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Energy Levels of Light Nuclei. V*

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INTRODUCTION

THE present compilation summarizes currently available experimental information on the location and properties of the energy levels of the light nuclei from He^5 to Ne^{23}. In form and arrangement, it follows closely the plan of four previous compilations[1–4] on the same subject. Each nucleus is represented by a diagram, on which the known energy levels are plotted, together with the nuclear reactions in which they are involved. The diagrams are supported by a text in which an attempt has been made to synthesize the pertinent information on each reaction as abstracted from published papers. Insofar as possible, the present edition has been made self-sufficient, in that each diagram entry of a level position or quantum-number assignment finds some defense in the cited literature. Because of space limitation, however, much important information contained in earlier versions of the summary has been omitted here, and for a more detailed discussion of certain reactions and for the complete (post-1937) bibliography, the reader may wish to refer to these earlier summaries, particularly the 1952 version.[4]

Arrangement of the Material

As before, the diagrams contain, in addition to a representation of the level structures, an indication in each case of the experiments through which particular levels have been found. Such experiments generally fall in one of two categories: those in which the given nuclide occurs as the intermediate stage in a reaction, and those in which it represents the final stage. Where a compound nucleus is formed, the excitation function may yield rather detailed information about the energy levels of the intermediate system. To illustrate the general nature of this information, particularly as regards the breadths, relative intensities of excitation, and preferred modes of decay of the various levels, the thin-target excitation functions are shown alongside the level diagram itself, with approximate relative yields plotted horizontally against bombarding energy in a vertical direction. To permit direct association with the levels, the vertical scale is adjusted to center-of-mass energies, with values of bombarding energy indicated in laboratory coordinates. The cross section scales are arbitrary, different for various products, and in some instances rather strongly distorted to exhibit weak resonances. All definitely established resonances are indicated by leaders, and where space permits, with the (laboratory) energy corresponding to the peak cross section. Where no resonances appear in an excitation function, or where there is reason to believe that the reaction proceeds without formation of a compound nucleus, a brace within the level diagram indicates what products are observed.

Reactions in which the nuclide of interest occurs as the residual nucleus are indicated by the notation $X+a-b$, where X, a, and b are the target nucleus, bombarding particle, and ejected particle respectively. Horizontal lines with this notation are located on the drawings at a height above the origin equal to the reaction Q value, as calculated from the mass table. The highest bombarding energy at which observations have been made is shown by a vertical arrow, roughly to scale, and observed groups of particles are indicated by slanting arrows, terminating on the levels with which they are presumed to be associated. Subsequent gamma transitions are indicated by vertical arrows. It should be noted that not necessarily all of the groups shown have been reported at the bombarding energy which appears on the diagram; bombarding energies used in particular experiments are given in the text. A few unreported reactions have been included in the diagrams to provide a convenient reference for their Q values.

On each level in the diagram appears a number which gives the excitation energy. Where a single level is reported in several experiments, a weighted mean value has been used for this number. It is, of course, not always certain that the different experiments refer to the same level, but we have assumed that they do so wherever the probable errors overlap and where there appears to be no obvious inconsistency in such an interpretation. Levels, particle groups, or γ transitions whose existence is uncertain are represented by dashed lines; uncertain quantum numbers are enclosed in parentheses. In some cases, where a level is particularly broad, this fact has been indicated by cross hatching. Among the lighter nuclei, where the level spacing is

* This work has been supported in part by the U. S. Air Force, through the Office of Scientific Research, and by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

1 W. F. Hornyak and T. Lauritsen, Revs. Modern Phys. 20, 191 (1948).
2 T. Lauritsen, N. R. C. Preliminary Report No. 5 (1949).
3 Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. 22, 219 (1950).
4 F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 24, 321 (1952).

large, the breadth of the cross hatching indicates the estimated half-width.

The discussion of reactions in the text is divided in the same way as on the diagrams. Features of the reactions such as cross sections, excitation functions, and alternate modes of decay, which relate primarily to the compound nucleus, will be found discussed under that nucleus; particle-group spectra, γ transitions, and Q values are entered under the residual nucleus. Angular distribution data are entered in one or the other category, depending upon which seems the more appropriate to the case in hand.

Since the emphasis in this summary is on experimental results, no attempt has been made to treat theoretical papers in any systematic way or to maintain a complete bibliography of such papers. An extensive theoretical discussion, specifically directed to the light nuclei, is presented in a recent article by D. R. Inglis.[5]

Masses and Q Values

The mass values used in the present compilation are listed at the end of the article. Almost all of these have been taken from the tables of Li *et al.*[6] and C. W. Li,[7] which are based on measured Q values. For nuclides not included in these tables, we have estimated the masses from the available experimental data; the details of these estimates will be found in the text. For each reaction, the Q value calculated from the masses, designated Q_m, is listed with the reaction heading, as is the binding energy of the bombarding particle in the compound nucleus, E_b. Both quantities are expressed in Mev. Although the mass values generally are assigned probable errors of fifteen to thirty kev, the Q values are usually more accurate. Experimentally determined Q values are cited in the text, whether they are among those used in fixing the masses or not. A summary of Q values has been recently published by D. M. Van Patter and W. Whaling.[8]

Conventions

Within the limitations imposed by the requirement of brevity, we have endeavored to avoid the use of unfamiliar conventions and abbreviations. We set forth here some of the symbols which we have used, together with their definitions:

- E Energy in Mev, laboratory coordinates unless otherwise specified. Subscripts p, d, t, etc., refer to protons, deuterons, tritons, etc.
- θ Angle of observation, in laboratory coordinates unless otherwise specified.
- E_{res} General: the bombarding energy at which resonance occurs; specific: the bombarding energy at which the resonant part of the phase shift of the partial wave in question reaches 90°.
- Γ Observed width of a resonance, in kev; laboratory coordinates unless otherwise specified.
- E_λ "Characteristic" energy of a level as determined by certain conditions on the logarithmic derivative of the wave function at the nuclear surface.[9]
- $\omega\Gamma_x$ Statistical weight factor times partial width of particle x.
- γ_λ^2 "Partial" width, after removal of barrier penetration factors, evaluated at E_λ.
- J Total angular momentum.
- π Parity.
- T,T_z Isotopic (or isobaric) spin quantum numbers: $T_z\equiv\frac{1}{2}(N-Z)$.

ACKNOWLEDGMENT

Whatever claim the present compilation may make to currency and accuracy is due in large measure to the generosity of a host of colleagues, too many to enumerate here, who have supplied us with material in advance of publication and who have read and criticized the draft manuscript. The active help and encouragement of C. C. Lauritsen, W. A. Fowler, R. F. Christy, W. Whaling, and C. A. Barnes of the Kellogg Laboratory staff has been much sought and is gratefull acknowledged.

He^5

(Fig. 1)

Mass of He^5

The most direct observations on the mass of He^5 appear to be:

1. $He^4(n\,n)He^4$: $E_{\text{res}}=0.95$ (center of mass); mass defect$=12.92\pm0.05$.
2. $Li^6(t\,\alpha)He^5$: $He^5=He^4+n+0.97\pm0.05$; mass defect$=12.94\pm0.05$.
3. $Li^6(d\,He^3)He^5$: $Q_0=0.91\pm0.09$; mass defect$=12.85\pm0.09$.
4. $Li^7(d\,\alpha)He^5$: $Q_0=14.23\pm0.07$; mass defect$=12.85\pm0.07$.

We adopt: He^5 mass defect$=12.92\pm0.08$ Mev.

I. (a) $H^3(d\,n)He^4$ $Q_m=17.577$ $E_b=16.63$
(b) $H^2(t\,n)He^4$

The yield exhibits a pronounced maximum near $E_d=107$ kev, with a cross section of 4.95 ± 0.14 b (Ar 54)† [see also (Aj 52c)]. Precise cross sections in the range $E_d=10$ to 1700 kev are tabulated by (Ar 52d),

[5] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).
[6] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[7] C. W. Li, Phys. Rev. **88**, 1038 (1952).
[8] D. M. Van Patter and W. Whaling, Revs. Modern Phys. **26**, 402 (1954).
[9] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947); T. Teichmann and E. P. Wigner, Phys. Rev. **87**, 123 (1952).
† References are indicated by the first two letters of the first named author and are listed at the end of the article.

(Co 52f), (Ar 54), and (Ja 53d). The course of the cross-section curve is adequately described by the single-level resonance formula, assuming s-wave deuterons forming an intermediate state with $J=3/2^+$, with d-wave emergent neutrons. Typical parameters are: $\gamma_d^2=10^{-9}$ kev-cm (0.42 of the sum-rule limit), $\gamma_n^2=2.8\times10^{-11}$ kev-cm (Co 52f, Ar 52d, and Vo 54). An analysis in terms of a complex scattering length has been made by (Fl 51). At low energies the cross section approaches the simple Gamow exponential form: $E\sigma=A\exp(-BE^{-\frac{1}{2}})$ with $B=44.40$ kev$^{\frac{1}{2}}$ (Ar 54), 43.8 kev$^{\frac{1}{2}}$ (Ja 53d) ($2\pi e^2/\hbar v=44.40\,E^{-\frac{1}{2}}$).

The angular distribution of products is isotropic at resonance and below [see (Aj 52c)]. Angular distributions have also been studied at $E_t=1.5$ Mev (Ar 54a), $E_d=2.21$ Mev (St 52c), and 10.5 Mev (Br 51b) [see (Aj 52c)]. The distribution at high energy is dominated by the stripping process (Bu 51i). See also (Ja 53e) and (Jo 54b).

II. $H^3(d\,p)H^4$

Not observed: (Mc 51a).

III. $H^3(d\,d)H^3$ $E_b=16.63$

Differential cross sections for $E_d=0.96$ to 3.22 Mev ($\theta=44°$ to 132°, c.m.) are tabulated by (St 52e), and for $E_d=10.2$ Mev ($\theta=29°$ to 140°, c.m.) by (Al 52b). See $He^3(d\,d)He^3$.

IV. $H^3(t\,n)He^5$ $Q_m=10.37$

Two neutron groups, attributed to the ground state and an excited state of He^5 at $\sim$2.6 Mev, are reported by (Le 51a).

V. $H^3(He^3\,p)He^5$ $Q_m=11.13$

$Q_0=11.18\pm0.07$ Mev [(Al 53a); photoplate]
$Q_0=11.13\pm0.07$ Mev [(Mo 53d); scint. spectrometer]

The spectrum shows a well-defined proton peak corresponding to the ground state, superposed on a considerable background attributed to the three-body breakup (Al 53a, and Mo 53d). There is no evidence in either spectrum for the existence of an excited state of He^5. If the transition in question occurs at all, it is either much less probable than that to the ground state, or else the level is much wider: see (Go 54c).

TABLE I(5). Total neutron cross sections: $He^4(n\,n)He^4$.

E_n (Mev)	σ(b)
1.15[a]	7.4
2.49[b]	3.16 ± 0.06
2.99[b]	2.79 ± 0.06
4.95[c]	2.183 ± 0.06
7.10[c]	1.780 ± 0.05
12.35[c]	1.177 ± 0.03
14.14[c]	1.005 ± 0.03
17.97[d]	0.848 ± 0.03
19.00[d]	0.816 ± 0.02
20.07[d]	0.770 ± 0.02

[a] (Ba 51a).
[b] J. H. Coon, reported in (Se 53).
[c] R. L. Henkel and J. E. Perry (private communication).
[d] (Da 53f).

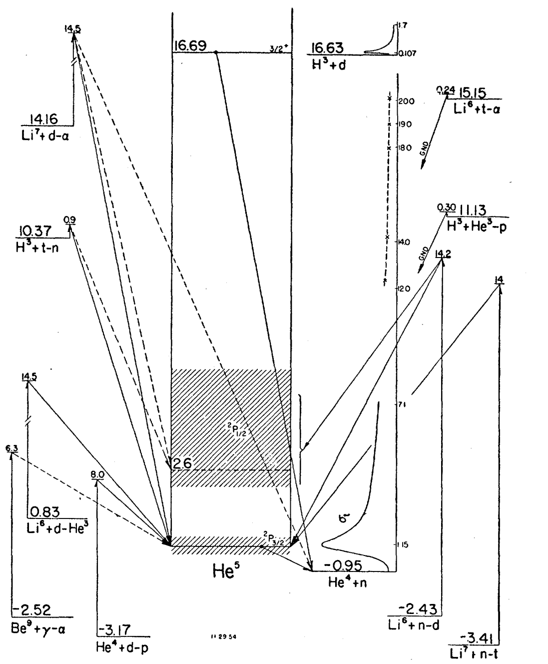


FIG. 1. Energy levels of He^5. In these diagrams, energy values are plotted vertically in Mev, based on the ground state as zero. Uncertain levels or transitions are indicated by dashed lines; levels which are known to be particularly broad are cross-hatched. Values of total angular momentum (J), parity, and isotopic spin (T) which appear to be reasonably well established are indicated on the levels; less certain assignments are enclosed in parentheses. For reactions in which He^5 is the compound nucleus, thin-target excitation functions are shown schematically (where known), with the yield plotted horizontally and the bombarding energy vertically. Bombarding energies are indicated in laboratory coordinates and plotted to scale in center-of-mass coordinates. Excited states of the residual nuclei involved in these reactions have generally not been shown; where transitions to such excited states are known to occur, a brace has been used to suggest reference to another diagram.

For reactions in which the present nucleus occurs as a residual product, excitation functions have not been shown; a vertical arrow with a number indicating some bombarding energy, usually the highest, at which the reaction has been studied, is used instead.

VI. $He^4(n\,n)He^4$ $E_b=-0.95$

The thermal cross section is 0.78 b (Hi 51). The total cross section has been measured from 40 kev to 5 Mev by (Ba 51a) and from 2.5 Mev to 20 Mev by the Los Alamos group. It exhibits a maximum of 7.4 b at $E_n=1.15$ Mev and thereafter decreases monotonically to 0.77 b at $E_n=20$ Mev. Total cross sections at several energies are listed in Table I(5).

Angular distributions have been studied in the range $E_n=0.4$ to 2.7 Mev by (Ad 52), $E_n=3$ to 4 Mev by (Hu 52c), at $E_n=2.6$, 4.5, 5.5, 6.5, and 14.3 Mev by (Se 53) and at $E_n=14.1$ Mev by (Sm 54). The course of the phase shifts is similar to that of $He^4(p\,p)He^4$

(see Li^5) and is described by the same level parameters, with a shift of about 1 Mev in the characteristic energies. There is evidence for an appreciable negative D-wave phase shift; a part of this may be associated with the $D_{\frac{3}{2}}$ level at 16.8 Mev as well as with another not yet located $D_{\frac{5}{2}}$ level [(Se 53), (Do 52b), and (Al 54c)]. The (negative) s-wave phase shift varies roughly as $(E_n)^{\frac{1}{2}}$, and can be accounted for by potential scattering in a well of radius 2.4×10^{-13} cm. A fit with a larger radius requires the assumption of a high, broad level corresponding to a $2s$ neutron (La 54a). See also (Si 53), (Br 54a), (Hu 54a), (Ta 54a), and (Hi 54c).

VII. (a) $He^4(d\ p)He^5$ $Q_m=-3.17$
(b) $He^4(d\ p)He^4+n$ $Q_m=-2.225$

Q values for reaction (a) of -2.9 and -3.2 Mev are reported [see (Aj 52c)]. $Q=-3.10\pm0.05$ (Fr 54h).

VIII. $Li^6(n\ d)He^5$ $Q_m=-2.43$

$Q_0=-2.57\pm0.10$[(Fr 54b); photoplate]

The deuteron spectrum, observed at $E_n=14$ Mev, shows a well-defined group with a width of 0.8 Mev (c.m.), corresponding to the ground-state transition. In addition there is observed a continuum of deuterons, attributed to transitions to a broad excited state, extending to at least 4 Mev in He^5. There is no evidence for a sharp group in this region. Angular distributions of both the ground-state and excited-state deuterons indicate a pickup process, with $l_p=1$ (Fr 54b).

IX. $Li^6(d\ He^3)He^5$ $Q_m=0.83$

$Q_0=0.91\pm0.09$ (Le 55; mag. spectrometer).

This reaction has been observed at $E_d=14.5$ Mev. The ground-state group has a c.m. width of 0.69 ± 0.2 Mev [(Le 54) and (Le 55)].

X. $Li^6(t\ \alpha)He^5$ $Q_m=15.15$

From the Q value of this reaction, determined at $E_t=230$ kev, it is found that $He^5=He^4+n+0.97\pm0.05$ Mev (Craig, Cross, and Jarvis, private communication).

XI. $Li^7(n\ t)He^5$ $Q_m=-3.41$

The angular distribution of tritons exhibits a forward maximum at $E_n=14$ Mev (Fr 54b).

XII. $Li^7(d\ \alpha)He^5$ $Q_m=14.16$

$Q_0=14.26\pm0.09$ (Le 55; mag. spectrometer).
$Q_0=14.2\pm0.1$ (Cu 53a; photoplate).

The observation that the angular correlation of ground-state α particles and those resulting from the He^5 breakup is not isotropic is consistent with a $P_{\frac{3}{2}}$ assignment (Fr 51b).

At $E_d=0.98$ Mev, using nuclear emulsions with partial magnetic separation, (Cu 53a) report α-particle groups corresponding to the ground state, with a width of 0.3 ± 0.1 Mev, and to an excited state at 2.5 ± 0.2 Mev with a width of 1.5 ± 0.3 Mev. [It does not appear excluded that the second group may come from levels at 7–10 Mev in Be^8, produced by $Li^7(d\ n)Be^8$.] At $E_d=14.5$ Mev, the ground-state group is observed to have a c.m. width of 0.66 ± 0.2 Mev (Le 55).

Li^5

(Fig. 2)

Mass of Li^5

The three most direct observations on the mass of Li^5 appear to be:

1. $He^3(d\ \gamma)Li^5$ $Q_0=16.36\pm0.2$: mass defect $=13.17\pm0.2$ Mev
2. $He^3(He^3\ p)Li^5$ $Q_0=10.86\pm0.15$: mass defect $=13.18\pm0.15$
3. $Li^6(d\ t)Li^5$ $Q_0=0.9\pm0.1$: mass defect $=12.85\pm0.1$

The weighted mean of these three values is in good agreement with an earlier adopted value of 12.99 ± 0.3 (Aj 52c); we adopt: Li^5 mass defect$=12.99\pm0.15$ Mev.

I. $He^3(d\ \gamma)Li^5$ $Q_m=16.54$

$Q_0=16.36\pm0.2$ (Hi 54, Bl 54: scint. counter)

Capture gamma radiation of energy $E_\gamma=16.6\pm0.2$ Mev is observed at $E_d=0.45$ Mev. The experimental radiation width at resonance is calculated to be 11 ± 2 ev consistent with the Γ_γ expected for an $E1$ transition. The excitation curve measured from $E_d=0.2$ to 2.85 Mev shows a broad maximum at $E_d=0.45\pm0.04$ Mev. Above this maximum, nonresonant capture is indicated by a slow rise of the cross section. The angular distribution is isotropic within 10 percent from 0° to 90° at $E_d=0.58$ Mev. At the resonance the cross section is estimated to be 0.05 ± 0.01 mb [(Hi 54) and (Bl 54)].

II. $He^3(d\ p)He^4$ $Q_m=18.341$ $E_b=16.54$

The cross section exhibits a broad maximum at $E_d=400$ kev (Bo 52a), $E_d=430\pm30$ kev (Ya 53), $E(He^3)=640$ kev ($E_d=430$) (Ku 53). The peak value is 0.69 ± 0.03 b (Bo 52a), 0.72 b (Ku 53), 0.90 ± 0.10 b (Ya 53), 0.94 ± 0.08 b (Fr 54a). Cross sections from 188 kev to 3.5 Mev are tabulated in these references. From 36 to 93 kev the cross section fits the Gamow exponential form $E_\sigma=A\exp(-BE^{-\frac{1}{2}})$ with $B=91.0$ kev$^{\frac{1}{2}}$ (Ar 54), 87.7 kev$^{\frac{1}{2}}$ (Ja 53d). Below about 600 kev, the cross-section curve is well fitted by the one-level formula, assuming s-wave deuterons forming a $J=\frac{3}{2}^+$ state, emitting d-wave protons. Suitable parameters are $\gamma_d^2=5.0\times10^{-10}$ kev-cm (0.21 of the sum-rule limit: Vo 54), $\gamma_p^2=9.7\times10^{-12}$ kev-cm (Bo 52a). (Bl 54) give $\gamma_p^2=12.8\times10^{-12}$ kev-cm, based on a peak cross section of 0.9 b.

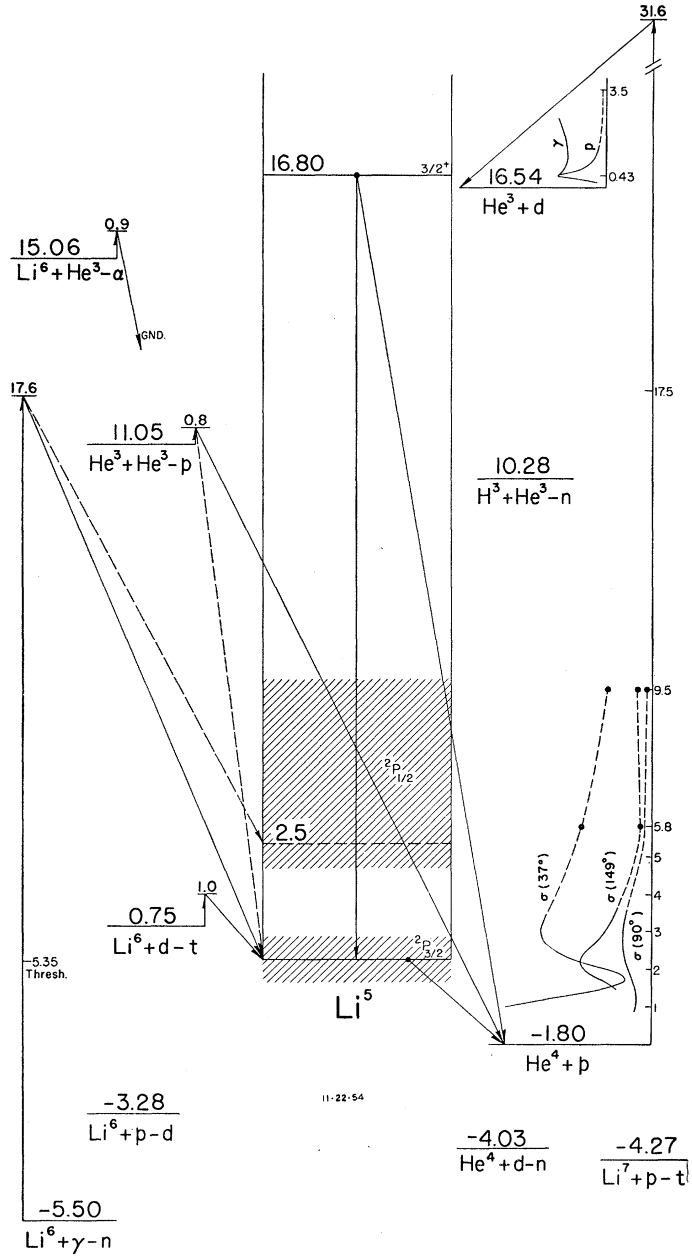


FIG. 2. Energy levels of Li^5: for notation, see Fig. 1.

The angular distribution of protons is isotropic at and below resonance [(Ja 53d), (Bo 52a), (Ya 53), and (Ku 53)]. Distributions at higher energies have been studied by (Bo 52a) and (Ya 53). At $E_d = 10.2$ Mev, the stripping process dominates (Bu 51i).

III. $He^3(d\ d)He^3$ $E_b = 16.54$

The elastic cross section is appreciably less than Rutherford scattering at 65.4° (c.m.) for $E_d = 380$ to 570 kev. The data are consistent with the assignment of $\frac{3}{2}^+$ for the 16.8-Mev state in Li^5 (Fr 54a). The variation with angle and energy of the cross section (measured with an accuracy of 4 to 8 percent) in the range $E_d = 1.0$ to 3.25 Mev is quite similar to that of $H^3(d\ d)H^3$ particularly at large scattering angles and at the higher energies (Br 54b). At $E_d = 10.2$ Mev, the differential cross sections are identical for angles $>45°$. The angular distribution at this energy indicates that incoming orbital angular momenta as high as 2 and possibly 3 may be involved (Al 52b).

IV. $He^3(He^3\ p)Li^5$ $Q_m = 11.05$

$Q_0 = 10.86 \pm 0.15$ Mev (Al 53a; photoplate).

The spectrum at $E(He^3) = 0.24$ Mev shows an unresolved proton group superposed on a continuous background attributed to the three-body breakup. The width of the ground state appears to be larger than 1 Mev (Al 53a). No evidence is found at $E(He^3)=0.36$ Mev for well-defined proton groups of lower energy than the ground-state group (Go 54c). See also Be^6.

V. $He^4(p\ p)He^4$ $E_b=-1.80$

1. $E_p<3.6$ Mev. Angular distributions have been measured at several energies: a broad maximum in the backward scattering appears at $E_p\sim 2.2$ Mev (Fr 49c).

2. $E_p=4.8$, 5.1 Mev: see (Br 51h).

3. $E_p=5.78$ Mev. Cross sections with a precision of about 2 percent have been measured at 26 angles by (Kr 54). The phase shifts found are $S=47.9°$, $P_{\frac{1}{2}}=38.7°$, $P_{\frac{3}{2}}=112.9°$, $D_{\frac{3}{2}}=-1.3°$, and $D_{\frac{5}{2}}=-0.49°$, assuming an inverted doublet.

4. $E_p=9.48$ Mev. Cross sections with a precision of about 3 percent have been measured at 43 angles by (Pu 52a). The phase shifts are given in (Do 52b). At $E_p=9.73$ Mev, (Co 54g) report general agreement with the results of (Pu 52a) at forward angles but find cross sections only about 75 percent as great at back angles.

5. $E_p=17.5$ Mev. Cross sections have been measured at 33 angles by (Br 54). The phase shifts found are $S=-100.7°$, $P_{\frac{1}{2}}=36.4°$, $P_{\frac{3}{2}}=81.2°$, $D_{\frac{3}{2}}=10.9°$, $D_{\frac{5}{2}}=157.7°$ or $(-22.3°)$, $F=1.2°$ (K. Brockman, private communication).

6. $E_p=19.5$ Mev: see (Co 53l)

7. $E_p=28$ Mev. Cross sections at 15 angles are given by (Wi 54d): an upper limit of 2 mb is set for the cross section of the reaction $He^4(p\ p\gamma)He^4$.

8. $E_p=31.6$ Mev. Cross sections at 6 angles are reported by (Co 53l).

A phase-shift analysis, covering experimental data for $E_p<3.6$ Mev, has been carried out by (Cr 49a) and extended to $E_p=5.78$ and 9.48 Mev by (Do 52b). The $P_{\frac{3}{2}}$ phase shift rises steeply, passing through 90°at about $E_p=2.5$ Mev (lab), flattening off at 110° at 5 Mev and decreasing slowly thereafter (see Kr 54). The $S_{\frac{1}{2}}$ (negative) and $P_{\frac{1}{2}}$ phase shifts show a monotonic increase with energy, and there are indications of small, negative D phase shifts at the higher energies. The behavior of the $P_{\frac{3}{2}}$ phase shift can be well accounted for by the one-level Breit-Wigner formula, with $E_{res}\sim 2.1$ Mev (c.m.), $\gamma^2=17.6\times 10^{-13}$ Mev-cm (Ad 52) (0.75 of the sum-rule limit: Vo 54), $\gamma^2=25\times 10^{-13}$ Mev-cm (Do 52b).

The situation of the $P_{\frac{1}{2}}$ "resonance" is not so clear: (Ad 52) suggests on the basis of the lower energy data that the two states are of about equal reduced width and are split by ~ 3 Mev (E_{res}, lab). (Do 52b), on the other hand, find a much greater width, $\gamma^2\sim 100\times 10^{-13}$ Mev-cm, for the $P_{\frac{1}{2}}$ level, and a considerably greater splitting ($\Delta E_\lambda=7.5$ Mev, c.m.). An analysis in terms of a one-body potential with spin orbit coupling appears to favor a Gaussian well over square or exponential shapes (Sa 54).

Early results on α-particle scattering in hydrogen (Ts 40) which indicated several resonances below the ground state of Li^5 are not confirmed by (Ru 54): $E_\alpha=3.1$ to 5.3 Mev.

VI. (a) $He^4(p\ d)He^3$ $Q_m=-18.341$ $E_b=-1.80$
(b) $He^4(p\ pn)He^3$ $Q_m=-20.566$

Angular distributions are reported at $E_p=27.9$ Mev (Wi 54d) and 31.6 Mev (Be 52a) for reaction (a). For reaction (b), see (Wi 54d).

VII. $He^4(p\ 2p)H^3$ $Q_m=-19.802$ $E_b=-1.80$

See (Wi 54d).

VIII. $Li^6(\gamma\ n)Li^5$ $Q_m=-5.50$

$Q_0=-5.6$ Mev (Ti 53c; photoplate).

The photoneutron threshold is 5.35 ± 0.2 Mev (Sh 51d). The existence of an excited state of Li^5 at ~ 2.5 Mev is suggested by the data of (Ti 51).

IX. (a) $Li^6(d\ t)Li^5$ $Q_m=0.75$
(b) $Li^6(d\ p)He^4+H^3$ $Q_m=2.56$

$Q_0=0.9\pm 0.1$ Mev [(Fr 53b); mag. spectrometer].

At $E_d=1$ Mev, a broad triton group corresponding to the ground-state transition is observed. The width of the ground state is 1.5 Mev. A continuous proton distribution, attributed to the Li^5 breakup, is also observed with a sharp upper limit at 2.80 Mev. The tritons are emitted preferentially in the forward direction (Fr 53b).

X. $Li^6(He^3\ \alpha)Li^5$ $Q_m=15.06$

$Q_0=14.85\pm 0.15$ (E. Almqvist, private communication; prop. counter).

See also (Ku 53b).

He^6

(Fig. 3)

I. $He^6(\beta^-)Li^6$ $Q_m=3.55$

$E_\beta(\max)=3.50\pm 0.05$ Mev (Wu 52).

The half-life is 0.799 ± 0.0034 sec (Kl 54), 0.86 ± 0.03 sec (Sh 52), 0.83 ± 0.03 sec (Ba 53), 0.84 ± 0.03 sec (Ve 52a): log ft=2.94 (Ki 52). See also (Aj 52c), (Al 53b), and (Ru 53).

II. (a) $H^3(t\ \alpha)2n$ $Q_m=11.320$ $E_b=12.25$
(b) $H^3(t\ \alpha)n^2$
(c) $H^3(t\ n)He^5$ $Q_m=10.37$

The spectrum of alpha particles emitted in reaction (a) has been observed at $E_t=220$ kev. A possible group from reaction (b) has not been confirmed. For reaction (c), see He^5. The cross section for neutron production rises monotonically from 0.1 to 2.2 Mev, reaching a value of about 0.18 b at 2.2 Mev. See also (Aj 52c).

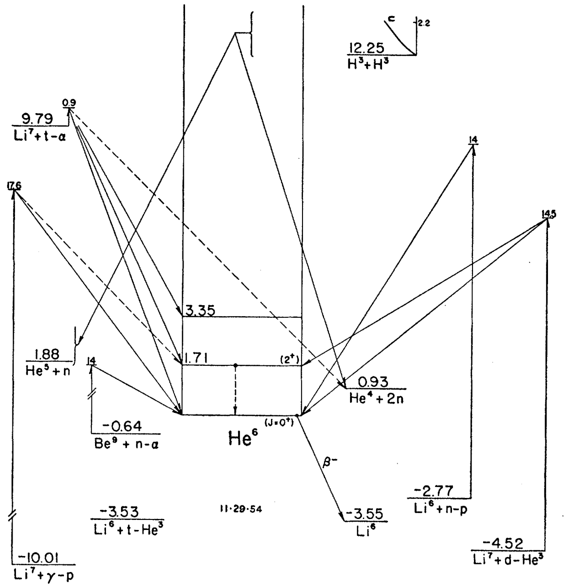


FIG. 3. Energy levels of He^6: for notation, see Fig. 1.

III. $Li^6(n\ p)He^6$ $\quad Q_m=-2.77$

See Li^7.

IV. $Li^7(n\ d)He^6$ $\quad Q_m=-7.79$

See Li^8 and (Fr 54b).

V. $Li^7(d\ He^3)He^6$ $\quad Q_m=-4.52$

He^3 groups to the ground state and the 1.71-Mev state have been observed at $E_d=14.5$ Mev. The He^3 angular distributions, analyzed by pickup theory, indicate an $l=1$ transfer for both groups and therefore even parity for the ground state and the 1.71-Mev state. At the maxima of the angular distributions ($\theta\sim 18°$, c.m.), the cross sections are, respectively, 8.0 mb/sterad and 2.0 mb/sterad (Le 54 and Le 55).

VI. $Li^7(t\ \alpha)He^6$ $\quad Q_m=9.79$

Two alpha groups are reported by (De 52), corresponding to the ground state and an excited state at 1.71 ± 0.01 Mev (see Aj 52c). Further studies at $E_t=215$ and 700 to 900 kev indicate a third group, corresponding to an excited state at 3.35 ± 0.09 Mev (K. W. Allen, private communication). Angular distributions of the α particles to the ground state and the 1.71-Mev level at $E_t=240$ kev are consistent with $J=0$ and 2, respectively, for these states (Al 54d: see Be^{10}).

VII. $Li^7(\gamma\ p)He^6$ $\quad Q_m=-10.01$

Analysis of tracks in Li-loaded emulsions are reported to indicate the excitation of a γ-emitting level at 1.6 ± 0.2 Mev (Ti 54a). See also (Ti 53b).

VIII. $Be^9(n\ \alpha)He^6$ $\quad Q_m=-0.64$

See Be^{10}.

Li^6

(Fig. 4)

I. (a) $H^3(He^3\ d)He^4$ $\quad Q_m=14.309$ $\quad E_b=15.786$
(b) $H^3(He^3\ p)He^5$ $\quad Q_m=11.13$
(c) $H^3(He^3\ p)He^4+n$ $\quad Q_m=12.084$

The relative intensities (43 ± 2, 6 ± 2, 51 ± 2) of reactions (a), (b), and (c), do not vary for $E(He^3)=225$ to 600 kev. The deuterons are isotropic (c.m.) at $E_t=360$ kev. The total cross section, reported for $E(He^3)=100$ to 800 kev, varies from 0.5 mb to 0.18 b, without showing resonance behavior, the main variation being accounted for by the Coulomb barrier effect (Mo 53d). See also (Al 53a).

II. $He^4(d\ \gamma)Li^6$ $\quad Q_m=1.477$

An upper limit for capture radiation at $E_d=1.055$ Mev (2.19-Mev state) is 0.1 mb (Si 54).

III. (a) $He^4(d\ d)He^4$ $\quad E_b=1.477$
(b) $H^2(\alpha\ \alpha)H^2$

The scattering cross section has been studied at 90°, 120°, and 156° (c.m.) for $E_d=1000$ to 1200 kev. A resonance is found at $E_{res}=1069$ kev (lab.), $\Gamma_{lab}=35$ kev, corresponding to the 2.189-Mev level of Li^6. Analysis of the scattering indicates $J=3^+$ and a reduced width of the order of the sum-rule limit; the most satisfactory fit to the data assumes a reduced width for the ground state of the same order [see Table I(6)] (La 53). (Ga 54) confirm the resonance and the assignment. Further measurements at nine angles for $E_d=0.3$ to 4.6 Mev show no evidence of a resonance corresponding to the 3.57-Mev level; this observation is consistent with the assignment $T=1$, $J=0^+$ to this state. A rise in the 173.6° (c.m.) cross section above 3 Mev, from 0.1 b/sterad at 3 Mev to 0.5 b/sterad at 4.6 Mev, coupled with a decrease by a factor of 2 in the 90° (c.m.) cross section, and a study of the angular distributions, is interpreted as indicating $T=0$ levels in Li^6 at 4.52 ± 0.08 Mev ($J=2^+$) and $\sim$5.4 Mev ($J=1^+$, $\Gamma=1$ Mev). (Ga 54a and A. Galonsky, private communication.) The location of the $J=3^+$, 2^+, and 1^+ levels is in good agreement with values predicted by (In 53).

Differential cross sections have previously been reported for $E_d=0.88$ to 3.51, 6.5, 7.94, and 10.3 Mev [see (Aj 52c)].

TABLE I(6). States in Li^6 from $He^4(d\ d)He^4$.

J, π, T	Li^{6*}	$\Gamma_{(lab)}$ (kev)	$\gamma^2/(3\hbar^2/2\mu a)$[a]
3, +, 0	2.188 ± 0.002[b,c]	30	
	2.189 ± 0.001[b,d]	35	0.5
2, +, 0	4.52 ± 0.08[d]	$\sim$900	0.6
1, +, 0	$4.9\rightarrow5.8$[d]		$0.2\rightarrow0.6$

[a] Values from (Vo 54) and A. Galonsky (private communication).
[b] The error assigned does not include the 0.026-Mev uncertainty in the $(He^4+H^2)-Li^6$ mass difference.
[c] (La 53).
[d] (Ga 54) and A. Galonsky (private communication).

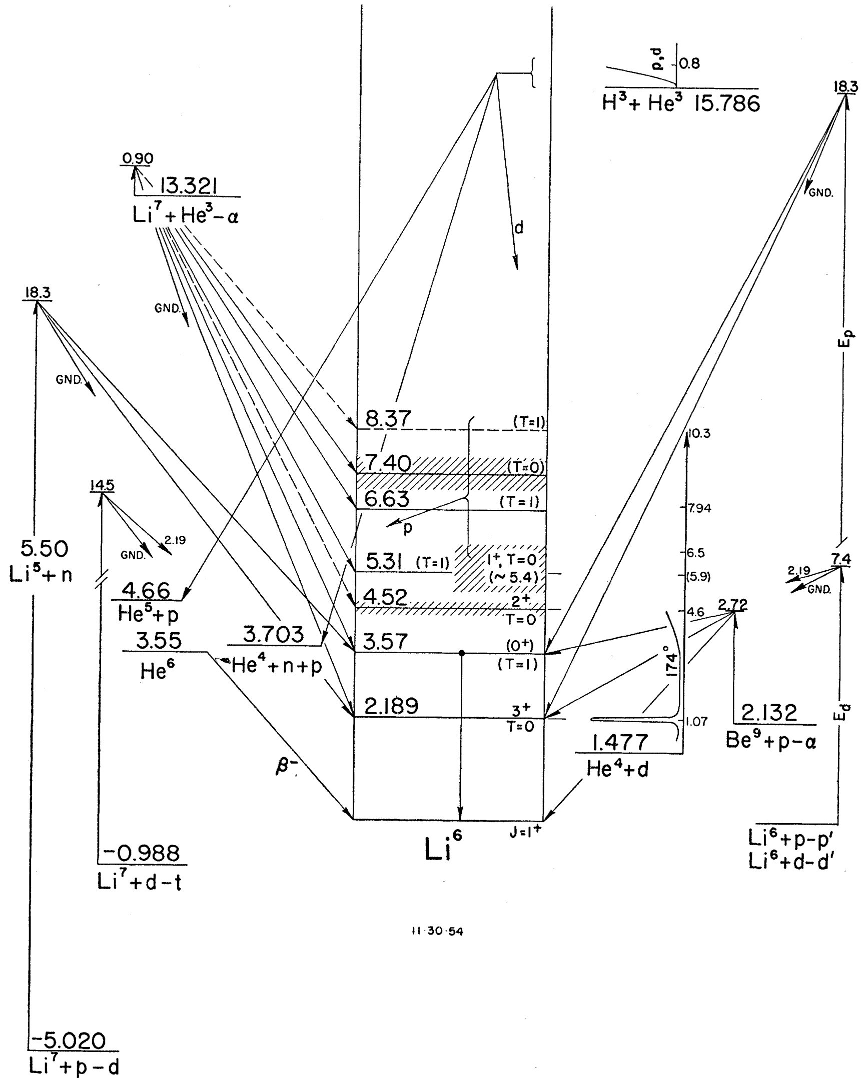


FIG. 4. Energy levels of Li^6: for notation, see Fig. 1.

IV. (a) $He^4(d\ p)He^5$ $Q_m=-3.17$ $E_b=1.477$
(b) $He^4(d\ p)He^4+n$ $Q_m=-2.225$
(c) $He^4(d\ n)Li^5$ $Q_m=-4.03$

Reactions (a) and (b) have been observed at 6.5, 7.94, and 10.3 Mev. The total cross section has been measured at 10.3 Mev. The angular distribution of protons is peaked forward [see (Aj 52c)]. Reaction (c) has not been reported.

V. $He^6(\beta^-)Li^6$ $Q_m=3.55$

See He^6.

VI. $Li^6(\gamma\ n)Li^5$ $Q_m=-5.50$

The cross section is 0.5 ± 0.2 mb for $E_\gamma=14.8$ to 17.6 Mev (Ti 51).

VII. $Li^6(\gamma\ d)He^4$ $Q_m=-1.477$

The cross section is $\lesssim 5\mu$b in the range $E_\gamma=2.6$ to 17 Mev (Je 53b, Gl 52a, Ti 52, and Ti 54b). The reaction is forbidden by isotopic spin selection rules insofar as electric dipole absorption is concerned (Ge 53a). See also (Ga 53a).

VIII. $Li^6(\gamma\ t)He^3$ $Q_m=-15.786$

This reaction has not been observed with 17.6-Mev gammas. The cross section is $\leq 6\pm4\mu$b (Ti 54b).

IX. $Li^6(e\ e')Li^6$

See Li^7: $Li^7(e\ e')Li^7$.

X. (a) $Li^6(p\ p')Li^{6*}$
(b) $Li^6(d\ d')Li^{6*}$

Proton and deuteron groups are observed corresponding to the state at 2.19 Mev. At $E_d=7.4$ Mev ($\theta=90°$), no deuteron group corresponding to the presumed $T=1$ state at 3.57 Mev is observed [(Br 53h) and C. P. Browne, private communication]. See also (Aj 52c).

XI. $Li^7(p\ d)Li^6$ $Q_m=-5.010$

Deuteron groups have been observed corresponding to the ground state, and to levels at 2.2±0.2 and 3.7 ±0.2 Mev (Fr 52). At $E_p=18$ Mev, angular distributions of the deuterons to the ground state and the 2.19-Mev level, analyzed by pickup theory, indicate $l_n=1$ and hence even parity, $J\leq 3$, for both states (Re 54a).

XII. $Li^7(d\ t)Li^6$ $Q_m=-0.988$

The angular distributions of the tritons, analyzed by pickup theory, indicates $l_n=1$, and hence even parity for the ground state (Ho 53c, Le 54) and for the 2.19-Mev state (Le 54). At $E_d=14.5$ Mev, the cross sections at the maxima of the angular distributions are 32.4 mb/sterad and 16.0 mb/sterad, respectively, for the ground state and the 2.19-Mev level [Levine, Bender, and McGruer, private communication and (Le 55)].

XIII. $Li^7(He^3\ \alpha)Li^6$ $Q_m=13.321$

Alpha-particle groups observed at $E(He^3)=700$ to 900 kev are listed in Table II(6). It is suggested that the narrow states at 5.31, 6.63, and 8.37 Mev may have $T=1$. A broad continuum with a maximum near $E_x=6$ Mev may indicate a $T=0$ state in this region (K. W. Allen and E. Almqvist, private communication).

TABLE II(6). States in Li^6 from $Li^7(He^3\ \alpha)Li^6$.[a]

Li^{6*}	Γ (kev)	Remarks
0		
2.189		
3.56±0.06		
4.3 ±0.2		weak, doubtful
5.31±0.07	$\lesssim$100	($T=1$)
~6	~2000	not certain; ($T=0$)
6.63±0.08	$\lesssim$100	($T=1$)
7.40±0.10	~1000	($T=0$)
8.37±0.08	$\lesssim$100	not certain; ($T=1$)

[a] K. W. Allen and E. Almqvist (private communication).

XIV. $Be^9(\gamma\ t)Li^6$ $Q_m=-17.670$

Several recoil tracks, observed in Be-loaded emulsions irradiated with 31-Mev bremsstrahlung, are attributed to this reaction (P. Stoll and P. Erdös, private communication).

XV. $Be^9(p\ \alpha)Li^6$ $Q_m=2.132$

$Q_0=2.126\pm0.003$ [(Co 53); mag. spectrometer].

In addition to the ground-state group, a group of α particles with $Q=-0.064\pm0.005$ Mev, corresponding to a level at 2.187 Mev is observed (Br 51f). Gamma-alpha coincidences with a short-range group corresponding to the 3.57-Mev level are observed at the 2.56-Mev resonance (Da 52). The fact that the ground-state and 2.19-Mev state α particles do not exhibit resonance at $E_p=2.56$ Mev is consistent with the assumption that the first two levels have $T=0$: see B^{10} (Ma 54g).

The gamma-ray energy is reported as 3.572±0.012 Mev (not corrected for possible Doppler shift). The internal pair spectrum is consistent with a magnetic dipole assignment to the radiation, and hence with $J=0, 1, 2$, even parity, for the 3.57-Mev state (Ma 54b).

XVI. $B^{10}(\gamma\ \alpha)Li^6$ $Q_m=-4.453$

See B^{10}.

Be^6

(Not illustrated)

Mass of Be^6

From the mass of He^6 and the 3.57-Mev excited state of Li^6, one can estimate the mass defect of Be^6 as 20.8±1 Mev.

I. (a) $He^3(He^3\ 2p)He^4$ $Q_m=12.848$ $E_b=10.8$
(b) $He^3(He^3\ p)Li^5$ $Q_m=11.05$

The total cross section shows a monotonic increase for $E(He^3)=100$ to 800 kev. At $E(He^3)=200$ kev, it is at least 2.5 μb. Below $E(He^3)=350$ kev, the cross section fits the simple Gamow exponential form. At higher energies, partial waves of $l\geq 2$ appear to be required (Go 54c). See also (Al 53a).

II. A radioactive material of 0.4-sec half-life, possibly to be identified with Li^4 or Be^6, is observed under bombardment of Li and Be with 50-Mev protons (Ty 54).

He^7

(Not illustrated)

A rough extrapolation from higher A suggests that the first $T=\frac{3}{2}$ state in Li^7 is located at an energy of the order of 15 Mev above the ground state. This means $He^7-Li^7\sim14.5$ Mev; mass defect ~31.5 Mev. He^7 would then be unstable (by ~4 Mev) to decay into He^6+n and (by ~3 Mev) into He^4+3n. See also (Pe 53c).

No evidence is found for the $Li^7(n\ p)He^7$ reaction (cross section ≤5 mb) for $-1.0>Q>-7.0$ (Fr 54b). From the mass defect suggested above, the Q for this reaction would be ~−14 Mev. Two other reactions, with very negative Q values, which lead to He^7 are $Li^7(t\ He^3)He^7$ and $Be^9(n\ He^3)He^7$. Neither reaction has been reported.

Li^7

(Fig. 5)

I. $Li^6(n\ n)Li^6$ $E_b=7.245$

The total neutron cross section has been measured for $E_n=0.035$ to 4.2 Mev by (Jo 54f). A resonance is observed at $E_n=255\pm10$ kev with a maximum cross section of 10.3 b and an observed width of 100 kev.

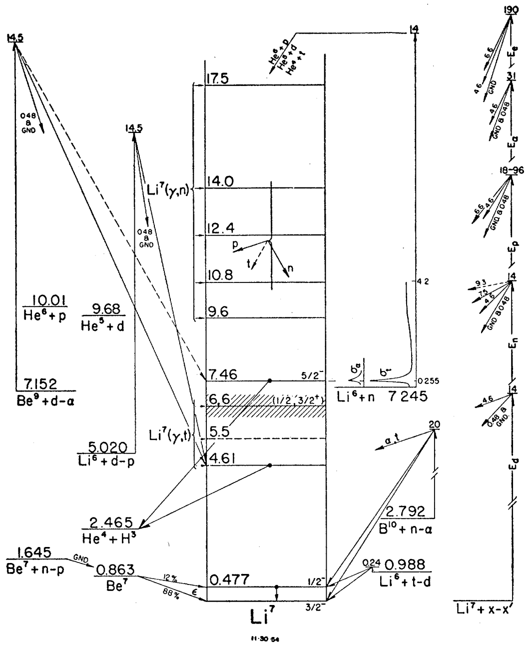


FIG. 5. Energy levels of Li^7: for notation, see Fig. 1.

The resonance is attributed to p-neutron formation of a state in Li^7 at 7.46 Mev with $J=5/2^-$ and reduced width $\gamma_n^2=0.42$ of the sum-rule limit [see also $Li^6(n\ \alpha)H^3$]. The cross section rises gradually from 1.3 to 2.1 b for $E_n=1.5$ to 4.2 Mev (Jo 54f).

The average total cross section shows a monotonic decrease from 1.9 to 1.7 b for $E_n=6$ to 9.7 Mev (Ne 54c). At $E_n=14$ Mev, the total cross section is 1.39 ± 0.05 b (Co 52h). See also (Hu 53c).

The large coherent thermal neutron scattering length suggests the existence of bound s-levels, possibly associated with the structure at 6.6 Mev (La 54a).

II. $Li^6(n\ p)He^6$ $Q_m=-2.77$ $E_b=7.245$

At $E_n=14$ Mev, the cross section is 6.7 ± 0.8 mb (Ba 53), 6 ± 2 mb (Fr 54b). The angular distribution of protons exhibits a minimum near $\theta=70°$ (Fr 54b).

III. $Li^6(n\ d)He^5$ $Q_m=-2.43$ $E_b=7.245$

At $E_n=14$ Mev, the cross section for long-range deuterons (to the ground state of He^5) is 89 ± 10 mb. The cross section for short-range deuterons (continuum, $Q=-4.3$ to -6.7 Mev) is 77 ± 9 mb. The angular distribution indicates a pickup process (Fr 54b).

IV. $Li^6(n\ \alpha)H^3$ $Q_m=4.780$ $E_b=7.245$
$Li^6(n\ t)He^4$

The isotopic thermal capture cross section is 930 b; up to $E_n\sim50$ ev, the cross section varies as 1/v (Hu 52e). A strong resonance is observed at $E_n=0.25$ Mev with a peak cross section of 3.2 b. The peak cross section and angular distribution establish that the 7.46-Mev state is formed by p-wave neutrons and has $J=5/2^-$ [see (Aj 52c), (Jo 54f), and (So 53)]. Partial widths at resonance are $\Gamma_n=114$, $\Gamma_\alpha=60$ kev (c.m.); $E_\lambda=7.70$ Mev (Jo 54f). See also (Co 53j) and (Sz 53).

The cross section has been measured for $E_n<0.6$ Mev by Blair and Holland [see (Hu 52e)] and for $E_n=0.88$ to 14.2 Mev by (Ri 52a) and (Ri 53). The cross section decreases monotonically above the resonance except for a broad hump at $E_n\sim2$ Mev. The cross section is 320 ± 60 mb at $E_n=1.5$ Mev, 270 ± 40 mb at 2.0 Mev (We 54), 188 ± 26 at 2.49 Mev, and 26 ± 4 mb at 14.2 Mev (Ri 52a). Angular distributions at $E_n=0.2$, 0.27, 0.4, and 0.6 Mev, reported by (Da 53b), are consistent with dominant s- and p-waves in this region. Angular distributions at $E_n=1.1$, 1.5, 2.0, and 2.5 Mev are reported by (We 54) and at 14.2 Mev by (Fr 54b). See also (Ne 54a), (Si 53), and (We 53).

VI. $Li^6(d\ p)Li^7$ $Q_m=5.020$

$Q_0=5.019\pm0.007$ [(St 51); mag. spectrometer].
$Q_0=5.028\pm0.003$ [(Co 53); mag. spectrometer].

The energy of the first excited state is given as 483 ± 6 kev (Bu 48c), 475 ± 3 kev (Co 53) from measurements of the proton groups, and 477.4 ± 2 kev from the γ-ray energy (Th 52, corrected for Doppler shift and broadening). At $E_d\sim1.0$ Mev, a level has been observed at 4.61 ± 0.02 Mev (Ge 52).

Angular distributions, at $E_d=8$ Mev (Ho 53c) and $E_d=14.5$ Mev [(Le 54) (Le 55), and Levine, Bender, and McGruer, private communication], of the protons to the ground state and to the 0.48-Mev level, analyzed by stripping theory, show odd parity, $J\leq5/2$ for both states. The neutron capture probability is approximately the same for both states, indicating that their reduced widths are about the same (Ho 53c). At $E_d=14.5$ Mev, the cross sections at the maxima of the angular distributions ($\sim18°$, c.m.) are 12.8 mb/sterad and 9.2 mb/sterad, respectively, for the ground state and the 0.48-Mev level (Le 55). At 22° (c.m.), the cross section for the formation of the 4.6-Mev state is 6 mb/sterad. A state at 5.5 Mev has not been observed: at 22°, $\sigma<0.5$ mb/sterad (Le 55). Angular distributions have also been measured at lower energies [see (Aj 52c)]. The angular correlation between protons to the 477-kev state and the γ rays from its subsequent decay has been shown to be isotropic in the range $E_d=0.4$ to 1.0 Mev [(Sa 53a), (Th 53), and discussion in (Aj 52c)]. This observation strongly indicates $J=\frac{1}{2}$ for Li^{7*}. A preliminary value for the half-life is 1.0×10^{-13} sec (S. Devons, private communication).

VI. $Li^6(t\ d)Li^7$ $Q_m=0.988$

$Q_0=0.982\pm0.007$ [(Pe 52); mag. analysis].

At $E_t=240$ kev, the reaction has been observed to the ground state and to the 477-kev level (Pe 52). See also (Cu 53c).

VII. $Li^7(\gamma\ n)Li^6$ $Q_m = -7.245$

The total cross section for neutron production (including the γ, np and γ, $2n$ processes) has a broad maximum ($\sigma = 4$ mb) at $E_\gamma \sim 18$ Mev. For the $(\gamma\ n)$ process alone, the peak cross section is estimated as ~ 2.7 mb at $E_\gamma \sim 14$ Mev (Go 54b). Discontinuities are reported in the integral yield curve at $E_\gamma = 9.6$, 10.8, 12.4, 14.0, and 17.5 Mev (Go 54f). The sum of the integrated cross sections of the resonances is 3 Mev-mb (Go 54f) while the total integrated cross section to $E_\gamma = 17.5$ Mev is 20 Mev-mb (Mo 53c). It is suggested that the difference is due to a number of weak unresolved levels or to a continuum of photon absorption (Go 54f). See also (Pe 53c).

VIII. $Li^7(\gamma\ p)He^6$ $Q_m = -10.013$

According to (Ti 53b) and (Ti 54a), the cross section in the range $E_\gamma = 12$ to 20 Mev exhibits a single broad maximum at 15 Mev with a width of ~ 4 Mev and a peak cross section $= 2.2 \pm 0.25$ mb (see also Go 54b). Re-evaluated results of (Tu 53) [see (Ti 54a)] are not in essential disagreement with the above results. (Ru 54a) find two asymmetric maxima with peak cross sections of 8 mb in the range $E_\gamma = 10$ to 30 Mev. See also (Tu 54).

IX. $Li^7(\gamma\ t)He^4$ $Q_m = -2.465$

The excitation function, obtained from analysis of tracks in Li-loaded emulsions, appears to exhibit peaks at $E_\gamma = 4.7$, 5.5, 6.8 [(St 53a), (St 54h), and (Er 54)], 9.3, 16.7(?), 21.5(?), and 23.5(?) Mev (Ti 53b). Angular distribution studies suggest $J = 5/2^-$ or $3/2^-$ for the 4.7-Mev level and $J \leq 5/2$ for the 5.5- and 6.8-Mev levels [(Er 54) and (St 54h)]. Absolute cross sections are 26.5 ± 8 μb at $E_\gamma = 6.1$ Mev (Na 52b), 15 ± 5 μb at $E_\gamma = 6$ to 7 Mev (Ti 53), and 0.47 ± 0.08 mb at 17.6 Mev (Ti 53).

X. $Li^7(e\ e')Li^{7*}$

At $E_e = 190$ Mev, there is observed a broad electron group believed to be due to a combination of elastic scattering from Li^6 and Li^7 and inelastic scattering from the 0.48-Mev state, and two resolved inelastic groups from the 4.6 and 6.6-Mev states of Li^7 (G. Hutchinson and R. Hofstadter, private communication).

XI. $Li^7(n\ n')Li^{7*} \rightarrow H^3 + He^4$ $Q_m = -2.465$

Analysis of 167 ($He^4 + H^3$) tracks observed in Li-loaded photoplates irradiated with 14-Mev neutrons yield evidence for Li^7 states at 4.6, 7.5, and 9.25(?) Mev (Al 54b). See also (Fr 54b).

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

Inelastic proton groups corresponding to the states at 0.48, 4.6, and 6.56 Mev have been observed at bombarding energies up to 18.3 Mev [see (Aj 52c)]. At $E_p = 96$ Mev, proton groups corresponding to the ground state and the 0.48-Mev state (unresolved) and to the 4.6-Mev level have been detected (K. Strauch and W. F. Titus, private communication).

XIII. $Li^7(d\ d')Li^{7*}$

Inelastic deuteron groups have been observed to the states at 0.48 and 4.6 Mev [see (Aj 52c)]. At $E_d = 14.5$ Mev, the angular distribution of the deuterons corresponding to the 0.48-Mev state is peaked at $\sim 35°$, c.m., $d\sigma/d\Omega = 7.7$ mb/sterad, while the differential cross section of the deuterons from the 4.6-Mev state increases with angle in the interval 17° to 90°, c.m. At 50°, c.m., $d\sigma/d\Omega = 8.8$ mb/sterad (Le 55). See also (Le 54).

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

Emission of 480-kev γ radiation is observed in the range $E_\alpha = 1.2$ to 3.5 Mev [(Li 54), (Te 54), and (He 54b)]: see B^{11}. From the observed Doppler shift, it is concluded that the lifetime of the 0.48-Mev excited state is $< 3 \times 10^{-13}$ sec (Li 54). Using Po α particles, (Zh 54) finds $E_\gamma = 478 \pm 2$ kev, and observes that the Doppler shift in Li^7 metal is very nearly the maximum possible. It is concluded that the upper limit for the lifetime of the first excited state is 1.3×10^{-13} sec [see $B^{10}(n\ \alpha)Li^7$]. At $E_\alpha = 1.9$ Mev, the angular distribution of the radiation is isotropic within 10 percent (Li 54).

At $E_\alpha = 31$ Mev, a group with $Q = -4.8 \pm 0.2$ Mev is observed, in addition to a continuum corresponding to $Li^7(\alpha\ 2\alpha)H^3$ (Go 51a). (It is possible that the 6.6-Mev state is responsible for part of this continuum.)

XV. $Be^7(\epsilon)Li^7$‡ $Q_m = 0.863$

The decay proceeds to the ground- and 0.48-Mev states. The fraction to the excited state is given as 0.107 ± 0.02 by (Wi 49b) and 0.118 ± 0.02 by (Tu 49a) and (Tu 49c). The latter value has been corrected to 0.123 ± 0.006 by (Di 51).

The γ-ray energy is given (in kev) as 474 ± 4 (Za 48), 485 ± 5 (Ku 48), 476.7 ± 0.8 (Ho 49a, and Ra 49a), 478.5 ± 0.5 (Te 49b), and 477.3 ± 0.4 (P. Marmier, high resolution magnetic spectrometer; private communication).

The half-life is 52.93 ± 0.22 days (Se 49), 53.61 ± 0.17 days (Kr 53c). Log $ft = 3.33$ for the ground-state transition and 3.48 for the excited state. Both transitions are super-allowed (Ma 54h).

XVI. $Be^7(n\ p)Li^7$ $Q_m = 1.645$

See Be^8.

XVII. $Be^9(\gamma\ d)Li^7$ $Q_m = -16.682$

Several tracks observed in Be-loaded photoplates exposed to 31 Mev bremsstrahlung are attributed to

‡ The symbol (ϵ) indicates orbital electron capture.

this reaction (P. Stoll and P. Erdös, private communication).

XVIII. (a) $Be^9(d\,\alpha)Li^7$ $Q_m=7.152$
(b) $Be^9(d\,2\alpha)H^3$ $Q_m=4.687$

The weighted mean of published Q-value determinations is 7.153 ± 0.003 Mev (Va 54): this includes a recent value of 7.153 ± 0.004 Mev (Co 53; mag. spectrometer).

The energy of the first excited state is given as 482 ± 3 kev (Bu 48c), 478 ± 4 kev (Co 53) from measurements of the α-particle groups. At $E_d=0.47$ to 1.0 Mev, three α-particle groups are observed, corresponding to the ground state, the 0.48-Mev state, and one at 4.62 ±0.02 Mev (Ge 53). A continuous distribution of α particles and tritons is also observed, which corresponds to the breakup of the 4.6-Mev Li^7 state into He^4+H^3 and to the reaction $Be^9(d\,t)Be^{8*}$ [(Ge 53) and (Cu 52)]. The fraction of alphas leading to the 0.48-Mev state varies from $\sim$60 percent at low bombarding energies to $\sim$40 percent at 1 Mev (Ge 53).

At $E_d=0.3$ to 0.7 Mev, the combined α_0 and α_1 groups, corresponding to the ground- and 0.48-Mev states, are approximately isotropic (Re 51a). The $(\alpha_1\gamma)$ angular correlation has been observed for $E_d=0.40$ Mev (Ue 53) and $E_d=0.84$ Mev (Co 54e). There is no significant departure from isotropy, indicating $J=\frac{1}{2}$ for the 0.48-Mev state.

At $E_d=5.3$ Mev, the second level is reported at 4.59 ± 0.1 Mev (As 52). At $E_d=14$ Mev, levels are reported at 4.76 ± 0.15 and 7.5 ± 0.17(?) Mev (Go 51a). See also (Ta 53b).

XIX. (a) $B^{10}(n\,\alpha)Li^7$ $Q_m=2.792$
(b) $B^{10}(n\,2\alpha)H^3$ $Q_m=0.328$

(a) Two groups of α particles are observed corresponding to the ground state and the 0.48-Mev state. With thermal neutrons, the fraction of transitions leading to the ground state is about 6 percent: see B^{11}. The ionization and range of α particles from this reaction have been extensively investigated. See (Aj 52c) and (Ha 52i).

The γ-ray energy is 478.5 ± 1.5 kev: study of the Doppler broadening in various materials yields a lifetime of $0.75\pm0.25\times10^{-13}$ sec (El 49). The angular correlation of γ rays and α particles is isotropic, consistent with the assignment $J=\frac{1}{2}$ to the excited state (Ro 50).

(b) This reaction has been observed with $E_n=12$ to 20 Mev (Fr 53d). See also (Br 52d), (Co 53j), (Da 53c), (Ja 54), (Sz 53), and (De 54).

XX. $B^{11}(\gamma\,\alpha)Li^7$ $Q_m=-8.667$

See B^{11}.

Be^7

(Fig. 6)

I. $Be^7(\epsilon)Li^7$ $Q_m=0.863$

The decay is complex; see Li^7.

II. $He^4(\alpha\,n)Be^7$ $Q_m=-18.983$

A search for this reaction at $E_\alpha=39$ Mev, 0.5 Mev (c.m.) above threshold, led to a negative result; the cross section is <0.7 mb. This result is consistent with the assumption that Be^7 has negative parity (Wa 52c).

III. $Li^6(p\,\gamma)Be^7$ $Q_m=5.600$

The gamma-ray decay is complex, involving the 0.43-Mev state and, possibly, other states as well. Resonances for production of 0.42-Mev radiation occur at $E_p=1.03$ Mev (weak) and 1.7 Mev (strong: $\Gamma\sim50$ kev). At $E_p=0.4$ Mev, the cross section is ~1 μb [(Er 54a) and private communication]. An upper limit for the capture cross section at $E_p=1.82$ Mev is 3 μb (J. M. Freeman, private communication). See also (Ba 54h) and (Ba 54i).

IV. (a) $Li^6(p\,\alpha)He^3$ $Q_m=4.016$ $E_b=5.600$
(b) $Li^6(p\,p)Li^6$

The weighted mean of Q values for reaction (a) reported in (Va 54) is 4.023 ± 0.002 Mev.

The cross section for reaction (a) follows the Gamow function from $E_p=30$ to 250 kev (Sa 53b). The yield of He^3 particles exhibits a broad, low maximum at $E_p=0.6$ to 0.9 Mev and a pronounced resonance at

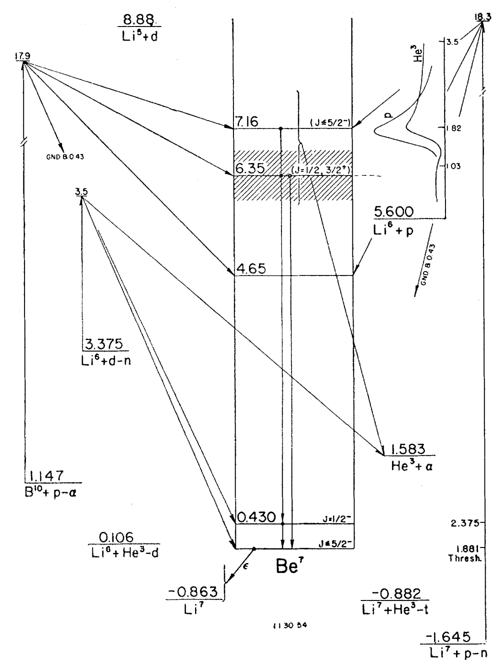


FIG. 6. Energy levels of Be^7: for notation, see Fig. 1. The super-allowed character of the decay of Be^7 to the $J=\frac{1}{2}^-$ state of Li^7 indicates $J\leq\frac{3}{2}^-$ for the ground state.

$E_p = 1.82 \pm 0.08$ Mev, where the differential cross section at 164° is ~8 mb/ster. In the range $E_p = 1.3$ to 3.1 Mev, the elastically scattered protons exhibit a single maximum, $\sigma = 120$ mb/sterad at $\theta = 164°$, at $E_p = 1.75 \pm 0.1$ Mev with a width $\Gamma = 0.5$ Mev (Ba 51e).

The low energy resonance is attributed to s-wave protons, forming a state in Be^7 with $J = \frac{3}{2}$ or $\frac{1}{2}$, even. This state corresponds both in location and in character to the (6.6-Mev) level required to account for the strong $1/v$ s-wave neutron absorption of Li^6. The 1.8-Mev resonance is formed either by s or p waves. The parameters γ^2 and E_λ agree with those for the corresponding level in Li^7 at 7.47 Mev only if $l = 1$ is assumed, and therefore $J \leq 5/2$, odd (Ba 51e).

It appears that the He^3 particles are peaked in the forward direction. For $E_p < 0.9$ Mev, the asymmetry increases with bombarding energy. This observation is consistent with the interference expected from two states of opposite parity (Ba 51e). At $E_p = 0.2$ Mev, the alpha particles are isotropic (Ne 37a).

V. (a) $Li^6(d\ n)Be^7$ $\quad Q_m = 3.375$
(b) $Li^6(d\ n)He^3 + He^4$ $\quad Q_m = 1.792$

At $E_d = 3.5$ Mev, the angular distributions of the neutron groups, analyzed by stripping theory, indicate odd parity and $J \leq 5/2$ for the ground and 0.43-Mev states. Reaction (b) is also observed (Aj 52).

The γ-ray energy is 428.9 ± 2 kev (corrected for Doppler shift and broadening). The difference between the Li^{7*} and Be^{7*} energies is 48.5 ± 1.0 kev (Th 52). The γ rays are emitted isotropically with respect to the neutrons at $E_d = 0.60$ Mev. Since the neutrons are not isotropic with respect to the deuteron beam, it is concluded that the 430-kev state of Be^7 has $J = \frac{1}{2}$ [(Th 51f) and (Th 53)]. The γ rays are isotropic with respect to the deuteron beam at $E_d = 0.7$ Mev (Cl 52). A preliminary value of the half-life of the 0.43-Mev state is 1.4×10^{-13} sec (S. Devons, private communication).

VI. $Li^7(p\ n)Be^7$ $\quad Q_m = -1.645$

A recent threshold measurement, based on the value of 411.770 kev for the Hg^{198} γ ray [crystal spectrometer measurement: (Mu 52b)] is $E_p = 1.8814 \pm 0.0011$ Mev; when based on the value 1.3325 for one of the Ni^{60} γ rays [measured in terms of the proton magnetic moment: (Li 53d)], the threshold is $E_p = 1.8797 \pm 0.0011$ Mev. The former value is in better agreement with earlier accepted values (Jo 54d). See also (Aj 52c).

At $E_p > 2.4$ Mev, two neutron groups are observed, corresponding to the ground and the first excited state of Be^7. The weighted mean value of five independent observations for the energy of the excited state is 431 ± 5 kev [see Table II(7) in (Aj 52c)]. A neutron threshold determination gives 430 ± 10 kev (Cook, Marion, and Bonner, private communication). At $E_p = 18.3$ Mev, Be^7 levels are observed at 4.6 ± 0.2 and 7.1 ± 0.2 Mev (Th 52d).

VII. $Be^9(p\ t)Be^7$ $\quad Q_m = -12.071$

See (Co 54b) and B^{10}.

VIII. $B^{10}(p\ \alpha)Be^7$ $\quad Q_m = 1.147$

The weighted mean of four ground-state Q determinations is 1.148 ± 0.002 Mev (Va 54); this includes a recent value by (Cr 52c) of 1.147 ± 0.0025 Mev. The weighted mean of five determinations of the energy of the first excited state gives 430.3 ± 2 kev [see (Aj 52c) and (Cr 52c)]. A recent determination of the energy of the γ ray from the first excited state gives 432 ± 3 kev [(Da 54); see also C^{11}].

Work at $E_p = 17.9$ Mev indicates α-particle groups corresponding to levels at 0.4, 4.71 ± 0.1, 6.29 ± 0.1, and 7.08 ± 0.1 Mev. The alpha groups corresponding to the two highest levels are strongly peaked in the backward direction (J. B. Reynolds, private communication).

Li^8

(Fig. 7)

I. $Li^8(\beta^-)Be^8$ $\quad Q_m = 15.987$

The half-life is given as 0.825 ± 0.02 sec by (Ra 51), 0.89 ± 0.01 sec by (Bu 53a), 0.875 ± 0.02 sec by (Br 53d),

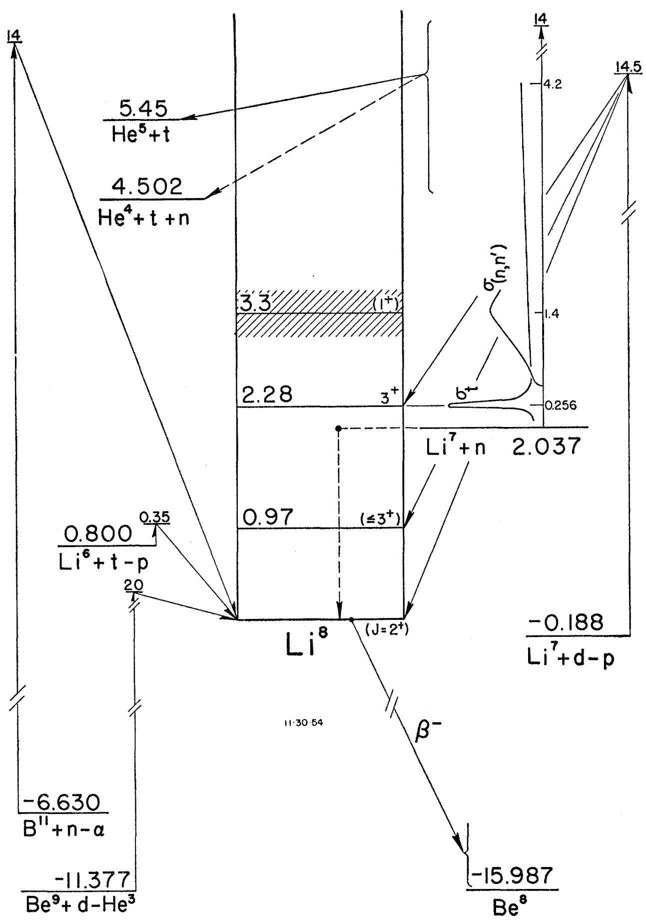


FIG. 7. Energy levels of Li^8: for notation, see Fig. 1.

0.85±0.016 sec by (Sh 52), 0.84±0.04 sec by (Wi 54f), and 0.841±0.004 sec by (Kl 54). The decay is complex; see Be^8. See also (Aj 52c).

II. $Li^6(t\,p)Li^8$ $Q_m=0.800$

$Q_0=0.784\pm0.015$ Mev (Pe 52; mag. analysis).

This reaction has been observed at $E_t=0.24$ Mev (Pe 52) and 0.35 Mev (Mo 52).

III. $Li^7(n\,\gamma)Li^8$ $Q_m=2.037$

The thermal capture cross section is 33±5 mb (Hu 47a). See also (Th 51g) and (Wi 53f).

IV. $Li^7(n\,n)Li^7$ $E_b=2.037$

The coherent scattering amplitude (thermal neutrons) is negative: $\sigma_{\text{coh}}=0.80\pm0.05$ bn, $\sigma_{\text{total}}=1.5\pm0.4$ b (bound atoms, epithermal neutrons) [(Sh 51b) and (Hu 52e)]. The cross section has a sharp peak, $\sigma\sim11.5$ b, at $E_n=256$ kev (Hu 54a). It rises monotonically from 1.2 b at $E_n=0.6$ Mev to 2.0 b at $E_n=3.4$ Mev (Bo 51c) and to 2.5 b at $E_n=4.2$ Mev [see (Jo 54f)]. The average total cross section of elemental Li decreases monotonically from 2.1 to 1.6 b from $E_n=6$ to 9.7 Mev (Ne 54c). The cross section of elemental Li has been measured at eight energies between $E_n=14.1$ and 18.0 Mev (Co 54f). At 14.1 Mev, the total cross section of Li^7 is 1.45±0.03 b (Co 52h).

Parameters for the resonance are:

$E_{\text{res}}=260$, $\sigma_{\text{max}}-\sigma_{\text{pot}}=$ 7 b, $\Gamma=45$ kev (Ad 50a)
$E_{\text{res}}=256$, $\sigma_{\text{max}}-\sigma_{\text{pot}}=10$ b, $\Gamma=40$ kev (St 51f)

The resonance is attributed to a state with $J=3^+$, formed by p-wave neutrons (St 51f). The reduced width γ_n^2 is $0.15\times3\hbar^2/2\mu a^2$ (Vo 54). The angular distribution at and above resonance shows some backward scattering (H. B. Willard, private communication; see also Wi 54 and La 54a).

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

The excitation function for 0.48-Mev γ rays shows an abrupt rise from threshold and a broad ($\Gamma\sim1$ Mev) maximum at $E_n=1.35$ Mev. Near threshold, the behavior of the curve indicates s-wave formation and s-wave emission. The resonance can be fitted on the assumption of incident s and d waves, $J=1^-$, or incident p waves, $J=1^+$, superposed on a strong s-wave background; the latter assignment gives the better fit (Fr 54c).

VI. $Li^7(n\,p)He^7$ $Q_m=-14$

Not observed: see He^7.

VII. $Li^7(n\,d)He^6$ $Q_m=-7.79$ $E_b=2.037$

At $E_n=14$ Mev, the cross section is 9.8±1.1 mb (Ba 53). See also (Fr 54b).

VIII. (a) $Li^7(n\,t)He^5$ $Q_m=-3.41$ $E_b=2.037$
(b) $Li^7(n\,t)He^4+n$ $Q_m=-2.465$

The cross section for reaction (a) is 55±8 mb at $E_n=14$ Mev. The angular distribution of tritons exhibits a forward peak (Fr 54b). The cross section for production of tritium [reactions (a) and (b)] is 72±18 mb for pile neutrons with an estimated effective energy of 3 Mev, and 30±20 mb for Po−Be neutrons (Ma 54f). See also (Ba 54).

IX. $Li^7(d\,p)Li^8$ $Q_m=-0.188$

At $E_d=8$ Mev, the angular distribution of the long-range protons, analyzed by stripping theory, indicates even parity for the ground state of Li^8(Ho 53c). At $E_d=14.5$ Mev, three proton groups are observed, corresponding to the ground state and to levels at 0.974±0.015 Mev and 2.28 Mev. The angular distributions of the protons, analyzed by the stripping theory, indicate $l_n=1$ and therefore even parity, $J\leq3$, for the ground state and the 0.97-Mev level. The cross sections at the maxima of the distributions are 26.1 mb/sterad and 10.2 mb/sterad, respectively, for the formation of these states ($\theta\sim10°$, c.m.) [(Le 54) and (Le 55)].

X. $Be^9(\gamma\,p)Li^8$ $Q_m=-16.871$

See Be^9.

XI. $Be^9(d\,He^3)Li^8$ $Q_m=-11.377$

This reaction has been observed at $E_d=20$ Mev by (Wi 54f).

XII. $B^{11}(n\,\alpha)Li^8$ $Q_m=-6.630$

See B^{12}.

Be^8

(Fig. 8)

I. $Be^8\rightarrow2He^4$ $Q_m=0.096$

A Q of 94.5±1.4 kev is quoted by (Jo 53a). The weighted mean of this and previous measurements is 94±1.3 kev (see Va 54). The half-life is $<5\times10^{-14}$ sec [(Mi 53c); see $C^{12}(\gamma\,\alpha)Be^8$], $<2\times10^{-14}$ sec (Ho 52d). (Tr 54e; see $B^{11}(p\,\alpha)Be^8$) finds $Q=90\pm5$ kev and a half-life $<4\times10^{-15}$ sec. See also (Al 53) and (Ed 52b).

II. $He^4(\alpha\,\alpha)He^4$ $E_b=-0.096$

Measurements of absolute differential cross sections have been made at 18 angles, with an accuracy of 5 to 10 percent, for 10 energies between $E_\alpha=12.88$ and 21.62 Mev. Phase shift analysis indicates states of Be^8 at 7.55±0.08 Mev ($\Gamma=1.2\pm0.4$ Mev, $J=0^+$) and 10.8±0.4 Mev ($\Gamma=1.2\pm0.4$ Mev, $J=4^+$). The d-wave phase shift shows only a slow increase in the range 6 to 12 Mev (c.m.) (St 53). Absolute differential cross

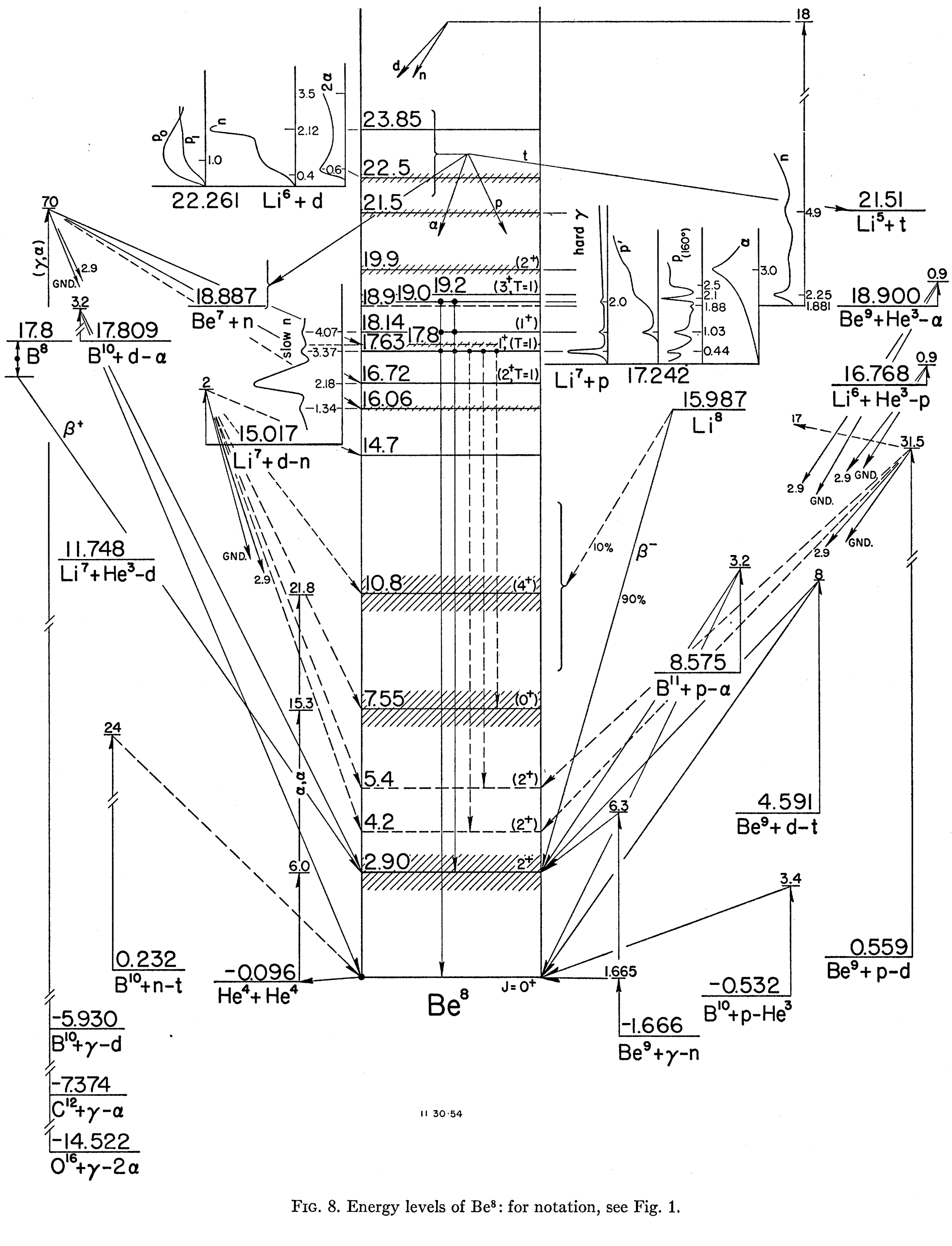


FIG. 8. Energy levels of Be^8: for notation, see Fig. 1.

sections have also been measured with an accuracy of 1 to 2 percent, at 33 angles, for $E_\alpha=22.4$ and 22.8 Mev, at 11 angles for $E_\alpha=21.6$ Mev [(Ke 53), (Br 53a), and (St 53)]. The scattering of 30-Mev α particles on He exhibits a strong angular dependence. The differential cross section is 28 ± 14 mb/sterad at 83° (c.m.) [(Gr 51) and (Gr 52)]. See also (Ed 52b), (Ma 51a), and (Te 53).

III. $Li^6(d\ \gamma)Be^8$ $Q_m=22.261$

Not observed: see (Sa 53b) and (Si 54).

IV. (a) $Li^6(d\ n)Be^7$ $Q_m=3.374$ $E_b=22.261$
(b) $Li^6(d\ n)He^4+He^3$ $Q_m=1.791$

Resonances are observed at $E_d=0.41$ Mev (wide) and 2.12 Mev (sharp) (Ba 52). In the range $E_d=60$ to 450 kev, the cross section for Be^7 production follows the penetration function accurately up to $E_d\sim200$ kev and drops below it thereafter. The branching ratio to the 0.43-Mev state of Be^7 remains substantially constant in this range (Hi 54b).

V. (a) $Li^6(d\ p)Li^7$ $Q_m=5.020$ $E_b=22.261$
(b) $Li^6(d\ p)He^4+H^3$ $Q_m=2.556$

Cross sections have been measured for $E_d=30$ to 250 kev by (Sa 53b), for $E_d<1.8$ Mev by (Wh 50d) and for $E_d=1.0$ to 3.0 Mev by (Ni 54). In the low-energy range, the cross section follows the simple Gamow function, reaching a value of ~10 mb at $E_d=200$ kev (Sa 53b). The excitation function for the ground-state group shows a broad maximum near $E_d=1.0$ Mev and falls slowly to 3 Mev. The yield of short-range protons continues to rise slowly above $E_d=1.0$ Mev [(Wh 50d) and (Ni 54)]. The maximum is interpreted by (Wh 50d) as indicating a level at $E_d=0.4$ Mev, $\Gamma\sim0.5$ Mev. The angular distributions at $E_d=1.0$, 2.0, and 3.0 Mev indicate stripping effects, with $l_n=1$ (Ni 54). See also (Th 52) and (Sa 53a).

VI. $Li^6(d\ d)Li^6$ $E_b=22.261$

See Li^6.

VII. $Li^6(d\ t)Li^5$ $Q_m=0.75$ $E_b=22.261$

In the range $E_d=0.4$ to 4.2 Mev, the cross section increases from 50 to 300 mb (Ma 54j). See Li^5.

VIII. $Li^6(d\ He^3)He^5$ $Q_m=0.83$ $E_b=22.261$

See He^5.

IX. $Li^6(d\ \alpha)He^4$ $Q_m=22.357$ $E_b=22.261$

$Q_0=22.375\pm0.014$ (Ph 53; mag. spectrometer)
$Q_0=22.396\pm0.012$ (Co 53; mag. spectrometer)

Cross sections have been measured for $E_d=30$ to 250 kev by (Sa 53b), for $E_d=60$ to 450 kev by (Hi 54b), and for $E_d=0.2$ to 1.6 Mev by (Wh 50d). Below 200 kev, the curve follows the simple Gamow function; $\sigma\simeq8$ mb at 200 kev [(Sa 53b) and (Hi 54b)]. At $E_d=0.6$ Mev, the cross section exhibits a broad maximum; correction for variation of the penetration factor yields a resonance at $E_d=347$ kev, with $\Gamma\sim520$ kev [(Wh 50d); see, however, (Hi 54b)]. Angular distribution data suggest a $J=2^+$ state in this neighborhood. See (Aj 52c).

X. $Li^6(t\ n)He^4+He^4$ $Q_m=16.100$

See (Cu 52a).

XI. $Li^6(He^3\ p)Be^8$ $Q_m=16.768$

$Q_0=16.60$ (Ku 53b; scin. spectrometer)

At $E(He^3)=720$ kev, proton groups are observed to the ground state of Be^8 and to an excited state at 2.87 ±0.25 Mev. There is no evidence of any other states in Be^8 below $E_x\simeq11$ Mev (Ku 53b). This result is confirmed by (E. Almqvist, private communication) at $E(He^3)=900$ kev.

XII. $Li^7(p\ \gamma)Be^8$ $Q_m=17.242$

The cross section has been studied for $E_p=30$ to 250 kev by (Sa 53b); it follows the Gamow function for this energy region. Resonances are observed at $E_p=441.1$ ±0.5 kev (Bo 48c, Fo 49b, and Kr 54a), 1.03 Mev (Kr 54a and Pr 54b) and 2.0 Mev (Pr 54b), 2.1 Mev (C. E. Mandeville, private communication). Resonance parameters are given in Table I(8). No resonances greater than 3 percent of the 440-kev resonance are observed from $E_p=1.8$ to 5.2 Mev (target thickness 18 kev) above the slowly rising background (Ba 52a).

The course of nonresonant radiation can be accounted for by the assumption of a direct capture mechanism, not involving compound nucleus formation. At the higher energies, >1 Mev, it is assumed that a process inverse to the "giant-resonance," familiar from electric-dipole induced $(\gamma\ n)$ and $(\gamma\ p)$ processes, is involved. A reasonable fit to the experimental curves is obtained with a radius of 3.2×10^{-13} cm and a giant resonance located at 22 Mev with $\Gamma\sim2.3$ Mev. Except for interference from the narrow resonances, the background radiation is expected to be isotropic and to proceed mainly to the 2.9-Mev Be^8 state (Wi 54a).

The γ radiation comprises two main components: $E_\gamma=17.2\pm0.2$ Mev (sharp) and $E_\gamma=14.4\pm0.3$ Mev (broad) with relative intensities which vary with bombarding energy. Both components exhibit resonance at 0.44 Mev (Wa 48). At the 441-kev resonance, the 14.8- and 17.6-Mev γ rays are individually isotropic, within ~6 percent (De 50a, St 51c, and Na 52). This observation is not inconsistent with p-wave formation of a $J=1^+$ state [(De 50a) and (Ch 53d); see also

TABLE I(8). Resonances in $Li^7(p\ \gamma)Be^8$.

E_p (kev)	Be^{8*} (Mev)	Γ (kev)	$\omega\Gamma_\gamma$ (ev)	$\gamma^2/(3\hbar^2/2\mu a)$
441.1 ± 0.5	17.63	12[a] 12.2 ± 0.5[c]	9.4[b]	0.064[d]
1030[e,f]	18.14		2[e]	
2000[f]	19.0			

[a] (Fo 49b) and (Bo 48c).
[b] (Fo 49b).
[c] (Hu 52f).
[d] (Vo 54).
[e] (Kr 54a).
[f] (Pr 54b) and C. E. Mandeville (private communication).

$Li^7(p\,p)Li^7$]. The angular correlation of internally-produced electron-positron pairs at the 441-kev resonance shows that the radiation (mainly the 17.6-Mev component) is magnetic dipole or electric quadrupole, confirming the assignment of even parity to the 17.63-Mev state (De 54b).

Study of $\gamma-\alpha$ coincidences at $E_p=0.44$ Mev reveals three α groups in addition to that resulting from the 14.8-Mev transition (Bu 50h), corresponding to weakly excited levels at 4.2, 5.4, and 7.6 Mev. The associated γ-ray intensities are 1.8 ± 0.3, 1.7 ± 0.3, and 1.0 ± 0.3 percent, respectively, of the total radiation. In the plane perpendicular to the proton beam, the $\gamma-\alpha$ angular correlations have the form $(1+0.85\cos^2\theta)$ for the 4.2- and 5.4-Mev levels and are isotropic for the 7.5-Mev level. For the first two, the results indicate a mixture of $M1$ and $E2$ radiation, $J=2^+$, while the isotropy in the third case suggests $J=0^+$ [(In 53a), (In 54), and E. Titterton, (private communication)]. See also (Na 52), (Go 52a) (Ne 54d), (Ti 53a), and (Ti 54).

The angular distribution off the 441-kev resonance is anisotropic and different for the 14.8- and 17.6-Mev γ rays (suggesting different J for the ground and the 2.9-Mev states), and contains a strong $(\cos\theta)$ term, indicating interference in the neighborhood of the resonance between the resonant (p) waves and other, nonresonant, waves of opposite parity [(De 49d), (St 51c), and (Na 52)]. Angular distributions of the total γ radiation have also been measured at and near the 1.03-Mev resonance. The results show anisotropy, and a study of the coefficients appears to indicate interference by nonresonant waves with at least two components of opposite parity (Kr 54a). See also (Aj 52c), (Fo 54a), and (Gl 54a).

XIII. $Li^7(p\,n)Be^7$ $Q_m=-1.645$ $E_b=17.242$

The neutron yield indicates a resonance near threshold (Ne 54; see also Ba 51e and Bo 51b), and at $E_p=2.25$ Mev, $\Gamma\sim0.2$ Mev, $\sigma_{\max}-\sigma_{\min}=0.25$ b [(Ta 48) and (Ad 54)], and $E_p=4.89$ Mev, $\Gamma\sim0.4$ Mev [(Ba 52a) and (Bl 51a)].

The angular distribution in the range $E_p=2.0$ to 2.5 Mev exhibits a strong $(\cos\theta)$ dependence, with a coefficient which changes rapidly in the neighborhood of the 2.25-Mev resonance, suggesting interference of entering waves of opposite parity (Ta 48). In an analysis by (Br 48a) it was assumed that the resonance is formed by s-wave protons with p waves contributing a broad background. An additional odd-parity level just below the reaction threshold was required to account for the behavior of the cross section near threshold. (Ad 54) finds that a good fit to the resonant part of the cross section can be obtained by assuming p-wave formation of a $J=3^+$ level using equal reduced widths $\gamma_p^2=\gamma_n^2=0.8\times10^{-13}$ Mev cm (2.5 percent of the sum rule limit) as derived from the observed width of the presumed analog 2.28-Mev level of Li^8. A satisfactory account of the nonresonant cross section and of the angular distribution requires two further states, formed by s waves, with $J=1^-$ and 2^- and $T=0$ (opposite to that of the 3^+ state) with undetermined location. A preliminary measurement of the polarization of neutrons produced at $E_p=2.23$ Mev is in agreement with calculations based on these parameters (Ad 54). (Wi 54c) find a polarization of 0.50 ± 0.04 at $\theta=42°$ for neutrons in the energy range of 0.3 to 0.55 Mev; above and below these energies, the polarization decreases slowly. See also (Ad 54a) and (Er 54a).

XIV. $Li^7(p\,p)Li^7$ $E_b=17.242$

The elastic scattering exhibits anomalies at $E_p=0.44$, 1.03, 1.9, 2.1, and 2.5 Mev [(Br 51a), (Ba 51e), (Wa 53), and P. Malmberg, private communication]. Absolute differential cross sections are reported for 7 angles in the energy range $E_p=0.36$ to 1.4 Mev (Wa 53) and at 6 angles for $E_p=1.35$ to 3.04 Mev (P. Malmberg, private communication). At $E_p=441$ kev, the observed scattering varies from 1.18 times Rutherford at $\theta=50°$ c.m. to 2.16 times Rutherford at $\theta=160°$ (Wa 53). Analysis in terms of s-wave and p-wave phase shifts establishes that the resonance has $J=1^+$ and is formed by p-wave protons with channel spins 1 and 2 in a ratio of 1 to 5. This ratio may correspond either to a pure $j-j$ state, with a $p_{\frac{1}{2}}$ proton $(\frac{3}{2},\frac{1}{2})_1$ or a pure $L-S$ state of the character $^3S_1$ or $^3P_1$; in either case isotropy of the capture γ radiation is guaranteed [(Li 53a), (Ch 53d), and D. A. Liberman, private communication].

At the $E_p=1.03$-Mev resonance, the observed elastic scattering cross section varies from 1.08 times Rutherford at $\theta=50°$ (c.m.) to 6.54 times Rutherford at $\theta=160°$ (Wa 53). The analysis is in agreement with a 1^+ resonance, again with a channel spin ratio of about 1:5 (D. A. Liberman, private communication). A cusp in the elastic scattering cross section curve (six angles) at the $Li^7(p\,n)Be^7$ threshold appears as a distinct peak for $\theta=70°$ to 130° (four angles, c.m.) and as a cusp at 150° and 167° (c.m.) (P. Malmberg, private communication). The structure near 2.1 Mev may be connected with the $Li^7(p\,\gamma)Be^8$ resonance at 2.0 Mev; the magnitude of the cross section (at 166°) is compatible with a $J=3^+$ assignment, and it is suggested that this, rather than the 2.25-Mev resonance observed in $Li^7(p\,n)Be^7$ is the $T=1$ state analogous to the 2.28-Mev state of Li^8 [see, however (Ad 54)].

XV. $Li^7(p\,p)Li^{7*}$ $E_b=17.242$
$Li^7(p\,p'\gamma)Li^7$

A pronounced resonance appears in the yield of inelastically scattered protons [(Br 51a) and (Mo 54a)] and 477-kev γ rays (Kr 54a) at $E_p=1.030\pm0.005$ Mev, $\Gamma=168$ kev. The absolute differential cross section for the inelastic scattering of protons has been measured at 10 angles near the resonance. It is nearly isotropic at $E_p \sim 1.03$ Mev, whereas at higher energies it is peaked in the backward direction. The total cross section for inelastic scattering is 41.6±3 mb at $E_p=1.05$ Mev, 35.4±2.8 mb at $E_p=1.14$ Mev, and 32.0±2.7 mb at $E_p=1.24$ Mev. The spherical symmetry at resonance and the asymmetry above it are consistent with either an s- or a p-wave resonance interfering with a nonresonant wave of opposite parity (Mo 54a). From $E_p=1.5$ to 3.5 Mev, the differential cross section at $\theta=164°$ rises smoothly except for a change in slope between 2.2 and 2.3 Mev (Ba 51e).

XVI. $Li^7(p\ d)Li^6$ $Q_m=-5.020$ $E_b=17.242$

See Li^6.

XVII. $Li^7(p\ \alpha)He^4$ $Q_m=17.337$ $E_b=17.242$

The weighted mean of experimental Q values is given as 17.346±0.010 Mev by (Va 54). This value includes two recent determinations: 17.344±0.013 Mev [(Fa 53); mag. spectrometer] and 17.352±0.009 Mev [(Co 53); mag. spectrometer].

The cross section has been measured for $E_p=30$ to 250 kev by (Sa 53b) and from $E_p=0.5$ to 3.75 Mev by (He 48e). The yield has a broad maximum at $E_p=3$ Mev [(He 48e) and (He 48g)]. Analysis of angular distributions indicates a level ~1 Mev broad, possibly at $E_p=3$ Mev, with $J=2^+$, and a several Mev broad level of $J=0^+$, underlying the region (In 48 and He 48e). See also (Hi 51a), (Ta 51a), (Hi 52a), (Ca 53d), and (Al 54d).

XVIII. $Li^7(d\ n)Be^8$ $Q_m=15.017$

A study of the neutron groups at several angles by means of a neutron spectrometer indicates a single broad level at $E_x=3.0$ Mev below $E_x \sim 8$ Mev superposed on a continuum attributed to the $2He^4+n$ breakup. Neutron groups corresponding to an excitation of 4 or 5 Mev would have been resolved if they had ten percent of the intensity of the ground-state group. A group leaving Be^8 with an excitation of 7.5 Mev would have been observed if it were twenty percent as intense as the ground-state group [(Tr 54b) and C. H. Johnson, private communication]. Work with photoplates has indicated levels at 2.3, 2.9, 4.1, 4.9, and 7.6 Mev [see, for instance, (Tr 53a)] as well as states at 10 Mev (Ri 41), 11.1, and 14.7 Mev (Wh 50c). A 4.9±0.3 Mev γ ray which had previously been assigned to Be^8 is now believed to be from the first excited state of C^{12} [see $C^{12}(n\ n')C^{12*}$]. At $E_d=0.68$ Mev, upper limits for the production of 5-, 6-, and 7-Mev γ radiation are <2 mb, <1 mb, and <0.5 mb, respectively (Si 54).

Thresholds for slow neutron production observed by (Bo 54c) are given in Table II(8). It is suggested that the prominent peak at $E_d=2.18$ Mev corresponds to the first $T=1$ level of Be^8 [see $C^{12}(\gamma\ \alpha)Be^8$] and that the sharp rise at $E_d=3.37$ and broad maximum at $E_d=4.07$ Mev correspond to the 0.44- and 1.03-Mev resonances observed in $Li^7(p\ \gamma)Be^8$. The fact that the slow neutron yield decreases only rather slowly after the rise at $E_d=3.37$ Mev is attributed to a possible threshold at $E_d=3.6$ Mev (Bo 54c).

A search for pairs in the range $E_\pi=5.0$ to 8.5 Mev at $E_d=0$ to 330 kev led to a negative result; an upper limit for the cross section is 0.02 μb (Bent, Sippel, and Bonner, private communication). See also [(Tr 52a), (Ca 53e), (Th 53), (Re 54b), and (Tr 54d)].

TABLE II(8). Slow neutron thresholds in $Li^7(d\ n)Be^8$ (Bo 54c).

E_d (Mev)	Q (Mev)	Be^{8*} (Mev)	Γ (kev)
1.34	−1.04	16.06	600
2.18	−1.70	16.72	190
3.37	−2.63	17.65	<20
3.6	−2.8	17.8	100
4.07	−3.17	18.19	170

XIX. $Li^7(He^3\ d)Be^8$ $Q_m=11.748$

See (Ku 54) and (Mo 54d).

XX. $Be^7(n\ p)Li^7$ $Q_m=1.645$ $E_b=18.887$
$Be^7(n\ \alpha)He^4$ $Q_m=18.983$

At thermal neutron energies, proton emission is more probable than alpha emission. This result is consistent with the odd parity of Be^7. The $(n\ p)$ cross section is 50 000 b (Ha 53f). (Ad 54) estimates a theoretical upper limit for this cross section of 18 500 b, assuming a single resonance.

XXI. $Li^8(\beta^-)Be^8$ $Q_m=15.987$

The α-particle distribution indicates decay through a state at 3.1 Mev, $\Gamma=0.8$ Mev (Bo 48), 2.98±0.06 Mev, $\Gamma=1.26$ Mev (W. Whaling and C. W. Li, private communication), and 2.9 Mev, $\Gamma=1.2$ Mev (Gi 54). In addition to decay through the 2.9-Mev state, (Fr 54d) indicate a possibility of decay through states of Be^8 at 4.3 and 7.4 Mev. The β spectrum indicates about 90 percent of the transitions going to the 2.9-Mev state and less than 2 percent to the ground state (Ho 50). The shape of the α and β spectra suggest the involvement of states of higher excitation in Be^8.

The $\alpha-\beta$ angular correlation is isotropic within 3 percent for all fractions, $E_\beta=0.1$ to 0.9 E_β(max); in the correlation expression $1+A\cos^2\theta$, $A=0.01\pm0.03$ (Ha 54d). For $E_\beta=9.8$ and 7.5 Mev, (Bu 53a) reports $A=0.04\pm0.2$ and 0.12±0.09 respectively. An isotropic distribution is consistent with a spin of 2^+ for Li^8 and 2^+ for the 2.9-Mev Be^8 state; a spin of zero for the 2.9-Mev state would also guarantee isotropy. Gamma-beta coincidences to the extent of 2±1 percent are reported by (Ve 51b) and (Ve 52a). (Bu 53a) reports an upper limit of 0.8±0.3 percent on the number of disintegrations leading to 4.9-Mev γ radiation. Logft for the transition to the 2.9-Mev state is 5.60 (Fe 51b). See also (Ga 51a), (Cl 53), and (Wi 53i).

XXII. $B^8(\beta^+)Be^8$ $Q_m=17.8$

It appears that B^8 decays mainly to the 2.9-Mev level of Be^8: $\log ft=5.54$ (Ki 52); the α-particle spectrum is similar to that of Li^8 [(Al 50g) and (Gi 54)].

XXIII. $Be^9(\gamma\, n)Be^8$ $Q_m=-1.666$

The weighted mean of three determinations is $Q=-1.665\pm0.002$ Mev (Va 54); this includes a recent value of -1.662 ± 0.003 Mev by (No 54; neutron threshold). At $E_\gamma=6$ Mev, most of the neutrons leave Be^8 in the 2.9-Mev state [(Ca 54e); see also Be^9].

XXIV. $Be^9(p\, d)Be^8$ $Q_m=0.559$

The weighted mean of eight Q-value determinations is 0.559 ± 0.001 Mev (Va 54). This includes a recent value of 0.560 ± 0.003 Mev by (Co 53; mag. spectrometer).

For $E_p=5$ to 8 Mev (Ha 51a), 18 Mev (Re 54a), and 22 Mev (Co 53e), the ground-state deuterons are strongly peaked forward. The angular distribution at $E_p=18$ Mev has been analyzed by pickup theory by (Re 54a) who find $l=1$ in agreement with odd parity for Be^9 and even parity $J<4$ for Be^8 [see also B^{10} and (Da 54a)]. At $E_p=8$ Mev, peaks observed in the spectrum of charged particles have been tentatively attributed to deuterons leading to levels in Be^8 at 2.9, 4.0, and 5.1 Mev (Ar 52e). See also (St 53d).

At $E_p=31.5$ Mev, deuteron groups corresponding to the ground state, the 2.9-Mev level, and a group of levels near 17 Mev have been identified [(Be 54c) and J. Benveniste, private communication].

XXV. (a) $Be^9(d\, t)Be^8$ $Q_m=4.591$
(b) $Be^9(d\, t)He^4+He^4$ $Q_m=4.687$

The weighted mean of five Q-value determinations for reaction (a) is 4.598 ± 0.012 Mev (Va 54). This includes a recent value of 4.60 ± 0.03 Mev obtained by [(Ca 52b); photoplate].

At $E_d\sim1$ Mev a pronounced triton group corresponding to the ground state is observed in addition to a continuum of α particles, corresponding to formation of the 2.9-Mev state of Be^8 and its subsequent breakup; see also $Be^9(d\,\alpha)Li^7$. The excited state is formed about twice as frequently as the ground state. The three-body reaction (b) appears not to occur [(Cu 52), (Cu 53), and (Ge 53); see also Li^7].

The angular distribution of ground-state tritons is reported by (De 52b): $E_d=0.15$ to 0.62 Mev, by (Re 51a): $E_d=0.6$ to 0.7 Mev, by (Ju 53): $E_d=1.16$ Mev, by (Cu 53): $E_d=1.3$ Mev, by (Fu 52): $E_d=3.6$ Mev, by (El 51): $E_d=7.7$ Mev, and by (Ho 53c): $E_d=8$ Mev. The distributions exhibit a pronounced forward bunching, suggesting that a pickup process occurs, with an l transfer of 1 [see e.g. (Ho 53c)]. See also B^{11} and (Ba 53c).

XXVI. $Be^9(He^3\,\alpha)Be^8$ $Q_m=18.900$

At $E(He^3)=900$ kev, alpha-particle groups are observed corresponding to the ground state (weak) and to the 2.9-Mev level (strong, broad) (E. Almqvist, private communication). See also (Mo 54b).

XXVII. (a) $B^{10}(\gamma\, d)Be^{8*}\rightarrow He^4+He^4$ $Q_m=-5.930$
(b) $B^{10}(\gamma\, np)He^4+He^4$ $Q_m=-8.155$

Reaction (a) is believed to occur and to involve excited states of Be^8. The ground-state transition is not observed at $E_\gamma=15$ to 18 Mev. Reaction (b) has been observed (Er 53). See also (Ge 53a), (Mu 52a), (Aj 52c), $B^{11}(\gamma\, t)Be^8$, and B^{10}.

XXVIII. $B^{10}(n\, t)Be^8$ $Q_m=0.232$

See (Ja 54), (Pe 51b), and (Ri 54a).

XXIX. $B^{10}(p\, He^3)Be^8$ $Q_m=-0.532$

$Q_0=-0.536\pm0.003$[(Cr 52c); electrostatic analyzer].

XXX. (a) $B^{10}(d\,\alpha)Be^8$ $Q_m=17.809$
(b) $B^{10}(d\,\alpha)He^4+He^4$ $Q_m=17.905$

The weighted mean of four experimental Q values is 17.86 ± 0.04 Mev (Va 54); this includes two values of 17.91 ± 0.06 by (Tr 53; ion chamber), 17.87 ± 0.06 Mev by (Cu 53b; photoplate). A recent value is 17.829 ±0.010 Mev by (El 54; mag. spectrometer). All observers agree that transitions occur to the ground state and to a state at 2.73 ± 0.2 Mev [(Wh 51b); $\Gamma=0.95$ ±0.20 Mev], 2.88 ± 0.08 Mev (Tr 53) and 2.87 ± 0.08 Mev [(Cu 53b), (Cu 54); $\Gamma=0.9\pm0.2$ Mev].

(Tr 53) finds that the shape of the α spectrum (omitting the ground-state peak) can be fitted by a Breit-Wigner single level formula: $J=2^+$ gives a slightly better fit than $J=0$: the reduced width $\gamma^2=13.4\times10^{-13}$ Mev-cm [of the order of 2 times the sum-rule limit], $E_\lambda=5.29$ Mev, with $J=2$, $a=4.48\times10^{-13}$ cm. An excess of α particles in the experimental spectrum in the region corresponding to $E_x\sim7$ Mev may be due to $B^{10}(d\; 3\alpha)$ or to a broad resonance. There is no evidence in this work for further peaks ($E_d=0.6$ to 1.07 Mev; Tr 53).

At $E_d=1$ Mev, $\theta=0°$, 30°, 60°, 90°, and 120°, groups are reported corresponding to states at 4.1, 5.1, 6.2(?), 7.5, 9.2, and 11.5 Mev in addition to the ground state and 2.9-Mev state groups [(Cu 53b), (Cu 54), and J. J. Jung, private communication]. (Ho 54e), on the other hand, find no evidence for any excited states below 10 Mev except the broad 2.9-Mev state. Observations were made with a magnetic spectrometer at several angles, with $E_d=2$ to 3.2 Mev. The three-particle reaction (b) has not been observed. At $E_d=1$ Mev it is less than 5 percent of the intensity of reaction (a) (Cu 53b).

At $E_d=0.6$ Mev, a search has been made for $\alpha-\gamma$ correlations from a 4.9-Mev state in Be^8. The upper limit of the alpha group intensity to such a state is 5 percent of the intensity to the ground state and the 2.9-Mev level (Th 53). See also (Ju 53a).

XXXI. (a) $B^{11}(\gamma\, t)Be^8$ $\quad Q_m = -11.227$
(b) $B^{11}(\gamma\, t)He^4 + He^4$ $\quad Q_m = -11.131$

These reactions have been observed in boron-loaded photographic emulsions. Reaction (a) is stated to involve states in Be^8 at 0, 2.2, 2.9, 3.4, 4.0, and 4.9 Mev. Reaction (b) has been observed (Er 53). See also B^{11}, (Mu 52a) and (Aj 52c).

XXXII. $B^{11}(p\, \alpha)Be^8$ $\quad Q_m = 8.575$

A recent Q-value determination is 8.589 ± 0.005 [(Co 53); mag. spectrometer]. The weighted mean is 8.585 ± 0.006 (Va 54), 8.579 ± 0.009 Mev (Jo 53a). A value of 94.5 ± 1.4 kev is found for the breakup energy of Be^8 produced in this reaction (Jo 53a).

Alpha groups corresponding to states at 0, 2.2, 2.9, 3.4, 4.0, and 4.9 Mev are reported by (Gl 53). Work with a high-resolution magnetic spectrometer sets an upper limit of 10 percent for any such groups other than the ground state and the broad 2.9-Mev level [(Ma 53g); $E_p = 1.98$ and 2.61 Mev; see also (Be 53)]. The energy of the excited state is given as 2.94 ± 0.06 Mev, $\Gamma = 1.1$ Mev [(Li 51) and W. Whaling, private communication]; $\Gamma = 0.84$ Mev (Be 53). For $E_p = 2$ to 3.2 Mev, no levels are observed between the ground state and $E_x = 10$ Mev except for the 2.9-Mev state (Ho 54e).

The ground-state α particles are strongly anisotropic at the $E_p = 0.16$ Mev (C^{12*}: $J = 2^+$, $T = 1$) resonance. It is thus unlikely that the ground state of Be^8 has $J = 2$ (Th 52c). The angular correlation of α particles leading to the 2.9-Mev state with those resulting from the break-up of Be^{8*}, observed at $E_p = 163$ kev, is consistent with the assignment $J = 2^+$ but not with $J = 0^+$ (Ge 54a). The fact that the α particles leading to the 2.9-Mev state are 50 times as intense as the ground-state group may indicate a difference in the isotopic spin purity of these two states (Be 53). Study of the directional correlation of successively emitted α particles indicates $J = 0$ for the ground state of Be^8 (Tr 54d; see $Be^8 \rightarrow 2He^4$). See also (Hu 53, Gl 54, Gl 54a, and Gl 54b).

At $E_p = 7.9$ Mev, nuclear pairs are reported with $E_\pi \sim 7$ Mev [(Ph 51b); see however $Li^7(d\, n)\, Be^8$].

XXXIII. (a) $C^{12}(\gamma\, \alpha)Be^8$ $\quad Q_m = -7.374$
(b) $C^{12}(n\, n')3He^4$ $\quad Q_m = -7.278$

The cross section for reaction (a) exhibits pronounced peaks at $E_\gamma \sim 18$ and ~ 28 Mev (possibly with fine structure; see C^{12}). For energies less than 20 Mev, the process proceeds predominantly, more than 75 percent, via the 2.9-Mev level of Be^8 [(Te 50c), (Mi 53c), and (Wi 55)]. No significant deviation from isotropy is found in the angular distributions by (Mi 53c). (Te 51b) and (Ed 52) find, on the other hand, that the shape of the α spectrum indicates some correlation and suggest that the transition involves $E2$ and $M1$ absorption, $J = 2^+$ for the Be^8 state. The small participation of the ground state suggests $J = 0^+$. A $J = 1^+$ state of C^{12} formed by $M1$ absorption, cannot disintegrate via a $J = 0^+$ state of Be^8. (Wi 55), analyzing some 2500 stars, find that the angular correlations indicate $E1$ and $E2$ absorption (see C^{12}) with little or no contribution from $M1$ except for $E_\gamma < 15.6$ Mev. It is suggested that the dominance of the 2.9-Mev state may be explained by a relatively small admixture of $T = 1$ in this state. There are indications of participation of Be^8 states at 4.0 ± 0.1, 6, 10, and 15 Mev, particularly for $E_\gamma = 25$ to 26 Mev (Wi 55).

Analysis of 200 stars produced by γ rays of energy > 26 Mev, indicates that about 2 percent involve transitions through the ground state of Be^8, 10 percent states in the range 3 to 16 Mev and 88 percent states near 17 Mev. Two levels of Be^8 are reported in this region, at 16.8 ± 0.2 and 17.6 ± 0.2 Mev, both with $\Gamma < 0.3$ Mev: a third level, at 16.4 Mev, may also exist. Angular correlation experiments indicate electric dipole absorption and $J = 2^+$ for the 16.8-Mev level and $J = 2^+$ or possibly $J = 0^+$ for the 17.6-Mev level. An upper limit of $\frac{1}{4}$ is set for the probability of γ emission for both levels. The observation that $E1$ absorption dominates, and the high fraction of transitions to the 17-Mev states suggests that they have $T = 1$ [(Wi 53e), (Wi 55), and J. J. Wilkins, private communication; see also (Ge 53a)]. [No evidence for a state near 17.6 Mev, other than the $J = 1^+$ state, is seen in $Li^7(p\, p)Li^7$; see (Wa 53).] The lifetime of Be^8, obtained from examination of $C^{12}(\gamma\, \alpha)Be^8$ stars, is $< 5 \times 10^{-14}$ sec (Mi 53c).

For reaction (b), see C^{12}. See also (Da 53d), (Li 53b), and (Gl 54b).

XXXIV. $O^{16}(\gamma\, \alpha)C^{12*} \rightarrow Be^8 + He^4$ $\quad Q_m = -14.522$

At $E_\gamma \sim 22$ Mev, the reaction appears to proceed mainly via the 9.6-Mev state of C^{12} to the ground state of Be^8. For $E_\gamma > 24$ Mev, transitions through a 16-Mev, $T = 1$ state of C^{12}, to the 2.9-Mev state of Be^8 appear to dominate. See (Ge 53a), (Hs 53), (Mi 53c), (Li 53b), (Li 52c), (Go 52a), and (Da 53d).

B^8

(Not illustrated)

I. $B^8(\beta^+)Be^8$ $\quad Q_m = 17.8$

The half-life is 0.46 ± 0.03 sec [see (Ho 53a)], 0.61 ± 0.11 sec (Sh 52). The decay is complex; see Be^8.

II. $B^{10}(p\, t)B^8$ $\quad Q_m = -18.3$

The threshold is $E_p \leq 21.2$ Mev (Al 50g).

The reaction $Li^6(He^3\, n)B^8$ ($Q_m = -1.8$ Mev) is not reported.

Li^9

(Not illustrated)

I. $Li^9(\beta^-)Be^{9*}\rightarrow Be^8+n$ $Q_m=12.4$

Li^9 decays to excited states of Be^9 which decay by neutron emission. The half-life is 0.168 ± 0.004 sec (Ga 51c), 0.170 ± 0.005 sec (Ho 52b). See also (Sh 52) and (Fr 53a).

II. $Be^9(d\ 2p)Li^9$ $Q_m=-15.5$

The threshold is 19 ± 1 Mev (Ga 51c).

III. $B^{11}(\gamma\ 2p)Li^9$ $Q_m=-31.4$

See (Sh 52).

IV. $C^{12}(\gamma\ 3p)Li^9$ $Q_m=-47.3$

See (Re 53).

The following reactions are not reported: $Li^7(t\ p)Li^9$ ($Q_m=-2.9$), $Be^9(n\ p)Li^9$ ($Q_m=-13.3$), $Be^9(t\ He^3)Li^9$ ($Q_m=-14.1$), and $B^{11}(n\ He^3)Li^9$ ($Q_m=-23.6$).

Be^9

(Fig. 9)

I. (a) $Li^6(t\ d)Li^7$ $Q_m=0.988$ $E_b=17.670$
(b) $Li^6(t\ p)Li^8$ $Q_m=0.800$
(c) $Li^6(t\ n)Be^8$ $Q_m=16.004$
(d) $Li^6(t\ \alpha)He^5$ $Q_m=15.15$
(e) $Li^6(t\ n)He^4+He^4$ $Q_m=16.100$

At $E_t=240$ kev, $\theta=90°$, the ratio of the long-range to the short-range deuteron group is 54:14. Protons from

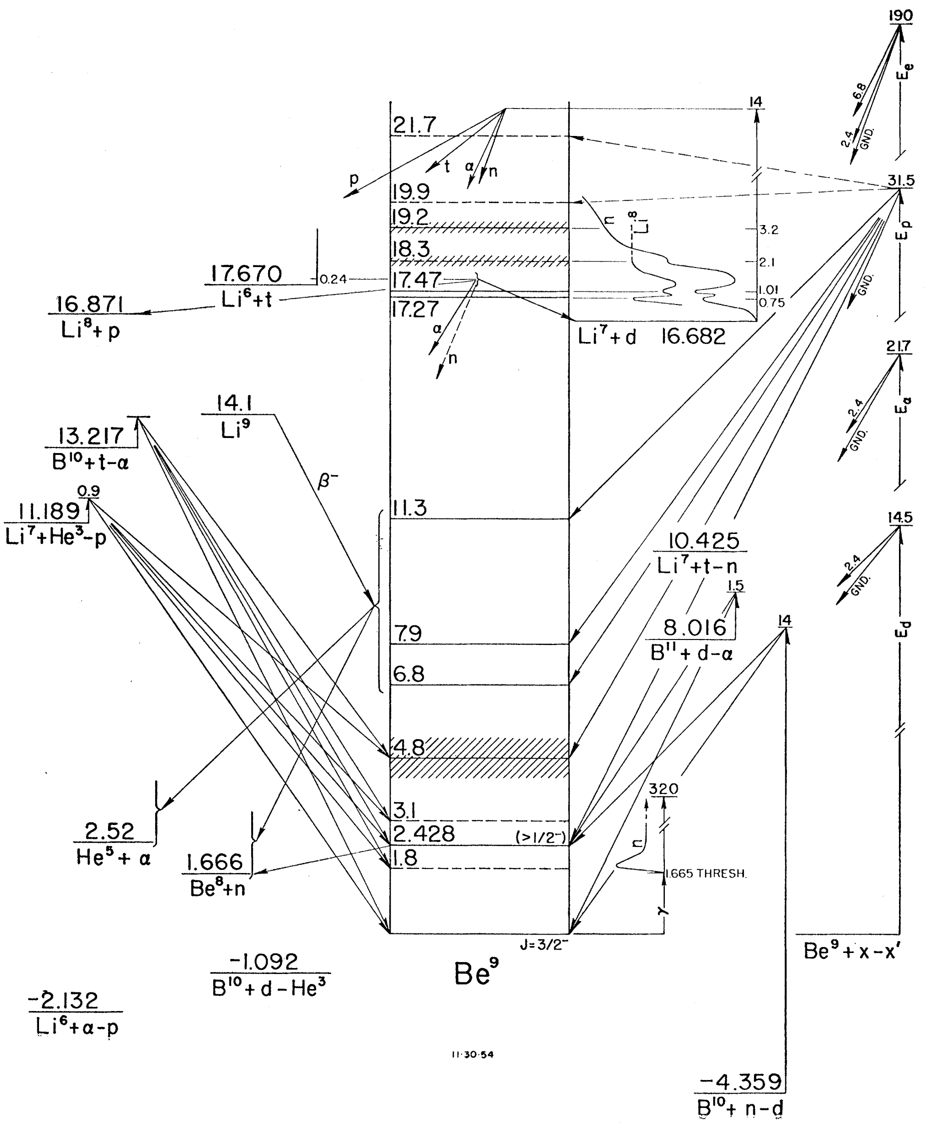


FIG. 9. Energy levels of Be^9: for notation, see Fig. 1. There is no evidence for the state at 19.2 Mev.

reaction (b) have intensity 2 on the same scale (Pe 52). A continuum of α particles from reactions (b), (c), (d), or (e) is also observed (Pe 51). See also (Mo 52).

II. $Li^6(\alpha\ p)Be^9$ $Q_m=-2.132$

Not observed: see B^{10}.

III. $Li^7(d\ p)Li^8$ $Q_m=-0.188$ $E_b=16.682$

Absolute cross sections have been measured for $E_d=0.7$ to 3.3 Mev by (Ba 54a). Resonances are observed at 0.80 and 1.04 Mev with peak cross sections of 0.15 and 0.12 b, respectively. Above 1.1 Mev the cross section rises monotonically, becoming essentially constant at 0.16 b above 1.8 Mev. The abrupt change of slope at 1.4 Mev, attributed by (Ba 52) to a resonance, is not confirmed, and it is suggested that the behavior of the cross section in this region reflects the increasing importance of the stripping process. Absolute cross sections reported by (Ba 54a) are about a factor of two lower than those of (Ba 52).

IV. (a) $Li^7(d\ n)Be^8$ $Q_m=15.016$ $E_b=16.682$
(b) $Li^7(d\ \alpha)He^5$ $Q_m=14.16$
(c) $Li^7(d\ n)He^4+He^4$ $Q_m=15.112$

The cross section for reaction (a) has been measured for $E_d=70$ to 110 kev by (Ra 54b). It follows the Gamow function as does the cross section for reaction (c) in the range $E_d=30$ to 250 kev (Sa 53b). Resonances for neutrons occur at $E_d=0.68$, 0.98, and 2.1 Mev; the cross sections are 39, 43, and 58 mb/sterad, and the widths are 0.25, 0.060, and 0.4 Mev, respectively (Ba 52). See also: Be^8 and He^5 and (Tr 53a).

V. (a) $Li^7(d\ d)Li^7$ $E_b=16.682$
(b) $Li^7(d\ t)Li^6$ $Q_m=-0.988$
(c) $Li^7(d\ He^3)He^6$ $Q_m=-4.52$

The cross section for reaction (b) is $\sim$100 mb at $E_d=2.5$ Mev (Ma 54a). For reactions (a) and (c), see Li^7 and He^6.

VI. $Li^7(He^3\ p)Be^9$ $Q_m=11.189$

At $E(He^3)=720$ kev, proton groups are observed corresponding to states in Be^9 at 1.8, 2.4, 3.2, and 4.9 Mev; the last of these would appear to be 0.5–1 Mev broad (Mo 54d) and (Ku 54). These states have also been observed at $E(He^3)=900$ kev by K. W. Allen and E. Almqvist (private communications) who find the two states at 2.4 and 3.2 Mev to be sharp ($\Gamma<100$ kev). No further levels were observed up to $E_x\sim9$ Mev. The indications of several low-lying states in Be^9 are not in contradiction with predictions of the shell model with intermediate coupling [(In 53) (the ^2P level in Fig. 9 of In 53 has been drawn 4 units too low, D. R. Inglis, private communication).]

VII. $Li^9(\beta^-)Be^{9*}\rightarrow Be^8+n$ $Q_m=12.4$

See Li^9.

VIII. (a) $Be^9(\gamma\ n)Be^8$ $Q_m=-1.666$
(b) $Be^9(\gamma\ \alpha)He^5$ $Q_m=-2.52$
(c) $Be^9(\gamma\ n)He^4+He^4$ $Q_m=-1.570$

The cross section for neutron production exhibits a peak of 1.0 mb at $E_\gamma\sim1.7$ Mev, and a minimum near $E_\gamma=2.2$ Mev rising to $\sim$0.7 mb at 2.76 Mev (Gu 49a). At $E_\gamma=2.185$ Mev, $\sigma=0.39\pm0.06$ mb (Ha 53b). The curve passes through a broad maximum near 10 Mev, $\sigma\sim1.6$ mb, falling to $\sim$0.8 mb at 17 Mev and rising to a peak of $\sim$3.0 mb at 22 Mev (Na 53a); see also (Jo 53f). At $E_\gamma=6.3$ and 8.1 Mev, the cross sections are 1.14 ± 0.1 and 1.38 ± 0.16 mb, respectively [(Wi 54b) and R. D. Edge and D. H. Wilkinson, private communication)]. The course of the cross section and angular distribution in the range $E_\gamma=1.7$ to 3 Mev are accounted for by a single-particle model, assuming electric dipole transitions to an $S_{\frac{1}{2}}$ level $\sim$0.1 Mev below threshold and a broad $D_{\frac{5}{2}}$ level at an energy >2.5 Mev (Gu 49a).

At $E_\gamma=6.1$ Mev, the cross section for neutron production is given by (Ca 54e) as 1.25 ± 0.12 mb. The cross section for production of α particles of energy greater than 0.4 Mev is 1.28 ± 0.25 mb, indicating that less than 20 percent of $(\gamma\ n)$ processes at this energy involve the ground state of Be^8. From the coincident α spectrum, it is concluded that the main processes are $Be^9(\gamma\ n)Be^{8*}$ (2.9-Mev state) and $Be^9\ (\gamma\ \alpha)He^5$ ground state, produced in ratio 1.2 to 1 (Ca 54e).

The cross section for reaction (c) is <1 mb at $E_\gamma=1.63$ Mev (Al 52a).

IX. $Be^9(\gamma\ p)Li^8$ $Q_m=-16.871$

The integrated cross section to 26 Mev is 13 Mev-mb. The yield has a broad maximum, $\Gamma=4.7$ Mev, at $E_\gamma=22.2$ Mev where $\sigma=2.72$ mb (Ha 53).

X. (a) $Be^9(\gamma\ d)Li^7$ $Q_m=-16.682$
(b) $Be^9(\gamma\ t)Li^6$ $Q_m=-17.670$
(c) $Be^9(\gamma\ \alpha)He^5$ $Q_m=-\ 2.52$

The integrated cross section for reactions (a) and (b) is ≤0.1 Mev-b for E_γ to 31 Mev (P. Stoll and P. Erdös, private communication). For reaction (C), see $Be^9(\gamma\ n)Be^8$.

XI. $Be^9(e\ e')Be^{9*}$

At $E_e=190$ Mev, inelastic electron groups are observed corresponding to levels of Be^9 at 2.54 and 6.96 Mev (Mc 54a).

XII. $Be^9(n\ n')Be^{9*}$

See (Gr 51a) and (Sc 54c).

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

The first inelastic proton group locates a level at 2.433 ± 0.005 Mev [(Br 51f); see also (Aj 52c)]. No other group is observed for $E_x<6$ Mev (Ar 52e) (weak groups corresponding to levels at ~1.6 and ~3 Mev do not appear to be excluded by this spectrum). At $E_p=7.1$ (Da 52e) and 7.5 Mev (St 53d), the inelastically scattered protons to the 2.4-Mev state are peaked in the forward direction. The width of the 2.4-Mev state is <3 kev (Br 51f).

At $E_p=31.5$ Mev, proton groups are reported corresponding to the ground state and states at 2.5 ± 0.2, 6.8 ± 0.3, and 11.6 ± 0.4 Mev by (Br 52c), and to states at 2.45, 5.0, 6.8, 7.9, 11.3, 19.9(?), and 21.7(?) Mev by (Be 54c) and J. Benveniste (private communication). There is no indication in this work of levels near 1.8 or 3.0 Mev.

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

At $E_d=14.5$ Mev, deuteron groups have been observed to the ground state and to the 2.4-Mev state (J. N. McGruer, private communication).

XV. $Be^9(\alpha\,\alpha')Be^{9*}$

At $E_\alpha=21.7$ Mev, a group corresponding to a level at 2.63 ± 0.15 Mev is observed (Mc 51b).

XVI. (a) $B^{10}(\gamma\,p)Be^9$ $Q_m=-6.585$
(b) $B^{10}(\gamma\,p)Be^8+n$ $Q_m=-8.250$

Reaction (a) has not been reported. For reaction (b) see Be^8 and B^{10}.

XVII. $B^{10}(n\,d)Be^9$ $Q_m=-4.359$

Deuteron groups corresponding to the ground state and to an excited state at 2.49 ± 0.12 Mev have been observed at $E_n=14$ Mev. No other deuteron groups were detected below $E_x\sim5.5$ Mev. In particular an upper limit of ~15 percent is given for a possible group leading to a state at ~1.5 Mev. The angular distribution of the deuterons, analyzed by pickup theory, indicates an $l=1$ transfer and odd parity, $\frac{1}{2}<J\leq9/2$ for both states (Ri 54a). See also B^{11}.

XVIII. $B^{10}(t\,\alpha)Be^9$ $Q_m=13.217$

Alpha groups are observed to the ground state and to levels at 1.73 ± 0.08, 2.39 ± 0.08, 3.10 ± 0.09 ($\Gamma<0.1$ Mev), and 4.74 ± 0.08 Mev ($\Gamma\sim1.4$ Mev) (K. W. Allen, private communication).

XIX. $B^{11}(d\,\alpha)Be^9$ $Q_m=8.016$

$Q_0=8.018\pm0.007$ (Va 51; mag. spectrometer)
$Q_0=8.029\pm0.005$ (El 54; mag. spectrometer).

Alpha groups have been observed to the ground state and to an excited state at 2.422 ± 0.005 Mev (Va 51: $\Gamma<7$ kev), 2.431 ± 0.006 Mev (El 54). At $E_d=1.51$ Mev, no other groups were observed which would correspond to states in Be^9 below 5 Mev; the upper limit to their intensity is 10 percent of the intensity of the group corresponding to the 2.4-Mev state (Va 51). The 2.4-Mev state decays mainly by neutron emission (Di 52).

XX. $C^{13}(\gamma\,\alpha)Be^9$ $Q_m=-10.656$

See (Mi 53c).

B^9

(Fig. 10)

I. $Li^6(He^3\,p)Be^8$ $Q_m=16.768$ $E_b=16.583$

See Be^8.

II. $Be^9(p\,n)B^9$ $Q_m=-1.851$

$Q_0=-1.852\pm0.002$ (Ri 50e; neutron threshold)

The width of the ground state is <2 kev (St 51e). At $E_p=6.59$ Mev, a neutron group is observed corresponding to a level at 2.37 ± 0.04 Mev. A continuous distribution of neutrons, attributed to the $(p\,pn)$ reaction, is also observed (Aj 53). Neutron threshold measurements indicate a narrow state at 2.37 ± 0.010 Mev

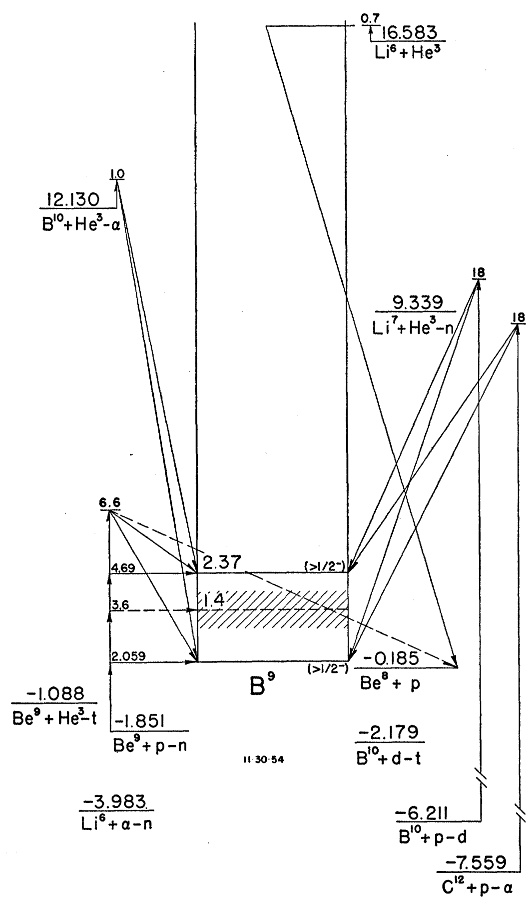


FIG. 10. Energy levels of B^9: for notation, see Fig. 1.

and, possibly, a broad state ($\Gamma \sim 1$ Mev) at $\sim$1.4-Mev excitation [(Ma 54c) and Cook, Marion, and Bonner, private communication].

III. $B^{10}(\gamma\, n)B^9$ $Q_m = -8.436$

$Q_0 = -8.55 \pm 0.25$ [(Sh 51d); neutron threshold]

IV. $B^{10}(p\, d)B^9$ $Q_m = -6.211$

At $E_p = 18$ Mev, deuteron groups are observed to the ground state of B^9 and to an excited state at 2.4 ± 0.15 Mev. The angular distributions of the deuterons to both states, analyzed by pickup theory, show an $l=1$ transfer indicating odd parity, $\frac{1}{2} < J \leq 9/2$, for the ground- and the 2.4-Mev states of B^9[(Re 54a) and J. B. Reynolds, private communication].

V. $B^{10}(He^3\, \alpha)B^9$ $Q_m = 12.130$

At E $(He^3) = 1$ Mev, alpha-particle groups have been observed to the ground state of B^9 and to an excited state at 2.58 ± 0.13 Mev (K. W. Allen and E. Almqvist, private communication).

VI. $C^{12}(p\, \alpha)B^9$ $Q_m = -7.559$

At $E_p = 18$ Mev, alpha-particle groups have been observed to the ground state of B^9 and to an excited state at 2.40 ± 0.08 Mev (J. B. Reynolds, private communication).

C^9

(Not illustrated)

Comparing the mass of C^9 with that of its mirror nucleus Li^9, and making appropriate Coulomb and $n-p$ mass difference corrections, we find a mass defect of 32.3 ± 2 Mev. C^9 is then stable to decay into $B^8 + p$ (by $\sim$0.5 Mev). C^9 has not been observed [see (Sh 52)]. Two reactions leading to C^9 are $Be^7(He^3\, n)C^9$ ($Q_m = -7$), $C^{12}(\gamma\, 3n)C^9$ ($Q_m = -54$).

Be^{10}

(Fig. 11)

I. $Be^{10}(\beta^-)B^{10}$ $Q_m = 0.556$

The weighted mean end-point energy is 0.556 ± 0.003 Mev (Li 51a). The mean half-life is $2.7 \pm 0.4 \times 10^6$ y (Hu 49a): $\log ft = 13.65$ (Fe 51b). The spectrum is of the D_2 type (Wu 50).

II. (a) $Li^7(t\, \alpha)He^6$ $Q_m = 9.79$ $E_b = 17.236$
 (b) $Li^7(t\, 2n)Be^8$ $Q_m = 8.759$
 (c) $Li^7(t\, n)Be^9$ $Q_m = 10.425$
 (d) $Li^7(t\, n)He^5 + He^4$ $Q_m = 7.91$

The neutron yield (elemental Li) at 0° exhibits two broad resonances at $E_t = 0.84$ and 1.70 Mev. The angular distributions are not isotropic (Cr 51b).

At $E_t = 240$ kev, reaction (a) accounts for 20 percent of the disintegrations yielding α particles at $\theta = 90°$ (De 52). The ground-state α particles are distributed as $1 - (0.66 \pm 0.06) \cos^2\theta$ (c.m.) while those corresponding to the 1.7-Mev state of He^6 are isotropic within 8 percent. The formation of the 1.7-Mev state is 8 times more probable than the formation of the ground state (Al 54d). These results indicate p-wave formation of the 0.84-Mev resonance and therefore $J = 2^+$ for the 17.82-Mev state [(Ch 53d) and (Al 54d)]. See also He^6 and (Aj 52c).

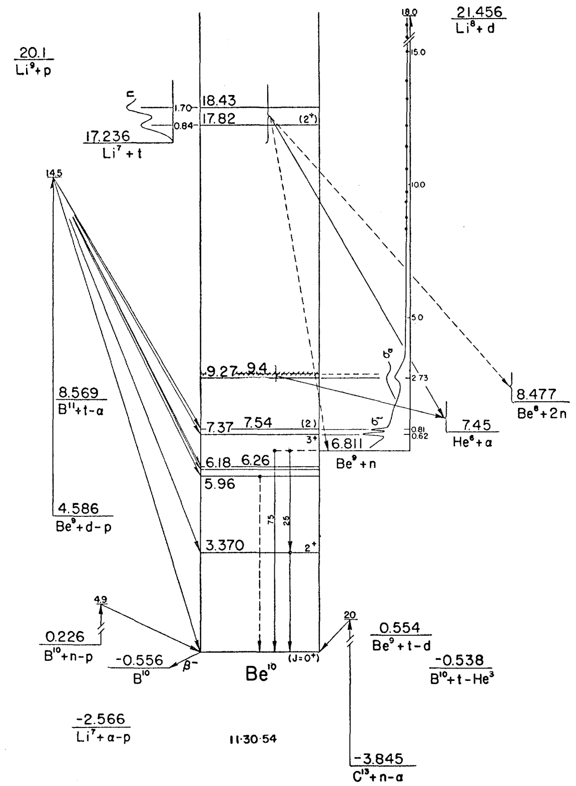


FIG. 11. Energy levels of Be^{10}: for notation, see Fig. 1.

III. $Li^7(\alpha\, p)Be^{10}$ $Q_m = -2.566$

See (Ec 37).

IV. $Be^9(n\, \gamma)Be^{10}$ $Q_m = 6.811$

$Q_0 = 6.816 \pm 0.006$ [(Ki 53b); pair spectrometer]

The thermal capture cross section is 9.0 ± 0.5 mb (Hu 52e). In addition to the ground-state transition, $E_\gamma = 6.81$ Mev, a 3.41 ± 0.06-Mev γ ray is observed, attributed to a cascade through the 3.4-Mev state. The intensity of the cascade transition is about 0.25 photon/capture (Ba 53d). See also (Wi 53f).

V. $Be^9(n\, n)Be^9$ $E_b = 6.811$

The total cross section is constant at 6.04 ± 0.03 b from 1 ev to 4 kev (Ho 52f): the spin dependent scattering is < 0.03 b (Pa 52).

In the region $E_n = 0$ to 18 Mev, three resonances are reported at 0.62, 0.81, and 2.73 Mev. The parameters of these resonances are exhibited in Table I(10). The angular distribution is of the form $1 + 0.28\, P_2$ $(\cos\theta)$ at the

0.62-Mev resonance, while the nonresonant scattering at 0.5 Mev is isotropic [(Wi 54) and (Wi 54e)]. The variation of the angular distribution with energy near the 0.62-Mev resonance is not well fitted by the assumption of a d-wave resonance interfering with s-wave potential scattering; a somewhat better fit is obtained with $l=1$, assuming channel spin one for the potential scattering (Wi 54e).

Angular distributions have also been measured at $E_n=2.30$, 2.60, 2.90, 3.32, and 3.66 Mev. At the higher energies, the neutrons are peaked in the forward direction (Me 53). The total cross section has been measured from 3 to 12 Mev, with a resolution in E_n of the order of 10 percent, by (Ne 53a) who find an approximately monotonic decrease from 2 b at 4 Mev to 1.6 b at 12 Mev. (Co 54f) have studied the region $E_n=14.1$ to 18.0 Mev and find a monotonic decrease in σ_t from 1.49 ± 0.02 b at 14.1 Mev to 1.38 ± 0.03 b at 18.0 Mev. (Co 52h) find the total cross section at $E_n=14$ Mev to be 1.53 ± 0.03 b. See also (Go 52d), (Hi 54d), and (Ne 54c).

VI. $Be^9(n\,n')Be^{9*}$ $E_b=6.811$

See (Gr 51a).

VII. $Be^9(n\,2n)Be^8$ $Q_m=-1.666$ $E_b=6.811$

At $E_n=3.7$ Mev, the reaction appears to involve a two-step process through the 2.43-Mev state of Be^9 [($Be^9(n\,n')Be^{9*}\rightarrow Be^8+n$] (Fo 54b). The cross section is 0.3 ± 0.1 b for Ra−Be neutrons (R. D. Edge and D. H. Wilkinson, private communication). See also (Ho 50b and Ag 52).

VIII. $Be^9(n\,\alpha)He^6$ $Q_m=-0.64$ $E_b=6.811$

A resonance (~1 Mev wide) for production of He^6 occurs at $E_n=2.6$ Mev; the cross section is ~50 mb (Al 47b). At 14 Mev, the cross section is 10 ± 1 mb (Ba 53).

IX. $Be^9(d\,p)Be^{10}$ $Q_m=4.586$

The weighted average of ground-state Q values is 4.588 ± 0.006 Mev (Va 54). A recent value is 4.586 ±0.009 Mev [(Bo 54d); mag. spectrometer].

Proton groups corresponding to levels in Be^{10} at 3.37, 5.96, 6.18, 6.26, 7.37, and 7.54 Mev have been observed

TABLE I(10). Resonances in $Be^9(n\,n)Be^9$.

E_{res} (Mev)	Be^{10*} (Mev)	Γ (kev)	σ'[a] (bn)	$\gamma^2/(3\hbar^2/2\mu a)$	J, π	Ref.
0.62	7.37	30	3.7	0.017	3^+	Ad 49
		25	4.35		3^+	Wi 54e
0.81	7.54	≤11	~1.3		>0	Bo 51c
		8	5.25[d]		(2)	Wi 54e
2.73[b]	9.27	~100	~1.8			Bo 51c
(2.85)	(9.4)	[c]				

[a] σ above background.
[b] See also (Al 47b), (St 51d), (Ri 51c), and (Me 53).
[c] The large cross section and asymmetry suggest two resonances, a sharp one at 2.73 and a much broader one at ~2.85 Mev (Bo 51c).
[d] Includes background.

TABLE II(10). $Be^9(d\,p)Be^{10}$ proton groups.[a]

Q (Mev) (Bo 54d)[b]	Be^{10*}	Be^{10*} (Rh 53)	l_n[c]	π	σ[d] mb/ster
4.586 ± 0.009	0	0	1	+	~5.4
1.218 ± 0.009	3.372	3.37	1	+	~5.7
-1.373 ± 0.008	5.959	5.94 ± 0.04			
-1.592 ± 0.007	6.178				
-1.676 ± 0.007	6.260	6.24 ± 0.04			
	7.37	7.37	1	+	~24.8
	7.54				

[a] See also (Aj 52c).
[b] See also (Bo 54) and J. J. Jung and C. K. Bockelman, private communication.
[c] From angular distribution at 14 Mev, analyzed by stripping theory (J. N. McGruer, private communication).
[d] Differential cross section at peak of angular distribution (10° to 20°, c.m.) (J. N. McGruer, private communication).

[see Table II(10)]. For $E_d=5.4$ to 7.4 Mev, the intensity of the group corresponding to the 6.18-Mev state is about 5 percent of the intensity of the group to the 6.26-Mev state ($\theta=90°$). The width of the proton group to the 7.37-Mev state is consistent with a Γ for the level of about 25 kev [see $Be^9(n\,n)Be^9$]. The 7.54-Mev state appears to be narrower and approaches the instrumental width of about 10 kev. The upper limit to the intensity of other proton groups at $\theta=90°$, and for $E_d=5.4$ to 7.4 Mev, is 5 percent of the strength of the group to the 6.26-Mev state [(Bo 54d) and J. J. Jung and C. K. Bockelman, private communication]. The angular distributions of the protons to the ground state and to two excited states have been studied at 14.5 Mev. The results are summarized in Table II(10) (J. N. McGruer, private communication). See also (Aj 52c).

The angular correlation of protons and 3.37-Mev γ rays, observed at $E_d=0.48$ and 0.84 Mev establishes that $J\geq2$ for the excited state. Since the stripping results show $J\leq3$, even parity, and since the internal pair conversion coefficient is consistent only with $E1$, $M1$, or $E2$ radiation (Ma 53e), the 3.37-Mev state appears to have $J=2^+$ (Co 54e and St 54f). There is evidence that a stripping process occurs even below $E_d=1$ Mev [(Ca 52) and (Tr 52)]. The energy of the γ line corresponding to the decay of the first excited state is 3.351 ± 0.027 Mev, with a yield at $E_d=2.5$ Mev of $20.4\pm2.0\times10^{-6}$ γ/d (Ma 53e). At $E_d=3.85$ Mev, a 6.02 ± 0.06-Mev γ ray (corrected for Doppler shift) is observed and is assigned to the 5.96-Mev state of Be^{10}: yield$=3.2\times10^{-6}$ γ/d (Bent, Sippel, and Bonner, private communication).

X. $B^{10}(n\,p)Be^{10}$ $Q_m=0.226$

See (Ja 54) and (Eg 48).

XI. $C^{13}(n\,\alpha)Be^{10}$ $Q_m=-3.845$

See C^{14}.

B^{10}

(Fig. 12)

I. $Li^6(\alpha\,\gamma)B^{10}$ $Q_m=4.453$

Resonances are observed for $E_\alpha=500\pm25$ and 1183 ± 5 kev ($\Gamma<10$ kev), corresponding to levels at 4.75 ± 0.02

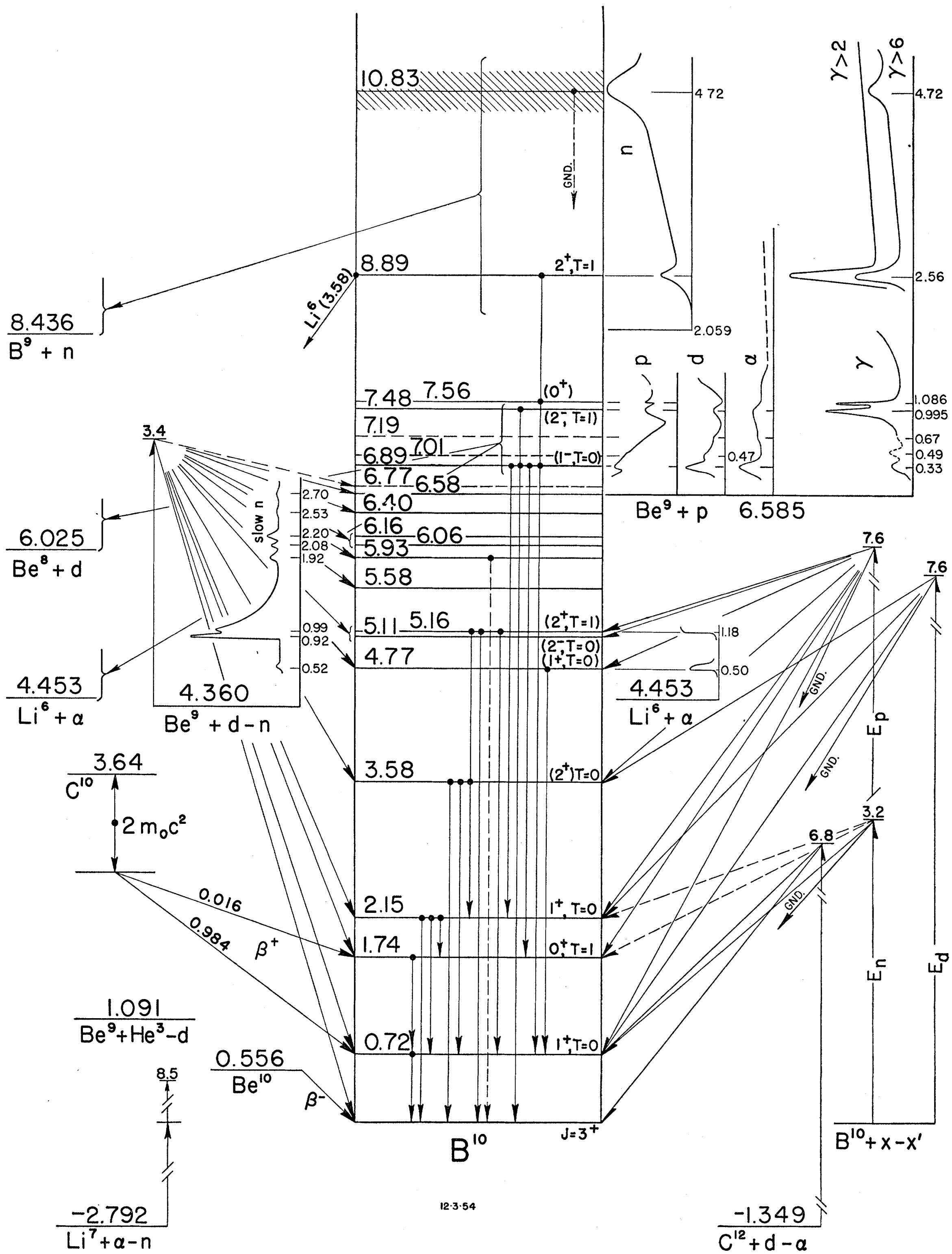


FIG. 12. Energy levels of B^{10}: for notation, see Fig. 1.

and 5.162±0.008 Mev. The former decays mainly via the 0.7-Mev state, with $\omega\Gamma_s \sim 0.15$ ev ($\Gamma_s = \Gamma_\gamma \Gamma_\alpha / \Gamma_\gamma + \Gamma_\alpha$); while the latter, with $\omega\Gamma_s \sim 1$ ev, decays to the ground state (5 percent), the 0.7-Mev state (25 percent), and the 2.15-Mev state (70 percent). No resonance corresponding to the 5.11-Mev level is observed: $\omega\Gamma_s < 0.02$ ev. These results are taken to indicate $J=1^+$ and $T=0$, for the 4.77, $J=2^-$ and $T=0$ for the 5.11, and $J=2^+$ and $T=1$ for the 5.16-Mev states of B^{10} [(Wi 53h) and (Jo 54e)]. The analysis assumes forbiddenness of $E1$ transitions between $T=0$ states in $T_z=0$ nuclei (Ge 53a), a 0.25 percent $T=1$ impurity in the ground state of Li^6 [(Ra 53) and (Jo 53c)], and/or a $T=0$ impurity in the 5.16-Mev state of B^{10} (D. H. Wilkinson, private communication).

II. $Li^6(\alpha\, p)Be^9$ $\quad Q_m = -2.132 \quad E_b = 4.453$

See (Sh 37).

III. (a) $Li^7(He^3\, p)Be^9$ $\quad Q_m = 11.189 \quad E_b = 17.774$
(b) $Li^7(He^3\, d)Be^8$ $\quad Q_m = 11.748$
(c) $Li^7(He^3\, \alpha)Li^6$ $\quad Q_m = 13.321$

See Li^6, Be^8, and Be^9.

IV. $Li^7(\alpha\, n)B^{10}$ $\quad Q_m = -2.792$

See (Ha 39a) and (Ba 53f).

V. $Be^9(p\, \gamma)B^{10}$ $\quad Q_m = 6.585$

The cross section has been measured for $E_p = 30$ to 250 kev by (Sa 53b). At the lowest energies, the curve approaches the simple Gamow function; the general course up to 200 kev reflects the effect of a higher resonance; $\sigma \sim 2\ \mu b$ at 200 kev (Sa 53b). Resonances for capture radiation are reported at $E_p = 0.336$, 0.492, 0.67, 0.998, 1.087, and 2.565 Mev [see (Aj 52c)]. Reduced widths are tabulated by (Vo 54). There appears to be some disagreement concerning the possibility of a resonance below 150 kev and also whether the reported resonance at 492 kev is properly assigned to this reaction (see Ta 46 and Hu 52h).

The 0.336-Mev resonance ($\Gamma = 175$ kev) is generally attributed to s-wave protons, because of its relatively great width [$\gamma^2 \geq 30$ percent of sum-rule limit: (La 54a)] and the fact that the γ radiation is isotropic (Ja 48). At $E_p = 315$-kev γ rays corresponding to the ground, 0.72, 1.74, and 2.15-Mev states are observed, with relative intensities (±25 percent) of 0.15, 0.40, 1.00, and 0.45. The observed relative intensities are taken to imply $J=1$ for the 6.89-Mev state in B^{10}. The cross section at resonance is $12 \pm 4\ \mu b$ (Ca 54). The several ev gamma width to the 1.74-Mev level implies an allowed $E1$ transition and hence $J=1^-$, $T=0$ (see also $Be^9(p\, d)Be^8$ and $Be^9(p\, \alpha)Li^6$). If $T=0$ for the 6.89-Mev level, the strong transitions to the 0.7- and 2.1-Mev states are difficult to understand (D. H. Wilkinson and A. B. Clegg, private communication).

The broad resonance at 0.99 Mev is also believed to be formed by s waves [$\gamma^2 = 3$ percent of sum-rule limit (Vo 54)]. The angular distribution of the γ radiation is $Y(\theta) = 1 + 0.09 \sin^2\theta$, suggesting dominant s-wave formation with some d-wave contribution (De 49d and Pa 53d). (Ho 53b) locate the resonance at $E_p = 993 \pm 2$ kev, $\Gamma = 88 \pm 3$ kev. The decay proceeds mainly to the ground state. The thick-target yield of 7.5-Mev radiation is $19 \times 10^{-9}\ \gamma/p$; $\Gamma_\gamma = 23$ ev (assuming $J=2$). An appreciable yield of 0.4, 0.7, 1.0, and 1.4-Mev radiation is observed, suggesting ~ 10 percent of cascade transitions (Ho 53b). Study of the angular correlation of internal conversion pairs indicates about equal contributions of $E1$ and $E3$ or $M2$ transitions (De 54b). The great strength of the $E1$ transition may indicate that this is a $T=1$ level (Wi 53a): see, however, $Be^9(p\, \alpha)Li^6$ and $Be^9(p\, d)Be^8$. Why the 7.48-Mev state does not couple with the 0.7-Mev state and why the $E3$ contribution is so large are not understood.

The narrow 7.56-Mev level [$E_p = 1085 \pm 2$ kev; (Ho 53b)] decays mainly to the 0.7-Mev state: yield $= 1.0 \times 10^{-9}\ \gamma/p$, $\Gamma_\gamma = 6.0$ ev (assuming $J=0$). Again the presence of softer radiation suggests a small contribution of cascades, possibly to high, α-unstable levels. The absence of transitions to the 1.74-Mev ($J=0^+$) state is consistent with the assumed $J=0$ character of the 7.56-Mev state (Ho 53b). The individual angular distributions of the γ rays to the 0.72-Mev state and of the subsequent 0.72-Mev γ rays are isotropic within 5 percent of the 1.09-Mev resonance. This is consistent with $J=0$ for the 7.56-Mev state (Pa 53d).

The excitation curve for $E_\gamma \gtrsim 6$ Mev shows a pronounced resonance at $E_p = 2.57 \pm 0.01$ Mev, and another one, ~ 0.5 Mev wide, superimposed on a general rise, at $E_p = 4.72 \pm 0.01$ Mev. The excitation curve for $E_\gamma \gtrsim 2$ Mev shows the first resonance and the general rise but not the 4.72-Mev resonance (Ha 52e). At the 2.6-Mev resonance, the capture radiation appears to proceed predominantly to the 0.7-Mev state; the yield is $\sim 3 \times 10^{-9}\ \gamma/p$ (Ma 53e). See also (Wi 53c) and (La 54a).

VI. $Be^9(p\, n)B^9$ $\quad Q_m = -1.852 \quad E_b = 6.585$

Resonances are observed at $E_p = 2.56$ and 4.72 Mev, superposed on a general rise to $E_p \sim 4.5$ Mev [(Ri 51) and (Ha 52e)]. See also (Aj 52c).

VII. $Be^9(p\, p)Be^9$ $\quad E_b = 6.585$

The yield of elastically scattered protons, observed at $\theta = 138°$, shows interference effects at the 0.33-, 0.995-, and 1.086-Mev resonances (Th 49). Analysis of these data suggests $J=2^-$ and $J=0$, respectively, for the states corresponding to the upper two resonances (Co 49).

Absolute differential cross sections have been measured at $E_p = 30.6$ Mev by (Wr 53a), and at $E_p = 31.5$ Mev by (Br 52c) who also list cross sections for the formation of excited states in Be^9. See also (Co 54a).

VIII. $Be^9(p\,t)Be^7$ $Q_m=-12.071$ $E_b=6.585$

An excitation function is given by (Co 54b) for $E_p \simeq 14$ to 23 Mev. The absolute cross section is 9.0 mb at 22 Mev.

IX. (a) $Be^9(p\,d)Be^8$ $Q_m=0.560$ $E_b=6.585$
(b) $Be^9(p\,\alpha)Li^6$ $Q_m=2.132$

The total cross section for reaction (a) exhibits peaks at 0.33, 0.47, 0.68, and 0.94 Mev. Reaction (b) shows all but the 0.47-Mev peak. The angular distributions indicate strong interference between states of opposite parity [see (Aj 52c)].

Reaction (b) exhibits a strong resonance at $E_p=2.56$ Mev [$\Gamma=41\pm2$ kev, (Ma 54g)]: short-range alpha particles and γ rays are observed corresponding to the reaction leading to the 3.58-Mev level in Li^6 and its subsequent γ decay to the ground state of Li^6. Alpha-particle groups to the ground and the first excited state of Li^6 and ground-state deuterons from reaction (a) do not show resonance at $E_p=2.56$ Mev (Ma 54g). Assuming $T=1$ for the 3.58-Mev state in Li^6, these data indicate that the 8.89-Mev state in B^{10} has $T=1$ or $J=0^+$.

The thick-target yield of 3.6-Mev γ rays at $E_p=2.72$ Mev is given as 4.76×10^{-6} γ/p by (Da 52) and 4.63×10^{-6} γ/p by (Ma 54b); the cross section at resonance is 0.11 b (Da 52). Assuming equality of the reduced proton and neutron widths (Ma 54b) finds that the observed cross section requires $J\geq2$. A J of 3^- would require an implausibly large reduced α-particle width, and it is concluded that the level has $J=2^+$, $T=1$, $\gamma_\alpha^2=19$ or 33 percent of the sum-rule limit, $\gamma_p^2=\gamma_n^2=0.5$ or 0.2 percent (Ma 54b).

X. $Be^9(d\,n)B^{10}$ $Q_m=4.360$

Neutron groups have been observed corresponding to states in B^{10} at 0.72, 1.75, 2.15, 3.53($\pm$0.06), 4.78, 5.14, 5.37(?), 5.58, 5.72(?), 5.93, 6.12, 6.38, 6.58, and 6.77(?)($\pm$0.04) Mev [(Aj 51) and (Aj 52c)]. A neutron group corresponding to a state at 2.85 ± 0.03 Mev is reported by (Dy 53) [see also (Re 54b)]. Angular distributions of the neutrons to the ground state and to the first few excited states have been studied at $E_d=0.95$ (Pr 53) and 3.4 Mev (Aj 52b). The data show evidence both for stripping and compound nucleus formation with more evidence of the former in the higher-energy work. Analysis by stripping theory indicates that the ground state and the first four excited states have even parity, $J\leq3$, and that one or both of the 5.11–5.16-Mev states have odd parity, $J=1$ or 2 (Aj 52b). Strong terms in $\cos\theta$ observed in the low-energy work are taken to indicate that, in addition to the stripping process, two compound nucleus (B^{11}) levels of opposite parity, possibly $J=5/2^-$ and $3/2^+$, are involved (Pr 53).

Gamma-gamma coincidences and angular correlations have been studied by (Sh 54a) who find essential agreement with the decay scheme proposed by (Aj 51) and (Ri 52b) except that the 1.4-Mev γ ray evidently occurs both as a transition between the 3.6- and 2.1-Mev levels and as a transition between the 2.1- and 0.7-Mev levels (Sh 54a). The lifetime of the 0.72-Mev state is $7\pm2\times10^{-10}$ sec (Th 53a). A decay scheme with (very approximate) relative intensities is given in Fig. 13.

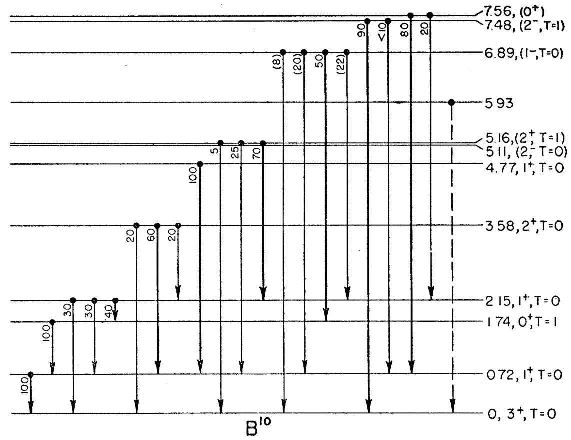


FIG. 13. Gamma-ray transitions in B^{10}. The horizontal lines indicate the pertinent levels of B^{10}, identified on the right by the level energies, and where known, the total angular momentum (J), parity, and isotopic spin (T). Solid vertical lines indicate observed transitions, while dashed lines indicate transitions whose assignment is not well established. Numbers on the vertical lines give the (estimated) percentage branching from each level; figures in parentheses are least certain.

Observed thresholds for slow neutron production are given in Table III(10). Data taken with $E_d=3$ to 5.4 Mev indicate no additional thresholds. The small yield of threshold neutrons from the 4.78-Mev state is consistent with p-wave neutrons and thus with even parity for that state. The small widths observed for the excited states from 5 to 6.6 Mev, despite the instability of these states to α emission, imply that they have relatively high angular momenta (Bo 54c).

At $E_d=2.5$ Mev, the yield of 3.595 ± 0.014 Mev γ rays is $5.7\pm0.7\times10^{-6}$ γ/d, and that of 5.98 ± 0.04 Mev γ rays is 1.6×10^{-6} γ/d. In addition, a γ ray of 4.44 ± 0.03 Mev is also observed and is believed to be due to the decay of one of the 5.1-Mev levels to the 0.72-Mev state. The 5.98-Mev γ ray may be located in Be^{10} (Doppler corrections to the E_γ have not been made) (Ma 53e). See also (Aj 52c), (Gr 53b), and (Sw 53a).

TABLE III(10). Slow neutron thresholds in $Be^9(d\,n)B^{10}$ (Bo 54c).

E_d (Mev)	B^{10*} (Mev)	Γ (kev)
0.52	4.78	<10
0.92	5.11	<10
0.99	5.17	<10
1.92	5.93	<10
2.08	6.06	<10
2.20	6.16	<20
2.53	6.43	
2.70	6.57	~30

XI. $Be^{10}(\beta^-)B^{10}$ $Q_m=0.556$

See Be^{10}.

XII. (a) $B^{10}(\gamma\, d)He^4+He^4$ $Q_m=-5.930$
(b) $B^{10}(\gamma\, \alpha)Li^6$ $Q_m=-4.453$
(c) $B^{10}(\gamma\, np)He^4+He^4$ $Q_m=-8.155$

In the range $E_\gamma=10$ to 30 Mev, reaction (a) proceeds almost entirely through excited states of Be^8: transitions via $(\alpha+d)$-emitting states of Li^6 apparently do not occur. The cross section exhibits a maximum at $E_\gamma=10.8$ Mev, possibly corresponding to the known level at that energy. The peak cross section is 1.5 mb [(Mu 52a), (Lo 53), and (Er 53)]. Reaction (b) is said to proceed via the ground state and γ-emitting states of Li^6 at 1.1 and 2.2 Mev. The cross section for (Li^7+p) γ rays is 0.2 mb. The corresponding cross section for reaction (c) is 0.3 mb. Neither reaction (b) nor (c) appears to exhibit the 10.8-Mev resonance (Er 53). See also (Aj 52c).

XIII. $B^{10}(n\, n')B^{10*}$

A gamma ray of energy 0.717 ± 0.007 Mev is observed with $E_n=2.5$ Mev [(Da 53c) and R. B. Day, private communication]. See also (Sc 54c).

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

$Q_1=-0.719\pm0.0016$ Mev (Cr 52c; elect. analyzer).
$Q_1=-0.718\pm0.005$ Mev (Da 54; scin. spectrometer).

Proton groups observed by (Bo 53) and (Br 53i) are exhibited in Table IV(10). See also (Aj 52c) and C^{11}.

TABLE IV(10). B^{10} levels from $B^{10}(p\, p')B^{10*}$ and $B^{10}(d\, d')B^{10*}$ [(Bo 53 and Br 53i)].

	Relative intensities					
	at 6 Mev		at 7 Mev		at 7.6 Mev	
B^{10*}	$(p\, p')$	$(d\, d')$	$(p\, p')$	$(d\, d')$	$(p\, p')$	$(d\, d')$
0	100	100	100	100	100	100
0.717 ± 0.005	7	7	6	9	4	7
1.739 ± 0.005	1	<0.4	1	<0.15	1	<0.15
2.152 ± 0.005	6	2	5	4	3	4
3.583 ± 0.005	4		5	4	7	7
$4.771^a\pm0.005$						
$5.105^a\pm0.007$						
$5.159^a\pm0.007$						

[a] Observed in $B^{10}(p\, p')$: intensities not reported.

XV. $B^{10}(d\, d')B^{10*}$

Deuteron groups observed by (Bo 53) are exhibited in Table IV(10). The absence of deuteron groups corresponding to the 1.74-Mev state of B^{10} is strong evidence [see (Ad 52a)] that this state is the $J=0^+$, $T=1$ analog of the ground states of Be^{10} and C^{10}.

XVI. $C^{10}(\beta^+)B^{10}$ $Q_m=3.64$

The half-life is 19.1 ± 0.8 sec (Sh 49); the maximum positron energy, obtained by absorption measurements, is 2.10 ± 0.1 Mev. Gamma rays of energy 723 ± 15 and 1033 ± 30 kev, the latter resulting from transitions to the 1.74-Mev state, are observed. Relative transition probabilities to the 0.72, 1.74, and 2.15-Mev levels are given as $98.4/1.65\pm0.2/<0.1$ by (Sh 53a). The corresponding $\log ft$ values, using $E_\beta(\max)=1.90$ and 0.88 Mev (obtained from $B^{10}(p\, n)C^{10}$) are 3.03 and 3.43. In view of direct evidence that the 1.74-Mev level has $J=0^+$ [see $Be^9(d\, n)B^{10}$], it is reasonably certain that the β^+ transition to this state is of the 0–0 type. Transitions to the 2.1-Mev state $(J=1^+)$ should be allowed and it is not clear why they are not observed (Sh 53a). See also (Ko 53).

XVII. $B^{11}(\gamma\, n)B^{10}$ $Q_m=-11.459$

See (Sh 51d).

XVIII. $B^{11}(p\, d)B^{10}$ $Q_m=-9.233$

At $E_p=18$ Mev, a deuteron group to the ground state of B^{10} has been observed. The angular distribution of the deuterons, analyzed by the pickup theory, indicates $l_n=1$, and therefore different parities for the ground states of B^{10} and of B^{11} (Re 54a).

XIX. $C^{12}(d\, \alpha)B^{10}$ $Q_m=-1.349$

At $E_d=7$ Mev, alpha-particle groups to the ground state and to the 0.72-Mev level are observed [(As 51) and (Sp 53c)].

XX. $N^{14}(\gamma\, \alpha)B^{10}$ $Q_m=-11.613$

See (Mi 53c).

Low-Lying States of B^{10}

The following arguments support the spin and parity assignments for the first five excited states of B^{10} [see (Ri 52b), (Aj 52b), and (Sh 53a)].

(a) *All have even parity:* $J=0$, 1, 2, or 3 (neutron angular distributions).

(b) *1.74-Mev state:* J is certainly not >1 because the C^{10} β^+ decay is allowed. C^{10} can reasonably be assumed to be $J=0^+$; if charge independence is assumed, the 1.74-Mev state is clearly established as $J=0^+$ [see (Pr 53)], $T=1$ by $B^{10}(d\, d')B^{10}$. The fact that the ground-state γ transition is not observed is consistent with a large spin difference.

(c) *0.72-Mev state:* C^{10} decay is allowed; therefore, J is certainly not >1; $J=0$ is eliminated by observation of the transition from the 1.74-Mev state, thus $J=1$. The lifetime of the state is consistent with $E2$.

(d) *2.15-Mev state:* The fact that the γ transition to the 1.74-Mev state is comparable in intensity to the ground-state transition argues strongly against $J=2$ and 3; $J=0$ is excluded by the observation of the transition to the 1.74-Mev level; therefore $J=1$.

(e) *3.58-Mev state:* The absence of a transition to the 1.74-Mev state argues against $J=1$. If $J=0$, the transition to the ground state should be very weak; if $J=3$, the transition to the 0.7-Mev state should be relatively weak. Thus $J=2$ appears to be more consistent with the observed decay scheme.

(f) *4.77-Mev state:* The only observed γ decay is to the 0.72-Mev state. This observation favors $J=0$ or 1 over $J=2$ or 3. The parity is even (Bo 54c). The fact that the state is seen in $Li^6(\alpha\ \gamma)B^{10}$ eliminates 0^+; therefore $J=1^+$.

C^{10}

(Fig. 14)

Mass of C^{10}

The mass difference $C^{10}-B^{10}$ is given as 3.84 ± 0.1 Mev from β end-point measurements (Sh 53a) and as 3.59 ± 0.05 Mev (Cook, Marion, and Bonner, private communication), 3.6 ± 0.2 Mev (Aj 54b) from the $B^{10}(p\ n)C^{10}$ Q value. The weighted mean of these three results yields a mass defect for C^{10} of 18.64 ± 0.06 Mev.

I. $C^{10}(\beta^+)B^{10}$ $Q_m=3.64$

The decay is complex. See B^{10}.

II. $B^{10}(p\ n)C^{10}$ $Q_m=-4.42$

$Q_0=-4.37\pm0.05$ Mev (Cook, Marion, and Bonner, private communication; neutron threshold).
$Q_0=-4.35\pm0.2$ Mev [(Aj 54b); photoplate].

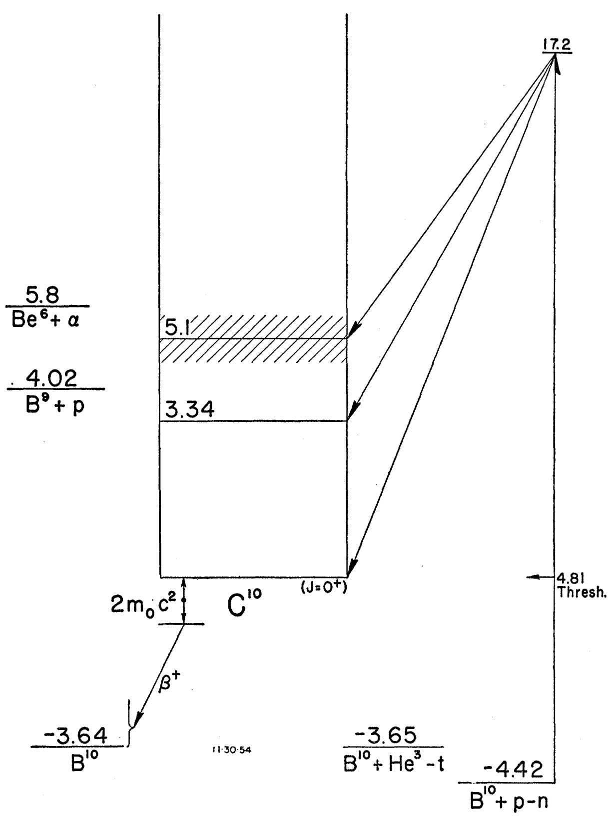


FIG. 14. Energy levels of C^{10}: for notation, see Fig. 1.

At $E_p=17.2$ Mev, neutron groups are observed to the ground state, to an excited state at 3.34 ± 0.2 Mev, and to wide or unresolved level(s) at $E_x\sim5.1$ Mev. The larger cross section for the formation of the 3.3-Mev state than for the formation of the ground state of C^{10} is consistent with the smaller J change involved if the first excited state is the analog to the $J=2$ state in Be^{10} at 3.37 Mev (Aj 54b).

Be^{11}

(Not illustrated)

A rough interpolation from other A suggests that the first $T=\frac{3}{2}$ state in B^{11} is located ~13 Mev above the ground state. This means $Be^{11}-B^{11}\sim11.5$ Mev; mass defect ~23.4 Mev. Be^{11} might then be stable by as much as 2 Mev with respect to $Be^{10}+n$. See also (Ba 39e).

No evidence is reported for this nucleus. Some of the reactions which would lead to it are: $Be^9(t\ p)Be^{11}$ $(Q_m=-1)$, $B^{11}(n\ p)Be^{11}$ $(Q_m=-11)$, $B^{11}(t\ He^3)Be^{11}$ $(Q_m=-12)$, and $C^{13}(n\ He^3)Be^{11}$ $(Q_m=-24)$.

B^{11}

(Fig. 15)

I. $Li^7(\alpha\ \gamma)B^{11}$ $Q_m=8.667$

Three resonances are reported below $E_\alpha=2.5$ Mev [(Be 51) and (He 54b)]. Their parameters are exhibited in Table I(11) as are their modes of decay (see also Fig. 16). Study of $\alpha-\gamma$ and $\gamma-\gamma$ angular correlations, taken together with the relative γ-ray intensities, leads to the following assignments: 9.28-Mev level: $J=5/2^+$, 9.19-Mev: $J=5/2^-$, 8.92-Mev: $J=\frac{3}{2}$ or 5/2, 6.81-Mev: $J=\frac{3}{2}^-$, 4.46-Mev level: $J=5/2^-$ [(Jo 52d) and D. H. Wilkinson, private communication]. See also (Jo 52c).

II. $Li^7(\alpha\ n)B^{10}$ $Q_m=-2.792$ $E_b=8.667$

See (Ho 50b).

III. $Li^7(\alpha\ p)Be^{10}$ $Q_m=-2.566$ $E_b=8.667$

See (Ec 37).

IV. $Li^7(\alpha\ \alpha')Li^{7*}$ $E_b=8.667$

The 0.48-Mev γ-ray yield shows resonances at $E_\alpha=1.91$ (He 54b), 1.889 ± 0.010 Mev (Li 54: peak $\sigma=110\pm20$ mb), at $E_\alpha=2.46$ (He 54b), 2.50 ± 0.03 Mev (Li 54: peak $\sigma=80\pm15$ mb, $\sigma_{res}\sim30$ mb), and at $E_p=3.06$ Mev (He 54b). Correction for barrier pene-

TABLE I(11). Resonances in $Li^7(\alpha\ \gamma)B^{11}$.

E_α[a] (Mev)	Γ(lab)[a] (kev)	B^{11*}	Partial widths,[b] $\omega\Gamma\gamma$ (ev), to states of B^{11} at 0	2.14	4.46	5.03	6.81
0.401	<1	8.922	0.15	<0.003	<0.003	~0.005	<0.003
0.819 ± 0.001	~4	9.188	<0.05	<0.02	2.0	<0.1	~0.35
0.958 ± 0.001	7	9.277	3.5	<0.17	8.1	<0.4	2.4

[a] (Be 51). Also see (He 54b).
[b] (Jo 52d) and D. H. Wilkinson (private communication). (Be 51) report total gamma widths of 0.04, 0.6, and 4.7 ev for the three resonances.

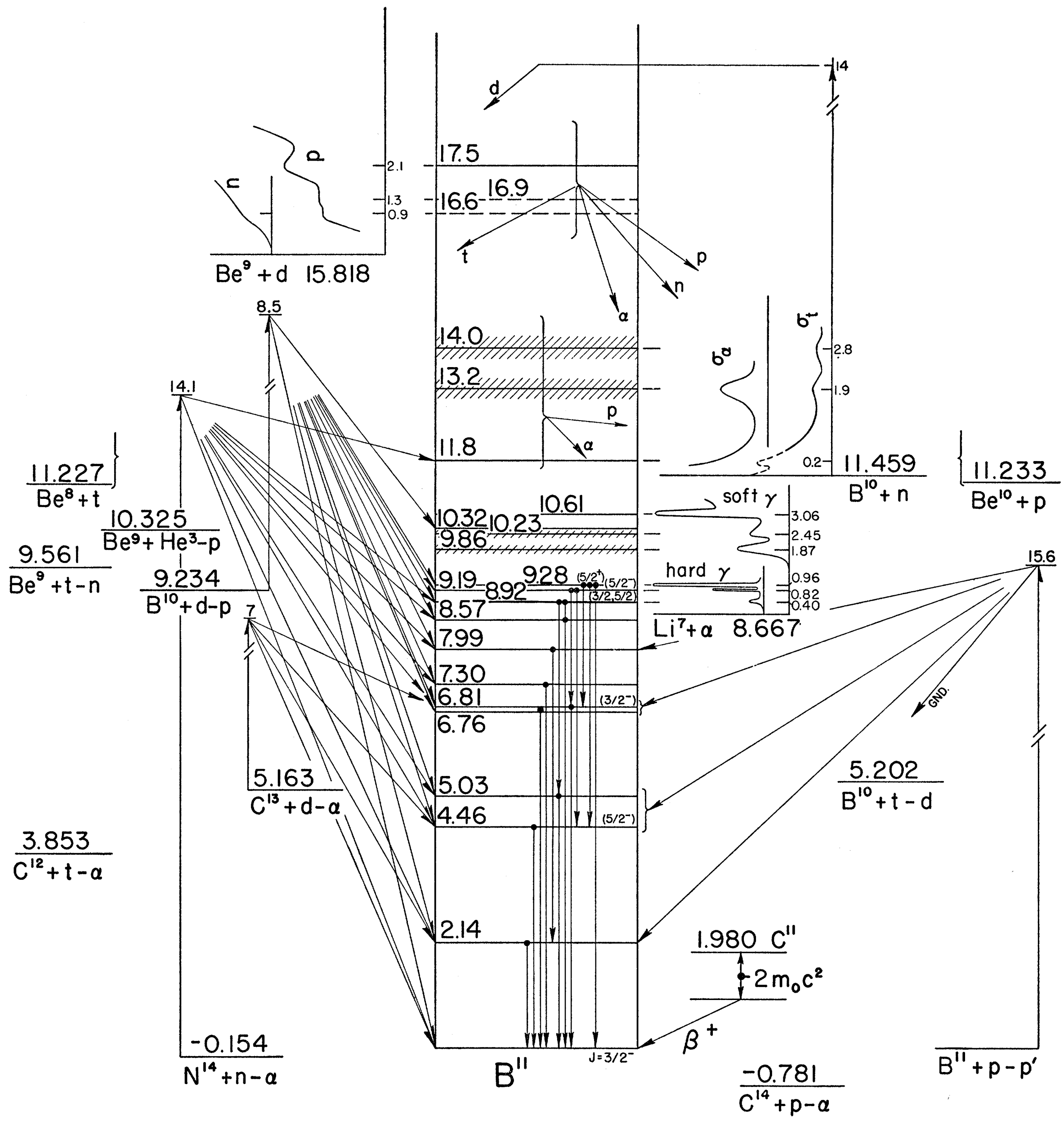


FIG. 15. Energy levels of B^{11}: for notation, see Fig. 1.

tration effects leads to values of $E_p=1.87$ and 2.45 Mev and Γ(c.m.)$=125\pm10$ and $\simeq155$ kev, respectively, for the first two resonances, corresponding to levels in B^{11} at 9.86 and 10.23 Mev. Calculation of the ratio of the reduced width to the Wigner sum-rule limit gives $J\leq5/2$ for the 9.86-Mev and $J\leq7/2$ for the 10.23-Mev states (Li 54). See also (Aj 52c).

V. $Be^9(d\ n)B^{10}$ $Q_m=4.360$ $E_b=15.818$

The cross section has been measured for $E_d=70$ to 110 kev by (Ra 54b); it follows the Gamow function for these energies.

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 (Ev 49). See also B^{10}, (Pr 53), and (Aj 52c).

VI. $Be^9(d\ d)Be^9$ $E_b=15.818$

See (El 52).

VII. (a) $Be^9(d\ p)Be^{10}$ $Q_m=4.586$ $E_b=15.818$
(b) $Be^9(d\ \alpha)Li^7$ $Q_m=7.151$
(c) $Be^9(d\ t)Be^8$ $Q_m=4.591$
(d) $Be^9(d\ 2\alpha)H^3$ $Q_m=4.687$

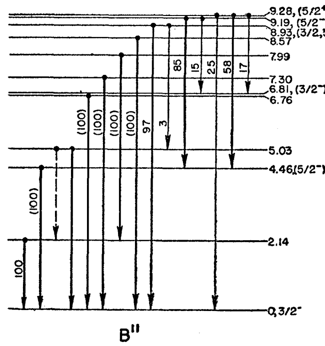


FIG. 16. Gamma-ray transitions in B^{11}: for notation, see Fig. 13.

Absolute cross sections for reactions (a) and (b) are reported by (Sa 53b) in the range $E_d=30$ to 250 kev, and for reactions (a) and (c) by (De 52b) in the range $E_d=150$ to 620 kev. In reaction (a), (Sa 53b) find a simple Gamow dependence for both the ground state and 3.37-Mev state protons; $\sigma\sim 25$ μb for each at $E_d=150$ kev, assuming isotropy. (De 52b) find the distributions markedly anisotropic even at this low energy (see also Be^{10}) and quote $\sigma=12.7$ μb. The cross section at $E_d=620$ kev is 5.26 mb (De 52b). (Ca 52) reports broad maxima in the $\theta=90°$ yield of ground-state protons at $E_d\sim 0.9$, (1.3), and 2.1 Mev.

The cross section for reaction (b) shows a simple Gamow rise to $E_d=250$ kev; $\sigma\sim 0.8$ mb at $E_d=200$ kev (Sa 53b). The angular distribution for combined ground-state and 0.48-Mev state α particles is approximately isotropic for $E_d=0.3$ to 0.7 Mev [(Re 51a); also see Li^7]. (De 52b) find the cross section for ground-state tritons [reaction (c)] and protons [reaction (a)] to be the same for $E_d=150$ to 450 kev. Above 450 kev, the $(d\ p)$ cross section rises more rapidly. For angular distributions, see Be^8. Relative yields for the various groups from reactions (a), (b), and (c) are given by (Ge 53). The direct three-body reaction (d) does not appear to occur (Ge 53).

VIII. $Be^9(He^3\ p)B^{11}$ $Q_m=10.325$

See (Mo 54b).

IX. $Be^9(\alpha\ d)B^{11}$ $Q_m=-8.016$

See (Mc 51b).

X. $B^{10}(n\ n)B^{10}$ $E_b=11.459$

The epithermal cross section (free) is 3.3 ± 0.5 b (Hu 54a). Broad maxima appear in the cross section at $E_n=1.9$ and 2.8 Mev, $\sigma\sim 2.5$ b; an additional peak near 0.2 Mev may be indicated (Bo 51c). Nonresonant scattering at 0.5 Mev is nearly isotropic. At $E_n=1.5$ Mev, strong forward scattering is observed (Wi 54). For $E_n=6$ to 9.7 Mev, the total cross section is nearly constant at 1.4 b (Ne 54c). At $E_n=14$ Mev, the total cross section is 1.47 ± 0.03 b (Co 52h). From $E_n=14.1$ to 18.0 Mev, σ_t is nearly constant at 1.45 ± 0.02 b (Co 54f).

XI. $B^{10}(n\ n')B^{10*}$ $E_b=11.459$

See (Ph 52b).

XII. $B^{10}(n\ p)Be^{10}$ $Q_m=0.226$ $E_b=11.459$

The thermal cross section is <0.2 b (Hu 52e); the cross section for fast pile neutrons is 3 mb (Eg 48). See also (Ja 54).

XIII. $B^{10}(n\ d)\ Be^9$ $Q_m=-4.359$ $E_b=11.459$

At $E_n=14$ Mev, the integrated cross sections (0° to 90°, c.m.) for the transitions to the ground and the 2.4-Mev states of Be^9 are 21 ± 3 mb and 16 ± 2 mb, respectively (Ri 54a). See also (Ja 54).

XIV. $B^{10}(n\ \alpha)Li^7$ $Q_m=2.792$ $E_b=11.459$

Recently quoted values for the thermal neutron absorption cross section in natural boron are 749 ± 4 b (Ca 53c), 755 ± 3 b (Ha 53g), 744 ± 20 b (Sc 54b). (Hu 53c) adopt $\sigma=750\pm 4$ b. From 7×10^{-4} to 200 ev, the cross section follows the $1/v$ law [(Hu 53c) and (Hu 52e)]. Whether a resonance exists near $E_n=0.2$ Mev is not clear [see (Go 47a), (Hu 52e), and (Hu 54a)]. A pronounced resonance exists at $E_n=1.9$ Mev with $\Gamma=400$ kev, $\sigma=0.5$ b (Pe 51c), which may actually be two resonances, at 1.81 ± 0.04 and 2.03 ± 0.04 Mev [(St 50d) and (Bi 52)]. The ratio of transitions leading to the ground state and to the 0.48-Mev state of Li^7 varies markedly with energy: see (Aj 52c) and (De 54).

XV. $B^{10}(d\ p)B^{11}$ $Q_m=9.234$

$Q_0=9.227\pm 0.006$ (El 54; mag. spectrometer).

Proton groups reported by (Va 51a) and (El 53) are listed in Table II(11). All the levels listed, except the last, have widths less than 15 kev; an upper limit of 4 kev is placed on the width of the 8.93-Mev level and

TABLE II(11). Proton groups from $B^{10}(d\ p)B^{11}$.

A (Va 51a)		B (El 53)		
Q (Mev)	$\frac{d\sigma}{d\Omega}$[a]	Q (Mev)	Rel. Int.[b]	B^{11*}
9.235 ± 0.011	2			0
7.097 ± 0.009	0.4			2.138
4.776 ± 0.008	1.2			4.459
4.201 ± 0.008	1.0			5.034
2.477 ± 0.007	2			6.758
2.427 ± 0.007	0.2			6.808
1.937 ± 0.006	1.2			7.298
		1.248 ± 0.009	0.088	7.987
0.667 ± 0.005	0.3	0.667 ± 0.008	0.087	8.568
0.309 ± 0.005	5	0.306 ± 0.008	0.58	8.927
0.045 ± 0.005	8	0.042 ± 0.008	1.0	9.191
-0.041 ± 0.005	4	-0.042 ± 0.007		9.276
		-1.08 ± 0.02	0.6	10.32

[a] Approximate differential cross sections in mb/ster at 90°, $E_d=1.51$ Mev.
[b] Approximate relative intensities at 90°, $E_d=8.06$ Mev.

of 10 kev on the levels at 7.99, 8.57, 9.19, and 9.28 Mev [see $Li^7(\alpha\,\gamma)B^{11}$]. The width of the 10.32-Mev level is 54±17 kev (El 53); it does not appear to correspond to the 10.23-Mev level observed in $Li^7(\alpha\,\alpha')Li^7$ (Li 54). No other levels are observed below $E_x=11.46$ Mev. For example, the upper limit for groups $\lesssim$50-kev wide is 15 percent of the intensity of the protons to the 9.19-Mev state (El 53). [The nonappearance of levels corresponding to those reported in $Li^7(\alpha\,\alpha')Li^7$ is presumably to be attributed to their large width.] At $E_d=4.153$ Mev, four proton groups are observed corresponding to excited states at 6.79, 7.25, and 8.96 Mev [(Kh 54): error given as ±0.02].

At $E_d=7.7$ Mev, the angular distributions of the protons to the ground state and to levels at 2.14, 4.46, 5.03, 6.76, and 6.81 (unresolved), 8.93, 9.19, and 9.28 Mev (unresolved) have been analyzed by stripping theory. The levels below 7 Mev seem to be fitted by $l_n=1$ assignments, although in the case of the unresolved levels, higher l_n are not excluded. The $l_n=1$ assignment restricts the states to odd parity and $\frac{3}{2}\leq J\leq 7/2$ [(Ev 54); see, however, (Pa 54a)]. The variation of the distributions with energy is of particular interest and may indicate interference between stripping and compound nucleus formation. Relatively large neutron capture probabilities suggest that the ground state and one of the states near 6.8 Mev may have a single-particle character (Ev 54).

Angular distributions have also been studied at $E_d=0.20$, 0.45, and 0.60 Mev by (Pa 54a), at $E_d=0.3$ Mev by (En 52), at $E_d=1$ to 3.7 Mev by (Re 50), at $E_d=1.06$ and 1.43 Mev by (Bu 54), at $E_d=3.03$ Mev by (Pr 54a) and at 8 Mev by (Ho 53c). It appears that the stripping process makes an appreciable contribution even at energies lower than 1 Mev for some proton groups [(Bu 54) and (Pa 54a)]. Assuming that compound nucleus formation contributes an approximately isotropic background, (Pa 54a) find that the angular distributions may be fitted by $l_n=1$, 3, 0, and 2 for the B^{11} states at 0, 2.14, 4.46, and 5.03 Mev, respectively.

Gamma rays reported by (Bent, Sippel, and Bonner, private communication: lens pair spectrometer) and attributed to the present reaction are listed in Table III(11) and indicated in Fig. 16. Studies on $p-\gamma$ coincidences and correlations are cited in (Aj 52c). In the correlation of the proton group leading to the 2.14-Mev level and the γ radiation due to its subsequent decay, (Th 53) finds $I(90°)/I(180°)=1.05\pm0.05$, consistent with $J=\frac{1}{2}$ for the excited state. See also (Th 54d).

TABLE III(11). γ rays from $B^{10}(d\,p)B^{11}$.[a]

E_γ[b]	Yield $10^{-6}\,\gamma/d$	Total σ[c] (mb)	Assignment B^{11*}
4.74±0.04	2.2	6.9	9.19–4.46[d]
8.98±0.04	2.3	7.2	8.93
8.62±0.07	0.6	1.9	8.57
5.87±0.07	0.9	2.8	7.99–2.14
7.32±0.04	1.3	4.1	7.30
6.79±0.04	3.8	12	6.76
5.03±0.04	1.3	4.1	5.03
4.50±0.10	1.9	6.0	4.46

[a] Bent, Sippel, and Bonner, private communication: $E_d=2.0$ Mev, thick B^{10} target.
[b] Includes ~0.5 percent correction for Doppler shift.
[c] Average, $E_d=0$ to 2 Mev.
[d] May also be from $B^{10}(d\,n)C^{11}$, 4.77-Mev state.

XVI. $B^{11}(\gamma\,n)B^{10}$ $Q_m=-11.459$

See (Sh 51d).

XVII. $B^{11}(\gamma\,t)He^4+He^4$ $Q_m=-11.131$

The reaction apparently proceeds mainly through excited states of Be^8, although events corresponding to $B^{11}(\gamma\,\alpha)Li^7$ and $B^{11}(\gamma\,\alpha)Li^{7*}\rightarrow H^3+He^4$ are also reported. The cross section exhibits a maximum near $E_\gamma=23$ Mev, $\sigma\sim0.25$ mb, and possibly a second maximum near 27.5 Mev. There is some indication of fine structure, corresponding to discrete levels of B^{11} in the region 16 to 28 Mev (Er 53). See also (Mu 52a) and (Lo 53).

XVIII. $B^{11}(n\,n')B^{11*}$

See (Sc 54c).

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

Inelastic proton groups corresponding to levels at 2.2, 4.8, 6.5, and 7.8 Mev are reported (Fu 48 and Co 52g). A 2.13-Mev γ ray is observed for $E_p=2.5$ to 2.9 Mev (Hu 53 and Ba 54g).

XX. $C^{11}(\beta^+)B^{11}$ $Q_m=1.980$

See C^{11}.

XXI. $C^{12}(\gamma\,p)B^{11}$ $Q_m=-15.949$

See C^{12}.

XXII. $C^{12}(d\,\alpha)B^{11}$ $Q_m=5.163$

The weighted mean of Q-value measurements is 5.164±0.004 Mev (Va 54). This number includes a recent value of 5.166±0.005 Mev [(Ph 53) and G. C. Phillips, private communication; mag. spectrometer].

An alpha-particle group has been observed corresponding to a level at 2.107±0.017 Mev (Li 51b). At $E_d=7$ Mev, alpha-particle groups corresponding to B^{11} levels at 4.45 and 6.83 Mev are reported by (Sp 53c). At $E_d=2$ and 4 Mev, a 4.48-Mev γ ray is observed which may be located either in B^{11} or in N^{14} [(Be 54a), (Be 53b), and Bent, Sippel, and Bonner, private communication].

XXIII. $N^{14}(n\,\alpha)B^{11}$ $Q_m=-0.154$

At $E_n=14.1$ Mev, evidence is found for states of B^{11} at 2.1, 4.4, 5.0, 6.7, 7.3, 8.0, 8.5, 8.9, and 11.8 Mev (Li 52).

C^{11}

(Fig. 17)

I. $C^{11}(\beta^+)B^{11}$ $Q_m=1.980$

The spectrum is simple. The half-life is 20.35 ± 0.08 (Sm 41), 20.50 ± 0.06 (So 41), 20.0 ± 0.1 (Di 51), 20.74 ±0.10 min (Ku 53a). The maximum beta energy is 968 ± 8 kev. Log$ft=3.62$ (using $\tau_{\frac{1}{2}}=20.4$ min) (Wo 54a).

II. $Be^9(He^3\ n)C^{11}$ $Q_m=7.563$

See (Po 52b, Ku 53a, and Mo 54b).

III. $B^{10}(p\ \gamma)C^{11}$ $Q_m=8.697$

The cross section has been measured for $E_p=0.5$ to 2.5 Mev. It indicates a broad resonance at $E_p=1.2$ Mev and, possibly, one at 2.4 Mev. In this energy interval, the γ transitions are mainly to the ground state; at $E_p=0.86$ Mev, $E_\gamma=9.9\pm0.5$ Mev; at $E_p=1.21$ Mev, $E_\gamma=9.4\pm0.5$ Mev (Da 54). The thick B^{10} target yield of 9.47 ± 0.12 Mev γ radiation is $3.4\times10^{-10}\ \gamma/p$ at $E_p=1.16$ Mev (Wa 50a). See also (Kr 53b) and (Wi 53c). A broad resonance, $\Gamma\sim0.5$ Mev, is reported at $E_p=4.0$ Mev [(Ba 54g): preliminary].

IV. $B^{10}(p\ n)C^{10}$ $Q_m=-4.42$ $E_b=8.697$

See C^{10}.

V. $B^{10}(p\ p)B^{10}$ $E_b=8.697$

The elastic scattering cross section at $\theta=138°$ rises from nearly the Rutherford value for $E_p<0.9$ Mev to 4 times Rutherford at $E_p=1.6$ Mev. Anomalies are observed at $E_p=1.15$ and 1.5 Mev (Br 51a). See also (Va 50).

VI. $B^{10}(p\ p')B^{10*}$ $E_b=8.697$

The cross section for 0.72 Mev γ radiation at $\theta=90°$ rises monotonically from 0.04 mb/sterad at $E_p=1.52$ Mev to 1.6 mb/sterad at 2.65 Mev [(Da 52) and (Da 54)]. At $E_p=2.19$ Mev, $\theta=135°$, the cross section for the corresponding proton group is $\sim$3 mb/sterad. For $E_p\lesssim4.2$ Mev, the cross section for excitation of higher states in B^{10} is <0.3 mb (Cr 52c).

VII. $B^{10}(p\ d)B^9$ $Q_m=-6.211$ $E_b=8.697$

See B^9.

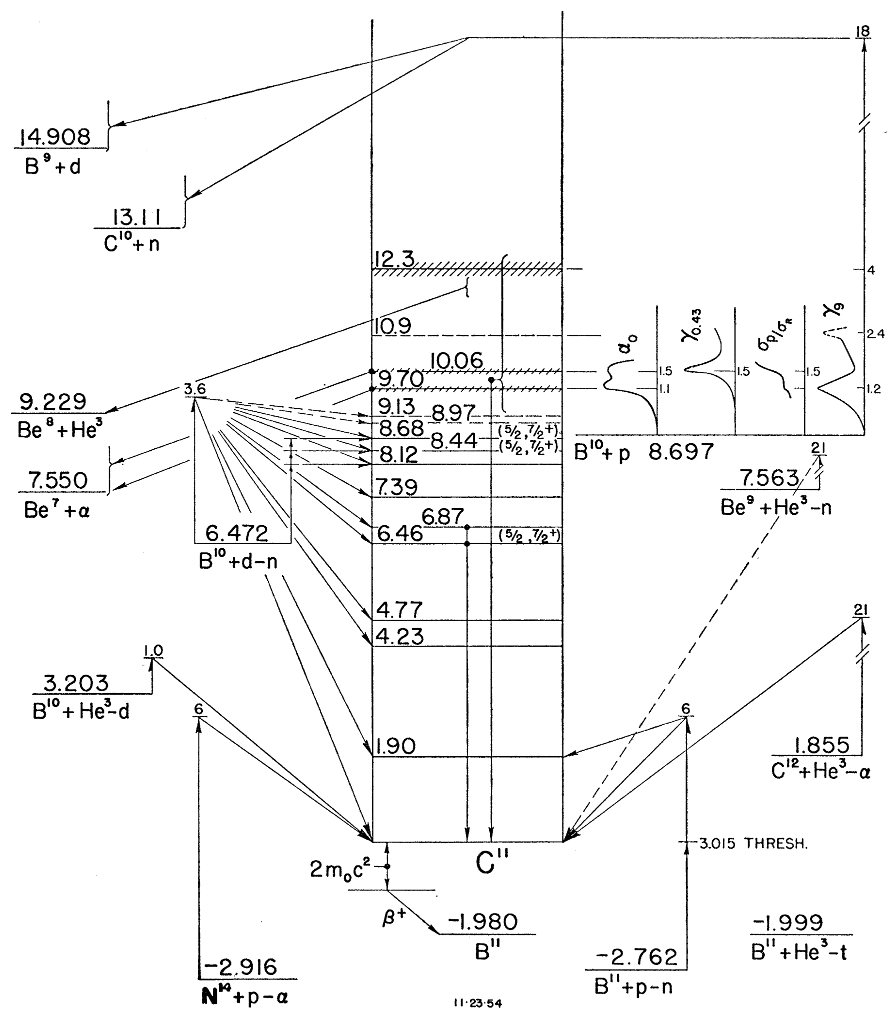


FIG. 17. Energy levels of C^{11}: for notation, see Fig. 1.

VIII. $B^{10}(p\ He^3)Be^8$ $Q_m=-0.532$ $E_b=8.697$

See (Cr 52c).

IX. $B^{10}(p\ \alpha)Be^7$ $Q_m=1.147$ $E_b=8.697$

The excitation function is a smooth exponential from $E_p=60$ to 200 kev. At $E_p=180$ and 205 kev, the cross sections are 0.26 ± 0.04 and 0.79 ± 0.12 mb, respectively (G. G. Bach and D. J. Livesey, private communication).

The ground-state α particles exhibit broad resonances at $E_p=1.1$ Mev and 1.5 Mev, superposed on a continuous background. At $E_p=1.1$ Mev, $\theta=138°$, the differential cross section $=16\pm3$ mb/sterad, dropping to half this value at $E_p=1.6$ Mev (Br 51a). At $E_p=3.33$ Mev, $\theta=135°$, the differential cross section is 20 mb/sterad (Cr 52c).

The short range alphas, $\theta=138°$, and 0.43-Mev γ rays, $\theta=90°$, exhibit only one resonance for $E_p\lesssim2.7$ Mev, at 1.52 Mev, with a width of 0.25 Mev and a peak cross section of 0.14 ± 0.03 b (Br 51a), 0.21 ± 0.07 b (Da 54). See also (Aj 52c).

X. $B^{10}(d\ n)C^{11}$ $Q_m=6.472$

At $E_d=3.40$ and 3.64 Mev, $\theta=0°$ and 80°, neutron groups are observed corresponding to states in C^{11} at 0, 1.85, 4.23, 4.77 ± 0.06, 6.40, 6.77, 7.39 ± 0.04, 8.08, 8.39, 8.62, 8.97(?), and 9.13 ± 0.02(?) Mev. Levels at 6.40, 8.39, and 8.62 Mev are believed to be formed by stripping, with $l_p=0$ transfer, and to have even parity, $J=5/2$ or 7/2 (Jo 52a). Angular distributions have been studied at $E_d=0.58$ Mev (Pa 54b) and at $E_d=0.71$ to 1.43 Mev (Bu 54); evidence is found for participation of the stripping process even at 0.6 Mev. Assuming an isotropic contribution from compound nucleus formation, (Pa 54b) find $l_p=1$, 3, and 0 for formation of C^{11} states at 0, 1.85, and 4.23 Mev, respectively.

Neutron threshold measurements indicate levels in C^{11} at 8.14 ± 0.02, 8.46 ± 0.02, and 8.70 ± 0.02 Mev (Cook, Marion, and Bonner, private communication). Gamma-ray measurements at $E_d=2$ Mev indicate two lines with $E_\gamma=6.52\pm0.04$ Mev ($\sigma_{ave}=12$ mb for $E_d=2$ Mev) and 7.01 ± 0.06 Mev ($\sigma_{ave}=6.0$ mb for $E_d=2$ Mev) (Bent, Sippel, and Bonner, private communication: corrected for Doppler shift). See also (Gi 53).

XI. $B^{10}(He^3\ d)C^{11}$ $Q_m=3.203$

The ground-state reaction has been observed for $E(He^3)=1$ Mev (E. Almqvist, private communication).

XII. $B^{11}(p\ n)C^{11}$ $Q_m=-2.762$

At $E_p=5.96$ Mev, neutron groups corresponding to the ground state and an excited state at 2.05 ± 0.1 Mev are observed (Rubin, Mazari, and Ajzenberg, private communication). See also (Ri 50e) and (Aj 54b).

XIII. $C^{12}(n\ 2n)C^{11}$ $Q_m=-18.711$

See C^{13}.

XIV. $C^{12}(\gamma\ n)C^{11}$ $Q_m=-18.711$

See C^{12}.

XV. $C^{12}(p\ d)C^{11}$ $Q_m=-16.486$

See N^{13}.

XVI. $C^{12}(He^3\ \alpha)C^{11}$ $Q_m=1.855$

See (Fr 52e, Po 52b, and Ku 53a).

XVII. $N^{14}(p\ \alpha)C^{11}$ $Q_m=-2.916$

See O^{15}.

XVIII. $O^{16}(\gamma\ n\alpha)C^{11}$ $Q_m=-25.859$

The threshold energy is 25.9 ± 0.2 Mev [P. Stoll and P. Erdös, private communication, and (Er 54c)].

B^{12}

(Fig. 18)

I. $B^{12}(\beta^-)C^{12}$ $Q_m=13.370$

The spectrum is complex: see C^{12}.

II. $Be^9(\alpha\ p)B^{12}$ $Q_m=-6.880$

At $E_\alpha=21.7$ Mev, proton groups are observed corresponding to the ground state of B^{12} and to levels at 0.95, 1.65, and 3.82 Mev (Mc 51b).

III. $B^{11}(n\ \gamma)B^{12}$ $Q_m=3.361$

$\sigma_{th}<50$ mb (Wa 50e). See also (Wi 53f).

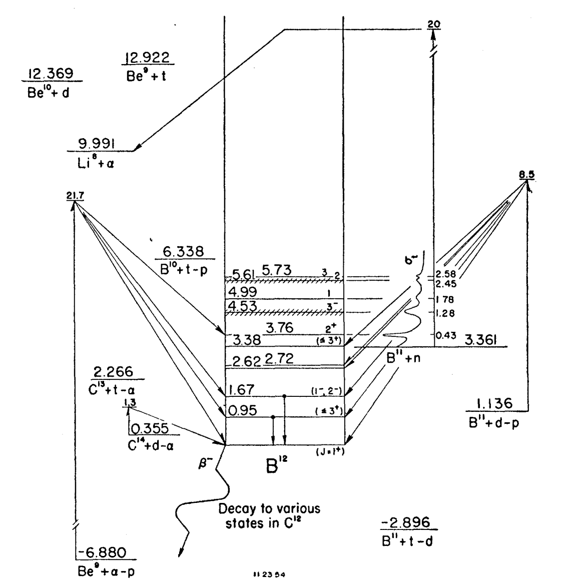


FIG. 18. Energy levels of B^{12}: for notation, see Fig. 1.

TABLE I(12). Resonances in $B^{11}(n\ n)B^{11}$ (Bo 51c).

E_n (Mev)	$\sigma_{max}-\sigma_{pot}$ (bn)	Γ (kev)	B^{12*} (Mev)	l	$\gamma^2/(3\hbar^2/2\mu a)$[a]	J, π
0.43	2.9	40	3.76	1	0.036	2^+
1.28	2	130	4.53	2	0.28	3^-
1.78	0.4	65	4.99	1	0.012	1
				2	0.056	
				(3)	1.6[b]	
2.45	0.5	120	5.61	1	0.017	2
				2	0.053	
				3	0.82[b]	
2.58	0.6	60	5.73	1	0.0082	3
				2	0.025	
				3	0.26[b]	

[a] Widths corrected for variation of level shift with energy.
[b] According to (Vo 54), $l=3$ yields an implausibly large value for γ^2/D.

IV. $B^{11}(n\ n)B^{11}$ $E_b=3.361$

Observed resonances are listed in Table I(12). The rise of the cross section at low energies may indicate a broad level formed by s-wave neutrons (Bo 51c). The angular distribution of scattered neutrons at the 0.43-Mev resonance is of the form $1+AP_1(\cos\theta)$ and indicates p-wave formation of a $J=2^+$ level. The distribution at the 1.28-Mev resonance agrees with d-wave formation of a $J=3^-$ level [(Wi 54) and (Wi 54e)]. Polarization of the neutrons has been observed at $E_n=0.43$ Mev (A. Okazaki, private communication).

The total cross section varies from 1.5 b at 6 Mev to 1.4 b at 9.7 Mev (Ne 54c). The total cross section decreases monotonically from 1.43 ± 0.02 b (Co 54f), 1.40 ± 0.03 b (Co 52h) at $E_n=14.1$ Mev to 1.30 b at 18.0 Mev (Co 54f). See also (Hi 54d).

V. (a) $B^{11}(n\ d)Be^{10}$ $Q_m=-9.008$ $E_b=3.361$
(b) $B^{11}(n\ t)Be^9$ $Q_m=-9.561$
(c) $B^{11}(n\ \alpha)Li^8$ $Q_m=-6.630$

Reactions (a) and (b) have not been reported. Cross sections for reaction (c) have been reported for nine energies in the range $E_n=12.5$ to 19.9 Mev by (Fr 54d). See also (Fr 53d) and (He 54c).

VI. $B^{11}(d\ p)B^{12}$ $Q_m=1.136$

Proton groups observed at $E_d=4.0$ to 8.5 Mev are listed in Table II(12). No other groups are observed for

TABLE II(12). Levels in B^{12} from $B^{11}(d\ p)B^{12}$ (El 53 and Bu 50d).

Q (Mev)	B^{12*}	I(90°)[a]
1.136 ± 0.004	0	1.0
0.189 ± 0.004	0.947 ± 0.005	0.78
-0.534 ± 0.008	1.674 ± 0.011	2.85
-1.478 ± 0.007	2.618 ± 0.011	0.69
-1.583 ± 0.008	2.723 ± 0.011	0.04
-2.243 ± 0.003	3.383 ± 0.009	1.86

[a] Relative intensities at 90° (±20 percent) at $E_d=8.06$ Mev.

$E_x=0$ to 3.15 Mev with an intensity greater than 4 percent of the ground-state group, or from 3.15- to 3.5-Mev excitation with an intensity greater than 8 percent. Association of these levels with known levels in C^{12} is discussed (El 53). At $E_d=4.153$ Mev, proton groups are observed to the ground state and to levels at 0.940 and 1.664 Mev [(Kh 54); mag. analyzer: ±20 kev].

At $E_d=8$ Mev, the angular distribution of the protons, analyzed by stripping theory, indicate $l_n=1$ and therefore $J\leq3$, even parity for the ground state of B^{12} and the levels at 0.95 and 3.38 Mev, $l_n=0$ for the 1.67-Mev state ($J=1, 2^-$) and $l_n=2$ for the 4.53-Mev level ($J\leq4^-$) of B^{12}(Ho 53c). At $E_d=1.05$ Mev, γ rays with energies of 0.94 and 1.64 Mev are observed with an intensity ratio of 2:1 (Th 54d).

VII. $C^{12}(n\ p)B^{12}$ $Q_m=-12.588$

See (Je 48c).

VIII. $C^{14}(d\ \alpha)B^{12}$ $Q_m=0.355$

See (Hu 50e) and N^{16}.

IX. $N^{15}(n\ \alpha)B^{12}$ $Q_m=-7.627$

See (Je 48c).

C^{12}

(Fig. 19)

I. (a) $Be^9(He^3\ n)C^{11}$ $Q_m=7.563$ $E_b=26.274$
(b) $Be^9(He^3\ p)B^{11}$ $Q_m=10.325$
(c) $Be^9(He^3\ \alpha)Be^8$ $Q_m=18.900$

See Be^8, B^{11}, and C^{11}.

II. $Be^9(\alpha\ n)C^{12}$ $Q_m=5.708$

The neutron spectrum at $E_\alpha=5.3$ Mev (thin target) indicates levels of C^{12} at 0, 4.2, and 7.5 Mev; in the forward direction, the intensity of the latter group is about 1/8 of that corresponding to the 4.4-Mev level (Gu 52). Study of $n-\gamma$ coincidences indicates that 60 ± 6 percent of disintegrations lead to the 4.4-Mev level; no indication of $n-\gamma$ coincidences involving other than the 4.4-Mev γ ray is observed [(Di 54); $E_\alpha=5.3$ Mev].

The energy of the γ ray from the first level is 4.425 ±0.020 Mev (corrected for Doppler shift). From the observed Doppler shift it is concluded that the lifetime of the level is $<3\times10^{-13}$ sec (Mi 54d). The internal pair conversion coefficient agrees with an $E2$ assignment (Mi 54d) while the angular correlation is consistent with either $E2$ or $M1$ (Ha 54a).

At $E_\alpha=5.3$ Mev, a γ ray of energy 3.16 ± 0.05 Mev is observed with an intensity relative to the 4.4-Mev γ ray of 3 percent (thick target). The intensity of 7-Mev γ radiation is $<1/2500$ (Be 53c). That the 3-Mev radiation results from a cascade transition is confirmed by the observation of $\gamma-\gamma$ coincidences (3.1–4.4 Mev)

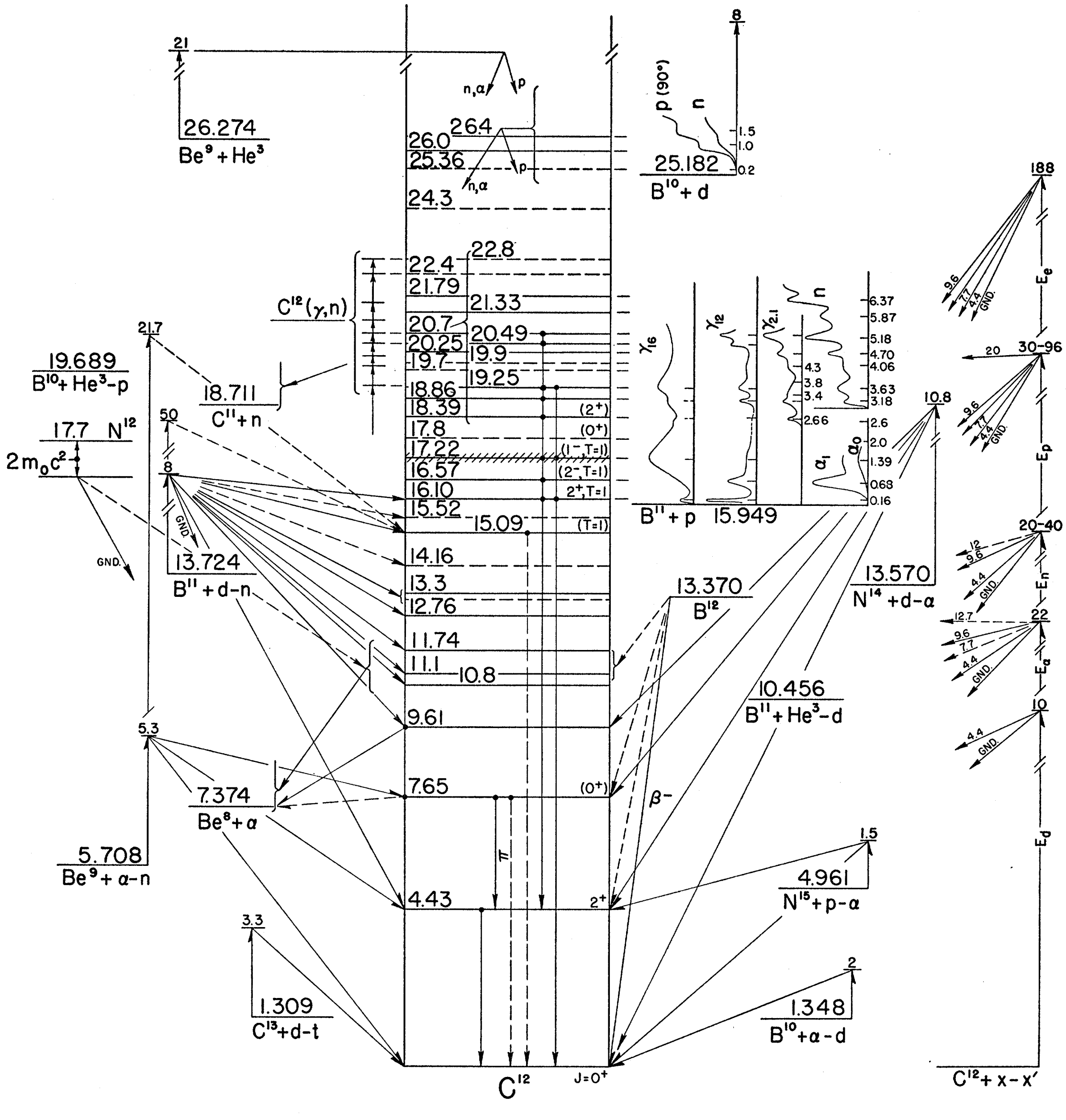


FIG. 19. Energy levels of C^{12}: for notation, see Fig. 1.

by (Ue 54) who finds an energy of 3.05±0.1 Mev and a relative intensity of 8–12 percent ($E_\alpha=5.3$ Mev, thin target). Comparing this intensity with the reported intensity of the neutron group, (Ue 54) concludes that most of the transitions from the 7.6-Mev level are of this nature (see, however, $C^{12}(\alpha\,\alpha')\,C^{12}$). [The sum of the γ-ray energies gives the level energy as 7.57±0.05 Mev, i.e. 0.2 Mev unstable with respect to Be^8+He^4: see $N^{14}(d\,\alpha)C^{12}$.] Internal (or monopole) pairs (seven cases *versus* 72 from the 4.4-Mev radiation at $E_\alpha=5.3$ Mev, thick target), corresponding to a transition energy of 7.0±0.6 Mev, are reported by (Ha 54a) who suggests that the 7.6-Mev level has $J=0$. See also Be^8: $B^{11}(p\,\alpha)Be^8$.

At $E_\alpha=21.7$ Mev, a 15.1±0.5-Mev γ ray is observed, with a yield comparable to that of the $Be^9(\alpha\,p)C^{12}$ process. Assuming a cross section for the $(\alpha\,n)$ reaction equal to the cross section for the $(\alpha\,p)$ reaction, it is concluded that $\Gamma_\alpha \lesssim 100\,\Gamma_\gamma$ for the level in question. So high a γ-ray yield from a level which is energetically unstable to α emission indicates the operation of a strong selection rule forbidding α decay. It is suggested that the level involved is the expected first $T=1$, $J=1^+$ state of C^{12} [see $C^{12}(p\,p')C^{12}$ and $B^{11}(d\,n)C^{12}$] (Ra 54a). See also (Gu 53) and (Ca 54g).

III. $B^{10}(d\,n)C^{11}$ $Q_m=6.472$ $E_b=25.182$

The thin-target excitation function in the range $E_d=0.3$ to 2.0 Mev shows a continuous rise, with some indication of a broad resonance near $E_d=0.9$ Mev. Angular distributions indicate that the stripping process is of considerable importance at energies >1 Mev (Bu 54). See also (Pa 54b).

IV. $B^{10}(d\,p)B^{11}$ $Q_m=9.234$ $E_b=25.182$

The differential cross section (at 170°) has been measured for $E_d=175$ to 700 kev. The relative intensities of four proton groups show irregularities at $E_d=210$ kev ($C^{12*}=25.36$ Mev) (Pa 54a). Excitation functions for ground-state protons at $\theta=0°$, 90°, 135°, and γ radiation are reported by (Bu 54) in the range $E_d=0.5$ to 2.0 Mev. The curves show indications of two broad resonances, at $E_d\sim1.0$ and 1.5 Mev, superposed on a general rise. Angular distributions suggest a stripping process. The absolute differential cross section at $E_d=1.5$ Mev, $\theta=90°$, is 35 ± 10 mb/sterad [(Bu 54): see however, (Va 51a)].

V. $B^{10}(d\,d)B^{10}$ $E_b=25.182$

See B^{10}.

VI. $B^{10}(d\,\alpha)Be^8$ $Q_m=17.809$ $E_b=25.182$

A resonance has been observed at $E_d=1.05$ Mev (Wh 51b).

VII. $B^{10}(\alpha\,d)C^{12}$ $Q_m=1.348$
$Q_0=1.39\pm0.01$ Mev (Sh 53b).

See (Cr 49c) and N^{14}.

VIII. (a) $B^{11}(p\,\gamma)C^{12}$ $Q_m=15.949$
(b) $B^{11}(p\,\alpha)Be^8$ $Q_m=8.575$ $E_b=15.949$

The capture radiation comprises two components: a 16-Mev line, representing the ground-state transition, and a 12+4-Mev cascade through the 4.4-Mev, $J=2^+$ level. Resonances for the 12-Mev radiation occur at $E_p=0.16$, 0.68, 1.39, 2.6(?), 3.14, 3.6, 4.95, and 5.12 Mev, while the 16-Mev radiation exhibits resonance only at $E_p=0.16$, 1.4, 2.6(?), 3.18(?), and 3.6 Mev (Hu 53, Co 52e, Go 53d, and Ba 54g). Reaction (b) leads to α particles to the ground state of $Be^8(\alpha_0)$ and to the 2.9-Mev excited state (α_1). The α_1 particles exhibit all the resonances listed up to 2.6 Mev, while the α_0 particles show all except the 0.68-Mev resonance [(Be 53) and (Pa 53b)]. Values for the cross sections and the derived partial widths are listed in Table III(12).

The resonance energy and width of the first resonance is given as 162 ± 1 kev, $\Gamma=5.3\pm1$ kev (Ta 46); 162.8 ± 0.2 kev, $\Gamma=4.5\pm1$ kev (Mo 49a); 163.8 ± 0.3, $\Gamma=7.3\pm0.5$ kev (Hu 53d).

The angular distribution of the 12-Mev γ rays has been studied in the range $E_p=0.15$ to 0.18 Mev by (Hu 52b), from 0.17 to 0.70 Mev by (Gr 54a), from 0.2 to 1.1 Mev by (Je 53c), from 0.6 to 2.0 Mev by (Gi 54a) and (Gi 54c), and from 0.7 to 2.6 Mev by (Go 53d). At $E_p=0.16$ Mev, the distribution has the form $(1+0.25\cos^2\theta)$; above this energy, a $(\cos\theta)$ term sets in, whose coefficient rises to a value of 0.15–0.2 at 0.4 Mev, passes through a minimum of 0–0.1 at 0.7 Mev, rising to a maximum of 0.4–0.5 near 1.5 Mev and vanishing again at 2.6 Mev. Various reports disagree on the course of the $(\cos^2\theta)$ term, but it appears to have a minimum (~0.1) near 0.7 Mev [(Gi 54c) and (Je 53c); see, however, (Gr 54a)] and a peak value of 0.4–0.6 near 2 Mev, falling to a value of -0.15 at 2.6 Mev.

The angular distribution of the 16-Mev radiation at $E_p=0.168$ is given by $1-A\cos\theta+B\cos^2\theta$ where $A=0.19\pm0.06$, $B=A+0.02\pm0.04$ [(Cr 54) and Craig, Cross, and Jarvis, private communication]. Values obtained by (Gr 54a) are consistent with these and with a theoretical distribution assuming $J=2^+$ for the $E_p=0.163$-Mev resonance with interference from a $J=1^-$ resonance at $E_p=1.39$ Mev (see, however, Gl 52b). From $E_p=0.6$ to 2.6 Mev, the value of A varies between $+0.05$ and -0.09, while B varies from 0.15 to 0.3, dropping to -0.43 at 2.6 Mev [(Gi 54a), (Gi 54c), and (Go 53d)].

The α-particle angular distributions are reported by (Ha 39) and (Th 52c). Again, the distributions depend upon energy, the long-range group exhibiting a $(\cos\theta)$ term which changes sign near $E_p=0.16$ Mev (Th 52c).

Since the C^{12} level corresponding to the $E_p=0.16$-Mev resonance yields α particles to the $J=0^+$ ground state of Be^8, the angular momentum and parity must be either even-even or odd-odd. Formation by s waves is ruled out by the observed anisotropy. Of the possible states formed by p waves, $J=0^+$ is excluded for the same reason, leaving $J=2^+$. This assignment is supported by study of the angular correlation of 12- and 4-Mev γ rays [(Hu 52b) and (Le 52)[1]], by the α_0-particle distribution (Th 52c), and by the angular correlation of α_1 and subsequent α particles (Ge 54a). (If the reported proton width of 5 ev is correct, formation by d waves cannot be ruled out on grounds of penetrability.) The very small values of the particle widths for α emission from the 16.10-Mev C^{12} level suggest the operation of a strong selection rule. It appears probable that the level has $T=1$ and that the difference in $\Gamma_{\alpha0}$ and $\Gamma_{\alpha1}$ reflects a difference in the isotopic spin purity of the Be^8 states (Be 53).

The proton width, $\Gamma_p=150$ kev, of the 16.57-Mev level ($E_p=0.68$ Mev) admits formation by either s or p waves. Assignment of $J=2^-$ would account for the absence of α_0 and γ_{16} from this level. The 15-ev value of $\Gamma_{\gamma12}$ suggests a relatively uninhibited $E1$ radiation, and hence $T=1$ for the level. An assignment of 3^+ is not excluded by these measurements (Be 53). The angular distribution of α particles is said to indicate $J=2^-$ [(Pa 53b); see, however, (Gr 54a)].

For the third resonance, $E_p=1.39$ Mev, $C^{12*}=17.22$ Mev, the large proton width suggests s or p wave forma-

[1] The angular correlation of (Le 52) was misquoted in (Aj 52c). The corrected relation should read: $W(100°, 100°, \phi)=1+(0.41\pm0.06)\cos^2\phi$ (G. M. Lewis, private communication).

TABLE III(12). Resonances in $B^{11}(p\ \gamma)C^{12}$ and $B^{11}(p\ \alpha)Be^8$.

E_p (Mev)	Γ (kev)	$\sigma(\gamma_{16})$[a] μb	$\sigma(\gamma_{12})$[a] μb	$\sigma(\alpha_0)$[c] mb	Y_{max} (α_0)[d]	$\sigma(\alpha_1)$[c] mb	Y_{max} (α_1)[d]	$\Gamma\gamma_{16}$[e] ev	$\Gamma\gamma_{12}$[e] ev	$\Gamma\alpha_0$[e] kev	$\Gamma\alpha_1$[e] kev	Γ_p[e] kev	C^{12*}	J, π T
0.163[a]	5	5.5	152	0.2		10		$\lesssim 3$	70	0.1	5	0.005	16.10	2^+ 1
0.675[a]	322	(<2.3)[f]	48	(<0.2)[f]	(<0.04)[f]	600	35.4	$\lesssim 0.5$	15	$\lesssim 0.05$	150	150	16.57	$(2^-)(1)$
1.388[a]	1270	35	18	6	1.0	150	8.8	40	20	7	200	1000	17.22	$(1^-, 2^+)$
2.0[b]	150	non res.			1.4		2.3						17.8	(0^+)
2.65[b,g]	300	(res.)	res.		2.6		10.5						18.38	(2^+)
3.14[g]		(res.)	res.										18.84	
3.6[g]		res.	res.										19.3	
4.95[g]		non res.	res.										20.49	
5.12[g]		non res.	res.										20.64	

[a] (Hu 53).
[b] (Go 53d) and (Pa 53b).
[c] (Be 53): values for $E_p = 0.16$ estimated from earlier work. These values are subject to considerable uncertainty.
[d] (Pa 53b): relative maximum yields: thin target.
[e] (Be 53).
[f] Nonresonant.
[g] (Ba 54g).

tion, although in view of the uncertainty in Γ_p, d wave is not excluded (Be 53). On the assumption of s-wave formation of a $J=1^-$ state (2^- is excluded by the observation of α_0), the large width for the $E1$ transition to the ground state of C^{12} points to $T=1$ (Be 53). However, the α-particle and γ-ray angular distributions are consistent with $J=2^+$ [(Pa 53b) and (Go 53d); see, however, (Gr 54a)]. An assignment of 0^+ is suggested for the 17.8-Mev level ($E_p=2.0$ Mev) on the basis of the intensity of the α_1 group. The 18.39-Mev level ($E_p=2.65$ Mev) is stated to be 2^+ by (Go 53d).

A search for pairs in the range $E_\pi=6.5$ to 9.5 Mev at $E_p=1.7$ to 4.0 Mev led to a negative result. An upper limit for the cross section is 0.03 μb [Bent, Sippel, and Bonner, private communication; see (Ph 51b): Be^8]. See also (Ch 53d), (Wi 53a), (Wi 53c), and (Fo 54a).

IX. $B^{11}(p\ n)C^{11}$ $Q_m=-2.762$ $E_b=15.949$

Resonances have been observed at $E_p=3.18$, 3.63, 4.06, and 4.70 Mev by (Ba 54g), and at $E_p=3.7$, 5.18, 5.87, and 6.37 Mev by (Bl 51a). See also (Aj 52c).

X. $B^{11}(p\ p')B^{11*}$ $E_b=15.949$

Resonances for 2.13-Mev γ radiation are observed at $E_p=2.664$ Mev [$\Gamma=48$ kev: (Hu 53); see also (Ba 54g)], and at $E_p=3.15$, 3.4, 3.78, 4.26, 4.68, and 5.13 Mev [(Ba 54g): $C^{12*}=18.40$, 18.84, 19.2, 19.42, 19.86, 20.25, and 20.64 Mev]. At the first resonance, the cross section is 31 mb, assuming isotropic distribution (Hu 53).

XI. $B^{11}(p\ d)B^{10}$ $Q_m=-9.233$ $E_b=15.949$

See B^{10}.

XII. $B^{11}(d\ n)C^{12}$ $Q_m=13.724$

Neutron groups corresponding to states in C^{12} at 0, 4.44, 9.6±0.1, 10.8±0.1, 11.1±0.1, 11.74±0.08, 12.76 ±0.08, 13.21±0.05(?), 13.36±0.05(?), 14.16±0.05(?), 15.09±0.03, 15.52±0.03(?), and 16.07±0.03 Mev have been observed by (Jo 52a). No group corresponding to a state at $E_x \sim 7.6$ Mev is observed with an intensity $\gtrsim 10$ percent (Jo 52a). At $E_d=8.1$ Mev, the angular distribution of the neutrons to the 4.4-Mev state, analyzed by stripping theory, indicates $l_p=1$ and therefore even parity for that state, $J \leq 3$ (Gi 53). Neutron threshold measurements show a level in C^{12} at 15.10 ±0.02 Mev (Cook, Marion, and Bonner, private communication).

At low-bombarding energies, a single γ ray is observed corresponding to the decay of the 4.4-Mev state; see (Aj 52c). At high energies ($E_d=10.8$ to 50 Mev), a 15.2±0.2-Mev γ ray is observed which is attributed to the ground-state transition from the first $T=1$ state of C^{12} at 15.09 Mev [(Co 54d), (Wa 54a), (Ra 54a): see $C^{12}(p\ p')C^{12*}$]. See also (Th 54d).

XIII. $B^{12}(\beta^-)C^{12}$ $Q_m=13.370$

The half-life is 0.022±0.002 sec (Be 39), 0.027±0.002 sec (Je 48c), 0.022±0.001 sec (Br 53d). The spectrum is complex. Most of the transitions go to the ground state of C^{12}; however a 4±1 percent branch to a γ-emitting level, perhaps the 4.4-Mev state, has been observed in a study of $\beta-\gamma$ coincidences (Ve 52a), and deviations from the Fermi plot below $E_\beta=6$ Mev may indicate a 5 percent branch to the 7.6-Mev and higher excited states of C^{12} (Ho 50). Logft for the ground-state transition is 4.17; assuming a 4 percent branch to the 4.4-Mev state, logft for this transition is 4.8. Since both branches are allowed, $J=1^+$ for B^{12} is indicated (Ve 52a).

XIV. $C^{12}(\gamma\ n)C^{11}$ $Q_m=-18.711$

Discontinuities in the yield of C^{11} (Ka 54a) and of neutrons (Go 54f) as a function of bremsstrahlung energy indicate levels in C^{12} at 19.3, 19.8, 20.1, 20.5, 20.7, 21.1, 21.6, 22.4, and 22.8 Mev (±0.1 Mev to ±0.2 Mev) The integrated cross sections, assuming sharp levels, are also given (Ka 54a). The sum of these integrals is 55 Mev-mb, while the integrated $(\gamma\ n)$ cross section over the same region, ignoring fine structure, is given as 29 Mev-mb by (Mo 53c) and as 27 Mev-mb by (Na 54). The approximate agreement implies that a substantial fraction of the observed $(\gamma\, n)$ cross section may be attributed to discrete states of C^{12}. On the assumption of $E1$ absorption, the states in question have $J=1^-$ (and, presumably, $T=1$) (Go 54f). If the fine structure is ignored, the general form of the cross-section curve exhibits a broad resonance at $E_\gamma \sim 22$ Mev with a width of 3 Mev and a peak cross section of 8.6 mb (Na 54), 9.5 mb (Ba 54c), 13.1 mb (Ha 51b) and (Ka 51a).

The integrated cross section to 38 Mev is 45 Mev-mb, while that from 38 to 200 Mev is 15 Mev-mb (Ba 54c). The integrated total nuclear absorption cross section is $\sim$100 Mev-mb to $E_\gamma=26$ Mev (Ha 53d). See also (Na 53, Ro 53b, and Bi 54).

XV. $C^{12}(\gamma\, p)B^{11}$ $Q_m=-15.949$

The cross section exhibits a resonance at $E_\gamma=21.5 \pm 0.5$ Mev, $\Gamma=1.7\pm0.5$ Mev. The peak cross section is 34 ± 8 mb; the integrated cross section to 24 Mev is 63 ± 16 Mev-mb (Ha 51f). The angular distribution of protons at $E_\gamma=23$ Mev indicates interference of a one percent quadrupole component with the dominant dipole absorption (Ha 52g). See also (St 54i).

XVI. $C^{12}(\gamma\, 3\alpha)$ $Q_m=-7.278$

Maxima in the yield of 3-prong stars are reported at $E_\gamma=17.3$, 18.3, 21.9, 24.3, and 29.4 Mev; some evidence of fine structure is also found. The integrated cross section is 1.21 ± 0.16 Mev-mb for $E_\gamma<20.5$ Mev, 2.8 ± 0.4 Mev-mb for $20.5\leq E_\gamma<42$ Mev, and <0.2 Mev-mb for $42 \leq E_\gamma<60$ Mev [(Go 53f): 2500 stars; see also (Wi 55)]. (Da 53d) find pronounced narrow peaks at $E_\gamma=18$ and 29 Mev. (Mi 53c) report a single broad peak at $E_\gamma=17$–18 Mev with a peak cross section of 0.08 mb, a width of $\sim$4 Mev and an integrated cross section (to $E_\gamma=27$ Mev) of 0.84 Mev-mb. Neither (Da 53d) nor (Mi 53c) excludes the possibility of fine structure. The mean cross section for the $(\mathrm{Li}+p)$ γ rays is 0.14 ± 0.026 mb (Go 53f), 0.175 ± 0.025 mb (Gl 52).

The character of the α spectrum at $E_\gamma=17.6$ Mev suggests that $E2$ and $M1$ radiation is mainly involved, leading to states in C^{12} with $J=2^+$ and 1^+ (Te 51b). See also (Aj 52c) and Be^8. (Wi 55) find, on the other hand, that above $E_\gamma=15.6$ Mev, the major contribution comes from $E1$ and $E2$ absorption, with $E1$ comprising 35 percent for $E_\gamma=15.6$ to 17.0 Mev, 70–75 percent from 17 to 20 Mev, 35 percent from 20 to 22.6 Mev, increasing to $\sim$100 percent for $E_\gamma>26$ Mev. It is pointed out by (Ge 53a) that the threshold for $E1$ absorption (into $T=1$ states) should be around 15 Mev and that the threshold for allowed α emission to the 16.8-Mev $T=1$ state of Be^8 should be near 26 Mev.

Histograms of (Wi 55) indicate that the direct three-body disintegration does not occur to any appreciable extent [see, however, (Mi 53c) and (Ch 54e)]. See also (Li 53b) and (Gr 54).

XVII. $C^{12}(e\, e')C^{12*}$

At $E_e=150$ and 188 Mev, inelastic electron groups are observed corresponding to states of C^{12} at 4.5, 7.6, and 9.7 Mev. The intensity of the 7.6-Mev line is 0.052 of the elastic peak and 0.125 of the $Q=-4.5$-Mev group ($E_e=188$ Mev, $\theta=80°$) [(Mc 54) and J. H. Fregeau and R. Hofstadter, private communication].

XVIII. (a) $C^{12}(n\, n')C^{12*}$
(b) $C^{12}(n\, n')3He^4$ $Q_m=-7.277$

A gamma ray of energy 4.42 ± 0.02 Mev is observed at $E_n=6.5$ Mev [(Da 53c) and R. B. Day, private communication]. At $E_n=14$ Mev, gamma rays of energy 2.8, 4.45, 6.0, and 7.0 Mev are reported to be produced, with cross sections of 36, 69, 2, and 2 mb, respectively (Sc 53); (Th 54b) report only a 4.4-Mev γ ray, with a cross section of about 300 mb. An inelastic neutron group corresponding to excitation of the 4.4-Mev level is reported by [(Wh 53): $E_n=14$ Mev]; there is evidence for a second group corresponding to a level near 11.5 Mev (Wh 53).

At high neutron energies, $E_n=8$ to 40 Mev, α-emitting levels of C^{12} are excited. A level at 9.7 Mev, with an observed half-width of 1.6 Mev, appears to be involved, and to decay mainly to the ground state of Be^8. Direct decay from this level into 3 α particles occurs less than 25 percent of the time (Ja 53). There are indications of the participation of another state, at $\sim$12 Mev, which decays predominantly to the 2.9-Mev state of Be^8 (Li 53b). See also (Ba 53a), (Fr 53d), (On 54), and (Sc 54c).

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

An inelastic proton group corresponding to the 4.4-Mev state of C^{12} has been observed at $E_p=7.3$ Mev (Go 52b), 8 Mev (Ar 52e), 9.5 Mev (Bu 53b), 10 Mev [(Fi 54) and (Fi 54b)], and 31.5 Mev (Br 52c). Near $E_p=10$ Mev, the angular distribution exhibits a minimum at $\theta=90°$ and maxima near $\theta=40°$ and 150°. (Bu 53b) report the distribution approximately symmetric about $\theta=90°$, while (Go 52b) and (Fi 54b) find the forward maximum somewhat higher. The angular distribution of 4.4-Mev γ rays is of the form $1+3.6\cos^2\theta-3.6\cos^4\theta$, consistent with $J=2$ for the excited state (Go 53e). The angular correlation of γ rays and inelastic protons is reported by (Go 53). Resonances for production of 4.4-Mev γ rays are reported at $E_p=5.37$ and 5.9 Mev [(Ma 53h) and (Ma 54k)]: see N^{13}. At $E_p=31.5$ Mev, groups corresponding to levels at 4.4, 7.5, and 9.5 Mev are observed (Br 52c). At $E_p=96$ Mev, inelastic groups are observed to levels at 4.4, 9.6, and 20.0 ± 1 Mev in C^{12} (St 54d). (There is no indication of a level near 15 Mev in this work.) From $E_p=30$ to 340 Mev, a 15.2 ± 0.2-Mev γ ray is observed which is attributed to the first $T=1$ state in C^{12}[(Wa 54a) and (Co 54d): see also $B^{11}(d\ n)C^{12}$].

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

At $E_d=10$ Mev, inelastically scattered deuterons corresponding to a state of C^{12} at 4.41 Mev are observed by (Ke 51b). At $E_d=19.1$ Mev, an additional group is observed corresponding to the formation of the 9.6-Mev state; angular distributions of the groups are also shown (Fr 54e).

XXI. (a) $C^{12}(\alpha\ \alpha')C^{12*}$
(b) $C^{12}(\alpha\ \alpha n)C^{11}$ $Q_m=-18.711$

At $E_\alpha=22$ Mev, inelastic groups corresponding to levels at 4.4, 7.65±0.07, 9.6, and, possibly, 12.7 Mev are observed. C^{12*} recoils have been observed corresponding to the ground state and that at 4.4 Mev, but not to the 7.6-Mev state; it is believed that this state yields Be^8+He^4 with >80 percent probability [see, however, $Be^9(\alpha\ n)C^{12}$] [(Mi 54c) and V. K. Rasmussen, private communication]. For reaction (b), see (Li 53c).

XXII. $C^{13}(d\ t)C^{12}$ $Q_m=1.309$

The weighted mean of two Q-value determinations is 1.310±0.003 Mev (Va 54). Absolute differential cross sections have been measured for the ground-state tritons from $\theta=5.8°$ to 137° at $E_d=3.29$ Mev and 2.19 Mev. At the higher energy, the distribution agrees well with that expected from pickup theory, with $l_n=1$, $R=6.25\times10^{-13}$ cm; discrepancies at the lower energy are attributed to effects of the Coulomb barrier (Ho 54c).

XXIII. $N^{12}(\beta^+)C^{12}$ $Q_m=17.7$

The decay is mainly to the ground state via an allowed transition. Delayed α particles with a total energy of ~4 Mev are also observed, suggesting that a state of C^{12} in the region 11 to 12 Mev is involved (Al 50g).

XXIV. $N^{14}(n\ t)C^{12}$ $Q_m=-4.007$

See N^{15} and (Li 52).

XXV. $N^{14}(d\ \alpha)C^{12}$ $Q_m=13.570$

Alpha particles have been observed corresponding to levels of C^{12} at 4.431±0.013 (Ma 51), 7.68±0.03 [(Du 53) and (Sp 53c)], 9.613±0.012 Mev (Ma 51). The intensity of the group corresponding to the 7.68-Mev state is 6 percent of the intensity of the group corresponding to the first excited state at $E_d=0.62$ Mev, $\theta=90°$; the width is <25 kev. No other group of intensity >1 percent appears for $E_x=3.7$ to 7.4 Mev (Du 53). The 9.6-Mev state has a width >10 kev (Ma 51). The angular correlation of α particles and 4.4-Mev γ rays at $E_d=0.63$ Mev indicates $J=2^+$ for the 4.4-Mev state [(St 54f: see also O^{16}]. A small yield of 15-Mev γ radiation is reported at $E_d=10.8$ Mev [(Ra 54a): see $Be^9(\alpha\ n)C^{12}$]. See also (Th 54d).

XXVI. $N^{15}(p\ \alpha)C^{12}$ $Q_m=4.961$

The weighted mean of seven Q-value determinations is 4.961±0.003 Mev (Va 54). This includes a recent value of 4.962±0.004 Mev obtained by (Co 53; mag. spectrometer).

Alpha particles have been observed to a state of C^{12} at 4.432±0.010 Mev (Sc 52). The γ-ray energy, after a Doppler correction of 20 kev, is 4.443±0.020 Mev. The necessity for the correction implies a lifetime for the 4.4-Mev state $<3\times10^{-13}$ sec. This upper limit is consistent with $E2$ decay of the 4.4-Mev level to the ground state and thus with $J=2^+$ (Th 52). The angular distributions of short-range alpha particles and 4.4-Mev γ radiation indicate that the 4.4-Mev state has $J=2^+$ or >4 (Kr 53). See also O^{16}.

XXVII. (a) $O^{16}(\gamma\ \alpha)C^{12}$ $Q_m=-\ 7.149$
(b) $O^{16}(\gamma\ 4\alpha)$ $Q_m=-14.426$

There is evidence of the involvement of C^{12} states at 9.6 and ~11 Mev, which decay to the ground state of Be^8, a state at 12–13 Mev, decaying mainly to the 2.9-Mev Be^8 state, and $T=1$ states at ~16 Mev, again leading mainly to the 2.9-Mev Be^8 state. The 4.4- and 7.7-Mev states of C^{12} seem to occur rarely, if at all (see O^{16}).

N^{12}

(Not illustrated)

I. $N^{12}(\beta^+)C^{12}$ $Q_m=17.7$

The half-life is 0.0125±0.001 sec; $E_\beta(\max)=16.6$ ±0.2 Mev (Al 49a). The decay is complex; N^{12} decays both to the ground state and to α unstable excited states of C^{12} (Al 50g). Log$ft=4.18$ for the ground-state transition [(Fe 51b); see also (Ki 52)].

II. $C^{12}(p\ n)N^{12}$ $Q_m=-18.5$

$E_{\text{thresh.}}=20.0\pm0.1$ Mev (Al 49a).

III. $N^{14}(\gamma\ 2n)N^{12}$ $Q_m=-30.9$

See N^{14}.

The following reactions leading to N^{12} are not reported: $B^{10}(He^3\ n)N^{12}$ ($Q_m=1.3$), $C^{12}(He^3\ t)N^{12}$ ($Q_m=-17.7$), $N^{14}(p\ t)N^{12}$ ($Q_m=-22.4$).

B^{13}

(Not illustrated)

Mass of B^{13}

(Ba 39e) computes a mass of 13.0207 amu for B^{13}: mass defect=19.3 Mev. A rough interpolation from other A suggests that the first $T=\frac{3}{2}$ state in C^{13} is located ~13.5 Mev above the ground state. This means $B^{13}-C^{13}$~12 Mev: mass defect=19±2 Mev. Assuming this value, B^{13} would then be stable by ~6 Mev to decay into $B^{12}+n$, and by ~12 Mev to decay into

Be^9+t and $Li^9+\alpha$. (Hu 53a) have attempted to detect B^{13} as a delayed neutron emitter with 5×10^{-4} sec $<\tau_{\frac{1}{2}}<1800$ sec formed in spallation reactions. The results were negative as were those of (Sh 52) who searched for B^{13} as a spallation product of 50 Mev bremsstrahlung irradiation. See also (Sn 48).

The following reactions leading to B^{13} are not reported: $B^{11}(t\,p)B^{13}$ ($Q_m=1$), $C^{13}(n\,p)B^{13}$ ($Q_m=-11$), $C^{13}(t\,He^3)B^{13}$ ($Q_m=-12$), $C^{14}(n\,d)B^{13}$ ($Q_m=-17$), $C^{14}(d\,He^3)B^{13}$ ($Q_m=-14$), $C^{14}(t\,\alpha)B^{13}$ ($Q_m=0$), $N^{15}(n\,He^3)B^{13}$ ($Q_m=-22$), $C^{14}(\gamma\,p)B^{13}$ ($Q_m=-20$).

C^{13}

(Fig. 20)

I. $Be^9(\alpha\,n)C^{12}$ $Q_m=5.708$ $E_b=10.656$

Resonances observed for $E_\alpha=0$ to 5.3 Mev are exhibited in Table I(13) [(Ha 49i), (Ta 53), (Be 54), and (Tr 54)]. See also (Aj 52c) and C^{12}.

TABLE I(13). Resonances in $Be^9(\alpha\,n)C^{12}$.

E_α[a] (Mev)	E_α[b] (Mev)	C^{13*}	J,π[c]	References
0.53	0.53	11.02		(Be 54)
0.61	0.61	11.08	$(\frac{1}{2}^+)$	(Be 54)
1.91	1.9	11.98	$(\frac{1}{2}^-)$	(Be 54), (Tr 54), and (Ta 53)
2.24		12.21		(Tr 54)
2.58	2.65	12.46		(Tr 54) and (Ta 53)
3.40		13.01		(Tr 54)
(4.4)		(13.7)		(Ha 49i)

[a] Resonances in neutron yield.
[b] Resonances in the 4.2 ± 0.2 Mev γ-ray yield.
[c] James, Jones, and Wilkinson, private communication; J, π from angular distributions of ground-state neutrons. The resonances appear to be superposed on a broad $J=7/2^-$ background.

II. $Be^9(\alpha\,p)B^{12}$ $Q_m=-6.880$ $E_b=10.656$

See B^{12}.

III. $Be^9(\alpha\,d)B^{11}$ $Q_m=-8.016$ $E_b=10.656$

See B^{11}.

IV. (a) $Be^9(\alpha\,\alpha')Be^{9*}$ $E_b=10.656$
(b) $Be^9(\alpha\,\alpha'n)Be^8$ $Q_m=-1.666$
(c) $Be^9(\alpha\,n)3He^4$ $Q_m=-1.570$

For reaction (a), see Be^9. For reactions (b) and (c), see (Aj 52c).

V. $B^{10}(t\,\alpha)Be^9$ $Q_m=13.217$ $E_b=23.873$

See Be^9.

VI. $B^{10}(\alpha\,p)C^{13}$ $Q_m=4.071$

The weighted mean of six Q-value measurements is 4.08 ± 0.10 Mev (Va 54). This does not include a recent value of 4.064 ± 0.011 Mev by [(Fa 54d) and W. J. Fader, (private communication; mag. spectrograph)]. Four proton groups are observed, corresponding to C^{13} levels at 0, 3.09, 3.68, and 3.85 Mev [(Sh 53b), (Fa 54a), and (Fa 54d)]. The relative intensities depend strongly on bombarding energy (see N^{14}), but generally the group to the 3.86-Mev level is the strongest, by a factor of 5 or more (Sh 53b). Upper limits for an earlier reported group corresponding to a level near 0.7 Mev are, relative to the ground-state group: 2 percent at $E_\alpha=1.14$ Mev, 0.5 percent at $E_\alpha=1.54$ Mev (Ma 53f), 7 percent at $E_\alpha=1.64$ Mev (Sh 53b), 1 percent at $E_\alpha=4.8$ and 5.8 Mev (Fa 54d). A limit for a 4.6-Mev level of 1 percent of the group leading to the 3.89-Mev state is given by (Fa 54d).

Gamma rays of energy 3.73 ± 0.06 and 0.21 ± 0.03 Mev are observed, the latter arising from the transition between the 3.86- and 3.68-Mev levels. It is estimated that the ratio of direct ground-state transitions and 0.2-Mev cascades from the 3.86-Mev state is 7:3, and it is suggested from the large intensity that the soft radiation is $E1$ [(Sh 53b) and (St 54c)]. The observed angular distributions confirm this assignment (St 54c). The angular distributions and $p-\gamma$ correlations for the higher-energy radiation contain terms in $(\cos^4\theta)$, indicating $J=5/2^+$ for the 3.86-Mev level ($J=3/2^+$ or $5/2^+$ from $C^{12}(d\,p)C^{13}$]. The distributions favor an $M1$ assignment for the 3.68-Mev radiation (St 54c).

Detailed study of proton angular distributions confirms the assignments $J=\frac{1}{2}^-$ and $\frac{1}{2}^+$ for the ground and 3.1-Mev states, and permits the selection $J=5/2^+$ for the 3.86-Mev state from the alternatives given by $C^{12}(d\,p)C^{13}$. An assignment of $J=\frac{3}{2}^-$, rather than $\frac{1}{2}^-$, for the 3.68-Mev state follows from the observation of $E1$ cascade radiation (Sh 53b).

VII. $B^{11}(d\,n)C^{12}$ $Q_m=13.723$ $E_b=18.671$

The neutron yield curve has been measured for $E_d=0.2$ to 2.0 Mev while the angular distributions have been observed at 0.71, 1.00, and 1.59 Mev. Even at these low energies, the contribution of the stripping process is conspicuous (Bu 54). See also C^{12}.

VIII. $B^{11}(d\,p)B^{12}$ $Q_m=1.136$ $E_b=18.671$

The thin-target yield rises smoothly from $E_d=0.3$ to 1.8 Mev with no evidence of resonances. At $E_d=1.47$ Mev, the cross section is 4 mb (Hu 49j). See also B^{12}.

IX. $B^{11}(d\,d)B^{11}$ $E_b=18.671$

See (Va 51).

X. $B^{11}(d\,\alpha)Be^9$ $Q_m=8.015$ $E_b=18.671$

See (Va 51).

XI. $C^{12}(n\,\gamma)C^{13}$ $Q_m=4.948$
$Q_0=4.949\pm0.006$ (Ki 53b; pair spectrometer)

The thermal capture cross section in graphite is 4.7 mb (Wa 50e). In addition to the 4.95-Mev ground-state transition, a γ ray is reported with an energy of 3.68 ±0.05 Mev and an intensity of 0.3 γ/capture. If 3.1- and 3.9-Mev γ rays occur, their intensities are less than

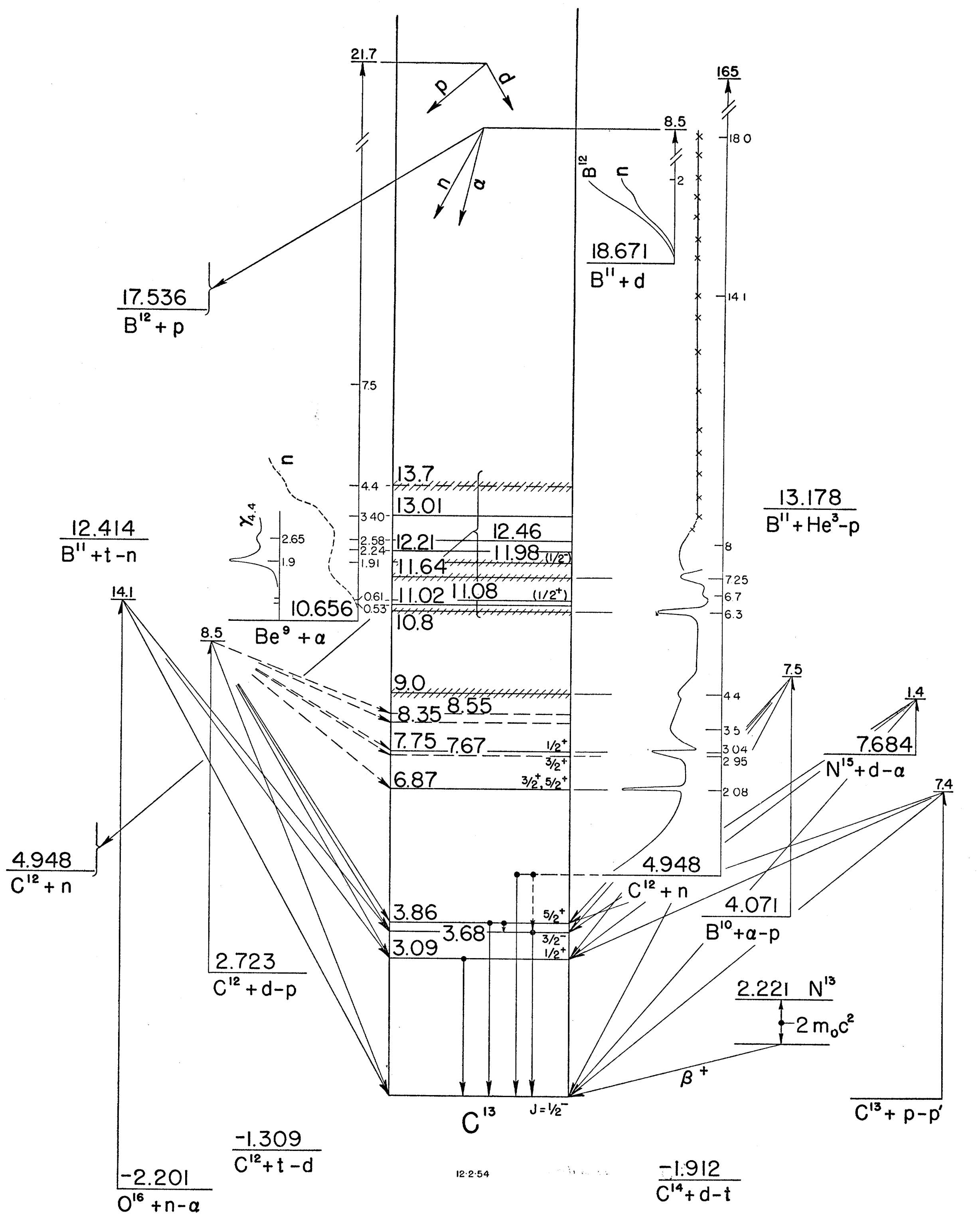


FIG. 20. Energy levels of C^{13}: for notation, see Fig. 1.

0.10 and 0.06 γ/capture, respectively (Ba 53d). See also (Th 52b).

XII. $C^{12}(n\ n')C^{12*}$ $E_b=4.948$
$C^{12}(n\ n')3He^4$ $Q_m=-7.277$

Both γ- and α-emitting states of C^{12} are excited. At $E_n=14$ Mev, the cross section for production of inelastic neutrons in the range $E_n=0$ to 11.5 Mev is 760±40 mb (Ph 52b), in the range $E_n=0.5$ to 12 Mev, $\sigma=520\pm200$ mb (Gr 53d). The cross section for production of γ rays is ~300 mb (Th 54b), 190 mb (Sc 53); the cross section for α-particle production is 135±17 mb (Hu 54a).

XIII. $C^{12}(n\ n)C^{12}$ $E_b=4.948$

The epithermal scattering cross section is 4.70±0.05 bn [free atoms: (Hu 52e)]. See also (Hu 53c) and (Hu 54a). No resonances with width >5 kev appear in the scattering cross section in the range $E_n=20$ to 1360 kev (Mi 50c). In that region, the cross section decreases monotonically from 4.8 bn at 20 kev to 2.4 bn at 1360 kev [(Mi 50c); see also (Ki 53) and (Hu 54a)]. The course of the cross section in this range can be accounted for by the broad s state at 3.09-Mev excitation (Th 52b). The nonresonant scattering at $E_n=0.5$ and 1.5 Mev is nearly isotropic (Wi 54). A resonance, <10 kev wide, is located at 2.08 Mev, $\sigma\geq2.7$ b, corresponding to a level at 6.87 Mev in C^{13} with $J\geq\frac{3}{2}$ (Bo 51c). The angular distribution of scattered neutrons at this resonance indicates d-wave scattering, $J=3/2^+$ or $5/2^+$ (Ri 53b).

A structure at 3.0 Mev [(Bo 51c) and (Ri 51e)] is attributed to strong interference between a resonance at that energy with $J=\frac{3}{2}$ and either potential scattering or another resonance, possibly that at 3.5 Mev [(Ri 50d) and (Ri 51c)], of the same spin. The angular distributions have been measured in the range $E_n=2.6$ to 4.15 Mev by (Hu 52d), who find, by a partial wave analysis, a $D_{\frac{3}{2}}$ resonance at $E_n=2.95$ Mev and a $S_{\frac{1}{2}}$ resonance at $E_n=3.04$ Mev. The rise in cross section at 3.5 Mev does not appear to be a resonance (Hu 52d).§ Another maximum appears at $E_n=4.4$ Mev (Fr 50b). Accurate cross sections in this region are quoted by (La 50a). At higher energies, the cross-section curve shows structure at $E_n=6.3$ Mev ($\sigma=2.8$ b, $\Gamma\sim0.1$ Mev), 6.7(?), 7.25 ($\sigma=1.8$ b, $\Gamma\sim0.2$ Mev) (Hu 53c) and ~8 Mev (broad) (Ne 52). The average total cross section varies from 1.1 b at $E_n=9$ Mev to 1.4 b at $E_n=14$ Mev (Ne 54c). At 14 Mev, the total cross section is 1.279±0.004 b (Po 52a), 1.32±0.02 b (Co 52h), 1.20±0.04 b (Go 52d), 1.29±0.02 b (Co 54f). From $E_n=14$ to 20 Mev, the cross section remains essentially constant [(Co 54f) and (Da 53f)]. At 20.07 Mev, $\sigma_t=1.52\pm0.05$ b. Total cross sections for $E_n=39.6$ to 165.2 Mev are listed in (Hu 54a). See also (Re 52a), (Gr 53d), (Ri 53c), and (Hi 54d).

§ See, however, Huber and Budde, Helv. Phys. Acta **27**, 512 (1954).

XIV. $C^{12}(n\ 2n)C^{11}$ $Q_m=-18.711$ $E_b=4.948$

The cross section for C^{11} production is 5±1 mb at 24.5±2 Mev and 10±1.5 mb at 27.5±0.5 Mev (Br 52e).

XV. $C^{12}(d\ p)C^{13}$ $Q_m=2.723$

The weighted mean of nine Q-value determinations is 2.722±0.003 Mev (Va 54); this includes recent values of 2.722±0.004 Mev by (Fa 53; mag. spectrometer), and 2.720±0.003 Mev by (El 54; mag. spectrometer).

Measurements on the proton groups are summarized in Table II(13). A number of additional groups are reported by (Ca 52a), of which the most prominent appear to correspond to levels at 6.92±0.08, 7.58±0.08, 7.75±0.08, 7.87±0.07, 8.35±0.08, and 8.55±0.07 Mev (Ca 52a). The level assignments in Table II(13) were obtained by analysis of angular distributions by means of stripping theory. Absolute differential cross sections for the ground-state protons have been measured at $E_d=3.29$ Mev by (Ho 54c). While the general shape of the distribution is consistent with the assumption of a stripping process as the dominant factor, discrepancies in detail suggest that compound nucleus formation also plays a role at this energy (Ho 54c). See also N^{14}. A careful search with $E_d=5$ to 8.5 Mev ($\theta=90°$) reveals no further proton groups corresponding to levels in the range 0 to 4.9 Mev with intensity greater than 0.5 percent of the ground-state group (Sp 54b).

Gamma rays observed by (Ma 53e), (Th 52), (Be 54a), and Bent, Sippel, and Bonner (private communication) are listed in Table III(13). Internal pair studies of the ground-state γ transitions from the 3.84- and 3.68-Mev levels appear most nearly consistent with an $M2$ or $E3$ assignment for the higher transition ($E1$ is excluded, $E2$ or $M1$ are possible) and either $E2$ or $E1$ for the lower transition ($M1$ not excluded). This information, together with the implication from the large intensity of the 0.17-Mev radiation that this is a lower multipole transition, supports selection of the values $J=5/2^+$ and $3/2^-$ for the 3.85- and 3.69-Mev states from the alternatives offered by the stripping analysis (Ma 53e; see also $B^{10}(\alpha\ p)C^{13}$). The internal conversion coefficient of the 0.17-Mev cascade radiation is consistent with an $E1$ transition (R. J. Mackin, private communication). At $E_d=2.4$ Mev, the upper limit of the cascade transitions of the 3.84- and 3.68-Mev

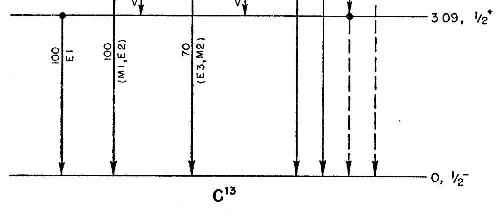


Fig. 21. Gamma-ray transitions in C^{13}: for notation, see Fig. 13.

TABLE II(13). Levels of C^{13} from $C^{12}(d\ p)C^{13}$.

C^{13*} (Mev)[a]	C^{13*} (Mev)[b]	C^{13*} (Mev)[c]	C^{13*} (Mev)[d]	J, π[e]
0	0	0	0	$1/2^-$, $3/2^-$
3.086±0.006	3.090±0.015	3.107	3.11	$1/2^+$
3.686±0.011	3.684±0.015	3.699	3.683	$1/2^-$, $3/2^-$
	3.855±0.015	3.869	3.884	$3/2^+$, $5/2^+$

[a] E_d=1.51 Mev, θ=90° [(St 51) and (Va 51a)].
[b] E_d=5 to 8.5 Mev, θ=90° [(Sp 53b) and (Sp 54b)].
[c] E_d=4.40 Mev (Kh 53).
[d] E_d=8 Mev, θ=15° to 160° [(Ro 51j) and (Ro 51k)].
[e] (Ro 51j), (Ro 51k), (Bl 52), and (Ca 53f).

states to the 3.10-Mev level is $0.2\times10^{-6}\ \gamma/d$ or 3 percent of the ground-state transitions (Ma 53e).

The lifetime of the 3.08-Mev state is $<3\times10^{-13}$ sec. The pair spectrum indicates an $E1$ transition (Th 52). Branching ratios of the γ radiation for the low levels of C^{13}, as derived from the present reaction, from $B^{10}(\alpha\ p)C^{13}$ and from $C^{12}(n\ \gamma)C^{13}$ are exhibited in Fig. 21. The reduced widths of the ground, 3.1- and 3.86-Mev states are ~0.1 to 0.5 of the single-particle value, while that of the 3.68-Mev state is much smaller [see (Fu 54), (La 53b), (La 54), (La 54b), and (In 53)]. See also (Bl 53), (Cu 53), and (Th 54d).

XVI. $C^{13}(\gamma\ n)C^{12}$ $Q_m=-4.948$

See (Se 49a) and (Go 53f).

XVII. $C^{13}(\gamma\ \alpha)Be^9$ $Q_m=-10.656$

See (Mi 53c).

XVIII. $C^{13}(p\ p')C^{13*}$

At $E_p=7.4$ Mev, $\theta=90°$, proton groups corresponding to levels at 3.14 and 4.03 Mev are observed (Co 52g). (This is the only one of the observed reactions which can directly lead to $T=\frac{3}{2}$ states in C^{13}.)

XIX. $N^{13}(\beta^+)C^{13}$ $Q_m=2.221$

See N^{13}.

XX. $N^{14}(n\ d)C^{13}$ $Q_m=-5.316$

See (Li 52).

TABLE III(13). Gamma radiation from $C^{12}(d\ p)C^{13}$.

$E\gamma$[a] (Mev)	$E\gamma'$[b] (Mev)	Yield $10^{-6}\gamma/d$	Reference
3.843±0.014	3.838	4.3[c]	(Ma 53e)
3.86 ±0.02	3.84 ±0.03	4.0[d]	(d)
0.170±0.001		~2[c]	(Ma 53e): cascade
3.684±0.020	3.677	5.8[c]	(Ma 53e)
3.76 ±0.02	3.74 ±0.03	3.5[d]	(d)
3.097±0.005	3.082±0.007	13.2[e]	(Th 52)
3.10		62[c]	(Be 54a)

[a] Uncorrected for Doppler shift.
[b] Corrected for Doppler shift.
[c] (Ma 53e) and R. J. Mackin (private communication): E_d=2.4 Mev.
[d] (Be 54a) and Bent, Sippel, and Bonner (private communication): E_d=4.0 Mev.
[e] (Th 52): E_d=1.46 Mev.

XXI. $N^{15}(d\ \alpha)C^{13}$ $Q_m=7.684$

$Q_0=7.681\pm0.006$ (Ma 51; mag spectrometer). Alpha groups are observed corresponding to states in C^{13} at 3.083±0.005 and 3.677±0.005 Mev (Ma 51).

XXII. $O^{16}(n\ \alpha)C^{13}$ $Q_m=-2.201$

$Q_0=-2.38\pm0.16$ [(Hu 51f); ion chamber].

At 14.1 Mev, alpha tracks corresponding to levels of C^{13} at 3.0 and 3.7 Mev have been observed by (Li 52). See also O^{17}.

N^{13}

(Fig. 22)

I. $N^{13}(\beta^+)C^{13}$ $Q_m=2.221$

The half-life is 10.05±0.03 min (Ch 53c), 10.05±0.1 min (Ho 50), 10.13±0.1 min (Si 45a), 9.93±0.03 min (Wa 39), $E_\beta(\max)=1.202\pm0.005$ Mev (Ho 50). The positron spectrum is simple: the Fermi plot is straight down to <150 kev. Logft=3.67 (Fe 51b). See also (La 54b).

II. $B^{10}(He^3\ \alpha)B^9$ $Q_m=12.130$ $E_b=21.634$

See B^9.

III. $B^{10}(\alpha\ n)N^{13}$ $Q_m=1.068$

See N^{14}.

IV. (a) $C^{12}(p\ \gamma)N^{13}$ $Q_m=1.945$
(b) $C^{12}(p\ \gamma p')C^{12}$

Observed resonances are exhibited in Table IV(13). The reduced width for the 0.46-Mev resonance is of the order of the Wigner limit, even for formation by s waves. This large width and the difference in boundary conditions at the nuclear surface account for the displacement between the 2.37-Mev state of N^{13} and the 3.10-Mev, $J=\frac{1}{2}^+$, state of C^{13} [(Th 52b) and (Eh 51)]. Consideration of the cross section at $E_p\sim100$ kev (Fo 51) and of the capture cross section in $C^{12}(n\ \gamma)C^{13}$ leads to an estimate of the reduced width of 2 percent of the sum-rule limit for the ground states of C^{13} and N^{13} [(Th 52b); also see (Fu 54)].

The angular distribution of the γ radiation of the 1.70-Mev resonance (ground-state transition) has the form $1+A\cos^2\theta$, where A varies with energy (Da 51 and Da 51b).

In the range $E_p=1.2$ to 2.5 Mev, a γ ray whose energy varies with bombarding energy as $E_\gamma=0.88\ (E_p-0.45)$ is observed. The radiation represents a transition to the 2.37-Mev level ($E_p=0.46$ Mev) which then decays preferentially by proton emission. Analysis of excitation functions at $\theta=0°$ and 90° indicates that interference between direct p wave capture from the continuum and resonant capture at $E_p=1.70$ Mev are involved. At resonance, the relative amplitude of the resonant and nonresonant γ rays is 1.1±0.1, and the

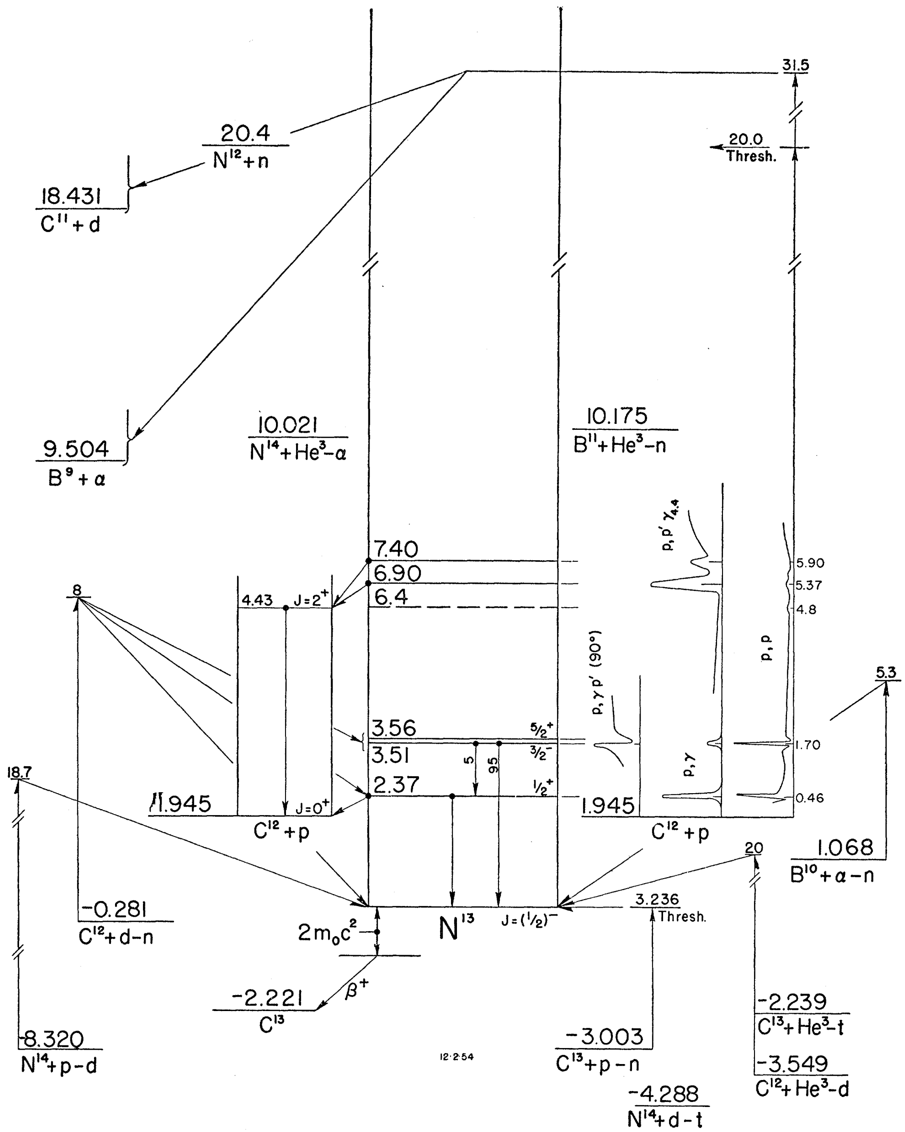


FIG. 22. Energy levels of N^{13}: for notation, see Fig. 1.

relative phase, excluding the resonance phase, is $214° \pm 10°$. The absolute yield indicates a width Γ_γ of 0.04 ev for the transition from the 3.51- to the 2.37-Mev level (Wo 54). At $E_p = 1.57$ and 1.68 Mev, the distribution for reaction (b) has the form $(0.14 \pm 0.03) + \sin^2\theta$

TABLE IV(13). Resonances in $C^{12}(p\ \gamma)N^{13}$.

E_p (kev)	Γ (kev)	σ_{res} (μb)	$\omega\Gamma_\gamma$ (ev)	$\gamma^2/\frac{3}{2}(\hbar^2/\mu a)$	N^{13*}	Reference
456.8±0.5	39.5±1.0				2.37	(Hu 53d)
456±2	35					(Fo 49b)
450	35	127	0.67	0.5[a]		(Se 51c) and (Se 51e)
1697±12	74±9				3.51	(Va 49)
1698±5	70±10	35	1.39	0.04[a,b]		(Se 51c) and (Se 51e)

[a] (Th 52b): $a = 4.9 \times 10^{-13}$ cm.
[b] Assuming incoming p waves.

(Heiberg, Alexander, and James, private communication: thick natural target). See also (Wi 53c).

V. $C^{12}(p\ n)N^{12}$ $Q_m = -18.5$ $E_b = 1.945$

See N^{12}.

VI. $C^{12}(p\ pn)C^{11}$ $Q_m = -18.711$ $E_b = 1.945$

See (Ch 47c and Mc 48).

VII. $C^{12}(p\ p)C^{12}$ $E_b = 1.945$

The elastic scattering exhibits anomalies at $E_p = 0.46$ Mev [(Ja 53c) and (Mi 54)], 1.7 and 1.75 Mev (Ja 53c). Further structure is reported by (Ma 53h) at $E_p = 3.2$, 4.8, 5.37, and 5.9 Mev: (Ja 53c), however, find only a smooth variation in the range $E_p = 2.0$ to 4.4 Mev. Angular distributions are reported by (Ja 53c) and (Mi 54).

TABLE V(13). Resonances in $C^{12}(p\ p)C^{12}$.

E_p[a] (kev)	Γ[a] (kev)	$\gamma^2/\frac{3}{2}(\hbar^2/\mu a)$[b]	N^{13*} (Mev)	J, π	Reference
462	35				(Mi 54)
461±3	34	0.54	2.369	$1/2^+$	(Ja 53b)
1.698	60	0.031	3.51	$3/2^-$	(Ja 53b)
1.748	66	0.21	3.56	$5/2^+$	(Ja 53b)
3.2(?)			4.9(?)		(Ma 53h)
4.8(?)			6.4(?)		(Ma 53h)
5.37			6.90		(Ma 53h)
5.90			7.40		(Ma 53h)

[a] Laboratory system.
[b] $a = 4.77 \times 10^{-13}$ cm.

The s-wave phase shift changes by nearly 180° in the neighborhood of the 0.46-Mev resonance and thereafter remains constant to $E_p = 1.3$ Mev; a further change of 8° in the range 1.4 to 3.6 Mev is indicated by the experimental data and is attributed to a broad S level at higher energy. Detailed analysis confirms earlier assignments of $J = \frac{1}{2}^+$, $\frac{3}{2}^-$, and $5/2^+$ for the three levels of N^{13} at 2.37, 3.51, and 3.56 Mev, and leads to the level parameters exhibited in Table V(13). The great breadth of the two even parity levels suggests single-particle excitation (Ja 53b).

At $E_p = 5.37$ and 5.9 Mev, strong resonances for 4.4-Mev γ radiation are attributed to inelastic excitation of the first level of C^{12}. Cross sections for γ radiation measured at $\theta = 105°$ are 6.3±3 and 3.0±1.6 mb/ster, respectively, at the two resonances [(Ma 53h) and (Ma 54k): see also (Bl 53a)].

Angular distributions of elastic and inelastic protons (see C^{12}) have been measured at $E_p = 9.5$ Mev by (Bu 53b), at 10 Mev by (Fi 54b), at 30.6 Mev by (Wr 53a), and at 31.5 Mev by (Br 52c). Characteristic maxima and minima are observed, indicating interference between Coulomb and nuclear scattering. See also (Co 54a).

VIII. $C^{12}(p\ d)C^{11}$ $Q_m = -16.486$ $E_b = 1.945$

See (Br 52c).

IX. $C^{12}(p\ \alpha)B^9$ $Q_m = -7.559$ $E_b = 1.945$

See B^9.

X. $C^{12}(d\ n)N^{13}$ $Q_m = -0.281$

$Q_0 = -0.281 \pm 0.003$ Mev [(Bo 49c); neutron threshold].

Neutron groups have been observed corresponding to excited states of N^{13} at 2.29±0.12 (Gr 49a), 2.38 ±0.05 Mev (Mi 53) and 3.48±0.12 (Gr 49a), 3.53±0.05 Mev (Mi 53). At $E_d = 8$ Mev, the angular distributions of the three neutron groups have been studied by (Mi 53); considerable deviations from the theoretical curves are noted.

XI. $C^{12}(He^3\ d)N^{13}$ $Q_m = -3.549$

See (Fr 52e).

XII. $C^{13}(p\ n)N^{13}$ $Q_m = -3.003$

$Q_0 = -3.003 \pm 0.003$ Mev [(Ri 50e); neutron threshold].

[This is one of only two observed reactions (see Sec. XIII) which can directly lead to $T = \frac{3}{2}$ states in N^{13}.] See also N^{14}.

XIII. $C^{13}(He^3\ t)N^{13}$ $Q_m = -2.239$

See (Fr 52e).

XIV. $N^{14}(\gamma\ n)N^{13}$ $Q_m = -10.545$

See (Bi 54) and (Ho 50b).

XV. $N^{14}(p\ d)N^{13}$ $Q_m = -8.320$

At $E_p = 18.7$ Mev, the angular distribution of the ground-state deuterons, analyzed by pickup theory, indicates $l_n = 1$ and therefore opposite parities for the ground states of N^{13} and N^{14}. No group corresponding to the first excited state was found; see N^{14} (St 54a).

XVI. $N^{14}(d\ t)N^{13}$ $Q_m = -4.288$

See (Bo 42).

C^{14}

(Fig. 23)

I. $C^{14}(\beta^-)N^{14}$ $Q_m = 0.155$

The mean of reported end points is 155±1 kev (Li 51a). A recent value is 155±1.5 kev (La 53c). The half-life is 5568±30 years (An 51), 5400±200 years (Ma 51e), 5900±250 years (Ca 54f): $\log ft = 9.03$. The spectrum does not appear to deviate from the allowed shape down to <3 kev (Mo 54e, E. Jensen, private communication, La 53c, and Wu 53).

Since the parities of the ground state of C^{14} and N^{14} are both even, it is not obvious why the half-life should be so large. It may be that a strong L forbiddeness is

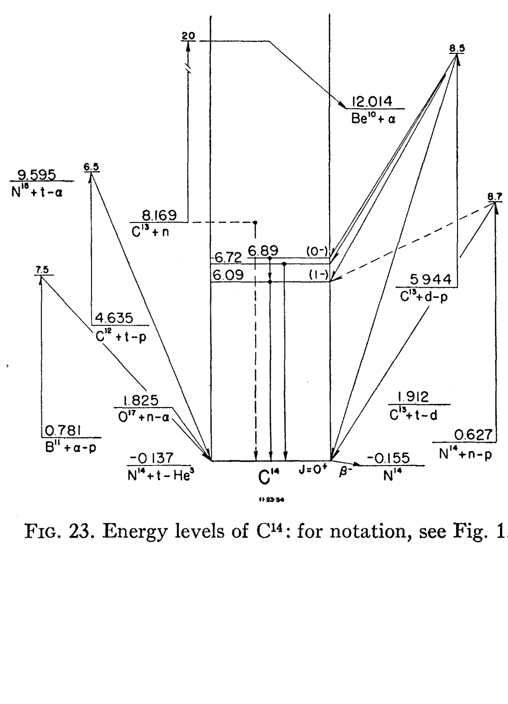


FIG. 23. Energy levels of C^{14}: for notation, see Fig. 1.

involved (transition $^1S_0$ to $^3D_1$) [see e.g. (No 51) and (Ge 51); see, however, (Me 52) and (St 54a)]. With tensor forces of appropriate magnitude, the calculated ft value may be made as large as necessary (Ja 54a). See also (Ki 52), (In 53), (Fe 53), and (Mi 53b).

II. $B^{11}(\alpha\ p)C^{14}$ $Q_m=0.781$

See (Fr 51c), (Ma 53f), and N^{15}.

III. $C^{12}(t\ p)C^{14}$ $Q_m=4.635$

See (Po 51).

IV. $C^{13}(n\ \gamma)C^{14}$ $Q_m=8.169$

The thermal cross section is 0.9±0.2 mb (He 54d). See also (Br 53g) and (Wi 53f).

V. $C^{13}(n\ n)C^{13}$ $E_b=8.169$

See (Ko 52).

VI. $C^{13}(n\ \alpha)Be^{10}$ $Q_m=-3.845$ $E_b=8.169$

See (Sa 54a) and (Hu 47).

VII. $C^{13}(d\ p)C^{14}$ $Q_m=5.944$

The weighted mean of six Q values is 5.942±0.004 (Va 54). A recent determination gives 5.942±0.010 Mev [(Sp 54b); mag. spectrometer].

At $E_d=5$ to 8.5 Mev, $\theta=90°$, proton groups are observed corresponding to states of C^{14} at 6.091±0.015, 6.723±0.015, and 6.894±0.015 Mev. In the region 0 to 8.1 Mev in C^{14} no other levels have been observed with an intensity greater than 0.25 of the group corresponding to the 6.1-Mev state (Sp 54b). At $E_d=4$ Mev, the angular distribution of the ground-state protons, analyzed by stripping theory, indicates $l_n=1$ and therefore even parity for the C^{14} ground state, $J\leq 2$ (known to be $J=0$) [(Br 52), see also (Be 53d) and (Ko 53a)], while the angular distribution of the protons to the 6.1-Mev state may indicate odd parity, $J=0$ or 1 for that state (Be 53d).

TABLE I(14). Gamma rays from $C^{13}(d\ p)C^{14}$.

$E\gamma$[a] (Mev)	$E\gamma'$[b] (Mev)	Yield $10^{-6}\gamma/d$	Reference
0.811±0.003		1.4	g
6.110±0.030	6.080	2.30	c
6.119±0.025			g
6.14 ±0.03	6.11±0.04	2.3[d]	f
6.14 ±0.03	6.10±0.04	3.8[e]	f
6.730±0.040			g
6.73 ±0.03	6.70±0.04	0.38[d]	f
6.72 ±0.03	6.68±0.04	2.4[e]	f

[a] Uncorrected for Doppler shift.
[b] Corrected for Doppler shift.
[c] (Th 52): $E_d=1.21$ Mev.
[d] $E_d=2.0$ Mev.
[e] $E_d=4.0$ Mev.
[f] (Be 54a) and Bent, Sippel, and Bonner (private communication).
[g] (Ma 54) and (Ma 55a): $E_d=2.5$ Mev.

Observed γ radiation assigned to C^{14} is exhibited in Table I(14). The internally-formed positron distribution suggests that the 6.10-Mev line is $E1$ in character, and hence that the level has $J=1^-$; $E2$ and $M1$ cannot be excluded, however. It appears probable that this level is the $T_z=1$ component of the 8.06-Mev, $J=1^-$, level of N^{14} (Th 52). The 0.811-Mev radiation is attributed to a cascade transition from the 6.894-Mev level to that at 6.091 Mev. The absence of the direct ground-state transition can be accounted for if the level has zero spin. In this case an association with the 8.70 Mev, $J=0^-$, level of N^{14} is reasonable [(Th 52) and R. J. Mackin and W. R. Mills, private communication.] That both the 6.1- and 6.9-Mev levels show a considerable shift with respect to their N^{14} counterparts is not surprising in view of the great reduced widths [see $C^{13}(p\ p)C^{13}$]. The 6.72-Mev level has about the right energy to match the narrow 9.17, $J=2^-$, level of N^{14}.

VIII. $N^{14}(n\ p)C^{14}$ $Q_m=0.627$

The weighted mean of eight Q-value determinations is 0.624±0.004 Mev (Va 54). For angular distributions see N^{15}. See also (St 51b) and (Li 52).

IX. $O^{17}(n\ \alpha)C^{14}$ $Q_m=1.825$

The isotopic cross section is 0.46±0.11 b for thermal neutrons (Ma 47).

N^{14}

(Fig. 24)

I. $B^{10}(\alpha\ n)N^{13}$ $Q_m=1.068$ $E_b=11.613$

Resonances reported by (Sh 53b) and (Sh 54f) occur at $E_\alpha=1.51$, 1.64, 2.16, and 2.27 Mev [see Table II(14)]. The reduced neutron width at the 1.51-Mev resonance is 0.175±0.012 of the reduced proton width, while at the 2.16-Mev resonance the ratio is 0.9±0.3. Angular distributions have been measured at $E_\alpha=1.51$ Mev $(1-0.9\cos^2\theta)$ and 2.16 Mev $(1-(0.5\pm0.1)\cos^2\theta)$ (Sh 54f). See also $B^{10}(\alpha\ p)C^{13}$.

II. $B^{10}(\alpha\ p)C^{13}$ $Q_m=4.071$ $E_b=11.613$

Observed resonances in the yields of γ rays (from C^{13*}) and of various proton groups are listed in Table II(14). Studies of the angular distributions of protons lead to assignment of 4^-, 3^-, 4^+, 4^-, and 4^+, respectively, for N^{14} levels at 12.42, 12.69, 12.79, 12.82, and 12.92 Mev (Sh 53b). The first three are confirmed by the γ-ray angular distributions and $(p-\gamma)$ correlations (St 54c). In the cases of the 12.69- and 12.79-Mev levels ($E_\alpha=1.51$ and 1.64 Mev), the reduced widths for ground-state protons are relatively small [(Sh 53b); see also (Sh 54f)]. Angular distributions of the protons at the 1.51- and 2.16-Mev resonances are identical with those of the neutrons at the same resonances; see (Sh 54f) and $B^{10}(\alpha\ n)N^{13}$.

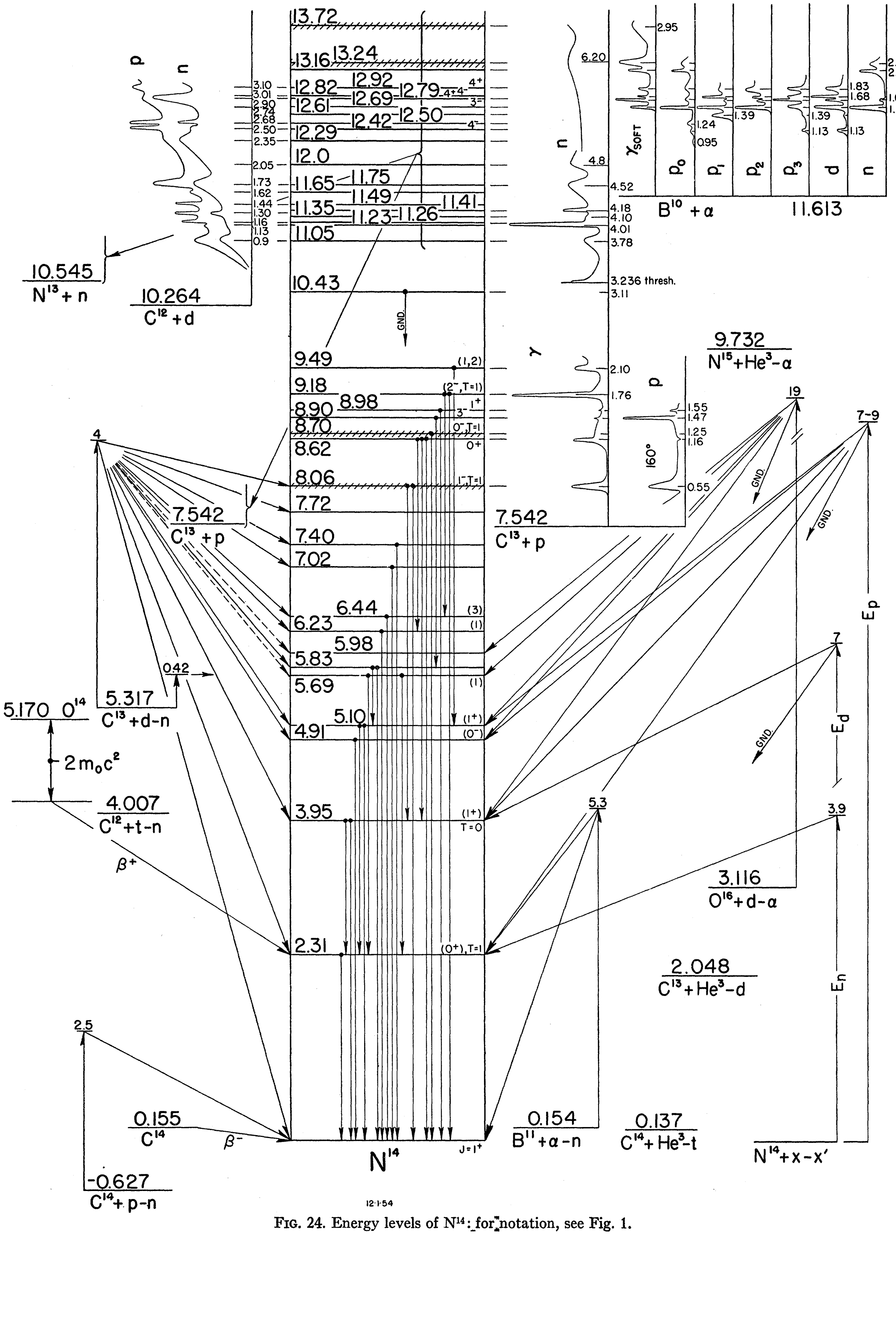


FIG. 24. Energy levels of N^{14}: for notation, see Fig. 1.

TABLE II(14). Resonances in $B^{10}+\alpha$.

$E\alpha$ (Mev)	$\Gamma_{c.m.}$ (kev)	Outgoing[a] particle (x)	σ_x (mb)	Γ_x (kev)	$\gamma_x^2/\frac{3}{2}(\hbar^2/\mu a)$[b]	N^{14*}	J, π[c]	Reference
0.95		p_0				12.29		(Ma 53f)
1.09		p_0						(Ma 53f)
1.13±0.01	43±4	p_0, p_3, d				12.42	4^-	(Sh 53b), (St 54c)
1.20		p_0						(Ma 53f)
1.24±0.01	36±5	p_0				12.50		(Sh 53b)
1.39±0.01	50±5	p_1, p_3				12.61		
1.51±0.01	14±4	α		1.7	6.0	12.69	3^-	(Sh 53b), (St 54c), (Ta 53)
		p_0	4.7	0.62	0.012			
		p_1	1.3	0.17	0.29			
		p_2	5.3	0.70	0.31			
		p_3	42	5.6	0.47			
		d	7.0	0.93	0.26			
		n	32	4.3	0.19			
1.64±0.01	14±4	α		1.0	8.2	12.79	4^+	(Sh 53b), (St 54c), (Ta 53)
		p_0	0.98	0.18	0.012			
		p_1	0.46	0.085	2.7			
		p_2	2.4	0.44	3.0			
		p_3	52	9.6	4.9			
		d	11	2.0	3.9			
		n	3.2	0.59	0.16			
1.68±0.01	5±2	p_1, p_2, p_3, d				12.82	4^-	(Ta 53), (Sh 53b), (St 54c)
1.83±0.01	21±4	p_0, p_1, p_2, p_3, d				12.92	4^+	(Ta 53), (Sh 53b), (St 54c)
2.16	sharp	p_0, γ, n				13.16		(Ta 53), (Sh 54f)
2.27	broad	p_0, γ, n				13.24		(Ta 53), (Sh 54f)
2.95	broad	p_0, γ, n				13.72		(Ta 53)

[a] p_0, p_1, p_2, p_3, correspond, respectively, to protons going to the ground state, the 3.1-, 3.7-, and 3.9-Mev states of C^{13}.
[b] $a=1.45\ (A_1^{1/3}+A_2^{1/3})\times10^{-13}$ cm.
[c] From angular distribution measurements: (Sh 53b) and (St 54c).

III. $B^{10}(\alpha\ d)C^{12}$ $Q_m=1.348$ $E_b=11.613$

Observed resonances are exhibited in Table II(14) (Sh 53b).

IV. $B^{11}(\alpha\ n)N^{14}$ $Q_m=0.154$

A γ ray of 2.2±0.2-Mev energy is observed at $E_\alpha=5.3$ Mev. See (Be 50h) and (St 39).

V. (a) $C^{12}(d\ n)N^{13}$ $Q_m=-0.281$ $E_b=10.264$
(b) $C^{12}(d\ p)C^{13}$ $Q_m=2.723$

In the range $E_d=1.86$ to 3.45 Mev, resonances are reported at 2.05, 2.35, 2.51, 2.67(?), 2.74, 2.92(?), 3.01, and 3.10 Mev. The angular distributions of protons at and off resonance show interference of stripping and resonant contributions (Jo 54h). See also (Aj 52c) and (Ta 54b).

VI. $C^{12}(d\ d)C^{12}$ $E_b=10.264$

See (Ke 51b) and (Cu 47).

VII. $C^{12}(d\ \alpha)B^{10}$ $Q_m=-1.349$ $E_b=10.264$

See B^{10}.

VIII. $C^{13}(p\ p)C^{13}$ $E_b=7.542$

Differential cross sections have been measured at five angles for $E_p=0.45$ to 1.60 Mev. Observed resonances are exhibited in Table IV(14) (Mi 54), together with the assignments of l, J, π which result from the scattering analysis. The broad, 1.25-Mev resonance [see $C^{13}(p\ \gamma)N^{14}$] appears in the form of a slow increase in the s wave, $J=0$, phase shift starting near 1 Mev [(Mi 54) and R. F. Christy and G. Speisman, private communication].

IX. $C^{13}(p\ \gamma)N^{14}$ $Q_m=7.542$

Observed resonances are exhibited in Table V(14) [(Se 52) and (Wo 53c)]. The decay schemes of various levels of N^{14}, as derived from the γ spectra, are exhibited in Fig. 25 [(Wo 53c) and (Cl 53a)]. Actual values of γ-ray energies observed at each resonance, as well as certain angular distributions are tabulated by (Wo 53c). See also (Cl 53a) and (Hi 53). The width of the $E_p=0.55$-Mev resonance (8.06-Mev state) indicates s wave formation ($J=0^-$, 1^-) (Wo 53c). The observed isotropy of the radiation supports this assignment (De 49d). The level is established as $J=1^-$ from $C^{13}(p\ p)C^{13}$. The γ width for the ground-state radiation indicates an $E1$ transition, and hence $T=1$ for the 8.06-Mev state; this assignment is confirmed by the absence (<0.7 percent) of the transition to the 2.31-Mev, $J=0^+$, $T=1$ level [(Cl 53a); see also (Ge 53a) and (Wi 53c)].

TABLE IV(14). Resonances in $C^{13}(p\ p)C^{13}$ (Mi 54).

E_p (Mev)	l	$\gamma^2/\frac{3}{2}(\hbar^2/\mu a)$[a]	J, π	N^{14*}
0.55	0	0.13	1^-	8.06
1.16	1	0.013	0^+	8.62
1.25	0	0.23	0^-	8.70
1.47	2	0.167	3^-	8.90
1.55	1	0.005	1^+	8.98

[a] $a=1.41\,(13^{1/3}+1)\times10^{-13}$ cm [see (Wo 53c)].

The $E_p=1.25$-Mev resonance is also established as due to s waves by its width (Wo 53c); its assignment as $J=0^-$ comes from $C^{13}(p\ p)C^{13}$. Again the large γ width is consistent with $E1$ radiation and $T=1$ (Wi 53c). The γ-ray angular distribution at the $E_p=1.76$-Mev resonance ($N^{14*}=9.18$ Mev) indicates $J=1^+$, 2^+, or 2^-. The large γ width suggests an $E1$ transition and hence $J=2^-$ (and therefore $T=1$) [(Da 51), (Da 51b), and (Wo 53c); see also (Ch 53d)]. If the transition to the 6.44-Mev level is dipole ($\omega\Gamma_\gamma=1.5$ ev), the angular distribution requires $J=3$ for the latter. Arguments based on the reduced width of the $E_p=2.10$-Mev resonance, the anisotropy and strength of the radiation, indicate $J=1^+$, 2^+, or 2^- for the 9.49-Mev state and the same J value for the 5.10-Mev state (Wo 53c). At the $E_p=3.11$-Mev resonance, the angular distribution of ground-state γ rays is of the form $1-(0.40\pm0.02)\ P_2(\cos\theta)$ (H. B. Willard, private communication).

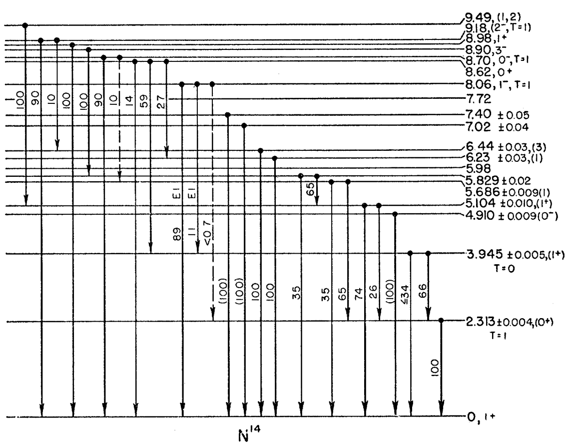


FIG. 25. Gamma-ray transitions in N^{14}: for notation, see Fig. 13.

X. $C^{13}(p\ n)N^{13}$ $Q_m=-3.003$ $E_b=7.542$

Observed resonances are exhibited in Table VI(14) [(Ba 53e), (Bl 51a), and (Ad 50b)]. The comparison with results from $C^{12}(d\ p)C^{13}$ in the same range is discussed by (Ba 53e). (Ignoring the possibility of isotopic spin impurity, only $T=0$ states should be formed in the latter reaction.)

XI. $C^{13}(d\ n)N^{14}$ $Q_m=5.317$

Neutron groups corresponding to levels in N^{14} at 2.23 ± 0.10, 3.85 ± 0.08, 4.80 ± 0.07, 4.97 ± 0.07, 5.5 ±0.1(?), 5.76 ± 0.05, 6.1 ± 0.1(?), 6.23 ± 0.05, 6.43 ±0.04, 7.00 ± 0.04, 7.50 ± 0.04(?), 7.72 ± 0.04, and 8.08 ± 0.06 Mev have been observed by (Be 53d; $E_d=3.89$ Mev). Analysis of the angular distributions of the neutrons indicates $l_p=1$, and therefore even parity for the ground state of N^{14} (Br 52), $l_p=1$, even parity, $J\leq2$ for the 2.3 and 3.9-Mev states, and $l_p=0$, odd parity, $J=0$ or 1, for the 4.9-Mev state (Be 53d). A neutron threshold measurement indicates a state of N^{14} at 5.683 ± 0.010 Mev (Cook, Marion, and Bonner, private communication).

TABLE V(14). Resonances in $C^{13}(p\ \gamma)N^{14}$ [(Se 52) and (Wo 53c)].

E_p (Mev)	Γ (kev)	Y_{max} ($10^{-8}\gamma/p$)	σ (mb)	$\omega\Gamma\gamma$ (ev)	$J,\ \pi$	N^{14*}
0.55	32.5 ± 1	0.9	1.44	8.6	1^-	8.06
1.16	6 ± 2	0.12	0.56	1.3		8.62
1.25	500	1.13	0.062	12.8	$0,1^-$	8.70
1.47	20		0.074	0.72		8.90
1.55	7		0.037	0.13		8.98
1.76	2.1 ± 0.2	1.15	12.0	14.8		9.18
2.10	45 ± 3	0.48	0.20	6.2		9.49
3.11[a]						10.43

[a] H. B. Willard, private communication.

TABLE VI(14). Resonances in $C^{13}(p\ n)N^{13}$ [(Ba 53e), (Bl 51a), and (Ad 50b)].

E_p (Mev)	Γ (kev)	E_x (Mev)
3.78	100	11.05
4.01	20	11.26
4.10	150	11.35
4.18	30	11.44
4.52	125	11.74
4.8	100	12.0
6.20		13.23

Observed γ rays attributed to transitions in N^{14} are shown in Table VII(14) [(Th 52), (Be 54a), (Ma 54), and Bent, Sippel, and Bonner, private communication]. See also (Be 53b).

XII. $C^{14}(\beta^-)N^{14}$ $Q_m=0.155$

See C^{14}.

XIII. $C^{14}(p\ n)N^{14}$ $Q_m=-0.627$

See N^{15}.

TABLE VII(14). Gamma rays from $C^{13}(d\ n)N^{14}$.

a		b		c	
$E\gamma^d$ (kev)	Yield $10^{-6}\gamma/d$	$E\gamma$ (kev)	Yield $10^{-6}\gamma/d$	$E\gamma^d$ (kev)	Assignment N^{14*}
725 ± 4	1.6^f			729^e	$5.829\rightarrow5.104$
1638 ± 8	1.5^f				$3.945\rightarrow2.313$
2310 ± 12	5.3^f				2.313
3381 ± 15	1.8^f, 1.85^g	3410 ± 40	1.8^i		$5.686\rightarrow2.313$
		3920 ± 70^h	0.31^i	3910 ± 50	3.945
		4460 ± 50^h	0.32^i		
		4940 ± 40	0.90^i	4930 ± 40	4.910
5052 ± 25	1.56^g	5100 ± 50	1.0^i	5130 ± 30	5.104
5690 ± 50	0.69^g	5720 ± 40	0.84^i	5730 ± 30	5.686
		6490 ± 50	0.90^j	6450 ± 50	6.44
			0.31^i		
		7050 ± 40	0.76^j		7.02
		7300 ± 50	0.29^j		7.40

[a] (Th 52).
[b] (Be 54a) and Bent, Sippel, and Bonner, private communication; values include ~0.5 percent Doppler correction.
[c] (Ma 54) and (Ma 55a): At $E_d=1.4$ Mev, the intensity of a 5.82-Mev line is <0.15 that of the 5.73-Mev line.
[d] Not corrected for Doppler shift.
[e] Yield $=1.0\times10^{-6}\gamma/d$ at $E_d=2.5$ Mev.
[f] $E_d=1.58$ Mev.
[g] $E_d=1.21$ Mev.
[h] Assignment not certain.
[i] $E_d=2.0$ Mev.
[j] $E_d=4.0$ Mev.

XIV. (a) $N^{14}(\gamma\, n)N^{13}$ $Q_m = -10.545$
(b) $N^{14}(\gamma\, p)C^{13}$ $Q_m = -\ 7.542$
(c) $N^{14}(\gamma\, np)C^{12}$ $Q_m = -12.489$
(d) $N^{14}(\gamma\, \alpha)B^{10}$ $Q_m = -11.613$

The cross section for neutron production [reactions (a) and (c)] exhibits a maximum at $E_\gamma = 22.5$ Mev, $\Gamma = 3.2$ Mev, $\sigma = 15.3$ mb (Fe 54). This cross section is considerably larger than that obtained by measurement of the N^{13} produced (Jo 51b). For relative yields of the various reactions, see (Wr 54). See also (Pe 52e), (Mi 53c), (Sp 53a), (Gr 54), and (St 54h).

XV. $N^{14}(\gamma\, 2n)N^{12}$ $Q_m = -30.9$

See (Pa 52a).

XVI. $N^{14}(n\, n')N^{14*}$

At $E_n = 3.9$ Mev, a 2.30±0.05-Mev γ ray is observed (R. B. Day, private communication). See also N^{15} and (Sm 54).

[$N^{14}(p\, d)N^{13}$ $Q_m = -8.320$

At $E_p = 18.7$ Mev, the angular distribution of ground-state deuterons indicates a pickup process, with $l_n = 1$ and hence opposite parity for the ground states of N^{14} and N^{13}. The intensity of a possible group leading to the first excited state of $N^{13}(S_{\frac{1}{2}})$ is less than 4, 4, and 15 percent for l_n values of 2, 1, and 0 respectively. The result is interpreted as excluding any appreciable admixture of s or d configurations in the ground state of N^{14} [(St 54a): see (Me 52) and (Fe 53)].]

XVII. $N^{14}(p\, p')N^{14*}$
$N^{14}(d\, d')N^{14*}$

Observed inelastic proton and deuteron groups are shown in Table VIII(14) (Co 52g, Ar 52e, and Bo 53). At $E_p = 9.5$ Mev, protons to the 2.31-Mev state are not observed: $\sigma < 0.4$ mb [(Ro 53d); see also (Fu 48)]. At $E_p = 6.98$ Mev, the ratio of the intensities of the proton groups corresponding to the 2.31 and 3.95-Mev levels to the elastic group is 5 and 10 percent, respectively. For deuterons, the ratio for the 3.95-Mev level is 10 percent while an upper limit of about 0.5 percent is set for the 2.31-Mev level. The failure of the 2.31-Mev state to appear with deuterons indicates that it is the $T = 1$ analog of the ground states of C^{14} and O^{14} (Bo 53; see Ad 52a).

TABLE VIII(14). N^{14} levels from $N^{14}(p\, p')N^{14*}$ and $N^{14}(d\, d')N^{14*}$.

N^{14*} $(p\, p')$[a]	N^{14*} $(p\, p')$[b]	N^{14*} $(p\, p')$[c]	N^{14*} $(d\, d')$[c]
2.35	2.32±0.02	2.313±0.005	reference d
3.95	3.96±0.02	3.945±0.005	3.95
		4.910±0.010	reference e
	5.09±0.02	5.104±0.010	reference e

[a] (Co 52g); $E_p = 7.4$ Mev.
[b] (Ar 52e); $E_p = 8$ Mev.
[c] (Bo 53); $E_p = 6.98$ and 7.6 Mev.
[d] Intensity <0.5 percent of elastic group at $E_p = 6.98$ Mev, $\theta = 90°$.
[e] No attempt to observe.

XVIII. $N^{14}(\alpha\, \alpha')N^{14*}$

See (Ca 53a).

XIX. $O^{14}(\beta^+)N^{14}$ $Q_m = 5.170$

The decay proceeds by emission of 1.835±0.008 (Ge 54), 1.830±0.030 Mev (Pe 54a) positrons with an allowed shape (Ge 54), followed by a 2.30±0.03 Mev γ ray (Sh 53a). The direct ground-state transition is <0.3 percent if it exists at all: $\log ft > 7.3$ [(Ge 54); see, however, (Pe 54a)]. The half-life is 72.1±0.4 sec: $ft = 3275 \pm 75$ sec (Ge 54). This is an example of a Fermi $0^+ \to 0^+$ interaction: see (Ja 54a), (Ro 53a), and (Ko 53).

XX. $O^{16}(d\, \alpha)N^{14}$ $Q_m = 3.116$

The weighted mean of six Q-value measurements is 3.115±0.0025 Mev (Va 54); this includes recent values of 3.113±0.0035 [(Cr 52c); elect. analyzer], and 3.119±0.005 Mev [(Fa 53); mag. spectrometer].

No alpha group corresponding to the 2.31-Mev state is observed at $E_d = 2$ Mev (Va 52b), 2.88 Mev (Cr 52c), 6.77 Mev (As 51), 7.73 Mev (Bu 51f), 8 Mev (Sp 53c), and 19 Mev (Fr 53e). This is consistent with the assignment $T = 1$ to this state [see $N^{14}(d\, d')N^{14*}$ and (Ad 52a)]. Groups have been observed corresponding to levels at 3.9 (Fr 53e), 3.95 [(As 51) and (Sp 53c)], 3.98±0.04 Mev (Bu 51f), 4.93 Mev (Sp 53c), 5.01 (As 51), 5.06±0.05 Mev (Bu 51f), 5.7 Mev (As 51), and 5.98 Mev (Sp 53c).

Low-Lying Energy Levels of N^{14}

[See (Be 53d), (Wo 53c), (Cl 53a), and (In 53).]

1. *Ground state:* $J = 1$; parity same as C^{12} and C^{14} (Br 52).

2. *2.3-Mev state:* $E_x = 2.313 \pm 0.005$ Mev from $N^{14}(p\, p')N^{14}$; gamma rays [$C^{13}(p\, \gamma)N^{14}$ and $C^{13}(d\, n)N^{14}$] average 2.313±0.007 Mev (without Doppler shift); $J \le 2^+$ from $C^{13}(d\, n)N^{14}$; $T = 1$ from $N^{14}(d\, d')N^{14}$ and $O^{16}(d\, \alpha)N^{14}$. The general assumption of $J = 0^+$, a consequence of the hypothesis of charge independence is not contradicted by any of the γ-ray evidence, and is given some support by the absence of any transition from the 8.62 Mev, $J = 0^+$, level.

3. *3.95-Mev state:* $E_x = 3.945 \pm 0.005$ Mev from $N^{14}(p\, p')N^{14}$; gamma rays give 3.944±0.012 Mev; $J \le 2^+$ from $C^{13}(d\, n)N^{14}$; $J = 0^+$ eliminated by observation of transition (1.63-Mev) to 2.31-Mev level; $J = 1^+$ favored by intensity of 1.63-Mev relative to direct ground-state transition. The strong $E1$ transition from the 8.06-Mev, $T = 1$, level suggests $T = 0$.

4. *4.9-Mev state:* $E_x = 4.910 \pm 0.010$ Mev from $N^{14}(p\, p')N^{14}$; gamma rays give 4.920±0.020, including the Doppler shift; $J = 0^-$ or 1^- from $C^{13}(d\, n)N^{14}$. $J = 0^-$ is favored by the absence of the transitions to the 2.31-Mev ($J = 0^+$) state and from the 8.62-Mev ($J = 0^+$) state.

5. *5.1-Mev state:* $E_x = 5.104 \pm 0.010$ Mev from

$N^{14}(p\,p')N^{14}$; gamma rays give 5.100 ± 0.025 Mev (including the Doppler shift). There is some evidence from $C^{13}(d\,n)N^{14}$ that $J\leq2^+$: $J=0$ is excluded and $J=1$ is favored by 2.7-Mev transition to 2.31-Mev level; $J=1$ or 2 is suggested by $C^{13}(p\,\gamma)N^{14}$.

6. *5.7-Mev state:* $E_x=5.683\pm0.010$ from neutron threshold in $C^{13}(d\,n)N^{14}$; gamma rays give 5.700 ± 0.020 Mev: mean 5.686 ± 0.009 Mev. $J=1$ suggested by relative strength of transition to 2.31-Mev state.

7. *5.8-Mev state:* $E_x=5.829\pm0.02$ from addition of energy of cascade γ (725 ± 4 kev: not corrected for Doppler shift) to E_x of 5.1-Mev state. Seen in $C^{13}(p\,\gamma)N^{14}$ and in $C^{13}(d\,n)N^{14}$.

O^{14}

(Not illustrated)

Mass of O^{14}

From the measurement of the positron energy as 1.835 ± 0.008 Mev (Ge 54) and of the energy of the first excited state of N^{14} as 2.313 ± 0.005 Mev (Bo 53), one obtains $O^{14}-N^{14}=5.170\pm0.009$ Mev; mass defect $=12.168\pm0.015$ Mev.

I. $O^{14}(\beta^+)N^{14}$ $Q_m=5.170$

See N^{14}.

II. $N^{14}(p\,n)O^{14}$ $Q_m=-5.952$

$Q_0=-6.03\pm0.2$ (Aj 54; photoplate).

At $E_p=17.3\pm0.1$ Mev, neutron groups are observed to broad or unresolved states of O^{14} at ~6.2, 7.5, and 9.3 Mev. No levels were observed below $E_x\sim5.5$ Mev; the upper limit to the intensities of such groups is 0.25 of the ground-state group ($\theta=30°$, $60°$, and $150°$) (Aj 54).

C^{15}

(Not illustrated)

Mass of C^{15}

The $C^{14}(d\,p)C^{15}$ Q value is given as 0.12 ± 0.05 Mev. This gives $C^{15}-N^{15}=8.64\pm0.06$ Mev; mass defect: 13.17 ± 0.06 Mev.

I. $C^{15}(\beta^-)N^{15}$ $Q_m=8.64$

The maximum β^- energy is 8.8 ± 0.5 Mev. There is evidence of 5.5-Mev delayed γ radiation. This radiation is presumably due to partial decay of C^{15} to either or both of the N^{15} states at ~5.3 Mev. There is some indication of weak components at higher energies. The half-life is 2.4 ± 0.3 sec (Hu 50a, Hu 50e, Hu 52, and Sp 54) ($\log ft=5.6$ and ~3.6 for transitions to the ground state and the 5.3-Mev states, respectively) (Ri 54b).

II. $C^{14}(d\,p)C^{15}$ $Q_m=0.12$

The excitation curve shows a single resonance (see N^{16}) superposed on a rising background. On the assumption that the background arises from nonresonant compound nucleus formation and that C^{15} has either $J=\frac{1}{2}^+$ or $5/2^+$, it is found that the latter assignment is the more probable, and that $Q_0=0.15\pm0.15$ (Ri 54b). A direct measurement of the proton energy gives $Q_0=0.12\pm0.05$ Mev [K. Spearman, preliminary result; see (Ri 54b)]. See also (Ri 54) and (Sp 54).

III. $C^{14}(n\,\gamma)C^{15}$ $Q_m=2.35$

The capture cross section is $<10^{-3}$ mb (Ya 51).

The following reactions leading to C^{15} are not reported: $C^{13}(t\,p)C^{15}$ ($Q_m=2.03$), $C^{14}(t\,d)C^{15}$ ($Q_m=-3.91$), $C^{14}(\alpha\,He^3)C^{15}$ ($Q_m=-18.22$), $N^{15}(n\,p)C^{15}$ ($Q_m=-7.86$), $O^{18}(n\,\alpha)C^{15}$ ($Q_m=-3.89$).

N^{15}

(Fig. 26)

I. $B^{11}(\alpha\,n)N^{15}$ $Q_m=0.154$ $E_b=10.988$

Resonances are observed at $E_\alpha=0.60$, 1.03, 1.18, 1.30, and 1.49 Mev [(Be 54) and W. E. Bennett, private communication: $N^{15*}=11.43$, 11.75, 11.86, 11.94, and 12.08 Mev]. A double resonance at $E_\alpha\sim1.58$ Mev and a single resonance at $E_\alpha=2.05$ Mev are reported by (Sh 54f), while (Tr 54) observes resonances at $E_\alpha=1.54$, 2.09, 2.63, 3.00, and 3.26 Mev ($N^{15*}=12.53$, 12.91, 13.19, and 13.38 Mev). See also (Ho 50b).

II. $B^{11}(\alpha\,p)C^{14}$ $Q_m=0.781$ $E_b=10.988$

A resonance is observed at $E_\alpha=1.58\pm0.03$ Mev (Sh 53b: Sh 54f report that it is a double resonance). See also C^{14}.

III. $C^{12}(\alpha\,p)N^{15}$ $Q_m=-4.961$

At $E_\alpha=21$ Mev, $\theta=90°$, proton groups are observed corresponding to the ground state and to states at 5.4 and 6.5 Mev (Bu 51).

IV. $C^{12}(t\,p)C^{14}$ $Q_m=4.635$ $E_b=14.841$

See (Po 51).

V. $C^{13}(d\,n)N^{14}$ $Q_m=5.317$ $E_b=16.150$

Resonances for neutrons with $E_n>3$ Mev are observed at $E_d=0.58$, 0.85, 1.55, and 1.78 Mev (Ri 50c). See also N^{14}.

VI. $C^{13}(d\,p)C^{14}$ $Q_m=5.944$ $E_b=16.150$

Resonances for ground-state protons appear at $E_d=0.65$ (Cu 50) and 1.55 Mev (Be 41). Study of the angular distribution in the range $E_d=0.28$ to 0.65 Mev indicates strong stripping effects at the lower energy, and some evidence of resonance near 0.63 Mev. At this energy, the cross section is 0.84 mb (Ko 53a).

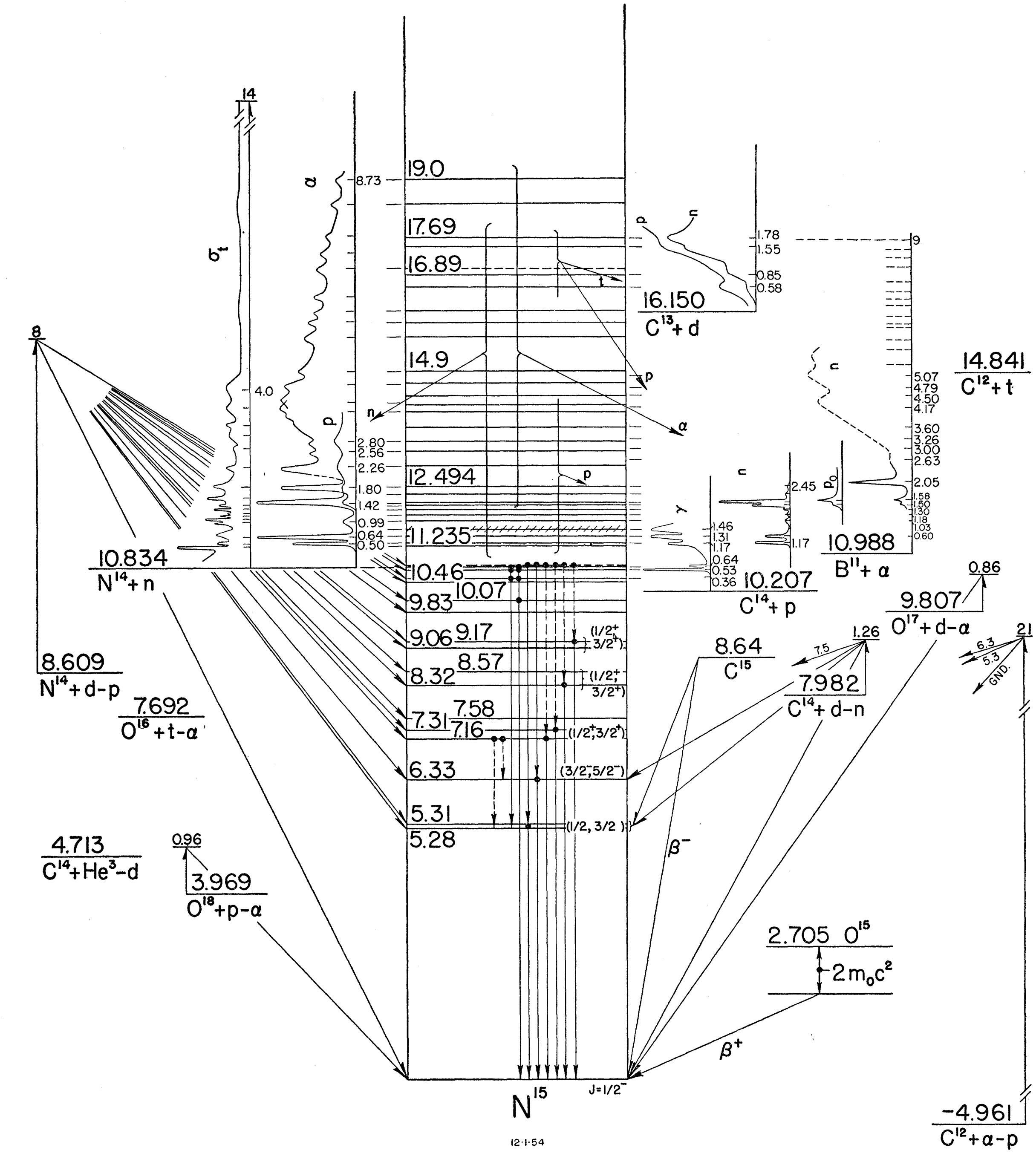


FIG. 26. Energy levels of N^{15}: for notation, see Fig. 1.

VII. $C^{13}(d\,\alpha)B^{11}$ $Q_m=5.163$ $E_b=16.150$

The yield rises smoothly from $E_d=0.4$ to 0.9 Mev (Cu 50). At $E_d=0.99$ Mev, $\theta=90°$, the differential cross section is 7 mb/sterad (Li 51b).

VIII. $C^{13}(d\,t)C^{12}$ $Q_m=1.309$ $E_b=16.150$

See C^{12}.

IX. $C^{14}(p\,\gamma)N^{15}$ $Q_m=10.207$

Resonances observed for production of ground-state radiation are listed in Table I(15); transitions to the 5.3-Mev levels are also observed. Level assignments are based on γ-ray angular distributions, neutron distributions [from $C^{14}(p\,n)N^{14}$] and comparison of $(p\,n)$ and $N^{14}(n\,n)N^{14}$ cross sections (Ba 54f). See also (Go 54g).

X. $C^{14}(p\ n)N^{14}$ $Q_m=-0.627$ $E_b=10.207$

Resonances reported by (Ba 54f) and (Ro 51h) are given in Table I(15) [see also (Aj 52c)]. The location of the levels and the relative yields are in good agreement with those from the inverse reaction [(Ro 51h) and (Ka 53)]. See also (Li 54a).

XI. $C^{14}(d\ n)N^{15}$ $Q_m=7.982$

Neutron groups have been observed corresponding to levels in N^{15} at 5.34, 6.32, and 7.46 Mev (Hu 50e).

XII. $C^{15}(\beta^-)N^{15}$ $Q_m=8.64$

See C^{15}.

XIII. $N^{14}(n\ \gamma)N^{15}$ $Q_m=10.834$

$Q_0=10.832\pm0.008$ (Ki 53b; pair spectrometer).

The thermal cross section is 100 ± 50 mb (Hu 52e). Observed γ rays are listed in Table II(15) together with the N^{15} levels with which they are presumed to be associated (Ki 51).

XIV. $N^{14}(n\ n)N^{14}$ $E_b=10.834$

The coherent scattering cross section is 11.1 ± 0.3 bn (Pe 52b); the total scattering cross section is 11.4 ± 0.5 bn (bound atoms, epithermal neutrons) [(Hu 52e) and (Me 49b)].

Resonances in the range $E_n=0.4$ to 1.8 Mev are tabulated in (Aj 52c). Angular distributions at several of these resonances have been studied by (Ba 50g), (Fo 53), and (Jo 54a). From $E_n=1.8$ to 4.0 Mev there is evidence for considerable structure in the cross section curve, but little agreement as to the exact location of the levels involved. One level, at $E_n=2.25$ Mev, is quite definite, and inspection of the curve of (Hu 52e) would suggest further levels at $\sim$2.9, 3.2, and 3.55 Mev. (Me 53a) list 14 resonances in the range $E_n=1.9$ to 3.6 Mev, while (Sp 54c), analyzing angular distributions of (Hu 54b), list 7 levels between $E_n=2.5$ and 4.4 Mev.

TABLE I(15). Resonances in $C^{14}(p\ n)N^{14}$ and $C^{14}(p\ \gamma_0)N^{15}$ [(Ba 54f) and (Ro 51h)].[a]

E_p (kev)	Yields $10^{-11}\gamma/p$	Yields $10^{-8}n/p$	Γ kev	Γ_n kev	Γ_p kev	$\Gamma\gamma_0$ ev	$J,\ \pi$	N^{15*}
360	0.01							10.54
525	5.75					0.12	$3/2^-$	10.697
643	0.49					0.01	$3/2^-$	10.807
1170	3.14	19.9	12	1.6	10.4	0.25	$1/2^-$[b]	11.294
1310	7.96	121.5	41	33	8	2.3	$1/2^+$[b]	11.430
1500	49.3	88.2	475	5	470	28	$1/2^+$	11.57
1664		17.1	38	37.5	0.5		$3/2^+$	11.760
1789		1.46	18	17.9	0.03		$(5/2^+)$	11.877
1883		5.55	15	14.7	0.3		$(1/2^-)$	11.964
2024		40.3	18	17.2	0.8		$(3/2^+)$[b]	12.096
2079		286	54	44.5	9.5		$(3/2^-)$[b]	12.147
2272		10.5	22	21.8	0.2		$(5/2^-)$	12.328
2451			45					12.495

[a] Ratios to single-particle widths are tabulated by (Ba 54f); all are of the order of a few percent or less except that at $E_p=1500$ kev which appears to have a proton width equal to the sum-rule limit. Yields are ±20 percent.
[b] See also (Ka 53) and H. Mark, private communication. There is some evidence from a study of the angular distributions of the neutrons that the states at 12.10 and 12.15 Mev may be $5/2^+$ and $3/2^+$, respectively.

TABLE II(15). Gamma radiation from $N^{14}(n\ \gamma)N^{15}$ (Ki 51)

E_γ	Rel. intens.	N^{15*}
10.816 ± 0.015[a]	1.00	
9.156 ± 0.030	0.09	9.156
8.278 ± 0.016	0.19	8.278
7.356 ± 0.012	0.56	7.356
7.164 ± 0.012	0.19	7.164
6.318 ± 0.010	0.9	6.325
5.554 ± 0.010	1.5	5.275
5.287 ± 0.010	2.3	5.275
4.485 ± 0.010	0.8	6.325

[a] See, however, (Ki 53b).

The average total cross section ($\Delta E\sim10$ percent) from $E_n=3$ to 14 Mev indicate broad maxima near 4, 5.5, and 8 Mev (Ne 54b). At 14 Mev, $\sigma_t=1.59\pm0.03$ b (Co 52h); of this, 0.82 b is due to elastic scattering, 0.27 b to two-particle disintegrations, 0.016 b to three-particle disintegrations, and 0.48 b to inelastic scattering exclusive of disintegrations (Sm 54). (Ph 52b) give 0.79 ± 0.05 b for the total cross section, excluding elastic scattering, at $E_n=14.5$ Mev. The elastic scattering at this energy shows a strong forward maximum and smaller maxima at $\theta=70°$ and 180°, indicative of diffraction scattering. The inelastic scattering is roughly isotropic (Sm 54). See also (Hi 54c).

XV. $N^{14}(n\ 2n)N^{13}$ $Q_m=-10.545$ $E_b=10.834$

At $E_n=14.5$ Mev, the cross section is given as 5.67 ± 0.8 mb by (Pa 53a), while (Du 54) find 3.4 ± 1.1 mb at 14 Mev (preliminary value).

XVI. $N^{14}(n\ p)C^{14}$ $Q_m=0.627$ $E_b=10.834$

The thermal cross section is 1.70 ± 0.05 bn; the total absorption cross section is 1.78 ± 0.05 bn (Hu 52e). Observed resonances are tabulated in (Aj 52c). (Gi 53a), using a continuous neutron spectrum and observing the distribution of total pulse sizes, reports values generally in agreement with those of (St 51b) and earlier workers, in addition to a number of new values which, if properly attributed to the present reaction, can be identified with N^{15} levels found in other reactions.

XVII. $N^{14}(n\ \alpha)B^{11}$ $Q_m=-0.154$ $E_b=10.834$

Observed resonances are tabulated in (Aj 52c) and by (Gi 53a): see $N^{14}(n\ p)C^{14}$.

XVIII. $N^{14}(n\ d)C^{13}$ $Q_m=-5.316$ $E_b=10.834$

See (Li 52).

XIX. $N^{14}(n\ t)C^{12}$ $Q_m=-4.007$ $E_b=10.834$

The cross section is 11 ± 2 mb averaged over a fission neutron spectrum (Fi 53).

TABLE III(15). N^{15} levels from $N^{14}(d\ p)N^{15}$.

a	b	J, π[c]
0		1/2, 3/2 or 5/2, odd
5.276±0.006	5.280±0.015 }	J large[d]
5.305±0.006		
6.328±0.006	6.330±0.015	3/2 or 5/2, odd
7.164±0.006	7.165±0.015 }	1/2 or 3/2, even
7.309±0.006	7.314±0.015 }	(one or both)
	7.575±0.015	
8.315±0.006	8.316±0.015	1/2 or 3/2 even
	8.571±0.015	
	9.062±0.015 }	1/2 or 3/2, even
	9.165±0.015 }	
	9.834±0.015	
	10.069±0.015	
	10.458±0.015	
	10.544±0.015	
	10.705±0.015	
	10.811±0.015	

[a] (Ma 50i): E_d=1.41 Mev, θ=90°.
[b] (Sp 53) and (Sp 54b): E_d=5 to 8 Mev, θ=90°.
[c] (Gi 52): E_d=8 Mev; analysis by stripping theory.
[d] (St 54f) finds J=1/2 or 3/2 for these states.

XX. $N^{14}(d\ p)N^{15}$ $\quad Q_m=8.609$

The weighted mean of eight Q-value determinations is 8.614±0.007 Mev (Va 54). Levels in N^{15} corresponding to observed proton groups are listed in Table III(15) [(Sp 53), (Sp 54b), (Ma 50i), and (Gi 52)]. Study of the angular distribution of ground-state protons at E_d=0.4, 0.5, and 0.6 Mev indicates both stripping (l_n=1) and compound nucleus formation (Jo 54c).

Gamma rays observed at E_d=4.0 Mev are exhibited in Table IV(15) (Bent, Sippel, and Bonner, private communication). At E_d=0.63 Mev, a study of $(p-\gamma)$ angular correlations indicates $J=\frac{1}{2}$ or $\frac{3}{2}$ for the 5.3-Mev levels (St 54f). See also (Fu 54) and (Th 54d).

XX. $N^{14}(t\ pn)N^{15}$ $\quad Q_m=2.352$

See (Cu 52a).

XXI. $O^{15}(\beta^+)N^{15}$ $\quad Q_m=2.705$

See O^{15}.

XXII. $O^{16}(\gamma\ p)N^{15}$ $\quad Q_m=-12.110$

See (Wa 49i).

XXIII. $O^{16}(n\ d)N^{15}$ $\quad Q_m=-9.884$

See (Li 52).

TABLE IV(15). Gamma rays from $N^{14}(d\ p)N^{15}$.[a]

E_γ[b] (Mev)	E_γ'[c] (Mev)	Yield ($10^{-6}\ \gamma/d$)
10.08±0.03	10.04±0.04	0.15
9.17±0.05	9.13±0.06	0.15
8.37±0.03	8.33±0.04	0.71
7.34±0.03	7.31±0.04	2.3
6.36±0.04	6.33±0.05	0.75
5.29±0.03	5.26±0.04	3.3[d]

[a] Bent, Sippel, and Bonner (private communication): E_d=4.0 Mev.
[b] Not corrected for Doppler shift.
[c] Corrected for Doppler shift.
[d] Possibly also from $N^{14}(d\ n)O^{15}$.

XXIV. $O^{17}(d\ \alpha)N^{15}$ $\quad Q_m=9.807$

Q_0=9.807±0.012 [(Pa 54); mag. spectrometer].

XXV. $O^{18}(p\ \alpha)N^{15}$ $\quad Q_m=3.969$

Q_0=3.961±0.009 [(Mi 54a); mag. spectrometer].

See also F^{19} and (Aj 52c) and (Ro 53c).

O^{15}

(Fig. 27)

I. $O^{15}(\beta^+)N^{15}$ $\quad Q_m=2.705$

The maximum positron energy is 1.683±0.005 Mev; the half-life is 118.0±0.6 sec (Br 50d), 123.4±1.3 sec (Kl 54). The Kurie plot is linear down to ~300 kev, indicating a simple allowed transition (Br 50d) ($\log ft$ =3.57: Fe 51b).

II. $C^{12}(\alpha\ n)O^{15}$ $\quad Q_m=-8.448$

See (Ki 39).

III. $N^{14}(p\ \gamma)O^{15}$ $\quad Q_m=7.347$

Observed resonances are exhibited in Table V(15) [see also (Du 51) and (Aj 52c)]. The 8.0- and 9.8-Mev states are believed to be formed by s-wave protons

TABLE V(15). Resonances from $N^{14}(p\ \gamma)O^{15}$.

E_p (Mev)	Γ (kev)	$\omega\Gamma_\gamma$(ev)	l	J, π	O^{15*}
277	<2[a]	0.02			7.606
700±30	100±30	0.02	0	1/2, 3/2+	8.00
1064±2	4.8±1	0.63			8.340
1550±20	50±20	0.16		1/2+[b]	8.79
1748±5	11±3	0.21		(3/2−)[b]	8.978
1815±4	7±1.5	0.52			9.041
2356±8	14±4	2.4			9.546
2489±7	11±3	3.3			9.670
2600±50	1270±50	46	0	1/2, 3/2+	9.77

[a] (Ta 46). Other values from (Du 51).
[b] Assignment from $N^{14}(p\ p)N^{14}$.

($J=\frac{1}{2}, \frac{3}{2}^+$) (Du 51). The reduced widths of these states are of the order of 20 percent of the single-particle value [(Vo 54) and (La 54a)].

At the 277-kev resonance, capture γ lines resulting from cascades through the states in O^{15} at 5.27, 6.14, and 6.82 Mev are observed; the direct ground-state transition has not been observed (Jo 52b). The ground-state transition is observed from all the other resonances. At the E_p=1.06-Mev resonance (O^{15*}=8.34 Mev), γ rays with energies 3.04±0.03, 5.27±0.03 (strong) and 1.46±0.03, 6.82±0.08 Mev (weak) are also found (Li 53). See (Ba 55b).

IV. $N^{14}(p\ n)O^{14}$ $\quad Q_m=-5.952 \quad E_b=7.347$

See O^{14}.

V. $N^{14}(p\ p)N^{14}$ $\quad E_b=7.347$

Anomalies in the scattering are observed at E_p=1.07 and 1.60 Mev by (We 53a) and at E_p=1.53, 1.72, and

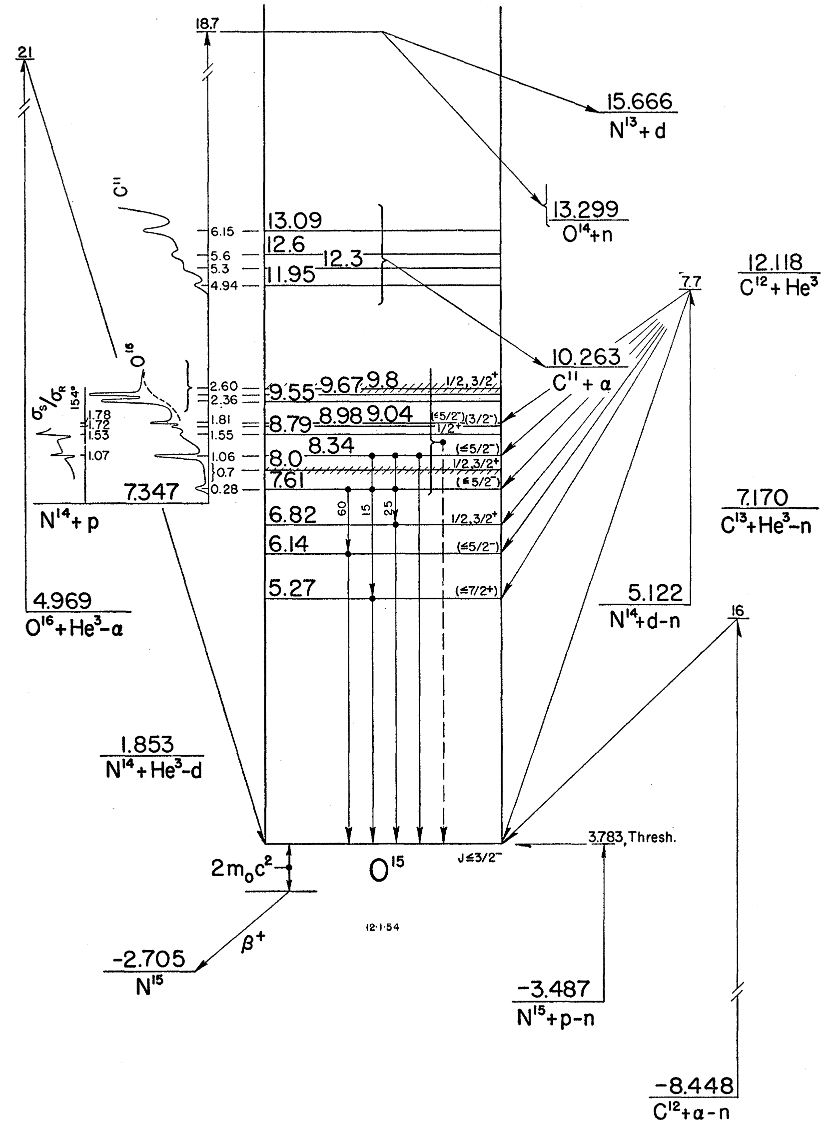


FIG. 27. Energy levels of O^{15}: for notation, see Fig. 1.

1.78 Mev by (Go 54). The anomalies are superposed on a background which decreases less rapidly than the Rutherford cross section [(We 53a); see also (Ta 55)]. Angular distributions have been measured at ten energies near the resonances. These are said to indicate $J=\frac{1}{2}^+$ for the 1.53-Mev resonance and possibly $J=\frac{3}{2}^-$ for the 1.72-Mev resonance. The background shows a larger s-wave phase shift and a smaller p-wave shift than is expected from hard-sphere scattering (Go 54).

VI. $N^{14}(p\ d)N^{13}$ $Q_m=-8.320$ $E_b=7.347$

See N^{13}.

VII. $N^{14}(p\ \alpha)C^{11}$ $Q_m=-2.916$ $E_b=7.347$

Broad resonances in the yield of C^{11} are observed at $E_p=4.94$ ($\sigma=10$ mb), 5.3 (28 mb), 5.6 (35 mb), and 6.15 Mev (66 mb) [(Bl 52a): stacked-foil method].

VIII. $N^{14}(d\ n)O^{15}$ $Q_m=5.122$

Neutron groups observed at $E_d=7.7$ Mev are listed in Table VI (15), together with J, π assignments obtained from the angular distributions, analyzed by stripping theory. Except for the ground state and that at 6.84 Mev, the fits to theoretical distributions are not completely satisfactory, and the assignments must be treated with some reserve (Ev 53).

At $E_d=4.0$ Mev, γ radiation has been observed with energies (corrected for Doppler shift) of 6.81 ± 0.04 Mev (1.6×10^{-6} γ/d), 6.12 ± 0.06 Mev (0.5×10^{-6} γ/d) and 5.26 ± 0.04 Mev (3.3×10^{-6} γ/d; probably includes $N^{14}(d\ p)N^{15}$) (Bent, Sippel, and Bonner, private communication).

IX. $N^{15}(p\ n)O^{15}$ $Q_m=-3.487$

The threshold is at $E_p=3.783\pm0.008$ Mev: $Q=-3.547$ Mev. This value is 60 kev higher than that

TABLE X(15). Neutron groups from $N^{14}(d\,n)O^{15}$ (Ev 53).

Q (Mev)	O^{15*}	l_p	Assignment
5.15 ± 0.16	0	1	$J=5/2, 3/2, 1/2$, odd
-0.14 ± 0.11	5.29 ± 0.17	2	$J=7/2, 5/2, 3/2, 1/2$, even
-1.04 ± 0.06	6.19 ± 0.16	1	$J=5/2, 3/2, 1/2$, odd
-1.69 ± 0.08	6.84 ± 0.16	0	$J=3/2, 1/2$, even
-2.33 ± 0.09	7.48 ± 0.16	1	$J=5/2, 3/2, 1/2$, odd
-3.27 ± 0.09	8.42 ± 0.16	1	$J=5/2, 3/2, 1/2$, odd
-3.91 ± 0.07	9.06 ± 0.16	1	$J=5/2, 3/2, 1/2$, odd

given by the beta decay (Ki 54a). See also (Du 38) and (Ba 39).

X. $O^{16}(\gamma\,n)O^{15}$ $Q_m=-15.597$

See (Ba 45).

XI. $O^{16}(He^3\,\alpha)O^{15}$ $Q_m=4.969$

See (Po 52b) and (Ku 53a).

N^{16}

(Fig. 28)

Mass of N^{16}

From the preliminary ground-state Q value for $O^{18}(d\,\alpha)N^{16}$: 4.237 ± 0.010 Mev (R. Pauli, private communication), a mass defect of 10.40 ± 0.03 Mev is obtained for N^{16}.

I. $N^{16}(\beta^-)O^{16}$ $Q_m=10.40$

From the character of the beta decay, it is concluded that N^{16} has $J=2^-$ (see O^{16}).

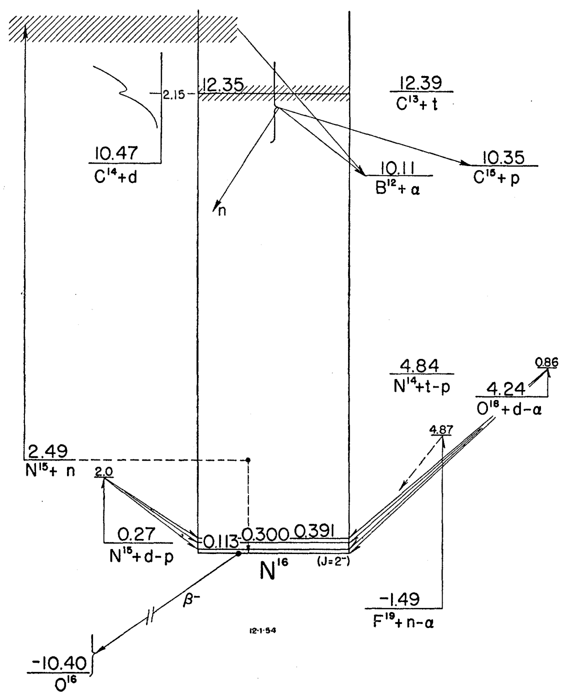


FIG. 28. Energy levels of N^{16}: for notation, see Fig. 1.

II. $C^{14}(d\,n)N^{15}$ $Q_m=7.982$ $E_b=10.47$

See (Hu 50e).

III. $C^{14}(d\,p)C^{15}$ $Q_m=0.12$ $E_b=10.47$

The excitation function has been studied for $E_d=0.6$ to 3.0 Mev. A resonance is observed at $E_d=2.15$ Mev, $\Gamma\sim400$ kev (Ri 54 and Ri 54b). See also C^{15} and (Hu 50e).

IV. $C^{14}(d\,\alpha)B^{12}$ $Q_m=0.355$ $E_b=10.47$

See (Hu 50e).

V. $N^{14}(t\,p)N^{16}$ $Q_m=4.84$

See (Cu 53c).

VI. $N^{15}(n\,\gamma)N^{16}$ $Q_m=2.49$

The thermal cross section is 24 ± 8 μb (Hu 52e).

VII. $N^{15}(n\,\alpha)B^{12}$ $Q_m=-7.627$ $E_b=2.49$

See (Je 48c).

VIII. $N^{15}(d\,p)N^{16}$ $Q_m=0.27$

At $E_d=2.0$ Mev, proton groups have been observed with Q values (preliminary) of 0.158, -0.022, -0.118 Mev, corresponding to excited states of N^{16} at 0.11, 0.29, and 0.39 Mev. The ground-state group was not observed (Th 54a). A group with $Q=-0.034\pm0.005$ Mev is reported by (Ma 50i). See also (Wy 49c).

IX. $O^{16}(n\,p)N^{16}$ $Q_m=-9.62$

See O^{17} and (Li 52).

X. $O^{18}(d\,\alpha)N^{16}$ $Q_m=4.24$

Thin separated targets of O^{18} bombarded with 0.855-Mev deuterons yield alpha groups with $Q_0=4.237\pm0.010$, $Q_1=4.121\pm0.010$, $Q_2=3.937\pm0.010$, and $Q_3=3.846\pm0.010$ Mev. No other α group with $Q=4.23$ to 5.60 Mev was found at 135°: The upper limit to the intensity is 5 percent of the weakest group observed. Assuming Q_0 to be the ground-state group, this work indicates excited states at 113, 300, and 391 kev (R. Pauli, private communication).

XI. $F^{19}(n\,\alpha)N^{16}$ $Q_m=-1.49$

At $E_n=4.87$ Mev, an α group has been observed with $Q=-1.77\pm0.13$ Mev, probably corresponding to a transition to an excited state of N^{16} (Ja 54). See also (Bl 47c).

O^{16}

(Fig. 29)

I. $C^{12}(\alpha\,\gamma)O^{16}$ $Q_m=7.149$

See (Jo 53e).

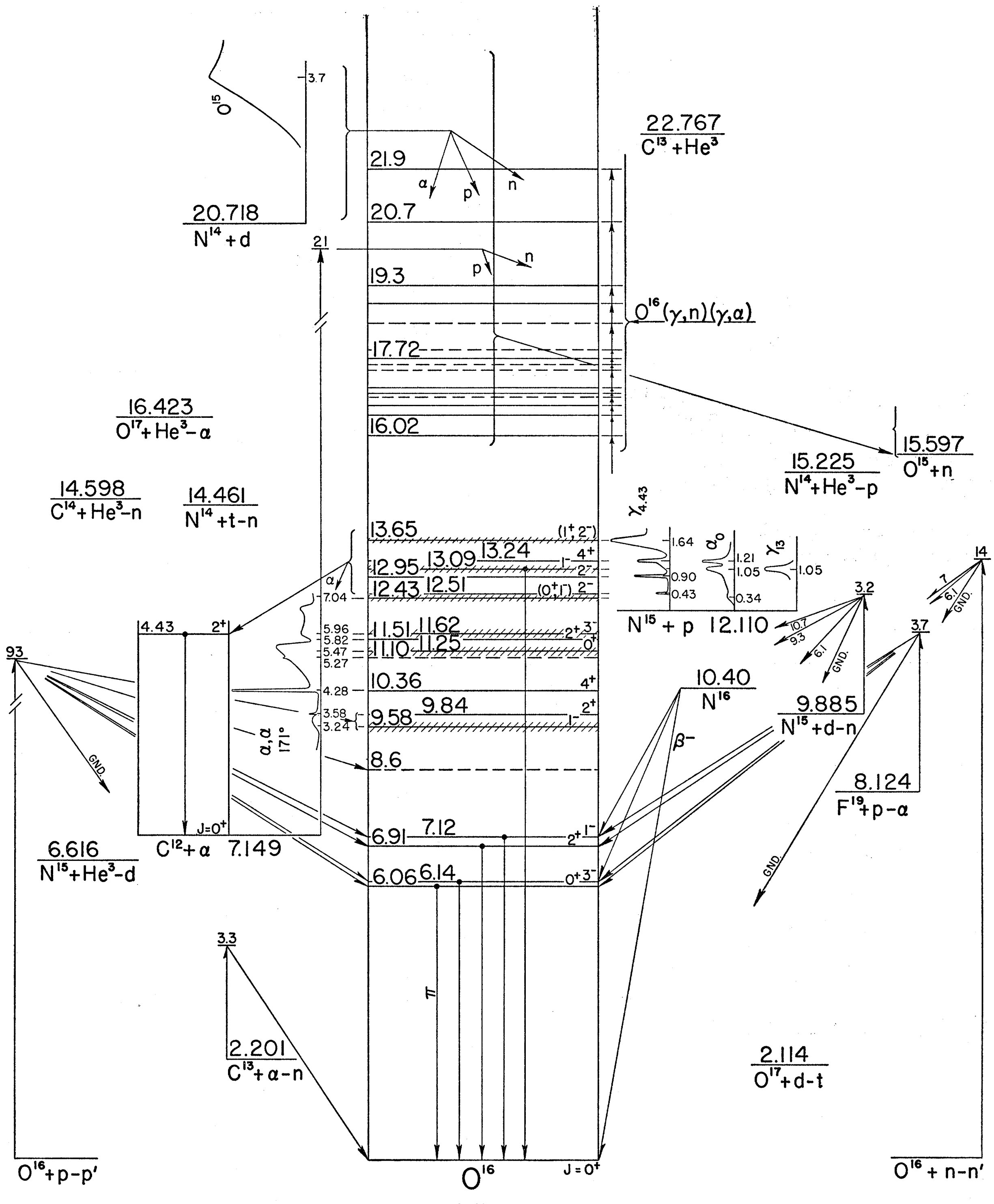


Fig. 29. Energy levels of O^{16}: for notation, see Fig. 1.

II. $C^{12}(\alpha\, n)O^{15}$ $Q_m=-8.448$ $E_b=7.149$

See (Ki 39).

III. $C^{12}(\alpha\, \alpha n)C^{11}$ $Q_m=-18.711$ $E_b=7.149$

See (Li 53c).

IV. $C^{12}(\alpha\, p)N^{15}$ $Q_m=-4.961$ $E_b=7.149$

See N^{15}.

V. $C^{12}(\alpha\, \alpha)C^{12}$ $E_b=7.149$

Resonances derived from a phase-shift analysis of the scattering at several angles are exhibited in Table I(16) [(Hi 53a) and (Bi 54a)]. At the upper limit of these experiments ($O^{16*}=12.5$ Mev), the existence of higher $J=0^+$ and 2^+ levels is indicated by a pronounced increase in the $l=0$ and $l=2$ phase shifts. The observed levels, which include several whose great width suggests a single-particle character, agree well with predictions based on the α-particle model. It is noted that only (J,π) even-even or odd-odd levels would appear in the present reaction [(Bi 54a) and (De 54c)].

VI. $C^{13}(\alpha\, n)O^{16}$ $Q_m=2.201$

See (Jo 51d) and O^{17}.

TABLE I(16) Resonances in $C^{12}(\alpha\,\alpha)C^{12}$.[a]

E_r (Mev)	Γ_{Lab} (kev)	$\gamma^2/\frac{3}{2}(\hbar^2/\mu a)$	O^{16*} (Mev)	J,π
3.24	860	0.85	9.58	1^-
3.582	1	0.0015	9.835	2^+
4.28	36	0.26	10.36	4^+
5.27	10		11.10(?)[b]	
5.47	3300	0.76	11.25	0^+
5.82	106	0.03	11.51	2^+
5.96	1600	0.73	11.62	3^-
7.04	230	0.04	12.43	1^-

[a] The first two entries are from (Hi 53a); the remainder from (Bi 54a).
[b] Assignment to present reaction not certain.

VII. $N^{14}(d\, n)O^{15}$ $Q_m=5.122$ $E_b=20.718$

See (Ne 37b) and O^{15}.

VIII. $N^{14}(d\, p)N^{15}$ $Q_m=8.609$ $E_b=20.718$

Angular distributions show strong indication of stripping even at $E_d=0.4$ Mev; see also (St 54f) and N^{15}.

IX. $N^{14}(d\, d)N^{14}$ $E_b=20.718$

See N^{14}.

X. $N^{14}(d\, t)N^{13}$ $Q_m=-4.288$ $E_b=20.718$

See (Bo 42).

XI. $N^{14}(d\, \alpha)C^{12}$ $Q_m=13.570$ $E_b=20.718$

The cross section rises gradually for $E_d=0.45$ to 0.90 Mev. Angular distributions have been studied in this range by (Ca 54d). At $E_d=0.63$ Mev, the angular distribution indicates interference between states of opposite parity (St 54f). See also C^{12}.

XII. $N^{14}(d\, 4\alpha)$ $Q_m=6.292$ $E_b=20.718$

See (Fo 47b).

XIII. $N^{15}(p\, \gamma)O^{16}$ $Q_m=12.110$

A resonance for capture radiation appears at $E_p=1.05$ Mev ($\Gamma\sim150$ kev, peak cross section $=1$ mb; $\Gamma_\gamma\sim150$ ev) (Sc 52). The large radiative width implies an allowed $E1$ transition to the ground state, and therefore $J=1^-$ [(Sc 52) and (Wi 53a)]. The angular distribution of 13-Mev γ rays is isotropic within 7 percent indicating $J=1$. The assignment $T=1$ would be indicated but for the fact that the level also appears to have a large α width (Wi 53a). A search for γ transitions leading to the 6.06-Mev, $J=0^+$, state of O^{16} yields a branching ratio $<1.3\times10^{-3}$ [(Go 54h) and (De 53d)]. The capture radiation is not resonant at $E_p=340$ kev [see $N^{15}(p\,\alpha)C^{12}$]; the yield is less than one percent of that for the $E_p=1050$-kev resonance (Kr 54b).

XIV. $N^{15}(p\, \alpha)C^{12}$ $Q_m=4.961$ $E_b=12.110$

Resonances for ground-state (α_0) and 4.4-Mev state (α_1) α particles are listed in Table II(16). Cross sections at low energies have been measured by (Sc 52). The resonance for α_0 and α_1 at $E_p=1050$ kev is believed to be the same as that exhibited in the capture radiation and is therefore $J=1^-$ [see $N^{15}(p\,\gamma)O^{16}$]. Support for this assumption comes from the angular distribution of long-range α particles which is inconsistent with $J=2^+$ or 3^- (Co 53k). With s-wave formation, the reduced widths are $\gamma_p^2=1.8\times10^{-13}$ Mev-cm, $\gamma_\alpha^2=0.04\times10^{-13}$ Mev-cm (Fo 53a). There is some question whether the α-particle emission violates an isotopic spin selection rule (Wi 53a).

The resonance at $E_p=338$ kev is attributed by (Sc 52) and (Fo 53a) to s-wave protons, forming a state with $J=1^-$. The reduced widths are $\gamma_p^2=1.3\times10^{-13}$ Mev-cm, $\gamma_\alpha^2=0.07\times10^{-13}$ Mev-cm, the former amounting to about 10 percent of $3\hbar^2/2\mu a$ (under the assumption of p-wave formation, $J=0^+$, a value for γ_p^2 of about $1.5\times3\hbar^2/2\mu a$ is obtained.) (Co 53k) and (Ne 53b) find, on the other hand, that while the angular distribution of α_0 particles is isotropic for $E_p<380$ kev, a strong $(\cos\theta)$ term sets in above this energy. The presence of the $(\cos\theta)$ term clearly indicates interference between states of opposite parity, and a satisfactory fit is obtained with $J=0^+$ for the $E_p=338$-kev state and $J=1^-$ for the $E_p=1050$-kev state ($O^{16*}=12.43$, 13.09 Mev) [see, however, $C^{12}(\alpha\,\alpha)C^{12}$].

Assignments indicated for the $E_p=429$-, 898-, 1210-, and 1640-kev resonances derive from angular distributions of the α_1 particles (Kr 53), 4.4-Mev (C^{12*}) γ rays [(Kr 53), (Kr 54b), (Ba 52g), and (Ne 53c)] and $\alpha_1-\gamma$ correlations (Se 52a). See also (Ch 53d).

XV. $N^{15}(p\ n)O^{15}$ $Q_m=-3.487$ $E_b=12.110$

See O^{15}.

XVI. $N^{15}(d\ n)O^{16}$ $Q_m=9.885$

Neutron groups corresponding to levels at 0, 6.1, 9.3, and 10.7 Mev are reported: see (Hu 49f) and (Wo 50).

TABLE II(16). Resonances in $N^{15}(p\ \alpha)C^{12}$ (α_0) and in $N^{15}(p\ \alpha\gamma)C^{12}$ (α_1).

E_p (kev)	Γ (kev)	$\sigma(\alpha_0)$[a] (mb)	$\sigma(\alpha_1)$[a] (mb)	J, π[e]	O^{16*}
338[b]	94[b]	75	non res.	0^+, 1^-	12.43
429[c]	0.9		300	2^-	12.51
898[c]	2.2		800	2^-	12.95
1050[c]	~150	500	15	1^-	13.09
1210[c]	22.5	600	300	4^+	13.24
1640[d]	~150	non res.	res.	1^+, 2^-	13.65

[a] (Sc 52): assuming isotropy.
[b] (Sc 52): corrected for variation of penetration (s wave); (Mi 52b) report $E_r=290$ kev, $\Gamma=150$ kev.
[c] (Sc 52).
[d] (Kr 54b).
[e] See text.

XVII. $N^{16}(\beta^-)O^{16}$ $Q_m=10.40$

The β spectrum exhibits components to the ground state (~18 percent) and to the excited states at 6.1 and 7 Mev (~40 percent each) [(Bl 47) and (So 46)]. Gamma rays of energy 6.133 ± 0.011 and 7.10 ± 0.02 Mev, with intensities in the ratio $1:0.08\pm0.02$, are observed (Mi 51a). The ratio of the intensity of the 7.12→6.14-Mev transition to the 6.14→ground transition is ≤ 0.05 (Bo 53a). This result implies that the β decay to the 7.12-Mev state must be weaker than indicated by the absorption measurement results. The preferred direct ground-state decay of the 7.12-Mev state is not necessarily a violation of the isotopic spin electric dipole rule [see $F^{19}(p\ \alpha)O^{16}$] (Ge 53a).

The half-life is 7.35 ± 0.05 sec (Bl 47), 7.38 ± 0.05 sec (Ma 54d). The ground-state transition is first forbidden ($\log ft=6.8$) while the transitions to the excited states are allowed. From this it is concluded that N^{16} has $J=2^-$ (Mi 51a).

XVIII. $O^{16}(\gamma\ n)O^{15}$ $Q_m=-15.597$

The cross section exhibits a slow rise for ~3 Mev above the threshold (Mo 53b) followed by the usual giant resonance. Characteristics of the giant resonance are: $E_\gamma=22.5$ Mev, $\Gamma=3.5$ Mev, $\sigma_{\max}=7.7$ mb, integrated cross section 31 Mev-mb (Fe 54), $E_\gamma=21.9$, $\sigma_{\max}=8.9$ mb, integrated cross section to peak = 19 Mev-mb (Mo 53c), $E_\gamma=24.2$, $\sigma_{\max}=11.4$ mb, integrated cross section to peak = 31.2 Mev-mb (Jo 51b).

Discontinuities in the activation curve indicate absorption into discrete levels of O^{16} [(Ka 54a) and (Sp 54a)]: see Table III(16). The sum over the observed resonances yields an integrated cross section of 14 Mev-mb to $E_\gamma=22$ Mev; it thus appears that a substantial fraction of the absorption takes place through discrete levels (Ka 54a). Detailed analysis of the 15.98-Mev break indicates a level position of 16.02 Mev and a width of 22 ± 8 kev. Radiative widths for the levels below 19 Mev, derived from the individual integrated cross sections, range from 2 to 30 ev, and are considerably smaller than would be expected from $E1$ absorption (A. S. Penfold and B. M. Spicer, private communication). The region 17.6 to 17.9 Mev has been investigated with monochromatic γ rays by (Ca 54c) who reports evidence for a level at 17.71 ± 0.01 Mev with $\Gamma\sim20$ kev. See also (Pe 52e), (Ha 53d), and (Mo 53c).

XIX. $O^{16}(\gamma\ p)N^{15}$ $Q_m=-12.110$

See (Wa 49i).

XX. $O^{16}(\gamma\ \alpha)C^{12}$ $Q_m=-7.149$

For $E_\gamma<27$ Mev, the cross section for production of C^{12} (indicated by observation of α+recoil tracks) exhibits a broad (~5 Mev) maximum near 17.5 Mev; the peak cross section is ~50 μb (Mi 53c). (Na 52b) find at $E_\gamma=17.6$ Mev, less than 10 percent of transitions leading to the 4.4-Mev state of C^{12}: they report a cross section $\sigma(17.6)=195\pm8$ μb. (St 54h) reports evidence for excited states of O^{16} at 14.2(?), 16.75, 17.3, 22.6, 23.15(?), and 24.6 Mev with $J=2^+$, $T=0$. See also (Er 54b) and (Gr 54).

XXI. $O^{16}(\gamma\ 4\alpha)$ $Q_m=-14.426$

The cross section for production of 4-pronged stars shows maxima at $E_\gamma=22.6$, 25.8, and 29.5 Mev, with possible indication of finer structure [(Go 52): 700 stars; see also (Mi 53c), (Li 53b), and (Hs 53)]. For E_γ near the first maximum, two classes of stars are reported by (Mi 53c) ascribed to $O^{16}(\gamma\ 2\alpha)Be^8$ (ground state) and $O^{16}(\gamma\ 4\alpha)$. It is considered improbable that excited states of Be^8 or C^{12} are involved (Mi 53c). (Li 53b) and (Go 50h), on the other hand, believe that a

TABLE III(16). Levels in O^{16} from $O^{16}(\gamma\ n)O^{15}$.

E_γ (Mev)[a]	$\int\sigma dE$ (Mev-mb)	E_γ (Mev)[b]	$\int\sigma dE$ (Mev-mb)
15.98	0.078	15.9	0.06
16.44	0.045	16.4	0.05
16.67	0.071	16.7	0.18
16.85	0.142	16.9	0.95
16.92	0.222		
17.04	0.575	17.1	0.80
17.44	0.236		
17.54	0.185		
17.69[c]	0.185		
17.88	0.077		
18.48	0.117		
18.76(?)			
18.91	0.511	18.9	0.66
		19.3	1.5
		20.7	2.1
		21.9	7.5

[a] (Sp 54a) and A. S. Penfold and B. M. Spicer (private communication), quoted to ±20 kev.
[b] (Ka 54a).
[c] (Ca 54c): 17.71 ± 0.01 Mev, $\Gamma\sim20$ kev.

large fraction of the stars involve levels of C^{12} at 9.6 Mev (Go 50h) and 11.3 Mev (Li 53b), yielding Be^8 in the ground state.

In the range $E_\gamma=23$ to 25 Mev, the reaction is believed to proceed mainly via a 12- to 13-Mev level of C^{12}[(Li 53b) and (Hs 53)], possibly leading to the 2.9-Mev state of Be^8 (Li 53b). For $E_\gamma>25$ Mev, the dominant mode by far is via levels in C^{12} near 16 Mev, yielding Be^8 in the 2.9-Mev state [(Li 53b) and (Hs 53)]. It is suggested that the process here involves $E1$ absorption into $T=1$ states of O^{16} which then decay preferentially to $T=1$ states of C^{12}. A few cases involving a 17-Mev, $T=1$, state of Be^8 are reported [(Hs 53): see (Ge 53a)]. See also (Li 52c).

XXII. (a) $O^{16}(\gamma\ n\alpha)C^{11}$ $Q_m=-25.859$
(b) $O^{16}(\gamma\ t)N^{13}$ $Q_m=-25.006$

See (Er 54c).

XXIII. $O^{16}(n\ n')O^{16*}$

At $E_n=14$ Mev, gamma rays have been observed from the excitation of the 6.13- and 7-Mev levels of O^{16}; $\sigma\sim0.2$ bn (Th 54b). See also O^{17}.

XXIV. $O^{16}(p\ p')O^{16*}$

Inelastic proton groups are observed corresponding to levels at 6.05, 6.13 [(Ar 52e): $E_p=8$ Mev; (Bu 53b): $E_p=9.5$ Mev], 6.9 and 7.1 Mev (Bu 53b), 8.6 and 9.7 Mev [(Fu 48): $E_p=15$ Mev]. At $E_p=93$ Mev, a broad inelastic group is observed corresponding to unresolved levels at 6 and 7 Mev (K. Strauch and W. F. Titus, private communication). See also (Co 52g).

XXV. $F^{19}(p\ \alpha)O^{16}$ $Q_m=8.124$

In addition to the ground-state group, four α-particle groups are observed, corresponding to levels at 6.06 (nuclear pair emitting), 6.14, 6.91, and 7.12 Mev [(Bu 50c), (Ch 50), and (Fr 50e)]. The reaction exhibits a large number of resonances (see Ne^{20}).

The existence of pairs and absence of γ radiation from the 6.06-Mev level clearly implies $J=0$ for this state. The energy spectrum and the angular correlation [(De 54a), (De 49b), and (Ph 51a)] are consistent with $J=0^+$. The half-life is $5.0\pm0.5\times10^{-11}$ sec, considerably longer than predicted by the α-particle model (De 54a). Two-quantum decay amounts to less than 10 percent [R. Latham and others, cited in (De 54a)].

The angular correlation of internal conversion pairs is consistent with $J=3^-$ for the 6.14-Mev state (De 54b), as is the $(\alpha_1\gamma_1)$ angular correlation [(Ar 50) and (Ba 50f)] and the polarization of the 6.1-Mev γ radiation (Fr 52a). The half-life of this state is $\leq10^{-11}$ sec (C. A. Barnes, private communication), $10^{-11}>\tau_{\frac{1}{2}}>5\times10^{-12}$ sec (S. Devons, preliminary value, private communication); see also (Go 53g).

Study of $(\alpha_2\gamma_2)$ and $(\alpha_3\gamma_3)$ angular correlations leads to assignments of $J=2^+$ and $J=1^-$ to the 6.91- and 7.12-Mev levels of O^{16}, respectively (Se 52b); polarization measurements support these assignments (Fa 53a). (Wi 53) find the $6.91\rightarrow0$ transition $(E2)>200$ times more probable that the $6.91\rightarrow6.14$ transition $(E1)$. Since on the single-particle model (ignoring isotopic spin), the expected ratio is about 1/6, this observation suggests that the isotopic spin selection rule inhibits the latter by a factor >1200. The $7.12\rightarrow0$ transition $(E1)$ is found to be >120 times more probable than the 7.12 to 6.14 transition $(E2)$. Since a ratio of $\sim2.4\times10^7$ would be expected, the observation indicates an inhibition of $<2\times10^5$ (Wi 53). According to (Ge 53a), the ground-state transition should be favored by a factor of ~200, even if the states are pure $T=0$. The half-life of the 6.91-Mev state is $\lesssim1.2\times10^{-14}$ sec, while that of the 7.12-Mev state is $\lesssim8\times10^{-15}$ sec (S. Devons, preliminary values, private communication).

A search for a 2^- level at $E_p=873$ kev reveals no such level in the range $E_x=7.1$ to 8.7 Mev and no evidence of degeneracy with the 6.91- and 7.12-Mev levels (Pe 54d). This result appears to be in agreement with predictions of the α-particle model of (De 54c). See also (In 53).

F^{16}

(Not illustrated)

Mass of F^{16}

The mass of F^{16} may be roughly estimated from that of N^{16}, assuming charge symmetry and making the necessary corrections for the difference in Coulomb energies and the neutron-proton mass. On this basis the mass defect of $F^{16}=10.4+5.5\simeq15.9\pm1$ Mev, and F^{16} is then ~1.1 Mev unstable with respect to proton emission. See (Al 50g).

The following reactions leading to F^{16} have not been reported: $N^{14}(He^3\ n)F^{16}$ $(Q_m=-1.5)$, $O^{16}(p\ n)F^{16}$ $(Q_m=-16.7)$, and $O^{16}(He^3\ t)F^{16}$ $(Q_m=-15.9)$.

N^{17}

(Not illustrated)

I. $N^{17}(\beta^-)O^{17*}\rightarrow O^{16}+n$ $Q_m=8.8$

The decay is complex. See O^{17}.

II. $C^{14}(\alpha\ p)N^{17}$ $Q_m=-9.8$

See O^{18}.

III. $O^{17}(n\ p)N^{17}$ $Q_m=-8.0$

See O^{18}.

IV. $O^{18}(\gamma\ p)N^{17}$ $Q_m=-16.1$

See (Re 54).

V. Photospallation reactions

A number of spallation reactions yielding N^{17} have been observed by (Re 54); the integrated cross sections to 180 Mev are given.

O^{17}

(Fig. 30)

I. $C^{13}(\alpha\, n)O^{16}$ $Q_m=2.201$ $E_b=6.344$

Resonances are reported at $E_\alpha=1.066\pm0.005$ ($\Gamma\sim3$ kev) and 1.344 ± 0.010 Mev (Jo 53e), and at $E_\alpha=2.44$, 2.66, 2.76, and 3.30 Mev (Tr 54). The narrowness of the first resonance may imply a large J for the 7.16-Mev state (Jo 53e).

II. $N^{14}(\alpha\, p)O^{17}$ $Q_m=-1.198$

$Q_0=-1.16$ Mev [(Ro 51g); photoplate].
$Q_0=-1.16$ Mev [(Hj 53) and (Hj 53a); photoplate].

Proton groups corresponding to an excited state of O^{17} at 0.8 Mev (Ro 51g), 0.86 Mev [(Hj 53) and (Hj 53a)] have been observed. See also (Ka 52a).

III. $N^{15}(d\, n)O^{16}$ $Q_m=9.885$ $E_b=14.027$

See O^{16}.

IV. $N^{15}(d\, p)N^{16}$ $Q_m=0.27$ $E_b=14.027$

See N^{16}.

V. $N^{15}(d\, \alpha)C^{13}$ $Q_m=7.683$ $E_b=14.027$

See (Ho 40).

VI. $O^{16}(n\, \gamma)O^{17}$ $Q_m=4.143$

$\sigma_{\text{capt}}<0.92$ mb (Sa 47).

VII. $O^{16}(n\, n)O^{16}$ $E_b=4.143$

At $E_n=8.2\times10^{-4}$ ev, the cross section is 11.7 b (Hu 54a). The epithermal scattering cross section (free) is 3.76 ± 0.02 bn (Hu 52e). The cross section is almost constant from thermal energies to $E_n=0.3$ Mev (Hu 53c). The course of the nonresonant cross section up to $E_n=2$ Mev can be accounted for by an s-wave interaction involving the 0.88-Mev level, with a reduced width of the order of the single-particle value (Th 52b).

Observed resonances are indicated in Table I(17). The level assignments are based on peak heights, peak shapes, and angular distributions. Polarization studies with $Li^7(p\, n)Be^7$ neutrons in the range $E_n=0.25$ to 0.6 Mev indicate strong interference between the $P_{\frac{3}{2}}$ level ($E_n=0.43$ Mev) and the $S_{\frac{1}{2}}$ background. The absolute magnitude of the polarization at $\theta=90°$ is in good agreement with the known level parameters (Wi 54c). The $E_n=1.0$-Mev resonance ($O^{17*}=5.08$ Mev) may be the $D_{\frac{3}{2}}$ component of the ^2D term of which the ground state is the other member (Ad 53). A search in the range $E_n=1.0$ to 1.3 Mev reveals no indication of a level corresponding to that reported at $E_x=5.229$ Mev in $F^{19}(d\, \alpha)O^{17}$ (R. L. Becker, private communication).

At $E_n=14.1$ Mev, the elastic scattering cross section is 0.7 b (Co 53b), while the total cross section is 1.65 ± 0.05 b (Co 54f), 1.59 ± 0.03 b (Co 52h), 1.64 ± 0.04 b (Po 52a), 1.68 ± 0.09 b (Ag 53). The total cross section has been measured from $E_n=14.1$ to 18 Mev; it remains essentially constant in that region (Co 54f). See also (Go 52d), (Hi 54c), (Ne 54c), and (Wi 54e).

TABLE I(17). Resonances in $O^{16}(n\, n)O^{16}$.

E_n (Mev)	Γ (kev)	σ (b)	l_n	$\gamma^2/(3\hbar^2/2\mu a)$	$J,\ \pi$	O^{17*}
0.443[a]	45	16.5	1	0.038	3/2−[i]	4.56
1.00[b]	100	7.9	2	0.26	3/2+[i]	5.08
1.32[b]	35	6.7	1	0.009	3/2−[i]	5.39
1.66[b]	≤7	5.2	>0		≥3/2	5.71
1.84[b]	≤10	3.8	>0		≥3/2	5.87
1.91[c]	30	3.0	1	0.0056	1/2−	5.94
2.37[d]	120	0.3	0	0.013	1/2+	6.37
3.33[e]	220	3.0	2	0.049[h]	3/2+	7.28
3.80[e]	800	3.0	1	0.080[h]	3/2−	7.72
4.35[f]	280	2.2	1	0.025[h]	1/2−	8.28
4.6[g]						8.5
4.8[g]						8.7
5.15[g]						8.98
5.7[g]						9.5
(5.9)[g]						(9.7)
(6.4)[g]						(10.2)
(6.7)[g]						(10.5)
(6.8)[g]						(10.6)

[a] R. L. Becker, private communication.
[b] (Bo 50f) and (Bo 51c).
[c] (Bo 51c) and (Ba 52b).
[d] (Bo 51c), (Ba 52b), and (Ri 51c).
[e] (Fr 50b) and (Ba 52b).
[f] (Fr 50b), (Ba 52b), and (Hu 53c).
[g] (Hu 53c).
[h] (Vo 54).
[i] (Ad 53).

VIII. $O^{16}(n\, n')O^{16*}$ $E_b=4.143$

The inelastic scattering cross section at $E_n=14.1$ Mev is 0.5 bn; the angular distribution is roughly symmetric (Co 53b). The cross section for production of 6–7 Mev γ rays is 0.25 b (Th 54b). See also (Ba 53a) and (Sc 53).

IX. $O^{16}(n\, 2n)O^{15}$ $Q_m=-15.597$ $E_b=4.143$

See (Je 44) and (Sh 45).

X. $O^{16}(n\, p)N^{16}$ $Q_m=-9.62$ $E_b=4.143$

The cross section rises from threshold to a peak of 89 ± 30 mb at $E_n=14$ Mev, falling to ~60 mb at 18 Mev (Ma 54d). The cross section is given as 35 mb at $E_n=14.1$ Mev (Hu 54a) and as 49 ± 25 mb at $E_n=14.5$ Mev (Pa 53a).

XI. $O^{16}(n\, d)N^{15}$ $Q_m=-9.885$ $E_b=4.143$

At $E_n=14.1$ Mev, the cross section is 15 mb (Hu 54a).

XII. $O^{16}(n\, \alpha)C^{13}$ $Q_m=-2.201$ $E_b=4.143$

Thirty-two resonances are reported by (Gi 53a), corresponding to levels in O^{17} between 6.8 and 12.8 Mev. At $E_n=14.1$ Mev, the cross section is 310 mb (Hu 54a). See also (Wi 37e).

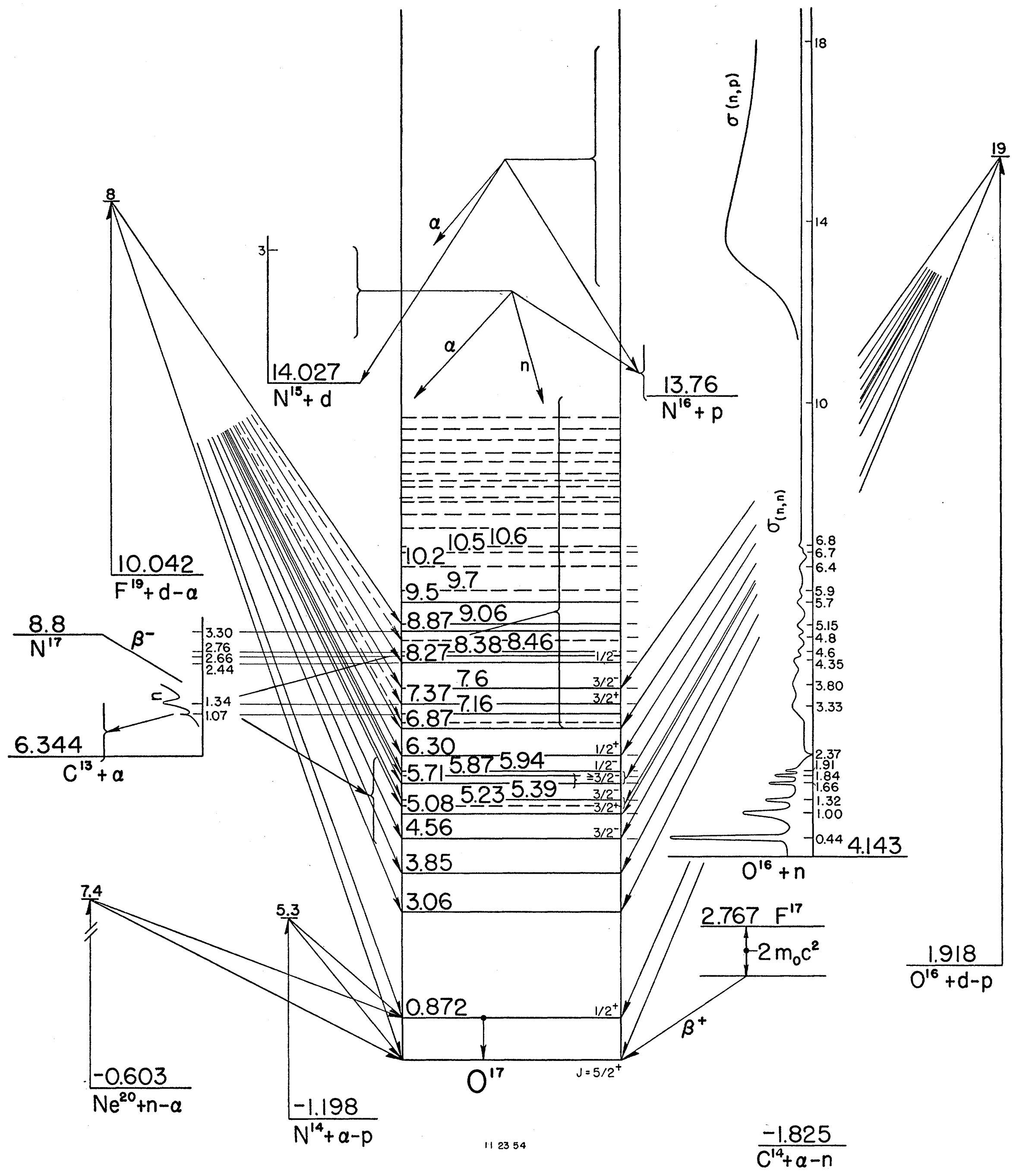


FIG. 30. Energy levels of O^{17}: for notation, see Fig. 1.

XIII. $O^{16}(d\ p)O^{17}$ $Q_m=1.918$

The weighted mean of nine Q-value determinations is 1.919 ± 0.004 Mev (Va 54). A recent result is 1.915 ±0.010 Mev [(Sp 54b); mag. spectrometer]. Recent values for the energies of the first three excited states are: 875, 3055, 3840 kev [(Sp 54b): ±12 kev], 893, 3005, 3853 [(Kh 53): mag. analyzer, no errors stated]. Other values, including higher levels, are tabulated in (Aj 52c). See also (Bu 49c).

At $E_d=8$ Mev [(Bu 50e), (Bu 51f), and (Bu 51h)] and 19 Mev (Fr 53e), the angular distributions, analyzed by stripping theory, indicate $l_n=2$, and therefore $J=\frac{3}{2}^+$ or $5/2^+$ for the ground state, and $l_n=0$, and therefore $J=\frac{1}{2}^+$ for the 0.88-Mev state of O^{17}: (see also F^{18}.) Reduced widths derived from the absolute cross sections are about 0.1 and $0.2\times 3\hbar^2/2\mu a$ for the ground state and 0.88-Mev state respectively: see (Fu 54) and (Fa 54c).

The energy of the γ ray from the first excited state is 870.5 ± 2.0 kev (without Doppler shift); the internal conversion coefficient is consistent with $E2$ radiation (Th 52). The $p-\gamma$ angular correlations are isotropic at $E_d=0.8$ Mev (Th 53) and at 1.7 and 2.0 Mev (Ph 52), consistent with $J=\frac{1}{2}$ for the excited state. The lifetime of $(2.5\pm 1)\times 10^{-10}$ sec is considerably shorter than predicted by the extreme independent-particle model and appears to indicate some participation of core excitation in the transition (Th 53a). See also (Be 54b), (Ho 54d), (Kh 54), and (Th 54d).

XIV. $N^{17}(\beta^-)O^{17**}\rightarrow O^{16}+n$ $Q_m=8.8$

The half-life is 4.14 ± 0.04 sec (Kn 48), 4.15 ± 0.1 sec (St 51a). $E_\beta(\max)=3.7\pm 0.2$ Mev (Al 49c): $\log ft=3.8$. The β decay proceeds to an excited state or states of O^{17} which in turn decay to O^{16} by neutron emission. The neutron spectrum has a maximum at 0.92 ± 0.07 Mev [(Al 49c) and (Ha 49c)] and a half-width <0.5 Mev.

XV. $O^{17}(p\,p')O^{17*}$

See (Wa 54).

XVI. $F^{17}(\beta^+)O^{17}$ $Q_m=2.767$

See F^{17}.

XVII. $F^{19}(d\,\alpha)O^{17}$ $Q_m=10.042$

The weighted mean of four Q-value determinations is 10.039 ± 0.010 Mev (Va 54); this includes a recent value of 10.028 by (Wa 52b; mag. spectrometer). Observed α-particle groups are tabulated in (Aj 52c).

XVIII. $Ne^{20}(n\,\alpha)O^{17}$ $Q_m=-0.603$

See (Jo 51e) and Ne^{21}.

F^{17}

(Fig. 31)

I. $F^{17}(\beta^+)O^{17}$ $Q_m=2.767$

The decay proceeds to the ground state of O^{17}: $E_{\beta^+}(\max)=1.748\pm 0.006$ Mev, $\log ft=3.38$. The spectrum has the allowed shape down to 570 kev and an upper limit of one percent is placed on possible transitions to the 875-kev state of O^{17}: $\log ft>4.3$ (Wo 54a). Recent values of the half-life are 66.0 ± 1.8 sec (Wo 54a), 62.5 ± 1.0 sec (Wa 54), 66.0 ± 0.5 sec (Ko 54). See also (Aj 52c).

II. $N^{14}(\alpha\,n)F^{17}$ $Q_m=-4.747$

See (Li 37) and F^{18}.

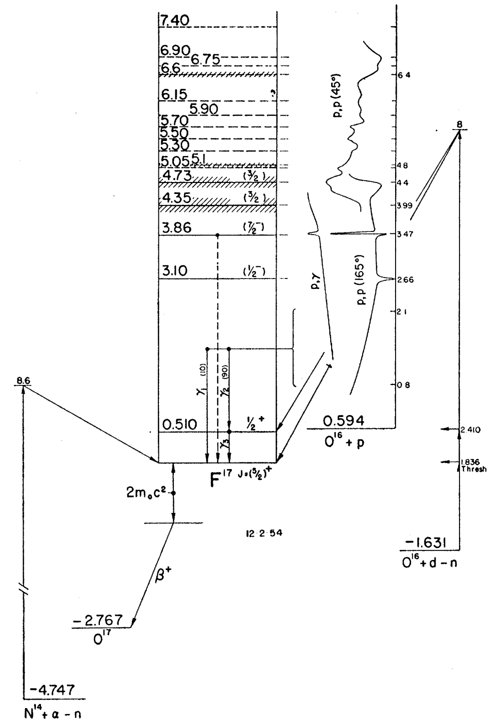


FIG. 31. Energy levels of F^{17}: for notation, see Fig. 1.

III. $O^{16}(p\,p)O^{16}$ $E_b=0.594$

Observed anomalies in the scattering are exhibited in Table III(17) [(La 51d), (La 51e), (Ep 53), and (Se 54)]. In addition, sharp resonances ($\Gamma<25$ kev) are reported by (Se 54) corresponding to excited states of F^{17*} at 5.05, 5.30, 5.50, 5.70, 5.90, 6.15, 6.75, 6.90, and 7.40 Mev. The differential cross section at $E_p=2.00$ Mev, $\theta=167.2°$ (lab) is 94 ± 2 mb/sterad. The low-energy cross section indicates a large S and a relatively large D phase shift (Ep 53). Differential cross sections have been measured at $E_p=9.5$ Mev (Bu 53b). See also (Bl 54a).

IV. $O^{16}(p\,\gamma)F^{17}$ $Q_m=0.594$

Nonresonant capture has been studied for $E_p=0.8$ to 2.1 Mev. This work indicates, in addition to the direct ground-state transition (γ_1), a transition (γ_2) to a state of F^{17} at 487 ± 10 kev which then radiates (γ_3)

TABLE III(17). Anomalies in $O^{16}+p$ scattering.

E_p (Mev)	Γ (kev)	F^{17*}	J, π	References
2.66	19.9	3.10	$1/2^-$	(La 51d), (La 51e), and (Ep 53)
3.47	<3.5	3.86	$7/2^-$	(La 51d) and (La 51e)
(3.99)	~500	4.35	$(3/2^+)$	(La 51d) and (La 51e)
4.1	400	4.5	$(3/2^-)$	(Se 54)
(4.39)	240	4.73	$(3/2^-)$	(La 51d) and (La 51e)
4.2	350	4.6	$(3/2^+)$	(Se 54)
4.8	200	5.1	$1/2^+$	(Se 54)
6.4	150	6.6	$1/2^+$	(Se 54)

to the ground state. The ratio of γ_2 to γ_1 is about 10 over the energy region studied. The γ_1 and γ_3 radiations are approximately isotropic, while γ_2 has an almost pure $(\sin^2\theta)$ distribution ($E_p=1.0$ to 1.9 Mev). At $E_p=1.35$ Mev, the cross section for production of γ_2 radiation is 6 ± 3 μb. The fact that most transitions involve the 0.51-Mev state (γ_2) indicates that the nonresonant yield is not to be attributed to this state; it is suggested that direct, one-stage capture is involved (Wa 54).

The relative F^{17} activity has been measured from $E_p=1.1$ to 4.1 Mev. The cross section increases almost linearly with proton energy from 1.1 to 3.75 Mev except for a sharp resonance at 3.47 Mev [(La 51d) and (La 51e)]. See also (Wi 53c).

V. $O^{16}(d\ n)F^{17}$ $Q_m=-1.631$

A neutron group has been observed corresponding to an excited state of F^{17} at 0.536 ± 0.010 Mev (Aj 51b), 0.53 ± 0.06 Mev [(El 51a) and (Mi 53)]. Angular distributions of neutron groups to the ground and first excited state of F^{17}, analyzed by stripping theory, indicate $J=\frac{3}{2}$ or $5/2^+$ for the ground state and $J=\frac{1}{2}^+$ for the first excited state [(El 51a), (Mi 53), and (Aj 51b): $E_d=8$ and 3.1 Mev].

A neutron threshold determination indicates that the first excited state of F^{17} is at 510 ± 5 kev (Cook, Marion, and Bonner, private communication).

VI. $F^{19}(\gamma\ 2n)F^{17}$ $Q_m=-19.567$

See F^{19}.

O^{18}

(Fig. 32)

I. $C^{14}(\alpha\ p)N^{17}$ $Q_m=-9.8$ $E_b=6.238$

See (Su 51b).

II. $O^{16}(t\ p)O^{18}$ $Q_m=3.724$

See (Cu 53c).

III. $O^{17}(n\ p)N^{17}$ $Q_m=-8.0$ $E_b=8.063$

See (Ch 49d).

IV. $O^{17}(n\ \alpha)C^{14}$ $Q_m=1.825$ $E_b=8.063$

The thermal cross section is 0.46 ± 0.11 b (Ma 47).

V. $O^{17}(d\ p)O^{18}$ $Q_m=5.838$

Proton groups have been observed corresponding to the ground state ($Q_0=5.821\pm0$ 010 Mev) and to a state at 1.986 ± 0.013 Mev. No other groups are observed corresponding to levels below 4.8 Mev [(Ah 54d) and (Ah 54e); mag. spectrometer: $E_d=0.9$ Mev]. However, at $E_d=1.39$ and 1.98 Mev, [(Ho 54f); mag. spectrometer] report two states with $Q=3.393\pm0.016$ and 3.861 ± 0.016 Mev corresponding to states of O^{18} at 1.98 and 2.45 Mev.

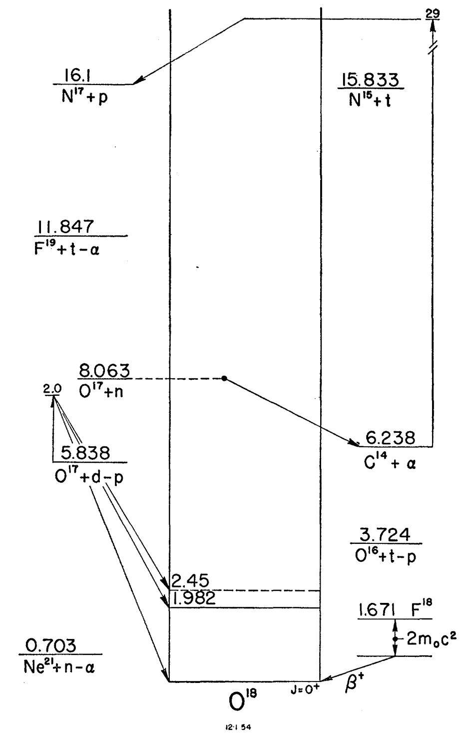


FIG. 32. Energy levels of O^{18}: for notation, see Fig. 1.

VI. $O^{18}(\gamma\ p)N^{17}$ $Q_m=-16.1$

The cross section rises slowly for ~3 Mev above threshold (Mo 53b) and then shows the usual giant resonance at $E_\gamma=24\pm2$ Mev ($\sigma=37$ mb). The integrated cross section to 25 Mev is 150 ± 100 Mev-mb (St 51a). The integrated cross section to 180 Mev is 500 Mev-mb (Re 54).

VII. $F^{18}(\beta^+)O^{18}$ $Q_m=1.671$

See F^{18}.

F^{18}

(Fig. 33)

I. $F^{18}(\beta^+)O^{18}$ $Q_m=1.671$

The positron end point is 635 ± 15 (Bl 49a), 649 ± 9 kev (Ru 51). The spectrum is simple. The half-life is 112 ± 1 min (Bl 49a): $\log ft=3.62$. [The fact that the β transition to the ground state of O^{18} ($J=0^+$, $T=1$) is allowed suggests that F^{18} (assumed $T=0$) has $J=1^+$, since 0–0 transitions in β decay require $\Delta T=0$ (see C^{10} and O^{14}).]

II. $N^{14}(\alpha\ \gamma)F^{18}$ $Q_m=4.412$

Resonances have been observed at $E_\alpha=1.530\pm0.003$ Mev ($\Gamma<1.5$ kev) and 1.617 ± 0.003 Mev ($\Gamma<1$ kev). In both cases, transitions have been observed to an excited state at 1.075 ± 0.010 Mev with $\omega\Gamma_\gamma=2.2\pm0.3$ ev. The transition from the first resonance to the ground

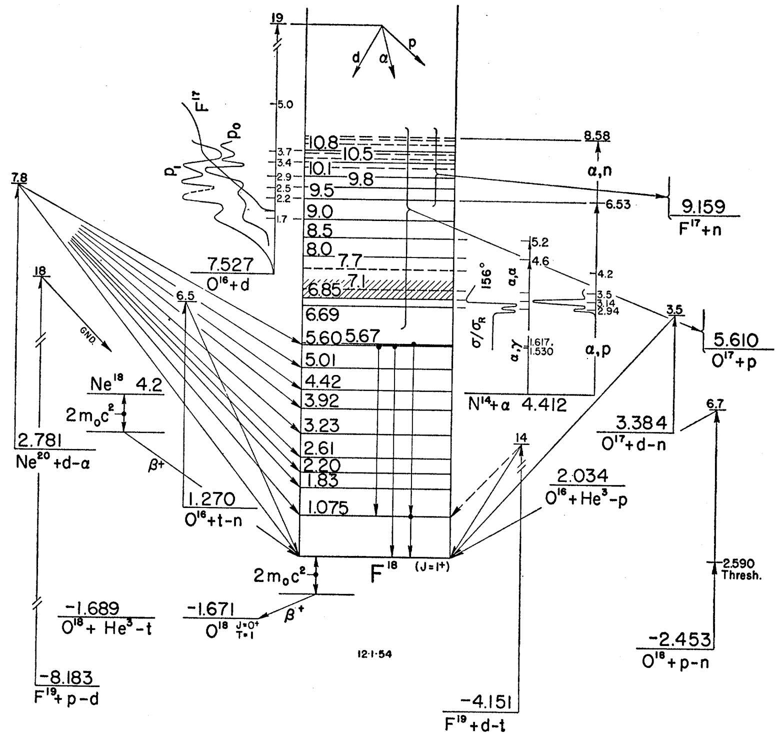


FIG. 33. Energy levels of F^{18}: for notation, see Fig. 1.

state has been found with $\omega\Gamma_\gamma=0.7\pm0.1$ ev. Angular distributions of the γ rays are also reported (Pr 54c).

III. $N^{14}(\alpha\ n)F^{17}$ $Q_m=-4.747$ $E_b=4.412$

Eleven resonances, from $E_\alpha=6.53$ to $E_\alpha=8.58$ Mev, are reported by (Fu 38).

IV. $N^{14}(\alpha\ p)O^{17}$ $Q_m=-1.198$ $E_b=4.412$

Observed resonances in the range $E_\alpha=1.5$ to 4.2 Mev are exhibited in Table I(18) [(He 53), (Ro 51g), and (Ch 47b)]. See also (Aj 52c), (Ka 52a), and (Ch 53d).

V. $N^{14}(\alpha\ \alpha)N^{14}$ $E_b=4.412$

Observed anomalies in the elastic scattering are exhibited in Table I(18) [(De 39a), (Br 39), and (He 53)]. The scattering cross section has nearly the Rutherford value for $E_\alpha<2.5$ Mev; there is no indication of an anomaly near $E_\alpha=1.7$ Mev [see $N^{14}(\alpha\ p)O^{17}$: (Aj 52c)].

TABLE I(18). Resonances in $N^{14}(\alpha\ p)O^{17}$ and $N^{14}(\alpha\ \alpha)N^{14}$.

E_α (Mev)	Γ(c.m.) (kev)	F^{18*}
2.935[a]	27±4	6.694
3.140[a]	93±8	6.854
~3.5[a,b]	~460	~7.1
4.2[b]		7.7
4.6[c]		8.0
5.2[d]		8.5

[a] $N^{14}(\alpha\ p)O^{17}$ and $N^{14}(\alpha\ \alpha)N^{14}$: (He 53) (widths are from first reaction).
[b] $N^{14}(\alpha\ p)O^{17}$: (Ro 51g).
[c] $N^{14}(\alpha\ \alpha)N^{14}$: (De 39a).
[d] $N^{14}(\alpha\ \alpha)N^{14}$: (De 39a) and (Br 39).

VI. $O^{16}(d\ \gamma)F^{18}$ $Q_m=7.527$

At $E_d=1.1$ Mev, the cross section is <0.5 mb (Si 54).

VII. $O^{16}(d\ n)F^{17}$ $Q_m=-1.631$ $E_b=7.527$

The excitation function has been studied for $E_d=1.8$ to 5 Mev [(Bo 51b) and (Ne 37b)].

VIII. $O^{16}(d\ p)O^{17}$ $Q_m=1.918$ $E_b=7.527$

Resonances for both the ground and the excited-state proton groups are reported at $E_d=1.7$, 2.2, and 3.0 Mev by (He 48a). Broad maxima in the ground-state proton yield curve are found at 2.5, 2.9, 3.4, and 3.7 Mev, while the short-range protons show broad maxima in the yield at 2.6 and 3.3 Mev ($E_d=2.4$ to 3.8 Mev). The angular distributions at these energies indicate that the emission of short-range protons proceeds almost entirely by stripping while the ground-state protons ($l_n=2$) show more the influence of compound nucleus formation [(Va 54a) and T. F. Stratton, private communication]: [Compare (Be 54b)]. At $E_d=19$ Mev, the cross sections for the formation of the ground and 0.87-Mev states of O^{17} are, respectively, 35.5±3.5 and 22.7±3.5 mb (Fr 53e).

IX. $O^{16}(d\ d)O^{16}$ $E_b=7.527$

See (Fr 53e).

X. $O^{16}(d\ \alpha)N^{14}$ $Q_m=3.116$ $E_b=7.527$

At $E_d=19$ Mev, the cross section for long-range alphas is 2.6 ± 0.3 mb; the cross section for formation of the 2.31-Mev, $T=1$, level of N^{14} is <0.1 mb (Fr 53e).

XI. $O^{16}(t\ n)F^{18}$ $Q_m=1.270$

See (Po 51).

XII. $O^{16}(He^3\ p)F^{18}$ $Q_m=2.034$

See (Ku 53a) and (Po 52b).

XIII. $O^{16}(\alpha\ pn)F^{18}$ $Q_m=-18.532$

See (Te 47).

XIV. $O^{17}(d\ n)F^{18}$ $Q_m=3.384$

See F^{19}.

XV. $O^{18}(p\ n)F^{18}$ $Q_m=-2.453$

The threshold is $E_p=2.590\pm0.004$ (Ri 50e), 2.584 ±0.010 Mev (Ma 55).

XVI. $O^{18}(He^3\ t)F^{18}$ $Q_m=-1.689$

See (Ku 53a).

XVII. $Ne^{18}(\beta^+)F^{18}$ $Q_m=4.2$

See Ne^{18}.

XVIII. $F^{19}(\gamma\ n)F^{18}$ $Q_m=-10.408$

See F^{19}.

XIX. $F^{19}(n\ 2n)F^{18}$ $Q_m=-10.408$

See F^{20}.

XX. $F^{19}(p\ d)F^{18}$ $Q_m=-8.183$

At $E_p=18$ Mev, the angular distribution of ground-state deuterons, analyzed by pickup theory, indicates $l=0$ and therefore even parity, $J=0^+$ or 1^+ for F^{18} (Re 54a).

XXI. $F^{19}(d\ t)F^{18}$ $Q_m=-4.151$

See (Bo 50d) and (Sh 51a).

XXII. $Ne^{20}(d\ \alpha)F^{18}$ $Q_m=2.781$

$Q_0=2.791\pm0.009$ [(Mi 54b); mag. spectrometer].

At $E_d=7.8$ Mev, alpha-particle groups have been observed corresponding to levels in F^{18} at 1.05, 1.83, 2.20, 2.61, 3.23, 3.92, 4.42, 5.01, and 5.61 Mev (Mi 51d). (No levels of F^{18} have yet been observed in reactions which could lead to $T=1$ states without violation of isotopic spin conservation.)

Ne^{18}

(Not illustrated)

Mass of Ne^{18}

From the beta decay (Go 54d), $Ne^{18}-F^{18}=4.2\pm0.2$ Mev. The mass defect is then 10.4 ± 0.2 Mev.

I. $Ne^{18}(\beta^+)F^{18}$ $Q_m=4.2$

The maximum energy of the positrons is 3.2 ± 0.2 Mev, the half-life is 1.6 ± 0.2 sec: $\log ft=2.9\pm0.2$ (Go 54d).

II. $O^{16}(He^3\ n)Ne^{18}$ $Q_m=-3.0$

See (Ku 53a)

III. $F^{19}(p\ 2n)Ne^{18}$ $Q_m=-15.4$

See (Go 54d).

O^{19}

(Fig. 34)

Mass of O^{19}

On the assumption that the proton group with the highest Q value, observed by (Th 54a), (Ah 54b), and (Ho 54f) in $O^{18}(d\ p)O^{19}$, corresponds to the ground state of O^{19}, the mass defect for $O^{19}=8.930\pm0.024$.

I. $O^{19}(\beta^-)F^{19}$ $Q_m=4.781$

The decay is complex: see F^{19}.

II. $O^{18}(n\ \gamma)O^{19}$ $Q_m=3.956$

The thermal cross section is 0.21 ± 0.04 mb (Hu 52e).

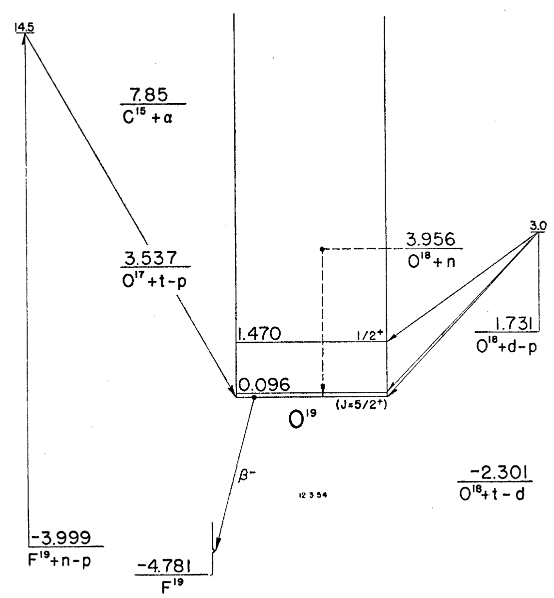


FIG. 34. Energy levels of O^{19}: for notation, see Fig. 1.

III. $O^{18}(d\ p)O^{19}$ $Q_m=1.731$

$Q_0=1.730\pm0.008$ [(Ah 54b); mag. spectrometer].
$Q_0=1.732\pm0.008$ [(Th 54a); mag. spectrometer].
$Q_0=1.735\pm0.008$ [(Ho 54f); mag. spectrometer].

A search for higher energy protons reveals no further groups with Q in the range 1.7 to 2.3 Mev or 2.6 to 3.4 Mev; the $Q=1.73$-Mev group is therefore presumed to represent the ground state (Mi 54e). Proton groups corresponding to excited states of O^{19} have been observed with $Q=1\ 636\pm0.008$ and 0.262 ± 0.006 Mev [(Ah 54b) and (Mi 54e)], 1.632 ± 0.008 Mev and 0.263 ±0.010 Mev (Th 54a), 1.641 ± 0.008 Mev and 0.264 ±0.013 Mev (Ho 54f); $O^{19*}=0.096$ and 1.470 Mev. No other proton groups are observed at $E_d=2.18$ Mev, $\theta=140°$, corresponding to states in O^{19} below 2.4 Mev (Th 54a).

Absolute differential cross sections have been measured at $E_d=3.01$ Mev for the $Q=0.3$-Mev group. The angular distribution is peaked in the forward direction ($\sigma=213\pm16$ mb/sterad at 5.4°, c.m.), and indicates $l_n=0$ and therefore $J=\frac{1}{2}^+$ for the 1.47-Mev excited state of O^{19} [T. F. Stratton, private communication and (St 54g)].

IV. $F^{19}(n\ p)O^{19}$ $Q_m=-3.999$

See F^{20} and (Je 50d).

F^{19}

(Fig. 35)

I. $O^{16}(t\ n)F^{18}$ $Q_m=1.270$ $E_b=11.678$

See (Kn 45) and (Ho 50b).

II. $O^{16}(\alpha\ p)F^{19}$ $Q_m=-8.124$

At $E_\alpha=20.6$ Mev, proton groups are observed corresponding to excited states at 1.36 ± 0.05, 2.67 ± 0.05, and 3.92 ± 0.05 Mev (Bu 51c).

III. $O^{17}(d\ n)F^{18}$ $Q_m=3.385$ $E_b=13.792$

See (Da 40) and (Ho 50b).

IV. $O^{17}(d\ p)O^{18}$ $Q_m=5.838$ $E_b=13.792$

See O^{18}.

V. $O^{17}(d\ \alpha)N^{15}$ $Q_m=9.807$ $E_b=13.792$

See N^{15}.

VI. $O^{18}(p\ n)F^{18}$ $Q_m=-2.453$ $E_b=7.955$

Observed resonances are listed in Table I(19) [(Ma 55), (Ri 50e), and (Bl 51a)]. See also (Ma 53d).

TABLE I(19). Resonances in $O^{18}(p\ n)F^{18}$.

E_p (Mev)	Γ (kev)[b]	Rel. yield	F^{19*}	J[d]
2.657 ± 0.002[a]	40 ± 2	0.399	10.471	
2.732 ± 0.006[b]		0.109	10.542	
2.778 ± 0.002[a]	35 ± 5	0.160	10.586	
3.045 ± 0.002[a]	60 ± 2	0.807	10.839	3/2
3.170 ± 0.002[b]	45 ± 10	0.420	10.957	1/2(?)
3.268 ± 0.002[a]	65 ± 2	1.000	11.050	3/2
3.386 ± 0.002[a]	45 ± 2	0.932	11.162	1/2(?)
3.495 ± 0.004[a]		0.580	11.265	
3.600 ± 0.020[b]	85 ± 20	0.966	11.37	
3.755 ± 0.020[b]		0.966	11.51	
3.3[c]		50[c]		
3.8		150		
4.25		250	12.0	
5.08		500	12.8	
5.63		330	13.3	
6.20		360	13.8	
6.67		450	14.3	

[a] [(Ma 55) and (Ri 50e)]: thin target neutron yields.
[b] (Ma 55).
[c] This and following values from (Bl 51a): stacked foil method; estimated cross sections in mb.
[d] (Ma 55): neutron angular distributions.

VII. $O^{18}(p\ \alpha)N^{15}$ $Q_m=3.969$ $E_b=7.955$

The excitation function indicates a small anomaly at $E_p=560$ kev (Co 53h), and resonances at $E_p=640\pm5$ kev, $\Gamma\sim15$ kev [(Se 51b) and (Co 53h)] [680 kev, (Mi 52b): $\Gamma=40$ kev], and 850 ± 5 kev, $\Gamma\sim45$ kev [(Se 51b) and (Co 53h)] superposed on what may be one or more broad resonances. From a study of angular distributions in this region, (Co 53h) finds $J=\frac{3}{2}$ and $\frac{1}{2}$, respectively, for the levels in F^{19} corresponding to the resonances at 640 and 850 kev. The absolute parity of these levels was not found but is stated to be opposite to that of the broad $J=\frac{1}{2}$ level(s) which give the main contribution to the yield away from the location of the sharp resonances. See also (Ro 53c).

VIII. $O^{18}(d\ n)F^{19}$ $Q_m=5.729$

At $E_d=2$ Mev, $\theta=0°$ and 20°, neutron groups are observed corresponding to levels of F^{19} at 0.2, 0.9, 1.4, 1.6, 2.2, 2.75, 3 85, 4.5, 4.8, 5.2, and 5.5 Mev [(Se 53c): ±0.1 Mev].

IX. $O^{19}(\beta^-)F^{19}$ $Q_m=4.781$

The decay branches 30 ± 10 percent to the 197-kev state ($E_\beta=4.5\pm0.3$ Mev) and 70 percent to a state at 1.57 Mev ($E_\beta=2.9\pm0.3$ Mev) [(Bl 47a) and (Jo 54g)]. With a half-life of 29 sec, $\log ft=5.55$ and 4.33 respectively (Fe 51b). Gamma rays of energy $\gamma_1=1366\pm8$ kev, $\gamma_2=199.6\pm1.5$ kev, and $\gamma_3=111.5\pm1.5$ kev with relative intensities 0.67:1.00:0.04 are reported, as is the transition, γ_4, from the 1570-kev level to the 110-kev level. The $\gamma_1-\gamma_2$ coincidences indicate that γ_1 arises from the transition 1570–197. The transition 197–110 has an intensity <0.5 percent, and the transitions 1570-ground state and 1570–1350 are ≤3 and 4 percent respectively. The lifetime of the 197-kev state is $(1.0\pm0.2)\times10^{-7}$ sec, while that of the 110-kev state is $\ll10^{-6}$ sec [compare $F^{19}(p\ p')F^{19*}$]. Lower limits on $\log ft$ for β transitions to the ground state and those at 110 and 1350 kev are 6.5, 7.3, and 5.3 (Jo 54g).

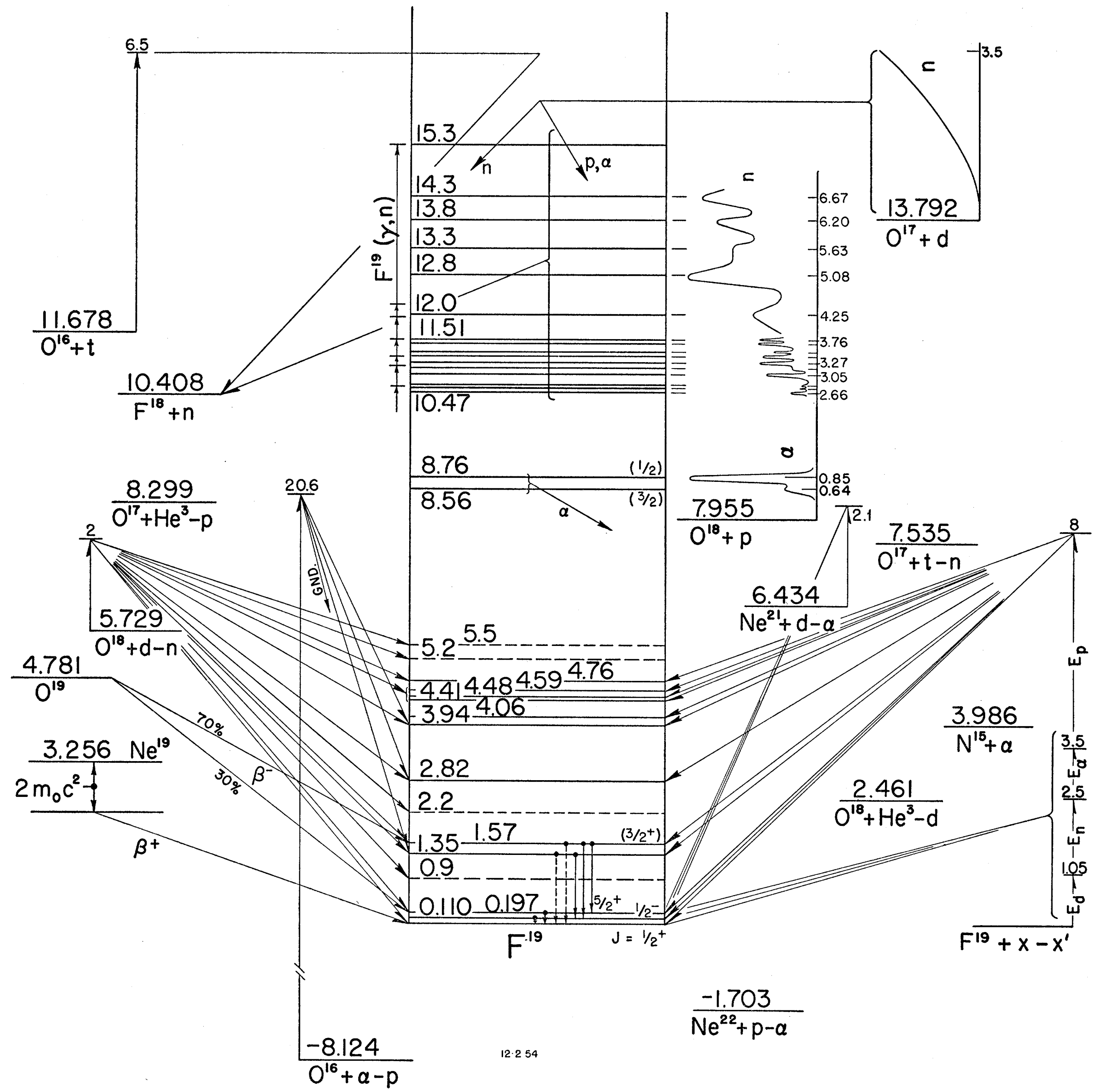


FIG. 35. Energy levels of F^{19}: for notation, see Fig. 1.

The present observations, together with Coulomb excitation data [$F^{19}(\alpha\,\alpha')F^{19*}$], require $J=\frac{1}{2}^-$ and $5/2^+$ for the 110-kev and 197-kev levels [see also $F^{19}(p\,p')F^{19*}$]. The assignment $J=\frac{3}{2}^+$ for the 1570-kev state is obtained from the O^{19} beta decay, from the $\gamma_1-\gamma_2$ angular correlation, and a study of γ_4. If the beta transitions to the 1570- and 197-kev states are allowed and that to the ground state is forbidden, it follows that O^{19} has $J=5/2^+$ (Jo 54g). See also (Ho 50b).

X. $F^{19}(\gamma\,n)F^{18}$ $Q_m=-10.408$

Discontinuities in the activation curve are observed at several γ-ray energies in the range $E_\gamma=10$ to 15 Mev [(Go 54f) and (Ta 54)] [see Table II(19)]. A "giant" resonance appears at $E_\gamma=22.2$ Mev, $\Gamma=5.6$ Mev, integrated cross section = 77 Mev-mb [(Fe 54): see also (Ho 52a)]. See also (Pe 52e), (Pe 53c), and (Sc 54).

XI. $F^{19}(\gamma\,2n)F^{17}$ $Q_m=-19.567$

See (Ho 52a).

XII. $F^{19}(n\,n')F^{19*}$

For $E_n<2.0$ Mev, gamma rays are observed with $E_\gamma=110$, 200, and 1380 kev. The threshold for the 1380 kev γ ray is at $E_n\sim1.7$ Mev, indicating that it arises from the 1.57-Mev, rather than from the 1.35-Mev, state. The excitation functions for the 110-kev and 200-kev gamma rays are consistent with $J=\frac{1}{2}^-$ and $5/2^+$ for the 0.110-Mev and 0.197-Mev states of F^{19} [J. M. Freeman, private communication]: (Va 54b) find the threshold for $E_\gamma=1.37$-Mev radiation to be at $E_p=1.57$ Mev.

At $E_n=2.5$ Mev, gamma rays are observed with $E_\gamma=110\pm1$, 197 ± 2, 1234 ± 20, 1349 ± 15, 1460 ± 30, and (1560 ± 30) kev. The upper limit to the intensity of the cascade decay of the 0.2-Mev state is 2 percent of the direct ground-state transition [(Da 53c) and R. B. Day, private communication]. See also F^{20}.

XIII. $F^{19}(p\,p')F^{19*}$

In the range $E_p=0.6$ to 1.9 Mev, two inelastic groups appear, corresponding to F^{19} levels at 110 and 197 kev [(Pe 54b), (Pe 54d), (Ba 55), and (Mi 55)]. See Table III(19). Ground-state transitions are observed for both levels; the intensity of the 197–110-kev cascade is less than 1 percent of the 197-kev transition (Ba 55). The mean lives, measured by the recoil technique, are $(1.0\pm0.25)\times10^{-9}$ sec for the 110-kev state and 0.8×10^{-7} sec (with an uncertainty of a factor of two) for the 197-kev state [(Th 54): compare $O^{19}(\beta^-)F^{19}$]. These lifetimes limit the 197-kev transition to $E2$ or faster, and the 110-kev transition to $E1$ or $M1$ [(Ba 55) and (Sh 54e)]. The K-shell internal conversion coefficients agree within experimental error, ±25 percent, with an $E1$ assignment for the 110-kev transition and with $E2$ for the 197-kev transition. Since the ground state has $J=\frac{1}{2}^+$, these results indicate $J=\frac{1}{2}^-$ or $\frac{3}{2}^-$ for the 110-kev state and $J=5/2^+$ for the 197-kev state (Mi 55). If the 197-kev state were $J=\frac{3}{2}^+$, the $M1$ transition would be expected to outweigh the $E2$ by a factor $\sim10^4$. If the 110-kev state were $J=\frac{3}{2}^-$, the cascade transition would be $E1$ and should be $>10^4$ times stronger than observed [(Ba 55) and (Sh 54e)].

The reaction exhibits a number of pronounced resonances (see Ne^{20}); in all cases, the angular distribution of 110-kev γ rays is isotropic, suggesting $J=\frac{1}{2}$ for the 110-kev state. At known $J=2^-$ resonances, the 197-kev radiation has the distribution $1+A\cos^2\theta$, with $A=0.17$ to 0.44 (Ba 55). Such a distribution requires $E2$ radiation, $J=\frac{3}{2}^+$ or $5/2^+$, and excludes $M1$ (Sh 54e). The angular distribution of protons leading to the 197-kev state from 2^- levels of Ne^{20} is consistent with $J=\frac{3}{2}^+$ or $5/2^+$ [(Pe 54b), (Pe 54d), (Ch 54b), and (Sh 54e)]. The assignment $J=5/2^+$ for the 197-kev state is consistent with, and the assignment $J=\frac{1}{2}^-$ for the 110-kev state is required by, the Coulomb excitation results. See $F^{19}(\alpha\,\alpha')F^{19*}$.

At $E_p=8$ Mev, proton groups are observed corresponding to states of F^{19} at 1.37, 1.59, 2.82, 3.94, 4.06, 4.41, 4.48, 4.59, and 4.76 Mev. No other groups of comparable intensity are observed for $E_x<6.7$ Mev (Ar 52e). See also (Ch 54d) and (Co 52g).

TABLE II(19). Discontinuities in $F^{19}(\gamma\,n)F^{18}$ cross section.

$E\gamma$ (Mev)[a]	$E\gamma$ (Mev)[b]	Yield (Mev-mb)
10.6		
10.9	11.0	0.2
11.2		
11.5	11.5	0.3
11.9	11.9	0.9
12.2		
15.3	15.3	0.5

[a] (Ta 54): F^{18} activity.
[b] (Go 54f): neutron yield. Yields are integrated cross sections for individual levels.

TABLE III(19). Energies of the first two excited states of F^{19}.

a	b	c	d	e	f	g
108.8 ± 0.8	110 ± 1	109.1 ± 1.0	110 ± 1	113 ± 2	112 ± 1	111.5 ± 1.5
196.0 ± 1.4	197.5 ± 1.5	196.8 ± 1.5	197 ± 2	196 ± 2	195 ± 1.5	199.6 ± 1.5

[a] (Pe 54d): from inelastic protons, mag. spectrometer.
[b] (Ba 55): $F^{19}(p\,p')F^{19*}$, γ rays.
[c] (Mi 55): $F^{19}(p\,p')F^{19*}$, internal conversion.
[d] R. B. Day, private communication: $F^{19}(n\,n')F^{19*}$, γ rays.
[e] (He 54b) and (Te 54b): $F^{19}(\alpha\,\alpha')F^{19*}$, γ rays.
[f] (Jo 54): $F^{19}(\alpha\,\alpha')F^{19*}$, γ rays.
[g] (Jo 54g): O^{19} decay, γ rays.

XIV. $F^{19}(d\,d')F^{19*}$

At $E_d=1.05$ Mev, γ rays are observed from the excitation of the 0.11- and 0.20-Mev states of F^{19} (Th 54d).

XV. $F^{19}(\alpha\,\alpha')F^{19*}$

Gamma radiation of energy 110 kev and 197 kev [see Table III(19)] is observed for $E_\alpha=0.6$ to 3.5 Mev [(He 54b), (Sh 54e), (Jo 54), and (Te 54b)]. The excitation function is characterized by a slow increase with energy over the entire range, with resonance structure superimposed for $E_\alpha>2$ Mev. The shape of the rise [(He 54b), (Sh 54e), (Jo 54), and (Te 54b)], the absolute cross sections at low energies, and the γ-ray angular distributions agree well with Coulomb excitation, assuming $E1$ and $E2$ excitation for the 110- and 197-kev levels respectively, and the derived transition probabilities are in satisfactory agreement with direct lifetime measurements (Sh 54e); see $F^{19}(p\,p')F^{19*}$. See also (Te 54) and (Sh 54c).

XVI. $Ne^{19}(\beta^+)F^{19}$ $Q_m=3.256$

See Ne^{19}.

XVII. $Ne^{21}(d\,\alpha)F^{19}$ $Q_m=6.434$

$Q_0=6.432\pm0.010$ Mev [(Mi 52); mag. spectrograph].

At $E_d=2.13$ Mev, alpha-particle groups are observed corresponding to excited states of F^{19} at 113 ± 8 and 192 ± 12 kev (Mi 52).

Ne^{19}

(Fig. 36)

I. $Ne^{19}(\beta^+)F^{19}$ $Q_m=3.256$

The positron end point is 2.18 ± 0.03 Mev (Sc 52a). The half-life is 18.5 ± 0.5 sec (Sc 52a), 20.3 ± 0.5 sec

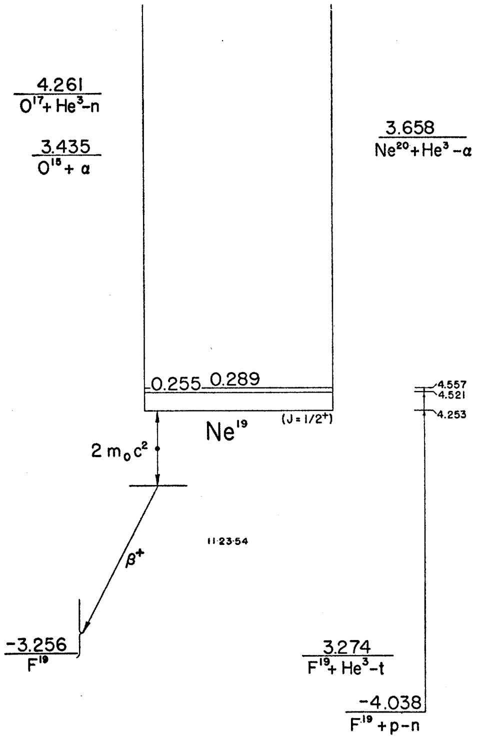


FIG. 36. Energy levels of Ne^{19}: for notation, see Fig. 1.

(Wh 39). The absence of low-energy γ rays (see F^{19}) indicates that the transition takes place to the ground state, $J=\frac{1}{2}+$, of F^{19}: $\log ft=3.30$; $\log ft$ for the 110-kev, $J=\frac{1}{2}-$, state of F^{19} is ≥ 6.0; $\log ft$ to the 200-kev, $J=5/2+$, state is ≥ 5.5. It follows that the ground state of Ne^{19} is $J=\frac{1}{2}+$ (Jo 54g).

The spectrum of Ne^{19} recoils suggests that the Fermi part of the beta interaction is scalar [(Al 54) and (Ma 54l)].

II. $O^{16}(\alpha\, n)Ne^{19}$ $\quad Q_m=-12.162$

See (Te 47).

III. $F^{19}(p\, n)Ne^{19}$ $\quad Q_m=-4.038$

The threshold for the ground state is 4.253 ± 0.005 Mev (Wi 52a). Slow neutron thresholds are observed corresponding to states of Ne^{19} at 255 ± 5 and 289 ± 5 kev (Cook, Marion, and Bonner, private communication).

IV. $Ne^{20}(\gamma\, n)Ne^{19}$ $\quad Q_m=-16.908$

See Ne^{20}.

O^{20}

(Not illustrated)

Mass of O^{20}

(Ba 39e) calculates the mass of O^{20} to be 20.0168 amu; mass defect = 15.6 Mev. By an extrapolation from heavier $A=4n$ isobars, (Sh 54d) predict a mass difference $O^{20}-F^{20}=7.4$ Mev, mass defect $O^{20}=13.3$ Mev. We adopt: O^{20} mass defect $=13.3\pm 2$ Mev. Then O^{20} would be stable to neutron emission by ~ 4 Mev.

O^{20} has not been observed. Two possible reactions leading to O^{20} are $O^{18}(t\, p)O^{20}$ ($Q_m=-0.5$), $Ne^{22}(n\, He^3)O^{20}$ ($Q_m=-22$).

F^{20}

(Fig. 37)

I. $F^{20}(\beta^-)Ne^{20}$ $\quad Q_m=7.052$

See Ne^{20}.

II. $O^{18}(d\, n)F^{19}$ $\quad Q_m=5.729$ $\quad E_b=12.329$

See F^{19}.

III. $O^{18}(d\, p)O^{19}$ $\quad Q_m=1.731$ $\quad E_b=12.329$

See O^{19}.

IV. $O^{18}(d\, \alpha)N^{16}$ $\quad Q_m=4.24$ $\quad E_b=12.329$

See N^{16}.

V. $F^{19}(n\, \gamma)F^{20}$ $\quad Q_m=6.600$

The thermal cross section is 9.4 ± 2 mb (Se 47). A γ ray of energy 6.63 ± 0.03 Mev is observed, with an intensity of 0.35 ± 0.10 photon per capture (Ki 51a). Two resonances for F^{20} production are observed at $E_n=280$ and 590 kev, with widths ~ 20 kev and peak cross sections of 1.2 and 1.3 mb, respectively; $\omega\Gamma_\gamma\sim 15$ ev [(He 50b) and (Hu 54a)].

VI. $F^{19}(n\, n)F^{19}$ $\quad E_b=6.600$

The coherent scattering cross section is 3.8 ± 0.3 b; the total cross section (epithermal, bound) is 4.0 ± 0.1 b (Hu 52e). The cross section is constant at 3.8 b from 600 ev to 20 kev (Hu 54a). Resonances in the total cross section are listed in Table I(20). If the 100-

TABLE I(20). Resonances in $F^{19}(n\, n)F^{19}$.

E_n (kev)	Γ (kev)	σ_{max} (bn)	F^{20*}
28.2[a]	3	29.0	6.63
49.7[a]	5	30.0	6.65
99.5[a]	16	25.0	6.70
275[b]	30	10.0	6.86
340[b]	$\sim$200	8.0	6.92
420[b]	25	8.8	7.00
510[b]	35	5.7	7.08
600[b]	30	6.0	7.17
950[c]		3.3	7.50
1240[c]		3.0	7.78
1660[c]		3.4	8.18
2040[c]		3.2	8.54

[a] (Hi 54d). Cross sections and widths estimated from published curves of (Hu 54a). See, however, (Hi 54d).
[b] (Bo 50f).
[c] (Wi 51) and (Hu 54a).

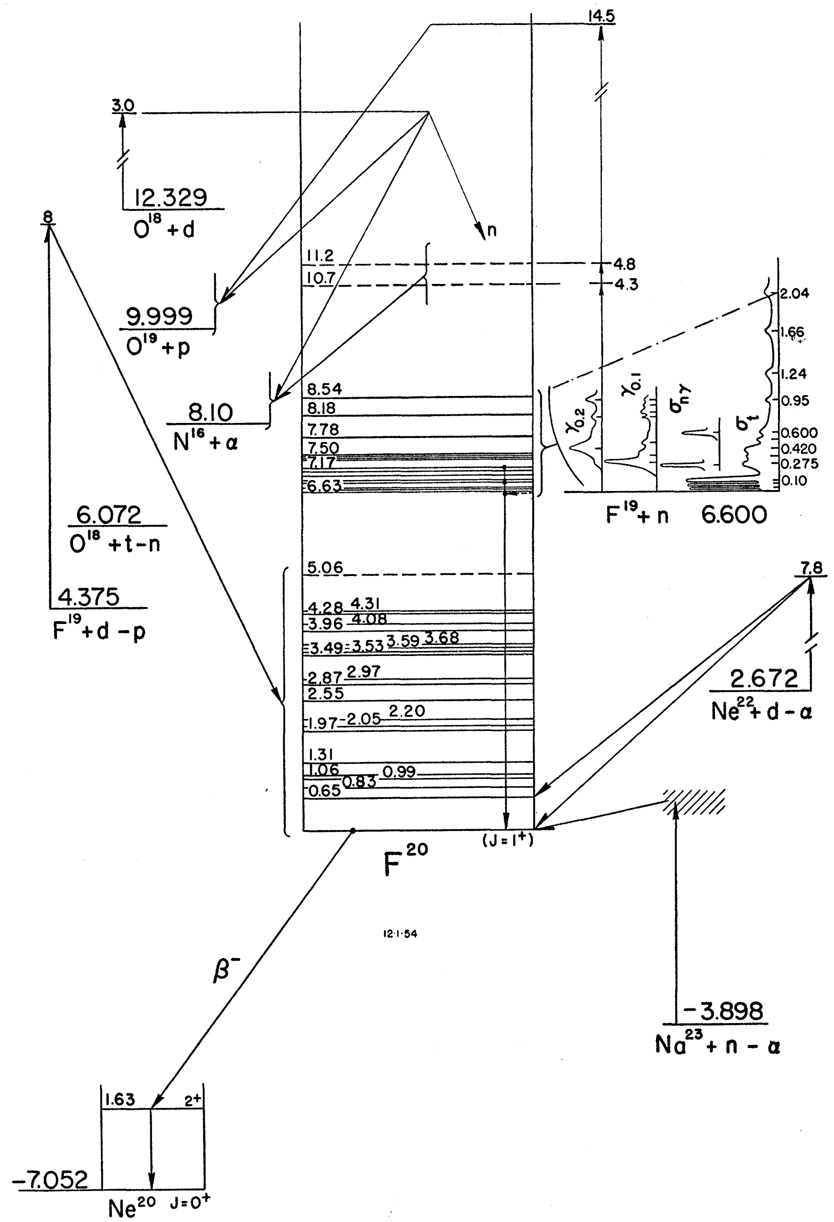


FIG. 37. Energy levels of F^{20}: for notation, see Fig. 1. The proton binding energy is 10.599 Mev.

kev resonance is assumed to arise from s-wave neutrons forming a state of $J=1$, the reduced width is 0.006 of the sum-rule limit [(Bo 50f) and (Vo 54)]. The average total cross section has been measured for $E_n=3$ to 14 Mev; it decreases from 2.2 b at 3 Mev to 1.7 b at 6 Mev and thereafter remains approximately constant at that value (Ne 54b). At $E_n=14$ Mev, $\sigma_t=1.70\pm0.05$ b (Co 52h). At 19.0 Mev, $\sigma_t=1.84\pm0.06$ b (Da 53f).

VII. $F^{19}(n\,n')F^{19*}$ $\qquad E_b=6.600$

Observed resonances in the yield of 0.1- and 0.2-Mev γ radiation (see F^{19}) for $E_n<1$ Mev are exhibited in Table II(20). A satisfactory fit to the excitation function for $E_n<0.35$ Mev is obtained on the assumption of an s-wave resonance at $E_n=0.100$ Mev and a p-wave resonance at $E_n=0.270$ Mev (J. M. Freeman, private communication). The cross section for production of 1.3-Mev radiation is 0.52 ± 0.18 b at $E_n=2.5$ Mev (Gr 51a). See also (Va 54b) and (Da 53c).

VIII. $F^{19}(n\,2n)F^{18}$ $\qquad Q_m=-10.408 \qquad E_b=6.600$

At $E_n=14.5$ Mev, the cross section is 60.6 ± 20 mb (Pa 53a). See also (Aj 52c).

IX. $F^{19}(n\,p)O^{19}$ $\qquad Q_m=-3.999 \qquad E_b=6.600$

At $E_n=14.5$ Mev, the cross section is 135 ± 50 mb (Pa 53a). See also (Ho 50b).

TABLE II(20). Resonances in $F^{19}(n\,n'\gamma)F^{19}$.
(J. M. Freeman, private communication)

E_r[1] (kev)	σ[a] (0.1-Mev γ) (bn)	E_r[2] (kev)	σ[a] (0.2-Mev γ) (bn)	F^{20*}
270	5.1	300(?)	0.7	6.86
390(?)	1.5	420	2.0	7.00
500(?)	1.1			7.08(?)
780(?)	0.6	780	0.8	7.34
830	0.8			7.39
880	0.7			7.44
950	0.7	950	1.3	7.50

[a] Cross sections ±40 percent.

X. $F^{19}(n\,\alpha)N^{16}$ $Q_m=-1.49$ $E_b=6.600$

Resonances are reported at $E_n=4.3$ and 4.8 Mev by (Wi 37e). See also N^{16}.

XI. $F^{19}(d\,p)F^{20}$ $Q_m=4.375$

Energy levels of F^{20} derived from the proton groups [see, in particular, (Wa 52b)] are tabulated in (Aj 52c). At $E_d=3.6$ Mev, the angular distribution of the ground-state protons, analyzed by stripping theory, indicates a mixture of $l_n=0$ and 2 and therefore $J=1^+$ for the ground state of F^{20}. The 0.65- and 2.05-Mev levels (unresolved) appear to be formed by $l_n=2$: $J=1,\ 2,\ 3^+$; the 3.49- and 3.53-Mev levels (unresolved) by $l_n=0$: $J=0,\ 1^+$. Possible configuration assignments consistent with these data and with the β decay are discussed (Br 53c). See also (Bl 53).

XII. $Ne^{22}(d\,\alpha)F^{20}$ $Q_m=2.672$

Alpha-particle groups have been observed at $E_d=7.8$ Mev corresponding to the ground state and to a level at 0.57 ± 0.13 Mev (Mi 51d).

XIII. $Na^{23}(n\,\alpha)F^{20}$ $Q_m=-3.898$

See (Je 50d).

Ne^{20}

(Fig. 38)

I. $O^{16}(\alpha\,n)Ne^{19}$ $Q_m=-12.162$ $E_b=4.746$

See (Te 47).

II. $O^{16}(\alpha\,p)F^{19}$ $Q_m=-8.124$ $E_b=4.746$

See F^{19}.

III. $O^{16}(\alpha\,pn)F^{18}$ $Q_m=-18.532$ $E_b=4.746$

See (Te 47).

IV. $O^{16}(\alpha\,\alpha)O^{16}$ $E_b=4.746$

The elastic scattering has been studied in the range $E_\alpha=0.9$ to 4.0 Mev by (Ca 53b) and from $E_\alpha=3.9$ to 6.9 Mev by (Fe 40). Observed resonances and assignments are exhibited in Table III(20).

TABLE III(20). Levels in Ne^{20} from $O^{16}(\alpha\,\alpha)O^{16}$.

E_r (Mev)	Γ_λ(lab) (kev)	$\gamma^2/(3\hbar^2/2\mu a)$	Ne^{20*}	$J,\ \pi$
2.490[a]	24	0.22	6.738	0^+
3.045	10	0.36	7.182	3^-
3.090	5	0.011	7.218	0^+
3.380	10	0.047	7.450	2^+
3.885	3	0.006	7.854	2^+
5.6			9.2	(1^-)
6.7			10.1	(1^-)

[a] The first five values are from (Ca 53b), and H. T. Richards, private communication; the last two are from (Fe 40).

V. $F^{19}(p\,\gamma)Ne^{20*}$ $Q_m=12.870$

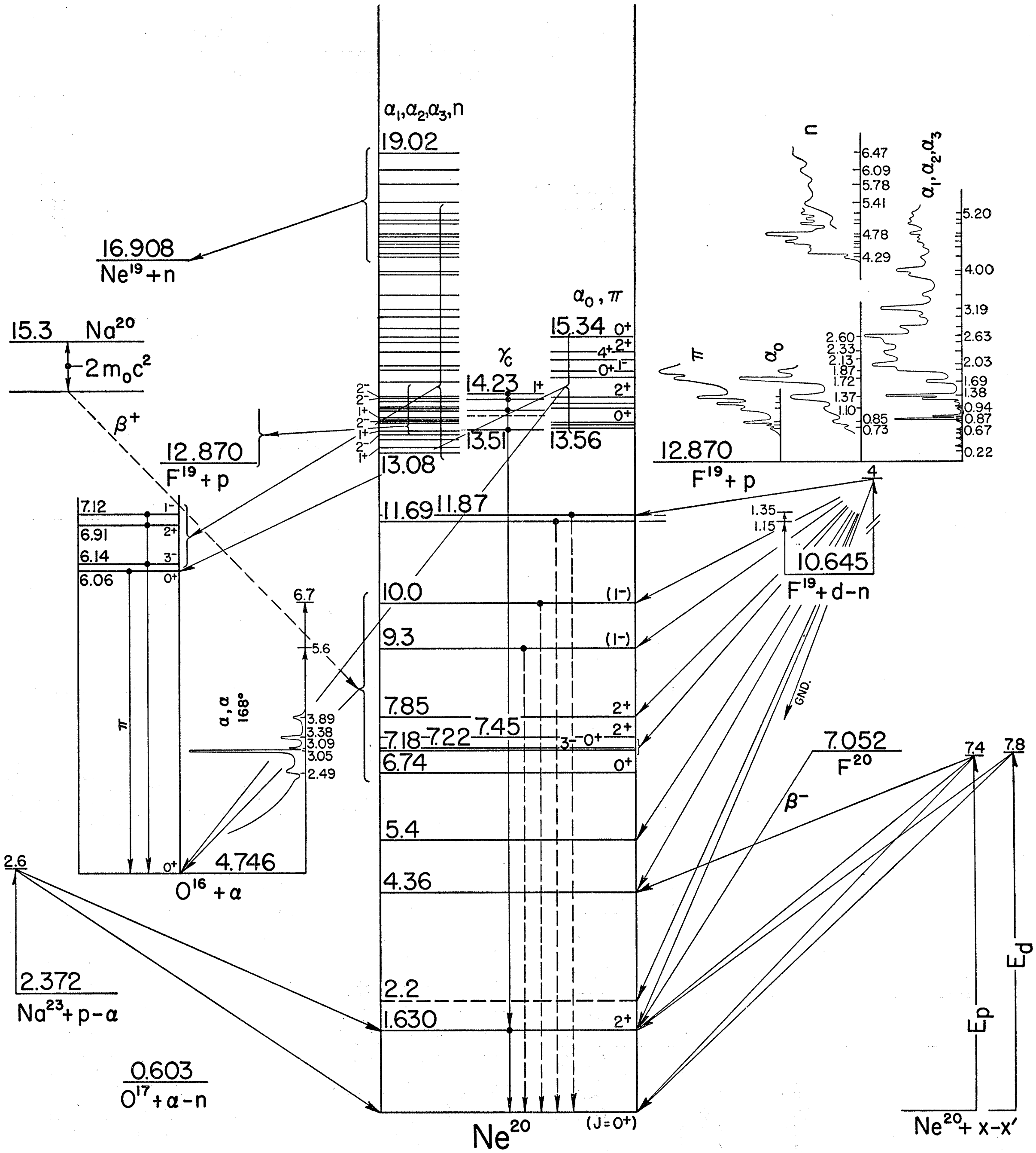
Resonances for capture radiation are listed in Table IV(20). In all cases the radiation is of about 12-Mev energy, indicating transitions to the 1.64-Mev, $J=2^+$ state of Ne^{20} (Si 54). For the $E_p=669$-kev resonance this assumption is confirmed by direct measurement of the γ-ray energy, $E_\gamma=12.09\pm0.28$ Mev (Ca 51a), and the observation of 1.66 ± 0.02-Mev radiation in coincidence, to the extent of approximately one quantum per capture (Jo 52e). The fraction of capture processes at this resonance is 1.72 ± 0.25 percent of the $(6+7)$ Mev radiation [from $F^{19}(p\,\alpha\gamma)O^{16}$] (Ca 51a). The angular distribution of the hard radiation is isotropic within 2 percent (Ha 54e). The γ-γ angular correlation is $1-(0.39\pm0.08)\cos^2\theta$, consistent with $J=1$ for the $E_p=669$-kev state [known to be $J=1^+$ from $F^{19}(p\,\alpha\gamma)O^{16}$], $J=1$ or 2 for the 1.63-Mev state, and $J=0$ for the ground-state; the high-energy component is dipole (Clegg, Jones, and Wilkinson, private communication). It is not clear why the direct ground-state transition does not occur.

A search for resonant capture radiation at $E_p=598$ kev ($J=2^-$ level) and $E_p=874$ kev ($J=2^-$) leads to an upper limit of 0.04 percent and 0.05 percent, respectively for the fraction of such transitions relative to $F^{19}(p\,\alpha\gamma)O^{16}$; $\Gamma_\gamma<15$ and <2 ev. For the upper level, assumed to be $T=0$, the expected $E1$ transition is inhibited by a factor of at least 30, presumably by the isotopic spin selection rule (Wi 53g). (Ha 54e) report weak resonances at $E_p=874$, 935, 1280, 1355, and 1380 kev [yield relative to $F^{19}(p\,\alpha\gamma)O^{16}\sim0.1$ percent] as well as a relatively strong resonance at $E_p=980$ kev, in addition to those found by (Si 54). See also (Wi 53c).

TABLE IV(20). Resonances in $F^{19}(p\,\gamma)Ne^{20*}$ (Si 54).

E_p (kev)	Γ (kev)	Yield[a] (percent)	σ (mb)	Ne^{20*}
669	7.5	1.8	0.48	13.505
1092	<1.2	1.3	>0.05	13.907
1324	4.0	>1.5[b]	0.081	14.129
1431	15.7	>1.5[b]	0.19	14.230

[a] Relative to $F^{19}(p\,\alpha\gamma)O^{16}$.
[b] No resonance is observed for $F^{19}(p\,\alpha\gamma)O^{16}$.



12·1 54

FIG. 38. Energy levels of Ne^{20}: for notation, see Fig. 1.

VI. (a) $F^{19}(p\ p)F^{19}$ $E_b = 12.870$
(b) $F^{19}(p\ p')F^{19*}$

The elastic scattering exhibits marked anomalies at energies corresponding to the $F^{19}(p\ \alpha\gamma)O^{16}$ resonances at $E_p=669$, 874, 935, 1355, 1381, to the $F^{19}(p\ \gamma)Ne^{20}$ resonance at 1431 kev and to the $F^{19}(p\ \alpha_0)O^{16}$ resonance at $E_p=845$ kev. Unresolved structure is also evident near $E_p=1700$ kev. Analysis of the angular distributions confirms the assignment [see $F^{19}(p\ \alpha)O^{16}$] of $J=1^+$ for the $E_p=669$-kev and 935-kev resonances and permits assignments of $J=0^+$ for the 845-kev resonance, of $J=2^-$ (1^- not excluded) for $E_p=1381$ kev, and of $J=1^+$ for $E_p=1431$ kev [(We 54a), (We 55), and (Ba 55a): see also (Pe 54b)].

Resonances for inelastic scattering involving the 110-kev, $J=\frac{1}{2}^-$, and 197-kev, $J=5/2^+$, states of F^{19} are listed in Table V(20). In general, the resonances observed are identical with those reported for other $F^{19}+p$ reactions, although the relative intensities differ greatly. The known $J=1^+$ levels formed by s-wave protons at $E_p=669$, 935, and 1431 kev lead to the 110-kev state of F^{19} in preference to that at 197 kev, while for the p-wave, $J=2^-$, 873-kev resonance the reverse is true; the $J=2^-$, 1355-, and 1381-kev resonances lead to both. The nonresonant yield of the 197-kev radiation appears to be mainly due to Coulomb excitation, while that of the 110-kev radiation suggests a contribution from broad, unresolved s-wave resonances [(Ba 55) and (Pe 54b): for angular distributions, see F^{19}]. Cross sections [see Table V(20)] and angular distributions of the inelastic protons at several resonances are reported by (Pe 54d) [see F^{19} and (Ch 54b)].

VII. $F^{19}(p\ \alpha)O^{16}$ $Q_m=8.124$ $E_b=12.870$

Five α-particle groups are reported. All show resonance effects with relative intensities varying greatly with bombarding energy. The long-range group (α_0) leaves O^{16} in the ground state ($J=0^+$); the next longest (α_π) results in the formation of a $J=0^+$ nuclear pair-emitting state at 6.06 Mev, while the three remaining groups ($\alpha_1,\alpha_2,\alpha_3$) lead to γ-ray emitting states at 6.14 ($J=3^-$), 6.91 ($J=2^+$), and 7.12 Mev ($J=1^-$). Resonances for α_0 and α_π [Tables VI(20) and VII(20)] are generally identical and different from those for α_1, α_2, α_3 [Table VIII(20)]. The resonances for α_0 and α_π are required to have even J and even parity or odd J and odd parity, while the α_1, α_2, and α_3 resonances, insofar as their assignments are known, are all odd-even or even-odd.

At $E_p=224$ kev, the angular distribution of 6-Mev radiation is anisotropic (Ne 54d). The 6–7-Mev radiation produced at the $E_p=340$, 483, 669, and 935-kev resonances is isotropic [(De 49d), (Da 51b), (Sa 52), and (Sa 53c)]. At $E_p=340$, 669, and 935 kev, the $\alpha_1-\gamma$ correlations establish that $J=1^+$ for the corresponding Ne^{20} levels [(Ar 50), (Ba 50f), and (Se 52b)]: this assignment is confirmed for the 935-kev resonance by the α_1-angular distribution (Pe 54d). Correlations and angular distributions at the $E_p=874$-kev resonance establish $J=2^-$ for this level [(Se 52b) and (Pe 54d)], and the observed polarization of the γ rays is consistent with this assignment (Fa 53a). The level corresponding to $E_p=598$ kev is assigned $J=2^-$ by (Ch 50a) on the basis of γ-ray angular distributions; this assignment is confirmed by J. Seed and G. Dearnley; see (Wi 53g). Levels corresponding to resonances at $E_p=1290$ and 1355 kev are assigned $J=3^+$ by (Ch 50a). Angular distributions of the α groups at $E_p=1290$ kev are not inconsistent with $J=3^+$, but lead to $J=2^-$ for the 1355-kev resonance (Pe 54d). Gamma-ray angular distributions at $E_p=1381$ kev indicate a pronounced anisotropy, and are consistent with $J=2^-$ [(Sa 53c); see also (Pe 54d) and $F^{19}(p\ p)F^{19}$]. This is evidently not the same as the 1.38-Mev α_0 resonance.

An analysis of certain Ne^{20} levels into partial widths, based on information from $F^{19}(p\ p)$, $(p\ p')$, $(p\ \gamma)$, and $(p\ \alpha)$ is given by (Ba 55) and (Ba 55a). It is noted that a number of $T=1$ levels may be expected in this region (compare F^{20}). See also (Aj 52c) and (Be 53b).

TABLE V(20). Resonances in $F^{19}(p\ p')F^{19*}$ (Ba 55).

E_p (kev)	J, π	Γ (kev)	$\sigma(\gamma_{110})$ (mb)	$\sigma(\gamma_{197})$ (mb)
669	1^+	7.5	20 ± 3	(<0.2)
780		~10	(<0.2)[a]	~5
831		8.3	(<0.2)	~8
845	0^+	30	~2	(<0.3)
873	2^-	5.2	(<0.3)	87 ± 20
900		4.8	(<0.3)	~20
935	1^+	8.0	147 ± 22	(<1)
1092		<1.2	>13	>100
1137		3.7	(<0.4)	~20
~1250		~80	17 ± 3	(<1)
1290		19	(<1)	3 ± 1
1355	2^-	4.5	17 ± 4	27 ± 7
1381	2^-	15	26 ± 4	40 ± 6[b]
1431	1^+	14.6	189 ± 30[c]	7 ± 2[d]
1620 ± 10		~5	12 ± 3	(<2)
1670 ± 10			3	(<2)
1710 ± 10			36 ± 7	17 ± 5

[a] Values in parentheses are upper limits of resonance contributions.
[b,c,d] (Pe 54d) report 42.7 ± 4, 187 ± 15, and 7 ± 2 for these cross sections, from the inelastic proton yields.

TABLE VI(20). Resonances for ground-state α particles (α_0) in $F^{19}(p\ \alpha)O^{16}$.[a]

E_p (kev)	Γ (kev)	σ (mb)	J, π	Ne^{20}
720	35	0.2		13.56
780	<10	>0.3		13.62
840	25	0.5	0^+[b]	13.68
1100	~60	2		13.92
1370	~25	16		14.17
1367	54	46.5	2^+	14.17
1720	142	54.7	0^+	14.50
1865	134	77.3	1^-	14.64
2125	<80	6.7	4^+	14.89
2325	<80	22.6	2^+	15.08
2600	~300	37.3	0^+	15.34

[a] The first five items are from A. L. Schardt and W. A. Fowler (private communication); cross sections include only the resonant part. See also (Ch 50). The remainder are from (Pa 53), (Pa 53c), and R. L. Clarke, private communication.
[b] From $F^{19}(p\ p)F^{19}$.

TABLE VII(20). Nuclear pair resonances (α_π) in $F^{19}(p\ \alpha)O^{16}$ [(Ch 50), (Ph 51a), and (De 54a)].

E_p (kev)	Γ^a (kev)	Γ^b (kev)	σ^a (mb)	Ne^{20*}
710		35		13.55
780				13.61
842	30	24	1.2	13.67
1130	60	43	1.0	13.94
1236	75	58	2.5	14.04
1367	25	26	8.5	14.17
(1.75)[b]				14.53
(1.9)				14.67

[a] (Ch 50).
[b] (Ph 51a).

VIII. $F^{19}(p\ n)Ne^{19}$ $Q_m=-4.038$ $E_b=12.870$

Observed resonances are listed in Table IX(20) [(Wi 52a), and (Bl 51a)].

IX. $F^{19}(d\ n)Ne^{20}$ $Q_m=10.645$

Neutron groups corresponding to levels at 1.5, 2.2, 4.2, 5.4, 7 1, 7.8, 9.0, and 10.1 Mev are reported [(Bo 40b) and (Po 42)]. Gamma rays of energy 9 34±0.1, 9.97±0.1, 10.61±0.1, and 11.51±0.2 Mev are reported by Bent, Bonner, and Sippel (private communication). See also (Te 51a). Thresholds for γ radiation are observed at $E_d=1.15$ and 1.35 Mev, corresponding to excited states of Ne^{20} at 11.69 and 11.87 Mev (Bu 54b). See also (Aj 52c) and (Th 54d). At $E_d=4$ Mev, the angular distribution of ground-state neutrons, analyzed by stripping theory, indicates $l_p=0$ and therefore the same parity for Ne^{20} and F^{19}, $J=0$ or 1 for the former (Br 52b).

X. $F^{20}(\beta^-)Ne^{20}$ $Q_m=7.052$

The decay is to the 1.6-Mev state of Ne^{20}: $E_\beta(\max)=5.419\pm0.013$ Mev (Wo 54b), 5.406±0.017 Mev (Al 52a). The energy of the subsequent gamma ray is 1.627±0.005 (Wo 54b), 1.631±0.006 Mev (Al 52a). The relative intensity of the ground-state transition is $<3.2\times10^{-4}$ (Wo 54b). The Fermi plot is straight to $E_\beta=1$ Mev. With a half-life of 11.4 sec, logft (excited state) = 4.99, logft (ground state) $\gtrsim 9$ (Wo 54b).

XI. $Ne^{20}(\gamma\ n)Ne^{19}$ $Q_m=-16.908$

A giant resonance is observed at 21.5 Mev with a width of 6.6 Mev and a peak cross section of 7.3 mb (Fe 54).

TABLE VIII(20). Resonances for 6–7 Mev γ rays[a] $(\alpha_1,\alpha_2,\alpha_3)$ in $F^{19}(p\ \alpha)O^{16}$.

Note added in proof.—Recent work indicates that the $E_p=1355$ and 1381-kev resonances are actually located at $E_p=1346$ and 1372 kev: see (Ba 55).

E_p (kev)[b]	Γ (kev)[c]	σ (mb)[c]	σ (mb)[b]	J, π	Ne^{20*}
224.4[d]	1.0[d]		>0.2		13.083
340.4[d]	2.9[d]	59	160	1^{+}[g]	13.193
483.1[d]	2.2[d]	29	>32		13.329
598	37	4	7.1	(2^-)[h]	13.438
669	7.5	25	57	1^+	13.505
831	8.3	7	19		13.659
873.5[e]	5.2	250	540	2^-	13.700
900	4.8	9	23		13.725
935.3	8.0	88	180	1^+	13.759
1092	<1.2[b]	≥4	>13		13.907
1137	3.7	8	15		13.950
1176	~130	7	19		13.987
1290	19.2	19	29	(3^+)	14.096
1355	4.5[f]	79	89	2^-	14.157
1381	15.0	190	300	2^-	14.182

[a] For $E_p>1.6$ Mev, see (Wi 52a).
[b] (Ch 50).
[c] (Bo 48c).
[d] (Hu 52f) and (Hu 53d).
[e] (He 49): ±0.8 kev. (Fa 53) find 872.5±1.8 kev.
[f] (Ba 55) and (Bo 48c).
[g] (Ch 50a), (Ar 50) and (Ba 50f).
[h] (Ch 50a) and (Wi 53g).

TABLE IX(20). Resonances in $F^{19}(p\ n)Ne^{19}$.[a]

E_p (Mev)	Γ (kev)	Ne^{20*}
4.29	45	16.95
4.46	80	17.11
4.49	20	17.14
4.57	20	17.21
4.62	60	17.26
4.71	25	17.35
4.78	45	17.41
4.99	20	17.61
5.07	30	17.69
5.20	70	17.81
4.84		
5.41		18.01
5.78		18.36
6.09		18.65
6.47		19.02

[a] The first ten values are from (Wi 52a), the others are from (Bl 51a), broad resonances, stacked-foil method.

XII. $Ne^{20}(\gamma\ \alpha)O^{16}$ $Q_m=-4.746$

The reaction has been observed with (Li^7+p) γ rays. The cross section for transitions to the 6- and 7-Mev states of O^{16} is one or two orders of magnitude greater than the cross section for the reaction to the ground state of O^{16} [(Er 53a) and C. A. Barnes, private communication].

XIII. $Ne^{20}(p\ p')Ne^{20*}$

Inelastic proton groups corresponding to levels at 1.44 and 4.36 Mev are reported by (Co 52g). A 1.64-Mev γ ray is observed for $E_p=2$ to 4 Mev (Co 54). No evidence is found for a level at 2.2 Mev [(Co 52g) and (Co 54)]. Study of the inelastic scattering at $E_p=2.725$ Mev indicates $2\leq J\leq 7$, even parity, for the 1.63-Mev state of Ne^{20} [(Ga 53) and A. Galonsky, private communication]. See also (Ro 53d) and (En 54).

XIV. $Ne^{20}(d\ d')Ne^{20*}$

At $E_d=7.8$ Mev, an inelastic deuteron group is observed corresponding to a state at 1.66±0.02 Mev (Mi 51d). At that energy the cross section is 98 mb for the inelastic group; the angular distribution shows a pronounced forward peak and a secondary maximum near $\theta_{c.m.}=85°$ (Mi 52c).

XV. $Ne^{20}(\alpha\ \alpha)Ne^{20}$

See (En 54): Mg^{24}.

XVI. $Na^{20}(\beta^+)Ne^{20}$ $Q_m=15.3$

The decay proceeds to excited states of Ne^{20} between 6.8 and 10.8 Mev which decay by α-particle emission (Al 50g). The half-life is 0.23±0.08 sec (Sh 51c), 0.385±0.01 sec (Ho 53a). See also (En 54).

XVII. $Na^{23}(p\ \alpha)Ne^{20}$ $Q_m=2.372$

The weighted mean of several Q-value determinations is 2.378±0.003 Mev (Va 54). A γ ray of energy 1.63

± 0.02 (St 54e), 1.629 ± 0.008 Mev (Ne 54e), has been observed as have alphas corresponding to an excited state of Ne^{20} at 1.634 ± 0.004 Mev (Do 53). At a resonance located at $E_p=1.255$ Mev, the $\alpha-\gamma$ correlation permits the unique assignment of $J=1^+$ to the Mg^{24} state and $J=2^+$ to the 1.63-Mev state of Ne^{20} (Se 53b). See also (Ca 54b).

Ne^{21}

(Fig. 39)

I. $O^{18}(\alpha\, n)Ne^{21}$ $Q_m=-0.704$

See (Ro 44a) and (Ho 50b).

II. $F^{19}(d\, n)Ne^{20}$ $Q_m=10.645$ $E_b=17.400$

See (Bu 52c).

III. $F^{19}(d\, p)F^{20}$ $Q_m=4.375$ $E_b=17.400$

See (Sn 50a).

IV. $F^{19}(d\, t)F^{18}$ $Q_m=-4.151$ $E_b=17.400$

See (Kr 41).

V. $F^{19}(d\, \alpha)O^{17}$ $Q_m=10.040$ $E_b=17.400$

See (Bu 38).

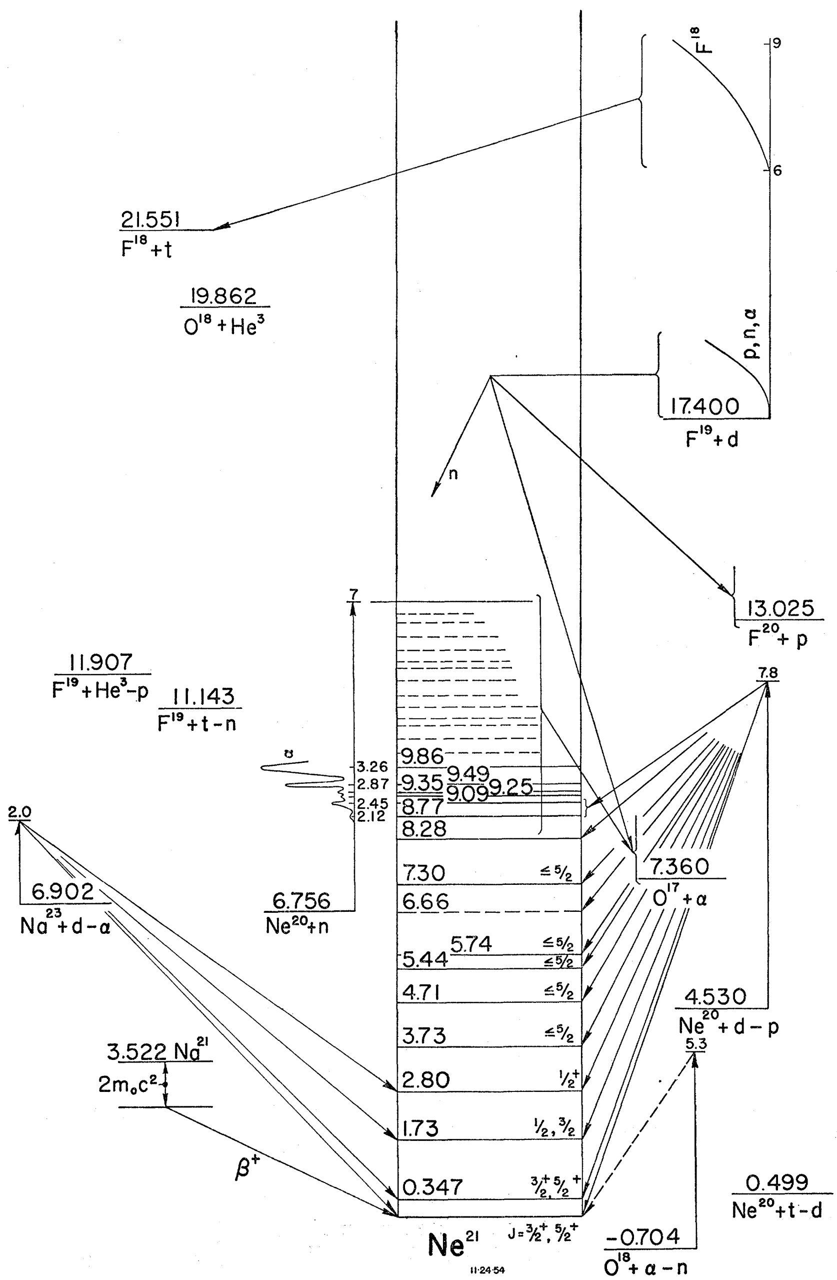


FIG. 39. Energy levels of Ne^{21} for notation, see Fig. 1.

VI. $Ne^{20}(n\ n)Ne^{20}$ $E_b=6.756$

The total cross section for thermal neutrons is 2.79 ±0.14 b (Ca 41); the scattering cross section is 2.4±0.2 b (Ha 50f).

VII. $Ne^{20}(n\ \alpha)O^{17}$ $Q_m=-0.603$ $E_b=6.756$

An excitation function from $E_n=1.8$ to 3.3 Mev indicates resonances at $E_n=2.12$, 2.45, 2.62, 2.72, 2.87, and 3.26 Mev [(Jo 51e); see (Aj 52c)]. Numerous additional resonances, extending to $E_n=7$ Mev, are reported by (Gi 54b: continuous neutron spectrum), and (Fl 53: $d-d$ neutrons). See also (Si 50).

VIII. $Ne^{20}(d\ p)Ne^{21}$ $Q_m=4.530$

$Q_0=4.529\pm0.007$ [(Va 52); mag. spectrometer].
$Q_0=4.526\pm0.009$ [(Ah 54); mag. spectrometer].

Levels derived from proton group observations are listed in Table I(21) [(Ah 54) and (Mi 51d)]. A study of the angular distributions of the proton groups,

TABLE I(21). Proton groups from $Ne^{20}(d\ p)Ne^{21}$.

Ne^{21*} (Mev)[a]	Ne^{21*} (Mev)[b]	J, π[c]	σ (mb)[c]
0	0	3/2, 5/2+	13
0.349±0.006	0.33±0.05	3/2, 5/2+	21
	1.68±0.07	1/2, 3/2	14
2.788±0.008	2.79±0.05	1/2+	50
	3.73±0.06	≤5/2	21
	4.71±0.05	≤5/2	97
	5.44±0.05	≤5/2	38
	5.74±0.05	≤5/2	41
	(6.66±0.09)		
	7.30±0.06	≤5/2	54
	8.28±0.06		
	8.91±0.06		

[a] (Ah 54) and K. Ahnlund, private communication; $E_d=0.875$ Mev.
[b] (Mi 51d); $E_d=7.8$ Mev.
[c] (Mi 52c); angular distributions analyzed by stripping theory.

analyzed by stripping theory, gives J, π assignments for the levels [see Table I(21)]; the ratio of the intensities of the ground and first excited state groups suggests that these states comprise a ^2D term, with $J=\frac{3}{2}$ and 5/2, respectively. At $E_d=8$ Mev, the cross section for the reaction is 500 mb (Mi 52c). See also (Zu 50a).

IX. $Na^{21}(\beta^+)Ne^{21}$ $Q_m=3.522$

The positron end point is $E_\beta(\max)=2.50\pm0.03$ Mev; no γ radiation with $E_\gamma>0.51$ Mev is observed (Sc 52a). The half-life is 22.8±0.5 sec (Sc 52a), 22.9±0.4 sec (Ph 53a), 27 sec (Bo 53d). Based on the first value, $\log ft=3.56$. See also (En 54).

X. $Na^{23}(d\ \alpha)Ne^{21}$ $Q_m=6.902$

Alpha particles are observed corresponding to levels of Ne^{21} at 0.343±0.010, 1.735±0.016, and 2.852±0.021 Mev [(Sp 51a); see also (Fr 51d)].

Ne^{22}

(Fig. 40)

I. $O^{18}(\alpha\ n)Ne^{21}$ $Q_m=-0.704$ $E_b=9.658$

See (Ro 44a) and (Ho 50b).

II. $F^{19}(\alpha\ p)Ne^{22}$ $Q_m=1.703$

Proton groups have been observed corresponding to levels of Ne^{22} at 1.27 and 3.35 Mev [(Fa 54d); see also (Fo 54)]. No evidence is found for an earlier reported level below 1.28 Mev; [see, however, (Hj 52)]. Gamma radiation from the 1.28-Mev level has been observed by (He 54b), (Sh 54e), and (Fo 54) and from levels at 3.3 and 4.9(?) Mev by (Fo 54). The radiation from the 3.3-Mev level to the 1.28-Mev, $J=2^+$, level is three times as probable as the ground-state transition, suggesting $J=1^+$, 1^-, or 2^+ for the 3.35-Mev level (Fo 54).

III. $Ne^{21}(d\ p)Ne^{22}$ $Q_m=8.137$

$Q_0=8.137\pm0.011$ [(Mi 52); mag. spectrometer].

A proton group corresponding to the first excited state has been observed by [(Am 50); $E_x=1.39$ Mev] and [(Zu 50a); $E_x=1.17$ Mev].

IV. $Ne^{22}(\gamma\ n)Ne^{21}$ $Q_m=-10.364$

See (Fe 54).

V. $Ne^{22}(p\ p')Ne^{22*}$

A 1.28-Mev γ ray is observed for $E_p=1.35$ to 4.4 Mev; there is no sign of an earlier reported level at 0.4 Mev (Co 54). See also (He 47).

VI. $Na^{22}(\beta^+)Ne^{22}$ $Q_m=2.841$

The decay proceeds almost entirely to the 1.28-Mev state of Ne^{22}: the half-life is 2.60 years (La 49a);

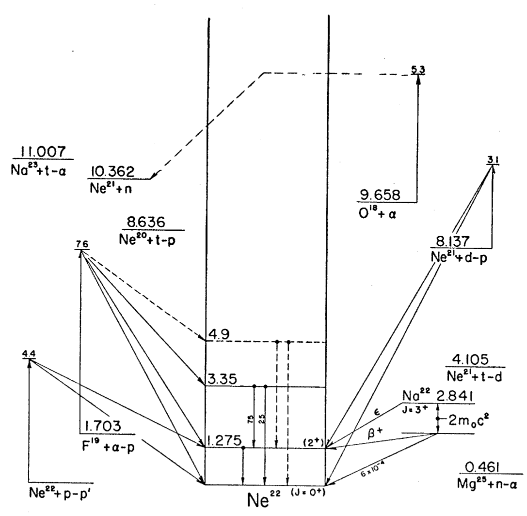


FIG. 40. Energy levels of Ne^{22}: for notation, see Fig. 1.

E_{β^+}(max) = 542±5 kev (Ma 50a), 540±5 kev (Wr 53); the γ-ray energy is 1275.0±0.5 kev (P. Marmier, private communication: magnetic spectrometer). Electron capture occurs in 9.9±0.6 percent of the disintegrations [(Sh 54b) and (Kr 54c)]. Logft for the positrons = 7.39 (Fe 51b); for $K+L$ capture, logft = 7.27 (Ma 54h).

The internal conversion coefficient indicates that the γ transition is probably $E2$, and hence that the 1.28-Mev state has $J=2^+$ (Hi 53b). Since Na^{22} has $J=3$, and presumably even parity, the beta transition should be allowed. The spectrum follows the allowed shape down to 25 kev (Ma 50a) and the $\beta-\gamma$ correlation is isotropic (St 51h). The capture ratio appears to exclude l-forbiddenness as an explanation of the large ft value (Sh 54b). The direct ground-state transition has been observed; logft ~13. The shape is consistent with the D_2 spectrum (Wr 53). See also (Ba 54e), (En 54), and (Zw 54).

Ne^{23}

(Fig. 41)

I. $Ne^{23}(\beta^-)Na^{23}$ $Q_m=4.388$

The decay is complex; the ground-state transition with E_β(max) = 4.21±0.015 Mev (compare with Q_m) comprises 93 percent while a 7 percent branch with E_β(max) = 1.18±0.04 Mev proceeds to an excited state of Na^{23} [perhaps the state at 3.01 Mev: see (En 54) for the Na^{23} level diagram]. The half-life is 40.2±0.04 sec; logft = 4.94 and 3.78 for the ground state and excited state transitions, respectively [(Br 50c); see

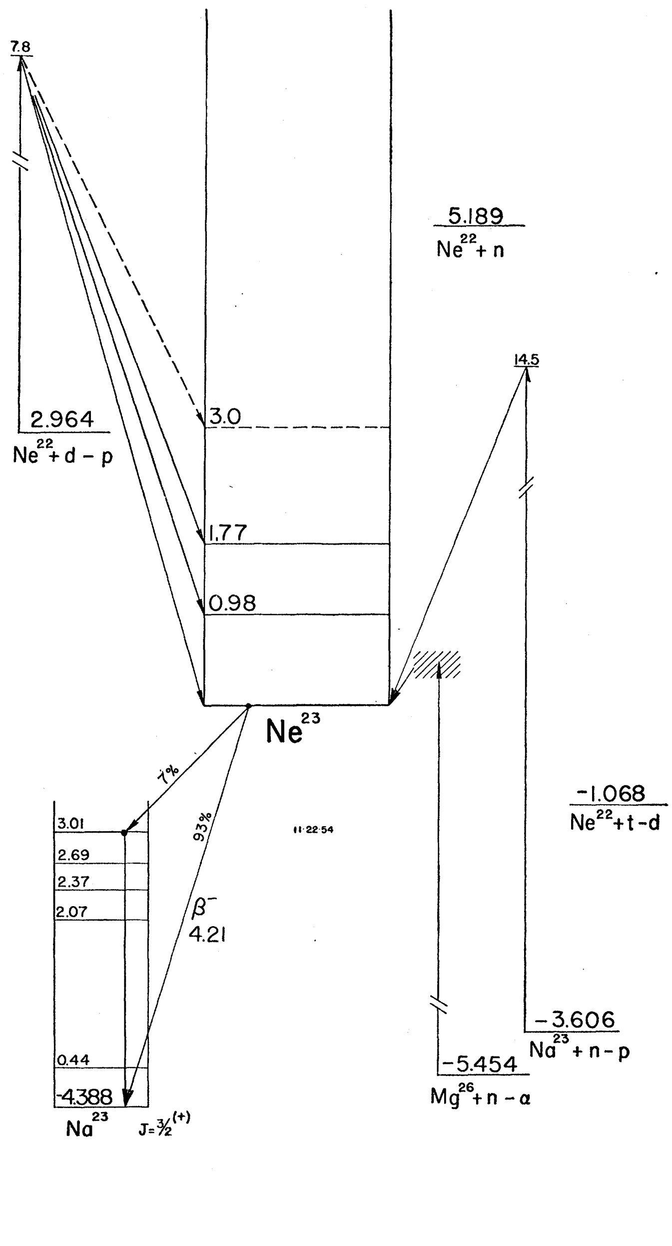


FIG. 41. Energy levels of Ne^{23}: for notation, see Fig. 1.

also (Ki 52)]. (Using Q_m for the ground-state transition energy, one obtains $\log ft = 5.17$.)

II. $Ne^{22}(n\,\gamma)Ne^{23}$ $Q_m = 5.189$

The thermal cross section is 36 ± 15 mb (Hu 52e).

III. $Ne^{22}(d\,p)Ne^{23}$ $Q_m = 2.964$

$Q_0 = 2.964\pm0.007$ [(Va 52); mag. spectrometer].
$Q_0 = 2.968\pm0.008$ [(Ah 54a); mag. spectrometer].

At $E_d = 0.875$ Mev, no proton groups are observed corresponding to excited states of Ne^{23} below 250 kev (Ah 54a). (Zu 50a) reports states at 0.98 and 1.75 Mev, while (Mi 51d) report states at 1.79 and 3.0(?) Mev.

IV. $Na^{23}(n(p)Ne^{23}$ $Q_m = -3.606$

At $E_n = 14.5$ Mev, the cross section is 34 ± 15 mb (Hu 53c).

V. $Mg^{26}(n\,\alpha)Ne^{23}$ $Q_m = -5.454$

See (Ho 50b).

Table of Atomic Mass Defects

Nuclide	$M-A$ (Mev)
n^1	8.3638 ± 0.0029[a]
H^1	7.5815 ± 0.0027[a]
H^2	13.7203 ± 0.006[a]
H^3	15.8271 ± 0.010[a]
He^3	15.8086 ± 0.010[a]
He^4	3.6066 ± 0.014[a]
He^5	12.92 ± 0.08[b]
He^6	19.40 ± 0.036[b]
He^7	31.5 ± 2[b]
Li^5	12.99 ± 0.15[b]
Li^6	15.850 ± 0.021[a]
Li^7	16.969 ± 0.024[a]
Li^8	23.296 ± 0.028[a]
Li^9	28.1 ± 1[b]
Be^6	20.8 ± 1[b]
Be^7	17.832 ± 0.024[a]
Be^8	7.309 ± 0.027[a]
Be^9	14.007 ± 0.028[a]
Be^{10}	15.560 ± 0.026[a]
Be^{11}	23.4 ± 2[b]
B^8	25.1 ± 0.3[b]
B^9	15.076 ± 0.029[a]
B^{10}	15.004 ± 0.026[a]
B^{11}	11.909 ± 0.022[a]
B^{12}	16.912 ± 0.020[a]
B^{13}	19.0 ± 2[b]
C^9	32.2 ± 2[b]
C^{10}	18.64 ± 0.06[b]
C^{11}	13.889 ± 0.022[a]
C^{12}	3.542 ± 0.015[a]
C^{13}	6.958 ± 0.013[a]
C^{14}	7.153 ± 0.010[a]
C^{15}	13.17 ± 0.06[b]
N^{12}	21.2 ± 0.1[b]
N^{13}	9.179 ± 0.013[a]
N^{14}	6.998 ± 0.010[a]
N^{15}	4.528 ± 0.011[a]
N^{16}	10.40 ± 0.03[b]
N^{17}	13.0 ± 0.2[b]
O^{14}	12.168 ± 0.015[b]
O^{15}	7.233 ± 0.012[a]
O^{16}	0 (standard)
O^{17}	4.221 ± 0.006[a]
O^{18}	4.522 ± 0.022[c]
O^{19}	8.930 ± 0.024[b]
O^{20}	13.3 ± 2[b]
F^{16}	15.9 ± 1[b]
F^{17}	6.988 ± 0.005[c]
F^{18}	6.193 ± 0.021[c]
F^{19}	4.149 ± 0.014[a]
F^{20}	5.913 ± 0.016[c]
Ne^{18}	10.4 ± 0.2[b]
Ne^{19}	7.405 ± 0.014[c]
Ne^{20}	-1.139 ± 0.019[c]
Ne^{21}	0.469 ± 0.021[c]
Ne^{22}	-1.529 ± 0.023[c]
Ne^{23}	1.646 ± 0.023[c]
Na^{20}	14.2 ± 0.5[b]
Na^{21}	3.991 ± 0.037[c]
Na^{22}	1.312 ± 0.023[c]
Na^{23}	-2.742 ± 0.023[c]
Mg^{24}	-6.864 ± 0.024[c]
Mg^{25}	-5.824 ± 0.025[c]
Mg^{26}	-8.565 ± 0.027[c]
Al^{27}	-9.245 ± 0.028[c]

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