be^8$ $Q_m=-11.20$

See: Go 50a.

XIII. $B^{11}(p\ p')B^{11*}$

Inelastic scattering of 15.6-Mev protons in boron yields groups corresponding to levels at 2.2±0.3 (weak), 4.8±0.4 (strong), 6.5±0.3 (strong), and 7.8±0.4 (weak). Some of these levels may be associated with B^{10}(Fu 48).

Fu 48 Fulbright and Bush, Phys. Rev. **74**, 1323 (1948).
See also: Ka 40.

XIV. $C^{11}(\beta^+)B^{11}$ $Q_m=0.94+1.02=1.96$

No transitions observed other than to ground state: see C^{11}.

XV. $C^{13}(d\ \alpha)B^{11}$ $Q_m=5.10$

Q=5.24 Mev from α-particle range (Li 37).

Q=5.160 Mev (magnetic spectrometer) (Bu 50c).

(Some of the γ-ray lines from $C^{13}+d$ may be associated with levels in B^{11}, see N^{14}: C^{13}, $d\ n$.)

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Bu 50c Buechner *et al.*, M.I.T. Progress Report (April 1, 1950).

XVI. $N^{14}(n\ \alpha)B^{11}$ $Q_m=-0.28$

TABLE XXIII. Ground state Q values.

Q (Mev)	Method	Reference
−0.3	Cloud chamber	Bo 36c
−0.43±0.1	Ion chamber	Ba 39b
−0.50±0.06	Ion chamber	Bl 47c
−0.24±0.08	Ion chamber	St 48a

Transitions to states in B^{11} at 2.25 and 4.25 Mev are reported by Ortner and Protiwinsky (Or 38a), see N^{15}.

Or 38a Ortner, Physik. Zeits. **39**, 883 (1938).
See also: Bo 36, Bo 36c, Or 38, Or 43, Ba 39b, Bl 47c, St 48a.

B^{11} Theory

$\mu=2.6886$; $Q=0.03$; $I=\frac{3}{2}$. Shell: $\alpha+1p_{\frac{3}{2}}{}^3$ (protons) $+1p_{\frac{3}{2}}{}^4$ (neutrons); Hartree atomic-type expected ground state, ${}^2P_{\frac{1}{2}}$, odd (though with spin-orbit forces, agreement can be obtained with measured I).

The measured magnetic moment implies that the state is mainly a ${}^2P_{\frac{3}{2}}$, though 0.2 of the time it may be ${}^2D$ (Sa 39a). The reactions with this nucleus are extremely useful, especially the strong neutron capture into the wide level at about 11.5 Mev. In spite of the many levels known, not much is to be said in detail about this nucleus. The lower states can be formed in several ways; they deserve more study.

Sa 39a Sachs, Phys. Rev. **55**, 825 (1939).

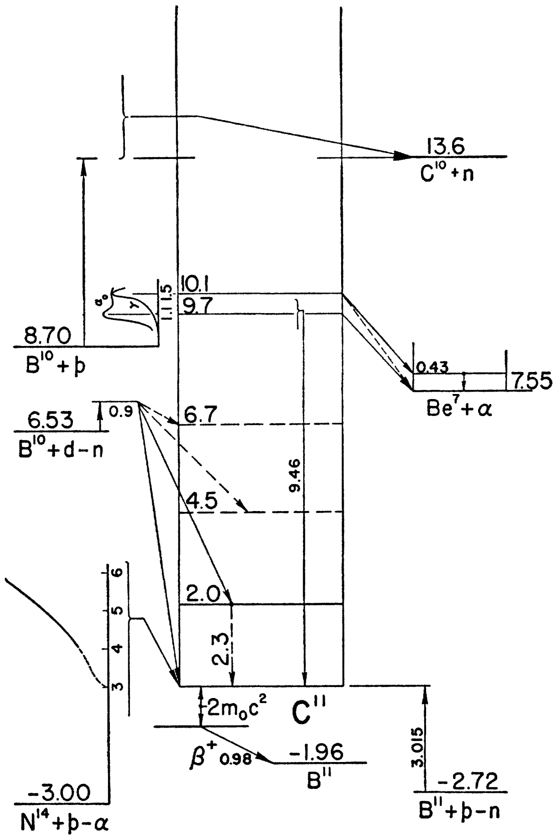

FIG. 11. Energy levels in C^{11}: for notation see Fig. 1.

C^{11}

(Mass: 11.014 95)

I. $C^{11}(\beta^+)B^{11}$ $Q_m=0.94+1.02=1.96$

The spectrum is simple: no $\gamma-\gamma$-coincidences observed (Si 45b); end point$=0.981\pm0.005$ Mev (To 40), 0.993 ± 0.01 (Si 44). Half-life: 20.35 ± 0.08 min. (Sm 41), 20.42 ± 0.06 min. (So 41).

Si 45b Siegbahn and Peterson, Arkiv. f. Ast. Math. Fys. **32B**, No. 5 (1945).
To 40 Townsend, Proc. Roy. Soc. **177**, 357 (1940, 41).
Si 44 Siegbahn and Bohr, Arkiv. f. Ast. Math. Fys. **30B**, No. 3 (1944).
Sm 41 Smith and Cowie, J. App. Phys. **12**, 78 (1941).
So 41 Solomon, Phys. Rev. **60**, 279 (1941).
See also: De 40, Mo 40, Co 41b.

II. $B^{10}(p\ \gamma)C^{11}$ $Q_m=8.70$

Capture radiation of energy 9.47 ± 0.12 Mev is observed at $E_p=1.16$ Mev (thick B^{10} target) (R. L. Walker, private communication).

See also: Cu 39a.

III. $B^{10}(p\ n)C^{10}$ $Q_m=-4.9$ $E_x=8.70$

C^{10} produced with 16- to 18-Mev protons (Sh 49).

Sh 49 Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).

IV. $B^{10}(p\ \alpha)Be^7$ $Q_m=1.15$ $E_x=8.70$

The ground state α-particle yield exhibits a resonance at $E_p\sim1.05$ Mev and possibly another at $E_p=1.5$ Mev, where the short-range alphas and 0.43-Mev γ-rays (from Be^{7*}) have a maximum. At $E_p=1.5$ Mev the yields of the two α-groups are about equal: $\sigma=0.14$ b (Br 50a). At $E_p=1.79$ Mev, the ground state group is 2.2 times as intense as the shorter range group (Bu 50c).

From $E_p=0.25$ to 0.55 Mev the yield of ground state α-particles rises smoothly: $\sigma=0.019$ b at $E_p=0.55$, 0.0045 b at $E_p=0.33$. At $E_p=0.43$ Mev, about one-fifth of the disintegrations lead to the excited state (Bu 50).

Br 50a Brown, Chao, Fowler, and Lauritsen, Phys. Rev. **78**, 88 (1950); Brown, Ph.D. thesis, California Institute of Technology (1950).
Bu 50c Buechner *et al.*, M.I.T. Progress Report (April 1, 1950).
Bu 50 Burcham and Freeman, Phil. Mag. **41**, 337 (1950).
See also: Ro 38a, Cu 39a, Bu 50c, Va 50.

V. $B^{10}(p\ p')B^{10*}$

Earlier reported 0.42-Mev γ-radiation was due to $(p\ \alpha)$ reaction: γ-yield from $(p\ p')$ reaction $<10^{-7}\ \gamma/p$ at $E_p=1.4$ Mev (thick B^{10} target) (La 50).

La 50 Lauritsen and Thomas, Phys. Rev. **78**, 88 (1950).

VI. $B^{10}(d\ n)C^{11}$ $Q_m=6.53$

Two neutron groups are observed at $E_d=0.93$ Mev: $Q=6.59\pm0.1$ (ground state), $\Delta Q=2.02\pm0.1$ (Gi 49). [The observed 2.3-Mev γ-ray (see B^{11}:B^{10}, $d\ p$) is presumably a doublet, since states in both B^{11} and C^{11} at $\sim$2. Mev seem well established.]

Swann and Hudspeth (Sw 49) find neutron groups at $E_d=1.4$ Mev of energies 7.8, 3.5, and 1.2 Mev (forward observation) (levels at 0, 4.5, and 6.7 Mev); the 1.2- and 3.5-Mev groups may be due to contamination.

Gi 49 Gibson, Proc. Phys. Soc. London **62**, 586 (1949).
Sw 49 Swann and Hudspeth, Phys. Rev. **76**, 168 (1949).
See also: Bo 36b.

VII. $B^{11}(p\ n)C^{11}$ $Q_m=-2.72$

Threshold: 3.015 ± 0.003 $Q=-2.762$ (Ri 50).

Ri 50 Richards and Smith, Phys. Rev. **77**, 752 (1950).
See also: Ba 39a, De 40, Ha 40a, Sh 49.

VIII. $C^{12}(n\ 2n)C^{11}$ $Q_m=-18.68$ (not illustrated)

Threshold: $E_n\sim21.5$ Mev (Sh 45).

Sh 45 Sherr, Phys. Rev. **68**, 240 (1945).

IX. $C^{12}(\gamma\ n)C^{11}$ $Q_m=-18.68$

Threshold ≤18.7 Mev (Mc 49); $18.7-19.4$ Mev (Ba 45).

Mc 49 McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).
Ba 45 Baldwin and Koch, Phys. Rev. **67**, 1 (1945).

X. $N^{14}(p\ \alpha)C^{11}$ $Q_m=-3.00$

C^{11} produced with 5- to 6-Mev protons (Ba 39a).

Ba 39a Barkas, Phys. Rev. **56**, 287 (1939).
See also: De 40.

C^{11} Theory

Beta$^{(+)}$-active. Shell: $\alpha+1p_{\frac{1}{2}}^{4}$ (protons) $+1p_{\frac{1}{2}}^{3}$ (neutrons). Expected ground state ${}^2P_{\frac{1}{2},\frac{3}{2}}$ while α-particle model suggests good mixture of ${}^2D$ and ${}^2P_{\frac{3}{2}}$, which would be in agreement with the known properties of its mirror nucleus B^{11}.

The decay is allowed, $ft=4300$ sec., in agreement with idea of mirror nuclei.

B^{12}

[Mass: $C^{12}+14.4_2$ mmu (13.43 Mev) $=12.018\ 2_4$ amu]

I. $B^{12}(\beta^-)C^{12}$ $Q_m=13.43$

End point: 13.3±0.5 Mev—absorption (He 48b), 13.43±0.06 Mev—spectrometer (Ho 50).

Spectrum is complex—see C^{12}. Half-life: 0.022±0.002 sec. (Be 39), 0.027±0.002 sec. (Je 48c).

He 48b Hereford, Phys. Rev. **74**, 574 (1948).
Ho 50 Hornyak and Lauritsen, Phys. Rev. **77**, 160 (1950).
Be 39 Becker and Gaerttner, Phys. Rev. **56**, 854 (1939).
Je 48c Jelley and Paul, Proc. Camb. Phil. Soc. **44**, 133 (1948).

II. $Be^9(\alpha\ p)B^{12}$ $Q_m=-6.02$

TABLE XXIV. Proton groups.[a]

Q (Mev)	Intensity	B^{12*}
−7.02	1	0
−8.06	2	1.04
−8.93	25	1.91
−11.11	40	4.09

[a] $E_\alpha=21.94$ Mev; $\theta=90°$ (Mc 50).

Mc 50 McMinn, Sampson, and Bullock, Phys. Rev. **78**, 296 (1950).

III. $B^{11}(n\ \gamma)B^{12}$ $Q_m=3.29$

$\sigma_{th}<0.05$ b (Wa 48d).

Wa 48d Way and Haines, AECD 2138 (1948).
See also: Bj 38a.

IV. $B^{11}(n\ t)Be^9(?)$ $Q_m=-9.57$ $E_x=3.29$

Tritons observed with 20-Mev neutrons (Co 41a).

Co 41a Cornog and Libbey, Phys. Rev. **59**, 1046 (1941).

V. $B^{11}(n\ n)B^{11}$ $E_x=3.29$

The total cross section indicates a resonance at $E_n=0.43$ Mev ($\sigma_t=6.7$ b, p wave, $I_{\text{level}}=3?$) (Bockelman, private communication). [It is supposed that this level at 3.7 Mev in B^{11} is the same as the one indicated by the shortest range proton group in the $Be^9(\alpha\ p)$ reaction since no further neutron resonance was found up to 1.0 Mev.]

See also: Ad 50.

Proton groups.

A		B		
Q (Mev)	Intens.	Q (Mev)	Intens.	B^{12*}
1.25	1	1.136±0.004	4	0
0.15	60	0.189±0.004	1	0.947±0.005

A: $E_d=1.68$ Mev, 90° observation (Hu 49j). (There is some question whether elastically scattered deuterons from some heavy contaminant may not be contributing to the second group: see Bu 50d.)
B: $E_d=1.5$ Mev, 90° observation (St 50b, Bu 50d).

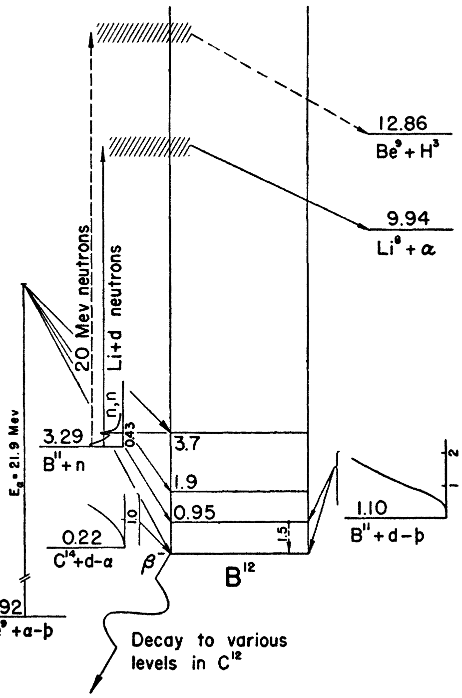

FIG. 12. Energy levels in B^{12}: for notation see Fig. 1.

VI. $B^{11}(n\ \alpha)Li^8$ $Q_m=-6.66$ $E_x=3.29$

Li^8 observed with Li+d neutrons (La 39).

La 39 Lawrance, Proc. Camb. Phil. Soc. **35**, 304 (1939).
See also: Pi 48, Fr 48d, Pi 49.

VII. $B^{11}(d\ p)B^{12}$ $Q_m=1.1$

A γ-ray ~1.5 Mev is reported (Hu 49j).

Hu 49j Hudspeth and Swann, Phys. Rev. **76**, 1150 (1949).
St 50b Strait, Van Patter, and Buechner, Phys. Rev. **79**, 240 (1950).
Bu 50d Buechner, Van Patter, Strait, and Sperduto, Phys. Rev. **79**, 262 (1950).
See also: Cr 35, Ga 39, Ha 39b, Hu 48e, Bu 50c.

VIII. $C^{12}(n\ p)B^{12}$ $Q_m=-12.7$

Not observed with Li+d neutrons (Je 48c).

Je 48c Jelley and Paul, Proc. Camb. Phil. Soc. **44**, 133 (1948).

IX. $C^{14}(d\ \alpha)B^{12}$ $Q_m=0.22$

Strong production of B^{12} is observed at $E_d=0.75$ Mev (Hu 50).

Hu 50 Hudspeth and Swann, Phys. Rev. **78**, 337 (1950).

X. $N^{15}(n\ \alpha)B^{12}$ $Q_m=-7.8$

B^{12} observed with Li+d neutrons (Je 48c).

Je 48c Jelley and Paul, Proc. Camb. Phil. Soc. **44**, 133 (1948).

B^{12} Theory

Beta$^{(-)}$-unstable. Shell: $\alpha+1p_{\frac{3}{2}}{}^3$ (protons) $+1p_{\frac{3}{2}}{}^4 1p_{\frac{1}{2}}{}^1$ (neutrons); possibly ${}^3P_1$, even.

This nucleus decays by a plainly allowed transition, $ft=14{,}000$ sec., to the $I=0$, even, ground state of C^{12}. Most probably it has a ground state $I=1$, even. It is not like the exceptional odd-odd nucleus B^{10}.

C^{12}

(Mass: 12.003 82)

I. $Be^9(\alpha\ n)C^{12}$ $Q_m=5.75$

At $E_\alpha=1.4$ Mev only two neutron groups are observed, indicating a single excited state at 4.45 Mev. At 90° the yield of the lower energy group is 1.30 times that of the ground state group: at 0° the ratio is 0.4, indicating different angular distributions for the two groups (Br 50). [States in $C^{12}>6.5$ Mev would not appear in this work.]

With Po α-particles (5.3 Mev, thick target), the neutron spectrum exhibits maxima at 3.2, 4.8, and 7.7 Mev, and less certain maxima at 1.2, 5.8, and 9.7 Mev (Wh 50a; see also Ri 44a, De 45). Analysis of the data, assuming isotropic emission of the neutrons and using the excitation curve of Halpern (Ha 49i), indicates that the spectrum is qualitatively consistent with levels of C^{12} at 2.5, 4.5, and 7.1 Mev (Wh 50a).

The γ-radiation observed in a pair spectrometer comprises a single line, at 4.3 Mev (Te 50): no evidence is found for the previously reported lines at 6.7 and 2.7 Mev (Ma 36). Pringle, *et al.* (Pr 50b) report a weak (~1 percent) line at 7 Mev.

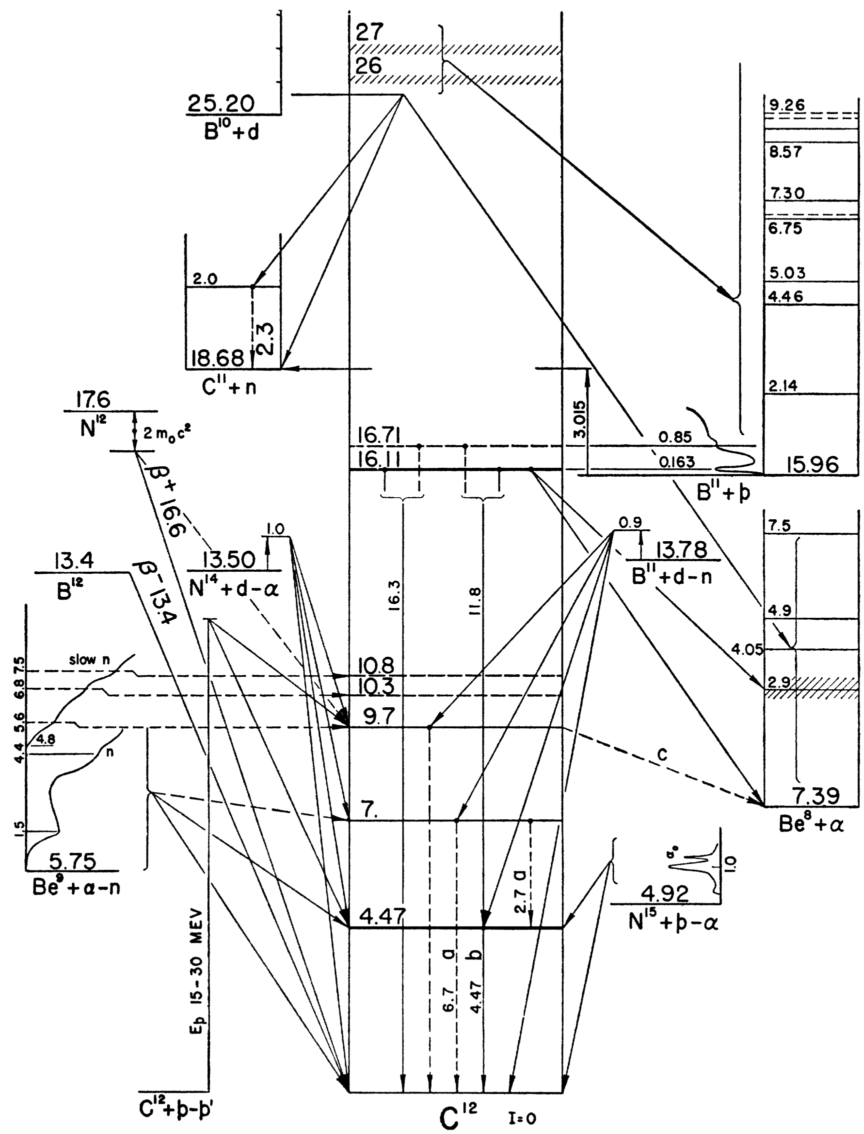

FIG. 13. Energy levels in C^{12}: for notation see Fig. 1. (*a*) 6.7- and 2.7-Mev γ-rays from $Be^9(\alpha\ n)$. (*b*) 4.47-Mev γ-rays from $Be^9(\alpha\ n)$, $N^{15}(p\ \alpha)$, $B^{11}(p\ \gamma)$, $B^{11}(d\ n)$, and $N^{14}(d\ \alpha)$. (*c*) α-particles from $Be^9(\alpha, \alpha n)$ and $N^{12}(\beta^+)$.

The thick target yield of slow neutrons shows changes in slope at $E_\alpha=4.8$ (threshold), 5.6, 6.8, and 7.5 Mev, indicating levels in C^{12} at 9.5, 10.3, and 10.8 Mev (St 39). The threshold at 4.8 Mev is attributed to the reaction $Be^9(\alpha\,\alpha')Be^{9*}$. (See Be^9, C^{13}.) (The discontinuities in the diagram result from the fact that, in laboratory coordinates, zero energy neutrons first appear slightly above the true threshold.)

The existence of an apparent threshold for γ-ray production at $E_\alpha=1.6$ Mev has been taken to indicate that γ-rays (and hence other than ground state neutron groups) are first produced when the 7-Mev level in C^{12} is reached (Sz 40). This hypothesis would appear to be in contradiction with evidence at $E_\alpha=1.4$ Mev (Br 50).

The most plausible interpretation of the somewhat conflicting evidence would appear to be the following:

(a) Resonances for both γ-ray and neutron production occur at $E_\alpha=1.5$ and 4.4 Mev, due to levels in C^{13} at 11.7 and 13.6 Mev [neutron excitation curve from (Ha 49i); γ-rays and neutrons have same excitation function <4.8 Mev (Bj 38): see C^{13}].

(b) For $E_\alpha \leqslant 5.3$ Mev, only one level of C^{12}, at 4.47 Mev, is involved (Te 50, Br 50).

(c) A threshold for slow neutron production would be expected to occur at $E_\alpha \sim 5.8$ Mev, representing transition to the 9.7-Mev level of C^{12}, which is unstable to α-particle emission and might therefore contribute little to the γ-radiation. If the reported threshold at $E_\alpha=4.8$ Mev is real, a level in C^{12} at 9.0 Mev may be indicated. [See parallel case of $Be^9(d\,n)B^{10}$].

Br 50 Bradford and Bennett, Phys. Rev. **78**, 302 (1950).
Wh 50a Whitmore and Baker, Phys. Rev. **78**, 799 (1950).
Ri 44a Richards, MDDC 1504 (1944).
De 45 Demers, N.R.C.A. Report MP 74 (1945).
Te 50 Terrell, Phys. Rev. **79**, 239 (1950).
Ma 36 Maier-Leibnitz, Zeits. f. Physik **101**, 478 (1936).
Pr 50b Pringle, Roulston, and Standil, Phys. Rev. **78**, 627 (1950).
St 39 Stuhlinger, Zeits. f. Physik **114**, 185 (1939).
Sz 40 Szalay and Zimonyi, Zeits. f. Physik **115**, 639 (1940).
Ha 49i Halpern, Phys. Rev. **76**, 248 (1949).
Bj 38 Bjerge, Proc. Roy. Soc. **164**, 243 (1938).
See also: Ri 46, Ya 46, An 48a, Sl 48b, Sl 48c, Dz 39, Be 50f, Gu 50.

II. $B^{10}(d\,p)B^{11}$ $Q_m=9.24$ $E_x=25.20$

The thin target yield of long-range protons exhibits two broad resonances in the range $E_\alpha=0.7$ to 2.0 Mev (Ph 50).

Thick, isotopic target yield at $E_d=0.55$ Mev: 0.8×10^{-8} p/d (Co 36a).

Angular distribution is complex: see Th 49d, Re 50.

Ph 50 Phillips, Phys. Rev. **79**, 240 (1950).
Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
Th 49d Thirion, Comptes Rendus **229**, 1007 (1949).
Re 50 Redman, Phys. Rev. **79**, 6 (1950).
See also: Hu 48c, Re 49a.

III. $B^{10}(d\,n)C^{11}$ $Q_m=6.53$ $E_x=25.20$

Thick, isotopic target yield of C^{11} at $E_d=550$ kev $\sim1.5\times10^{-8}n/d$ (Co 36a).

Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
See also: Cr 34, Cr 34a, Hu 49j, Fa 49.

IV. $B^{10}(d\,\alpha)Be^8$ $Q_m=17.81$ $E_x=25.20$

Thick, isotopic target yield at $E_d=550$ kev $\sim4\times10^{-8}$ α/d (Co 36a).

Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
See also: Sm 39.

V. $B^{10}(\alpha\,d)C^{12}$ $Q_m=1.44$ (not illustrated)

See: Zl 38, Cr 49c.

VI. $B^{11}(d\,n)C^{12}$ $Q_m=13.78$

TABLE XXV. Neutron groups observed.

A			B		
Q	Intens.	C^{12*}	Q	Intens.	C^{12*}
13.4	36	0	13.92±0.5	35	0
9.0	38	4.4	9.45±0.15	55	4.47±0.10
6.0	7	7.4	6.2	∼5	(7.7)
3.9	20	9.5	4.20±0.1	35	9.72±0.15

A: $E_d\sim0.9$ Mev (peak), normal B target, $\theta=90°$ (Bo 36b).
B: $E_d=0.9$ Mev, B^{11} target, $\theta=90°$ (Gi 49).

Gamma-radiation: apparently due principally to $B^{10}(d\,p)$ and $B^{10}(d\,n)$; a gamma ray line at 4.5 Mev has been identified from $B^{11}+d$ (Terrell and Phillips, private communication), presumably from this reaction—see B^{11}. [There appears to be some inconsistency in the yield estimates for the various $B+d$ reactions: the present reaction is responsible for most of the neutrons (>4 Mev, <13 Mev) from a normal B target (Gi 49), the $B^{10}(d\,p)$ reaction is not as intense as $B^{10}(d\,n)$ (Co 36a) and yet most of the γ-rays >2 Mev appear to come from B^{10}(Hu 49j); the answer may lie in the new, low Q proton groups from B^{10}, which were not observed by Co 36a.]

Bo 36b Bonner and Brubaker, Phys. Rev. **50**, 308 (1936).
Gi 49 Gibson, Proc. Phys. Soc. London **62**, 586 (1949).
Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
Hu 49j Hudspeth and Swann, Phys. Rev. **76**, 1150 (1949).
See also: St 37, Ga 39, Ha 39b, Po 39b, Po 42, Hu 48c, Sw 49.

VII. $B^{11}(p\,\gamma)C^{12}$ $Q_m=15.96$

Resonances: $E_p=0.1628\pm0.0002$ Mev; width $=4.5\pm1.5$ kev (Mo 49a); 0.162 ± 0.001 Mev; width $=5.3\pm1$ kev (Ta 46).

Less certain resonances are reported at $E_p=0.65$, 0.85, 0.95 (Cu 39a), 0.82 (He 37). The rapid rise in

TABLE XXVI. Gamma-ray energies.

A	B	C
16.6±0.6	16.34±0.25	16.70±0.17
11.8±0.5	11.76±0.18	12.12±0.12
4.3±0.3		4.41±0.15

A: $E_p=0.9$-Mev peak, thick target; relative intensities =0.15:1:1. Absolute yield $\geqslant5\times10^{-10}$ (Fo 38).
B: $E_p=0.51$ Mev, thick target: (R. L. Walker, private communication).
C: $E_p=1.15$ Mev, thick target: (R. L. Walker, private communication).

yield >1400 kev (He 37) may be due to $B^{10}(p\ \alpha)$. The resonance cross section at 162 kev is ~0.02 b.

The radiation at the 162-kev resonance is softer than that off-resonance (Ta 46); it is isotropic (within 10 percent) at resonance (Ja 48).

Mo 49a Morrish, Phys. Rev. **76**, 1651 (1949).
Ta 46 Tangen, Kgl. Nord. Vid. Selsk. Skr. No. 1 (1946).
Cu 39a Curran, Dee, and Petrzilka, Proc. Roy. Soc. **169**, 269 (1939).
He 37 Herb, Kerst, and McKibben, Phys. Rev. **51**, 691 (1937).
Fo 38 Fowler, Gaerttner, and Lauritsen, Phys. Rev. **53**, 628 (1938).
Ja 48 Jacobs, Malmberg, and Wahl, Phys. Rev. **73**, 1130 (1948).
See also: Bo 37e, Ge 37, Ge 37a, Ka 37, Wa 38, Ka 40, Ho 41, Zu 43.

VIII. $B^{11}(p\ \alpha)Be^8$ $Q_m=8.57$ $E_x=15.96$

The ground state α-particles appear as a homogeneous group with $Q=8.60$ Mev (Co 36a, Li 37). A continuous distribution <4 Mev is attributed to the broad state of Be^8 at 2.8 (2.9) Mev (Li 37, Wh 41). At $E_p=185$ and 360 kev, the homogeneous group comprises 1/60 and 1/240, respectively, of the total α-particle yield (Co 36a). Both the homogeneous and the continuous groups exhibit resonance at $E_p=162$ kev (Mc 40a, Ub 42) and are isotropic at $E_p=160$ and 200 kev (Ja 41). The resonance for $(p\ \alpha)$ is identical with that for $(p\ \gamma)$ (Wa 38). At $E_p=0.4$ Mev, the thick B target yield of 4.4-cm α-particles is $1.3\times10^{-9}\ \alpha/p$ (Bo 39b).

Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
Li 37 Livingston and Bethe, Rev. Mod. Phys. 9, 245 (1937).
Wh 41 Wheeler, Phys. Rev. **59**, 27 (1941).
Mc 40a McLean, Young, Whitson, Plain, and Ellett, Phys. Rev. **57**, 1083 (1940).
Ub 42 v. Ubisch, Kgl. Nord. Vid. Selk. Forh. **15**, 71 (1942).
Ja 41 Jacobs and Whitson, Phys. Rev. **59**, 108 (1941).
Wa 38 Waldman, Waddel, Calihan, and Schneider, Phys. Rev. **54**, 543, 1017 (1938).
Bo 39b Bowersox, Phys. Rev. **55**, 323 (1939).
See also: (Experimental) Wi 37a, Al 38, Ne 37, Ne 37a, Ne 38a, Ne 38b, Ne 39, Ha 39, Ja 41a, Ma 45. (Theoretical) Ka 37, Op 38, Hi 39.

IX. $B^{11}(p\ n)C^{11}$ $Q_m=-2.72$ $E_x=15.96$

Threshold at $E_p=3.015\pm0.003$ Mev ($Q=-2.762$) (Ri 50).

Ri 50 Richards and Smith, Phys. Rev. **77**, 752 (1950).
See also: Ch 47c.

X. $B^{12}(\beta^-)C^{12}$ $Q_m=13.4$

Fermi plot is straight from 6 Mev to end point of 13.43 ± 0.06 Mev; deviations below 6 Mev may indicate transitions to states in C^{12} at 7 and 11 Mev (five percent total) (Ho 50).* No definite evidence exists for delayed γ-radiation (Bo 39d, Hu 49j).

Ho 50 Hornyak and Lauritsen, Phys. Rev. **77**, 160 (1950).
Bo 39d Bower and Burcham, Proc. Roy. Soc. **173**, 379 (1939).
Hu 49j Hudspeth and Swann, Phys. Rev. **76**, 1150 (1949).
See also: Bi 36, Fo 36, Ba 37, Ho 48f.

* *Note added in proof:* These transitions were inadvertently omitted from the diagram.

XI. $C^{12}(\gamma\ n)C^{11}$ $Q_m=18.68$

Threshold ⩽18.7 Mev (Mc 49).

The cross section has a maximum at ~30 Mev (Ba 48a, St 50c.)

Mc 49 McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).
Ba 48a Baldwin and Klaiber, Phys. Rev. **73**, 1156 (1948).
St 50c Strauch, Phys. Rev. **79**, 241 (1950).
See also: Ba 45, Pe 47, La 48b, Pe 48b, Ga 49a, Le 50a.

XII. $C^{12}(\gamma\ \alpha)Be^8$ $Q_m=-7.39$

For $E_\gamma=14$ to 25 Mev, the reaction goes predominantly (~95 percent) to the 3-Mev state of Be^8. The cross section has a maximum at $h\nu=18$ Mev, falling off to <10 percent at 22 Mev ($\sigma_{max}\sim10^{-28}$ cm²: see Be^8 diagram) (Go 50b). For the Li+p radiation (17.6/14.8 Mev), $\sigma=0.8\pm0.3\times10^{-28}$ cm² (Wa 49i).

Go 50b Goward, Telegdi, and Wilkins, Proc. Phys. Soc. London **63**, 402 (1950).
Wa 49i Wäffler and Younis, Helv. Phys. Acta **22**, 614 (1949).
See also: Ha 48c, Te 49c, Wa 49h, Mi 50b, We 50.

XIII. $C^{12}(p\ p')C^{12*}$

TABLE XXVII. Levels observed from inelastically scattered protons.[a]

A		B		C	
Level	Intens.	Level	Intens.	Level	Intens.
4.4±0.2	(Strong)	4.8±0.2	2.2	4.7	1.6
5.5±0.3	(Medium)				
9.7±0.6	(Weak)	10.2±0.4	1	10.1	2

[a] C^{13}, $p\ p'$ may also contribute
A: $E_p=12-15$ Mev; $\theta=162°$ (Fu 48) (The 5.5-Mev level is not confirmed by Le 50).
B: $E_p=16.3$ Mev; $\theta=96°$ (Le 50).
C: $E_p=31.6$ Mev; $\theta=96°$ (Le 50).

For elastically scattered protons see N^{13}.

Fu 48 Fulbright and Bush, Phys. Rev. **74**, 1323 (1948).
Le 50 Levinthal, Martinelli, and Silverman, Phys. Rev. **78**, 199 (1950).

XIV. $C^{12}(d\ d')C^{12*}$

Inelastic scattering of 14-Mev deuterons indicates a level of C^{12} at 4.2 Mev (Boyer, private communication).

See also: Ho 49e.

XV. $N^{12}(\beta^+)C^{12}$ $Q_m=16.6+1.02=17.6$‡

Transitions to the ground state are observed (Al 49a), as are also transitions to higher states in C^{12} leading to α-particle emission (Alvarez, private communication).

Al 49a Alvarez, Phys. Rev. **75**, 1815 (1949).
See also: Al 49j, Al 50g.

XVI. $N^{14}(d\ \alpha)C^{12}$ $Q_m=13.50$

‡ Mass of N^{12} from this reaction.

TABLE XXVIII. Q values from α-particle groups.

A Q (Mev)	B Q (Mev)	σ (cm²)	C Q (Mev)	C^{12*}
13.40±0.1	13.39±0.08	1×10^{-27}	13.622	0
9.08	9.02±0.07	3×10^{-27}	9.137	4.485
	5.77±0.07	3×10^{-28}		(7.6)
			3.955	9.667

A: E_d = 550 kev (Co 36, Li 37).
B: E_d = 1.01 Mev, gas target, θ = 90° (Ho 40).
C: E_d = 1.42 Mev, θ = 90° (Ma 50c).

At $E_d=550$ kev, the thick (N^{14}) target yield $=0.5\times10^{-9}$ disintegrations per deuteron (Co 36).

A continuum of short-range α-particles is also observed, attributed to $N^{14}(d\ 2\alpha)Be^8$: the production of four α-particles has also been observed in photographic emulsions ($E_d=9$ Mev) (Fo 47b).

TABLE XXIX. Gamma-radiation from $N^{14}+d$.

No.	Ga 40	Cr 40	Assignment
1	2.2	2.5	
2	4.2	~4.1	C^{12*}
3	5.3±0.4	5.1±0.3	N^{15*}
4	7.2±0.4	6.6±0.3	C^{12*}
5		8.2±0.5	N^{15*}
6	~11		

Lines 2 and 4 are probably from $N^{14}(d\ \alpha)$ [The $(d\ \alpha)$ reaction is ~2.5 times as intense as the $(d\ p)$ at $E_p=550$ kev (Co 36)]. Lines 3 and 5 are probably from $N^{14}(d\ p)$: see N^{15}. *Note added in proof:* Terrell (private communication) reports lines at 5.3, 7.4, and 8.5 Mev.

Co 36 Cockroft and Lewis, Proc. Roy. Soc. **154**, 261 (1936).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Ho 40 Holloway and Livingston, Phys. Rev. **58**, 847 (1940).
Ma 50c Malm, Ph.D. thesis, Massachusetts Institute of Technology (1950).
Fo 47b Fowler, Burrows, and Curry, Nature **159**, 569 (1947).
Ga 40 Gaerttner and Pardue, Phys. Rev. **57**, 386 (1940).
Cr 40 Crane, Halpern, and Oleson, Phys. Rev. **57**, 13 (1940).
See also: Ho 39a, Gu 47, Bu 50f.

XVII. $N^{15}(p\ \alpha)C^{12}$ $Q_m=4.92$

Q for ground state α-particles: 5.0±0.15 Mev (Bu 39a), 4.960±0.007 Mev (Bu 50f), 4.96±0.05 Mev (Fr 50c).

Q for short-range α-particles 0.529±0.008 Mev (Sc 50).

Gamma-ray transition energy = 4.465±0.02 Mev (Thomas and Lauritsen, unpublished). Wilkinson (private communication) reports an energy of 4.45±0.04 Mev and a high order of anisotropy, of order $1+0.3\cos^2\theta$, near the 900 kev resonance.

Bu 39a Burcham and Smith, Nature **143**, 795 (1939).
Bu 50f Buechner, *et al.*, M.I.T. Progress Report (July 1, 1950).
Fr 50c Freeman, Proc. Phys. Soc. London **63**, 668 (1950).
Sc 50 Schardt, Fowler, and Lauritsen, Phys. Rev. **80**, 136 (1950). Schardt, Ph.D. thesis, California Institute of Technology (1950).
See also: La 41.

XVIII. $O^{16}(\gamma\ \alpha)C^{12}$ $Q_m=-7.19$

See O^{16}.

C^{12} Theory

Spherically symmetric; $I=0$. Shell: $\alpha+1p_{\frac{3}{2}}^4$ (protons) $+1p_{\frac{3}{2}}^4$ (neutrons); ground state expected $^1S_0$, from either a Hartree or an α-particle picture.

The absence of low lying states indicates the qualitatively reliable nature of the idea of a closed sub-shell, or of not-much-polarized α-particles. There are many levels known, made in numerous ways, and mostly seen to combine with the ground state. The levels at 16.11 and 16.71 Mev seem from their modes of formation to be different in character, and they do indeed radiate differently to ground. The 16.11-Mev level, which gives isotropic radiation and high yield for low proton energies in the $B^{11}(p\ \gamma)$ reaction, must be either $I=1$ or 2, from s wave proton capture. If I were 1, and since the ground state of B^{11} and thus this state probably has odd parity, strong electric dipole radiation to the ground would be expected. The observed dominance of the 11.8-Mev gammas makes more likely then the $I=2$ value. The major part of the resonant gammas are then probably electric dipole, to the state at 4.47 Mev with $I=1$, even.

This assignment tends to explain the weakness of α-transitions to the ground state of Be^8 compared with those to the excited state. From the $B^{11}(p\ \alpha)$ reaction alone one would be led to argue that the Be^8 ground state is $I=0$, even, and the excited state perhaps $I=2$, even. Then the difference in yield can be ascribed to the need for emission of d wave alphas to form the ground state.

About the remaining many levels not much can be said (cf. O^{16}).

N^{12}

(not illustrated)

[Mass: $C^{12}+18.9$ mmu (17.6 Mev) = 12.0227 amu]

I. $N^{12}(\beta^+)C^{12}$ $Q_m=16.6+1.02=17.6$*

The half-life determination gives 0.0125±0.001 sec. and a Feather analysis of the absorption in Al gives $E_{\beta^+\max}=16.6\pm0.2$ Mev. The presence of annihilation radiation has been detected (Al 49a). Transitions to excited states in C^{12} followed by α-particle emission has been observed (Alvarez, private communication).

Al 49a Alvarez, Phys. Rev. **75**, 1815 (1949).

II. $C^{12}(p\ n)N^{12}$ $Q_m=-18.5$

The excitation function for a 17-mg/cm² polystyrene target gives a threshold of 20.0±0.1 Mev (Al 49a).

Al 49a Alvarez, Phys. Rev. **75**, 1815 (1949).

N^{12} Theory

Beta$^{(+)}$-active. Shell: $\alpha+1p_{\frac{3}{2}}^4 1p_{\frac{1}{2}}^1$ (protons) $+1p_{\frac{3}{2}}^3$ (neutrons). Expected possibly $^3P_1$, even.

* From this reaction.

This nucleus is similar to its mirror nucleus B^{12}, but still more energetic. It is stable with respect to heavy-particle disintegration by less than 200 kev. The β-transition is perhaps allowed, though $ft=17{,}000$ is high, and forbiddedness does not imply a big factor for such high energy. The $I=1$ state must be a little unusual, with mixed orbital momenta. The expected complex spectrum is not observed, but conditions are not at all favorable.

C^{13}

(Mass: 13.007 51)

I. $Be^9(\alpha\, n)C^{12}$ $Q_m=5.75$ $E_x=10.63$

Resonances for production of neutrons, observed with thin target, 10 percent resolution Po-alphas, appear at $E_\alpha=1.5$ Mev ($\sigma=0.13$ b) and 4.4 Mev ($\sigma=0.32$ b). The value of the cross section at the first resonance suggests $I=\frac{3}{2}$ or 5/2 for the state in C^{13} involved (Ha 49i). Additional resonances for $E_\alpha>5$ Mev probably exist but have not been well resolved.

Thick target yield with Po-alphas (5.3 Mev) $=80\times10^{-6}$ n/α (Ro 44a), 73×10^{-6} n/α (Se 44a), 50×10^{-6} n/α (Ha 49i).

Ha 49i Halpern, Phys. Rev. **76**, 248 (1949).
St 39 Stuhlinger, Zeits. f. Physik **114**, 185 (1939).
Sz 40 Szalay and Zimonyi, Zeits. f. Physik **115**, 639 (1940).
Ro 44a Roberts, MDDC 731 (1944).
Se 44a Segrè and Wiegand, MDDC 185 (1944).
See also: Do 37, Ba 37a, Am 37a, Bj 38, Fu 39, Sl 48b, Sl 48c, An 48a, Al 50f.

II. $Be^9(\alpha, \alpha' n)Be^8$ $Q_m=-1.63$ $E_x=10.63$

Observation of slow neutrons not accompanied by γ-radiation, starting at $E_\alpha=4.9$ Mev, suggests this reaction (Bj 38). There is some disagreement regarding

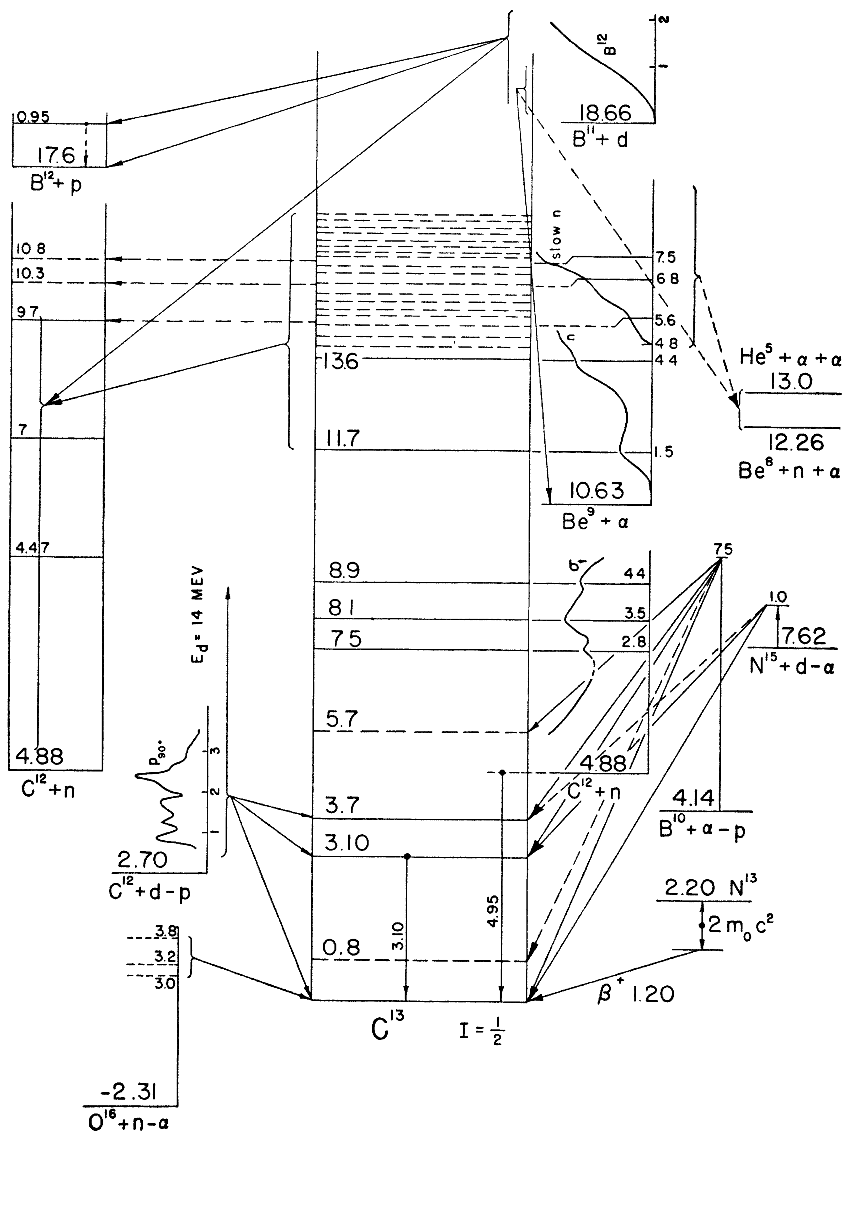

FIG. 14. Energy levels in C^{13}: for notation see Fig. 1. Levels are reported at 3.1, 3.7, 3.9, 6.3, 6.9, 7.6, 7.9, and 8.3 Mev by Rotblat. See text.

the existence of these slow neutrons: see C^{12}(Ya 46, An 48a).

Bj 38 Bjerge, Proc. Roy. Soc. **164**, 243 (1938).
Ya 46 Yalow, Yalow, and Goldhaber, Phys. Rev. **69**, 253 (1946).
An 48a Anderson, N.R.C. Nuclear Science Series, No. 3 (December, 1948).

III. $B^{10}(\alpha\, p)C^{13}$ $Q_m=4.14$ $E_x=10.63$

Q values for ground state: 3.86 (Je 40), 3.85 (Me 40), 4.16 (Zl 38), 4.07±0.2 (Cr 49c). Considerable uncertainty attaches to the existence of a proton group at $Q=3.3$, corresponding to an excited state of C^{13} at 0.8 Mev. Such a group has been reported by a number of workers (Je 40, Me 40, Li 37, Ro 49), although it appears to be resolved only in the work of Jurka (see Me 40). On the other hand, Creagan (Cr 49c), bombarding isotopic targets with 7.45-Mev α-particles, finds no evidence for this group either at 0° or 90°. *Note added in proof:* Perkin [Phys. Rev. **79**, 175 (1950)] reports Q values: 4.08±0.12, 3.35±0.25, 0.65±0.15, 0.15±0.15 (doublet?), −0.57±0.15 with the relative yields for the first four groups 10:1:100:50.

TABLE XXX. Q values for higher states.

Li 37	Cr 49c	C^{13*}
3.3		0.8
—	(0.85±0.2: due to B^{11}, $\alpha\, p$)	
0.5	0.31	3.8
0.1	0.07	4.0
−0.8	(−0.31 may be B^{10}, $\alpha\, d$)	
−1.86	−1.57	5.7

Je 40 Jentschke and Wieninger, Physik. Zeits. **41**, 524 (1940).
Me 40 Merhaut, Physik. Zeits. **41**, 528 (1940).
Zl 38 Zlotowski, Comptes Rendus **207**, 148 (1938).
Cr 49c Creagan, Phys. Rev. **76**, 1769 (1949).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937)
Ro 49 Roy, Phys. Rev. **75**, 1775 (1949).
See also: Ba 35, Bo 35, Bo 37d, Ma 37a, Po 37a, Jo 38, Ju 39, Sz 40, Sl 48b, Sl 48c.

IV. $B^{11}(d\, n)C^{12}$ $Q_m=13.78$ $E_x=18.66$

At $E_d=0.93$ Mev about 80 percent of the 90° yield of neutrons from a thick normal B target appears to be due to this reaction (Gi 49); see C^{12}.

Gi 49 Gibson, Proc. Phys. Soc. London **62**, 586 (1949).

V. $B^{11}(d\, p)B^{12}$ $Q_m=1.1$ $E_x=18.66$

The thin target yield rises smoothly from $E_d=0.3$ to 1.8 Mev with no evidence of resonances. At 1.47 Mev, the yield is 10^7 β/microcoulomb, $\sigma=0.004$ b (Hu 49j). About four-fifths of the protons result in the ground state of B^{12} at $E_d=1.5$ Mev (St 50b): see B^{12}.

Hu 49j Hudspeth and Swann, Phys. Rev. **76**, 1150 (1949).
St 50b Strait, Van Patter, and Buechner, Phys. Rev. **79**, 240 (1950).
See also: Cr 35, Hu 48c, Hu 48e, Bu 50d.

VI. $B^{11}(d\, \alpha)Be^9$ $Q_m=8.03$ $E_x=18.66$

Thick, isotopic target yield $=1.4\times10^{-9}$ α/d at $E_d=0.55$ Mev (Co 36a). Disintegration into $(3\alpha+n)$ may also occur (Co 36a, Li 37).

Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
See also: Sm 39, Bu 50f.

VII. $C^{12}(n\, n)C^{12}$ $E_x=4.88$

The scattering cross section has three maxima, at $E_n=2.8$, 3.5, and 4.4 Mev indicating levels in C^{13} at 7.5, 8.1, and 9.0 Mev (Fr 50b), (see, however, Ad 50).

A careful search in the energy range $E_n=20-1360$ kev (nuclear excitation $E_x=4.89$ to 6.14 Mev) failed to reveal any scattering resonances of width >5 kev (Mi 50c). [Doubt is thus cast on the existence of the 5.7-Mev level apparent in the $C^{12}(d\, p)$ and $B^{10}(\alpha\, p)$ reactions.]

Cross sections from 6 to 20 Mev are reported by Sleator (Sl 47).

Fr 50b Freier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950).
Mi 50c Miller, Phys. Rev. **78**, 806 (1950).
Sl 47 Sleator, Phys. Rev. **72**, 207 (1947).
See also: Ma 46b, Ag 47, Ba 47, Go 47a, Ha 49, Ba 46a, Fr 46, Ma 46b, Ag 47, Ba 47, Fi 47, Ha 49, La 49b, Ad 50, Ba 50g, Ri 50c.

VIII. $C^{12}(n\, \gamma)C^{13}$ $Q_m=4.88$

σ_{th}(rad.) = 3.5 mb (Wa 48d).

$E_\gamma=4.947\pm0.008$ Mev (pair spectrometer) (Ki 50a).

Wilson (Wi 50a) reports capture γ-rays with energies 4.95±0.05, 4.1, 3.65, 3.4, and 3.05 Mev.

Wa 48d Way and Haines, AECD 2138 (1948).
Ki 50a Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950).
Wi 50a Wilson, Phys. Rev. **80**, 90 (1950).
See also: Be 48e, Ki 50.

IX. $C^{12}(n\, \alpha)Be^8+n\rightarrow3\alpha+n$ $Q_m=-7.34$ $E_x=4.88$

Green and Gibson (Gr 49d) have observed 168 stars from this reaction in photographic plates. The cross section rises from 0.023 b at $E_n=10.8$ Mev to 0.16 b at 14.5 Mev.

Gr 49d Green and Gibson, Proc. Phys. Soc. London **62**, 296 (1949).

X. $C^{12}(n\, 2n)C^{11}$ $Q_m=-18.68$ $E_x=4.88$ (not illustrated)

See: Po 37, Je 44, Sh 45, Kn 47, He 48, Mc 48a (see C^{11}).

XI. $C^{12}(d\, p)C^{13}$ $Q_m=2.70$

A γ-ray at 3.11 Mev, corresponding to a level energy (corrected for Doppler shift) of 3.09±0.01 Mev has been observed (Do 48, Ho 49). Measurement of the internal pair conversion coefficient indicates that the radiation is electric dipole (Th 50a).

Work with 7- to 14-Mev deuterons indicates the existence of proton groups corresponding to levels in

TABLE XXXI. Q values for low levels of C^{13}.

Co 36, Li 37	Be 41	He 49c	Bu 49c[a]	C^{13*}
2.71±0.05	—	2.72	2.729±0.009	0
	−0.52±0.07	−0.40	−0.370±0.003	3.098±0.008
		−1.19		3.91

[a] A more recent value for the ground state is 2.716±0.005 (Strait, *et al.* private communication).

C^{13} at 3.1 and 3.9 Mev (Bo 50, and Boyer, private communication).

Note added in proof: Berlman, Phys. Rev. **79**, 411 (1950), using 10 Mev deuterons reports a proton group corresponding to a 1.0 Mev level in C^{13}. Rotblat *et al.*, (Harwell Conference, 1950), report levels at 3.1, 3.7, 3.9, 6.3, 6.9, 7.6, 7.9, and 8.3 Mev ($E_d=8$ Mev) and give an upper limit of 0.5 percent for excitation of a level near 1.0 Mev.

Co 36 Cockroft and Lewis, Proc. Roy. Soc. **154**, 261 (1936).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Be 41 Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).
He 49c Heydenburg, Inglis, Whitehead, and Hafner, Phys. Rev. **75**, 1147 (1949).
Bu 49c Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).
Do 48 Dougherty, Hornyak, Lauritsen, and Rasmussen, Phys. Rev. **74**, 712 (1948).
Ho 49 Hornyak, Ph.D. thesis, California Institute of Technology (1949).
Bo 50 Boyer, Phys. Rev. **78**, 345 (1950); M.I.T. Progress Reports (October 1, 1949; January 1, 1950).
Th 50a Thomas, Phys. Rev. **80**, 138 (1950).
See also: Be 40, Be 40a, Ro 40, Sc 40, Sc 40a, Bo 41a, Hu 41, Bo 49a, Ph 49b.

XII. $C^{13}(\gamma\ n)C^{12}$

See: Se 49a.

XIII. $N^{13}(\beta^+)C^{13}$ $Q_m=1.18+1.02=2.20$

Decay proceeds only to ground state of C^{13}: the spectrum is simple (Si 45a, La 47, Co 48f).

Si 45a Siegbahn and Slätis, Arkiv. f. Math. Ast. Fys. **32A**, No. 9 (1945).
La 47 Langer, Cook, and Sampson, Phys. Rev. **71**, 906 (1947).
Co 48f Cook, Langer, Price, and Sampson, Phys. Rev. **74**, 502 (1948).
See also: Ri 37, Ly 39, Ly 39a, Ki 39a, Op 39, Ri 39, Va 39, Wa 39, Wa 39a, Mo 40, To 40, Wa 40, At 43a, La 47a, Si 45, Si 45b, Ho 48f, Ho 50.

XIV. $N^{15}(d\ \alpha)C^{13}$ $Q_m=7.62$

Ho 40 Holloway and Moore, Phys. Rev. **58**, 847 (1940).
Ma 50C Malm, Ph.D. thesis, Massachusetts Institute of Technology (1950).
See also: Ho 39, Bu 50c, Bu 50f.

TABLE XXXII. Q values.

A	B	C^{13*}
7.54	7.681	0
	4.598	3.083
	4.004	3.677

A: $E_d=1.0$ Mev (Ho 40).
B: $E_d=1.42$, $\theta=90°$, (Ma 50c).

XV. $O^{16}(n\ \alpha)C^{13}$ $Q_m=-2.31$

Only the ground state transition has been observed (see O^{17}).

C^{13} Theory

$\mu=0.7023$; $I=\frac{1}{2}$. Shell: $\alpha+1p_{\frac{3}{2}}^4$ (protons) $+1p_{\frac{3}{2}}^4 1p_{\frac{1}{2}}^1$ (neutrons); Hartree ground state, $^2P_{\frac{1}{2}}$, odd, with indication of admixtures from lack of agreement with measured magnetic moment.

The many states, even low lying ones, are plausible for such a nucleus, mainly a single particle outside a closed α-shell. Only a few levels have been reached by more than one or two means, usually necessary for identification. The resonance peaks in the neutron scattering will however yield evidence on the states involved with further work on widths and angular distribution.

N^{13}

(Mass: 13.009 88)

I. $N^{13}(\beta^+)C^{13}$ $Q_m=1.18+1.02=2.20$

TABLE XXXIII. End-point and half-life determinations.

Half-life (min.)	End point (Mev)	Reference
	1.198±0.006	Ly 39
9.93±0.03		Wa 39
	1.218±0.004	To 40
10.13±0.1	1.24 ±0.02	Si 45a
	1.25 ±0.03	Co 48f
10.05±0.1	1.202±0.005	Ho 50

The positron spectrum is simple: the Fermi plot is straight down to <0.15 Mev (Si 45a, Co 48f, Ho 50); see C^{13}.

Ly 39 Lyman, Phys. Rev. **55**, 234 (1939).
Wa 39 Ward, Proc. Camb. Phil. Soc. **35**, 523 (1939).
To 40 Townsend, Proc. Roy. Soc. **177**, 357 (1940).
Si 45a Siegbahn and Slätis, Arkiv. f. Math. Ast. Fys. **32A**, No. 9 (1945).
Co 48f Cook, Langer, Price, and Sampson, Phys. Rev. **74**, 502 (1948).
Ho 50 Hornyak and Lauritsen, Phys. Rev. **77**, 160 (1950).

II. $B^{10}(\alpha\ n)N^{13}$ $Q_m=1.18$

N^{13} is observed from this reaction: no neutron groups or γ-rays have been identified (see N^{14}).

III. $C^{12}(p\ \gamma)N^{13}$ $Q_m=1.92$

No other resonances appear >4 percent from $E_p=0.95$ to 1.6 Mev, or >12 percent from 1.7 to 2.1 Mev (Va 49). The thick target yield from the 456-kev resonance is $7.3\times10^{-10}\ \gamma/p$ (Fo 49b); from the 1.7-Mev resonance it is 1.3±0.2 times as great (Va 49) (rad. widths=0.63, 1.2 ev, probably elect. dipole). Using $C^{12}+p-N^{13}=1.956\pm0.007$ Mev, as obtained from the associated Q values, Van Patter locates the N^{13} levels at 2.377±0.009

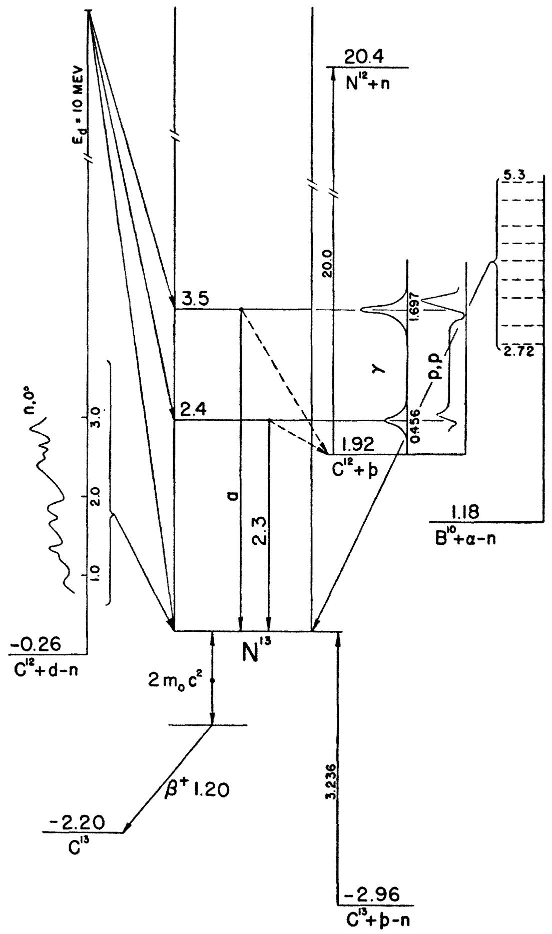

FIG. 15. Energy levels in N^{13}: for notation see Fig. 1. (*a*) γ-radiation from $C^{12}(p\ \gamma)$.

and 3.523±0.019 Mev (Va 49; M.I.T. Progress Report October, 1949).

The cross section for production of N^{13} has been measured from $E_p=88$ to 200 kev (Wo 49a, Ha 50, Ba 50). At 96 kev $\sigma=1.0\times10^{-10}$ b (Ha 50).

The radiation at $E_p=500$ kev (thick target) is isotropic: this result is consistent with formation of a state $I=\frac{1}{2}$, odd, by *s* wave protons (De 49d).

TABLE XXXIV. Summary of observations on resonances.

E_p (kev)	Half-width (kev)	E_γ (Mev)	Reference
450	30		Ro 38
480	—	2.5, 2.2	Cu 39a
460	50		Ho 41
456±2	35		Fo 49b
460±10	40±5	2.2	Ta 46
1697±12	74±9		Va 49

Ro 38 Roberts and Heydenburg, Phys. Rev. **53**, 374 (1938).
Cu 39a Curran, Dee, and Petrzilka, Proc. Roy. Soc. **169**, 269 (1939).
Ho 41 Hole, Holtsmark, and Tangen, Zeits. f. Physik **118**, 48 (1941).
Fo 49b Fowler and Lauritsen, Phys. Rev. **76**, 314 (1949).
Ta 46 Tangen, Kgl. Nord. Vid. Selsk. Skr. No. 1 (1946).
Va 49 Van Patter, Phys. Rev. **76**, 1264 (1949).
Wo 49a Woodbury, Hall, and Fowler, Phys. Rev. **75**, 1462 (1949).
Ha 50 Hall and Fowler, Phys. Rev. **77**, 197 (1950).
Ba 50 Bailey and Stratton, Phys. Rev. **77**, 194 (1950).
De 49d Devons and Hine, Proc. Roy. Soc. **199**, 56, 73 (1949).
See also: De 38, Fo 48, Fo 48b.

IV. $C^{12}(p\ p)C^{12}$ $E_x=1.92$

The yield of elastically scattered protons in the energy range $E_p=0.3$ to 4 Mev ($\theta_{\text{lab}}=164°$) shows only the two resonance anomalies evident in the $p\ \gamma$ reaction. Tentative results give $E_R=475$ kev, $\Gamma=38$ kev, and *s* wave protons for the low energy anomaly and $E_R\sim1.7$ Mev for the other anomaly. (Goldhaber, Williamson, Jackson, and Laubenstein, private communication.)

See also: Wh 50f.

V. $C^{12}(p\ n)N^{12}$ $Q=-18.5$† $E_x=1.92$

The threshold is 20.0±0.1 Mev (Al 49a).

Al 49a Alvarez, Phys. Rev. **75**, 1815 (1949).
See also: Al 49g.

VI. $C^{12}(p,\ pn)C^{11}$

See: Ch 47c, Mc 48.

VII. $C^{12}(d\ n)N^{13}$ $Q_m=-0.26$

Ground state Q, determined by observation of threshold, $=-0.281\pm0.003$ Mev (Bo 49c). Neutrons are monochromatic at $E_d=2.0$ Mev (Be 47b). At $E_d=10$ Mev, two new groups appear, corresponding to levels in N^{13} at 2.29±0.12 and 3.48±0.12 Mev (Gr 49a).

Bo 49c Bonner, Evans, and Hill, Phys. Rev. **75**, 1398 (1949).
Be 47b Bennett and Richards, Phys. Rev. **71**, 565 (1947).
Gr 49a Grosskreutz, Phys. Rev. **76**, 482 (1949).
See also: Bo 36b, Bo 38d, Be 41, Ha 49s.

VIII. $C^{13}(p\ n)N^{13}$ $Q_m=-2.96$

Threshold = 3.236±0.003 Mev ($Q=-3.003$ Mev) (Ri 50).

Ri 50 Richards and Smith, Phys. Rev. **77**, 752 (1950).
See also: Ha 40a, Ha 40b.

IX. $N^{14}(n\ 2n)N^{13}$ $Q_m=-10.52$

See N^{15}.

X. $N^{14}(\gamma\ n)N^{13}$ $Q_m=-10.52$ (not illustrated)

Threshold = 11.1±0.5 Mev (Ba 45), 10.65±0.2 Mev (Mc 49).

Ba 45 Baldwin and Koch, Phys. Rev. **67**, 1 (1945).
Mc 49 McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).

XI. $N^{14}(d\ t)N^{13}$ $Q_m=-4.36$ (not illustrated)

Threshold = 6.8±0.1 Mev (Bo 42).

Bo 42 Borst, Phys. Rev. **61**, 106 (1942).
See also: Bo 41c.

† Q from β^+-decay.

N^{13} Theory

Beta$^{(+)}$-active. Shell: $\alpha+1p_{\frac{3}{2}}{}^4 1p_{\frac{1}{2}}{}^1$ (protons) $+1p_{\frac{3}{2}}{}^4$ (neutrons); state presumably like C^{13}; $^2P_{\frac{1}{2}}$, odd expected.

The ground state makes an allowed transition, consistent with the mainly $^2P_{\frac{1}{2}}$ character expected for the ground state; the value $ft=4500$ sec. The two higher levels whose widths are known are of great interest. The level at 2.4 Mev is formed by s wave protons (isotropic gammas, elastically scattered protons, and width about 35 kev observed, and uncomfortably large if a centrifugal barrier were present). The dipole radiation to the ground state yields a very reasonable radiation width of about 0.6 ev (Fo 49b). The higher state, with observed proton width of some 75 kev, seems to have about twice the radiation width. The higher state may be formed by p wave protons without implying unduly large widths without barrier. Its radiation is consistent with a $I=\frac{3}{2}$, odd character, coupled by electric quadripole radiation to the ground state, while the lower state certainly decays by electric dipole radiation, and has the properties $I=\frac{1}{2}$, even.

A valuable result has been obtained in the comparison of this nucleus with its mirror nucleus C^{13}. The N^{13} excited states at 2.4 and 3.5 Mev appear to be the homologues of the C^{13} states at 3.1 and 3.9 Mev. This has been verified in detail in two ways: (a) The radiation from the lower of these states has been shown to be of the same character—electric dipole—in both nuclei. (b) Agreement between the level energies can be obtained by taking account of the "reactive" level shift implied by the sizeable "resistive" widths in the N^{13} case. The real similarity between mirror nuclei is made very graphic by this ingenious work (Th 50b).

Fo 49b Fowler and Lauritsen, Phys. Rev. **76**, 314 (1949).
Th 50b Thomas, Phys. Rev. **80**, 136 (1950).

TABLE XXXV. Summary of half-life and end-point determinations.

Half-life (yr.)	End point (kev)	Reference
1000	90 ±15 absorption	Ru 40
10^3–10^5	145 ±15 absorption	Ru 41
5300±15%		No 46
4700±10%		Re 46
	154 ±3 spectrometer	Le 47a
	151 ±2 absorption	St 47
	154 ±4 absorption	So 47
5100±200		No 48
	155 ±2 spectrometer	Be 48b
	156.3±1 spectrometer	Co 48c
6360±200		Ha 49r
7200±500		Ya 48
	152 ±5 spectrometer	Le 48a
	(28.5±0.5 mg/cm² Al)	Gl 48
	155 ±1 spectrometer	Fe 49
5589±75		Jo 49
5720±47		En 49
	157.5±5 prop. counter	An 49b
6360±200		Mi 50
5513±200		Mi 50

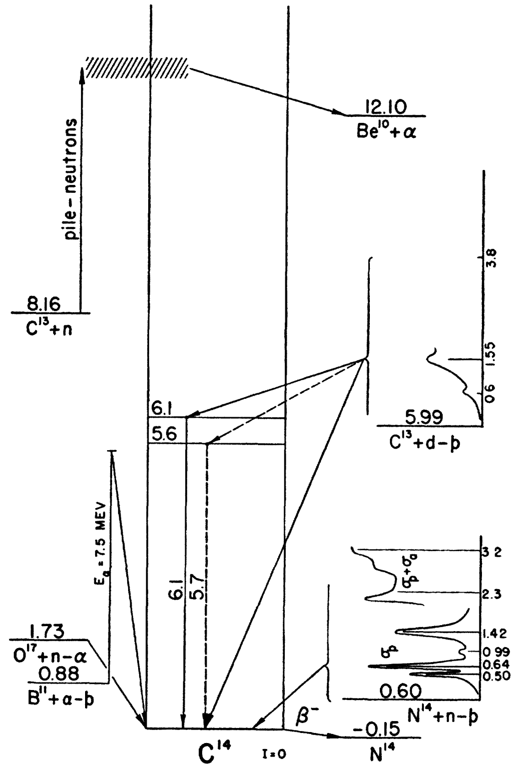

FIG. 16. Energy levels in C^{14}: for notation see Fig. 1.

C^{14}

(Mass: 14.007 67)

I. $C^{14}(\beta^-)N^{14}$ $Q_m=0.15$

It is suggested (Mi 50) that the counter methods yielding ~6400 yr. for the half-life are subject to error, and that the lower values, 5500 to 5700 yr. are more reliable. (See Table XXXV.)

The consensus appears to be that the Fermi plot is straight down to ~25 kev and that the spectrum is reconcilable with $\Delta I=1$, yes (Be 48b, Gl 48, Fe 49; see, however: Co 48c, An 49b, Wa 50b).

Mi 50 Miller, Ballentine, Bernstein, Friedman, Nier, and Evans, Phys. Rev. **77**, 714 (1950).
Be 48b Berggren and Osborne, Phys. Rev. **74**, 1240 (1948).
Gl 48 Glendenin and Solomon, Phys. Rev. **74**, 700 (1948).
Fe 49 Feldman and Wu, Phys. Rev. **75**, 1286 (1949).
Co 48c Cook, Langer, and Price, Phys. Rev. **74**, 548 (1948).
An 49b Angus, Cockroft, and Curran, Phil. Mag. **40**, 522 (1949).
See also: Po 39, Ru 40, Ru 40a, Sc 40, Ru 41, In 46, No 46, Re 46, Sa 46, Le 47a, St 47, So 47, Ha 48a, Ha 49r, Le 48a, No 48, Ya 48, En 49, Jo 49, Bo 50c, Wa 50b.

II. $B^{11}(\alpha\, p)C^{14}$ $Q_m=0.88$

$Q=0.85$ (±0.2) determined from proton range (Cr 49c).

No other groups observed.

Cr 49c Creagan, Phys. Rev. **76**, 1769 (1949).
See also: Po 39, Ru 41, Ro 49.

III. $C^{13}(d\,p)C^{14}$ $Q_m=5.99$

TABLE XXXVI. Q values.

Bo 39d	Be 41	Hu 41	Cu 50	A	C^{14*}
6.1	6.09 ± 0.2	5.82 ± 0.3	5.91 ± 0.03	5.948 ± 0.014	0
		0.58 ± 0.3	0.32 ± 0.03		5.59 ± 0.04
				-0.148 ± 0.012	6.096 ± 0.018

A: Holland and Buechner, private communication.

Two γ-ray lines at 6.115 ± 0.03 and 5.69 ± 0.05 Mev, observed in $C^{13}+d$ are thought to be associated with this reaction. (See N^{14}:C^{13}, dn). Holland and Buechner (private communication) find no group >0.2 of the intensity of the $Q=-0.148$-Mev group ($E_d=1.51$ Mev, $\theta=90°$) in the range 5.1 to 6.15 Mev in C^{14}).

Bo 39d Bower and Burcham, Proc. Roy. Soc. **173**, 379 (1939).
Be 41 Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).
Hu 41 Humphreys and Watson, Phys. Rev. **60**, 542 (1941).
Cu 50 Curling and Newton, Nature **165**, 609 (1950).
See also: Po 39, Ho 40c, Sc 40, Be 40a, Ru 40a, Sc 40a, Ru 41, Bu 50f, Th 50.

IV. $C^{13}(n\,\alpha)Be^{10}$ $Q_m=-3.94$ $E_x=8.16$

Production of Be^{10} has been observed (Hu 47).

Hu 47 Hughes, Eggler, and Huddleston, Phys. Rev. **71**, 269 (1947).

V. $N^{14}(n\,p)C^{14}$ $Q_m=0.60$

TABLE XXXVII. Summary of observed Q values.

Proton range (cm) (thermal neutrons)	Q (Mev)	Reference	Method
1.03	(0.62)[a]	Bo 36c, Li 37	Cloud chamber
	0.57 ± 0.04	Hu 40b, Hu 48	Ion chamber pulse size
	0.55 ± 0.04	Hu 41a	Ion chamber pulse size
1.00	(0.60)	Bo 45	Cloud chamber
	(0.70 ± 0.04)	St 47a	Recalc. from Bo 36c
0.985	0.60 ± 0.03	Cu 47a	Photo-plate
	0.63 ± 0.01	St 48a	Ion chamber pulse size
0.991	(0.596 ± 0.025)	Hu 48b	Cloud chamber
0.996		Co 48e	Cloud chamber
	0.620 ± 0.009	Sh 49a	$C^{14}(p\,n)$ threshold, based on $Li(p\,n)=1.8823$
	0.630 ± 0.006	Fr 50	Ionization in argon

[a] The proton range in this reaction is now used as a fixed point on the range-energy curve (Be 50d): Q values in parentheses are based on old curves.

Bo 36c Bonner and Brubaker, Phys. Rev. **49**, 778 (1936).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Hu 40b Huber, Huber, and Scherrer, Helv. Phys. Acta **13**, 209 (1940).
Hu 48 Huber and Stebler, Phys. Rev. **73**, 85 (1948).
Hu 41a Huber, Helv. Phys. Acta **14**, 163 (1941).
Bo 45 Bøggild, Kgl. Dansk. Vid. Sels. Math.-Fys. Medd. **23**, 4, 26 (1945).
St 47a Stephens, Rev. Mod. Phys. **19**, 19 (1947).
Cu 47a Cuer, J. de phys. et rad. **8**, 83 (1947).
St 48a Stebler and Huber, Helv. Phys. Acta **21**, 59 (1948).
Hu 48b Hughes and Eggler, Phys. Rev. **73**, 809 (1948).
Co 48e Cornog, Franzen, and Stephens, Phys. Rev. **74**, 1 (1948).
Sh 49a Shoupp, Jennings, and Sun, Phys. Rev. **75**, 1 (1949).
Fr 50 Franzen, Halpern, and Stephens, Phys. Rev. **77**, 641 (1950).
See also: Ru 41, Bl 47c, Hu 48a, Fr 49e, Je 49b, Be 50d.

VI. $O^{17}(n\,\alpha)C^{14}$ $Q_m=1.73$

Isotopic cross section $=0.46\pm0.11$ b for thermal neutrons (Ma 47).

Ma 47 May and Hincks, Can. J. Research **25**, 77 (1947).
See also: Hi 46.

C^{14} Theory

Beta$^{(-)}$-active; $I=0$ measured. Shell: $\alpha+1p_{\frac{3}{2}}^4$ (protons) $+1p_{\frac{3}{2}}^4 1p_{\frac{1}{2}}^2$ (neutrons). Expected $^1S_0$, even.

The β-transition is perhaps consistent with the observed spin change of 1. The value $ft=9.3\times10^8$ sec. is very high, but if there were parity change, and the nuclear matrix element were small, one might reach such a value. The spectral shape does seem approximately allowed, or first forbidden (to allow for parity change). Agreement is strained, though, even if the transition involves the change from $^1S_0$ to $^3D_1$. A few higher levels are seen.

N^{14}

(Mass: 14.007 51)

I. $B^{10}(\alpha\,n)N^{13}$ $Q_m=1.18$ $E_x=11.70$

Thick, isotopic target yield $=13\times10^{-6}$ n/α at 5.3 Mev (Ro 44a). [Estimated from measured yield of normal B target: most of yield is due to $B^{11}(\alpha\,n)$: see An 48a.] At $E_\alpha=9$ Mev the yield of N^{13} is $4.6\times10^{-6}/\alpha$ (Ri 37).

Resonances for production of N^{13} occur at $E_\alpha=2.72$, 2.98, 3.43, 3.70, 4.05, 4.33, 4.59, 4.94, and 5.22 Mev (Sz 39).

Ro 44a Roberts, MDDC 731 (1944).
An 48a Anderson, N.R.C. Nuclear Science Series, No. 3 (December, 1948).
Ri 37 Ridenour and Henderson, Phys. Rev. **52**, 889 (1937).
Sz 39 Szalay, Zeits. f. Physik **112**, 29 (1939).
See also: Ma 37, Fu 39, St 39, Se 44a, Ri 46, Sz 40.

II. $B^{10}(\alpha\,p)C^{13}$ $Q_m=4.14$ $E_x=11.70$

Gamma-ray resonances attributed to this reaction occur at $E_\alpha=3.2$, 3.7, 4.4, 4.8, and 5.3 Mev (Sz 40). Angular distribution: see Cr 49c.

Sz 40 Szalay and Zimonyi, Zeits. f. Physik **115**, 639 (1940).
Cr 49c Creagan, Phys. Rev. **76**, 1769 (1949).
See also: Sl 48b, Sl 48c.

III. $B^{10}(\alpha\,d)C^{12}$ $Q_m=1.44$ $E_x=11.70$

See: Zl 38, Cr 49c.

IV. $B^{11}(\alpha\,n)N^{14}$ $Q_m=0.28$

Thresholds for production of slow neutrons suggest excited states of N^{14} at 4.0, 4.75, 5.5, 6.1, and 6.6 Mev (St 39).

The neutron spectrum at $E_\alpha=5.3$ Mev from a thick target extends to 6 Mev, exhibiting a broad maximum at $\sim$2.5 Mev (Ri 46, An 48a).

St 39 Stuhlinger, Zeits. f. Physik **114**, 185 (1939).
Ri 46 Richards, Speck, and Perlman, Phys. Rev. **70**, 118 (1946).
An 48a Anderson, N.R.C. Nuclear Science Series, No. 3 (December, 1948).
See also: Be 50h.

V. (*a*) $C^{12}(d\ p)C^{13}$ $Q_m=\ 2.70$ $E_x=10.26$
(*b*) $C^{12}(d\ n)N^{13}$ $Q_m=-0.26$

The yield of long-range protons (C^{13} ground state) has been studied at 10°, 90°, and 132.5° (He 49c, Ph 50). In some cases the peaks for the three angles coincide in energy and exhibit close correspondence with γ-ray or neutron resonances. In other cases, the peaks for various angles occur at different energies, and can only with difficulty be identified with a common resonance. It is suggested that the apparent displacements may be ascribed to the mutual interference of closely spaced, broad levels. The short-range protons corresponding to excitation of the C^{13} level at 3.12 Mev were observed to have resonances at $E_d=2.72$ [2.76?] and 3.2 Mev (He 49c).

TABLE XXXVIII. Resonances for γ-ray production (from C^{13*}).

E_d (Mev)	Bo 49a Width (kev)	σ_R (barns)	Ba 48 E_d (Mev)
0.91	200	0.29	0.92
1.16	200	0.34	1.17
1.30	80	0.39	1.30
1.435	5.5	0.62	1.43
1.73	200	0.97	1.75
			2.2?
			2.49
			2.68
			2.90
			3.08

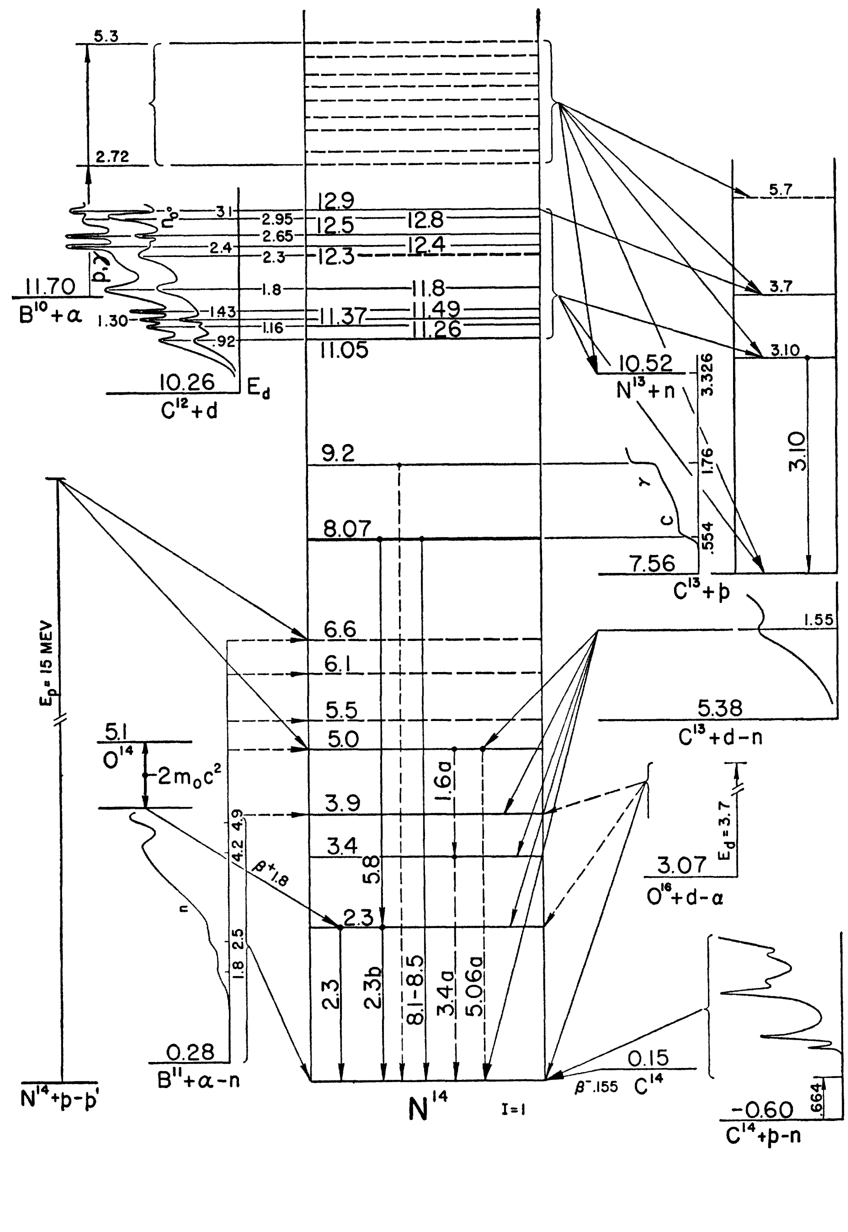

FIG. 17: Energy levels in N^{14}: for notation see Fig. 1. (*a*) γ-radiation from $C^{13}(d\ n)$. (*b*) 2.3-Mev γ-ray from $C^{13}(d\ n)$, $C^{13}(p\ \gamma)$, and $O^{14}(\beta^+)$. (*c*) $C^{13}(p\ \gamma)$ yield is for a thick target.

Resonances for production of N^{13} and of neutrons at 0° and 90° coincide with the γ-ray resonances in many cases, but again show significant differences (Bo 49a, Ba 48). The narrow 1.435-Mev resonance does not appear in the $d\ n$ reaction: other resonances are shifted, possibly again because of interference effects. The angular distributions of both neutrons and protons exhibit pronounced anomalies (He 49c, Bo 49a, Ba 48, Ph 50b, Ph 49b).

Absolute cross sections for neutrons and γ-rays are given in Ha 49s and Bo 49a.

Bo 49a Bonner, Evans, Harris, and Phillips, Phys. Rev. **75**, 1401 (1949).
Ba 48 Bailey, Freier, and Williams, Phys. Rev. **73**, 274 (1948).
He 49c Heydenburg, Inglis, Whitehead, and Hafner, Phys. Rev. **75**, 1147 (1949).
Ph 50b Phillips and Bonner (to be published).
Ph 49b Phillips, Bonner, and Richardson, Phys. Rev. **76**, 169 (1949).
Ha 49s Hanson, Taschek, and Williams, Rev. Mod. Phys. **21**, 635 (1949).
See also: Ne 37b, Ro 38, Ba 42, Ri 47, Wi 49a.

VI. $C^{12}(d\ d)C^{12}$ $E_x=10.26$

See: Gu 47, Ho 49e.

VII. $C^{12}(d\ \alpha)B^{10}$ $Q_m=-1.44$ $E_x=10.26$

Observed in photographic plate (Po 47a).

Po 47a Powell and Occhialini, *Nuclear Physics in Photographs* (Oxford University Press, London, 1947).

VIII. $C^{13}(p\ \gamma)N^{14}$ $Q_m=7.56$

A resonance is observed at $E_p=554\pm2$ kev, of half-width 40 kev; $\sigma_R=2.0\times10^{-27}$ cm^2 (Fo 49b). Three γ-rays are observed, at 8.1±0.2, 5.8±0.3, and 2.3±0.4 Mev, of about equal intensity (Fo 49b, La 40). An additional resonance of width <2.5 kev occurs at $E_p=1.76$ Mev (Perry: private communication).

A γ-ray of energy 8.14±0.08 Mev ($E_p=570$ kev, semi-thick target) and one of relative intensity ~0.07 and energy 5.81±0.25 Mev is reported by Wilkinson, private communication.

The radiation at $E_p=625$ kev is isotropic, consistent with formation of a state with $I=0$ or 1, by s wave protons (De 49d).

Fo 49b Fowler and Lauritsen, Phys. Rev. **76**, 314 (1949).
La 40 Lauritsen and Fowler, Phys. Rev. **58**, 193 (1940).
De 49d Devons and Hine, Proc. Roy. Soc. **199**, 56, 73 (1949).
See also: De 38, Ro 38b, Cu 39a, Ho 41, Fo 48, Fo 48b, Cu 50.

IX. $C^{13}(p\ n)N^{13}$ $Q_m=-2.96$ $E_x=7.56$

Threshold=3.236±0.003 Mev ($Q=-3.003$ Mev) (Ri 50).

A resonance at $E_p=3.76$ Mev is observed (Bu 50f).

Ri 50 Richards and Smith, Phys. Rev. **77**, 752 (1950).

X. $C^{13}(d\ n)N^{14}$ $Q_m=5.38$

Of the γ-rays indicated in Table XL, lines 7 and 8 are assigned to $C^{13}(d\ p)C^{14*}$, the former because of its correspondence with a proton group (see C^{14}), the latter because it is also observed at $E_d\sim0.6$ Mev where only this assignment is energetically possible. Lines 2 and 4 may be cascade transitions from a level at 5.0 Mev (line 6) in N^{14}; line 3 is probably associated with the 2.3-Mev level of N^{14}. Line 5, if it exists, can be associated with the 3.87-Mev level. Line 1 can be from N^{14*}, C^{14*}, or B^{11*}.

TABLE XXXIX. Neutron groups.

A: Q (Mev)	B: Q (Mev)	N^{14} level
5.2	5.17±0.05	0
	2.98±0.05	2.19±0.07
	1.70±0.05	3.47±0.07
	1.30±0.05	3.87±0.07
0.4±0.05	0.27±0.05	4.90±0.07

A: $E_d=1.4$ Mev, 90° observation (Bo 36b, Be 41).
B: $E_d=1.43$ Mev, 0° and 90° observation (Sw 50 and C. E. Mandeville, private communication).

TABLE XL. Gamma-radiation from $C^{13}+d$.[a]

No.	E_γ, Mev	Yield per $10^6\ d$	Assignment
1	0.729±0.002	1.3	
2	1.643±0.004	1.4	N^{14*}
3	2.318±0.008	4.5	N^{14*}
4	3.390±0.010	1.6	N^{14*}
5	3.9?		(N^{14*})
6	5.056±0.025	1.2	N^{14*}
7	5.69 ±0.050	0.6	(C^{14*})
8	6.115±0.030	2.0	C^{14*}

[a] Fifty percent C^{13} target; $E_d=1.58$ Mev (Th 50).

Bo 36b Bonner and Brubaker, Phys. Rev. **50**, 308 (1936).
Be 41 Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).
Sw 50 Swann and Mandeville, Phys. Rev. **79**, 240 (1950).
Th 50 Thomas and Lauritsen, Phys. Rev. **78**, 88 (1950).

XI. $C^{14}(p\ n)N^{14}$ $Q_m=-0.60$

Threshold=0.664±0.009 Mev ($Q=-0.620$ Mev): (Sh 49a).

Sh 49a Shoupp, Jennings, and Sun, Phys. Rev. **75**, 1 (1949).
See also: Ha 40a, Ha 40b.

XII. $C^{14}(\beta^-)N^{14}$ $Q_m=0.15$

No transitions other than to ground state are observed (see C^{14}).

XIII. $N^{14}(\gamma\ n)N^{13}$ $Q_m=-10.52$

See: Bo 37, Bo 39c, Hu 42, Hu 43, Pe 47, Pe 48b, Wa 48b, Ga 50, Ga 50a, Ga 50b, Je 50b.

XIV. $N^{14}(\gamma\ \alpha)B^{10}$ $Q_m=-11.70$

See: Ga 50b, Mi 50b, Wi 50.

XV. $N^{14}(p\ p')N^{14*}$

Inelastic scattering of 15-Mev protons indicate levels at 5.1±0.4 and 6.7±0.4 Mev (Fu 48).

Fu 48 Fulbright and Bush, Phys. Rev. **74**, 1323 (1948).

XVI. $O^{16}(d\ \alpha)N^{14}$ $Q_m=3.07$

Q from α-particle range$=3.13\pm0.04$ Mev (Co 36a, Li 37). Observation of 4.0- and 2.3 (?)-Mev γ-radiation from PbO_2 bombarded by 3.7-Mev deuterons may be associated with this reaction (Al 49i).

Co 36a Cockroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Al 49i Alburger, Phys. Rev. **75**, 51 (1949).
See also: Gu 47, Ro 47a.

XVII. $O^{14}(\beta^+)N^{14}$ $Q=4.1+1.02=5.1$

The decay proceeds by emission of 1.8 ± 0.1-Mev positrons, followed by a 2.3-Mev γ-ray. Consideration of the effect of Coulomb energy lead to a mass estimate of 5.12 Mev greater than N^{14} and suggest transition to a 2.3-Mev level in N^{14} (Sh 49). [The existence of such a level is supported by the re-evaluation of the γ-ray energy data in $C^{13}(p\ \gamma)$ by Fowler *et al.* (Fo 48), giving 2.3 and 5.8 Mev in place of the earlier cited values of 2.8 and 5.4. The higher energy component no longer fits with the ~5.0-Mev level from the neutron groups in $C^{13}(d\ n)$ and it would appear more likely that a level at 2.3 Mev may be involved. The present uncertainties are too large to make a definite assignment. Additional evidence for a level ~2.3 Mev has been found recently in C^{13}, *dn*.]

Sh 49 Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).
Fo 48 Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. **20**, 236 (1948).

N^{14} Theory

$\mu=0.4037$; $Q=0.02$; $I=1$. Shell: $\alpha+1p_{\frac{3}{2}}^4 1p_{\frac{1}{2}}^1$ (protons) $+1p_{\frac{3}{2}}^4 1p_{\frac{1}{2}}^1$ (neutrons), and expected state $^3S_1$, even.

The measured μ-value implies a strong mixture of other states than the expected S; in fact, one would predict starting from an $L-S$ model that more than half the time the ground state is $^3D_1$, and that ^3S is no more important than ^3P, and perhaps less important than ^1P. The dense levels above 11 Mev show for the first time in our listing of nuclei that in a region of high enough excitation one can expect a distribution of states whose description becomes essentially statistical. Near 11 Mev the shapes of the complex resonances have been carefully studied, together with angular distributions for the various products. The situation is complex, but generally consistent with the interference possibilities inherent in the dispersion theory. The strong gammas from the 8.07-Mev level are known to be approximately isotropic, and to have a radiation width of about 10 ev, while the total proton width of the level makes plausible the s wave nature of the capture protons. The level is almost certainly $I=0$ or 1, odd, decaying to the ground state with $I=1$, even. The intensity of the γ-rays to the intermediate state at 2.3 Mev imply a large dipole oscillator strength, some 0.2 or 0.3. That the β-decay of O^{14} goes preferentially to the 2.3-Mev level, while the gammas from the 8.07-Mev level divide about equally between the ground and 2.3-Mev states is not explained. If the 2.3-Mev level is indeed the expected Coulomb-excited analog of the $I=0$, even, ground states of C^{14} and O^{14} (its energy is quite accurately that) then the observed transition of O^{14} would not be allowed, and the ground state transition would occur, at least on the well-established Gamow-Teller rules. One cannot retain: (a) equivalence of all non-Coulomb nuclear forces, (b) Gamow-Teller rules, and (c) the expected spherical symmetry of the even-even nucleus O^{14}. Perhaps some additional unresolved state is involved.

The difficulty with the very slow β-decay of C^{14} to the ground state is another residue of the old problems of the $4n+2$ nuclei which the measurement of the spin of B^{10} did not quite remove. It is suggested that the C^{14} decay is indeed allowed, but the nuclear rearrangement involved in the transition from a mainly ^1S state to a mainly ^3D state reduces the matrix element greatly. If this is correct, the 2.3-Mev state in N^{14} may be a spin 1 state, but with nuclear orbital momentum nearer the S state of the O^{14} nucleus. No other case of such partial selection rules for nuclear L seems well established.

O^{14}

(not illustrated)

(Mass: 14.0131)

I. $O^{14}(\beta^+)N^{14}$ $Q_m=4.2+1.02=5.2$

The half-life is reported as 76.5 ± 2 sec. (Sh 49). The decay is complex; see N^{14}.

Sh 49 Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).

II. $N^{14}(p\ n)O^{14}$ $Q_m=-6.0$

A rough excitation function gives a threshold of 6.0 ± 0.5 Mev (Sh 49). This value is consistent with the assumption of a complex decay for O^{14}; see N^{14}: $O^{14}(\beta^+)N^{14}$.

Sh 49 Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).

O^{14} Theory

Beta$^{(+)}$-active. Shell: $\alpha+1p_{\frac{3}{2}}^4 1p_{\frac{1}{2}}^2$ (protons) $+1p_{\frac{3}{2}}^4$ (neutrons), presumed ground state $I=0$, even.

This nucleus decays to the ground state of N^{14} only infrequently. There is here some difficulty with the nuclear matrix element (see N^{14}). The expected mirror state of the nucleus, as a state of N^{14} excited, is not found with certainty. The ft value for the decay to the excited state is 3000 sec.

C^{15}

(not illustrated)

[Mass: $N^{15}+9.4_5$ mmu (8.8 Mev)$=15.0143$ amu]*

* Assuming the β-transition is to the ground state of N^{15}.

I. $C^{15}(\beta^-)N^{15}$ $Q_m=8.8$†

Radioactive C^{15} has been produced by the $C^{14}(d\ p)$ reaction; see this reaction for details. The half-life is 2.4±0.3 sec. and an Al absorption measurement gives 8.8±0.5 Mev as the upper energy limit. There is some evidence for delayed γ-emission (Hu 50a).

Hu 50a Hudspeth, Swann, and Heydenburg, Phys. Rev. **77**, 736 (1950).

II. $C^{14}(d\ p)C^{15}$ $Q_m=0.0$

See N^{16}.

III. $C^{14}(n\ \gamma)C^{15}$

No evidence for this reaction was found at Chalk River (Ya 50a), $\sigma<10^{-6}$b.

Ya 50a Yaffe and Stevens, Phys. Rev. **79**, 893 (1950).

N^{15}

(Mass: 15.004 89)

I. $B^{11}(\alpha\ n)N^{14}$ $Q_m=0.28$ $E_x=11.03$

At $E_\alpha=5.3$ Mev, the yield of neutrons per 10^6 α from a thick boron target is reported as 19 by Se 44a, 24 by Ro 44a, and 19±4 by Wa 49a. Roberts (Ro 44a) estimates a yield of 26 for isotopic B^{11}.

TABLE XLI. Resonances reported: (E_α in Mev).

Wa 49a	Ma 37[a]	Fu 39	N^{15*}
1.8	1.90		12.4
2.5	2.68	2.65	12.9
	3.15	3.25	
	3.59	3.60	
4.2	4.26	4.10	14.1
	4.55	4.45	
	4.85	4.73	
4.9	5.02	5.08	14.6

[a] Recalculated (Wa 49a).

Stuhlinger (St 39) reports 19 resonances between $E_\alpha=4$ to 9 Mev (N^{14} excitation 14.6 to 17.5 Mev).

An absolute thick target yield curve is given by Wa 49a.

Se 44a Segrè and Wiegand, MDDC 185 (1944).
Ro 44a Roberts, MDDC 731 (1944).
Wa 49a Walker, Phys. Rev. **76**, 244 (1949).
Ma 37 Maurer, Zeits. f. Physik **107**, 721 (1937).
Fu 39 Fünfer, Ann. d. Physik **35**, 147 (1939).
St 39 Stuhlinger, Zeits. f. Physik **114**, 185 (1939).
See also: Bo 37c, Sz 39, An 48a.

II. $B^{11}(\alpha\ p)C^{14}$ $Q_m=0.88$ $E_x=11.03$

Q from proton range = 0.85 Mev; $E_\alpha=6.64$ Mev (Cr 49c).

Cr 49c Creagan, Phys. Rev. **76**, 1769 (1949).
See also: Po 39, Ru 41, Ro 49.

III. $C^{13}(d\ n)N^{14}$ $Q_m=5.38$ $E_x=16.13$

Resonances for neutrons >3 Mev ($\theta=0°\pm30°$) are observed at $E_d=0.58$, 0.90, 1.55, and 1.8 Mev, with widths 0.1, 0.4, 0.1, and 0.5 Mev respectively. (J. Richardson, private communication) (levels in N^{15} at 16.7, 16.9, 17.47, and 17.69 Mev).

See also: Bo 36b, Be 41.

IV. $C^{13}(d\ p)C^{14}$ $Q_m=5.99$ $E_x=16.13$

Resonances for long-range protons appear at $E_d=0.6$ Mev (Cu 50) and 1.55 Mev (Be 41). The long-range protons are not isotropic (Cu 50).

Cu 50 Curling and Newton, Nature **165**, 609 (1950).
Be 41 Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).
See also: Bo 39d, Be 40a, Ho 40c, Ru 40a, Sc 40, Sc 40a, Hu 41, Ru 41.

V. $C^{13}(d\ \alpha)B^{11}$ $Q_m=5.10$ $E_x=16.13$

The yield rises smoothly from $E_d=0.4$ to 0.9 Mev (Cu 50).

Cu 50 Curling and Newton, Nature **165**, 609 (1950).
See also: Li 37, Ho 40c, Be 41.

VI. $C^{14}(p\ n)N^{14}$ $Q_m=-0.60$ $E_x=10.15$

Threshold = 0.664±0.009 Mev. Resonances observed at $E_p=1.14$, 1.30, 1.47, 2.05, 2.21, and 2.65 Mev (Sh 49a). [See Table XLII: $N^{14}(n\ p)$, $(n\ \alpha)$.]

Sh 49a Shoupp, Jennings, and Sun, Phys. Rev. **75**, 1 (1949).

TABLE XLII. Recent determinations of N^{15} levels[a] (Mev above $C^{14}+H^1$).

Sh 49a	St 48a		A		Si 48	
$C^{14}(p\ n)$	$N^{14}(n\ p)$	$N^{14}(n\ \alpha)$	$N^{14}(n\ p)$	$N^{14}(n\ \alpha)$	$N^{14}(n,\ p\alpha)$	N^{15*}
0.620±0.009	0.63±0.01					(10.77)
1.07 ±0.02	1.08±0.04		1.095			11.22
1.21 ±0.02	1.23±0.03		1.23			11.35
1.37 ±0.05			(1.56)			11.68
1.92 ±0.02	1.96±0.06	1.92±0.04	1.95	1.95		12.07
2.07 ±0.05						12.22
2.48 ±0.05	2.28±0.1	2.29±0.03		2.31		12.4
	2.67±0.1	2.69±0.06			2.71	12.8

[a] Table computed using $Q=0.63$, -0.24.
A: Johnson and Barschall, private communication.

† From this reaction.

VII. $C^{14}(d\ n)N^{15}$ $Q_m=7.97$

Neutron groups corresponding to transitions to the ground state, and to excited states at ~5.3 and 6 to 8 Mev are observed at $E_d=1.26$ Mev (Hu 50).

Hu 50 Hudspeth and Swann, Phys. Rev. **78**, 337 (1950).
See also: Hu 49k.

VIII. $C^{15}(\beta^-)N^{15}$ $Q=8.8$*

Half-life $=2.4\pm0.3$ sec.; $E_\beta=8.8\pm0.5$ Mev; there is some evidence of delayed γ-radiation (Hu 50a).

Hu 50a Hudspeth, Swann, and Heydenburg, Phys. Rev. **77**, 736 (1950).

IX. (*a*) $N^{14}(n\ p)C^{14}$ $Q_m=0.60$ $E_x=10.75$
(*b*) $N^{14}(n\ \alpha)B^{11}$ $Q_m=0.28$
(*c*) $N^{14}(n\ n)N^{14}$

Thermal cross section ($n\ p$ reaction): 1.76 ± 0.05 b (Co 49b); ($n\ n$: total) ~14 b (Go 47a).

An absolute cross section curve is given in (Go 47a).

Resonances appear for proton production at $E_n=499\pm5$, 640 ± 7, (993 ± 12), and 1415 ± 15 kev. Resonances for α-particles occur at $E_n=1415\pm50$ and 1800 ± 15 kev (Johnson and Barschall, private communication). At higher neutron energies a strong peak is observed for ($\alpha+p$) at 2.23 Mev (0.2 b) and indication is found for another at ~3.2 Mev (Si 48). At $E_n=2.8$ Mev, $\sigma_\alpha=4\times\sigma_p=0.16$ b (Ba 39c).

For Q determinations, see C^{14}, B^{11}.

Resonances have also been studied by observing the energy distribution of (α+B) and (p+C) recoils produced by a continuous spectrum of neutrons. Stebler and Huber (St 48a) find five levels yielding protons for

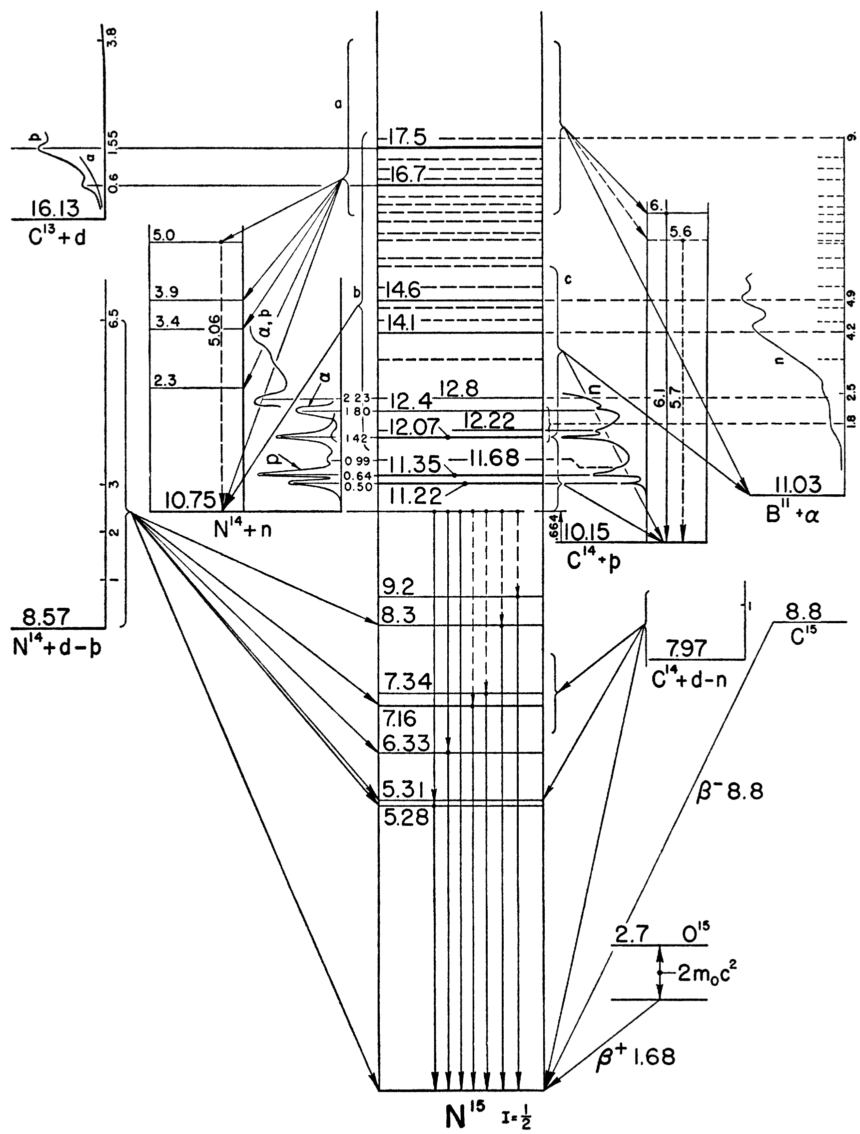

FIG. 18. Energy levels in N^{15}: for notation see Fig. 1.

* From this reaction.

neutrons <2.2 Mev, of which the upper three also yield α-particles (see Table XLII). Numerous resonances have been reported for higher neutron energies (Fi 42, Za 45) (12- to 18-Mev excitation in N^{15}) but are not sufficiently well resolved to permit unique location of levels.

Co 49b Coon and Nobles, Phys. Rev. **75**, 1358 (1949).
Si 48 Sikkema, Nature **162**, 698 (1948).
Ba 39c Baldinger and Huber, Helv. Phys. Acta **12**, 330 (1939).
St 48a Stebler and Huber, Helv. Phys. Acta **21**, 59 (1948).
Fi 42 Fischer, Physik. Zeits. **43**, 507 (1942).
Za 45 Zagor and Valente, Phys. Rev. **67**, 133 (1945).
Sh 49a Shoupp, Jennings, and Sun, Phys. Rev. **75**, 1 (1949).
See also: Bo 36, La 37, Wi 37e, Wi 37f, Th 38, Or 38, Or 38a, Or 39, Or 39a, Or 43, Ba 39b, Ba 39d, Co 39b, Hu 40a, La 40a, Co 41d, Ru 41, Ba 46c, Va 46, Cu 47a, Go 47a, Hu 48a, Me 49, Me 49b, Sh 49b, Ad 50, Ba 50g, Ri 50c.

X. $N^{14}(n\ \gamma)N^{15}$ $Q_m=10.75$

σ_{th}(rad.) ∼100 mb (Ki 50).

TABLE XLIII. Gamma-radiation (Ki 50).

E_γ	Rel. intens.	N^{15*}
10.816±0.015	1.0	0
9.156±0.030	0.1	9.16
8.278±0.016	0.4	8.28
7.356±0.012	0.8	7.36
7.164±0.012	0.1	7.16
6.318±0.010	2	6.32
5.554±0.010	4	5.29
5.287±0.010	5	5.29
4.485±0.010	3	6.32

Best value for ground state transition = 10.823±0.012 Mev (Ki 50a).

Ki 50 Kinsey, Bartholomew, and Walker, Phys. Rev. **77**, 723 (1950).
Ki 50a Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950).

XI. $N^{14}(n\ 2n)N^{13}$ $Q_m=-10.52$ $E_x=10.75$ (not illustrated)

σ for neutrons from 14 Mev d+Be = 0.255 mb (Co 49c).

Co 49c Cohen, Carnegie Institute of Technology Report No. 2 (1949).
See also: Po 37, Je 44, Sh 45, Kn 47, Je 50b, Wa 50.

XII. $N^{14}(d\ p)N^{15}$ $Q_m=8.57$

TABLE XLIV. Q values observed from proton groups.

A	B	C	D	E	N^{15*}
8.51	8.65	8.55	8.61±0.1	8.615	0
3.15	3.26	3.5	3.29±0.1	3.339	5.276
				3.310	5.305
		2.5?	2.30±0.1	2.287	6.328
		1.3	1.40±0.1	1.451	7.164
				1.306	7.309
		0.3		0.300	8.315

A: E_d = 1.0 Mev (Ho 40).
B: (Da 47).
C: E_d = 6.5 Mev: last two may be doublets (Cu 47).
D: E_d = 3.3 Mev: relative intensities = 1:5:2:25 (Wy 49c).
E: E_d = 1.5 Mev, magnetic spectrograph, θ = 90°; probable error ∼8 kev (Ma 50, Ma 50c).

Two of the γ-ray lines observed in $N^{14}+d$ may be from this reaction; see C^{12}.

Ho 40 Holloway and Moore, Phys. Rev. **58**, 847 (1940).
Da 47 Davidson and Pollard, Phys. Rev. **72**, 162 (1947).
Gu 47 Guggenheimer, Heitler, and Powell, Proc. Roy. Soc. **190**, 196 (1947).
Wy 49c Wyly, Phys. Rev. **76**, 316 (1949).
Ma 50 Malm and Buechner, Phys. Rev. **78**, 337 (1950).
Ma 50c Malm, Ph.D. thesis, Massachusetts Institute of Technology (1950).
See also: Ho 39a, Cr 40, Ga 40, Ch 44a, Wy 49, Bu 50f, In 50b.

XIII. $N^{14}(n\ t)C^{12}$ $Q_m=-4.1$ $E_x=10.75$ (not illustrated)

H^3 observed with 20-Mev neutrons (Co 41a).

Co 41a Cornog and Libby, Phys. Rev. **59**, 1046 (1941).

XIV. $O^{15}(\beta^+)N^{15}$ $Q_m=1.7+1.02=2.7$

No transitions other than to ground state observed; see O^{15}.

XV. $O^{18}(p\ \alpha)N^{15}$ $Q_m=3.9$

A reaction energy of $Q=3.97\pm0.05$ Mev is reported (Fr 50c).

Fr 50c Freeman, Proc. Phys. Soc. London **63**, 668 (1950).

N^{15} Theory

$\mu=-0.283$; $I=\frac{1}{2}$. Shell: $O^{16}-1p_{\frac{1}{2}}{}^1$ (proton); expected wave function ${}^2P_{\frac{1}{2}}$, odd.

Again level density increases markedly with excitation above 11 or 12 Mev. While many resonances have been studied, no assignment seems convincing. The apparent resolution of the narrow pair of levels at 5.3 Mev causes concern for the many other cases where the uniqueness of levels much less well-defined has been glibly assumed. With a mean spacing of about 1.2 Mev these two levels are distant only 30 kev! Magnetic analysis may be a necessity for other charged particle reactions.

O^{15}

(Mass: 15.0078)

I. $O^{15}(\beta^+)N^{15}$ $Q_m=1.7+1.02=2.7$

The β-spectrum end-point determinations are summarized in Table XLV.

The Kurie plot is linear down to ∼300 kev, indicating a simple allowed transition (Br 50d).

The half-life determinations are: 126±5 sec. (Mc 35), 126±2 sec. (Sh 49), 130±6 sec. (Hu 43), 118.0±0.6 sec. (Br 50d).

TABLE XLV.

E_{β^+max} (Mev)	Comments	Reference
1.7	Visual end-point cl. chbr.	Fo 36
1.2	Feather end-point Al abs.	Mc 35
1.68	Absorption	Sh 49
1.683±0.005	Semicircular spectrometer	Br 50d

TABLE XLVI.

E_R (Mev)	0.277[a]	1.065	1.550	1.748	1.815	2.356	2.489
$Y_{max}(\infty)$	0.4	6	1	1.5	4	15	20 all $\times 10^{-10}$ per p
$\omega\gamma$(ev)	0.02	0.6	0.2	0.2	0.5	2	3
Γ (kev)	<2[a]	5	50	11	7	14	11
σ_R (cm²)	—	3.5	0.06	0.3	1	2	3.5 all $\times 10^{-28}$

[a] Ta 46.

Br 50d Brown and Perez-Mendez, Phys. Rev. **78**, 649 (1950).
See also: Mc 35, Fo 36, Bo 39c, Hu 43, Sh 49.

II. $C^{12}(\alpha\ n)O^{15}$ $Q_m = -8.4$

O^{15} activity has been observed with 16-Mev α-particles (Ki 39).

Ki 39 King, Henderson, and Risser, Phys. Rev. **55**, 1118 (1939).

III. $N^{14}(p\ \alpha)C^{11}$ $Q_m = -3.00$ $E_x = 7.29$

The chemical identification of the C^{11} has been made. The excitation function shows a smooth rise from $E_p = 4.5$ to 6 Mev (Ba 39a).

Ba 39a Barkas, Phys. Rev. **56**, 287 (1939).
See also: De 40, Mc 48.

IV. $N^{14}(p\ \gamma)O^{15}$ $Q_m = 7.29$

A resonance at 277±3 kev with $\Gamma < 2$ kev is reported (Ta 46). Additional resonances found in a recent preliminary investigation are found in Table XLVI (Du 50).

These resonances are superimposed on a non-resonant yield whose cross section is 0.4, 3, 6×10^{-29} cm² at 1, 2, and 2.5 Mev, respectively. Extrapolation of these yields to low energies indicates that the non-resonant reaction is dominant in the Bethe sun cycle (Du 50). A cross section of 8.5×10^{-10} b at $E_p = 128$ kev is reported (Wo 49a).

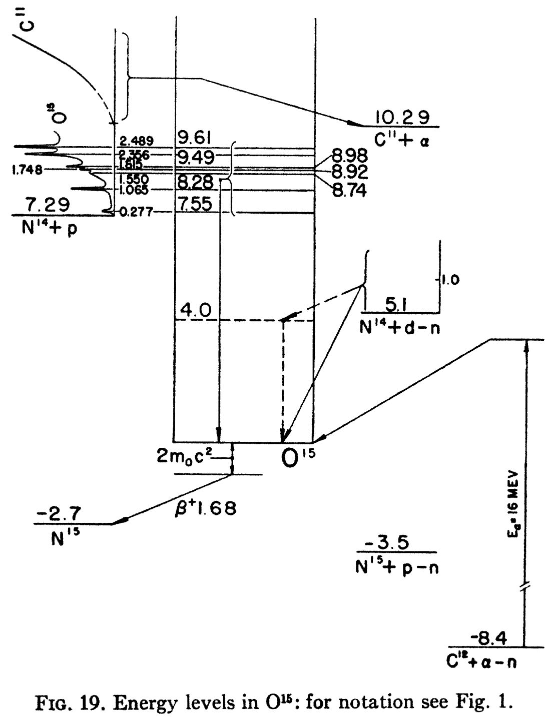

FIG. 19. Energy levels in O^{15}: for notation see Fig. 1.

Ta 46 Tangen, Kgl. Nord. Vid. Selsk. Skr. No. 1 (1946).
Du 50 Duncan and Perry, Phys. Rev. **80**, 136 (1950).
Wo 49a Woodbury, Hall, and Fowler, Phys. Rev. **75**, 1462 (1949).
See also: Du 38, Cu 40a.

V. $N^{14}(p\ p)N^{14}$ $E_x = 7.29$

The scattering of 4.2-Mev protons in nitrogen indicates strong Coulomb and S wave scattering, only weak P and D waves are indicated (He 47).

He 47 Heitler, May, and Powell, Proc. Roy. Soc. **190**, 180 (1947).

VI. $N^{14}(d\ n)O^{15}$ $Q_m = 5.1$

Reaction energies of 5.1±0.2 and 1.1±0.2 Mev are reported from the cloud-chamber investigation of the recoil protons ($E_d = 0.93$ Mev) (St 37a). Recent photographic emulsion work (Hu 49f) has verified both groups —a third group of low energy is evident. A Q value of 5.15±0.10 Mev is reported (Gi 48). This work does not confirm the low energy neutron group.

The 4-Mev γ-radiation observed for N+d may be from this reaction, although it can be accounted for as well by the $N^{14}(d\ \alpha)$ reaction; see C^{12}.

St 37a Stephens, Djanab, and Bonner, Phys. Rev. **52**, 1079 (1937).
Hu 49f Hudspeth and Swann, Phys. Rev. **76**, 464 (1949).
Gi 48 Gibson and Livesey, Proc. Phys. Soc. London **60**, 523 (1948).
See also: Li 37.

VII. $N^{15}(p\ n)O^{15}$? $Q_m = -3.5$

This reaction has possibly been observed (Du 38, Ba 39).

Du 38 DuBridge *et al.*, Phys. Rev. **53**, 447 (1938).
Ba 39 Barkas and White, Phys. Rev. **56**, 288 (1939).

VIII. $O^{16}(\gamma\ n)O^{15}$ $Q_m = -15.6$ (not illustrated)

A threshold of 16.3±0.4 Mev is reported (Ba 45); see also O^{16}.

Ba 45 Baldwin and Koch, Phys. Rev. **67**, 1 (1945).

IX. $O^{16}(n\ 2n)O^{15}$ $Q_m = -15.6$
X. $F^{19}(n\ p4n)O^{15}$ $Q_m = -35.6$ (not illustrated)
XI. $F^{19}(p\ \alpha n)O^{15}$? $Q_m = -7.5$

For the above three reactions see the appropriate compound nucleus.

O^{15} Theory

Beta$^{(+)}$-active. Shell: $\alpha+1p_{3/2}^4 1p_{1/2}^2$ (protons) $+1p_{3/2}^4 1p_{1/2}^1$ (neutrons). Expected state $^2P_{1/2}$, $\frac{1}{2}$, odd.

The ground state makes an allowed β-transition to the N^{15} ground; $ft=3700$ sec. This confirms the description of the ground state expected. The higher levels ought to be about as numerous as those of the mirror nucleus N^{15}.

N^{16}

[Mass: $O^{16}+10.9$ mmu (10.2 Mev) $=16.0109$ amu]

I. $N^{16}(\beta^-)O^{16}$ $Q_m=10.2$*

The half-life is reported as 7.2 ± 0.3 sec. (So 46). The β-decay is complex; see O^{16}.

So 46 Sommers and Sherr, Phys. Rev. **69**, 21 (1946).

II. $C^{14}(d\ \alpha)B^{12}$ $Q_m=0.2$ $E_x=10.7$

A large yield of high energy B^{12} decay electrons has been observed at $E_d=750$ kev. The yield was found to increase rapidly with bombarding voltage (Hu 50).

Hu 50 Hudspeth and Swann, Phys. Rev. **78**, 337 (1950).

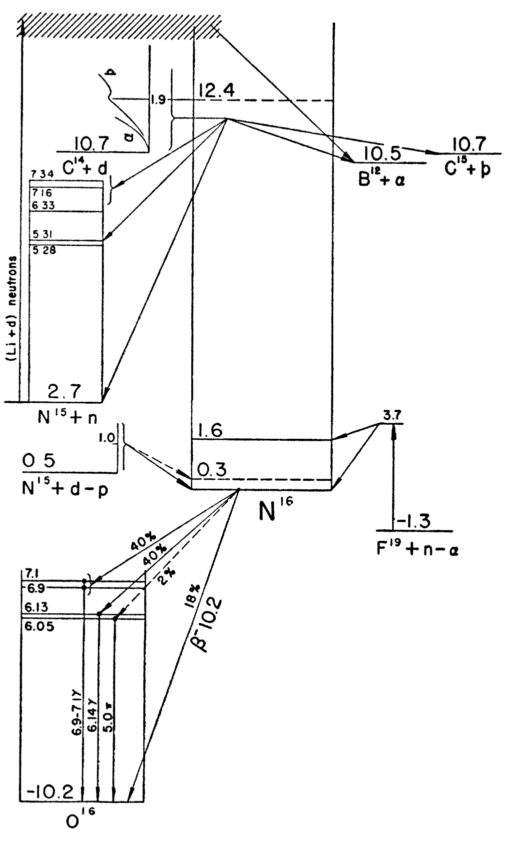

FIG. 20. Energy levels in N^{16}: for notation see Fig. 1.

* From this reaction.

III. $C^{14}(d\ p)C^{15}$ $Q_m=0.0$ $E_x=10.7$

The excitation function for the production of 2.4-sec. C^{15} rises smoothly from $E_d=1.4$ to 2.8 Mev except for a possible resonance at ~1.9 Mev (Hu 50a).

Hu 50a Hudspeth, Swann, and Heydenburg, Phys. Rev. **77**, 736 (1950).

IV. $C^{14}(d\ n)N^{15}$ $Q_m=8.0$ $E_x=10.7$

The cross section is greater than that for the $C^{12}(d\ n)$ reaction at the same bombarding voltage. Neutron groups have been observed; see N^{15}(Hu 50).

Hu 50 Hudspeth and Swann, Phys. Rev. **78**, 337 (1950).

V. $N^{15}(n\ \alpha)B^{12}$ $Q_m=-7.8$ $E_x=2.7$

B^{12} observed with Li+d neutrons (Je 48c).

Je 48c Jelley and Paul, Proc. Camb. Phil. Soc. **44**, 133 (1948).

VI. $N^{15}(d\ p)N^{16}$ $Q_m=0.5$

Both long- and short-range proton groups have been observed with enriched targets. The longer range group gives $Q_0=0.23\pm0.15$ Mev, while the shorter range group indicates a possible excitation level in N^{16} at 0.3 Mev (Wy 49c). Proton group found with enriched N^{15} target, $E_d=1.5$ Mev, gives $Q=-0.034\pm0.005$ Mev (Malm and Buechner, private communication).

Wy 49c Wyly, Phys. Rev. **76**, 316 (1949).
See also: Ho 40, Bu 50f.

VII. $O^{16}(n\ p)N^{16}$ $Q_m=-9.4$

A rough excitation function gives a threshold of $E_n\sim12.5$ Mev (So 46). The 6.2- and 7.0-Mev γ-rays from O^{16} have been observed (Mi 50a).

So 46 Sommers and Sherr, Phys. Rev. **69**, 21 (1946).
Mi 50a Millar, Cameron, and Glicksman, Phys. Rev. **77**, 742 (1950).
See also: Ch 37, Wi 37e, Bl 47.

VIII. $F^{19}(n\ \alpha)N^{16}$ $Q_m=-1.3$

Reaction energies of $Q_0=-0.73\pm0.25$ and $Q_1=-2.27\pm0.15$ Mev (monoenergetic neutrons, $E_n=3.68$ Mev) have been reported. A level in N^{16} at 1.6 Mev is thus indicated (Bl 47c); see also F^{20}: $F^{19}(n\ \alpha)$.

Bl 47c Bleuler and Rossel, Helv. Phys. Acta **20**, 445 (1947).

N^{16} Theory

Beta$^{(-)}$-active. Shell: $\alpha+1p_{3/2}^4 1p_{1/2}^1$ (protons) $+1p_{3/2}^4 1p_{1/2}^2$ (neutrons) $+1d_{5/2}^1$ (neutron)? Expected on $j-j$ model: $I=2$ or 3, odd.

This nucleus almost surely has high angular momentum in the ground state. The β-decay to the ground state of O^{16} is slower than the decay of Li^8, with an $ft=6.4\times10^6$ sec. This transition, like the one to the 6-Mev state in O^{16}, is presumably $\Delta I=2$, yes. The decay to the higher states is then allowed, though a little weak. The higher excited states in N^{16} are not implausible.

O^{16}

(Mass: 16.000 000)

I. $C^{12}(\alpha\ \alpha)C^{12}$ $E_x=7.19$

Anomalous scattering is observed for $E_\alpha=4.4$, 5.0, and 5.6 Mev (Fe 40); 4.2, 4.6, and 5.0 Mev (Ri 40a). (States in O^{16} at ~10.5, 10.8, and 11.2 Mev; widths ~0.2 Mev.)

Fe 40 Ferguson and Walker, Phys. Rev. **58**, 666 (1940).
Ri 40a Riezler, Ann. d. Physik **38**, 304 (1940).
See also: De 39a, Ro 40a.

II. $C^{12}(\alpha\ n)O^{15}$ $Q_m=-8.4$ $E_x=7.19$

O^{15} activity is observed with 16-Mev α-particles (Ki 39).

Ki 39 King, Henderson, and Risser, Phys. Rev. **55**, 1118 (1939).

III. $N^{14}(d\ n)O^{15}$ $Q_m=5.1$ $E_x=20.69$

The yield rises smoothly to $E_d=3.2$ Mev and drops sharply above this value (Ne 37b). At $E_d=8$ Mev, σ~0.2 b (Br 49).

Ne 37b Newson, Phys. Rev. **51**, 620 (1937).
Br 49 Brown and Perez-Mendez, Phys. Rev. **75**, 1286 (1949).

IV. $N^{14}(d\ p)N^{15}$ $Q_m=8.57$ $E_x=20.69$

At $E_d=0.95$ Mev, $\sigma=4.5\times10^{-28}$ cm^2 for the ground state transition; at $E_d=1.01$ Mev, $\sigma=3\times10^{-27}$ cm^2 for transition to the 5.4- (5.29-, 5.32-) Mev state (Ho 40). The angular distribution has been studied by (Wy 49).

Ho 40 Holloway and Moore, Phys. Rev. **58**, 847 (1940).
Wy 49 Wyly, Phys. Rev. **75**, 1292 (1949).

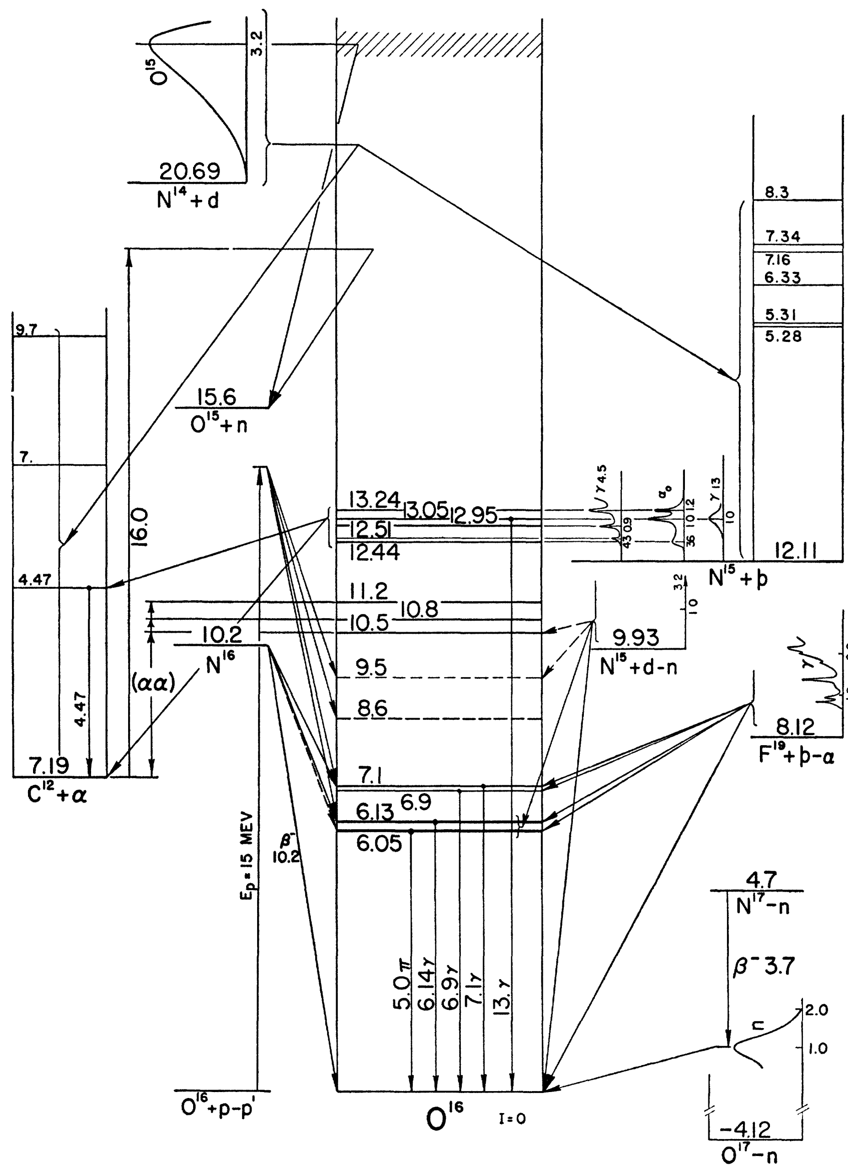

FIG. 21. Energy levels in O^{16}: for notation see Fig. 1.

V. $N^{14}(d\ \alpha)C^{12}$ $Q_m=13.50$ $E_x=20.69$

At $E_d=1.01$ Mev the cross section for the ground state transition is 1×10^{-27} cm^2 (Ho 40: see C^{12}).

Ho 40 Holloway and Moore, Phys. Rev. **58**, 847 (1940).

VI. $N^{14}(d\ 4\alpha)$ $Q_m=6.16$ $E_x=20.69$

Observed in photographic plate with 9-Mev deuterons (Fo 47b).

Fo 47b Fowler, Burrows, and Curry, Nature **159**, 569 (1947).

VII. $N^{14}(d\ t)N^{13}$ $Q_m=-4.36$ $E_x=20.69$ (not illustrated)

Threshold = 6.8±0.1 Mev (Bo 42).

Bo 42 Borst, Phys. Rev. **61**, 106 (1942).
See also: Bo 41c.

VIII. $N^{14}(d\ d)N^{14}$

See: Gu 47.

IX. $N^{15}(p\ \gamma)O^{16}$ $Q_m=12.11$

A single broad resonance (~120 kev wide) for capture radiation is observed at $E_p=1.0$ Mev ($O^{16*}=13.05$ Mev); $\sigma\sim10^{-27}$ cm^2. The γ-ray energy is ~13 Mev (Sc 50).

Sc 50 Schardt, Fowler, and Lauritsen, Phys. Rev. **80**, 136 (1950).
See also: Ta 46.

X. $N^{15}(p\ \alpha)C^{12}$ $Q_m=4.92$ $E_x=12.11$

TABLE XLVII. Resonances observed (Sc 50).

E_R (Mev)	Width (kev)	Cross section (barns) α_0	α_1	O^{16*}
0.36[a]	94	0.09	0	12.42
0.429±0.001	0.9		0.3	12.51
0.898±0.001	2.2		0.8	12.95
1.0	~160	0.5	0.015	13.05
1.21	22.5	0.6	0.3	13.24

α_0: Ground state transition.
α_1: Transition to 4.47-Mev state in C^{12}.
[a] Correction for s wave penetration factor gives $E_R=0.338$ Mev.

Holloway and Bethe (Ho 40b) report $\sigma=0.013$ b at $E_p=0.36$ Mev. Cochrane and Hester (Co 49e) report the first resonance ~0.4 Mev, $\Gamma\sim150$ kev, $\sigma_R=0.014$ b. The angular distribution of ground state α-particles is isotropic (±10 percent) at $E_p=0.34$ and 0.40 Mev (Co 49e).

Tangen (Ta 46) reports $E_p=428\pm4$ kev, width <2 kev for the first γ-ray (α_1) resonance.

The cross section for reaction to the ground state is 5×10^{-7}b at $E_p=100$ kev (Sc 50).

Sc 50 Schardt, Fowler, and Lauritsen, Phys. Rev. **80**, 136 (1950).
Ho 40b Holloway and Bethe, Phys. Rev. **57**, 747 (1940).
Co 49e Cochrane and Hester, Proc. Roy. Soc. **199**, 458 (1949).
Ta 46 Tangen, Kgl. Nord. Vid. Selsk. Skr. No. 1 (1946).
See also: La 41.

XI. $N^{15}(d\ n)O^{16}$ $Q_m=9.93$

TABLE XLVIII. Neutron groups.

A E_n (Mev)	(Q)	B Q (Mev)	O^{16*}
11.	11.3	10.9 ±0.5	0
~4.5	4.1	4.8 ±0.3	6.1±0.3
(~2.5)	1.6	1.55	9.3
		0.19	10.7

A: $E_d=1.2$ Mev, $\theta=0°$ (Hu 49f).
B: $E_d=3.2$ Mev, $\theta=0°$; assignment of last two groups not certain (Wo 50).

Hu 49f Hudspeth and Swann, Phys. Rev. **76**, 464 (1949).
Wo 50 Worth, Phys. Rev. **78**, 378 (1950).

XII. $N^{16}(\beta^-)O^{16}$ $Q_m=10.2$

Analysis of the β-spectrum indicates the decay scheme (Bl 47, So 46) of Table XLIX.

TABLE XLIX.

β_{max} (Mev)	Intens.	O^{16*}
10.2	18	0
(4.5)	(2)	(6.0π)
4.3	40	6.2γ
3.8	40	6.7γ
(5.0?)		(5.1?)

The γ-radiation, measured in a deuterium-loaded plate, comprises two components, 6.2 and 7.0 Mev, of relative intensity 6:1 (Mi 50a). Kinsey, private communication, gives $E_\gamma=6.13\pm0.01$ and 7.10 ± 0.02 Mev, relative intensity 12:1.

Bl 47 Bleuler, Scherrer, Walter, and Zünti, Helv. Phys. Acta **20**, 96 (1947).
So 46 Sommers and Sherr, Phys. Rev. **69**, 21 (1946).
Mi 50a Millar, Cameron, and Glicksman, Phys. Rev. **77**, 742 (1950).
See also: Bl 47c, Bl 45.

XIII. $N^{17}(\beta^-)O^{17*}\rightarrow n+O^{16}$ $Q=4.7$

No transitions other than to ground state are observed; see O^{17}.

XIV. (a) $O^{16}(\gamma\ n)O^{15}$ $Q_m=-15.6$
(b) $O^{16}(\gamma\ p)N^{15}$ $Q_m=-12.11$
(c) $O^{16}(\gamma\ \alpha)C^{12}$ $Q_m=-7.19$

Threshold for $(\gamma\ n)$ reaction = 16.3±0.4 Mev (Ba 45).

Cross sections for 17.5-Mev γ-radiation (Wa 49i): $\sigma(a)=5.4\pm1.4\times10^{-28}$ cm^2, $\sigma(b)=6.8\pm1.7\times10^{-28}$ cm^2, $\sigma(c)=1.8\pm0.6\times10^{-28}$ cm^2.

The reaction $O^{16}(\gamma\ 4\alpha)$ is also observed (Mi 50b, Go 49d).

Ba 45 Baldwin and Koch, Phys. Rev. **67**, 1 (1945).
Wa 49i Wäffler and Younis, Helv. Phys. Acta **22**, 614 (1949).
Mi 50b Millar and Cameron, Phys. Rev. **78**, 78 (1950).
Go 49d Goward, Titterton, and Wilkins, Proc. Phys. Soc. London **62**, 460 (1949).
See also: Bo 39c, Ch 37, Hu 43, Pe 47, Pe 48b, Wa 48b, Ga 50a, Ga 50b, We 50.

XV. $O^{16}(p\ p')O^{16*}$

Inelastic scattering of 15-Mev protons indicates the existence of levels in O^{16} at 5.8±0.3, 6.7±0.3 (strong), 8.6±0.4, and 9.7±1.0 Mev (weak) (Fu 48).

For elastic scattering see F^{17}.

Fu 48 Fulbright and Bush, Phys. Rev. **74**, 1323 (1948).
See also: Po 40c, He 47, Rh 50.

XVI. $F^{19}(p\ \alpha)O^{16}$ $Q_m=8.12$

The reaction results in five groups of α-particles, leaving O^{16} in the ground state (α_0), a state at 6.05 Mev yielding nuclear pairs (α_π), and γ-emitting states at 6.13, 6.9, and 7.1 Mev ($\alpha_1\alpha_2\alpha_3$). The relative intensities of the various groups depend markedly on bombarding energy (see Ne^{20}). (Table L.)

The nuclear pairs are assumed (Op 39a, Op 41) to result from the transition: $(I=0,+)\rightarrow(0+)$. The energy spectrum (Ra 50, Ko 43b), the angular correlation of the positron with respect to the electron ($1+0.85\cos\theta$, De 49b), and the lifetime ($7\pm1\times10^{-11}$ sec., De 49c) are all in good agreement with calculations based on electromagnetic interaction.

The angular distribution of γ-radiation has the form: $I(\theta)=1+a\cos^2\theta$, where a has the values in Table LI.

Measurement of the angular correlation of the 6.1-Mev γ-ray with the corresponding α-particles at $E_p=0.33$ Mev indicates that the 6.13-Mev level has a spin of 3, with odd parity, and that the Ne^{20} level has spin 1, even parity (Ar 50, Ba 50f). Tentative assignments for other levels are discussed by Chao (Ch 50a) on the basis of angular distributions and intensities.

St 50 Strait, Van Patter, and Buechner, Phys. Rev. **78**, 337 (1950).
Bu 50c Buechner *et al.*, M.I.T. Progress Report (April 1, 1950).
Ch 50 Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).
Bu 49a Burcham and Freeman, Phys. Rev. **75**, 1756 (1949).
Ra 50 Rasmussen, Hornyak, Lauritsen, and Lauritsen, Phys. Rev. **77**, 617 (1950).
Wa 48 Walker and McDaniel, Phys. Rev. **74**, 315 (1948).
Ph 49c Phillips and Kruger, Phys. Rev. **76**, 1471 (1949).
Op 39a Oppenheimer and Schwinger, Phys. Rev. **56**, 1066 (1939).
Op 41 Oppenheimer, Phys. Rev. **60**, 164 (1941).
Ko 43b Kojima, Proc. Imp. Acad. Tokyo **19**, 282 (1943).
De 49b Devons and Lindsey, Nature **164**, 539 (1949).
De 49c Devons, Hereward, and Lindsey, Nature **164**, 586 (1949).

TABLE LI.

E_p (Mev)[a]	340	486	598	669	874
a	0	0	0.2	0	0.1
E_p (Mev)[b]	874	935	1290	1355	1381
a	0.10	0.0	0.69	0.28	−0.08

[a] De 49d.
[b] Da 50.

De 49d Devons and Hine, Proc. Roy. Soc. **199**, 56, 73 (1949).
Da 50 Day, Chao, Fowler, and Perry, Phys. Rev. **80**, 131 (1950).
Ar 50 Arnold, Phys. Rev. **79**, 170 (1950); Phys. Rev. **80**, 34 (1950).
Ba 50f Barnes, French, and Devons, Nature **166**, 145 (1950).
Ch 50a Chao, Phys. Rev. (in press).
See also: Ga 37, Ge 37a, Bu 38, Bu 39, Bu 39a, Cu 39a, De 39, Ha 39c, Mc 39, De 40a, Cu 40, Ge 40, Mc 40, Se 40, Be 41c, La 41, Sh 41, Sh 41a, To 41, Va 41, Be 42, Ko 43a, Ro 44, Ph 47, Ru 47c, Fr 48c, Fo 48, Fo 48b, Go 48d, Ja 48, Fo 49b, Bu 50f, In 50b.

O^{16} Theory

Spherically symmetric; $I=0$. Clearly $^1S_0$, even. The p shell is completely filled in this nucleus: $\alpha+1p_{\frac{3}{2}}{}^4 1p_{\frac{1}{2}}{}^2$ (neutrons and protons). The α-particle model would agree.

The absence of levels to 6 Mev confirms the strongly closed-shell nature of this nucleus. The unique property of the 6.05-Mev state, which decays by emitting an electron-positron pair with a measured lifetime and energy distribution, fixes its character as $I=0$, even. Only pair emission occurs because single-quantum emission is rigorously forbidden. That the pair is emitted mainly in a $^3P_0$ state seems confirmed by direct check on the angular and energy distribution of the electron-positron. These two lowest states are then assigned with certainty, and it is all but sure that no intermediate state exists (the only possible, and very unlikely, candidates are those with very high I values), for if there were such intermediate states some single quantum radiation would take place. That a pure P wave pair has even parity is a consequence of the Dirac equation (Ya 50). Some types of specific *ad hoc* nucleon-pair couplings, not electromagnetic in origin, do allow emission of odd-parity pairs with very similar angular and energy distributions. These seem excluded by the agree-

TABLE L. Q values.

	Q_α (Mev)			Q_γ (Mev)			O^{16*}
No.	A	B	C	D	E	F	G
0	8.117	(8.113±0.030)					0
π	2.073	2.061±0.010		6.04±0.03			6.048
1	1.988	1.977±0.008	1.93±0.06	6.14±0.04	6.13±0.06	6.13±0.06	6.133
2	1.210	1.204±0.008	1.18±0.08	6.9 }	6.98±0.07 }	7.12±0.07	6.908
3	1.007	1.002±0.008	0.96±0.08	7.09±0.06 }			7.110

A: Magnetic spectrometer: (St 50, Bu 50c). More recent values for Q_0 are 8.118±0.009 Mev (Strait *et al.*, private communication) and 8.06±0.04 Mev (Fr 50c).
B: Magnetic spectrometer: ground state value obtained from sums of Q_α and Q_γ's (Ch 50).
C: Magnetic analysis, range (Bu 49a).
D: Lens spectrometer: 6.9- and 7.1-Mev lines not resolved (Ra 50).
E: Pair spectrometer: Wa 48.
F: Cloud-chamber gas pairs, $E_p=5$ Mev (Ph 49c).
G: Weighted means from A, B, and D.

ment of the lifetime with pure electromagnetic coupling expectations (Christy, private communication).

Above the pair-emitting state come a series of states which readily combine with the ground state by radiative transitions. Without resolution of the several γ-ray lines for the many resonances of the $F^{19}(p\ \alpha)$, assignment in terms of observed intensities and angular distributions is uncertain. It is enough to point out here that both electric and magnetic dipole (and electric quadrupole) radiations are likely; assignments of $I=1$ with both odd and even parity are plausible. The situation is discussed a little more fully in the account of the Ne^{20} states involved. There is, however, strong indication that the 6.13-Mev level has $I=3$, odd parity (see reaction XVI, above).

The group of levels between 12 and 13.5 Mev give rise to well-defined resonances. The wide level emitting 13-Mev gammas (level at 13.05 Mev) is presumably showing mainly the proton width for s wave protons. The state decays by γ-radiation because it is then presumably $I=1$, odd, and could yield only p wave alphas with reduced probability because of the barrier. The narrower levels are perhaps due to p wave or d wave protons and can have higher I, odd or even parity. They decay by α-emission (probably s wave alphas) sometimes to the excited state at 4.47 Mev in C^{12}. The two lowest levels of the group (12 to 13.5 Mev), one of which decays by long-range alphas only (12.44-Mev level) and the other of which decays by short-range alphas only (12.51-Mev level) can be roughly accounted for by assuming $I=1$, even, for the C^{12} excited state (see C^{12}) and giving the states of O^{16} the properties $I=1$, odd (s wave protons), and $I=1$, even (p wave protons), respectively. A slowly varying background of alphas may also arise from s wave capture.

These considerations are qualitative only.

Ya 50 Yang, Phys. Rev. **77**, 242 (1950).

N^{17}

(not illustrated)

[Mass: $O^{17}+9.4$ mmu $(3.7+5.1$ Mev$)=17.0139$ amu]

I. $N^{17}(\beta^-)O^{17*}\rightarrow O^{16}+n$

The β-spectrum maximum energy is 3.7 ± 0.2 Mev (Al 49c). The half-life has been determined as 4.14 ± 0.04 sec. (Kn 48), and 4.25 ± 0.5 sec. (Sh 50). The decay is to an excited state in O^{17}; see O^{17}.

Al 49c Alvarez, Phys. Rev. **75**, 1127 (1949).
Kn 48 Knable *et al.*, Phys. Rev. **74**, 1217 (1948).
Sh 50 Sher, Halpern, and Stephens, Phys. Rev. **79**, 241 (1950).

II. $C^{14}(\alpha\ p)N^{17}$ $Q_m=-9.7$

An upper limit of ~16 Mev has been reported for the threshold (Su 49).

Su 49 Sun, Jennings, and Shoupp, Phys. Rev. **75**, 1302 (1949).

III. $O^{17}(n\ p)N^{17}$ $Q_m=-7.9$

See O^{18}.

IV. $O^{18}(\gamma\ p)N^{17}$ $Q_m=-15.9$

A threshold of 18.2 ± 0.3 Mev was observed using the bremsstrahlung from a 25-Mev betatron. The delayed neutrons have been observed (Sh 50).

A threshold of 17.1 Mev and an excitation function with a broad maximum of $\sim2\times10^{-27}$ cm^2 b at 24 Mev is reported (Stephens, private communication). The delayed neutrons were observed.

Sh 50 Sher, Halpern, and Stephens, Phys. Rev. **79**, 241 (1950).

V. $F^{19}(\gamma\ 2p)N^{17}$ $Q_m=-23.8$

Langmuir and Pollock (private communication) report the production of N^{17} at $E_\gamma=70$ Mev.

VI. d-spallation

Chupp and McMillan (Ch 48c) have observed the 4.13-sec. delayed neutrons from the bombardment of several elements with 195-Mev deuterons. They report relative yields of:

O (not including O^{16})	F	Na	Mg	Al	Si	P	S	Cl	K
100 000	8400.	2600.	840.	840.	230.	230.	70.	78.	25.

Ch 48c Chupp and McMillan, Phys. Rev. **74**, 1217 (1948).
See also: Kn 48.

N^{17} Theory

Beta$^{(-)}$-active. Shell: $\alpha+1p_{\frac{3}{2}}{}^41p_{\frac{1}{2}}{}^1$ (protons) $+1p_{\frac{3}{2}}{}^41p_{\frac{1}{2}}{}^2$ (neutrons) $+2s_{\frac{1}{2}}{}^2$ (neutrons) or $2d_{\frac{5}{2}}{}^2$ (neutrons); perhaps $I=\frac{1}{2}$, odd.

This nucleus is interesting because its decay confirms the Bohr-Wheeler theory of delayed neutron emitters in fission. Note the long life for decay to the ground state, and to several additional states of O^{17}, all below the neutron-emission threshold. These transitions must occur, but even from the over-all lifetime one can conclude that they involve a spin change of at least 2, or perhaps of only 1 but parities unfavorable.

O^{17}

(Mass: 17.00450)

I. $C^{13}(\alpha\ n)O^{16}$ $Q_m=2.31$ $E_x=6.44$

This reaction has not been observed.

II. $N^{14}(\alpha\ p)O^{17}$ $Q_m=-1.13$

Early work by Stetter and by Fischer-Colbrie indicates proton groups corresponding to Q values of -1.4 and -2.8 Mev. The presence of γ-radiation of 1.3 to 1.5 Mev has been reported by Savel. Haxel gives $Q=-1.26$ Mev for the ground state transition (Li 37).

Proton groups giving Q values -1.31 and -2.12 Mev have been reported, indicating a level at 0.81 Mev in O^{17}.

Another group with $Q=-2.90$ may also be associated with this reaction; the possibility however, that this group consists of scattered deuterons or $N^{14}(\alpha\ d)$ deuterons cannot be excluded (Po 47).

The presence of γ-radiation at $E_\alpha=5.3$ Mev has been confirmed (Sl 48b, Sl 48c).

The angular distribution and yield of protons have been studied; see F^{18}: $N^{14}(\alpha\ p)$.

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Po 47 Pollard and Davison, Phys. Rev. **72**, 736 (1947).
Sl 48b Slätis, Nature **161**, 899 (1948).
Sl 48c Slätis, Arkiv. f. Ast. Math. Fys. **35A**, No 31 (1948).
See also: Ha 35.

III. $N^{15}(d\ \alpha)C^{13}$ $Q_m=7.63$ $E_x=14.07$

A cross section of $\sigma=1$ mb at $E_d\sim1.0$ Mev is reported (Ho 40). Alpha-particle groups to various excited states in C^{13} are known; see C^{13}.

Ho 40 Holloway and Moore, Phys. Rev. **58**, 847 (1940).
See also Ho 39a.

IV. $N^{15}(d\ p)N^{16}$ $Q_m=0.54$ $E_x=14.07$

Holloway and Moore (Ho 40) have observed a 9.5 ± 1.0-sec. activity at $E_d\sim1.0$ Mev which may be attributed to this reaction. The corresponding protons were not found by them over the strong α-particle yields. These protons have since been observed; see N^{16}: $N^{15}(d\ p)$.

Ho 40 Holloway and Moore, Phys. Rev. **58**, 847 (1940).

V. $N^{15}(d\ n)O^{16}$ $Q_m=9.94$ $E_x=14.07$

See O^{16}: $N^{15}(d\ n)$

VI. $N^{17}(\beta^-)O^{17*}\rightarrow O^{16}+n$

The β-decay proceeds to an excited state of O^{17} which in turn decays to O^{16} emitting a neutron spectrum with a maximum at 0.92 ± 0.07 Mev (Al 49c, Ha 49c) (nuclear excitation in O^{17} at $4.13+17/16\times0.92=5.00$ Mev) and a half-width <0.5 Mev. It seems not unlikely that the principal level in O^{17} involved in the β-decay is the

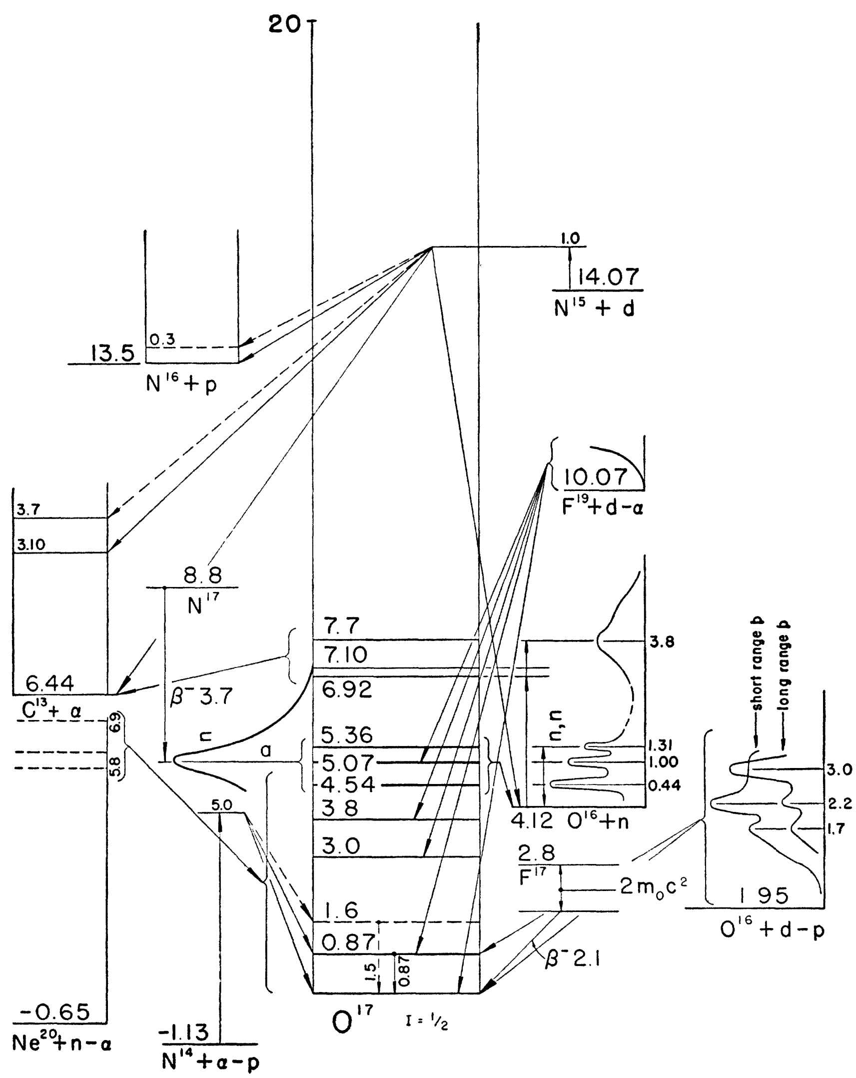

FIG. 22. Energy levels in O^{17}: for notation see Fig. 1. (a) delayed neutrons from $N^{17}(\beta^-)$. Levels at 0.875, 3.02, 3.88, 4.54, 5.17, 5.72, 6.33, 6.93, 7.60, and 8.23 are reported by Rotblat. See text.

same as the 5.07-Mev level evident in the $O^{16}(n\ n)$ and $F^{19}(d\ \alpha)$ reactions. Since the neutron spectrum extends to an energy of ~2 Mev other levels in O^{17} may be involved in the N^{17} decay.

Al 49c Alvarez, Phys. Rev. **75**, 1127 (1949).
Ha 49c Hayward, Phys. Rev. **75**, 917 (1949).
See also: Da 48c.

VII. $O^{16}(n\ \alpha)C^{13}$ $Q_m=-2.31$ $E_x=4.12$

Wilhelmy (Wi 37e) observed $(\alpha+C^{13})$ recoils having energies $E_\alpha+E_c=0.65$, 0.85, and 1.5? Mev with Po-Be and Rn-Be neutrons. The corresponding level excitations in O^{17} are 6.92, 7.10, and 7.7? Mev.

Wi 37e Wilhelmy, Zeits. f. Physik **107**, 769 (1937).
See also: Li 37.

VIII. $O^{16}(n\ 2p4n)C^{11}$ $Q_m=-54.0$ $E_x=4.12$ $O^{16}(n\ p3n)N^{13}$ $Q_m=-33.4$ (not illustrated)

These reactions have been observed and the relative yields obtained at $E_n=90$ Mev (Kn 47).

Kn 47 Knox, Phys. Rev. **72**, 1254 (1947).

IX. $O^{16}(n\ p)N^{16}$ $Q_m=-9.4$ $E_x=4.13$ (not illustrated, see N^{16})

X. $O^{16}(n\ 2n)O^{15}$ $Q_m=-15.6$ $E_x=4.13$ (not illustrated)

The relative yield of O^{15} has been compared with other $n\ 2n$ reactions (Je 44).

Je 44 Jensen, Zeits. f. Physik **122**, 387 (1944).
See also: Po 37, Kn 47.

XI. $O^{16}(n\ n)O^{16}$ $E_x=4.13$

Adair *et al.* (Ad 49) (and private communication) have observed anomalous scattering of fast neutrons in transmission experiments. See Table LII.

The experiments of Nuckolls *et al* (Nu 46), indicate in addition to a resonance at 1.0 Mev, a broad (possibly unresolved) resonance of 3 b for ~3.8-Mev neutrons. There may be a correlation between the level at 7.7 Mev indicated by this high energy resonance and the resonance occurring in the $O^{16}(n\ \alpha)$ reaction.

The slow neutron cross section, $E_n<100$ ev, has been observed (Me 48, Me 49b).

Ad 49 Adair *et al.*, Phys. Rev. **75**, 1124 (1949).
Nu 46 Nuckolls *et al.*, Phys. Rev. **70**, 805 (1949).
Me 48 Melkonian *et al.*, Phys. Rev. **73**, 1399 (1948).
Me 49b Melkonian, Phys. Rev. **76**, 1750 (1949).
See also: Ba 50g, Ri 50c.

TABLE LII.

E_R (Mev)	E_{level} (Mev)	Γ (kev)	σ (barns)	L	$I(O^{17})$
0.44±0.02	4.54	40	14	P wave	3/2
1.00±0.02	5.07	90	8	P wave	3/2
1.31±0.02	5.36	40	7	(P wave)?	3/2

XII. $O^{16}(d\ p)O^{17}$ $Q_m=1.95$

Numerous investigators have determined the reaction energy for the long- and short-range proton groups accompanying the deuteron bombardment of O^{16}. Their results are summarized in Table LIII.

TABLE LIII.

Q_0 (Mev)	Q_1 (Mev)	E_{level} (O^{17})	Reference
1.95 ±0.06	1.12 ±0.07	0.83	Li 37
1.75	0.89	0.86	Po 47
1.90 ±0.2	0.99 ±0.2	0.91	He 48a, He 49c
1.925±0.008	1.049±0.007	0.876±0.009	Va 49a, Bu 49c
1.917±0.005			[a]

[a] Strait *et al.*, private communication.

Rotblat (Ro 47a) reports the excitation of 10 levels in O^{17} through this reaction. See $F^{19}(d\ \alpha)$ below.

Thomas and Lauritsen (unpublished) have measured the γ-ray energy in a spectrometer as 871±3 kev. Gamma-rays of energy 0.90±0.05, (2.1±0.3)?, and 4.0±0.3 Mev were observed in the bombardment of PbO_2 at $E_d=3.7$ Mev (Al 49i); the low energy γ-ray is undoubtedly associated with this reaction; see also N^{14}: $O^{16}(d\ \alpha)$.

The cross section for this reaction and the angular distribution of the proton groups has been observed; see F^{18}.

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937)
Po 47 Pollard and Davison, Phys. Rev. **72**, 736 (1947).
He 48a Heydenburg and Inglis, Phys. Rev. **73**, 230 (1948).
He 49c Heydenburg *et al.*, Phys. Rev. **75**, 1147 (1949).
Va 49a Van de Graaff and Buechner, M.I.T. Prog. Report (July 1, 1949).
Bu 49c Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).
Ro 47a Rotblat, Harwell Conference, Nature **160**, 493 (1947).
Al 49i Alburger, Phys. Rev. **75**, 51 (1949).
See also: Bu 38, Ho 40c, Da 47, Gu 47, La 47b.

XIII. $F^{17}(\beta^+)O^{17}$ $Q_m=1.8+1.02=2.8$

No transitions other than to the ground state have been observed; see F^{17}.

XIV. $F^{19}(d\ \alpha)O^{17}$ $Q_m=10.07$

Burcham and Smith (Bu 38) identified the α-groups from this reaction giving Q values of 9.84, 9.01, 6.89, 6.07, and 5.35 Mev corresponding to levels in O^{17} at 0.83, 2.95, 3.77, and 4.99 Mev. (Evidence of very faint α-group corresponding to a transition to the 1.6?-Mev level cannot be ruled out in their data, although the $d\ p$ protons from oxygen contamination could equally well account for this group.)

French *et al.* (Fr 50d) report α-particle groups giving $Q=2.81$ 5.26, 6.03, and 6.79 Mev. They also give evidence for the $F^{19}(d\ n)Ne^{20*}\rightarrow O^{16}+\alpha$-reaction.

Rotblat (Harwell Conference 1950, also Ro 47a) using photographic plates with $E_d=7.8$ Mev reports proton groups from $O^{16}(d\ p)$ and α-particle groups from $F^{19}(d\ \alpha)$ giving levels in O^{17} at: 0.875, 3.02, 3.88, 4.54, 5.17, 5.72 (may be doublet), 6.33, 6.93, 7.60 (may be doublet), 8.23 (α-particles only).

$Q_0 = 10.050 \pm 0.010$ mag. spectrometer (Strait *et al.*, private communication).

Bu 38 Burcham and Smith, Proc. Roy. Soc. **168**, 176 (1938).
Fr 50d French, Meyer, and Treacy, Proc. Phys. Soc. London **63**, 666 (1950).

XV. $Ne^{20}(n\ \alpha)O^{17}$ $Q_m = -0.65$

Cloud-chamber investigations, using Po-Be neutrons ($2 < E_n < 10$ Mev), resulted in Q values of -0.7 and -5.3 Mev indicating the excitation of a level at ~ 4.6 Mev in O^{17} (Ja 35, Li 37). A reaction energy of -0.6 Mev is reported using $(d+d)$ neutrons ($E_n \sim 2.5$ Mev) (Gr 46).

The decay of excited states in the compound nucleus Ne^{21} by the emission of α-particles to various excited states in O^{17} has been reported; see Ne^{21}: $Ne^{20}(n\ \alpha)$.

Ja 35 Jaeckel, Zeits. f. Physik **96**, 151 (1935).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Gr 46 Graves and Coon, Phys. Rev. **70**, 101 (1946).

O^{17} Theory

Measured spin probably $I = \frac{1}{2}$; $|Q| < 0.02$. Shell: $O^{16} + 2s_{\frac{1}{2}}{}^1$ (neutron); Hartree state expected ${}^2S_{\frac{1}{2}}$, even.

The level scheme is complex, more than expected for a single particle outside a closed shell. Identification of levels is not easy, since most are obtained in only one way. An interesting exception is the set of levels observed in neutron scattering. These resonances have measured widths and cross sections, from which can be deduced the spin of the O^{17} state, using the dispersion theory with statistical factors (Ad 49). The radiations which connect some of these states with lower lying states and ground would seem at first sight as fair evidence that the states up to some 5 Mev are distributed between values of $I = \frac{3}{2}$ and $I = \frac{1}{2}$, with various parities. This probably means that N^{17} has a spin as high as $I = 5/2$.

Ad 49 Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949).

F^{17}

(Mass: 17.0075)

I. $F^{17}(\beta^+)O^{17}$ $Q_m = 1.8 + 1.02 = 2.8$

Cloud-chamber observation gives a visual end point of 2.1 Mev (Ku 36). The half-life determinations are: 1.16 min. (Ne 35), 1.10 ± 0.02 min. (Br 49), 1.23 ± 0.1 min. (Du 38), 1.07 ± 0.1 min. (Ri 37).

Ku 36 Kurie, Richardson, and Paxton, Phys. Rev. **49**, 368 (1936).
Ne 35 Newson, Phys. Rev. **48**, 790 (1935).
Br 49 Brown and Perez-Mendez, Phys. Rev. **75**, 1286 (1949).
Du 38 DuBridge, Barnes, Buck, and Strain, Phys. Rev. **53**, 447 (1938).
Ri 37 Ridenour and Henderson, Phys. Rev. **52**, 889 (1937).

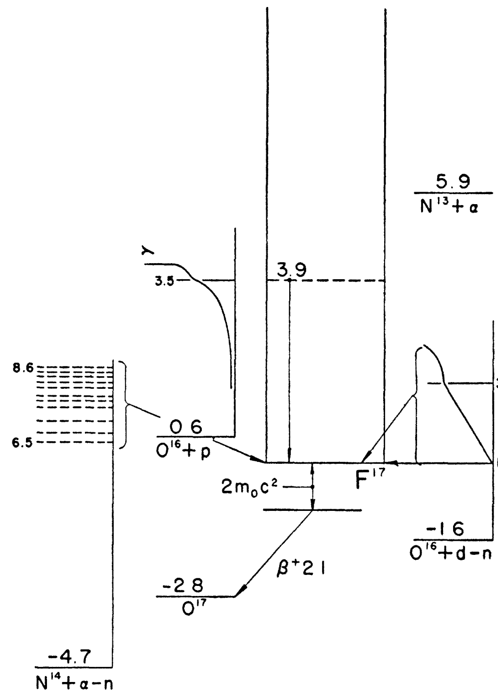

FIG. 23. Energy levels in F^{17}: for notation see Fig. 1. The narrow level at 3.9 Mev is verified and additional levels at 3.1 and ~ 4.7 Mev reported. See text.

II. $N^{14}(He^3\ \alpha)N^{13}$ $Q_m = 9.9$ $E_x = 15.8$ (not illustrated)

Stovall, Fowler, Williams, and Squires (St 49a) observed the N^{13} activity using a $H^2(d\ n)He^3$ source (8.3 Mev He^3). They give the upper limit for the cross section as $\sigma < 1 \pm 1$ b.

St 49a Stovall LAMS 820 (1949).

III. $N^{14}(\alpha\ n)F^{17}$ $Q_m = -4.7$

Early investigators (Li 37) have observed this reaction by detecting the 1.2-min. β^+-activity from the F^{17} produced. The positrons were observed only for α-particles having energies in excess of 7 Mev, thus indicating a $Q \sim -5.5$ Mev.

Numerous excitation levels in F^{18} are known; see F^{18}: $N^{14}(\alpha\ n)$.

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).

IV. $O^{16}(p\ 3p3n)C^{11}$ $Q_m = -54.0$ $E_x = 0.6$ (not illustrated)

This yield of this reaction has been compared with the $C^{12}(p\ pn)C^{11}$ yield for high energy protons by McMillan and Miller (Mc 48).

Mc 48 McMillan and Miller, Phys. Rev. **73**, 80 (1948).

V. $O^{16}(p\ p)O^{16}$ $E_x = 0.6$ (not illustrated)

Heitler, May, and Powell (He 47) observed the angular distribution of elastically scattered protons, $E = 4.2$

Mev and find that the Coulomb term combined with an S wave accounts for the observed data. No evidence is found for inelastically scattered protons at this energy; see also O^{16}: $O^{16}(p\ p')O^{16}$.

Laubenstein, private communication, studied the yield of elastically scattered protons $E_p=0.6-4.5$ Mev. Narrow anomalies at 2.66 and 3.47 Mev and a very broad anomaly at ~4.4 Mev was found.

He 47 Heitler, May, and Powell, Proc. Roy. Soc. **190**, 180 (1947).

VI. $O^{16}(p\ \gamma)F^{17}$ $Q_m=0.6$

Curran and Strothers (Cu 40a) observed the yield of F^{17} produced by this reaction up to proton energies of 0.96 Mev. The thick target yield at $E_p=0.96$ Mev is 8.0×10^{-12} β^+ per proton. DuBridge *et al.* (Du 38) observed the thick target yield up to 4 Mev and give a cross section of 1.5×10^{-5} b at this energy. A possible resonance at 3.5 Mev is observed.

Cu 40a Curran and Strothers, Nature **145**, 224 (1940).
Du 38 DuBridge, Barnes, Buck, and Strain, Phys. Rev. **53**, 447 (1938).

VII. $O^{16}(d\ n)F^{17}$ $Q_m=-1.6$

$Q=-1.61\pm 0.01$ Mev from threshold determination (He 48a); see also F^{18}: $O^{16}(d\ n)$.

He 48a Heydenburg and Inglis, Phys. Rev. **73**, 230 (1948).
See also: Li 37.

VIII. $F^{19}(\gamma\ 2n)F^{17}$ $Q_m=-19.5$
IX. $F^{19}(n\ 3n)F^{17}$ $Q_m=-19.5$ (not illustrated)

See corresponding compound nuclei.

F^{17} Theory

Beta$^{(+)}$-active. Shell: $O^{16}+2s_{\frac{1}{2}}{}^1$ (proton). Hartree state $^2S_{\frac{1}{2}}$, even, expected.

A relatively large number of reactions involving this nucleus have been seen, but no excited states have been clearly found. There is a suggestion of a state at 3.9 Mev. The β-decaying ground state goes to the ground state of O^{17} with an allowed but not very favorable transition, $ft=5400$ sec. The ground state may well be $I=\frac{1}{2}$, even, as expected.

O^{18}

(Mass: 18.0049)

I. $C^{14}(\alpha\ p)N^{17}$ $Q_m=-9.7$ $E_x=6.21$

$\sigma=0.06$ b at $E_\alpha=28$ Mev (Su 49).

Su 49 Sun, Jennings, and Shoupp, Phys. Rev. **75**, 1302 (1949).

II. $O^{17}(n\ \alpha)C^{14}$ $Q_m=1.73$ $E_x=7.94$

A cross section of 0.46 ± 0.11 b is reported for thermal neutrons (used $\sigma_N=1.7$ b, th$-n$): various isotopic enrichments were used. The reaction energy was estimated between 1 to 2 Mev (Ma 47).

Ma 47 May and Hincks, Can. J. Research **25**, 77 (1947).
See also: Hi 46, Hu 46a.

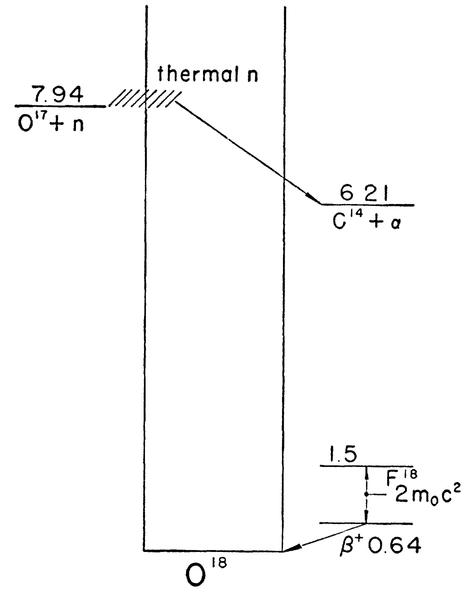

FIG. 24. Energy levels in O^{18}: for notation see Fig. 1.

III. $O^{17}(n\ p)N^{17}$ $Q_m=-7.9$ Mev $E_x=7.94$ (not illustrated)

Charpie *et al.* (Ch 49d) observed this reaction by identifying the delayed neutrons and report an average cross section of 10^{-2} b for $E_n=8$ to 29 Mev.

Ch 49d Charpie, Sun, Jennings, and Nechaj, Phys. Rev. **76**, 1255 (1949).

IV. $O^{18}(\gamma\ p)N^{17}$ $Q_m=-15.9$

See N^{17}: $O^{18}(\gamma\ p)$.

V. $F^{18}(\beta^+)O^{18}$ $Q_m=0.5+1.02=1.5$

No transitions other than to the ground state are observed; see F^{18}.

O^{18} Theory

Spin probably 0; $|Q|<4\times 10^{-3}$. Shell: $O^{16}+2s_{\frac{1}{2}}{}^2$ (neutrons). Expected state $^1S_0$, even, on any model.

There are no excited levels observed in this nucleus to date.

F^{18}

(Mass: 18.0065)

I. $F^{18}(\beta^+)O^{18}$ $Q_m=0.5+1.02=1.5$

The end point of the spectrum has been observed by numerous investigators, see Table LIV.

TABLE LIV.

$E_{\beta^+\max}$ (Mev)	Remarks	Reference
0.7 ±0.05	Cloud chamber	Ya 38
0.74	Al abs.	Du 38
0.72 ±0.02	Al abs. compared with RaE	Kr 41
0.7	Feather range 225 cm/cm² Al	Kn 45
0.635±0.015	β-ray spectrometer	Bl 49a

The half-life has been reported as 112±2 min. (Kr 41, Sn 37, We 46, Bl 49a), while Huber *et al.* (Hu 43) give 115±4 min.

Knight *et al.* (Kn 45) find the absorption in Pb indicates the presence of annihilation radiation only. Knox (Kn 48a) finds the $\beta^+-\gamma$-ratio to be the same as for C^{11} (no γ) and reports a half-thickness measurement of the γ-radiation to give 0.5 Mev (annihilation radiation). Blaser, Boehm, and Marmier (Bl 49a) find the spectrum to be simple; there is thus no confirmation of the complex decay reported by Ho (Ho 48a).

Ya 38 Yasaki and Watanabe, Nature **141**, 787 (1938).
Du 38 DuBridge, Barnes, Buck, and Strain, Phys. Rev. **53**, 447 (1938).
Kr 41 Krishnan, Nature **148**, 407 (1941).
Kn 45 Knight *et al.*, Plut. Proj. Report CC 2605 (February, 1945).
Bl 49a Blaser, Boehm, and Marmier, Phys. Rev. **75**, 1953 (1949).
Sn 37 Snell, Phys. Rev. **51**, 143 (1937).
We 46 Welles, Phys. Rev. **69**, 586 (1946).
Hu 43 Huber *et al.*, Helv. Phys. Acta **16**, 33 (1943).
Kn 48 Knable *et al.*, Phys. Rev. **74**, 1217 (1948).
Ho 48a Ho, Comptes Rendus **226**, 1187 (1948).
See also: Da 40, Hu 42, Te 47.

II. $N^{14}(\alpha\ \alpha)N^{14}$ $E_x=4.57$

Two narrow resonances in the scattering of α-particles in nitrogen at 4.6 and 5.2 Mev are reported. It is suggested that the 5.2-Mev resonance may be due to D wave α-particles (De 39a). The scattering at various angles from 53° to 104° has been studied and the resonance at 5.2 Mev verified (Br 39).

De 39a Devons, Proc. Roy. Soc. **172**, 127 (1939).
Br 39 Brubaker, Phys. Rev. **56**, 1181 (1939).

III. $N^{14}(\alpha\ p)O^{17}$ $Q_m=-1.13$ $E_x=4.57$

The early work of Stemann (Li 37) indicated two close resonances at $E_\alpha=3.6$ and 4.1 Mev. Champion and Roy (Ch 47b) verify the resonance at 3.5 Mev and report a further resonance at 1.7 Mev. They find the angular distribution of the protons to be isotropic for $E_\alpha \leqslant 3.0$ Mev. The distribution shows a pronounced maximum at 90° at 3.5 Mev. The yield at $E_\alpha=3.5$ Mev is $\sim$1 p per 2×10^6 α.

Haxel (Ha 35) gives the cross section as 0.06 b at $E_\alpha=6$ Mev. He found a sharp decrease in the $\alpha\ p$ cross section above the $\alpha\ n$ threshold.

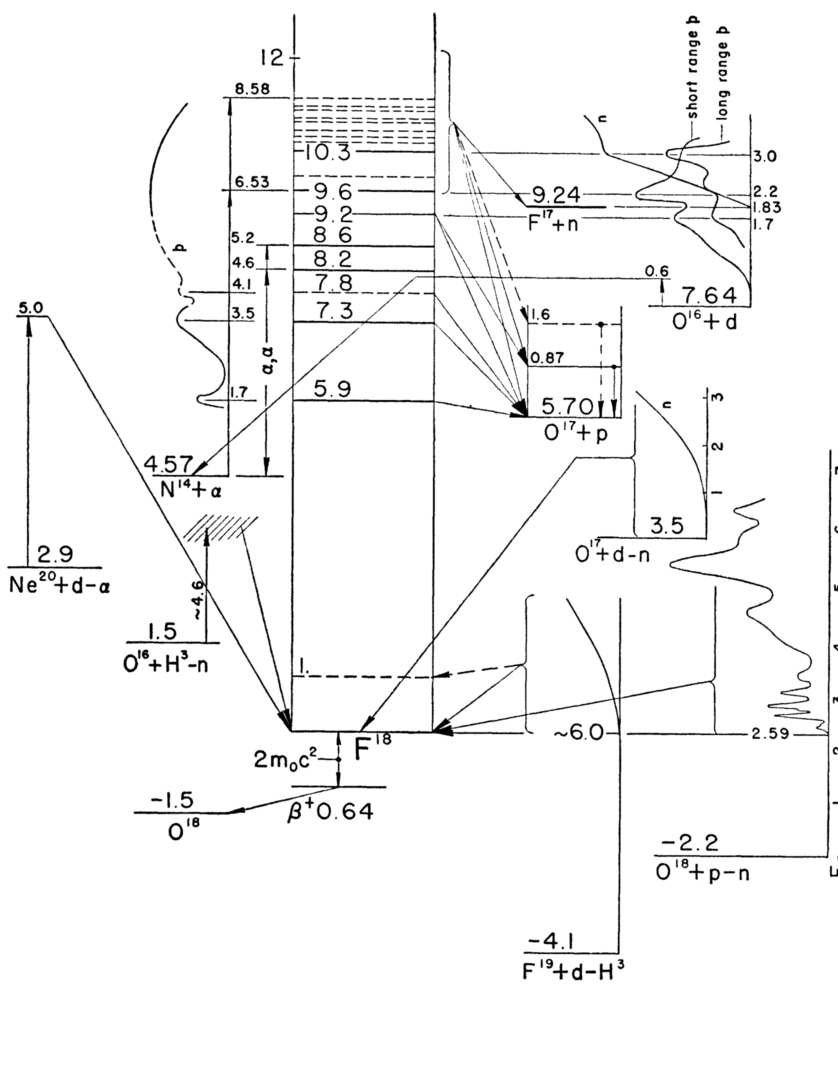

FIG. 25. Energy levels in F^{18}: for notation see Fig. 1.

Several proton groups are known; see O^{17}:$N^{14}(\alpha\ p)$.

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Ch 47b Champion and Roy, Proc. Roy. Soc. **191**, 269 (1947).
Ha 35 Haxel, Zeits. f. Physik **93**, 400 (1935).

IV. $N^{14}(\alpha\ n)F^{17}$ $Q_m=-4.7$ $E_x=4.57$

Fünfer (Fu 38) reports 11 resonances from $E_\alpha=6.53$ to $E_\alpha=8.58$ Mev using Th C' α-particles.

Fu 38 Fünfer, Ann. d. Physik **32**, 313 (1938).
See also: Ha 35, Li 37, Ri 37, Ro 44a.

V. $O^{16}(d\ \alpha)N^{14}$ $Q_m=3.07$ $E_x=7.64$

Early work of Cockcroft and Lewis (Li 37) gives a yield of 3α per 10^{10} deuterons at 0.57 Mev.

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
See also: Gu 47.

VI. $O^{16}(d\ p)O^{17}$ $Q_m=1.95$ $E_x=7.64$

Early investigations (Li 37) indicate a yield of 1 p per 10^9 d at 0.57 Mev.

An extensive survey of the angular distribution in the range $0.65<E_d<3.05$ Mev for both the long-range protons (to ground state of O^{17}) and short-range protons (to 0.87-Mev excited state in O^{17}) has been made by Heydenburg and Inglis (He 48a). The angular distribution for both groups is found to be a marked function of the bombarding voltage. Resonance yields for both groups were observed at $E_d=1.7$, 2.2, and 3.0 Mev, using slightly thick targets. [Some of the resonances reported by Fünfer (Fu 38) for the $N^{14}(\alpha\ n)$ reaction may possibly be correlated with these $d\ p$ resonances. A resonance in the $d\ p$ reaction (at $\sim$1.1 Mev) corresponding to the 5.2-Mev anomaly in the scattering of α-particles in N^{14} cannot be excluded.] Diosendruck (Di 50) reports a theoretical analysis to give spins and parities of 2^+, 1^-, and 3^+, respectively, for the resonances at 1.7, 2.2, and 3.0 Mev in the data of He 48a.

Reaction energy determinations for both proton groups as well as the observation of the accompanying γ-radiation have been made by numerous investigators, see O^{17}:$O^{16}(d\ p)$.

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
He 48a Heydenburg and Inglis, Phys. Rev. **73**, 230 (1948).
Fu 38 Fünfer, Ann. d. Physik **32**, 313 (1938).
Di 50 Diesendruck, Phys. Rev. **77**, 753 (1950).

VII. $O^{16}(d\ n)F^{17}$ $Q_m=-1.6$ $E_x=7.64$

The excitation function for this reaction has been studied from $2<E_d<5$ Mev. A discontinuity is observed in the smooth rise at $\sim$3.1 Mev, the cross section at this energy is 0.06 b (Ne 37b).

$\sigma=\sim0.2$ b, $E_d=8$ Mev (Br 49).

Ne 37b Newson, Phys. Rev. **51**, 620 (1937).
Br 49 Brown and Perez-Mendez, Phys. Rev. **75**, 1286 (1949).
See also: Ya 38.

VIII. $O^{16}(H^3\ n)F^{18}$ $Q_m=1.5$

Knight *et al.* (Kn 45) identified the production of F^{18} with pile $Li^6(n\ \alpha)$ tritons; the yield has been determined.

Kn 45 Knight, Novey, Cannon, and Turkevich, Plut. Proj. Report CC 2605 (February, 1945).

IX. $O^{16}(\alpha\ pn)F^{18}$ or $O^{16}(\alpha\ 2n)Ne^{18} \xrightarrow{\text{short}} F^{18}$ (not illustrated)

Templeton, Howland, and Perlman (Te 47) observed a 110-min. activity on bombarding PbO with 40-Mev α-particles. Chemical separation indicated F as a possibility. About one percent of the radiation penetrated 2 g/cm^2 of lead.

Te 47 Templeton, Howland, and Perlman, Phys. Rev. **72**, 758 (1947).

X. $O^{17}(d\ n)F^{18}$ $Q_m=3.5$

See F^{19}:$O^{17}(d\ n)$.

XI. $O^{18}(p\ n)F^{18}$ $Q_m=-2.2$

Threshold determinations give: $E_{\text{thr}}=2.56\pm0.04$ Mev (Du 38); $E_{\text{thr}}=2.592\pm0.003$ Mev [using $Li^7(p\ n)$ threshold as 1.882 Mev] (Ri 50).

Du 38 DuBridge, Barnes, Buck, and Strain, Phys. Rev. **53**, 447 (1938).
Ri 50 Richards and Smith, Phys. Rev. **77**, 752 (1950).

XII. $F^{19}(\gamma\ n)F^{18}$ $Q_m=-10.2$; XIII. $F^{19}(n\ 2n)F^{18}$ $Q_m=-10.2$ (not illustrated)

See corresponding compound nuclei.

XIV. $F^{19}(d\ H^3)F^{18}$ $Q_m=-4.1$

Threshold determinations give: $E_{\text{thr}}\sim6.0$ (Kr 41); $E_{\text{thr}}=6.6\pm0.2$ (Bo 42).

A triton group indicating a level in F^{18} at $\sim$1.0 Mev is reported (Boyer, private communication).

Kr 41 Krishnan, Nature **148**, 407 (1941).
Bo 42 Borst, Phys. Rev. **61**, 106 (1942).

XV. $Ne^{20}(d\ \alpha)F^{18}$ $Q_m=2.9$

Snell (Sn 37) observed the production of the 112-sec. F^{18} at $E_d=5$ Mev; chemical identification was made.

Sn 37 Snell, Phys. Rev. **51**, 143 (1937).

XVI. $Na^{23}(\gamma\ \alpha n)F^{18}$? $Q_m=-21.5$ (not illustrated)

Baldwin and Klaiber (Ba 46d) observed a weak 2.2-hr. activity from the irradiation of NaOH with 100-Mev γ-rays. They suggest Na^{23} $(\gamma\ \alpha n)$ as the possible reaction.

Ba 46d Baldwin and Klaiber, Phys. Rev. **70**, 259 (1946).

F^{18} Theory

Beta$^{(+)}$-active. Shell: $O^{16}+2s_{\frac{1}{2}}{}^1$ (proton) $+2s_{\frac{1}{2}}{}^1$ (neutron). Expected state like the deuteron, $^3S_1$, even.

The allowed β-transition to the even-even O^{18} would tend to confirm the assignment for the ground state, $I=1$, even. The value of ft is 4100 sec. The assignments made for the states between 5 and 8 Mev from a detailed application of the dispersion theory both for energy and angular dependence are tentative (Di 50).

Di 50 Diesendruck, Phys. Rev. **77**, 753 (1950).

O^{19}

(not illustrated)

[Mass: $F^{19}+4.6$ mmu (4.3 Mev) = 19.0091 amu]

I. $O^{19}(\beta^-)F^{19}$ $Q_m=4.3$*

The β-decay is complex, see F^{19}.

The half-life determinations are: 27.0±0.5 sec. (Bl 47a), 29.4 sec. (Fu 44a), 29.5 sec. (Hu 46).

Bl 47a Bleuler and Zunti, Helv. Phys. Acta **20**, 195 (1947).
Fu 44a Fulbright *et al.*, Plut. Proj. Report CP-1357 (February, 1944).
Hu 46 Hughes and Wallace, private communication to Seaborg and Perlman (1946).
See also: Na 37a, Hu 45a, Se 46.

II. $O^{18}(n\ \gamma)O^{19}$ $Q_m=-4.4$

$\sigma_{\text{th}-n}=2.2\times10^{-4}$ b (Se 46, Se 47).

Se 46 Seren, Moyer, and Strum, Phys. Rev. **70**, 561 (1946).
Se 47 Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947).
See also: Ma 43a.

III. $F^{19}(n\ p)O^{19}$ $Q_m=-3.6$

The Q determination of Scherrer, Huber, and Rossel (Sc 41) is in error; see Bl 47c.

$Q=-3.9\pm0.75$ Mev (Je 50d).

Sc 41 Scherrer, Huber, and Rossel, Helv. Phys. Acta **14**, 618 (1941).
Bl 47c Bleuler and Rossel, Helv. Phys. Acta **20**, 445 (1947).
Je 50d Jelley and Paul, Proc. Phys. Soc. London **63**, 112 (1950).

F^{19}

(Mass: 19.00450)

I. $O^{16}(H^3\ n)F^{18}$ $Q_m=1.5$ $E_x=11.66$

See F^{18}: $O^{16}(H^3\ n)$.

II. $O^{17}(d\ 2p)N^{17}$ $Q_m=-10.2$ $E_x=13.70$

Not illustrated, see N^{17} d-spallation.

III. $O^{17}(d\ n)F^{18}$ $Q_m=3.5$ $E_x=13.70$

Yasaki and Watanabe (Ya 38) detected the production of F^{18} resulting from the bombardment of oxygen with 2-Mev deuterons. Davidson (Da 40) found the production of F^{18} to be a smoothly rising function characteristic of $d\ n$ reactions. Cross sections of 0.077 and 0.060 b at $E_d=3.45$ and 3.25 Mev, respectively, are reported.

Welles (We 46) using oxygen targets enriched in O^{17} has definitely established the reaction responsible for the F^{18} activity to be the $d\ n$ rather than the $O^{16}(d\ \gamma)$ reaction.

Ya 38 Yasaki and Watanabe, Nature **141**, 787 (1938).
Da 40 Davidson, Phys. Rev. **57**, 1086 (1940).
We 46 Welles, Phys. Rev. **69**, 586 (1946).
See also: We 41.

* From this reaction.

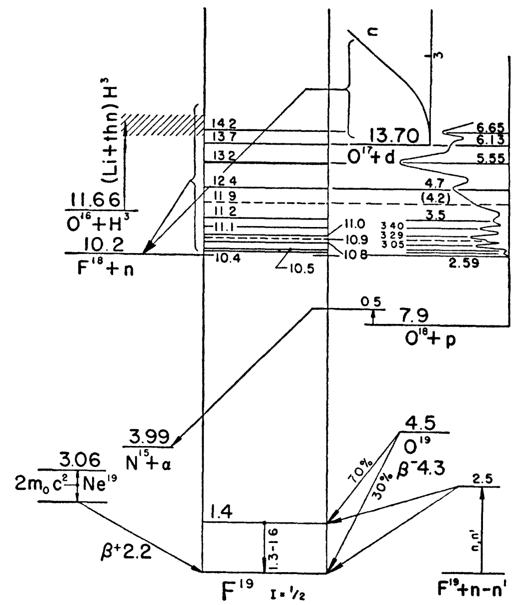

FIG. 26. Energy levels in F^{19}: for notation see Fig. 1. A level at 8.6 Mev is reported. See text.

IV. $O^{18}(p\ \alpha)N^{15}$ $Q_m=3.9$ $E_x=7.9$

Note added in proof: Mileikowsky and Pauli, Nature **166**, 602 (1950) report a resonance in the thin target yield at 680 kev.

See N^{15}.

V. $O^{18}(p\ n)F^{18}$ $Q_m=-2.2$ $E_x=7.9$

The excitation function has been studied by a number of investigators, see Table LV.

Du 38 DuBridge, Barnes, Buck, and Strain, Phys. Rev. **53**, 447 (1938).
Br 50b Browne, Smith, and Richards, Phys. Rev. **77**, 754 (1950).
Bl 49b Blaser *et al.*, Helv. Phys. Acta **22**, 598 (1949).

VI. $O^{19}(\beta^-)F^{19}$ $Q_m=4.3$*

Bleuler and Zunti (Bl 47a) using $\beta-\gamma$-coincidence and β-absorption techniques find the decay spectrum

TABLE LV.

A		B	C		
E_R (Mev)	σ_R (mb)	E_R (Mev)	E_R (Mev)	σ_R (mb)	F^{19*} (Mev)
		2.68			10.4
		2.78			10.5
		3.05			10.8
		(3.2)			(10.9)
		3.29			11.0
		3.40			11.1
3.55	75.	3.50	3.5	~90.	11.2
			(4.2)	(180.)	(11.9)
			4.7	310.	12.4
			5.55	570.	13.2
			6.13	390.	13.7
			6.65	430.	14.2

A: Du 38.
B: Thin target, forward neutrons (Br 50b, and Richards, private communication).
C: Bl 49b.

* From this reaction.

to be complex, 30±10 percent decaying to the ground state of F^{19}, $E_{\beta max}=4.5\pm0.3$ Mev; and 70±10 percent to an excited state in F^{19} at 1.6 Mev, $E_{\beta max}=2.9\pm0.3$ Mev. The work of Fulbright *et al.* (Fu 44a) verifies this conclusion with a reported visual absorption end point of 4.1 Mev and the observation of γ-radiation with $\mu_{Pb}=0.56$ cm^{-1} and $\mu_{Cu}=0.40$ cm^{-1} giving $E_\gamma=1.6$ Mev.

Bl 47a Bleuler and Zunti, Helv. Phys. Acta **20**, 195 (1947).
Fu 44a Fulbright *et al.*, Plut. Proj. Report CP-1357 (February, 1944).

VII. (*a*) $F^{19}(\gamma\ n)F^{18}$ $Q_m=-10.2$ (*b*) $F^{19}(\gamma\ 2n)F^{17}$ $Q_m=-19.5$ (not illustrated)

(*a*) A cross section 1/40 of the $Cu^{63}(\gamma\ n)$ cross section is reported, giving $\sigma=3$ mb at $E_\gamma=17.5$ Mev (Wa 48b). A yield 2.8 and 2.7 times that for $N^{14}(\gamma\ n)$ at $E_\gamma=50$ and 100 Mev respectively, is observed (Pe 48b).

(*b*) The production of F^{17} with a 100-Mev betatron is reported (Ba 46d, Pe 48b).

Wa 48b Wäffler and Hirzel, Helv. Phys. Acta **21**, 200 (1948).
Pe 48b Perlman and Friedlander, Phys. Rev. **74**, 442 (1948).
Ba 46d Baldwin and Klaiber, Phys. Rev. **70**, 259 (1946).
See also: Bo 37, Bo 39c, Hu 42, Hu 43, Pe 47, Je 50b.

VIII. $F^{19}(n\ n')F^{19*}$

An inelastic scattering cross section of 0.62±0.1 b at $E_n=2.5$ Mev is reported. Absorption measurement of the accompanying γ-ray gave an energy of 1.3±0.1 Mev (Be 50a).

(For elastic scattering see F^{20}.)

Be 50a Beghian *et al.*, Phys. Rev. **77**, 286 (1950).

IX. $Ne^{19}(\beta^+)F^{19}$ $Q_m=2.06+1.02=3.08$

No transitions other than to the ground state are observed; see Ne^{19}.

F^{19} Theory

$\mu=2.628$; $I=\frac{1}{2}$. Shell: $O^{16}+2s_{\frac{1}{2}}{}^2$ (neutrons) $+2s_{\frac{1}{2}}{}^1$ (proton). Ground state like that of a closed-shell Ne^{20} core, with a missing proton, therefore $^2S_{\frac{1}{2}}$, even. The magnetic moment is nearly that of an odd proton in an S state, confirming such a model. The scarcity of low lying states is not what one would expect in general from the model. The first excited state seems to be like the ground state. The β-decay of O^{29} feeds these two states, favoring the excited state by a factor of about two, too small to represent a real forbiddedness in either mode of decay; ft values being 3.0×10^5 (ground state) and 1.8×10^4 (excited state).

Ne^{19}

(not illustrated)

(Mass: 19.00781)

I. $Ne^{19}(\beta^+)F^{19}$ $Q_m=2.06+1.02=3.08$

White, Delsasso, Fox, and Creutz (Wh 39) report $E_{\beta^+ max}=2.20$ Mev using a cloud chamber and 2.3 from absorption measurements. They observe $T_{\frac{1}{2}}=20.3\pm0.5$ sec. Bleuler and Zunti (Bl 46) using an absorption technique give 2.2±0.1 Mev as the end point.

Wh 39 White, Delsasso, Fox, and Creutz, Phys. Rev. **56**, 512 (1939).
Bl 46 Bleuler and Zunti, Helv. Phys. Acta **19**, 375 (1946).

II. $O^{16}(\alpha\ n)Ne^{19}$ $Q_m=-11.96$

This reaction has not been observed.

III. $F^{19}(p\ n)Ne^{19}$ $Q_m=-3.84$

White *et al.* (Wh 39) have observed the production of Ne^{19} with 6-Mev protons. A rough excitation function indicates a threshold within ±0.25 Mev of the expected value, which they give as 4.18 Mev.

Wh 39 White, Delsasso, Fox, and Creutz, Phys. Rev. **56**, 512 (1939).

Ne^{19} Theory

Beta$^{(+)}$-active. Shell: $O^{16}+2s_{\frac{1}{2}}{}^2$ (protons) $+2s_{\frac{1}{2}}{}^1$ (neutron). Expected state like the mirror, F^{19}, $^2S_{\frac{1}{2}}$, even.

The decay is allowed to the ground state of F^{19}, with an ft value of 2000 sec., three times that of the most favorable transition of this class, $^2S_{\frac{1}{2}}\rightarrow{}^2S_{\frac{1}{2}}$. Presumably the ground states of the nuclei with $A=19$ are not very pure $^2S_{\frac{1}{2}}$ states, or else differ considerably in radial distribution.

F^{20}

[Mass: $F^{19}+d-p-4.6$ mmu (4.3 Mev) = 20.0065 amu]

I. $F^{20}(\beta^-)Ne^{20}$ $Q_m=7.2$

Decay is complex, see Ne^{20}.

$T_{\frac{1}{2}}=12.4$ sec. (Bu 38); $T_{\frac{1}{2}}=10.7\pm0.2$ sec. (Sn 50).

Bu 38 Burcham and Smith, Proc. Roy. Soc. **168**, 176 (1938).
Sn 50 Snowdon, Phys. Rev. **78**, 299 (1950).

II. $O^{18}(d\ 2pn)N^{17}$ $Q_m=-18.1$ (not illustrated)

See N^{17}, d-spallation.

III. $F^{19}(n\ 3p6n)C^{11}$ $Q_m=-74.0$ $E_x=6.5$
$F^{19}(n\ 2p5n)N^{13}$ $Q_m=-53.4$
$F^{19}(n\ p4n)O^{15}$ $Q_m=-35.6$
$F^{19}(n\ 3n)F^{17}$ $Q_m=-19.5$
(not illustrated)

These reactions were observed at $E_n=90$ Mev (Kn 47); see also F^{20}: $F^{19}(n\ 2n)$.

Kn 47 Knox, Phys. Rev. **72**, 1254 (1947).

IV. (*a*) $F^{19}(n\ \alpha)N^{16}$ $Q_m=-1.2$ $E_x=6.5$
(*b*) $F^{19}(n\ p)O^{19}$ $Q_m=-3.6$ $E_x=6.5$

(*a*) Wilhelmy (Wi 37e) using Rn-Be neutrons reports peaks for $(E_\alpha+E_n)=3.1$ and 3.6 Mev, indicating levels in F^{20} at 10.6 and 11.1 Mev. [Another possibility is the excitation of only one level at 11.1 Mev, the lower energy $(\alpha+n)$ peak corresponding to an excited state in N^{16} at $3.6-3.1=0.5$ Mev (0.3-Mev level).]

TABLE LVI.

E_n		σ (mb)[a] $n\ \alpha$	$n\ p$
Li+d	E=10−16 Mev	126.4	78.1
B+d	~10 Mev	56.4	35.6
Be+d	~4 Mev	82.6	14.5
H^2+d	3.8 Mev	36.8	6.0

[a] Je 50d.

Reaction energies for the ground state transitions are: $Q_0=-0.73\pm0.25$ Mev (Bl 47c); $Q_0=-1.2\pm0.9$ Mev (Je 50d).

A shorter range α-particle group has also been observed, see N^{16}: $F^{19}(n\ \alpha)$.

Chemical identification of the N^{16} has been reported (Po 37b).

(b) For this reaction see also O^{19}: $F^{19}(n\ p)$.

Cross-section determinations for these two reactions are given in Table LVI.

Wi 37e Wilhelmy, Zeits. f. Physik **107**, 769 (1937).
Bl 47c Bleuler and Rossel, Helv. Phys. Acta **20**, 445 (1947).
Je 50d Jelley and Paul, Proc. Phys. Soc. London **63**, 112 (1950).
Po 37b Polessetsky, Physik. Zeits. Sowjetunion **12**, 339 (1937).
See also: Li 37, Na 37a, Sc 41.

V. $F^{19}(n\ 2n)F^{18}$ $Q_m=-10.2$ $E_x=6.5$ (not illustrated)

The production of 112-min. F^{18} by the $n\ 2n$ reaction at various neutron energies has been observed by numerous investigators and the relative yield has been compared with other $n\ 2n$ reactions. Chemical identification has also been made.

See: Po 37, Je 44, Kn 47, Kn 48a, Ho 48a, Co 49c, Je 50b.

VI. $F^{19}(n\ n)F^{19}$ $E_x=6.5$

Transmission experiments indicate numerous resonances (Bockelman, private communication) as shown in Table LVII.

For inelastic scattering see F^{19}: $F^{19}(n\ n)$.

VII. $F^{19}(n\ \gamma)F^{20}$ $Q_m=6.5$

Bjerge and Westcott (Bj 34) determined the relative yield of F^{20} to be (100), 10, 1, $\frac{1}{2}$ at E_n=Rn-Be, Li+d, Be+d, d+d, respectively. Manley, Haworth, and Luebke (Ma 41) give $\sigma=0.01$ b for d+d neutrons. The cross section for thermal neutrons has been determined to be 9.4 mb (Se 47).

TABLE LVII.

E_R (kev)	E_{level} (Mev)	Γ (kev)	σ_R (b)	$I(F^{20})$	Wave
30.	~6.5+0.03	~15	5.2		
50.	+0.05	~10	9.5		
105.	+0.10	15	17.2	1	S
275.	+0.26	30	10.0		
350.	+0.33	Broad ~200	8.0		
420.	+0.40	25	8.8		
510.	+0.49	35	5.7		
600.	+0.57	30	6.0		

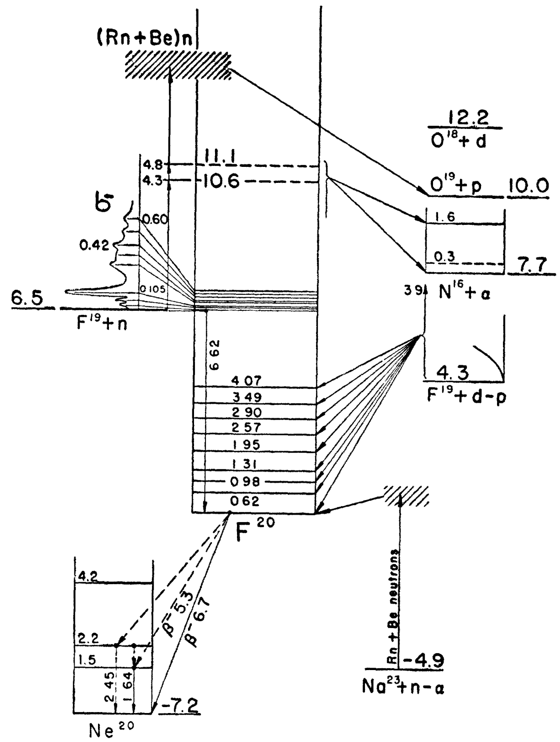

FIG. 27. Energy levels in F^{20}: for notation see Fig. 1.

The scattering of low energy neutrons by F^{19} is discussed by Rainwater *et al.* (Ra 48) who also cite numerous references. It is suggested that there might be a broad resonance between E_n=130 to 220 kev. The $n\ \gamma$ absorption cross section has since been measured (Henkel and Barschall, private communication), showing two resonances at 275 and 420 kev Γ~30 kev, σ_R~2 mb, for both).

The energy of the capture γ-ray with thermal neutrons has been measured as 6.63±0.03 Mev (Ki 50a).

Bj 34 Bjerge and Westcott, Nature **134**, 177 (1934).
Se 47 Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947).
Ra 48 Rainwater, Havens, Dunning, and Wu, Phys. Rev. **73**, 733 (1948).

TABLE LVIII.

Q (Mev) A	B	Relative yield (A)	E_{level} (Mev)
4.3	4.29±0.08	0.21	Gnd.
3.6	3.65	1.00	0.64
3.3	3.31	0.56	0.98
2.95	2.98	0.27	1.31
2.4	2.34	1.35	1.95
	1.72		2.57
	1.39		2.90
	0.80		3.49
	0.22		4.07

A: E_d=0.8 Mev (Bo 39d).
B: E_d=3.9 Mev (Al 50d).

Ki 50a Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950).
See also: Am 35, Na 37a, Ma 41, On 41.

VIII. $F^{19}(d\ p)F^{20}$ $Q_m=4.3$*

Numerous proton groups have been reported, see Table LVIII.

The best value for the ground state transition is 4.373 ± 0.007 Mev (Strait *et al.*, private communication).

The excitation function is known; see Ne^{21}: $F^{19}(d\ p)$.

Bo 39d Bower and Burcham, Proc. Roy. Soc. **173**, 379 (1939).
Al 50d Allen and Rall, Phys. Rev. **78**, 337 (1950).
See also: Li 37, Bu 38, Cu 40b.

IX. $Na^{23}(n\ \alpha)F^{20}$ $Q_m=-4.9$

$Q_0=-5.4\pm0.3$ (Je 50d).

The relative yield for various energy fast neutrons is known (Je 50d).

Je 50d Jelley and Paul, Proc. Phys. Soc. London **63**, 112 (1950).
See also: Na 37a.

F^{20} Theory

Beta$^{(-)}$-active. Shell: $O^{16}+2s_{\frac{1}{2}}{}^1$ (proton) $+2s_{\frac{1}{2}}{}^2$ (neutrons) $+1d_{\frac{5}{2}}{}^1$ (neutron)? Hard to estimate ground state expected; even on $j-j$ coupling model, level order is uncertain.

Unfortunately, the exact mode of β-decay is not certain at the present time, but that decay to the ground state is forbidden seems clear.

The many excited states, about which not much is known, are to be expected; both proton and neutron shells are incomplete.

Ne^{20}

(Mass: 19.998 77)

I. $O^{16}(\alpha\ \alpha)O^{16}$ $E_x=4.78$

Scattering anomalies indicate levels at 9.0 and 10.1 Mev (Fe 40).

Fe 40 Ferguson and Walker, Phys. Rev. **58**, 666 (1940).
See also: Br 38a, De 39a.

II. $F^{19}(p\ n)Ne^{19}$ $Q_m=-3.84$ $E_x=12.90$

Threshold = 4.2 Mev (Cr 39a).

Cr 39a Creutz, White, Delsasso, and Fox, Phys. Rev. **56**, 207 (1939).

III. $F^{19}(p\ \gamma)Ne^{20}$ $Q_m=12.90$

A resonance for capture radiation occurs at $E_p=669$ kev with a yield of (2.2 ± 0.8) percent of the 6- to 7-Mev radiation from $F^{19}(p\ \alpha)$. The angular distribution is isotropic within 10 percent. No other resonances appear <1 Mev (De 48c). At $E_p=2.6$ Mev (thick target) the 13- to 14-Mev radiation is <0.2 percent of the 6/7-Mev radiation (Go 50, and Goldhaber, private communication).

Note added in proof: Rae *et al.*, Proc. Phys. Soc. London **63**, 775 (1950) gives 12.0 ± 0.2 Mev for the γ-ray energy ($E_p=0.7$ Mev) and concludes that the transition goes to the 1.5 Mev state rather than the ground state.

Wilkinson (private communication) gives $E_\gamma=12.09\pm0.2_8$ ($E_p=669$ kev) and a relative intensity of 1.7 percent of the 6/7 Mev radiation compared to a relative intensity of 2 percent obtained by Rae *et al.*

De 48c Devons and Hereward, Nature **162**, 331 (1948).
Go 50 Goldhaber, Phys. Rev. **77**, 753 (1950).

IV. $F^{19}(p,\ \alpha n)O^{15}$? $Q_m=-7.5$ (not illustrated)

This reaction is reported by (Sh 49).

Sh 49 Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).

V. $F^{19}(p\ \alpha)O^{16}$ $Q_m=8.12$ $E_x=12.90$

Five α-particle groups result from this reaction: all show resonance effects, with relative intensities varying greatly with bombarding energy. The long-range ($\sim$5.9 cm) group leaves O^{16} in the ground state; the next longest ($\sim$2 cm) results in the formation of a pair-emitting state at 6.05 Mev (see O^{16}) while the three remaining groups result in γ-radiation at 6.13, 6.9, and 7.1 Mev, respectively. Chao *et al.* (Ch 50), have tabulated resonances and absolute yields for $E_p=0-1.5$ Mev.

Thick target γ-ray yields for higher energies (Ha 41):

E_p (Mev)	1.0	1.5	2.0	2.9	3.0	3.2	3.4
Rel. yield	1.0	3.4	10.5	52	55	63	70

At $E_p=2.6$ Mev (thick target), the 7-Mev component is 3.2 ± 0.2 times as intense as the 6-Mev line, as determined in a deuterium-loaded plate ($\theta=0°$), not cor-

TABLE LIX. Gamma-ray resonances.[a]

E_p (Mev)	Relative intensities of the three components 6.13	6.9	7.1	Yield[d] $\times10^7$	Width (kev)
0.222				0.0002	<2
0.3404[b]	0.96	0.04		0.174[e]	1.7
0.486 }	~0.8 }	~0.2		0.054	<2
0.598 }				0.27	37
0.669	0.75	<0.06	0.19	0.48	7.5
0.831				0.2	8.3
0.8735[b]	0.65	0.24	0.11	3.7	5.2
0.900	>0.95	<0.05		0.15	4.8
0.9353	0.76	0.025	0.21	2.0	8.0
1.092				0.024	<1.2
1.137				0.1	3.7
1.176				3.9	~130
1.290	0.74	0.075	0.18	0.92	19.2
1.355	0.53	0.12	0.35	1.37	8.6
1.381	0.87	0.08	0.05	8.2	15.0
1.69[c]					
1.94[c]					
2.03[c]					

[a] From Ch 50; data of Ch 50, Bo 48c, Wa 48, Ta 46.
[b] The values of these two resonances (Mo 49a, He 49) serve as calibration points for high voltage scales, see also Be^7: $Li^7(p\ n)$.
[c] Be 38 and Perry and Day, private communication.
[d] Thick CaF_2 target: number of quanta per proton; measured α-particle yields at $\theta=138°$ average 0.92 of these values; see Ch 50.
[e] Yield of short-range α-particles $=0.153$ (Ch 50), $0.14_8\pm0.01$ (Va 41) per 10^7 protons.

* From this reaction.

TABLE LX. Pair resonances.[a]

E_p (Mev)	Yield $\times 10^{7d}$	Width (kev)
0.843	0.048	30
1.115	0.089	60
1.236	0.31	75
1.380	0.39	25
(1.40)[b]	0.85	
1.63[c]		
1.73[c]		
1.87[c]		
2.20[c]		

[a] From Ch 50; data of Ch 50, Be 46a, Ra 50.
[b] Non-resonant: see Ch 50.
[c] Perry and Day, preliminary results.
[d] Thick CaF_2 target: number of pairs per proton.

rected for variation of the photo-disintegration cross section; the upper line has an energy of 7.1±0.1 Mev (Go 50 and Goldhaber, private communication). The ratio $Y(7)/Y(6)=1.7\pm0.4=4$ Mev (Ph 49c).

Note added in proof: Devons, Hine, and Lindsay find resonances at $E_p=0.71$, 0.79, and 0.84 Mev for pairs and long range α-particles (Harwell Conference, 1950).

TABLE LXI. Long-range α-particle resonances.[a]

E_p (Mev)	Yield $\times 10^{7c}$	Width (kev)
0.72	~0.006	35
0.78	~0.002	~10
0.84	0.006	30
~1.1	0.06	~60
1.38	0.14	~25
(1.40)[b]	0.5	

[a] From Ch 50; data of Ch 50, St 41, and Fowler and Schardt, private communication.
[b] Non-resonant: see Ch 50.
[c] Thick CaF_2 target yield per proton at $\theta=90°$.

Ch 50 Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).
Bo 48c Bonner and Evans, Phys. Rev. **73**, 666 (1948).
Wa 48 Walker and McDaniel, Phys. Rev. **74**, 315 (1948).
Ta 46 Tangen, Kgl. Nord. Vid. Selsk. Skr. No. 1 (1946).
Va 41 Van Allen and Smith, Phys. Rev. **59**, 501 (1941).

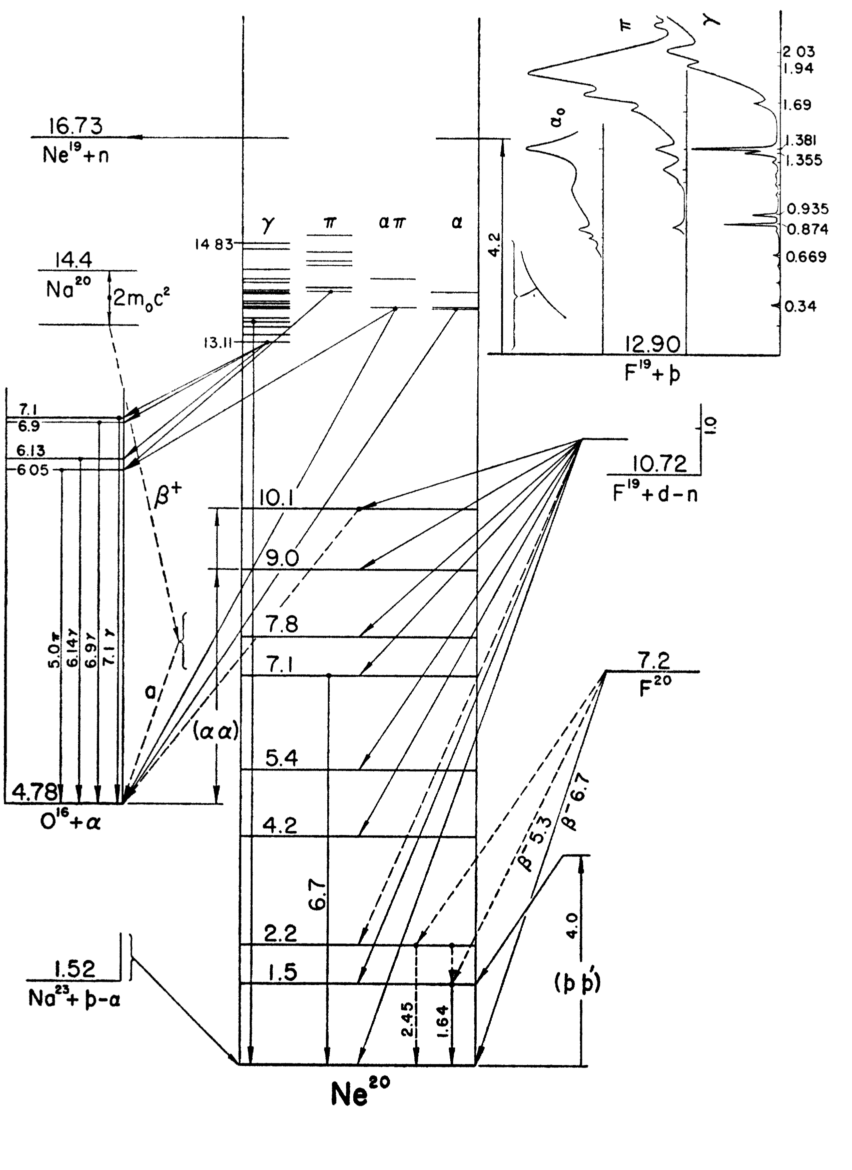

FIG. 28. Energy levels in Ne^{20}: for notation see Fig. 1. (*a*) delayed α-particles from $Na^{20}(\beta^+)$. The capture proton γ-radiation is to the 1.5 Mev state rather than the ground state as shown.

Be 38 Bernet, Herb, and Parkinson, Phys. Rev. **54**, 398 (1938).
Mo 49a Morrish, Phys. Rev. **76**, 1651 (1949).
He 49 Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).
Ha 41 Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **59**, 57 (1941).
Go 48d Goldhaber, Phys. Rev. **74**, 1725 (1948).
Ph 49c Phillips and Kruger, Phys. Rev. **76**, 1471 (1949).
Be 46a Bennett, Bonner, Mandeville, and Watt, Phys. Rev. **70**, 882 (1946).
Ra 50 Rasmussen, Hornyak, Lauritsen, and Lauritsen, Phys. Rev. **77**, 617 (1950).
St 41 Streib, Fowler, and Lauritsen, Phys. Rev. **59**, 253 (1941).
See also: Bo 37e, Ge 37a, Bu 39, Cu 39a, Ka 40, Be 41c, La 41, Be 42, Ha 44, Sc 46, Fo 48, Fo 48b, Fo 49b, Bu 49a, De 49d, Ar 50, Ba 50f, Ch 50a, Da 50.

VI. $F^{19}(d\ n)Ne^{20}$ $Q_m=10.72$

Neutron groups are observed corresponding to levels of Ne^{20} at 1.5, 2.2, 4.2, 5.4, 7.1, 7.8, 9.0, and 10.1 Mev (Bo 40b, Po 42). The level at 10.1 may decay by α-emission (Bo 40b). Gamma-radiation of energy 6.7 ± 0.3 Mev, in addition to softer components is observed (Be 41c).

Note added in proof: French *et al.*, Proc. Phys. Soc. London **63**, 666 (1950), have identified α-particles from a level at 9.7 Mev in Ne^{20}.

Phillips and Terrell (private communication) report γ-ray lines at 11.7, 9.4, and 8 Mev.

Bo 40b Bonner, Proc. Roy. Soc. **174**, 339 (1940).
Po 42 Powell, Proc. Roy. Soc. **181**, 344 (1942).
Be 41c Bennett, Bonner, and Watt, Phys. Rev. **59**, 793 (1941).
See also: Bu 38, Po 40a.

VII. $F^{20}(\beta^-)Ne^{20}$ $Q_m=7.2$

Approximately 3.5 percent of transitions occur directly to the ground state: $E_{\beta(\max)}=6.74\pm0.1$ Mev (Littauer, private communication). The more intense β-particle group has a limit of 5.33 ± 0.03 Mev (Littauer), 5.03 ± 0.05 Mev (Je 50a), and is accompanied by a γ-ray of energy 1.63 ± 0.02 Mev (Littauer), 1.64 ± 0.05 Mev (Je 50a). The best value for the total energy release is 6.96 ± 0.06 Mev. A second γ-ray exists, of energy 2.45 ± 0.06 Mev and relative intensity $\frac{1}{8}$ (Je 50a), but there is some doubt of its assignment to F^{20} (Littauer). The absence of $\gamma-\gamma$-coincidences indicates that not more than two percent of the disintegrations result in cascade γ-rays (Littauer).

Je 50a Jelley, Proc. Phys. Soc. **63**, 538 (1950).
See also: Fo 36, Bu 38, Be 39a, Bo 39d, Cu 40b, At 43, Sn 50.

VIII. $Ne^{20}(p\ p')Ne^{20*}$

Inelastic scattering of 4-Mev protons indicates a level in Ne^{20} at 1.4 Mev (Po 40c).

Po 40c Powell, May, Chadwick, and Pickavance, Nature **145**, 893 (1940).
See also: He 47.

IX. $Na^{20}(\beta^+)Ne^{20}$ $Q=13.4+1.02=14.4$*

Half-life $\sim\frac{1}{4}$ sec. Delayed α-particles, corresponding to decay into $O^{16}+\alpha$, are observed. The threshold for $Ne^{20}(p\ n)Na^{20}$ is $\sim$16 Mev (Alvarez, private communication).

* Q from $p\ n$ threshold.

X. $Na^{23}(p\ \alpha)Ne^{20}$ $Q_m=1.52$

$Q=2.35\pm0.04$ Mev from α-particle range (Fr 48c, Fr 50c).

Fr 48c Freeman and Baxter, Nature **162**, 696 (1948).
Fr 50c Freeman, Proc. Phys. Soc. London **63**, 668 (1950).

Ne^{20} Theory

Spherically symmetric, $I=0$. Shell: $O^{16}+2s_{\frac{1}{2}}^2$ (protons) $+2s_{\frac{1}{2}}^2$ (neutrons). Closes the 2*s* shell, and expected state therefore $^1S_0$, even.

With the Ne^{20} states above 13 Mev the real complexity of nuclear energy levels is made clear for the first time; the many beautiful experiments with the $F^{19}(p, \alpha,$ and $\gamma)$ served to show this feature in its full interest. The ground state is of closed-shell type, like O^{16} or the α-particle. But by now it is not so costly in energy to excite the closed shell. The two lowest lying excited states must be different in character from each other and from the ground state, judging by the behavior observed for β-decay and proton re-emission. The strong capture γ-ray from the proton resonance for 669-kev protons on fluorine is essentially isotropic, and therefore probably formed with *s* wave protons. Since the state does not decay by α-emission to the ground state of O^{16} one can conclude that it has I odd, parity even, or even I, parity odd, recalling the $I=0$ assignment of the O^{16} ground state. This selection rule is the one chiefly exploited to correlate the decay of the approximately twenty close-lying states in this excitation region. The probably assignment for this state is then $I=1$, even, and the γ-ray is then likely a strong magnetic dipole. It is clear that any level which can disintegrate to give long-range alphas, leaving O^{16} unexcited, should also yield pairs from the 0, even, state at 6.05 Mev; where this is not experimentally verified, the situation requires detailed examination for possible unresolved levels, etc. The close-lying levels at 7 Mev in O^{16} somewhat confuse interpretation of the Ne states, especially in the earlier experiments. Much detailed discussion of the Ne levels, now a little out-of-date, appears in the literature. In particular there is a suggestion that the apparent weakness of transitions to the O^{16} ground state, even when the capture of *p* wave protons satisfies the selection rule, may be explained by invoking a tendency for separate conservation of spin and orbital momenta in the nuclear transitions. The evidence is very tentative.

Ne^{21}

(Mass: 20.99963)*

I. $O^{18}(\alpha\ n)Ne^{21}$ $Q_m=0.3$

See Ne^{22}: $O^{18}(\alpha\ n)$.

* See: $Ne^{20}(d\ p)$ reaction.

II. $F^{19}(d\ 3pn)N^{17}$ $Q_m=-26.1$ $E_x=18.24$

Not illustrated, see N^{17} *d*-spallation.

III. $F^{19}(d\ \alpha)O^{17}$ $Q_m=10.07$ $E_x=18.24$

The excitation function for this reaction up to an energy of $\sim$0.9 Mev has been observed (Bu 38). Transitions to various excited states in O^{17} are known; see O^{17}: $F^{19}(d\ \alpha)$.

Bu 38 Burcham and Smith, Proc. Roy. Soc. **168**, 176 (1938).

IV. $F^{19}(d\ H^3)F^{18}$ $Q_m=-4.1$ $E_x=18.24$

A smooth increase in the yield of F^{18} from the threshold at $\sim$6.0 Mev up to 9 Mev is observed. The cross section at 8.8 Mev is 3.9±0.4 mb (Kr 41); see also F^{18}: $F^{19}(d\ H^3)$.

Kr 41 Krishnan, Nature **148**, 407 (1941).
See also: Bo 42.

V. $F^{19}(d\ p)F^{20}$ $Q_m=4.3$ $E_x=18.24$

The cross section shows a smooth increase from 0.7 to 1.8 Mev, with $\sigma\sim$10 mb at $E_d=1$ Mev (Hu 48c, Sn 50). Several proton groups have been observed; see F^{20}: $F^{19}(d\ p)$.

Hu 48c Hudspeth and Swann, Phys. Rev. **74**, 1227 (1948).
Sn 50 Snowdon, Phys. Rev. **78**, 299 (1950).

VI. $F^{19}(d\ n)Ne^{20}$ $Q_m=10.72$ $E_x=18.24$

Hudspeth and Swann (Hu 48c) report an excitation function for γ-radiation from $F^{19}+d$, which may be from the *d n* or possibly the *d p* reaction. Transitions to various excited states in Ne^{20} are known; see Ne^{20}: $F^{19}(d\ n)$.

Hu 48c Hudspeth and Swann, Phys. Rev. **74**, 1227 (1948).

VII. $Ne^{20}(n\ \alpha)O^{17}$ $Q_m=-0.65$ $E_x=7.52$

Gailer (Ga 38), Ortner and Protiwinsky (Or 39a, Or 43) and Zagor and Valente (Za 45) have observed a preferential yield of α-particles with various (E_0+E_α) energies. (While no unique level assignments in Ne^{21} or O^{17} can be given, levels in Ne^{21} at 13.1, 13.4, and 14.1 Mev decaying to states in O^{17} at 0.87, 1.6?, 3.0, 3.8,

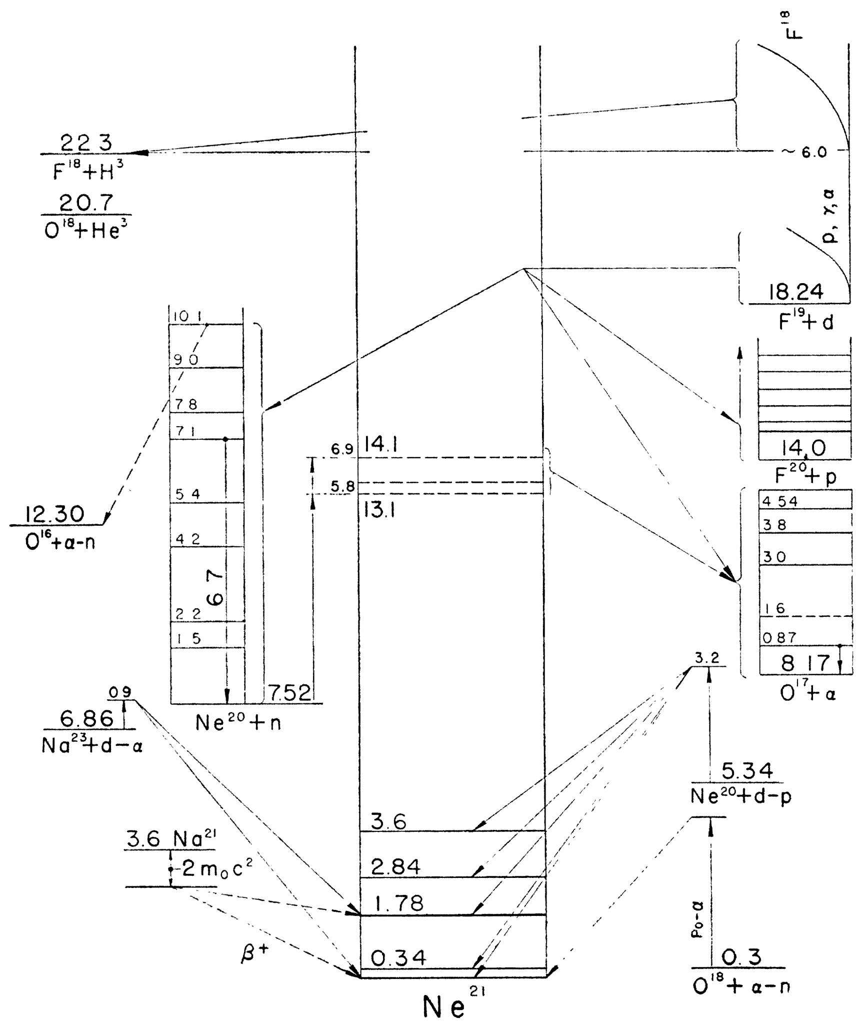

FIG. 29. Energy levels in Ne^{21}: for notation see Fig. 1. Levels at 9.86 and 10.33 Mev are reported. See text.

and 4.54 Mev can most simply account for the observed groups.)

Note added in proof: Sikkema, Nature **165**, 1016 (1950), reports resonances at $E_n=2.47$, 2.96, and possibly 3.4 Mev. At least some of the groups reported above seem to be due to these resonances.

A cross section of 5 mb for neutrons of 2.5-Mev energy is observed (Gr 46).

Ga 38 Gailer, Zeits. f. Physik **110**, 605 (1938).
Or 39a Ortner and Protiwinsky, Mitt. Inst. f. Radforschung Wien. **434** (1939).
Or 43 Ortner and Protiwinsky, Physik. Zeits. **44**, 116 (1943).
Za 45 Zagor and Valente, Phys. Rev. **67**, 133 (1945).
Gr 46 Graves and Coon, Phys. Rev. **70**, 101 (1946).
See also: Ja 35, Li 37.

VIII. $Ne^{20}(d\ p)Ne^{21}$ $Q_m=5.34$

The bombardment of both natural neon and "heavy neon" has established the proton groups given in Table LXII.

TABLE LXII.

A	Q (Mev) B	C	D	E_{level} (Mev)
4.48±0.10	4.50±0.09	4.54	4.88	Ground
4.17±0.09	4.19±0.07	4.15		0.34
2.73±0.09	2.73±0.06		3.13	1.78
1.65±0.10	1.68±0.07		2.15	2.84
0.90±0.11			1.02	3.61

A: $E_d=3.2$ (El 47). B: Zu 50a. C: Am 50. D: Po 40b.

The mean value for the ground state Q is from the above 4.51±0.07 Mev. This value is in considerable disagreement with the mass spectroscopy determination for the $Ne^{20}H^1-Ne^{21}$ doublet.

El 47 Elder, Motz, and Davidson, Phys. Rev. **71**, 917 (1947).
Zu 50a Zucker and Watson, Phys. Rev. **78**, 14 (1950).
Am 50 Ambrosen and Bisgaard, Nature **165**, 888 (1950).
Po 40b Pollard and Watson, Phys. Rev. **58**, 12 (1940).
See also: Sc 40.

IX. $Na^{21}(\beta^+?)Ne^{21}$ $Q_m=2.6+1.02=3.6$

Creutz, Fox, and Sutton (Cr 40a) produced a $T_{\frac{1}{2}}=23$ ±2-sec. activity by bombarding Ne with 6-Mev protons which they attributed to $Na^{21}[Ne^{21}(p\ n)Na^{21}]$. Bradner and Gow (Br 48b) produced $Na^{21}(T_{\frac{1}{2}}\sim 20$ sec.) by irradiating MgO with protons from the Berkeley linear accelerator $[Mg^{24}(p\ \alpha)Na^{21}]$. Pollard and Watson (Po 40b) observed delayed γ-radiation ($T_{\frac{1}{2}}=26\pm 3$ sec.) from the bombardment of Ne with 2.6-Mev deuterons $[Ne^{20}(d\ n)Na^{21}]$. It is conjectured from the absorption coefficient observed for this radiation that it consists of a mixture of annihilation radiation and a higher energy component, possibly 1.7-Mev radiation.

The β-spectrum has not been reported in the literature. A private communication from White to Stephens (St 40a) gives the end point as 3 to 4 Mev.

Cr 40a Creutz, Fox, and Sutton, Phys. Rev. **57**, 567 (1940).
Br 48b Bradner and Gow, Phys. Rev. **74**, 1559 (1948).
Po 40b Pollard and Watson, Phys. Rev. **58**, 12 (1940).
St 40a Stephens, Phys. Rev. **57**, 938 (1940).

X. $Na^{23}(d\ \alpha)Ne^{21}$ $Q_m=6.86$

Murrell and Smith (Mu 39) observed 5.0±0.1- and 2.4±0.1-cm α-particles from the bombardment of Na with 0.85-Mev deuterons. The Q values of $6.7_5\pm 0.1$ and $5.1_5\pm 0.1$ Mev indicate an excited state in Ne^{21} at 1.6 Mev. (The resolution was not adequate to observe possible structure in the long-range group.) Lawrence, McMillan, and Thornton observed 6.5±0.2-cm α-particles at a deuteron energy of 2.15 Mev giving a $Q=6.8$ ±0.2 (Li 37).

Mu 39 Murrell and Smith, Proc. Roy. Soc. **173**, 410 (1939).
Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).

Ne^{21} Theory

$I=\frac{3}{2}$ or perhaps greater. Shell: $Ne^{20}+1d_{\frac{5}{2}}^1$ (neutron). Expected state not very well-defined; perhaps $^2D_{\frac{3}{2}}$ even.

The low first excited state is interesting. The ground state I, still uncertain from the measurements, is at least $\frac{3}{2}$; perhaps the two lowest states are members of a spin doublet.

Ne^{22}

(Mass: 21.99844)

I. $O^{18}(\alpha\ n)Ne^{21}$ $Q_m=0.3$ $E_x=9.7$

Roberts (Ro 44a) has detected a thick target neutron yield of 29 n per 10^6 Po α-particles which is probably attributable to this reaction, the reaction $O^{17}(\alpha\ n)Ne^{20}$ cannot be ruled out, however.

Ro 44a Roberts, MDDC 731 (1944).

II. $F^{19}(\alpha\ p)Ne^{22}$ $Q_m=1.71$

Early investigators (Li 37) using Po and Ra C' α-particles give a Q of 1.58 Mev for the ground state transition. Proton groups corresponding to excited states in Ne^{22} at 0.60, 1.4, 3.4, and 4.5 Mev have been observed. Resonances at α-particle energies of 3.7 and 4.1 Mev were reported and γ-radiation of 1.2 Mev has been observed. The yield at 7.8 Mev is $2p$ per 10^6 α.

Saha (Sa 38) reports resonances at 3.78, 4.71, and 5.09 Mev, the first and last of which appear in the $\alpha\ n$ reaction as well; the first also occurs in the γ-ray yield.

Champion and Roy (Ch 48) verify the resonance at $E_\alpha\sim 3.7$ Mev. They find that the longest range proton group is preferentially forward at $E_\alpha\sim 3.5$ Mev, while the other groups are essentially isotropic.

Li 37 Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).
Sa 38 Saha, Zeits. f. Physik **110**, 473 (1938).
Ch 48 Champion and Roy, Phys. Rev. **74**, 5 (1948).

III. $Ne^{21}(d\ p)Ne^{22}$ $Q_m=7.25$

Two long-range proton groups are reported for isotopically enriched Ne^{21} targets, see Table LXIII.

In view of the uncertainties it is not unlikely that the level at 1.4 Mev indicated in Table LXIII is the same as the 1.28-Mev level evident in Na^{22} decay.

TABLE LXIII.

Q (Mev) A	B	E_{level} (Mev)
(Not observed)	8.34	Ground
6.79±0.10	6.95	~1.4

A: (0.75 percent Ne^{21}) E_d = 3.12 Mev (Zu 50a).
B: Am 50.

Zu 50a Zuker and Watson, Phys. Rev. **78**, 14 (1950).
Am 50 Ambrosen and Bisgaard, Nature **165**, 888 (1950).

IV. $Ne^{22}(p\,p')Ne^{22}$?

Heitler, May, and Powell (He 47) observed inelastically scattered protons in neon. In addition to the group leading to the 1.5-Mev state in Ne^{20} [see Ne^{20}: $Ne^{20}(p\,p')$] two other groups indicating excited states of ~0.9 and ~2.0 Mev in one of the stable neon nuclei were found. They suggest that these levels may be in Ne^{22}.

He 47 Heitler, May, and Powell, Proc. Roy. Soc. **190**, 180 (1947).

V. $Na^{22}(\beta^+)Ne^{22}$ $Q_m = 1.9 + 1.02 = 2.9$

Radioactive Na^{22} has been made using the reactions $F^{19}(\alpha\,n)$, $Ne^{21}(p\,\gamma)$, $Ne^{21}(d\,n)$?, $Na^{23}(n\,2n)$, and $Mg^{24}(d\,\alpha)$; see Se 48 and Ma 49a.

The decay of Na^{22} proceeds by positron emission (with no presence of K-capture) almost entirely to the 1.3-Mev excited state in Ne^{22}, the transition to the ground state apparently being highly forbidden (Fe 49b).

Various determinations of the positron spectrum end point and the γ-ray energy are given in Table LXIV.

A branching ratio $\lambda_{\beta^+}/\lambda_{\beta^+}+\lambda_K = 1.00\pm0.05$ was observed, and the $1.3\gamma-\beta^+$-coincidences were found to be equal (Go 46a). A cloud-chamber investigation revealed high energy positrons of ~1.8 Mev end point with a branching ratio of one to 26,000 (upper limit) when compared to the excited state transition (Mo 49).

The decay scheme is further verified by the $Ne^{22}(p\,n)Na^{22}$ threshold being reported to be greater than 3.35 Mev (Ri 48).

Laslett (La 49a) reports a half-life of 2.60 yr., while Saha (Sa 41) gives 2.8 yr.

Se 48 Seaborg and Perlman, Rev. Mod. Phys. **20**, 585 (1948).
Ma 49a Mattauch and Flammersfeld, Zeits. f. Naturforschung (special issue) (1949).
Fe 49b Feenberg and Hammack, Phys. Rev. **75**, 1877 (1949).
Op 39 Oppenheimer and Tomlinson, Phys. Rev. **56**, 858 (1939).
Bl 46 Bleuler and Zunti, Helv. Phys. Acta **19**, 375 (1946).

TABLE LXIV.

$E_{\beta^+ max}$ (kev)	E_γ (Mev)	Reference
550	1.3	Op 39
530±40		Bl 46
575±10	1.30 ±0.03	Go 46a
552±5	1.277±0.004	Al 49d
546±5	1.28 ±0.01	Ma 50a[a]

[a] And private communication.

Go 46a Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).
Al 49d Alburger, Phys. Rev. **76**, 435 (1949).
Ma 50a Macklin, Lidofsky, and Wu, Phys. Rev. **78**, 318 (1950).
Mo 49 Morgenstern and Wolf, Phys. Rev. **76**, 1261 (1949).
Ri 48 Richards and Smith, Phys. Rev. **74**, 1871 (1948).
La 49a Laslett, Phys. Rev. **76**, 858 (1949).
Sa 41 Saha, Trans. Bose Res. Inst (Calcutta) **14**, 57 (1939–41).
See also: La 37, Ma 41a, We 43, Bo 44, Ma 44.

Ne^{22} Theory

Spherically symmetric, I probably 0. Shell: $Ne^{20} + 1d_{\frac{5}{2}}^2$ (neutrons). Ground state: $^1S_0$, even.

The long-lived Na^{22}, with measured $I = 3$, goes almost entirely to the state at 1.27 Mev. Presumably this state has $I = 2$, with the other lower lying states all of spin 1 or 0.

Ne^{23}

(Mass: 23.0013)

I. $Ne^{23}(\beta^-)Na^{23}$ $Q_m = 4.8$

The decay is complex. The electron distribution is found to consist of two superimposed spectra, end points 4.21±0.05 (93 percent) and 1.18±0.04 Mev (7 percent). A γ-ray having the proper half-life with an energy 2.5 to 3.5 Mev has also been detected (Br 50e).

The half-life determinations are: 40.7±0.8 sec. (Hu 44), 43±3 sec. (Po 40b), 40.2±0.4 sec. (Br 50e).

Br 50e Brown and Perez-Mendez, Phys. Rev. **78**, 812 (1950).
Hu 44 Hüber *et al.*, Helv. Phys. Acta **17**, 139 (1944)
Po 40b Pollard and Watson, Phys. Rev. **58**, 12 (1940).
See also: Bl 46, Br 49.

II. $Ne^{22}(d\,p)Ne^{23}$ $Q_m = 3.5$

Several proton groups from isotopically enriched Ne^{22} targets are known, see Table LXV.

σ~0.2 b at $E_d = 8$ Mev (Br 49).

El 47 Elder, Motz, and Davidson, Phys. Rev. **71**, 917 (1947).
Zu 50a Zucker and Watson, Phys. Rev. **78**, 14 (1950).
Am 50 Ambrosen and Bisgaard, Nature **165**, 888 (1950).
Br 49 Brown and Perez-Mendez, Phys. Rev. **75**, 1286 (1949).
See also: Po 40b, Sc 40.

III. $Na^{23}(n\,p)Ne^{23}$ $Q_m = -4.0$

$Q = -3.6\pm0.8$ Mev (Je 50d).

Chemical identification has been made (Bj 37, Po 37b). The relative yield at various neutron energies has been measured (Je 50d).

TABLE LXV.

Q (Mev) A	B	C	E_{level}
2.89±0.11	2.88±0.06	2.96	Ground
1.90±0.15	1.90±0.07		1.01
1.23±0.15	1.13±0.10		1.74

A: E_d = 3.2 Mev (El 47).
B: (93 percent Ne^{22}) (Zu 50a).
C: Am 50.

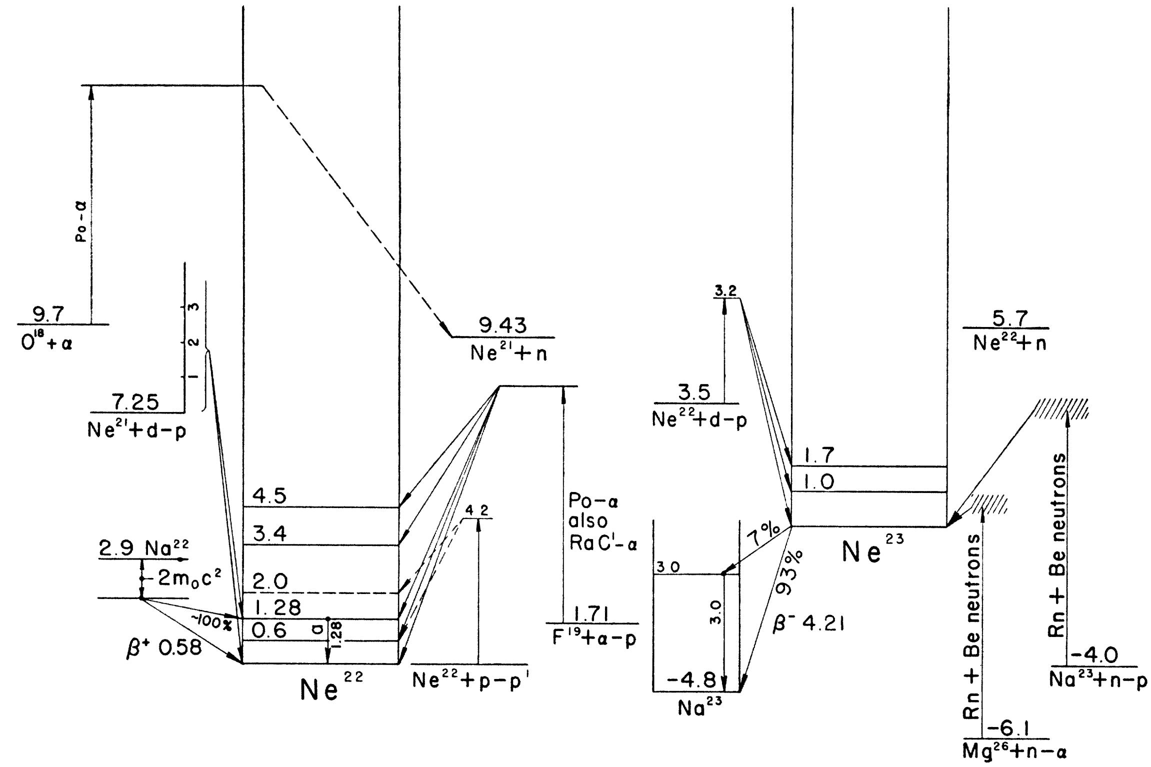

FIG. 30. Energy levels in Ne^{22} and Ne^{23}: for notation see Fig. 1. (*a*) 1.28-Mev γ-ray from $F^{19}(\alpha\ p)$ and $Na^{22}(\beta^+)$.

Je 50d Jelley and Paul, Proc. Phys. Soc. London **63**, 112 (1950).
Bj 37 Bjerge, Nature **139**, 757 (1937).
Po 37b Polessetsky, Physik. Zeits. Sowjetunion **12**, 339 (1937).
See also: Am 35, Na 37a, Hu 44.

IV. $Mg^{26}(n\ \alpha)Ne^{23}$ $Q_m = -6.1$

Amaldi *et al.* (Am 35) observed a $T_{\frac{1}{2}} = 40$-sec. activity upon irradiating MgO with Rn-Be neutrons. Slowing the neutrons with water produced no increase in yield. This reaction has been verified by Nahmias and Walen (Na 37a).

Am 35 Amaldi *et al.*, Proc. Roy. Soc. **149**, 522 (1935).
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See also: Bj 37.

Ne^{23} Theory

Beta$^{(-)}$-active. Shell: $Ne^{20} + 1d_{\frac{5}{2}}{}^3$ (neutrons).

The β-decay of this nucleus to the ground state of Na^{23}, with $I = \frac{3}{2}$, seems to be about first forbidden, or perhaps only weakened for reasons of a small nuclear matrix element. This would imply a spin of at least $\frac{5}{2}$ (a *d* shell is now filling) although the argument is not conclusive.

TABLE LXVI. Beta-decay constants.

Emitter[a]		Radiation	$T_{\frac{1}{2}}$[b]	$T_{\frac{1}{2}}/\lambda$ (sec.)	$E_{\beta\max}$ (Mev)	W_0 (m_0c^2)	λ[d]	ft[c] (sec.)
n	gnd.	β^-	~10 m	~600	0.782	2.531	1.00	~1000.
H^3	gnd.	β^-	12.4 y	3.91×10^8	0.0185	1.0362	1.00	1100.
He^6	gnd.	β^-	0.83 s	0.83	3.22	7.30	1.00	590.
Li^8	gnd.	β^-, α	0.89 s	>45.	16.0	32.3	<0.02	$>5.7\times10^7$
	2.9			0.99	12.7	25.9	~0.90	4.4×10^5
	~10				~6.		~0.05	
	~13				~3.		~0.05	
Be^7	gnd.	K	52.9 d	5.13×10^6	0.863	1.69	0.89	2300.
	0.478			4.2×10^7	0.385	0.75	0.11	3600.
Be^{10}	gnd.	β^-	2.7×10^6 y	8.5×10^{13}	0.555	2.086	1.00	7.9×10^{13}
B^8	gnd.	β^+, α	0.65 s					
	2.9			~0.65	13.7	27.8	~1.00	$\sim3.2\times10^5$
B^{12}	gnd.	β^-	0.025 s	0.026	13.43	27.29	0.95	1.4×10^4
	~7				~6		~0.03	
	~11				~2		~0.02	
C^{10}	gnd.	β^+	19.1 s					
	0.71			~19.1	2.2	5.3	~1.00	~2100.
C^{11}	gnd.	β^+	20.4 m	1220.	0.984	2.926	1.00	4300.
C^{14}	gnd.	β^-	5680 y	1.79×10^{11}	0.155	1.303	1.00	9.3×10^8
C^{15}	gnd.	β^-	2.4 s	2.4?	8.8	18.2	1.00?	1.7×10^5?
N^{12}	gnd.	β^+, α	0.0125 s	0.0125	16.6	33.5	~1.00	$\sim1.7\times10^4$
	~11				~6		?	?
N^{13}	gnd.	β^+	10.0 m	600.	1.202	3.353	1.00	4500.
N^{16}	gnd.	β^-	7.2 s	40.	10.2	21.0	0.18	6.4×10^6
	6.0π			360.	4.5	9.8	0.02	1.2×10^6
	6.13γ			18.	4.3	9.4	0.40	4.9×10^4
	(6.9–7.1)γ			18.	3.8	8.4	0.40	2.9×10^4
N^{17}	gnd.	β^-, n	4.14 s					
	5.07			~4.14	3.7	8.2	~1.00	~5600.
O^{14}	gnd.	β^+	76.5 s					
	2.3			76.5	1.8	4.5	1.00	3000.
O^{15}	gnd.	β^+	118. s	118.	1.683	4.294	1.00	3700.
O^{19}	gnd.	β^-	29 s	97.	4.4	9.6	0.30	3.0×10^5
	1.6			41.	2.8	6.5	0.70	1.8×10^4
F^{17}	gnd.	β^+	1.10 m	66.0	2.1	5.1	1.00	5400.
F^{18}	gnd.	β^+	112. m	6730.	0.635	2.243	1.00	4100.
F^{20}	gnd.	β^-	10.7 s	~310.	6.96	14.62	~0.04	$\sim8.1\times10^6$
	1.6			11.1?	5.33	11.43	0.96?	8.6×10^4?
	2.4			?	(4.2)?	(9.2)?	?	?
Ne^{19}	gnd.	β^+	20.3 s	20.3	2.20	5.31	1.00	2000.
Ne^{23}	gnd.	β^-	40.4 s	43.4	4.21	9.24	0.93	1.2×10^5
	3.0			580.	1.18	3.31	0.07	6900.
Na^{20}	gnd.	β^+, α	~0.25 s		13.4		?	?
	~7.5			0.25	5.9	12.5	~1.0?	2000?
Na^{21}	gnd.	β^+?	24 s		?		1.0?	
Na^{22}	gnd.	β^+	2.6 y	2.1×10^{12}	1.83	4.58	3.8×10^{-5}	9.1×10^{13}
	1.28			8.2×10^7	0.549	2.075	~1.00	2.2×10^7

[a] Indications are for the states in the daughter nucleus.
[b] s = sec., m = min., d = day, y = year.
[c] The ft functions used are those calculated by G. L. Trigg at Washington University.
[d] λ = branching ratio.

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