REVIEWS OF MODERN PHYSICS VOLUME 20, NUMBER 1 JANUARY, 1948

Energy Levels of Light Nuclei

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THE study of the excited states of atomic nuclei has been the object of intensive experimental and theoretical investigation since the earliest days of nuclear physics. With the increasing availability in recent years of convenient sources of high energy particles and with the development of more versatile and reliable detecting equipment the field has advanced with great rapidity, with the result that a large body of information on the behavior of excited nuclei is now available in the literature.

In the following sections, we have attempted to summarize the present experimental evidence concerning the existence and location of energy levels in certain of the light nuclei. Each nucleus is represented in a diagram on which the known levels are plotted, located according to their excitation energy on a vertical scale. On the same diagram and plotted to the same energy scale are the various nuclear transitions by which the level is identified, both as to method of formation and mode of decay. Thus, the diagram contains a representation of each nuclear reaction in which the nucleus in question occurs as either the compound or the residual member. In the case of levels characterizing compound states in a given reaction, some information concerning the lifetimes and the relative probabilities of various modes of decay is given by the measurement of the yields of various products as a function of bombarding energy. These excitation functions, where they are known, are indicated schematically with the pertinent reactions. (The curves refer to thin target yields except where otherwise specifically noted.) Where the excitation function is not known or does not exhibit resonance, we have indicated the bombarding voltage used in a typical experiment.

The existence of levels in the nucleus residual to a reaction is ordinarily revealed through the observation of particle groups or by measurement of the gamma-radiation from the subsequent decay to the ground state. Such groups or transitions are represented by arrows connecting the indicated reactions with the level in question. The vertical projection of any arrow gives directly the energy change and can be used to determine the particle energy by application of the appropriate momentum relations. To facilitate identification of gamma-ray transitions the measured energy values are indicated on the diagram. Since the excited levels to which they correspond may be more accurately located by other means, there will be discrepancies between the indicated gamma-ray energy and the value calculated from the level differences. The same type of discrepancy will occur in that section of the text relating to various determinations of level locations. The values plotted represent the weighted mean of all valid determinations.

As support for the representations of the diagrams, a brief discussion—largely in the form of an annotated bibliography—of each pertinent reaction is included. Since a given reaction usually gives information concerning two nuclei, most reactions are discussed twice, leading inevitably to some duplications. Where possible, the discussion has been divided in such a way as to place the emphasis on the appropriate nucleus in each case, but such separation is often rather arbitrary. The same sort of redundancy also applies to the diagrams: in a sense, each must be regarded as a portion of a single master diagram in which all the nuclei are represented side by side with all nuclear reactions represented by cross connections between levels of neighboring systems—that the excerpted portions should overlap is then only natural and reasonable. In a number of cases, where the decay of the nucleus under consideration leads to transitions to several states in a neighboring nucleus, this fact has been indicated on the diagram. More detailed information in such cases will be found on the diagram of the residual nucleus.

Since most experiments permit the location of only the relatively sharply defined levels, the diagrams give little information concerning the

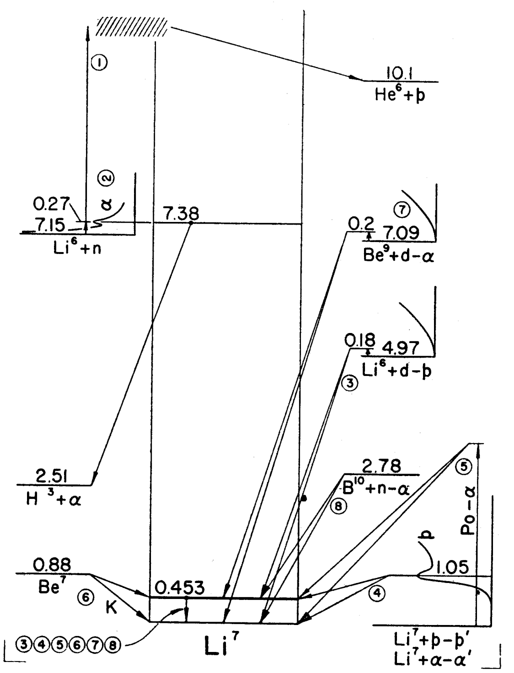


FIG. 1. *Energy levels in* Li^7. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Arrows in Be^7 decay indicate neutrino energy.

broad, continuous states which exist to some extent throughout the entire energy range. Locations in this continuum are indicated by short lines leading part way into the well, as opposed to sharp levels, which are given by lines extending the full width.

No attempt has been made to present the evidence for particular levels in historical order. On the contrary, we have in many cases relegated original discoveries to the undiscussed bibliography in favor of more recent or more definitive measurements. References discussed in the classical work of Livingston and Bethe (Rev. Mod. Phys. **9**, No. 3, 1937) are generally omitted here, except where no later work exists.

In the interest of uniformity, energy change values have been computed from a single mass table: that contained in E. Segrè's isotope chart (Se 45)* and in H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).

The authors are indebted to Professors C. C. Lauritsen, R. F. Christy, and W. A. Fowler for many helpful suggestions and discussions in connection with this compilation. Acknowledgment is also made of the valuable assistance of Mr. V. K. Rasmussen and Mr. C. B. Dougherty who aided in the literature search and of Mr. V. F. Ehrgott who prepared the figures. This work was assisted by the Office of Naval Research.

Li^7

I. $Li^6(np)He^6$ $Q=-2.9$ Mev

(1)** Poole and Paul (Po 46) have identified the He^6 produced in this reaction from its β-ray spectrum.

Ref: Na 37, Ve 37, Bj 38a, Bj 38b, Po 46

II. $Li^6(n\alpha)H^3$ $Q=4.64$ Mev

(2) The curves of Goldsmith and Ibser (Go 46) indicate a resonance cross section of 4 barns at $E_n=0.27$ Mev. The cross section for thermal neutrons is 860 barns (pure Li^6) (Se 45).

Livingston and Hoffman (Li 38) and Rumbaugh, Roberts, and Hafstad (Ru 38) give Q values of 4.86 and 4.97 Mev, respectively. In view of the existence of the resonance for 0.27 Mev-neutrons, it does not seem impossible that measurements based on the extrapolated range may give too high a Q value.

Ref: Li 37, Li 38, Ru 38, Se 45, Go 46

III. $Li^6(dp)Li^7$, Li^{7*} $Q=4.97$ Mev

(3) Rumbaugh, Roberts, and Hafstad (Ru 38) have measured the separation of the two proton groups as 455 ± 15 kev.

Williams, Shepherd, and Haxby (Wi 37c) determined the γ-ray energy as 400 ± 25 kev using an absorption method.

Ref: Wi 37c, Ru 38, Po 42

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

(4) Non-capture excitation of Li^7 occurs for $E_p>0.6$ Mev. The energy of the γ-radiation was determined by Hudson, Herb, and Plain (Hu 40) to be 459 kev.

Ref: Fo 39, Hu 40

* References are to be found at the end of this article.

** The numbers in parentheses refer to circled numbers on diagram.

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

Bothe (Bo 36a) reported several low energy γ-rays which he attributed to this reaction.

(5) Siegbahn and Slätis (Si 46a) have measured the energy of the radiation from Li bombarded with Po α-articles and give 0.462 Mev as the result. They found no other γ-rays with energies <1 Mev.

Ref: Bo 36a, Si 46a, Si 47

VI. $Li^7(\gamma p)He^6$ $Q=-10.1$ Mev (not illustrated)

Becker, Hansen, and Diven (Be 47a) report the threshold as 9.5 ± 0.3 Mev.

Ref: Be 47a

VII. $Be^7(K)Li^7$, Li^{7*} $Q=0.88$ Mev

(6) Be^7 decays by electron capture with a half life of 53 ± 2 days (Hi 40) (52 days: Segrè, private communication).

Rumbaugh, Roberts, and Hafstad (Ru 38) found that about 10 percent of the disintegrations lead to γ-ray emission.

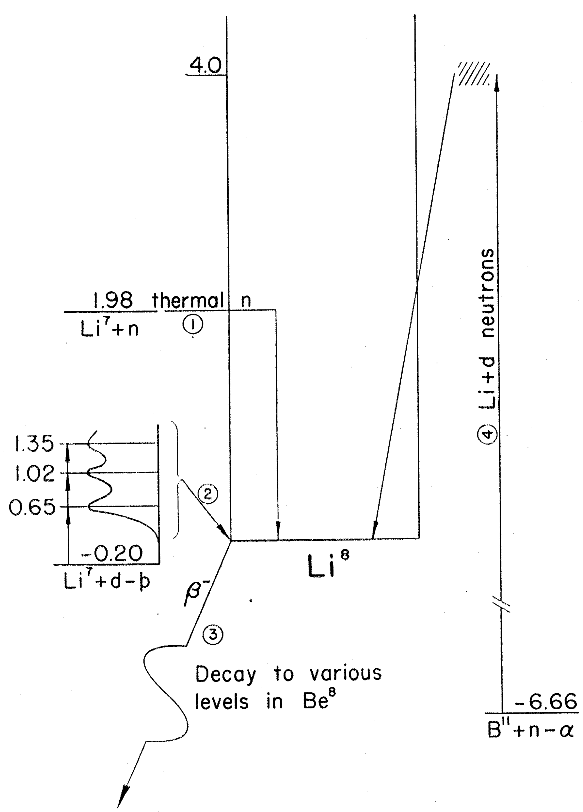
Siegbahn (Si 46) determined the γ-ray energy with a magnetic spectrometer to be 453 ± 5 kev.

Haxby, Shoupp, Stephens, and Wells (Ha 40b) estimate $Q=0.87$ Mev for transition to the ground state from their value for the $Li^7(pn)$ threshold.

Ref: Br 38, Br 38b, Ma 38, Ru 38, Hi 39a, Ma 39, Ha 40b, Hi 40, Ru 41a, Al 42, Zl 42, Ru 46, Si 46

VIII. $Be^9(d\alpha)Li^7$, Li^{7*} $Q=7.09$ Mev

(7) Graves (Gr 40) measured two groups of α particles differing in energy by 494 ± 16 kev. The Q value for the ground state transition is given as 7.093 ± 0.022 Mev.



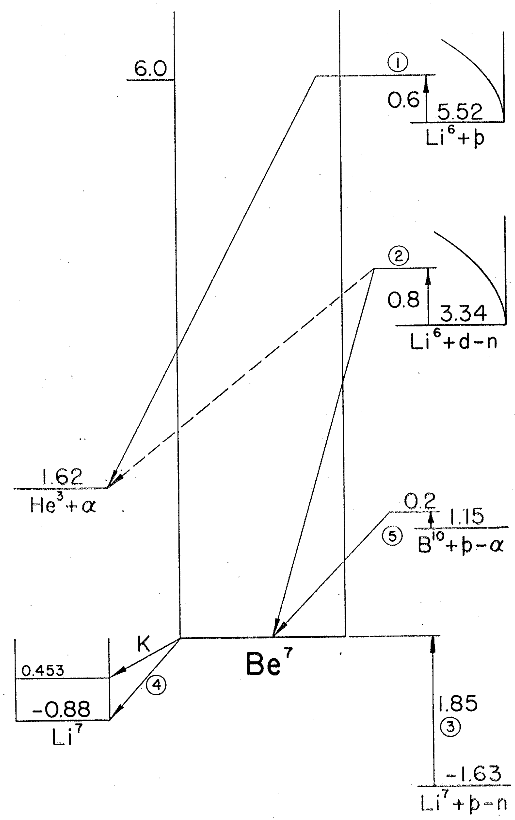


FIG. 2. *Energy levels in* Li^8. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale.

FIG. 3. *Energy levels in* Be^7. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Arrows in Be^7 decay indicate neutrino energy.

Fowler, Lauritsen, and Lauritsen (unpublished) have measured the γ-ray energy as 0.48 Mev using a magnetic spectrometer.

Ref: Ha 37a, Wi 37d, Al 40, Gr 40, Sk 40

IX. $B^{10}(n\alpha)Li^7$, Li^{7*} $Q=2.78$ Mev

(8) Haxel observed two groups of α-particles giving Q values of 1.8 and 2.8 Mev (Li 37). Wilson (Wi 40) observed $\gamma-\alpha$-coincidences and obtained 0.5 Mev for the γ-ray energy.

Bøggild (Bo 45) estimates that 93 percent of the disintegrations lead to the excited level and gives Q values of 2.40 and 2.82 Mev.

Ref: Li 37, Wi 40, Bo 45—See B^{11}

Li^8

I.(*a*) $Li^7(n\gamma)Li^8$ $Q=1.98$ Mev
(*b*) $Li^6(np)He^6$ $Q=-2.9$ Mev

(1) Veldkamp and Knol (Ve 37) reported an activity attributed to reaction (*a*), but the closeness of the half-lives of Li^8 and He^6 made it difficult to exclude reaction (*b*) which is known to take place with fast neutrons (Li 37).

Bjerge (Bj 38a) studied the effect of slow neutrons and concluded that the activity is increased when the neutron source is surrounded by paraffin, indicating that reaction (*a*) contributes at least a part of the activity.

Rumbaugh, Roberts, and Hafstad (Ru 38) looked for radioactivity in a pure Li^7 target under intense neutron bombardment with negative results.

Poole and Paul (Po 46) have confirmed reaction (*a*) with slow neutrons by observation of the β-ray spectrum and of the α-particles. They estimate $\sigma\sim10^{-3}$ barn. Hughes, Hall, Eggler, and Goldfarb (Hu 47a) give 0.033 ± 0.005 barn as the cross section for thermal neutrons. They have confirmed that the activity is due to Li^7.

Ref: Li 37, Na 37, Ve 37, Bj 38a, Ru 38, Po 46, Hu 47a

II. $Li^7(dp)Li^8$ $Q=-0.20$ Mev
see (Be^9: Li^7, *dp*)

(2) Li^8 is known to be produced in this reaction, but the protons have not been observed. Rumbaugh, Roberts, and Hafstad (Ru 38) estimate $Q=-0.20\pm0.03$ Mev from the excitation function.

Ref: Ru 38

III. (3) Li^8 decay—see Be^8

IV. $Be^9(\gamma p)Li^8$ $Q=-16.86$ Mev
(not illustrated)

Ogle, Brown, and Conklin (Og 47) observed Li^8 production at 18 ± 1 Mev.

Ref: Og 47

V. $B^{11}(n\alpha)Li^8$ $Q=-6.66$ Mev

(4) Lawrance (La 39) has observed this reaction with $Li+d$ neutrons.

Ref: Na 37, La 39

Be^7

I. $Li^6(p\gamma)Be^7$ $Q=5.52$ Mev (not illustrated)

Curran and Strothers (Cu 39) searched for Be^7 from this reaction with negative results. They estimate the yield as $<2.5\times10^{-10}$ at $E_p=0.95$ Mev.

Ref: Cu 39

II. $Li^6(p\alpha)He^3$ $Q=3.90$ Mev

(1) Rumbaugh, Roberts, and Hafstad (Ru 38) measured the α-particle yield to $E_p=0.6$ Mev and found a smooth exponential rise.

Bowersox (Bo 39b) gives $\sigma=0.07$ barn at $E_p=0.4$ Mev.

Miller (Mi 40) and Perlow (Pe 40) have made precision determinations of the Q value and give 3.94 ± 0.08 Mev and 3.945 ± 0.06 Mev, respectively.

Neuert (Ne 37a) found that the angular distribution of the α-particles is isotropic.

Ref: Ne 37a, Ru 38, Bo 39b, Al 40b, Mi 40, Pe 40

III.(*a*) $Li^6(dn)Be^7$ $Q=3.34$ Mev
(*b*) $Li^6(dn)He^3+\alpha$ $Q=1.72$ Mev

(2) Roberts, Heydenburg, and Locher (Ro 38a) observed radioactive γ-rays from the Be^7 produced in reaction (*a*).

Rumbaugh, Roberts, and Hafstad (Ru 38) report a smooth increase in yield to $E_d=0.8$ Mev and conclude from the neutron spectrum that reactions (*a*) and (*b*) are about equally probable.

Ref: Ro 38a, Ru 38

IV. $Li^7(pn)Be^7$ $Q=-1.63$ Mev

(3) The threshold is 1.85 ± 0.02 Mev (see Be^8).

V. (4) Be^7 decay—see Li^7

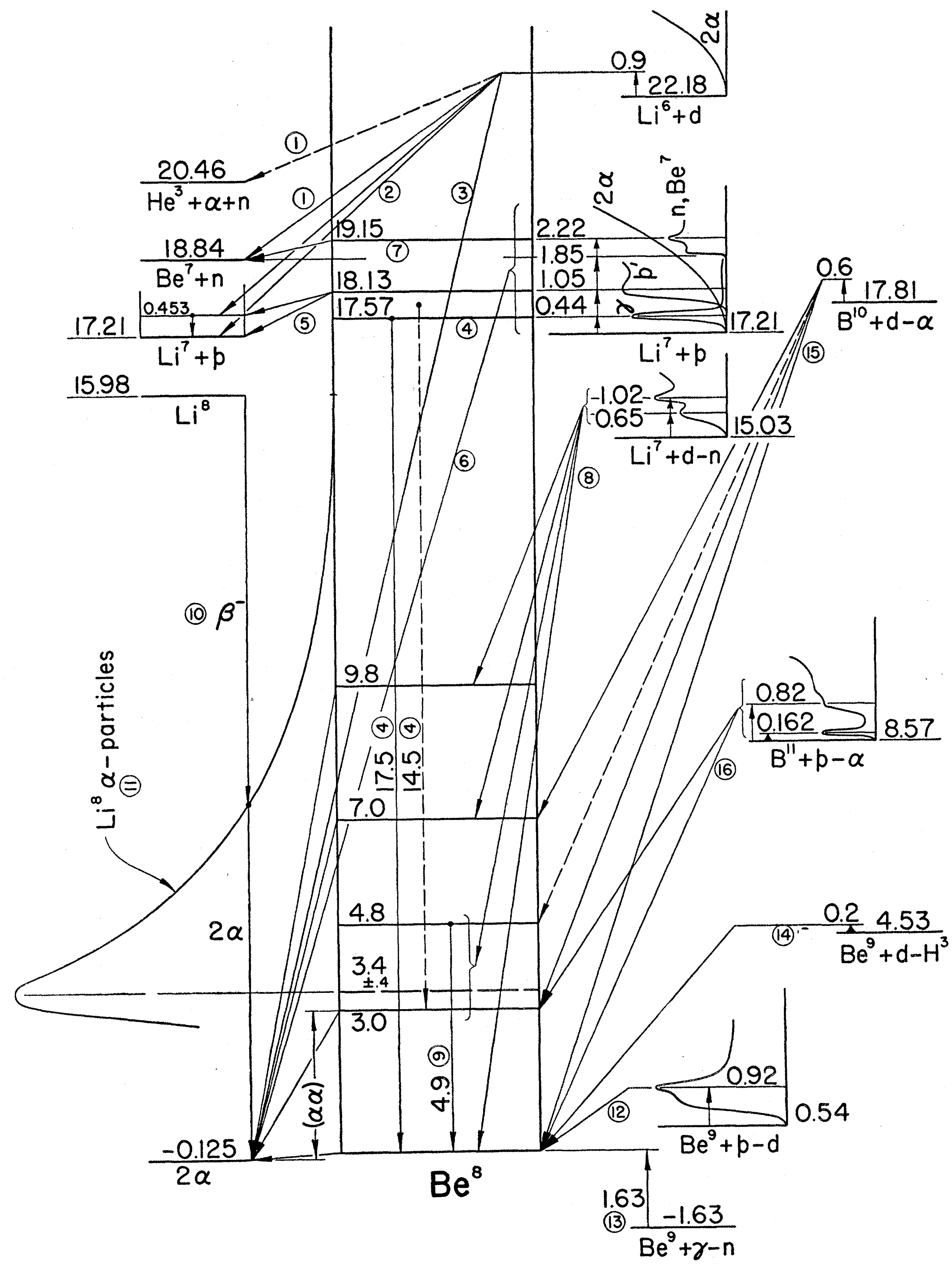


FIG. 4. *Energy levels in* Be^8. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. The observed energy distribution of α-particles from the Li^8 decay is indicated by a curve on the left with numbers plotted horizontally. The Li^8 β-decay is complex.

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

(5) Roberts, Heydenburg, and Locher (Ro 38a) observed radioactive γ-rays from Be^7 produced in this reaction.

Maier-Leibnitz (Ma 39) measured the γ-ray energy as 0.425 Mev.

Ref: Ma 38, Ro 38a, Ma 39

Be^8

I. $He^4(\alpha, \alpha)He^4$

From an analysis of scattering data, Wheeler (Wh 41a) concludes the existence of a state in Be^8 at about 3 Mev of zero angular momentum and with a half width $\sim$0.8 Mev, and possibly an additional state at 4–5 Mev with angular momentum two.

Ref: Mo 37, De 39b, Wh 41a

II. (*a*) $Li^6(dn)Be^6$ $Q=3.34$ Mev
(*b*) $Li^6(dn)He^3+\alpha$ $Q=1.72$ Mev

(1) Rumbaugh, Roberts, and Hafstad (Ru 38) made a chemical identification of the Be^7 resulting from this reaction. From the neutron spectrum (pure Li^6 target), they conclude that reactions (*a*) and (*b*) are equally probable at $E_d=0.9$ Mev.

Ref: Ro 38a, Ru 38, Ri 41

III. $Li^6(dp)Li^7$, Li^{7*} $Q=4.97$ Mev

(2) Rumbaugh, Roberts, and Hafstad (Ru 38) measured the excitation function from $E_d=0.2$ to 1.0 Mev and found that the relative probability of leaving Li^7 in the excited state increases with voltage. The mean separation of the two proton groups corresponds to a difference in Q value of 455 ± 15 kev.

Ref: Ne 37, Wi 37c, Ru 38, Ne 39, Po 42

IV. $Li^6(d\alpha)He^4$ $Q=22.23$ Mev

(3) Rumbaugh, Roberts, and Hafstad (Ru 38), using a Li^6 target, showed that the α-particles are homogeneous and that the yield increases smoothly up to $E_d=1.0$ Mev.

Smith (Sm 39a) determined the Q value as 22.20 ± 0.04 Mev.

Neuert (Ne 39) and Haxby, Allen and Williams (Ha 39) found that the α-particles have an isotropic distribution ($E_d\sim0.29$ Mev).

Ref: Wi 37c, Ru 38, St 38a, Al 39a, Ha 39, Ne 39, Sm 39a

V. $Li^7(p\gamma)Be^8$, Be^{8*} $Q=17.21$ Mev

(4) Delsasso, Fowler, and Lauritsen (De 37, Fo 48) determined the energy of the radiation from the analysis of pairs in the cloud chamber. They obtained a line at 17.5 ± 0.5 Mev and (probably) a line about 0.25 as intense near 14 Mev. No radiation was found between 2 and 10 Mev.

Gaerttner and Crane (Ga 37) report lines at 17, 14.5, 11.5, and (8.5?) Mev from the analysis of Compton electrons in the cloud chamber. Pairs observed in the same experiment showed only the 17-Mev line clearly.

Gentner (Ge 37a) determined the energy of the γ-rays at bombarding voltages of 300 and 550 kev and found no significant difference. The yield function below 440 kev is similar to that for the Li^7, $p\alpha$-reaction.

Hudson, Herb, and Plain (Hu 40) have obtained yield curves for the high energy radiation showing a resonance at $E_p=440$ kev, but no others <1.8 Mev.

Tangen (unpublished) reports that the radiation above the resonance is slightly less energetic, as determined from the absorption of secondaries, suggesting that softer components between 10 and 17 Mev may be caused by a broad resonance on which the 440-kev resonance is superposed. This result has been confirmed at this laboratory, the difference in half-value thickness for secondary electrons amounting to 6 percent at 600 kev (excluding effect of 450-kev radiation).

Creutz (Cr 39) has observed resonance scattering of protons from Li at 440 kev.

The value of this resonance bombarding energy is used as a standard for high voltage calibrations. The value in general use is 0.440 Mev, determined by Hafstad, Heydenburg, and Tuve (Ha 36) with a calibrated resistance voltmeter.

A value of 0.4465 ± 0.0015 has been given by Hanson and Benedict (Ha 44) using an absolute electrostatic deflection method.

The width of the resonance at 440-kev has been determined by Hafstad, Heydenburg, and Tuve (Ha 36) as 11 kev, by Hole, Holtsmark, and Tangen (Ho 41) as 10 kev, and by Fowler, Lauritsen, and Lauritsen (Fo 48) as 12 kev ($\omega\gamma=8.9$ ev).

Ageno *et al.* (Ag 41) find that the γ-radiation is emitted isotropically at $E_p=500$ kev (thick target).

Ref: Ha 36, Bo 37e, De 37, Ga 37, Ge 37a, Ka 38, Ru 38, Cr 39, Cu 39, Fo 39, Hu 40, Ag 41, Ho 41, Ha 44, Fo 48

VI. $Li^7(pp')Li^{7*}$

(5) Fowler and Lauritsen (Fo 39) and Hudson, Herb, and Plain (Hu 40) have shown that radiation of ~455-kev energy is produced for $E_p>600$ kev and found resonances at $E_p=1.05$, (1.6?), (1.7?), and (1.8?) Mev. This radiation is caused by excitation of the known level of Li^7 at 453 kev (see Li^7).

Ref: Cr 39, Fo 39, Hu 40

VII. $Li^7(p\alpha)He^4$ $Q=17.27$ Mev

(6) Rumbaugh, Roberts, and Hafstad (Ru 38) studied the yield to $E_p=1.0$ Mev and found a smooth rise with no evidence of resonance near 440 kev. They found no short range α-particles (pure Li^7 target) at $E_p=475$ kev. Kanne and Ragan (Ka 38) found that the γ-ray and α-particle yields are similar from $E_p=150$ to 300 kev.

Rubin, Fowler, and Lauritsen (Ru 47) have studied the angular distribution of the α-particles from $E_p=0.35$ to 1.4 Mev and report a single anisotropy at 0.9 Mev.

Smith (Sm 39a) gives a Q value of 17.28 ±0.03 Mev.

Ref: Ha 38, Ka 38, Ru 38, Al 39a, Ne 39, Sm 39a, Yo 40, Cr 41, Ei 44, Sw 44, Ch 47a, Ru 47

VIII. $Li^7(pn)Be^7$ $Q=-1.63$ Mev

Haxby, Shoupp, Stephens, and Wells (Ha 40a) report $E_p=1.85\pm0.02$ Mev as the threshold for neutron production, while Hanson and Benedict (Ha 44) give 1.883 ± 0.005 Mev based on a slightly different voltage scale.

Hill and Valley (Hi 39a) and DuBridge (Du 39) have identified the Be^7 from this reaction and studied the yield to $E_p=6.5$ Mev.

(7) Taschek and Hemmendinger (Ta 48)*** have measured the absolute neutron and Be^7 yields and find them to be in agreement. They observed a pronounced resonance at $E_p=2.22$ Mev ($\sigma\sim0.5$ barn).

Ref: Du 39, Hi 39a, Ha 40a, Hi 40, Ha 44, Ar 46, Ta 48

IX. $Li^7(dn)Be^8$, Be^{8*} $Q=15.03$ Mev (see Be^9: Li^7, $d\alpha$)

(8) Richards (Ri 41) determined the neutron spectrum by a photographic plate technique, and reports groups at 14, 10.8, 7.5, and 5 Mev with observed half-widths of ~0.5, 2.0, 1.5, and 1.5 Mev, respectively. The first group represents the transition to the ground state of Be^8, while the breadth of the second group was taken to indicate an unresolved group involving the excited states at 3.0 and 4.8 Mev. (The existence of a transition to a level at 3.4 Mev is not excluded by this data.) The last two groups involve the broad levels at 7.0 and 9.8 Mev.

(9) Bennett, Bonner, Richards, and Watt (Be 41a, 47) have detected a γ-ray of 4.9 ± 0.3 Mev energy and have shown that both neutron and γ-ray yields have resonances at $E_d=0.65$ and 1.02 Mev. They estimate the γ-ray yield as 3.3 percent of the neutron yield.

Ref: Wi 37c, Ru 38, St 38, St 38a, St 39a, Be 41a, Bo 41b, Ri 41, Be 47

X. $Li^8(\beta^-)Be^{8*}$ $Q=15.98$ Mev

(10) Bayley and Crane (Ba 37) studied the β-ray spectrum and obtained 12.0 ± 0.6 Mev for the upper limit. The spectrum is complex.

(11) Bonner, Evans, Malich, and Risser (Bo 47) report the maximum in the α-particle distribution at $E_\alpha=1.65$ Mev with a half-width ~0.9 Mev indicating preferential transition to a state in Be^8 at about 3.3 Mev. Alpha-particles have been observed with energies up ot 7.75 Mev (Sm 38).

Hughes *et al.* (Hu 47a) give the half-life of Li^8 as 0.89 ± 0.02 sec.

Ref: Ba 37, Bo 37a, Fo 37, Ru 38, Sm 38, Ki 39b, La 39, Wh 41, Bo 47, Ch 47, Hu 47a

XI. $Be^9(pd)Be^8$ $Q=0.54$ Mev

(12) Allison, Skaggs, and Smith (Al 40a) have determined the Q as 0.547 ± 0.006 Mev (see B^{10}).

Ref: Al 40a, Ma 40

XII. $Be^9(\gamma n)Be^8$ $Q=-1.63$ Mev

(13) The threshold is observed at 1.630 ± 0.006 Mev—see Be^9

Glückauf and Paneth (Gl 38) have made a chemical identification of the He found in this reaction.

Goloborodko (Go 41) found that the neutron spectrum is monochromatic for RaTh γ-rays, thus indicating the formation of Be^8 rather than the occurrence of the three body reaction.

Ref: Gl 38, Go 40, Go 41

*** We are indebted to Dr. R. Taschek for this information.

XIII. $Be^9(dH^3)Be^8$ $Q=4.53$ Mev

(14) Williams, Haxby, and Shepherd (Wi 37d) determined the Q as 4.32 Mev.

O'Neal and Goldhaber (On 40) have made a chemical identification of the H^3 produced.

Ref: Wi 37d, Li 39, On 40

XIV. $B^{10}(d\alpha)Be^8$, Be^{8*} $Q=17.81$ Mev

(15) Smith and Murrell (Sm 39), using separated isotopes, found α-particle groups at 14, 11, 8.6, and 6.2 cm in addition to a continuous distribution at low energy. Of these, the first, second, and fourth are associated with transitions to the Be^8 ground state and the excited states at 3.0 and 7.0 Mev. The third group is assigned to Li contamination, but may correspond to a state at 4.8 Mev.

Ref: Sm 39

XV. $B^{10}(nH^3)Be^8$ $Q=0.22$ Mev (not illustrated)

Cornog and Libby (Co 41a) report the formation of H^3 with high energy neutrons on boron (see B^{12}: B^{11}, nH^3).

Ref: Co 41a

XVI. $B^{11}(p\alpha)Be^8$, Be^{8*} $Q=8.57$ Mev

(16) The α-particles from this reaction occur as a homogeneous group ($\sim$4.4 cm) and a continuum at lower ranges. Both groups show resonance at $E_p=162\pm1$ kev (Ja 41a, Ma 45), and have an isotropic angular dependence (Ja 41). The continuum is attributed to the transition to a level in Be^8 at 2.8 (3.0) Mev having a half width of 0.8 Mev (Be 37, Wh 41).

Kirchner, Laaf, and Neuert (Ki 37), Laaf (La 38), and Fink (Fi 39) have shown that Be^8 formed simultaneously with the homogeneous α-particle group exists for an appreciable time and conclude that its instability amounts to 0.1—0.2 Mev. An analysis by Wheeler (Wh 41) indicates that a value of 0.125 Mev for the instability is consistent with these experiments.

Ref: Be 37, Ge 37, Ki 37, Ne 37, Ne 37a, Wi 37a, Al 38, La 38, Ne 38a, Ne 38b, Op 38, Wa 38, Bo 39b, Fi 39, Ha 39, Hi 39, Ne 39, Ja 41, Ja 41a, Wh 41, Ma 45

Be^9

I. $Li^6(\alpha p)Be^9$ $Q=-2.12$ Mev (not illustrated)

Not observed—see B^{10}

II. $Li^7(dp)Li^8$ $Q=-0.20$ Mev

(1) Bennett *et al.* (Be 47) investigated the excitation curve for $E_d=0.55$ to 1.4 Mev, finding broad resonances for the production of Li^8 at $E_d=0.75$, 1.02 and 1.35. The first two resonances also occur in the neutron and γ-ray yields (Li^7, dn, Be^8).

Ref: Fo 37, Ru 38, Be 41b, Be 47

III. $Li^7(dn)Be^8$, Be^{8*} $Q=15.03$ Mev

(2) Bennett *et al.* (Be 41a, Be 47) observed radiation of 4.9 ± 0.3 Mev and report resonances for γ-ray and neutron production at 0.65 and 1.02 Mev. There is some indication that the angular distribution of the neutrons differs for the two resonances. Neutron groups corresponding to transitions to several levels in Be^8 are known (see Be^8).

Ref: Am 37, Wi 37c, Ru 38, Be 41a, Be 47

IV. $Li^7(d\alpha)He^5$ $Q=14.3$ Mev

(3) Williams, Shepherd, and Haxby (Wi 37) observed a homogeneous α-particle group at 7.10 cm ($E_d=0.2$ Mev) and conclude that the He^5 formed is unstable by 0.9 Mev and has a lifetime $\sim6\times10^{-20}$ sec.

Staub and Stephens (St 39a) confirmed the presence of the 7-cm α-particle group and found a plateau in the neutron spectrum which they interpreted as caused by neutrons from the He^5 breakup.

Richards (Ri 41) observed the neutron spectrum by a photographic plate technique but could not confirm the existence of the plateau reported by Staub and Stephens. He does not, however, consider that his data excludes the existence of the present reaction.

Ref: Am 37, Wi 37, Wi 37c, Ru 38, St 38, St 39a, Ri 41, La 47b

V. $Be^9(\gamma n)Be^8$ $Q=-1.63$ Mev

(4) Myers and Van Atta (My 42) give for the threshold 1.627 ± 0.010 Mev, while Wiedenbeck and Marhoefer (Wi 45) give 1.630 ± 0.006 Mev. Wiedenbeck (Wi 46) obtained yield curves for the $Be^9(\gamma n)$ and $Be^9(e, e'n)$ reactions.

Ref: Gl 38, Ha 38b, Co 39a, Go 40, Go 41, My 42, Wi 45, Wi 46

VI. $Be^9(e, e'n)Be^8$ $Q=-1.63$ Mev

(5) Collins, Waldman, and Guth (Co 39a) give the threshold for the $(e, e'n)$ and (γn) re-

actions as 1.63±0.05 Mev and find a value for the cross section in good agreement with theory.

Ref: Co 39, Co 39a, Gu 39, Ma 43

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

(6) Bjerge (Bj 38) observed a sharp increase in slow neutrons from $(Be^9+\alpha)$ at $E_\alpha=4.9$ Mev. It is not clear which of the three possibilities is involved (see C^{13}).

Stuhlinger (St 39) confirms the step in the yield curve at $E_\alpha=4.8$ Mev.

Ref: Bj 38, St 39

VIII. $Be^9(\gamma p)Li^8$ $Q=-16.86$ Mev (not illustrated)

Ogle, Brown, and Conklin (Og 47) observed the formation of Li^8 and give the threshold as 18±1 Mev.

Ref: Og 47

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

(7) Smith and Murrell (Sm 39) observed 4.6-cm α-particles at $E_d=0.55$ Mev from this reaction.

Ref: Sm 39

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

This reaction has been observed in cloud chamber photographs (Li 37).

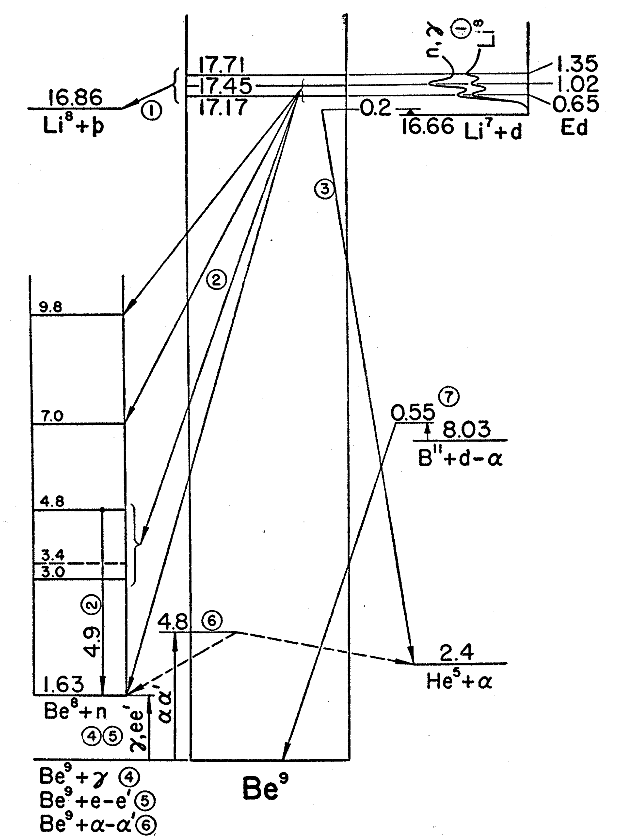
XI. $B^{11}(nH^3)Be^9$ $Q=-9.57$ Mev (see B^{12}) (not illustrated)

Be^{10}

I. $Be^9(n\gamma)Be^{10}$ $Q=6.69$ Mev

(1) Hughes, Eggler, and Huddleston (Hu 47) observed Be^{10} activity in BeO samples irradiated in the Hanford pile.

Ref: Hu 47, Le 47, Og 47



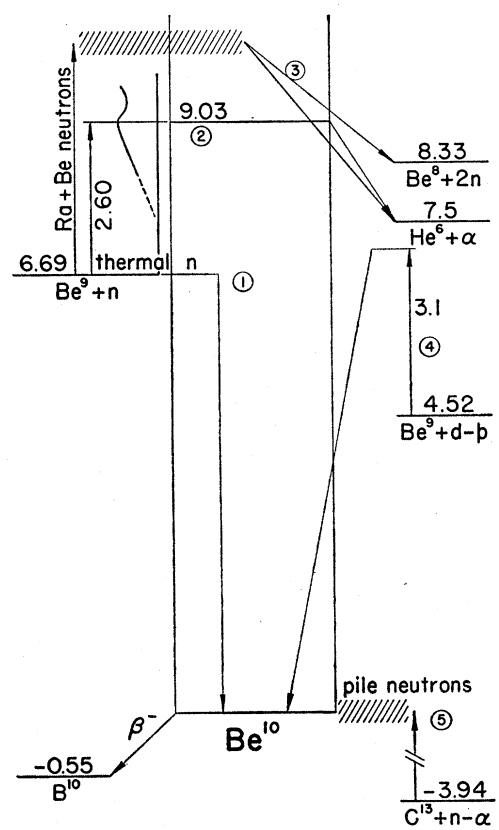


FIG. 5. *Energy levels in* Be^9. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale.

FIG. 6. *Energy levels in* Be^{10}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale.

II. $Be^9(n\alpha)He^6$ $Q=-0.8$ Mev

Bjerge and Brostrøm (Bj 36) established the formation of a radioactive inert gas by neutron bombardment of Be.

(2) Allen, Burcham, and Wilkenson (Al 47) studied the neutron absorption in Be and found a maximum at $E_n=2.6$ Mev which they ascribe to a level in Be^{10} having a half-width ~ 1 Mev and leading to this reaction. There is some indication of a resonance for neutron scattering at $E_n \sim 0.6$ Mev.

Fünfer and Bothe (Fu 44) estimate $\sigma \sim 0.1$ barn for Ra α+Be neutrons.

Ref: Bj 36, Na 37, Bj 38a, Bj 38b, Fu 44, So 46, Al 47, Ca 47, Og 47

III. $Be^9(n2n)Be^8$ $Q=-1.63$ Mev

(3) Fünfer and Bothe (Fu 44) estimate $\sigma=0.3$ barn from measurements with Raα+Be neutrons.

Ref: Fu 44

IV. $Be^9(dp)Be^{10}$ $Q=4.52$ Mev

(4) Pollard (Po 40), using 3.1 Mev deuterons, found a 52.6-cm proton group, giving $Q=4.52$ Mev. No other proton groups have been reported.

Ref: Po 40, Mc 47

Note added in proof: Lattes, Fowler, and Cuer (La 47b, c) using 900 kev. deuterons observed short range protons indicating a level in Be^{10} at 3.40 Mev.

V. $B^{10}(np)Be^{10}$ $Q=0.20$ Mev (not illustrated)

Not observed—see B^{11}

VI. Be^{10} decay—see B^{10}

VII. $C^{13}(n\alpha)Be^{10}$ $Q=-3.94$ Mev

(5) This reaction was observed by Hughes, Eggler, and Huddleston (Hu 47).

Ref: Hu 47

B^{10}

I. $Li^6(\alpha p)Be^9$ $Q=-2.12$ Mev (not illustrated)

Shepherd, Haxby, and Hill (Sh 37) searched for protons, using RaC′ α-particles on Li, with negative results. They estimate $\sigma<0.01$ barn.

Ref: Sh 37

II. $Li^7(\alpha n)B^{10}$, B^{10*} $Q=-2.78$ Mev

(1) Haxel and Stuhlinger (Ha 39a) found levels in B^{10} by observing resonances in the production of slow neutrons at various α-particle energies. Steps in the slow neutron yield curve were observed for $E_\alpha \sim 5.0$ (threshold), 6.3, 7.2, 8.5 Mev, corresponding to excited levels in B^{10} at 0.8, 1.3, and 2.1 Mev. (The diagram representing these transitions is slightly distorted, since the energy required to produce neutrons of zero energy in laboratory coordinates is somewhat greater than the threshold value.)

Ref: Ha 39a

III. $Be^9(p\gamma)B^{10}$, B^{10*} $Q=6.49$ Mev

Herb, Kerst, and McKibben (He 37) studied the γ-ray yield from 0.6 to 1.6 Mev and reported a single broad resonance at $E_p=0.99$ Mev.

(2) Curran, Dee, and Petrzilka (Cu 39a) found resonances at 0.35 and 0.67 Mev and measured the γ-ray energies with coincidence counters as 6.8, 7.0, 7.15 Mev at $E_p=0.40$, 0.65, and 0.85 Mev.

Hole, Holtsmark, and Tangen (Ho 40d) confirm the resonance at 0.330 Mev and give the half-width as 150 kv.

(3) Hushley (Hu 45) resolved broad and narrow resonances at 0.96 and 1.06 Mev. He measured the energy of the radiation primarily from the 0.96 resonance as 7.50 Mev in good agreement with the value expected from mass calculations. He also found weak resonances at 1.36 and 0.86 and a strong resonance at 2.52 Mev, the latter leading to 3-Mev γ-radiation. This resonance coincides with a resonance for neutron production but the γ-rays and neutrons are not believed to be from the same reaction (see Be^9, pn). The γ-ray may be associated with the Be^9, $p\alpha$-reaction or may be from cascade transitions to the B^{10} ground state. Considerations of intensity and level width indicate the former as the more probable course of the decay.

(4) Fowler, Lauritsen, and Lauritsen (Fo 47, 48) locate the broad resonance at 988 kev and give the half-width as 94 kev ($\omega\gamma=12.5$ ev); they also confirm the 7.5 Mev-γ-ray. Study of the narrow resonance placed it at 1.077 Mev and gave a half-width of 4 kev ($\omega\gamma=0.77$ ev), γ-radiation of 6.7 ± 0.2 Mev (secondary absorption), and 0.7 ± 0.1 Mev (magnetic lens spectrometer) energies were observed, indicating a two-stage emission through the level at ~ 0.65 Mev.

Creutz (Cr 39) has observed proton scattering

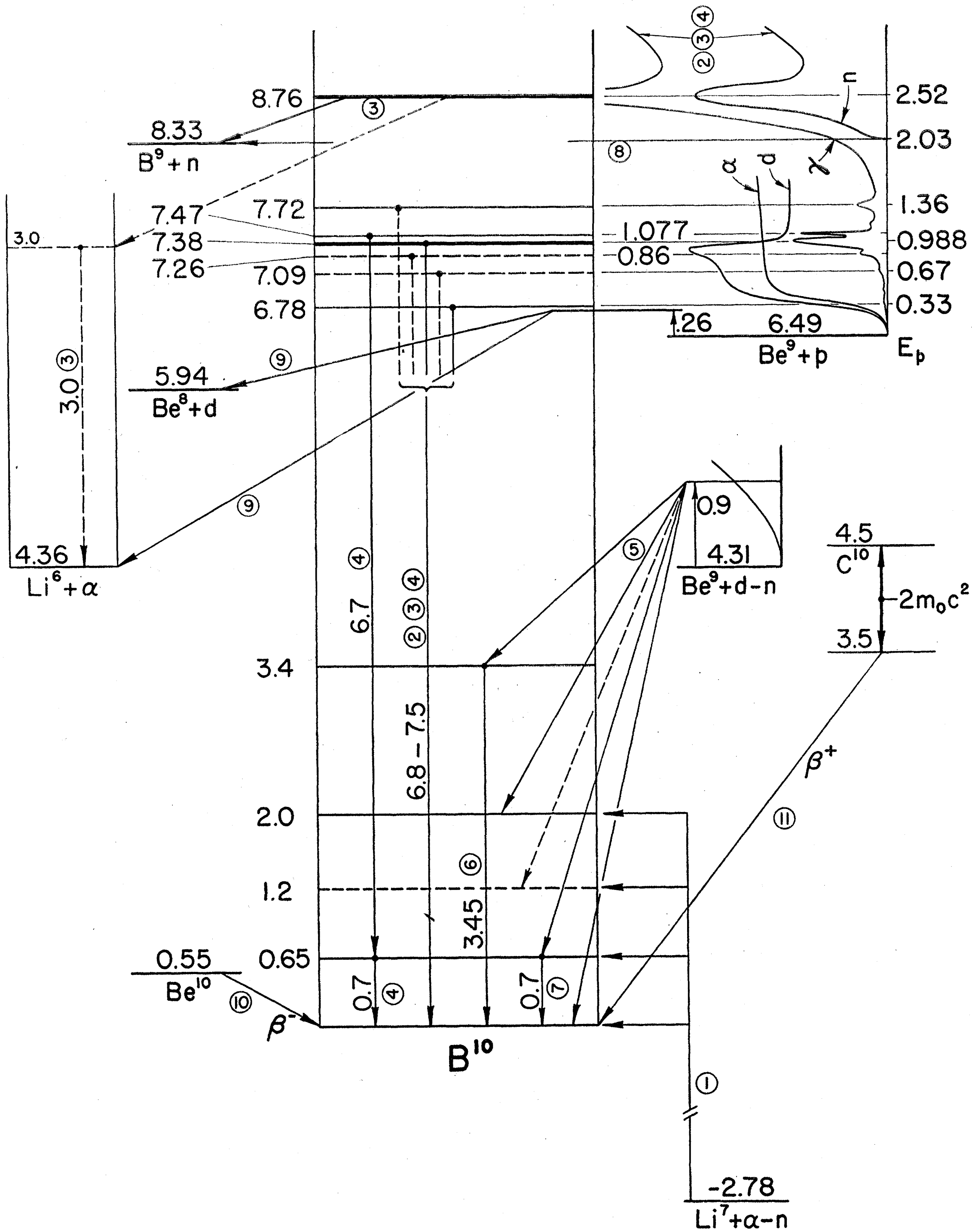


FIG. 7. *Energy levels in* B^{10}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Total energy change in the positron decay of C^{10} is $E_{max}^{+}+2m_0c^2$.

in Be from $E_p=0.3$ to 0.5 Mev and finds no anomalies.

Ref: He 37, Cr 39, Cu 39a, Ho 40d, Fo 47, Fo 48, Ru 47b

IV. $Be^9(dn)B^{10}$, B^{10*} $Q=4.31$ Mev

(5) Bonner and Brubaker (Bo 36b) measured the neutron spectrum at $E_d=0.9$, yielding levels in B^{10} at 0.55, 2.15, and 3.45 Mev. Staub and Stephens (St 39b) measured the neutron groups at $E_d=0.6$ and 0.88 Mev (max) yielding levels at 0.63, 1.93, and 3.52 Mev. A neutron group corresponding to a level at 1.2 Mev is not excluded by either set of data.

Kruger, Stallman, and Shoupp (Kr 39) report 31 γ-lines, from Compton electrons and pairs and deduce levels in B^{10} at 0.26, 0.50, 0.61, 1.44, 1.93, 2.92, 3.64, 4.73 Mev.

(6) Crane, Halpern, and Oleson (Cr 40) measured Compton recoils from γ-rays with 0.6 Mev deuterons and obtained lines at 3.45 ± 0.2 and ≤ 1.0 Mev. They find no evidence for the other lines reported by Kruger, Stallman, and Shoupp.

(7) Fowler, Lauritsen, and Lauritsen (unpublished) have established a γ-ray line at 0.7 Mev (magnetic lens spectrometer).

Note added in proof: Recent work has resolved the 0.65 Mev level into two levels at 0.42 and 0.72 Mev. The 1.2 Mev level has been relocated at 1.46 Mev.

Ref: Bo 36b, Am 37, Kr 37, Kr 39, Po 39b, St 39b, Cr 40, Po 42

V. $Be^9(pn)B^9$ $Q=-1.84$ Mev

(8) Haxby, Shoupp, Stephens, and Wells (Ha 40a) give 2.03 Mev as the threshold for the production of neutrons by proton bombardment of Be^9 ($Q=-1.83$).

Hanson and Benedict (Ha 44) give 2.058 ± 0.006 Mev based on slightly different voltage scale (see Be^8: Li^7, $p\gamma$).

Hushley (Hu 45) observed a resonance for neutron production at $E_p=2.52$ Mev (see Be^9, $p\gamma$).

Ref: Do 37, Ha 40, Ha 40a, Hi 40, My 42, Ha 44, Hu 45

VI. $Be^9(p\alpha)Li^6$ $Q=2.12$ Mev
$Be^9(pd)Be^8$ $Q=0.54$ Mev

(9) Allison, Skaggs, and Smith (Al 40a) have determined Q values for the reactions $Be^9(p\alpha)Li^6$ and $Be^9(pd)Be^8$ as 2.115 ± 0.04 and 0.547 ± 0.006 by electrostatic deflection of the α-particles and deuterons. Mattauch (Ma 40) suggest values of 2.078 and 0.534 from this work. Excitation functions for deuterons and α-particles have been studied in this laboratory (unpublished). The 3.0-Mev γ-radiation discussed under Be^9, $p\gamma$ is probably to be associated with the Be^9, $p\alpha$ reaction indicating an otherwise unconfirmed level in Li^6 at 3.0 Mev.

Ref: Al 37, Wi 37d, Al 38a, Ha 38a, Al 39, Sk 39, Al 40a, Ma 40

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

(10) Hughes, Eggler, and Huddleston (Hu 47) give 2.9×10^6y for the half-life and 0.58 ± 0.03 Mev for the maximum energy of the electron spectrum.

Levinger and Meiners (Le 47) searched for γ-radiation with negative results. McMillan (Mc 47) reports a half-life of $2.5\pm0.5\times10^6$y and 0.56 ± 0.01 Mev for the spectrum limit.

Ref: Po 40, Co 41, Mc 46, Pi 46, Hu 47, Le 47, Mc 47

VIII. $C^{10}(\beta^+)B^{10}$ $Q=3.5$ Mev

(11) Delsasso *et al.* (De 40) give a half-life of 8.8 ± 0.8 sec. and a maximum positron energy of 3.36 ± 0.1. No transitions other than to the ground state of B^{10} have been observed.

Ref: De 40, Co 41

B^{11}

I. $Li^7(\alpha\alpha')Li^{7*}$—see Li^7 (not illustrated)

II. $Li^7(\alpha n)B^{10}$, B^{10*} $Q=-2.78$ Mev

Bothe and Becker, and Curie and Joliot observed neutron production with Po α-particles (Li 37).

(1) Haxel and Stuhlinger (Ha 39a) observing resonances for the production of neutrons, found indications of levels at 13.0, 13.5, 13.8, and 14.2 Mev in B^{11}.

Ref: Sc 35, Li 37, Ha 39a

III. $Be^9(d\alpha)Li^7$, Li^{7*} $Q=7.09$ Mev

(2) Graves (Gr 40) has measured two groups of α-particles indicating transition to the ground state and the first excited state in Li^7. The yield of α-particles rises monotonically from 235 to 390 kv. The Q for the ground state transition is given as 7.093 ± 0.022 Mev.

Ref: Ha 37a, Al 40, Gr 40, Sk 40

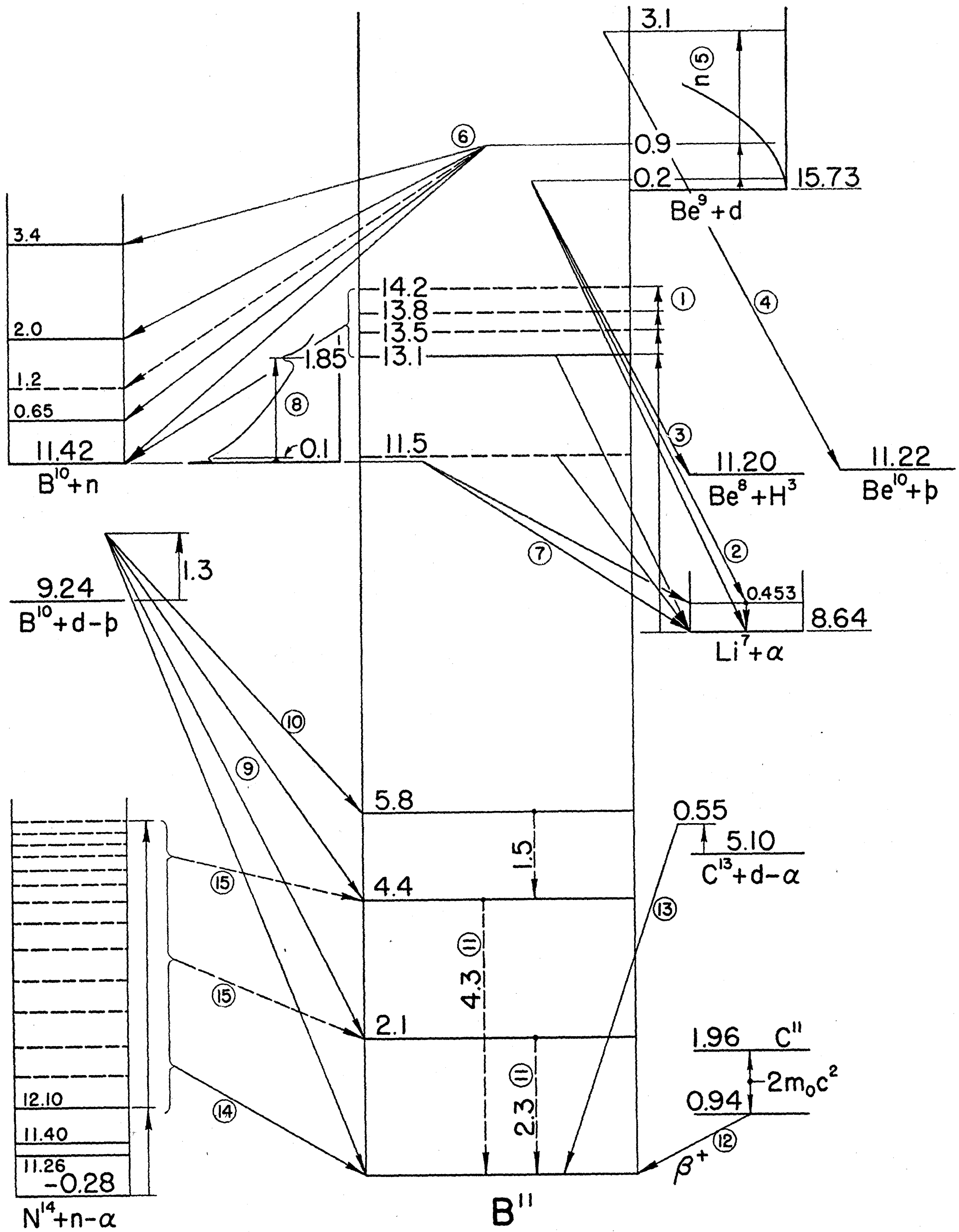


FIG. 8. *Energy levels in* B^{11}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Total energy change in the positron decay of C^{11} is $E_{max}{}^{+}+2m_0c^2$.

IV. $Be^9(dH^3)Be^8$ $Q=4.53$ Mev

(3) Williams, Haxby, and Shepherd (Wi 37d), using deuterons of 0.225 Mev energy, observed H^3 particles of 8.94±0.10-cm range giving a Q of 4.32±0.06 Mev.

O'Neal and Goldhaber (On 40) made a chemical identification of the H^3 from Be bombarded by 1-Mev deuterons.

Ref: Wi 37d, Li 39, On 40

V. $Be^9(dp)Be^{10}$ $Q=4.52$ Mev

McMillan (Mc 47) has obtained a rough excitation function for this reaction, indicating a maximum between $E_d=6$ and 9 Mev.

(4) Pollard (Po 40) measured the proton range as 52.6 cm with $E_d=3.1$ Mev, giving a Q value of 4.52 Mev. Williams, Haxby, and Shepherd (Wi 37d) report a Q of 4.44 Mev.

Ref: Wi 37d, Po 40, Mc 46, Pi 46, Le 47, Mc 47

VI. $Be^9(dn)B^{10}$, B^{10*} $Q=4.31$ Mev

(5) Amaldi, Hafstad, and Tuve (Am 37) found a smooth rise in the neutron yield from $E_d=0.3$ to 1.0 Mev.

(6) Bonner and Brubaker, and Staub and Stephens have studied the neutron groups from this reaction (see B^{10}).

Ref: Am 37, Be 37a

VII. $B^{10}(n\alpha)Li^7$, Li^{7*} $Q=2.78$ Mev

(7) Two α-particle groups exist, with Q values of 2.82 (7 percent) and 2.40 Mev (93 percent) (Bo 45), corresponding to transitions to the ground and first excited states of Li^7 (see Li^7: B^{10}, $n\alpha$).

Roaf (Ro 36) observed a single cloud chamber track indicating this reaction for a neutron of energy $>10^5$ ev.

(8) The curves of Goldsmith and Ibser (Go 46) indicate a resonance for 1.85-Mev neutrons and possibly one for 0.1-Mev neutrons, indicating levels at 11.5 and 13.1 Mev in B^{11}.

Ref: Ku 35, Ta 35a, Ro 36, Fu 37, Ha 37, Bo 38, Bü 38a, Ku 38, Li 38, Oc 38, Fi 39a, Go 39, Go 39a, Hi 39b, Ma 39a, Wi 40, Ch 44, Bo 45, Ba 46, Ba 46b, Go 46, Ma 46, Ma 46a, Ra 46, Fe 47, Su 47

VIII. $B^{10}(nH^3)Be^8$ $Q=0.22$ Mev
(not illustrated)

Chadwick and Goldhaber, and Taylor observed this reaction, presumably due to fast neutrons (Li 37).

Ref: Li 37, Co 41a

IX. $B^{10}(np)Be^{10}$ $Q=0.20$ Mev (not illustrated)

Maurer and Fisk (Ma 39a) and Kurtschatow *et al.* (Ku 38) claimed to observe this reaction with slow neutrons, but Bøggild (Bo 45) finds no trace of it (<1 percent of B^{10}, $n\alpha$-yield). Bretscher (Br 40) estimates $\sigma<2\times10^{-4}$ barn.

Ref: Ku 35, Ku 38, Fi 39a, Ma 39a, Br 40, Bo 45

X. $B^{10}(dp)B^{11}$ $Q=9.24$ Mev

(9) Cockroft and Lewis found proton groups with extrapolated ranges (Li 37) of 90.7 ± 0.6, 58.7 ± 0.7 and 30.7 ± 0.3 cm, indicating levels in B^{11} at 2.14 and 4.43 Mev.

(10) Pollard, Davidson, and Schultz (Po 39a) found levels at 1.92 and 4.22 Mev confirming earlier results and, in addition, report a new level at 5.83 Mev.

(11) Gaerttner, Fowler, and Lauritsen (Ga 39) and Halpern and Crane (Ha 39b) report several γ-ray lines, three of which, at 1.5, 2.3, and 4.3 Mev, may possibly be identified with transitions in B^{11} (see C^{12}: B^{11}, *dn*).

Ref: Li 37, Ga 39, Ha 39b, Po 39a, Po 39b, Po 42, La 47b

XI. $C^{11}(\beta^+)B^{11}$ $Q=0.94$ Mev

(12) Townsend (To 40) has determined the spectrum limit as 0.981 ± 0.005 Mev and concludes that the spectrum is simple.

Siegbahn and Peterson (Si 45b) searched for γ-ray coincidences with negative results.

Smith and Cowie (Sm 41), and Solomon (So 41) give half-lives of 20.35 ± 0.08 and 20.42 ±0.06 min., respectively.

Ref: De 40, To 40, Co 41, Sm 41, So 41, Si 44, Si 45b

XII. $C^{13}(d\alpha)B^{11}$ $Q=5.10$ Mev

(13) Cockcroft and Lewis observed 2.7-cm α-particles at $E_d=0.55$ Mev giving $Q=5.24$ Mev (Li 37).

Holloway and Moore (Ho 40c) give 2.86 cm as the range for α-particles produced by 1.02 Mev deuterons.

Bennett, Bonner, Hudspeth, Richards, and Watt (Be 41) have confirmed that the reaction is due to C^{13}.

Ref: Li 37, Ho 40c, Be 41

XIII. $N^{14}(n\alpha)B^{11}$, B^{11*} $Q=-0.28$ Mev

(14) Numerous resonances have been detected (largely by measuring the distribution of recoils produced by continuous energy-spectrum neutron sources) some of which can be correlated with resonances in the inverse process, indicating

that these, at least, leave B^{11} in the ground state (see N^{15}).

(15) Ortner and Protiwinsky (Or 38) report that some of the resonances can be associated with disintegrations leaving B^{11} excited to 2.25 or 4.25 Mev.

Szalay and Zimonyi (Sz 40) have investigated the γ-ray excitation curve for $N^{14}+n$, but transitions in B^{11}, if present, are masked by the np, γ-rays (see C^{13}: N^{14}, np).

Ref: Or 38, Or 38a, Or 39, Or 39a, Sz 40, Or 43

B^{12}

I. $B^{11}(n\gamma)B^{12}$ $Q=2.6$ Mev (not illustrated)

This reaction has not been observed.

II. $B^{11}(dp)B^{12}$ $Q=0.4$ Mev

(1) The activity of B^{12} produced in this reaction was studied by Lawrence and Thornton and by Crane and Lauritsen (Li 37). Protons have not been observed.

Ref: Ba 37, Li 37

III. $B^{11}(nH^3)Be^9(?)$ $Q=-9.57$ Mev

(2) Cornog and Libby (Co 41a) have observed H^3 produced in boron targets by 20 Mev-neutrons, possibly ascribable to this reaction.

Ref: Co 41a

IV. $B^{11}(n\alpha)Li^8$ $Q=-6.66$ Mev

(3) Lawrance (La 39) observed the α-particle radioactivity with $Li+d$ neutrons.

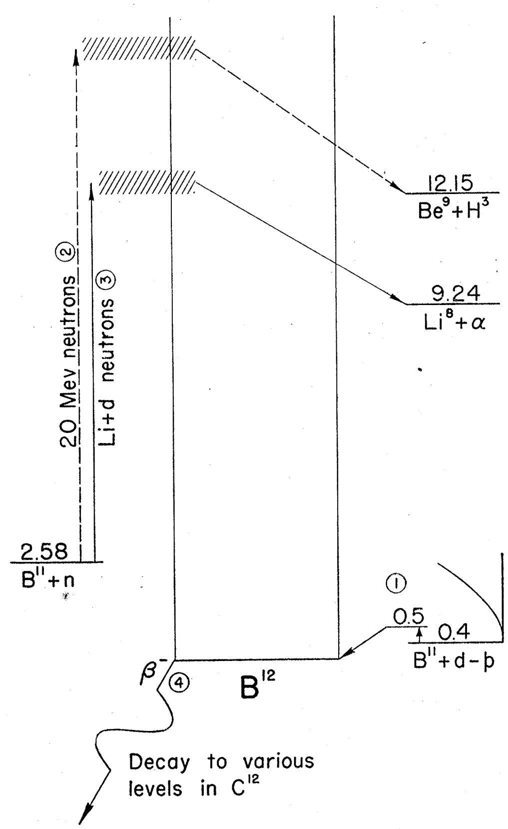
Ref: La 39

V. (4) B^{12} decay—see C^{12}

C^{10} (not illustrated)

I. $B^{10}(pn)C^{10}$ $Q=-5.2$ Mev

Delsasso *et al.* (De 40) observed the production of C^{10} with 6.4-Mev protons. They give a half-life



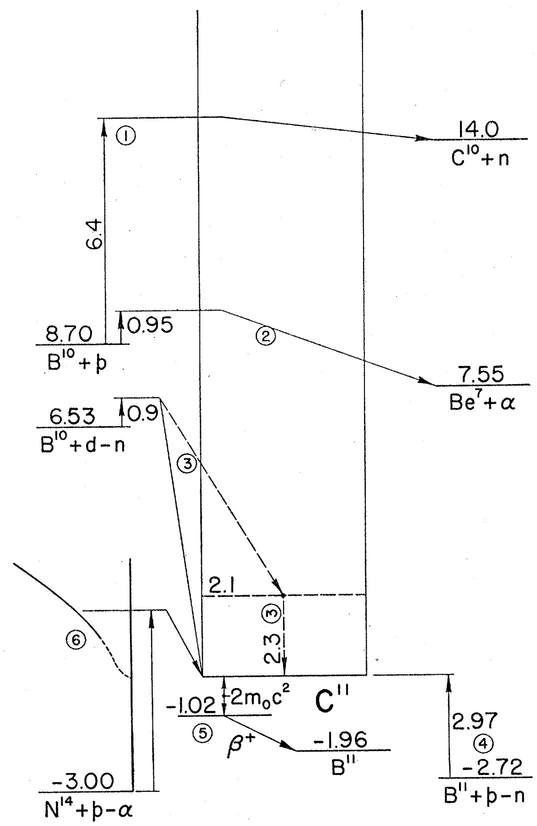


FIG. 9. *Energy levels in* B^{12}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale.

FIG. 10. *Energy levels in* C^{11}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Total energy change in the positron decay of C^{11} is $E_{max}^{+}+2m_0c^2$.

of 8.8±0.8 sec. and a visual positron upper limit of 3.36±0.1 Mev (see B^{10}).

Ref: De 40

II. C^{10} decay—see B^{10}

C^{11}

I. $B^{10}(p\gamma)C^{11}$ $Q=8.70$ Mev (not illustrated)

Crane and Lauritsen (Cr 34) reported C^{11} production at $E_p=0.9$ Mev.

Curran, Dee, and Petrzilka (Cu 39a) could find no effect at $E_p=0.96$ Mev and suggest that the earlier results may have been due to deuteron contamination (B^{10},dn,C^{11}). The expected ~9 Mev γ-ray has not been observed (Fo 38).

Ref: Cr 34, Fo 38, Cu 39a

II. $B^{10}(pn)C^{10}$ $Q=-5.2$ Mev

(1) Delsasso *et al.* (De 40) observed this reaction at $E_p=6.4$ Mev.

Ref: De 40

III. $B^{10}(p\alpha)Be^7$ $Q=1.15$ Mev

(2) Roberts, Heydenburg, and Locher (Ro 38a) observed the Be^7 activity at $E_p=0.95$ Mev. Alpha-particles were not observed.

Ref: Ma 38, Ro 38a, Cu 39a

IV. $B^{10}(dn)C^{11}$ $Q=6.53$ Mev

(3) The C^{11} activity was observed by Crane and Lauritsen (Li 37). Two of the neutron groups observed from $B+d$ may be associated with this reaction (see C^{12}: B^{11}, dn).

Ref: Li 37

V. $B^{11}(pn)C^{11}$ $Q=-2.72$ Mev

(4) Barkas (Ba 39a) observed this reaction at $E_p=5.9$ Mev.

Haxby *et al.* (Ha 40a) determined the threshold for neutron production as $E_p=2.97\pm0.01$ Mev.

Ref: Ba 39a, De 40, Ha 40a

VI. (5) C^{11} decay—see B^{11}

VII. $C^{12}(n2n)C^{11}$ $Q=-18.68$ Mev (not illustrated)

Sherr (Sh 45) gives $E_n\sim21.5$ Mev for the threshold.

Ref: Po 37, Je 44, Sh 45

VIII. $N^{14}(p\alpha)C^{11}$ $Q=-3.00$ Mev—see B^{11}

(6) Barkas (Ba 39a) observed the reaction and made a chemical identification of the C^{11}. The excitation function shows a smooth rise from $E_p\sim5$ to 6 Mev.

Ref: Ba 39a

C^{12}

I. $Be^9(\alpha n)C^{12}$, C^{12*} $Q=5.75$ Mev

(1) Early work (Li 37) indicated neutron groups corresponding to levels in C^{12} at 3.0, 4.4, and 6.4 Mev. In addition, a preponderance of relatively slow neutrons was observed for thorium α-particles not evident with polonium α-particles (see C^{13}: $Be^9,\alpha\alpha',Be^{9*}$). Gamma-radiation of energy 6.7, 4.2, and 2.7 Mev was measured by Bothe. Maier-Leibnitz (Ma 36) observed $\gamma-n$ and $\gamma-\gamma$ coincidences and concluded that the components at 4.2 and 2.7 Mev are the result of a cascade transition from the 6.7-Mev state. (Particle groups and γ-rays in this and other reactions variously quoted as leading to levels from 6.0 to 7.6 Mev have arbitrarily been associated here with a single level at 7.1±0.4 Mev.)

Szalay and Zimonyi (Sz 40) studied the γ-ray yield for $E_\alpha=0$–5 Mev. They observed a threshold at $E_\alpha=1.62$ Mev but found no resonances to 5 Mev. They conclude that the predominant mode of disintegration involves a transition to the 6.7 (7.1±0.4)-Mev state in C^{12} from a continuum in C^{13}, and that the neutron resonances observed (see C^{13}: $Be^9,\alpha n$) relate to transitions to the ground state. Resonant transitions to other states (<9 Mev) must be very weak indeed, since the corresponding γ-ray resonances do not appear.

(2) Stuhlinger (St 39) observed resonances for slow neutron production at $E_\alpha=4.8$ (threshold) 5.6, 6.8, and 7.5 Mev ($Q=-3.9$, -4.7, -5.2) the last three of which are attributed to levels in C^{12} at 9.5, 10.3, and 10.8 Mev. The threshold at 4.8 is attributed to the onset of the reaction $Be^9(\alpha\alpha')Be^{9*}$.

Ref: Ma 36, Ba 37a, Do 37, Li 37, St 39, Sz 40, Ri 46

II. $B^{11}(dn)C^{12}$, C^{12*} $Q=13.78$ Mev

(3) Bonner and Brubaker (Bo 36b) observed neutron groups with $Q=13.4$, 9.0, 6.0, and 3.9 Mev, and relative intensities (Ga 39) 0.36, 0.38,

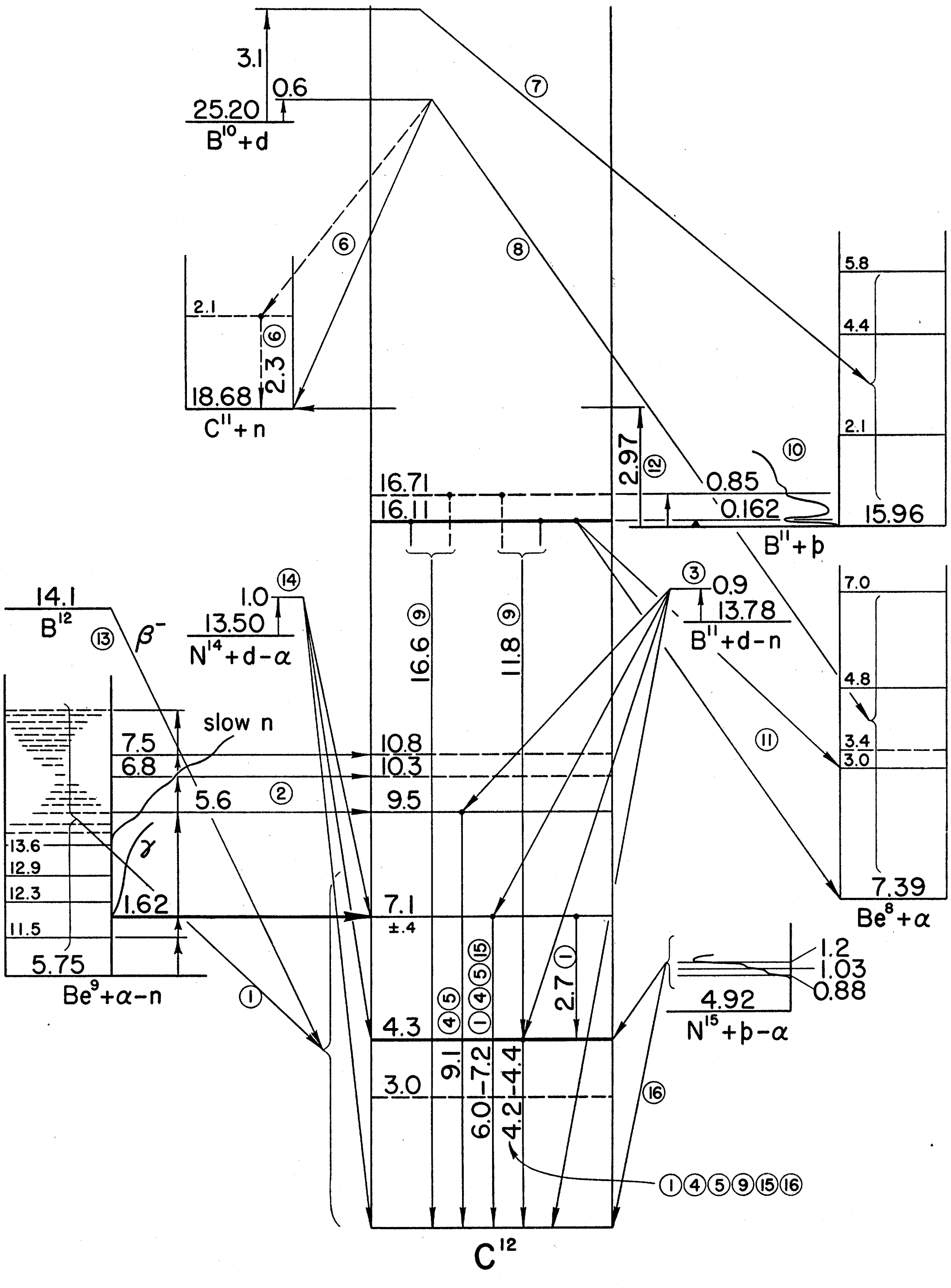


FIG. 11. *Energy levels in* C^{12}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Yield functions for the $Be^9(\alpha n)$ and $N^{15}(p\alpha)$ reactions are for thick targets. The B^{12} β-decay is complex.

0.07, 0.2 (last two may be due to the reaction B^{10}, *dn*). These groups have been confirmed by Powell (Po 42). (States in $C^{12}=4.4$, 7.4, 9.5 Mev.)

(4) Gaerttner, Fowler, and Lauritsen (Ga 39) report γ-rays of 1.5, 2.2 ± 0.3, 4.4 ± 0.3, 6.9 ± 0.4, and 9.1 ± 0.4 Mev with relative intensities of >2.5, ~2.5, 1.0, 0.3, 0.1. The first three of these lines may be associated with the $B^{10}(dn)$ or $B^{10}(dp)$ reactions.

(5) Halpern and Crane (Ha 39b) confirm the above lines, giving values of 1.4, 2.4, 4.2, 6.0, and 9.1 Mev with relative intensities of 1, 1, 6, 2, 1 (different bombarding energy).

Ref: Bo 36b, St 37, Ga 39, Ha 39b, Po 39b, Po 42

III. $B^{10}(dn)C^{11}$, (C^{11*}?) $Q=6.53$ Mev

(6) Neutron groups from $B+d$ at $Q=6.0$ and 3.9 may relate to this reaction. The production of C^{11} has been observed (Li 37).

Ref: Li 37

IV. $B^{10}(dp)B^{11}$, B^{11*} $Q=9.24$ Mev

(7) Proton groups corresponding to transitions to several states in B^{11} are known. Excitation function not reported. See B^{11}.

V. $B^{10}(d\alpha)Be^8$, Be^{8*} $Q=17.81$ Mev

(8) Smith and Murrell (Sm 39) observed transitions to ground state and to excited states at ~3.0 and ~7.5 Mev in Be^8.

Ref: Sm 39

VI. $B^{10}(\alpha d)C^{12}$ $Q=1.44$ Mev (not illustrated)

Zlotowski (Zl 38), using a cloud chamber with a magnetic field, found evidence for deuterons from this reaction. Ten tracks ascribed to deuterons were observed.

Ref: Po 35, Jo 38a, Zl 38

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

(9) Fowler, Gaerttner, and Lauritsen (Fo 38) report three γ-ray lines, at 16.6 ± 0.6, 11.8 ± 0.5, and 4.3 ± 0.3 Mev, with relative intensities of <0.12, 1, <1.5, indicating transitions to ground state of C^{12} and to the excited state at 4.3 Mev.

(10) Waldman *et al.* (Wa 38) report that γ-rays and α-particles (from B^{11}, $p\alpha$) have the same resonance, at $E_p=165\pm4$ kev.

Herb, Kerst, and McKibben (He 37) found a weak resonance at 0.850 Mev and a smooth rise up to 1.8 Mev.

Curran, Dee, and Petrzilka (Cu 39a) report γ-ray resonances at 0.850, 0.950, and possibly 0.650 Mev.

Ref: Bo 37e, Ge 37, Ge 37a, He 37, Fo 38, Wa 38, Cu 39a, Ka 40, Ho 41, Zu 43

VIII. (*a*) $B^{11}(p\alpha)Be^8$ $Q=8.57$ Mev
(*b*) $B^{11}(p\alpha)Be^{8*}$ (3.0 Mev level) $Q^*=5.62$

(11) Alpha-particles from reaction (*a*) occur as a homogeneous group (~1 percent) with $Q=8.60$ (Li 37); those from (*b*) as a continuous distribution with a pronounced maximum at ~4 Mev with $Q=5.77$ (Li 37, Wh 41). The angular distribution has been studied by Neuert (Ne 39), Haxby, Allen, and Williams (Ha 39), and Jacobs and Whitson (Ja 41). The last named authors conclude that the distribution is spherically symmetric for both groups at $E_p=160$ and 200 kev.

Williams, Wells, Tate, and Hill (Wi 37a) reported a resonance for the homogeneous α-particles from reaction (*a*) but found that reaction (*b*) gave a continuous rise. Jacobs and McLean (Ja 41a), on the other hand, report that all α-particles of range >2.0 cm (i.e., including group b) show a resonance at 158 ± 3 kev.

Marvin (Ma 45) gives 162 ± 1 kev for the location of the α-particle resonance and <5.5 kev for the half-width.

Ref: Ki 37, Ne 37, Ne 37a, Wi 37a, Al 38, La 38, Ne 38a, Ne 38b, Op 38, Bo 39b, Fi 39, Ha 39, Hi 39, Ne 39, Ja 41, Ja 41a, Wh 41, Ma 45

IX. $B^{11}(pn)C^{11}$ $Q=-2.72$ Mev

Barkas (Ba 39a) observed the C^{11} activity with 5-Mev protons.

(12) Haxby, Shoupp, Stephens, and Wells (Ha 40a) give as the threshold $E_p=2.97\pm0.01$ Mev.

Ref: Ba 39a, De 40, Ha 40a

X. $B^{12}(\beta^-)C^{12}$, C^{12*} $Q=14.1$ Mev

(13) Fowler, Delsasso, and Lauritsen (Fo 36) and Bayley and Crane (Ba 37) studied the electron spectrum of B^{12} and found it to be complex, indicating transitions to several states in C^{12}. The latter authors estimated 12 Mev for the upper limit but could find no evidence of γ-radiation. Bower and Burcham (Bo 39d) searched for γ-radiation, again with negative result.

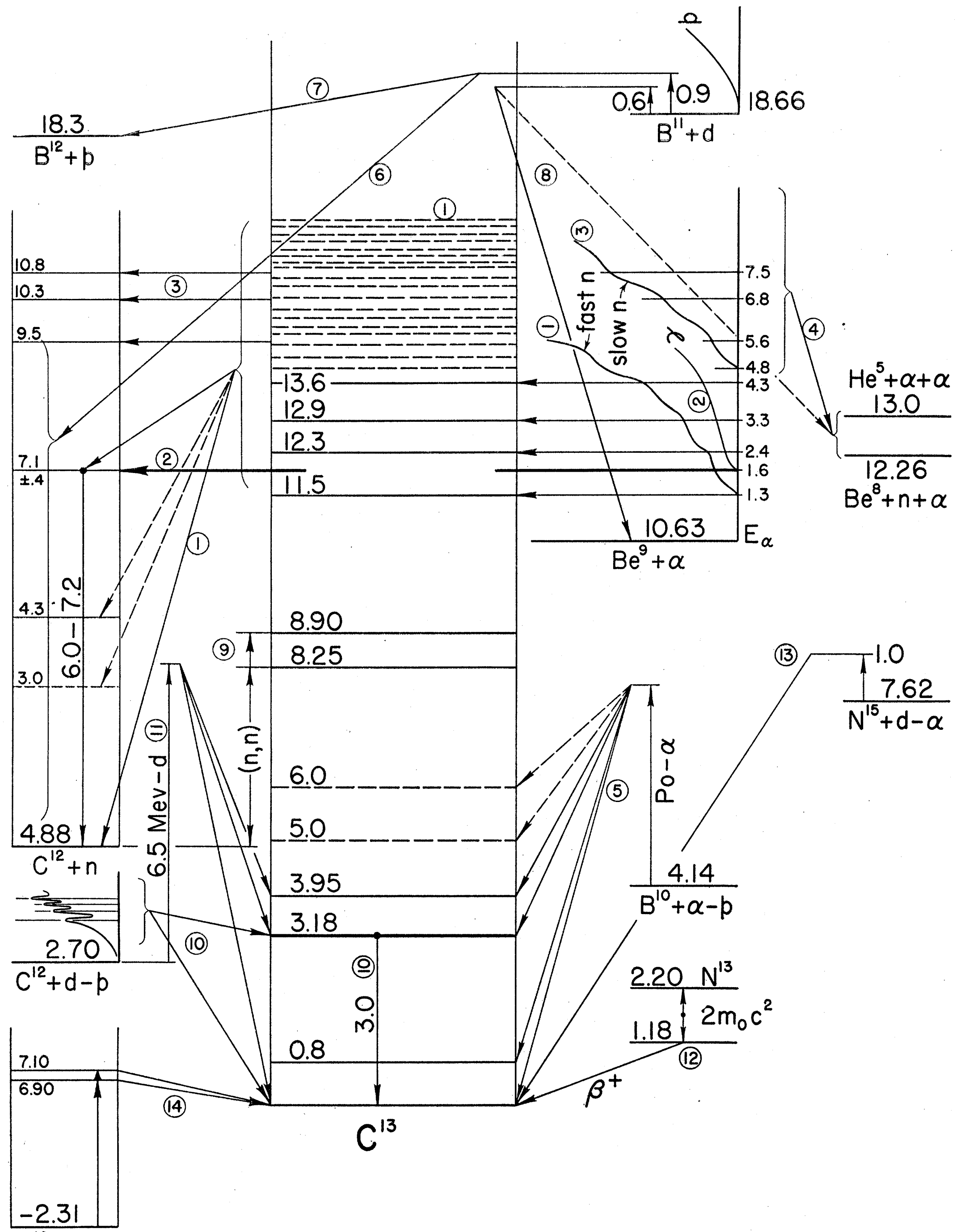


FIG. 12. *Energy levels in* C^{13}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Yield functions for the $Be^9(\alpha n)$ reaction are for thick targets. Total energy change in the positron decay of N^{13} is $E_{max}^{+}+2m_0c^2$.

Becker and Gaerttner (Be 39) determined the half-life as 0.022 ± 0.002 sec.

Ref: Fo 36, Ba 37, Be 39, Bo 39d

XI. $C^{12}(\gamma n)C^{11}$ $Q=18.68$ Mev (not illustrated)

Baldwin and Koch (Ba 45) give 18.7–19.4 Mev for the threshold.

Ref: Ba 45

XII. $N^{14}(d\alpha)C^{12}$, C^{12*} $Q=13.50$ Mev

(14) Holloway and Moore (Ho 40) report three groups of α-particles, yielding Q values of 13.39, 9.02, and 5.77 Mev, and levels in C^{12} at 4.37 and 7.62 Mev; this result has been confirmed by Guggenheimer *et al.* (Gu 47).

(15) Gaerttner and Pardue (Ga 40) observed γ-ray lines at 2.2, 4.2, 5.3 ± 0.4, 7.2 ± 0.4, ~ 11 Mev, of which the second and fourth may be associated with this reaction (see N^{14}, dp).

Ref: Pa 39, Cr 40, Ga 40, Ho 40, Ch 44a, Gu 47

XIII. $N^{15}(p\alpha)C^{12}$, C^{12*} $Q=4.92$ Mev

(16) Holloway and Bethe (Ho 40b) observed the α-particles and give $\sigma = 1.3 \times 10^{-26}$ cm² at $E_p = 0.36$ Mev. (Short range α-particles have not been observed.)

Fowler and Lauritsen (Fo 40) measured the γ-ray energy as 4.4 ± 0.2 Mev and found resonances at $E_p = 0.88$, 1.03, and 1.2 Mev.

Ref: Fo 40, Ho 40b, La 41

C^{13}

Ia. $Be^9(\alpha n)C^{12}$, C^{12*} $Q=5.75$ Mev

(1) Fünfer (Fu 39) reports 22 levels for excitation energies of 2 to 6 Mev (12.6 to 16.6 Mev in C^{13}).

Stuhlinger (St 39) gives resonances for the production of fast neutrons at $E_\alpha = 1.3$ (threshold), 2.4, 3.3, and 4.3 Mev (levels in C^{13} at 11.5, 12.3, 12.9, 13.6 Mev). Values of earlier workers, summarized in this reference, are in good agreement on the first two levels.

(2) Szalay and Zimonyi (Sz 40) studied the γ-ray yield for $E_\alpha = 0$–5 Mev. They observed a threshold at 1.6 Mev but found no resonances to 5 Mev. They conclude that the predominant mode of disintegration involves a transition to the 6.7 (7.1 ± 0.4) Mev state in C^{12} from a continuum in C^{13} and that the resonances observed for neutron production involve only the ground state of C^{12}.

(3) Stuhlinger (St 39) observed resonances for the production of slow neutrons at $E_\alpha = 4.8$ (threshold: see Be^9, $\alpha\alpha'$, Be^{9*}), 5.6, 6.8, and 7.5 Mev, indicating levels in C^{12}. Since this region is higher in excitation than that investigated by Szalay and Zimonyi, the experiments are not contradictory.

Ref: Am 37a, Bj 38, Fu 39, St 39, Sz 40

Ib. $Be^9(\alpha\alpha')Be^{9*}$ $Q=-1.63$ Mev

(4) Bjerge (Bj 38) showed that the slow neutron yield attributed to this reaction started at $E_\alpha = 4.9$ Mev and that the observed γ-rays do not accompany this reaction (see Be^9).

Ref: Bj 38

II. $B^{10}(\alpha p)C^{13}$, C^{13*} $Q=4.14$ Mev

(5) Early work (Li 37) indicated proton ranges corresponding to Q values of (4.7 ± 0.5), 3.3, 0.5, 0.1, -0.78 and -1.86 Mev. Some of these groups may be due to the B^{11}, αp-reaction.

Jentschke (Je 40) and Merhaut (Me 40) give the Q for longest group as 3.86 and 3.85 Mev, respectively. Both authors confirm the next lower energy group ($Q \sim 3.3$ Mev). Joliot and Zlotowski (Jo 38a) obtained $Q=4.3$ Mev for the longest group but did not observe a group corresponding to $Q=3.3$. They did observe a group at $Q=2.0$. A later measurement (Zl 38) gave $Q=4.16$ for the long range group.

Bothe and v. Baeyer (Bo 35) observed γ-ray coincidences with the $Q=0.5$ group (3.18-Mev level) but Bothe and Maier-Leibnitz (Bo 37d) did not observe γ-radiation accompanying the $Q=3.3$ group. They conclude that C^{13} is left in a metastable state at ~ 0.8 Mev.

The evidence seems to indicate definitely transitions to the ground state and excited states at 0.8 and ~ 3.6 Mev, the latter being accompanied by γ-ray emission. It is probable that the levels at ~ 3.6 and 4.0 Mev, respectively, can be identified with the states at 3.18 and 3.95 Mev known from the C^{12}, dp-reaction. The levels at 5.0 and 6.0 Mev are uncertain.

Ref: Ba 35, Bo 35, Bo 37d, Li 37, Ma 37a, Po 37a, Jo 38, Jo 38a, Zl 38, Ju 39, Je 40, Me 40, Sz 40

III. $B^{11}(dn)C^{12}$, C^{12*} $Q=13.78$ Mev

(6) Neutrons ($Q_{max}=13.4$) and γ-rays corresponding to transition to several states in C^{12} have been measured (see C^{12}: B^{11}, *dn*).

IV. $B^{11}(dp)B^{12}$ $Q=0.4$ Mev

(7) Bayley and Crane (Ba 37) measured the excitation curve for production of B^{12} and report a smooth rise from $E_d=0.2$ to 0.7 Mev. Protons have not been observed.

Ref: Ba 37

V. $B^{11}(d\alpha)Be^9$ $Q=8.03$ Mev

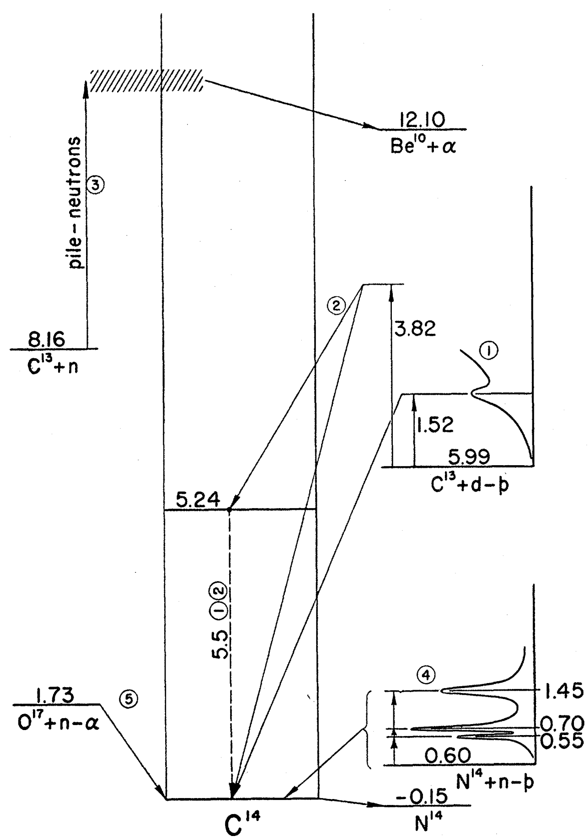
(8) Smith and Murrell (Sm 39), using isotopically enriched targets, established that the 4.6-cm α-particle group is caused by this reaction. The continuous group of α-particles below this range which might be expected from the formation of Be^{9*} with its subsequent decay by heavy particle emission could not be observed because of carbon contamination (α-particles from the C^{13}, $d\alpha$-reaction).

Ref: Sm 39

VI. $C^{12}(nn)C^{12}$

(9) Bailey *et al.* (Ba 46a) determined the scattering cross section for carbon from $E_n=0.35$ to 6.0 Mev, using monochromatic sources. Their results indicate levels in C^{13} at 8.25 and 8.90 Mev.

Ref: Ki 39c, Sa 39, Al 40c, Sa 40, Wa 40a, Ag 43, Sh 45, Ba 46a, Fr 46, Ma 46, Ag 47, Sl 47



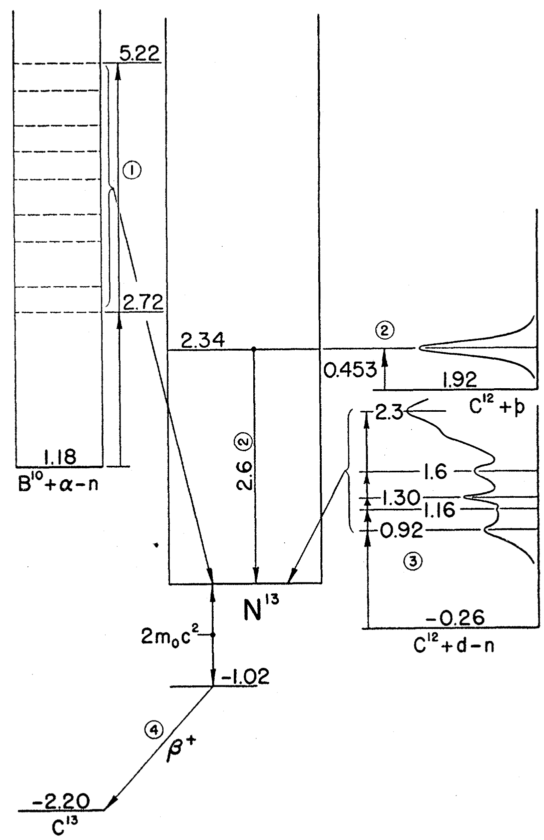


FIG. 13. *Energy levels in* C^{14}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, and yield plotted horizontally and bombarding particle energy indicated on a vertical scale.

FIG. 14. *Energy levels in* N^{13}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Total energy change in the positron decay of N^{13} is $E_{max}^{+}+2m_0c^2$.

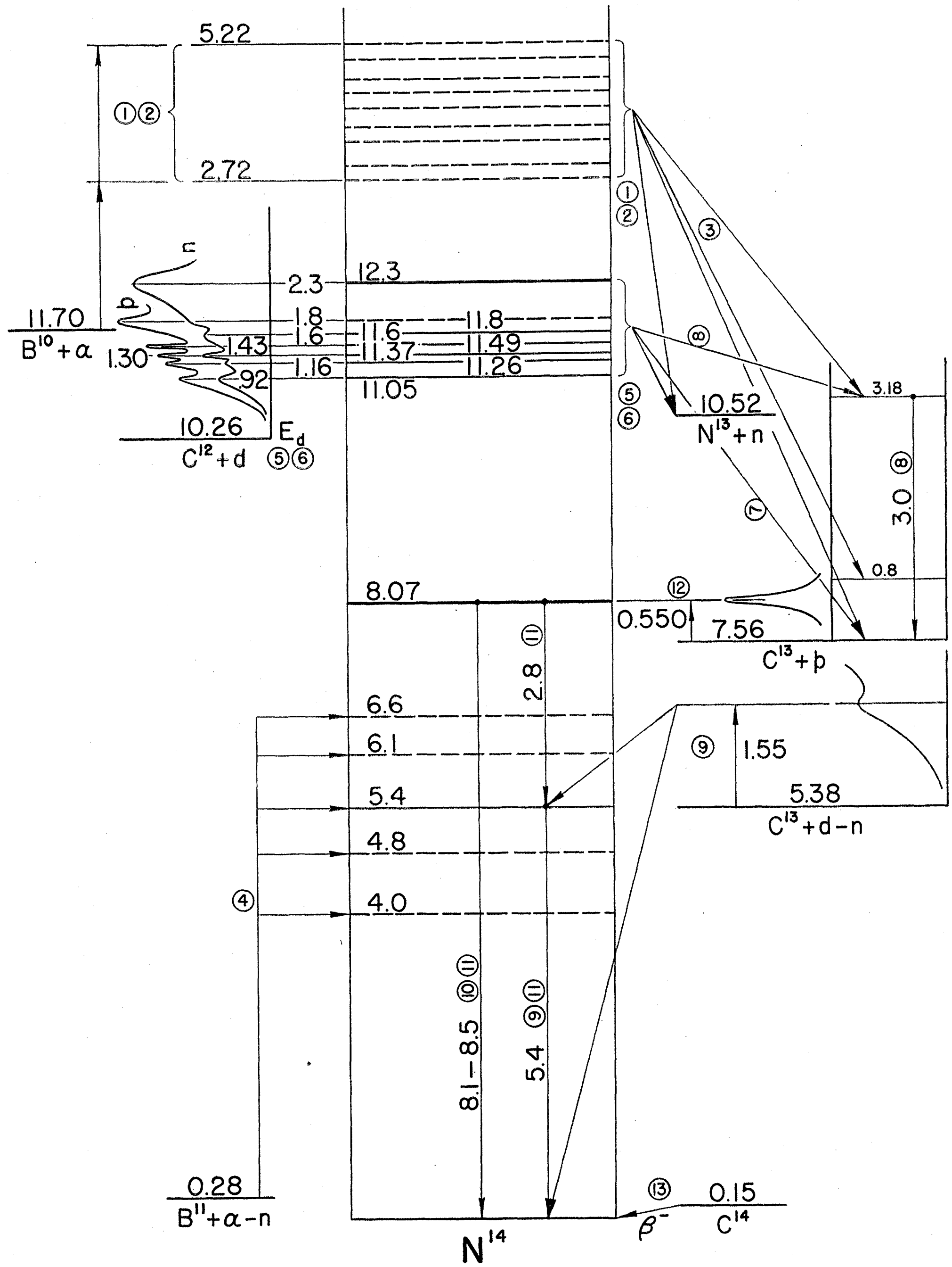


FIG. 15. *Energy levels in* N^{14}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale.

VII. $C^{12}(n2n)C^{11}$ $Q=-18.68$ Mev
(not illustrated)

Sherr (Sh 45) measured the threshold as ~ 21.5 Mev.

Ref: Po 37, Je 44, Sh 45

VIII. $C^{12}(n, n)3\alpha$ $Q=-7.34$ Mev
(not illustrated)

Aoki (Ao 38) observed nine stars in a cloud chamber attributed to this reaction (Li+d neutrons).

Ref: Li 37, Ao 38

IX. $C^{12}(dp)C^{13}$, C^{13*} $Q=2.70$ Mev

(10) Bennett *et al.* (Be 41) have observed two proton groups, $Q=2.71$ and -0.52 Mev. They obtained resonant yields for γ-rays and long range protons which were similar although not identical (see N^{14}: C^{12}, dp). At $E_d=1.6$ Mev about equal numbers of protons and γ-rays were observed.

Bonner, Becker, Rubin, and Streib (Bo 41) have measured the γ-ray energy as 3.0 ± 0.2 Mev.

(11) Guggenheimer, Heitler, and Powell (Gu 47), studying the scattering of 6.5-Mev deuterons in carbon, observed proton groups corresponding to states in C^{13} at 3.15 and 3.95 Mev.

Schultz, Davidson, and Ott (Sc 40a) looked for doublet structure in the protons and concluded that no transitions exist to levels in C^{13} in region of 0.3 Mev (see N^{13}, β^+, C^{13}).

Ref: Be 40, Be 40a, Ro 40, Sc 40, Sc 40a, Be 41, Bo 41a, Hu 41, Gu 47

X. $N^{13}(\beta^+)C^{13}$ $Q=1.18$ Mev

(There has been some question as to the existence of a γ-ray accompanying the decay of N^{13}, indicating a level in C^{13} at 0.29 Mev.)

(12) Siegbahn and Slätis (Si 45a) find that the β-spectrum is simple, with an upper limit of 1.24 ± 0.02 Mev and give the half-life as 10.13 ± 0.1 min. Examination of the γ-rays with a magnetic spectrometer (Si 45b) showed no radiation other than the annihilation radiation. Townsend (To 40) gives the spectrum end point as 1.218 ± 0.004 Mev, while Ward (Wa 39) gives 9.93 ± 0.03 min. for the half-life.

Langer, Cook, and Sampson (La 47) studied the annihilation γ-ray with high resolution and concluded that no other radiation exists >0.002 per disintegration from $E_\gamma=0.135$ to 0.70 Mev.

Ref: Ki 39a, Ly 39, Ly 39a, Op 39, Ri 39, Va 39, Wa 39, Wa 39a, Mo 40, To 40, Wa 40, Si 45, Si 45a, Si 45b, La 47, La 47a

XI. $N^{15}(d\alpha)C^{13}$ $Q=7.62$ Mev

(13) Holloway and Moore (Ho 40) observed 5.25-cm particles at $E_d=1.0$ Mev, giving $Q=7.54$ Mev (α-particles corresponding to transitions to excited states would not be observed in these experiments).

Ref: Ho 39a, Ho 40

XII. $O^{16}(n\alpha)C^{13}$ $Q=-2.31$ Mev

(14) Wilhelmy (Wi 37e) observed $\alpha+C^{13}$ recoils having energies of 0.65, 0.85, and 1.5(?) Mev with Po Be neutrons.

Ref: Wi 37e

C^{14}

I. $B^{11}(\alpha p)C^{14}$ $Q=0.88$ Mev (see N^{15}: B^{11}, αp)

II. $C^{13}(dp)C^{14}$, C^{14*} $Q=5.99$ Mev

Bower and Burcham (Bo 39d) observed 48-cm protons at $E_d=0.8$ and gave a Q value of 6.1 Mev.

(1) Bennett *et al.* (Be 41) observed a resonance for production of (54 cm) protons at $E_d=1.52$ Mev and gave $Q=6.09\pm0.2$ Mev. No other protons were found >20 cm, indicating that there are probably no levels in C^{14} below 2.8 Mev.

(2) Humphreys and Watson (Hu 41) observed two groups of protons at $E_d=3.82$ Mev with Q values of 5.82 and 0.58 Mev, indicating a level in C^{14} at 5.24 Mev. The known γ-ray (Bo 41a, Be 41) of 5 Mev may be associated with this level (see N^{14}: C^{13}, dn). (A corresponding proton group in the data of Bennett *et al.* would be masked by the C^{12}, dp-reaction.)

Ruben and Kamen (Ru 41) made a chemical identification of C^{14} from this reaction.

Ref: Bo 39d, Po 39, Be 40a, Ho 40c, Ru 40, Ru 40a, Sc 40, Sc 40a, Be 41, Bo 41a, Hu 41, Ru 41

III. $C^{13}(n\alpha)Be^{10}$ $Q=-3.94$ Mev

(3) Hughes, Eggler, and Huddleston (Hu 47) observed the Be^{10} radioactivity from this reaction.

Ref: Hu 47

IV. $N^{14}(np)C^{14}$ $Q=0.60$ Mev (see N^{15}: N^{14}, np)

(4) No transitions other than to the ground state are known.

V. $O^{17}(n\alpha)C^{14}$ $Q=1.73$ Mev

(5) Hincks (Hi 46) observed 1.4-Mev α-particles with an enriched sample bombarded with slow neutrons. He gives $\sigma=0.38$ barn.

Ref: Hi 46

VI. C^{14} decay—see N^{14}

N^{13}

I. $B^{10}(\alpha n)N^{13}$ $Q=1.18$ Mev

Ridenour and Henderson (Ri 37) give 4.6×10^{-6} disintegration per α-particle for the thick target yield at $E_\alpha=9$ Mev (pure B^{10} target).

(1) Szalay (Sz 39) observed resonances for production of N^{13} at several α-particle energies, from 2.7 to 5.2 Mev, all of which he attributes to levels in N^{14}. His data do not indicate whether transitions other than to the ground state may be involved.

Szalay and Zimonyi (Sz 40) studied the excitation of the γ-rays, but concluded that any effect in N^{13} would be obscured by the $\alpha-p$ reaction.

Ref: Ma 37, Ri 37, Sz 39, Sz 40, Ri 46

II. $C^{12}(p\gamma)N^{13}$ $Q=1.92$ Mev

Roberts and Heydenberg (Ro 38) observed a resonance for production of N^{13} at $E_p=0.450$ Mev and give the half-width as 30 kev. They estimated the integrated cross section as 8.4×10^{-24} volt cm^2.

(2) Curran, Dee, and Petrzilka (Cu 39a) reported the resonance for γ-rays at 480 kev and determined the γ-ray energy as 2.6 Mev.

Hole, Holtsmark, and Tangen (Ho 41) give the resonance value as 460 kev and estimate the half-width as 50 kev.

Fowler, Lauritsen, and Lauritsen (Fo 48) locate the resonance at $E_p=0.453$ Mev and give the half-breadth as 35 kev ($\omega\gamma=0.63$ ev).

Ref: De 38, Ro 38, Cu 39a, Ho 41, Fo 48

III. $C^{12}(dn)N^{13}$ $Q=-0.26$ Mev

Roberts and Heydenburg (Ro 38) have investigated the relative yield of neutrons and N^{13} from this reaction.

(3) Bennett and Richards (Be 47b) have shown that the neutrons are monochromatic at $E_d=2.0$ Mev, and give a Q value of -0.27 Mev.

Ref: Ro 38, Be 47b (see N^{14})

IV. $C^{13}(pn)N^{13}$ $Q=-2.96$ Mev (see N^{14})

V. (4) N^{13} decay (see C^{13})

N^{14}

I. $B^{10}(\alpha n)N^{13}$ $Q=1.18$ Mev

(1) Maurer (Ma 37) gives resonances for 3.02 and 4.42-Mev α-particles. (See N^{15}: B^{11}, αn.)

(2) Szalay (Sz 39) observed resonances for production of N^{13} at $E_\alpha=2.72$, 2.98, 3.43, 3.70, 4.05, 4.33, 4.59, 4.94, 5.22. He attributes Maurer's value of 4.42 Mev to B^{11}.

Ref: Ma 37, Ri 37, Sz 39

II. $B^{10}(\alpha p)C^{13}$, C^{13*} $Q=4.14$ Mev

(3) Several groups of protons have been observed, the longest range group being so weak as to have escaped observation in the earliest experiments.

Jentschke (Je 40) and Merhaut (Me 40) give $Q=3.86$ and 3.85 Mev, respectively, for this group.

Miller, Duncanson, and May, and Pollard (Li 37) report a resonance for 2.9-Mev α-particles and determine the top of the Coulomb barrier as 4.3 Mev.

Ref: Li 37, Je 40, Je 40a, Me 40, Me 40a, see C^{13}: $B^{10}(\alpha p)$

III. $B^{11}(\alpha n)N^{14}$, N^{14*} $Q=0.28$ Mev

(4) Stuhlinger (St 39) observed resonances for the production of slow neutrons by α-particles at $E_\alpha=5.1$, 6.15, 7.15, 8.05, 8.65 Mev, corresponding to states in N^{14} at 4.0, 4.75, 5.5, 6.1, 6.6 Mev. Of these, only the level at 5.5 Mev appears from other evidence (C^{13}, dn; C^{13}, $p\gamma$).

Szalay and Zimonyi (Sz 40) looked for γ-radiation but could not detect it in the presence of the radiation from $B^{10}(\alpha p)C^{13}$.

Ref: Li 37, St 39, Sz 40, Ri 46, see N^{15}: $B^{11}(\alpha n)$

IV. $C^{12}(dn)N^{13}$ $Q=-0.26$ Mev

Newson (Ne 37b) measured the yield of N^{13} for $E_d=2$ to 5 Mev and found a pronounced maximum at 3.0 Mev associated with the top of the Coulomb barrier.

(5) Bennett *et al.* (Be 41) report neutron and N^{13} resonances at $E_d=0.92$, 1.16, 1.30, (1.74?), and 1.82 Mev.

(6) Bailey, Phillips, and Williams (Ba 42) observed resonances in essential agreement with those of Bennett *et al.* and, in addition, a prominent peak at $E_d=2.3$ Mev.

Bennett and Richards (Be 47b) give $Q=-0.27 \pm 0.02$ Mev.

Ref: Ne 37b, Ro 38, Be 40, Bo 40a, To 40, Be 41, Ba 42, Be 47b

V. $C^{12}(dp)C^{13}$ $Q=2.70$ Mev

Cockroft and Lewis (Li 37) give $Q=2.71\pm0.05$ Mev.

Schultz, Davidson, and Ott (Sc 40a) observed 25-cm protons at $E_d=3.2$ Mev.

(7) Bennett *et al.* (Be 41) observed resonances for the ($\sim$15 cm) protons at $E_d=0.92$, 1.16, 1.23, (1.5?), and (1.7?) Mev and found 1.1-cm protons ($Q=-0.52\pm0.07$ Mev) corresponding to the observed 3.0-Mev γ-radiation. Gamma-ray resonances were found at $E_d=0.92$, 1.16, 1.30, 1.43, and 1.74 Mev. (Some slight differences appear in resonances for γ-rays, short range protons, and long range protons. The diagram illustrates the γ-ray and short-range proton yields.)

Humphreys and Watson (Hu 41) have observed 35-cm protons at $E_d=3.82$ Mev, giving $Q=2.38\pm0.15$.

(8) Bonner *et al.* (Bo 41a) measured the γ-radiation energy as 3.0 ± 0.2 Mev, with a weak line at 5.5 Mev due to C^{13}.

Ref: Li 37, Be 40, Be 40a, Ro 40, Sc 40, Sc 40a, Be 41, Bo 41a, Hu 41

VI. $C^{13}(dn)N^{14}$, N^{14*} $Q=5.38$ Mev

Bonner and Brubaker (Bo 36b) found a neutron group attributed to this reaction, having a Q of 5.2 Mev and a possible weaker group giving a Q of 1.2 Mev.

(9) Bennett *et al.* (Be 41), using enriched targets, determined the Q value of the neutron group leaving N^{14} in an excited state as 0.40 ±0.05 Mev. Using the Q for the ground state transition, based on mass values, of 5.38 Mev, the above neutron group must then leave N^{14} excited to $\sim$5.0 Mev. The γ-radiation which they associated with this reaction was determined to have an energy of 5.5 ± 0.2 Mev (see N^{15}: C^{13}, dp). The 5.5-Mev γ-rays show a resonance at $E_d=1.55$ Mev.

Ref: Bo 36b, Be 41, Bo 41a

VII. $C^{13}(p\gamma)N^{14}$, N^{14*} $Q=7.56$ Mev

(10) Curran, Dee, and Petrzilka (Cu 39a) observed a resonance for this reaction at $E_p=0.57$ Mev and determined the maximum energy of the γ-ray as 8.5 Mev. The spectrum appeared to be complex, indicating cascade transitions in addition to the direct transition to the ground state.

(11) Lauritsen and Fowler (La 40) measured the γ-ray energy in a cloud chamber, giving three lines, at 8.1 ± 0.2, 5.4 ± 0.3, and 2.8 ± 0.4, all of about equal intensity.

(12) Fowler, Lauritsen, and Lauritsen (Fo 48) locate the resonance at $E_p=0.550$ Mev and give the half-width as 40 kev ($\omega\gamma=15$ ev).

Ref: De 38, Ro 38b, Cu 39a, La 40, Ho 41, Fo 48

VIII. $C^{13}(pn)N^{13}$ $Q=-2.96$ Mev (not illustrated)

Haxby *et al.* (Ha 40a) give 3.20 ± 0.03 Mev for the threshold.

Ref: Ha 40a

IX. $C^{14}(\beta^-)N^{14}$ $Q=0.15$ Mev

(13) Ruben and Kamen (Ru 41) give 145 ± 15 kev for the maximum of the β-ray spectrum and estimate the half-life at 10^3–10^5 years.

Norris and Inghram (No 46) and Reid *et al.* (Re 46) give $5300y\pm15$ percent and $4700y\pm10$ percent, respectively, for the half-life.

Levy (Le 47a) studied the β-ray spectrum from a thick source in a spectrometer, concluding that the spectrum is probably simple and gives the upper limit as 154 ± 3 kev.

Ref: Po 39, Ru 40, Ru 40a, Sc 40, Ru 41, No 46, Re 46, Le 47a, St 47

X. $N^{14}(\gamma n)N^{13}$ $Q=-10.52$ Mev (not illustrated)

Bothe and Gentner (Bo 37) observed this reaction with 17-Mev γ-rays.

Baldwin and Koch (Ba 45) determined the threshold as 11.1 ± 0.5 Mev.

Ref: Bo 37, Bo 39c, Hu 42, Hu 43, Ba 45

XI. $O^{16}(d\alpha)N^{14}$ $Q=3.07$ Mev (not illustrated)

Guggenheimer, Heitler, and Powell (Gu 47) observed particle groups at $E_d=6.5$ Mev, but were unable to make a definite assignment to this reaction.

Ref: Gu 47

N^{15}

I. $B^{11}(\alpha n)N^{14}$ $Q=-0.28$ Mev

(1) Maurer (Ma 37) observed the neutron yield from boron as a function of the α-particle energy and reported resonances at $E_\alpha=1.76$, 2.53, 3.42, 4.11, 4.73, 4.91, 3.02, 4.42 Mev. Of these, the first four check well with Wilhelmy's data, obtained from the reverse reaction (see N^{14}, $n\alpha$). The last two are ascribed to $B^{10}(\alpha n)$.

Szalay (Sz 39) (see N^{14}: B^{10}, αn) has subsequently assigned the last value to $B^{11}(\alpha n)$.

Stuhlinger (St 39) has studied the excitation of neutrons as a function of α-particle energy in the region from $E_\alpha=4$ to 9 Mev. He reports 19 levels in N^{15} between 14.6 and 17.5 Mev, most of which fit reasonably well with those reported by Fünfer (Fu 39).

Ref: Bo 37c, Ma 37, Fu 39, St 39, Sz 39

II. $B^{11}(\alpha p)C^{14}$ $Q=0.88$ Mev (not illustrated)

Pollard (Po 39) reports protons of 42.1 and 97.6-cm range with Po and Th α-particles, respectively.

Ruben and Kamen (Ru 41) searched for C^{14} produced by 32-Mev α-particles, with negative results.

Ref: Po 39, Ru 41

III. $C^{13}(dn)N^{14}$, N^{14*} $Q=5.38$ Mev

(2) Bennett *et al.* (Be 41), using enriched targets, found a low energy group at $E_n=1.49$ Mev ($Q=0.40$ Mev) indicating a state in N^{14} at ~ 5.0 Mev. They also showed that a 5.5-Mev γ-ray is due to C^{13} and attributed it to this process (see C^{13}, dp). This γ-ray shows a resonance at $E_d=1.55$ Mev, superimposed on a general rise.

Ref: Bo 36b, Be 41

IV. $C^{13}(dp)C^{14}$ $Q=5.99$ Mev

(3) Bennett *et al.* (Be 41) give the proton range as 53.7 cm at $E_d=1.0$ Mev ($Q=6.09\pm 0.2$ Mev). The yield curve shows a broad resonance at $E_d=1.55$ Mev. No other protons were found <15 cm. (A group corresponding to a transition to the excited state in N^{14} reported by Humphreys and Watson would be masked by the C^{12}, dp-reaction.)

(4) Humphreys and Watson (Hu 41) observed 19- and 85-cm protons with 3.82-Mev deuterons in isotopically enriched targets, giving Q values of 0.58 and 5.82 Mev and indicating a 5.24-Mev excited level in C^{14}. These authors suggest that the 5.5-Mev γ-ray may be from this level. See $C^{13}(dn)$ above.

Ruben and Kamen (Ru 41) have made a chemical identification of C^{14} from this reaction.

Ref: Bo 39d, Be 40a, Ho 40c, Ru 40a, Sc 40, Sc 40a, Be 41, Hu 41, Ru 41

V. $C^{13}(d\alpha)B^{11}$ $Q=5.10$ Mev

(5) Cockcroft and Lewis observed the α-particles and gave $Q=5.24$ Mev (Li 37).

Holloway and Moore (Ho 40c) give 2.86 cm for the range with $E_d=1.02$ Mev (enriched target).

Ref: Li 37, Ho 40c, Be 41

VI. $N^{14}(dp)N^{15}$ $Q=8.57$ Mev

(6) Holloway and Moore (Ho 40) measured the proton ranges with isotopically enriched gas targets, at $E_d\sim 1.0$ Mev, yielding Q values of 8.51 and 3.15 Mev, indicating an excited state of 5.36 Mev in N^{15}.

Davidson and Pollard (Da 47) give Q values of 8.65 and 3.26, or 5.39 Mev for the level in N^{15}.

(7) Guggenheimer, Heitler, and Powell (Gu 47) studied the scattering in nitrogen of 6.5 Mev deuterons and measured proton groups corresponding to levels in N^{15} at 5.0, (6.0?), 7.2, and 8.2 Mev. The last two they believe to be doublets.

(8) Gaerttner and Pardue (Ga 40) observed γ-ray lines at 2.2, 4.2, 5.3 ± 0.4, 7.2 ± 0.4, and ~ 11 Mev, from N^{14} bombarded by deuterons, of which the third may be associated with this reaction. (The 4- and 7-Mev lines are probably associated with the N^{14}, $d\alpha$-reaction: see C^{12}.)

Crane, Halpern, and Oleson (Cr 40) observed lines at ~ 2.5, ~ 4.1, 5.1 ± 0.3, 6.6 ± 0.3, and 8.2 ± 0.5 Mev, the last of which may be from the 8.2-Mev level in N^{15}.

Ref: Ho 39a, Pa 39, Cr 40, Ga 40, Ho 40, Ch 44a, Da 47, Gu 47

VII. $N^{14}(np)C^{14}$ $Q=0.61$ Mev

Baldinger and Huber (Ba 39b) give $\sigma=0.04$ barn for 2.8-Mev neutrons.

LaPointe and Rasetti (La 40a) give $\sigma=1.2$ barns for thermal neutrons.

(9) Barshall and Battat (Ba 46c) observed resonances for $E_n=0.55$, 0.70, and 1.45 Mev and give $Q=0.71$ Mev. Huber (Hu 41a) gives $Q=0.55\pm 0.04$ Mev. Early data of Bonner (Li 37), recalculated by Stephens (St 47a) gives $Q=0.70$ Mev.

Bøggild (Bo 45) gives $Q=0.6$ Mev from cloud chamber measurements with slow neutrons.

Ruben and Kamen (Ru 41) detected the C^{14} produced.

Ref: Ba 39b, Ba 39c, Ba 39d, Hu 40a, Hu 40b, La 40a, Hu 41a, Ru 41, Bo 45, Ba 46c, St 47a

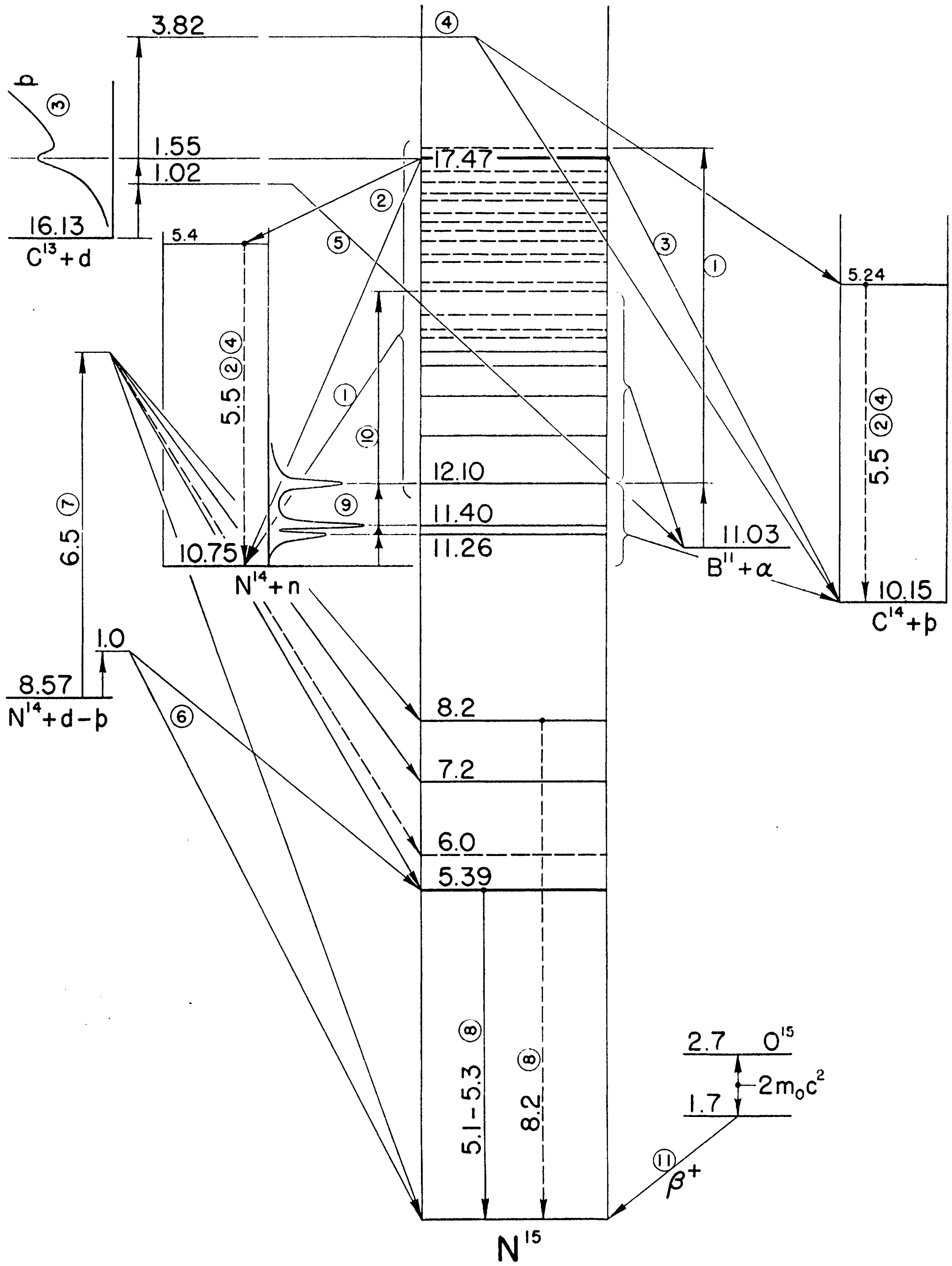


FIG. 16. *Energy levels in* N^{16}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. Total energy change in the positron decay of O^{15} is $E_{max}^{+}+2m_0c^2$.

VIII. $N^{14}(n\alpha)B^{11}$ $Q=-0.28$ Mev

(10) Wilhelmy (Wi 37e) observed the distribution of $\alpha+B$ recoils resulting from the bombardment of nitrogen by a continuous neutron spectrum. Groups are reported at $E_{\alpha+B}=1.42$, 2.04, 2.59, 3.21, and 4.9 Mev.

Fischer (Fi 42) obtained values of $E_{\alpha+B}$ of 1.55, 2.12, 2.59, 3.30, and 3.96 and compares his values with recalculated values from Wilhelmy and Maurer (see B^{11}, αn, above).

Ortner and Protowinsky (Or 43) and Zagor and Valente (Za 45) report numerous resonances for N^{15} with excitation energies of 12 to 18 Mev. (It does not seem that the correspondence of levels reported by all the various workers is sufficiently good to permit a unique determination of a level system.)

Barshall and Battat (Ba 46c) studied the excitation of α-particles with variable energy monochromatic neutrons and obtained a single resonance at $E_n=1.45$ Mev (no others <1.7). They give $\sigma=0.12$ barn and $Q=-0.26$ Mev.

Baldinger and Huber (Ba 39c) give $\sigma=0.16$ barn for 2.8-Mev neutrons and $Q=-0.43$ Mev.

Ref: Bo 37c, Wi 37e, Wi 37f, Or 38, Or 38a, Th 38, Ba 39b, Ba 39c, Ba 39d, Co 39b, Or 39, Or 39a, Hu 40a, Co 41d, Fi 42, Or 43, Ch 44b, Za 45, Ba 46c, Va 46

IX. $N^{14}(nH^3)C^{12}$ $Q=-4.10$ Mev
$N^{14}(nH^3)3\alpha$ $Q=-11.43$ Mev
$N^{15}(nH^3)C^{13}$ $Q=-9.97$ Mev
(not illustrated)

Cornog and Libby (Co 41a) have reported the formation of H^3 in the bombardment of nitrogen compounds by 20-Mev neutrons.

Ref: Co 41a

X. $O^{15}(\beta^-)N^{15}$ $Q=1.7$ Mev

(11) O^{15} decays with a half-life of 126 sec. The spectrum limit is 1.7 Mev; no γ-ray is known.

Ref: Se 44

O^{16}

I. $C^{12}(\alpha\alpha)C^{12}$

(1) Ferguson and Walker (Fe 40) and Riezler (Ri 40a) report anomalous scattering for $E_\alpha=4.4$, 5.0, 5.6 and 4.2, 4.6, 5.0 Mev, respectively, corresponding to states in O^{16} at ~10.5, 10.8, and 11.2 Mev with half-widths ~0.2 Mev.

Ref: De 39a, Fe 40, Ri 40a, Ro 40a

II. $C^{12}(\alpha n)O^{15}$ $Q=-8.4$ Mev

(2) King, Henderson, and Risser (Ki 39) report O^{15} activity with 16-Mev α-particles.

Ref: Ki 39

III. $N^{14}(dn)O^{15}$ $Q=5.1$ Mev

(3) Newson (Ne 37b) studied the yield of O^{15} and found a smooth increase to $E_d=3.2$ Mev and a sharp decrease above this value.

Ref: Li 37, Ne 37b

IV. $N^{14}(dp)N^{15}$ $Q=8.57$ Mev

(4) Transitions to several states in N^{15} have been observed (see N^{15}). The excitation function has not been studied.

Ref: Ho 40, Da 47, Gu 47

V. $N^{14}(dH^3)N^{13}$ $Q=-4.36$ Mev
(not illustrated)

Borst (Bo 42) gives a threshold of 6.8 ± 0.1 Mev. The percentage of the barrier height at which H^3 particles may escape is estimated to be 58 percent.

Ref: Bo 41c, Bo 42

VI. $N^{14}(d\alpha)C^{12}$ $Q=13.50$ Mev

(5) Three groups of α-particles corresponding to two excited states in C^{12} were observed by Holloway and Moore (Ho 40) at $E_d=1.0$ Mev.

Ref: Ho 39a, Cr 40, Ga 40, Ho 40, Gu 47

VII. $N^{14}(d\alpha)3\alpha$ $Q=6.16$ Mev (not illustrated)

Fowler, Burrows, and Curry (Fo 47b) observed several stars in photographic emulsions attributed to this reaction, using 9-Mev deuterons.

VIII. $N^{15}(p\alpha)C^{12}$ $Q=4.92$ Mev

(6) Fowler and Lauritsen (Fo 40) observed resonances for the production of 4.4-Mev γ-rays at $E_p=0.88$, 1.03, and 1.2 Mev.

Holloway and Bethe (Ho 40b) obtained $\sigma=0.013$ barn at $E_p=0.36$ Mev.

Ref: Fo 40, Ho 40b, La 41

IX. $N^{16}(\beta^-)O^{16}$, O^{16*} $Q=10.2$ Mev

(7) Sommers and Sherr (So 46) studied the β-spectrum and found it to be complex, with a component (~25 percent) extending to 10 ± 0.5

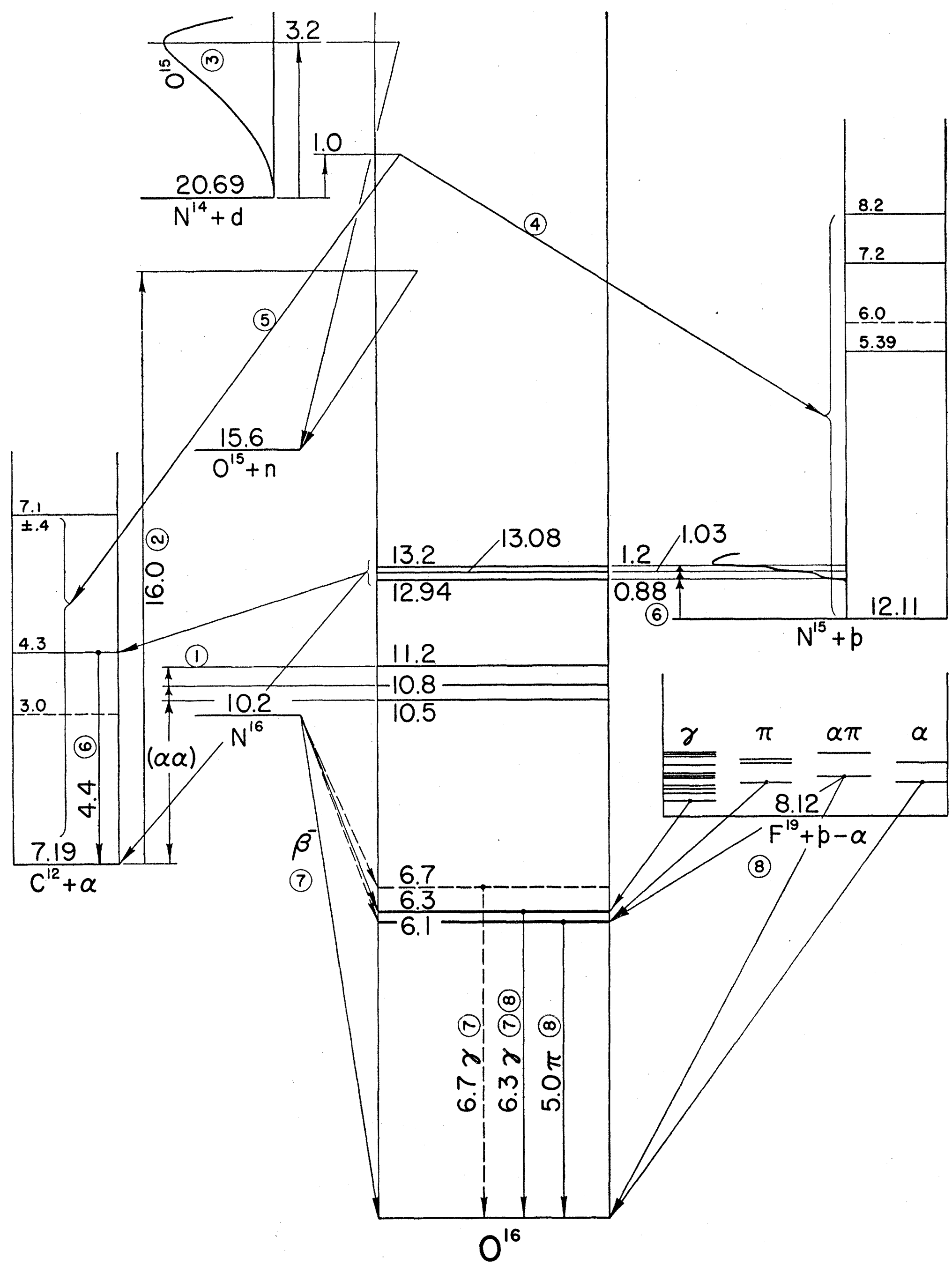


FIG. 17. *Energy levels in* O^{16}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. The yield function for the $N^{15}(p\alpha)$ reaction is for a thick target. The β-decay of N^{16} is complex. The levels in Ne^{20} have been grouped according to the type of coupling with O^{16}.

Mev and one ending at ~4 Mev. A γ-ray >5 Mev was observed, attributed to the 6.3 Mev level in O^{16}. The half-life is reported as 7.2±0.3 sec.

Bleuler, Scherrer, Walter, and Zünti (Bl 47) using both absorption and cloud chamber methods, concluded that the lower energy β-spectrum is complex, implying transitions to states at 6.2 Mev (40 percent), 6.7 Mev (40 percent), 6.0 Mev (2 percent), and possibly 5.1 Mev. Secondary electron absorption measurements indicate a mean γ-ray energy between 6.2 and 6.7 Mev.

Ref: Sc 41, Bl 45, So 46, Bl 47

X. $O^{16}(\gamma n)O^{15}$ $Q=-15.6$ Mev (not illustrated)

Baldwin and Koch (Ba 45) report a threshold of 16.3±0.4 Mev.

Ref: Ch 37, Bo 39c, Hu 43, Ba 45

XI. $O^{16}(n2n)O^{15}$ $Q=-15.6$ Mev (not illustrated)

Jensen (Je 44) places the threshold between $E_n=15$ and 22 Mev.

Ref: Po 37, Je 44

XII. $F^{19}(p\alpha)O^{16}$, O^{16*} $Q=8.12$ Mev

(8) Transitions to the ground state and to the levels at 6.1 and 6.3 Mev are known. The state at 6.1 Mev decays by pair emission, that at 6.3 Mev by γ-radiation. (See Ne^{20}.)

Ne^{20}

I. $O^{16}(\alpha\alpha)O^{16}$

(1) Brubaker (Br 38a) studied the scattering of α-particles in O^{16} and found resonance scattering attributed to a level in Ne^{20} at 9.3 Mev.

Devons (De 39a) found anomalous scattering in O^{16} indicating a level in Ne^{20} at 9.4 Mev ($E_\alpha=5.8$ Mev).

Ferguson and Walker (Fe 40) report scattering anomalies attributed to levels at 9.0 and 10.1 Mev.

Ref: Br 38a, De 39a, Fe 40, Ro 40a

II. $F^{19}(pn)Ne^{19}$ $Q=-3.84$ Mev

(2) Creutz, White, Delsasso, and Fox (Cr 39a) observed a radioactive product with a half-life ~20 sec. at a threshold of $E_p=4.2$ Mev attributed to this reaction.

Ref: Cr 39a

III. $F^{19}(p\alpha)O^{16}$, O^{16*} $Q=8.12$ Mev

The reactions observed in the proton bombardment of fluorine have been discussed extensively by Bennett, Bonner, Mandeville, and Watt (Be 46a).

The following processes are known to occur for $E_p=0$–2 Mev:

a. $F^{19}(p\alpha)O^{16}$ (6 cm α)
b. $F^{19}(p\alpha)\gamma O^{16}$ (1 cm α, 6.2 Mev γ)
c. $F^{19}(p\alpha)\pi O^{16}$ (1.1 cm α, 5.0 Mev π).

All three reactions exhibit resonances: in some cases the same level in Ne^{20} may apparently lead to both processes (a) and (c).

IIIa. $F^{19}(p\alpha)O^{16}$

Burcham and Smith (Bu 38) made a precise determination of the range of the α-particles and give $Q=7.95$ Mev.

(3) The excitation function for long range α-particles has been studied by Burcham and Devons (Bu 39) and Streib, Fowler, and Lauritsen (St 41). A number of resonances, superimposed on a general rise, is reported as follows: (St 41) (see also Table I)

Γ = estimated true width of resonance.
Y = thick CaF_2 target yield per proton.
$\omega\gamma$ = calculated effective minimum width ($\sim\Gamma_p$, in this case) multiplied by statistical weight factor.

McLean, Ellett and Jacobs (Mc 40), Rossi and Swartz (Ro 44) and Rubin (Ru 47a) have investigated the angular distribution of the α-particles from $E_p=0.3$ to 1.4 Mev. The distribution is markedly anisotropic.

Ref: Bu 38, Bu 39, Op 39a, De 40a, Ge 40, Ka 40, Mc 40, St 41, Ro 44, Ru 47a

TABLE I.

E_p (Mev)	Γ (kev)	$Y\times10^7$	$\omega\gamma$ (ev)
0.72	15	0.007	1.6
0.84	15	0.006	1.4
0.9–1.2	—	0.06	—
1.35	25	0.13	36
non-res. to 1.5		0.69	—
Total to 1.5		0.90	—

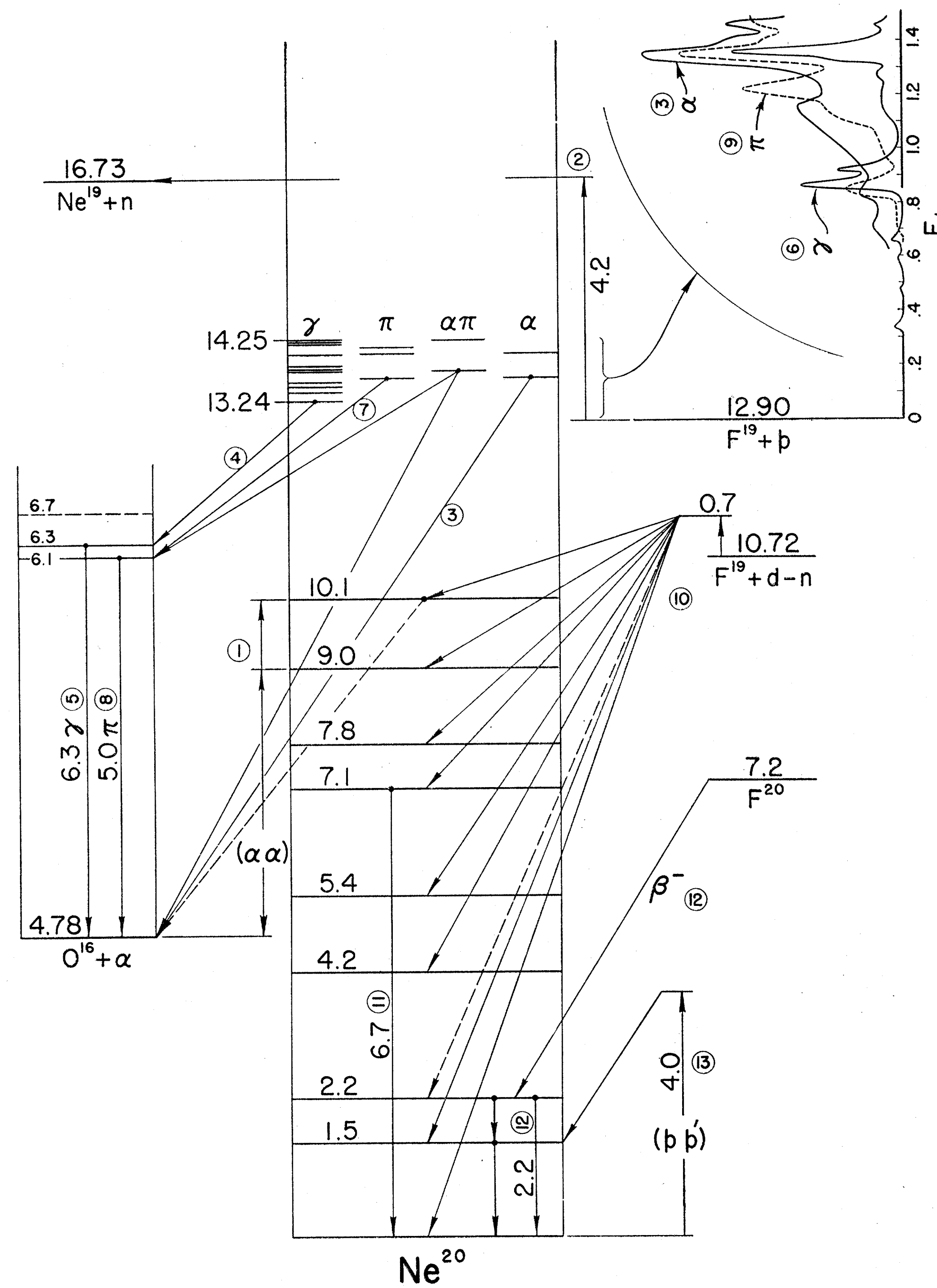


FIG. 18. *Energy levels in* Ne^{20}. Energy values are plotted vertically, in Mev, based on ground state as zero. Uncertain levels or transitions are indicated by dashed lines. Yield functions for thin targets, when known, are indicated with the reactions, with yield plotted horizontally and bombarding particle energy indicated on a vertical scale. The β-decay of F^{20} is complex. The excitation curves for the $F^{19}+p$ reactions are indicated on an expanded scale. The levels in Ne^{20} from 13.24 to 14.25 Mev have been grouped according to the type of coupling with O^{16}.

TABLE II.

E_p (kev)	(St 41): Γ (kev)	$Y \times 10^7$	ωγ (ev)	(Be 46a): E_p (kev)	Γ (kev)
334	<10	0.18	33	820	7.6
479	<10	0.05	10	862	5.2
589	25	0.24	49	890	4.8
660	<10	0.46	96	927	8.0
862	<10	3.34	760	1076	< 1.9
927	<10	2.21	520	1107	~30
1100–1300	—	3.03		1122	4.1
1335	<10	1.25	330	1161	~50
1363	10	7.71	2020	1274	19
Total to 1500		22.0		1335	4.8
				1363	15

IIIb. $F^{19}(p\alpha)\gamma O^{16}$

(4) Becker, Fowler, and Lauritsen (Be 42) measured the short range α-particles from this reaction and give $Q=1.81\pm0.04$ Mev for $E_p=0.334$, 0.867, 0.927, and 1.363 Mev.

(5) The energy of the γ-radiation is given as 6.3 ± 0.2 by Lauritsen, Lauritsen, and Fowler (La 41, Fo 48), 6.2 ± 0.1 by Shinohara and Hatoyama (Sh 41a) (cloud chamber pairs) and as 6.5 ± 0.2 by Curran, Dee, and Strothers (Cu 40) (magnetic spectrograph). That the γ-radiation occurs in O^{16} is attested to by the facts that the hardness is independent of bombarding voltage (the α-particles take up difference) and that no $\gamma-\gamma$ coincidences are observed (De 39).

Phillips and Kruger (Ph 47) have reported a number of lines from 5 to 7 Mev with $E_p=5$ Mev.

Burcham and Devons (Bu 39) studied the excitation functions of short range α-particles and γ-rays and found identical resonances for both.

The absolute yield of short range α-particles has been measured by Van Allen and Smith (Va 41) as $8.9\pm0.5\times10^4$ α-particles per microcoulomb at $E_p=0.360$ with a thick CaF_2 target. They find that the angular distribution of the α-particles and γ-rays is spherically symmetric.

(6) The excitation function for γ-rays has been studied by Bernet, Herb, and Parkinson (Be 38) to $E_p=2.2$ Mev, by Streib, Fowler, and Lauritsen (St 41) to 1.6 Mev, and by Bennett *et al.* (Be 46a) from 0.8 to 1.4 Mev. The known resonances and yields are tabulated in Table II.

Fowler, Lauritsen, and Lauritsen (Fo 48) locate the first resonance at $E_p=338$ kev and give a half-width of 4 kev ($\omega\gamma=30$ ev).

Hanson and Benedict (Ha 44), using an absolute voltage calibration, report the first prominent γ-ray resonance at 0.877 ± 0.0026 Mev.

Ref: Bo 37e, Ge 37a, Be 38, Bu 39, Bu 39a, Cu 39a, De 39, Ha 39c, Mc 39, Cu 40, Be 41c, Ha 41, La 41, Sh 41, Sh 41a, St 41, Va 41, Be 42, Ha 44, Be 46a, Fo 48, Ph 47

IIIc. $F^{19}(p\alpha)\pi O^{16}$

(7) Becker, Fowler, and Lauritsen (Be 42) found α-particles corresponding to a pair state in Ne^{20} and give $Q=1.93\pm0.07$ Mev.

(8) Tomlinson (To 41) measured the pair energy in a magnetic spectrograph as 5.0 ± 0.2 Mev.

(9) Resonances for pair production have been studied by Streib, Fowler, and Lauritsen (St 41) and Bennett *et al.* (Be 46a). Their values are given in Table III.

IV. $F^{19}(dn)Ne^{20}$, Ne^{20*} $Q=10.72$ Mev

(10) Bonner (Bo 40b) measured the energy spectrum of the neutrons and found groups corresponding to levels in Ne^{20} at 1.5, 4.2, 5.4, 7.3, 9.0, and 10.1 Mev. Of these, the last four have sufficient energy to decay to $O^{16}+\alpha$. Bonner suggests that an α-particle group at 2.8 cm observed by Burcham and Smith (Bu 38) may be from the 10.1-Mev level. The width of this level is <0.3 Mev.

Powell (Po 42), using the photographic plate technique, finds lines generally in good agreement with those given by Bonner. His distribution suggests two levels at ~7.1 and ~7.8 in place of the single one at 7.3 and gives an additional level at 2.2 Mev not resolved in Bonner's work.

(11) Bennett, Bonner, and Watt (Be 41c) investigated the γ-rays by the coincidence counter

TABLE III.

E_p (Mev)	(St 41): Γ (kev)	$Y \times 10^7$	(Be 46a): E_p (kev)	Γ (kev)
0.6–0.8	—	0.013		
0.85	15	0.10	832	28
1.14	30	0.07	1100	~70
1.22	30	0.20	1220	85
1.35	25	0.19	1362	36
non resonant		1.18		
Total to 1.5		1.78		

Ref: Ga 37, Fo 39a, Ha 39c, Se 40, Op 41, St 41, To 41, Be 42, Be 46a, Sc 46 technique, finding a maximum energy of 6.7 ± 0.3 Mev and possibly other components somewhat less energetic.

Ref: Bu 38, Bo 40b, Po 40a, Be 41c, Po 42

V. $F^{20}(\beta^-)Ne^{20}$, Ne^{20*} $Q \sim 7.2$ Mev

Burcham and Smith (Bu 38) observed radioactive γ-radiation with a half-life of 12.4 sec.

(12) Bower and Burcham (Bo 39d) measured the β-spectrum in a cloud chamber and obtained 5.1 Mev for the maximum energy. They also measured the γ-ray energy and found a line at 2.2 Mev, with other unresolved, softer components. From proton range measurements (in the F^{19}, dp, F^{20} reaction) they obtain $Q=7.0$ Mev and suggest several possible decay schemes, of which the most satisfactory involves a β-transition to the state in Ne^{20} at 2.2 Mev and subsequent γ-radiation.

Curran and Strothers (Cu 40b) found both $\beta-\gamma$ and $\gamma-\gamma$ coincidences, and conclude that the β-transition is to a level in Ne^{20} at 2.2 Mev, followed by an (equally probable) direct transition to the ground state and cascade through the level at 1.5 Mev.

Ref: Bu 38, Be 39a, Bu 39d, Cu 40b

VI. $Ne^{20}(pp')Ne^{20*}$

(13) Powell, May, Chadwick, and Pickavance (Po 40c) have observed inelastic scattering of 4-Mev protons in Ne, with an energy loss of 1.4 Mev. The inelastically scattered protons are isotropically distributed.

Ref: Po 40c, He 47

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(Closed, Nov. 1, 1947)

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