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Energy Levels of Light Nuclei ($Z=11$ to $Z=20$)

P. M. ENDT, *Physisch Laboratorium der Rijksuniversiteit, Utrecht, Netherlands*

AND

J. C. KLUYVER, *Stichting Fundamenteel Onderzoek der Materie, Utrecht, Netherlands*

INTRODUCTION

THIS compilation of nuclear energy levels in the $Z=11$ to $Z=20$ region is designed as an extension of the series of papers covering the region up to $Z=10$.[1–4] We have followed their method of presentation of the material in detail not only for the sake of uniformity, but also because according to our experience their presentation gave clear, concise, and complete information to the experimenter. Although their example simplified our task considerably, we were aware of the fact that it might not be easy to come up to their standard.

There exists one other compilation covering the same region of nuclides, *viz.*, that of Alburger and Hafner.[5] They gave a list of excitation energies, values averaged over different reactions and different observers, without error limits and without discussion of experimental details or of the consistency of the data. Since in the last few years a vast mass of new experimental data has accumulated, we feel that the writing of a new summary is justified. A recent compilation by Cappeller[6] covering the region from $Z=9$ to $Z=17$ does not supply this need because of the brevity of its presentation and its limited scope.

New experimental material is especially copious in the lower half of the Z region considered, containing the elements sodium, magnesium, aluminum, silicon, and phosphorus. Accurate links between the ground states of many nuclides have been established by magnetic analysis of charged particles from (d,p) and (d,α) reactions (notably by the group working at Massachusetts Institute of Technology) and the positions of many low energy levels have been determined by the same method with an accuracy of 15 kev or better. The perfect agreement obtained for the level schemes in the cases (e.g., Mg^{25} or Si^{29}) where the same nucleus can be reached both by a (d,p) and a (d,α) reaction is very gratifying and gives full confidence in this method.

Our knowledge regarding nuclei above phosphorus is by no means in such a satisfactory state, and it would have been only natural to break off the present compilation at this dividing line. However, recently work at Massachusetts Institute of Technology has been started on elements above phosphorus (e.g., on potassium and calcium), and also Holt and Marsham's[7] measurements of (d,p) angular distributions and the accurate determinations of γ-ray energies resulting from thermal neutron capture by Kinsey *et al.*[8] extend up to $Z=20$. These arguments convinced us that it is useful to include the $Z=16$ to $Z=20$ region into this compilation (in accordance with Alburger and Hafner).

The most important quantities characterizing nuclear states are energy, spin, and parity. In principle one could add magnetic dipole moment and electric quadrupole moment, but as this compilation is concerned chiefly with excited nuclear states and as next to nothing is known about their magnetic and electric moments we have not included any data on these moments. For ground-state moments the reader is referred to Mack's[9] tables.

Neither have we given a thorough discussion of the shell-model assignment of the observed nuclear states. There are arguments both against and in favor of this attitude. Of course the success of the shell model in predicting spin and parities of ground states cannot be denied. The sequence of subshells in our region of nuclides would be $d_{\frac{5}{2}}$, $s_{\frac{1}{2}}$, $d_{\frac{3}{2}}$, $f_{7/2}$, $p_{\frac{3}{2}}$. But the order of the $d_{\frac{5}{2}}$ and $s_{\frac{1}{2}}$ subshells is none too certain as is evidenced by the notable shell-model exception F^{19} ($J=\frac{1}{2}$), while Na^{23} ($J=\frac{3}{2}$) helps further to confuse the simple picture in this region. Nor do excited states adhere to the order given above, as there seem to be at least as many low multiple-excitation levels as single-particle levels in the region of nuclides considered here. Thus, the shell model should be handled with caution and we have preferred to present only the experimental spin and parity determinations without possible shell-model inferences. Most data on spins and parities of low (nonresonance) levels are obtained from (d,p) angular distribution measurements and from β decay. In several cases it has been possible to make unique spin and parity assignments just by putting together the data from these two sources. The β decay ft values have all been recomputed for this compilation in view of the better set of mass defects now available. For $\Delta J=2$, yes,

[1] W. F. Hornyak and T. Lauritsen, Revs. Modern Phys. **20**, 191 (1948).
[2] T. Lauritsen, National Research Council 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). The notation of Ajzenberg and Lauritsen is used in the present paper.
[5] D. E. Alburger and E. M. Hafner, Revs. Modern Phys. **22**, 373 (1950).
[6] M. Cappeller, Ergeb. exakt. Naturw. **27**, 125 (1953).
[7] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 249, 258, 467, 565 and 1032 (1953).
[8] Kinsey, Bartholomew, and Walker, Phys. Rev. **83**, 519 (1951) and **85**, 1012 (1952).
[9] J. E. Mack, Revs. Modern Phys. **22**, 64 (1950).

transitions, also $\log(W_0^2-1)ft$ has been computed, where W_0 is the maximum electron or positron energy inclusive of the rest mass of electron or positron in units mc^2.

ISOTOPIC SPIN

It is interesting to look for experimental facts in the $Z=11$ to $Z=20$ region which can be correlated with the important concept of isotopic spin. A direct consequence is the similarity of level schemes of mirror nuclei to which rule apparently no exceptions are known in the lower Z region. There are two cases in our region where such a comparison can also be made, *viz.*, for the mirror pairs $A=25$ and $A=33$. The level schemes of the nuclei concerned are given in Fig. 1 and Fig. 2. The experimental material both regarding excitation energies and spins and parities is still pretty incomplete but it may safely be said that there are no apparent contradictions and that especially the lower states show a satisfactory agreement. On the average the excitation energy of a level in the odd-proton nucleus is somewhat lower than that of its mirror level in the odd-neutron nucleus, which is also the general rule for levels in lighter mirror pairs.

The next point to look for is the occurrence of analog states of the same isotopic spin in even A isobars. The most interesting example in the $Z=11$ to $Z=20$ region is $A=34$. If the mass of Cl^{34} is lowered by an amount equal to the Coulomb energy difference with S^{34} (taking the nuclear radius equal to $R=1.4\ A^{\frac{1}{3}}\ 10^{-13}$ cm) and raised by an amount equal to the $n-p$ mass difference, the Cl^{34} mass comes out nearly equal to that of S^{34}

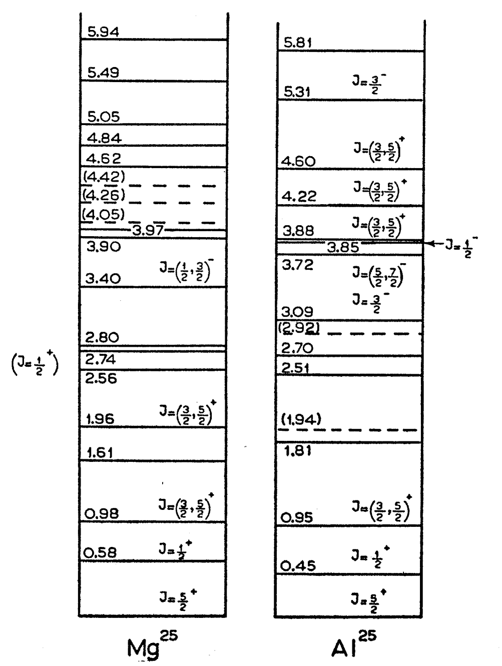

FIG. 1. Comparison of the level schemes of the mirror nuclei Mg^{25} and Al^{25}.

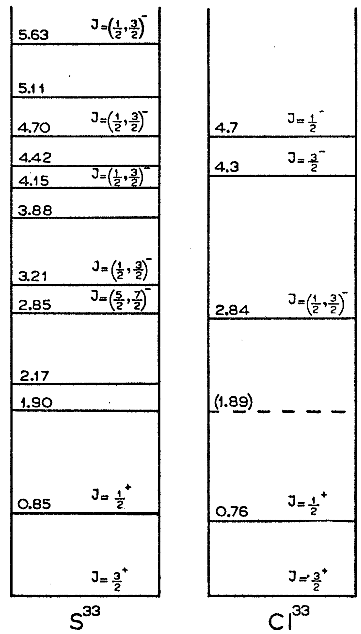

FIG. 2. Comparison of the level schemes of the mirror nuclei S^{33} and Cl^{33}.

(actually 0.2 Mev higher). One would then be inclined to regard the Cl^{34} and S^{34} ground states as components of an isotopic spin triplet ($T=1$, $J=0^+$).[10] The excited state in Cl^{34} at 142 kev (Cl^{34m}) is then the first $T=0$ state ($T=0$, $J=3^+$). The spin assignments quoted here follow from the Cl^{34} and Cl^{34m} β^+ decay.[11] It is remarkable that in Cl^{34} the lowest state is a $T=1$ state in contradistinction to Li^6, B^{10}, and N^{14} where the ground states are $T=0$ states. Also in Na^{22}, Al^{26}, and P^{30} one might expect $T=0$ ground states with the first $T=1$ states (corresponding to the ground states of Ne^{22}, Mg^{26}, and Si^{30}) at about 0.8 Mev, 0.5 Mev, and 0.5 Mev, respectively. None of these latter levels have been observed as yet. On the other hand it would be logical to assume that the K^{38} ground state (and that of the unknown Sc^{42}) is a $T=1$ state like the Cl^{34} ground state. Arguments in favor of these isotopic spin assignments in Al^{26}, P^{30}, and K^{38} have recently been given by Stähelin.[12]

SCOPE

The criteria of selection of experimental data to be included in the present compilation were very similar to those used in the $Z=1$ to $Z=10$ reviews. As a deadline, December 1, 1953 was chosen but in a few cases references could be inserted to papers received somewhat later.

The limited availability (also to us) of theses, U. S. Atomic Energy Commission Reports, and other analogous papers has made us decide to quote them only

[10] D. C. Peaslee, Nuovo cimento **10**, 1349(L) (1953).
[11] W. Arber and P. Stähelin, Helv. Phys. Acta **26**, 433(A) (1953); P. Stähelin and P. Preiswerk, Nuovo cimento **10**, 1219 (1953).
[12] P. Stähelin, Helv. Phys. Acta **26**, 691 (1953).

in exceptional cases. The same applies to papers or communications to which we had no direct access (e.g., private communications to others).

As a general rule, no very high energy or spallation reactions have been included and the presentation of papers bearing on theoretical aspects is also certainly incomplete. The same pertains to elastic neutron scattering especially at very low energies.

No relative intensities have been given of particle groups observed from a specific reaction at only one particular angle (e.g., 90°).

MASSES

The mass defect used for each nucleus is stated under the heading for that nucleus. In the region from Na^{21} to S^{33} the masses are taken (whenever possible) from Li's[13] tables. These are given without further comment or reference. In accordance with Li the mass defect is defined as $M-A$ in Mev; a better name would be "mass excess." The masses of the nuclei in this region which are not present in Li's table are computed from the Q values of reactions connecting these nuclei to Li's set. In these cases they are called "adopted mass defects" and the pertinent reactions or investigations are reported.

The absence of a continuous chain of carefully determined Q values complicates the situation for the nuclei above S^{33}. Mass-spectrographic measurements of all stable isotopes except S^{36} and Ca^{46} have been performed by Collins *et al.*;[14] of S^{34}, Cl^{35}, Cl^{37}, and A^{40} by Ogata and Matsuda;[15] of S^{34} and A^{40} by Ewald;[16] and of A^{40}, K^{40}, and Ca^{40} by Johnson.[17] However, their results are not directly comparable as they have used different mass values for the substandards H^1, C^{12}, and S^{32}. Obviously the best connection to the masses below S^{33} will be obtained if as masses of substandards Li's values from nuclear reaction energies are used. This attitude has been adopted for H^1 and C^{12}. However, for S^{32} the error in Li's mass surpasses (by the accumulation of errors through successive steps) considerably the mass-spectrographic value derived directly from the $O_2^{16}-S^{32}$ doublet. For these reasons the following substandards have been chosen:

$$H^1 = 1.008\,142 \pm 3, \text{ (reference 13)},$$

$$C^{12} = 12.003\,804 \pm 17, \text{ (reference 13)},$$

$$S^{32} = 31.982\,236 \pm 7, \text{ (reference 14)}.$$

This combination of substandards has also been used by Collins *et al.* as an alternate method. For the stable isotopes the weighted mean of the cited measurements has been taken, if necessary after correction of the reported values to the adopted substandards. In view of this rather arbitrary convention and the possibility of unaccounted systematic errors in mass spectrography, the final values have been rounded off to 0.1 Mev which is about (or perhaps somewhat larger than) the internal consistency of the mass-spectrographic data.

Microwave mass determinations are generally inferior to mass spectrography and have not been taken into account, except for S^{36} where the microwave measurement[18] is the only available mass determination. The mass of Ca^{46} is as yet unknown.

Masses of many unstable nuclides from sulfur to scandium are linked to stable nuclides by nuclear reaction Q values and our adopted mass defects are discussed under each heading.

The procedure of mass assignment followed here for the nuclei from sulfur upwards is certainly not without objection. Accurate Q value determinations connecting two stable nuclei have been neglected. For instance, the masses of K^{39} and K^{40} (determined mass spectrographically) have been rounded off to 100 kev although the mass difference is known with 10 kev accuracy from the $K^{39}(d,p)K^{40}$ Q value. However, the construction of a more accurate set of masses in this region should await the establishment of at least one chain of nuclei connected through accurate Q values. In one such chain ($S^{33}-Cl^{35}-S^{35}-Cl^{37}-A^{37}-K^{39}-K^{40}-Ca^{40}-Ca^{41}$) all links are known with an accuracy of 15 kev or better, but for the Q values of the reactions $Cl^{35}(d,\alpha)S^{33}$ ($Q_m=8.3$ Mev), $Cl^{37}(d,\alpha)S^{35}$ ($Q_m=7.6$ Mev), and $K^{39}(d,\alpha)A^{37}$ ($Q_m=7.8$ Mev). Also the mass of A^{39} is already directly connected to this chain by a precision measurement.

ARRANGEMENT OF THE MATERIAL

Generally each nuclear reaction is treated under the heading of the final nucleus. Exceptions form reactions where resonances have been observed which are treated under the compound nucleus. A second exception forms the β decay of unstable nuclei which is treated under the parent nucleus and then as the first reaction. The order of the other reactions is determined by the initial nucleus starting with the lowest-Z element and within that element with the lowest-A isotope. Angular distributions, cross sections, and excitation curves are discussed under the final nucleus (apart from resonances). Also included are reactions which have not yet been reported but which could (if observed) give additional information about the final nucleus and which are in principle feasible with natural or enriched targets.

Discussions on the energy levels of a particular nucleus which do not fit naturally under the heading of a specific reaction leading to that nucleus have been given as "General Remarks" at the end of the treatment of that nucleus.

The diagram is the synthesis of the discussions of

[13] C. W. Li, Phys. Rev. **88**, 1038 (1952); Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[14] Collins, Nier, and Johnson, Phys. Rev. **84**, 717 (1951); **86**, 408 (1952).
[15] K. Ogata and H. Matsuda, Phys. Rev. **89**, 27 (1953).
[16] H. Ewald, Z. Naturforsch. **6a**, 293 (1951).
[17] W. H. Johnson, Phys. Rev. **88**, 1213(L) (1952).
[18] W. Low and C. H. Townes, Phys. Rev. **75**, 529(L) (1949).

the experimental material. The excitation energies given in the diagrams are the weighted means of all separate determinations available. Levels known with an accuracy of 15 kev or better, and found preferably from two or more reactions, are marked by thick lines, doubtful levels by hatched lines. Three decimal figures are reserved for levels known with an accuracy of 5 kev or better.

All reactions leading to a particular nucleus have been indicated in its level diagram, also unobserved reactions. If the absolute value of the reaction energy of an unobserved reaction is so large that the horizontal line representing it falls outside the energy range of the diagram, this line is drawn in an arbitrary position and provided with two arrows pointing upwards or downwards.

The indication of resonances in the diagram has been somewhat simplified in comparison to the presentation in the $Z=1-10$ papers. The density of resonance levels in our higher-Z region is so much larger that it proved impossible to represent resonances by schematic yield curves. Instead resonance levels have only been indicated by marking their position on the primary particle energy scale. Relative intensities and widths can only be found in the text or relevant tables. In some cases (e.g., Si^{28} where some 100 resonance levels are known) it has even been necessary to omit every indication of individual resonances in the diagram. Reactions in which the central nucleus in the diagram occurs as a compound nucleus have also generally been omitted, unless resonances were observed.

Resonance energies, both in level diagrams and in the text, have always been given in laboratory coordinates, except in one or two cases where the use of center-of-mass coordinates is explicitly mentioned.

OTHER COMPILATIONS

Apart from the compilations mentioned elsewhere in this introduction, the following review papers also considerably simplified the present work:

(a) the 1937 Livingston and Bethe[19] compilation of nuclear reactions;

(b) the 1949 "Isotopenbericht" by Mattauch and Flammersfeld;[20]

(c) the National Bureau of Standards, Nuclear Data;[21]

(d) the Nuclear Science Abstracts;

(e) the 1952 Van Patter[22] compilation of ground-state Q values and beta-decay energies (up to $Z=20$);

(f) the 1952 compilation of neutron cross sections by Hughes *et al.*;[23]

(g) the 1953 "Table of isotopes" by Hollander *et al.*[24]

ACKNOWLEDGMENTS

We are especially grateful to Dr. D. M. Van Patter who was the originator of this compilation and has guided us with frequent advice and criticism. Also our thanks are due to Dr. W. W. Buechner, Dr. T. Lauritsen, and Dr. B. B. Kinsey, and several of their co-workers for kindly reading through the manuscript and suggesting many improvements and additions. We are finally indebted to the many physicists who have sent us results before publication.

Na^{20}

(not illustrated)

Adopted mass defect: 14.2 Mev (Al 50a).*

I. $Na^{20}(\beta^+)Ne^{20}$ $Q_m=15.3$†

The positron decay proceeds at least partly to states of Ne^{20} between 6.8 and 10.8 Mev which decay by α emission. The half-life measured by α detection is 0.25 sec (Al 50a) and by β^+ detection is 0.23 ± 0.08 sec (Sh 51b). Another value for the half-life: 0.385 ± 0.01 sec is reported by Birge (Aj 52). The energy of the α's is >2 Mev (Al 50a).

For a theoretical prediction of the Na^{20} spin see De 53a.

II. $Ne^{20}(p,n)Na^{20}$ $Q_m=-16.1$

The threshold for this reaction is 16.9 Mev (Al 50a).

III. $Na^{23}(\gamma,3n)Na^{20}$ $Q_m=-42.0$

The Na^{20} activity has been produced by bombarding sodium with the γ rays of a 76-Mev betatron (Sh 51b).

Na^{21}

Mass defect: 3.991 Mev

I. $Na^{21}(\beta^+)Ne^{21}$ $Q_m=3.522$

The half-life is 23 ± 2 sec (Cr 40) and 22.8 ± 0.5 sec (Sc 52). The maximum β^+ energy is 2.50 ± 0.03 Mev as determined with a 180° spectrometer (Sc 52). Whereas early investigations indicate a γ ray in this decay (Po 40), more recent observations show no γ ray of $E_\gamma>0.5$ Mev (Sc 52).

The log ft value is 3.6, the usual value for super-allowed transitions between mirror nuclei.

[19] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (1937).
[20] J. Mattauch and A. Flammersfeld, Z. Naturforsch. (special issue) (1949).
[21] Natl. Bur. Standards U. S. circ. No. 499 (1950) with 3 supplements (1950, 1951).
[22] D. M. Van Patter, Technical Report No. 57, (L.N.S.E.), Massachusetts Institute of Technology (1952).
[23] Hughes *et al.*, A.E.C.U.—2040 (1952).
[24] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).
* All references indicated in this manner, initials and year, are listed at the end of the article.
† For each reaction the Q value calculated from the masses is designated Q_m.

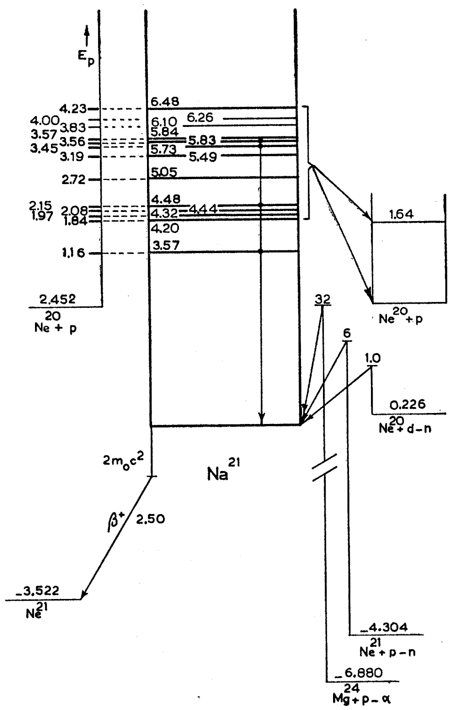

FIG. 3.

II. $Ne^{20}(p,\gamma)Na^{21}$ $Q_m=2.452$

A weak resonance at $E_p=1.165$ Mev was found in the γ-ray yield for protons in the 0.5–1.3 Mev region bombarding a thin isotopic Ne^{20} target (Br 47). This corresponds to a level in Na^{21} at 3.566 Mev. See Table I (last column) for more resonances in this reaction (Va 53).

III. $Ne^{20}(p,p)Ne^{20}$, $Ne^{20}(p,p')Ne^{20}$ $\Big\}$ $E_b=2.452$

Elastically scattered protons observed at 6 angles from 90° to 167.5° indicate resonances at $E_p=1.84$, 1.95, 2.13, 2.72, 3.20, 3.55, 3.57, and 4.23 Mev corresponding to levels in the range from $E_x=2.64$ to 6.61 Mev at 4.20, 4.31, 4.48, 5.04, 5.50, 5.83, 5.85, and 6.48 Mev (Ha 53). At each elastic resonance inelastic scattering

TABLE I. Resonances in the $Ne^{20}(p,p'\gamma)Ne^{20}$ reaction (Va 53, Co 53b).

E_p (lab) (Mev)	Exp. halfwidth (kev)	Relative yield (1.64 Mev γ ray)	Proton capture (annih. radiation from $Na^{21}(\beta^+)Ne^{21}$)
1.970	16	15	...
2.085	17	5	...
2.150±0.005	29	260	Yes
2.725±0.005	35	24 000	No
3.190±0.007	100	2400	No
3.450±0.005	(36)	900	(Weak)
3.560*	...	...	Yes
3.565±0.005	46	5800	Yes
3.835±0.005	(12)	1500	...
4.005	14	240	...

* Asymmetry of the 3.565 resonance probably due to a double peak.

also occurs to the 1.64 Mev level in Ne^{20} with cross sections at 168°: 0.13 b ($E_p=2.72$ Mev), 0.006 b (3.21 Mev), 0.013 b (3.56 Mev), and 0.015 b (3.58 Mev). Moreover, there is an inelastic resonance at $E_p=3.42$ Mev of cross section 0.014 b and 10-kev width. The angular distribution of the inelastically scattered protons at the 2.72-Mev resonance is not isotropic (Ga 53a).

With a scintillation spectrometer the yield has been measured of the 1.64-Mev γ ray (photopeak) resulting from inelastic scattering. Observed resonances, experimental half-widths, and relative yields are collected in Table I. Some resonances (last column of Table I) show also proton capture detected by the annihilation radiation from the positron decay of 23 sec Na^{21}. For a number of resonances the γ-ray angular distribution has also been measured. No evidence was found from the γ ray spectrum for a level in Ne^{20} at about 2.2 Mev (Co 53b, Va 53). For Ne^{20} levels found from inelastic scattering see Aj 52.

IV. $Ne^{20}(d,n)Na^{21}$ $Q_m=0.226$

At $E_d=1.0$ Mev recoil protons have been detected in nuclear emulsions. The measured $Q=-0.17\pm0.05$ Mev would perhaps indicate that this neutron group does not lead to the ground state, or that the β^+ decay of Na^{21} is followed by a γ transition (Sw 52). See also Po 40.

V. $Ne^{21}(p,n)Na^{21}$ $Q_m=-4.304$

The Na^{21} activity has been observed in the bombardment of neon with 6-Mev protons (Cr 40).

VI. $Mg^{24}(p,\alpha)Na^{21}$ $Q_m=-6.880$

The Na^{21} activity has been observed from natural magnesium bombardments at $E_p=18.5$ Mev (Sc 52) and from bombardments of targets enriched in Mg^{24} at $E_p=32$ Mev (Br 48).

Na^{22}

Mass defect: 1.312 Mev

I. $Na^{22}(\beta^+)Ne^{22}$ $Q_m=2.841$

The half-life is given as 3.0±0.2 yr (La 37), 2.8 yr (Sa 39), and 2.60 yr (La 49).

The decay proceeds predominantly by β^+ emission followed by a γ ray. Determinations of the end point of the β^+ spectrum and of the γ-ray energy are collected in Table II. See also Me 34a, Fr 35.

TABLE II. Decay of Na^{22}.

Author	Method	$E_{\beta^+ max}$ (kev)	E_γ (Mev)
La 37	cl. chamber	580±30	
La 37, Bl 46c	abs.	530±40	
Op 39	spectrom.	550	1.3
Ma 41	spectrom.	600±60	
Go 46a	spectrom.	575±10	1.30 ±0.03
Al 49a	spectrom.		1.277±0.004
Ma 50a	spectrom.	542±5	
Wr 53	spectrom.	540±5	

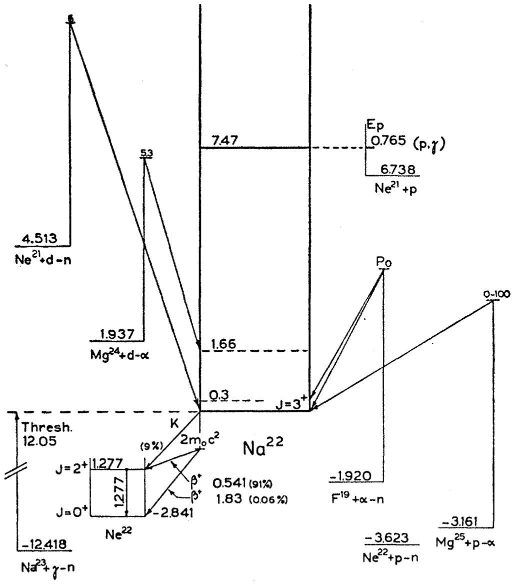

FIG. 4.

The ground-state β^+ transition is very weak. The end point of this high-energy β^+ spectrum is 1.83 ± 0.06 Mev and its intensity is (0.062 ± 0.015) percent (Wr 53). Its log ft value is 13.1. See also Mo 49.

Besides β^+ emission electron capture also occurs. Recent measurements are (9.9 ± 0.6) percent (Mi 53, Sh 53b) and (7.1 ± 2.0) percent (Ho 53g) for the number of electron captures per disintegration. Earlier measurements were mutually contradictory (Ma 43a, We 43, Go 46a).

The internal K-conversion coefficient of the 1.28-Mev γ ray has been measured as $(6.3\pm2)\times10^{-6}$ (Hi 53) which points to an $E2$ transition. The spin of the 1.27 Mev level in Ne^{22} is then 2^+, in agreement with the general rule for even-even nuclei (Sc 53). The spin of Na^{22} being $J=3$ (Da 48, Da 49b), the predominant β^+ branch is allowed in agreement with the shape of the spectrum (Ma 50a, Al 50b), although the ft value is rather high (log $ft=7.6$). The allowed character is confirmed by the absence of $\beta-\gamma$ angular correlation (St 51a).

For a theoretical discussion of the Na^{22} ground-state spin see De 53a.

II. $F^{19}(\alpha,n)Na^{22}$ $Q_m=-1.920$

By bombarding a thick CaF_2 target with Po α's and detecting recoil protons in a cloud chamber, neutron groups were found corresponding to Q values of -2.3 and -2.6 Mev (Bo 34, Li 37). This would point to a level in Na^{22} at 0.3 Mev. See also Fr 35.

With α particles from a Van De Graaff accelerator thresholds in the neutron production are observed at $E_\alpha=2.4$ and 3.05 Mev. For $E_\alpha>3.05$ Mev γ rays are observed of $E_\gamma=593\pm3$ kev, measured by a scintillation spectrometer. The half-life for γ emission of the first level is <0.1 sec (Te 54a).

For resonances see Na^{23}.

III. $Ne^{21}(p,\gamma)Na^{22}$ $Q_m=6.738$

In the region $E_p=0.6-1.3$ Mev one resonance at $E_p=0.765$ Mev was found in the γ-ray yield by use of a thin enriched Ne^{21} target (Br 47).

IV. $Ne^{21}(d,n)Na^{22}$ $Q_m=4.513$

Weak long-lived sodium β^+ activity has been observed from neon bombarded by deuterons (La 37).

V. $Ne^{22}(p,n)Na^{22}$ $Q_m=-3.623$

The threshold is greater than $E_p=3.35$ Mev (Ri 48).

VI. $Na^{23}(\gamma,n)Na^{22}$ $Q_m=-12.418$

The threshold was measured as 12.05 ± 0.20 Mev (Sh 51a).

The excitation curve has a maximum at 18.3 Mev of half-width 6.0 Mev. The maximum cross section is 13 mb and the integrated cross section for the (γ,n), (γ,np), and $(\gamma,2n)$ reactions together is 81-Mev mb (Mo 53a). See also Mc 50.

VII. $Na^{23}(n,2n)Na^{22}$ $Q_m=-12.418$

Not observed.

VIII. $Mg^{24}(d,\alpha)Na^{22}$ $Q_m=1.937$

From the bombardment of natural magnesium by deuterons at $E_d=5.3$ Mev one α group of $E_\alpha=4.32$ Mev is found by magnetic analysis at $\theta=90°$. If assigned to Mg^{24} the Q value would be 0.28 Mev, yielding a level in Na^{22} at 1.66 Mev (As 51). See also La 37. The excitation curve has been measured up to $E_d=14$ Mev and shows a maximum of 150 mb at $E_d=9.5$ Mev (Cl 46).

IX. $Mg^{25}(p,\alpha)Na^{22}$ $Q_m=-3.161$

The Na^{22} yield has been measured from threshold to $E_p=100$ Mev (Me 51).

GENERAL REMARKS

For isotopic spin predictions in Na^{22} see St 53b, St 53c, Mo 53b. A $J=0^+$, $T=1$ state is expected at about 0.6-Mev excitation, and it is very probable, that the 593-kev level found in reaction II may be identified with this state (Te 54a).

Na^{23}

Mass defect: -2.742 Mev

I. $F^{19}(\alpha,n)Na^{22}$ $E_b=10.498$ $Q_m=-1.920$

From thick target bombardments with Po α particles resonances in the neutron yield are found at $E_\alpha=3.31$, 3.81, 4.29, 4.56, 4.91, and 5.16 Mev (Sa 38). Resonances

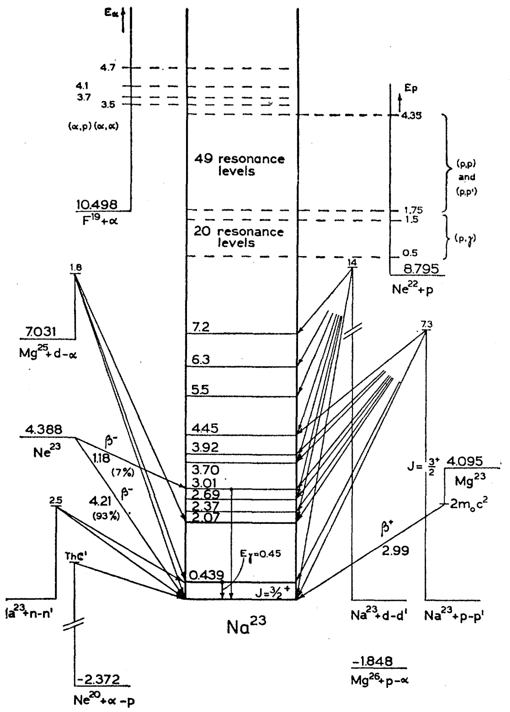

FIG. 5.

are also reported at 3.4 and 4.1 Mev (Bo 34, Li 37). Resonances in the γ-ray yield are found at 3.34, 3.85, and 4.54 Mev (Sa 38). For Q values see Na^{22}.

II. $F^{19}(\alpha,p)Ne^{22}$ $E_b=10.498$ $Q_m=1.703$

With Po α's broad resonances have been found at $E_\alpha=3.7$ and 4.1 Mev for two proton groups with Q values of 1.58 and 0.98 Mev (Ch 32, Ch 34, Li 37). Later work with Po α particles has shown resonances at 3.78, 4.71, and 5.09 Mev (Sa 38). For Q values see Aj 52.

III. $F^{19}(\alpha,\alpha)F^{19}$ $E_b=10.498$

Broad resonances at $E_\alpha=3.5$ and 4.7 Mev were found for RaC′ α's scattered at 90° (De 39).

Recently resonances have been observed at $E_\alpha=2.48$, 2.55, 2.64, 2.77, 2.90, 3.02, 3.05, 3.18, and 3.34 Mev. Gamma rays of $E_\gamma=108\pm2$ and 196 ± 2 kev observed by scintillation spectrometry indicate inelastic scattering. There is evidence for Coulomb-excitation of the 196 kev level in F^{19} below $E_\alpha=2.2$ Mev (He 54).

IV. $Ne^{20}(\alpha,p)Na^{23}$ $Q_m=-2.372$

One proton group ($Q=-2.54$ Mev) has been found with ThC′ α particles (Po 37, Li 37). See also Ru 24, Ch 48.

V. $Ne^{22}(p,\gamma)Na^{23}$ $Q_m=8.795$

Twenty narrow resonances in the γ-ray yield were found for protons in the 0.5–1.5 Mev region on a thin isotopic Ne^{22} target. A plot is presented from which positions and relative intensities of the resonances may be estimated (Br 47).

VI. $\left.\begin{matrix} Ne^{22}(p,p)Ne^{22} \\ Ne^{22}(p,p')Ne^{22} \end{matrix}\right\} E_b=8.795$

Resonances both for elastic scattering and for inelastic scattering to the 1.28-Mev Ne^{22} level have been observed at $E_p=2.43$, 2.67, 2.83, 2.87, and 3.19 Mev corresponding to Na^{23} levels at 11.12, 11.35, 11.50, 11.54, and 11.85 Mev (Ha 53, Ga 53a).

With a scintillation spectrometer the yield of the 1.28-Mev γ ray (photopeak) resulting from inelastic scattering has been measured. A list of the observed resonances, their experimental half-widths and relative yields is given in Table III. No indication can be found in the γ-ray spectrum of a Ne^{22} level at about 0.4 Mev (Va 53).

VII. $Ne^{23}(\beta^-)Na^{23}$ $Q_m=4.388$

The half-life has been given as 40 sec (Am 35), 33 ± 1 sec (Na 36), 35 to 40 sec (Bj 37), 43 ± 3 sec (Po 40) and 40.2 ± 0.4 sec (Br 50). The β^- decay is complex and consists of two components with end points 4.21 ± 0.01^5 Mev (93 percent) and 1.18 ± 0.04 Mev (7 percent) (Br 50). Both transitions are allowed (log ft=5.0 and 3.8). See also Po 40, Bl 46c. A γ ray of 2.5 to 3.5 Mev has been observed (Pe 50). Note that there is a striking disagreement between the measured β^- ray end point and the one calculated from Li's masses (Li 52) which is based on a Q value of 2.964 ±0.007 Mev (Va 52a) for the $Ne^{22}(d,p)Ne^{23}$ reaction.

TABLE III. Resonances in the $Ne^{22}(p,p'\gamma)Ne^{22}$ reaction (Va 53).

E_{lab} (Mev)	Exp. half width (kev)	Relative yield (1.28 Mev γ ray)	E_{lab} (Mev)	Exp. half width (kev)	Relative yield (1.28 Mev γ ray)
1.755	17	···	3.435	22	70
1.915	15	···	3.470	18	120
1.970	32	···	3.560	36	270
2.130	22	50	3.585	(22)	90
2.190	20	22	3.645	(32)	20
2.220	17	77	3.685	(29)	30
2.240	20	40	3.725	16	90
2.355	15	10	3.755	9	320
2.405	25	10	3.800	24	45
2.430	16	45	3.845	16	120
2.565	20	40	3.895	(22)	35
2.610	24	40	3.920	11	370
2.675	18	175	3.940	(15)	90
2.795	11	40	3.985	(45)	150
2.835	20	130	4.035	15	130
2.865	24	85	4.055	16	170
2.940	37	30	4.090	18	160
2.965	16	40	4.125	23	290
3.020	20	50	4.165	(15)	280
3.055	26	160	4.190	29	350
3.105	(29)	100	4.235	(12)	120
3.160	···	···	4.255	23	210
3.215	(29)	160	4.300	16	255
3.330	18	35	4.345	15	360
3.380	22	185			

VIII. $Na^{23}(n,n')Na^{23}$

With 2.5 Mev neutrons incident on a NaI scintillation crystal a photopeak was observed at 0.45 Mev (Gr 52). This might be explained by inelastic scattering leading to the 0.44-Mev level in Na^{23}.

IX. $Na^{23}(p,p')Na^{23}$

A level in Na^{23} at 0.439±0.001 Mev has been determined by electrostatic analysis of incoming and scattered protons at $E_p=1.5$ Mev (Do 53). A γ ray of 0.45±0.01 Mev was found by scintillation spectrometer at proton energies between 1.0 and 2.6 Mev (St 52a). At $E_p=7.26$ Mev the energies of scattered protons have been determined with a thin NaI-crystal scintillation spectrometer yielding Na^{23} levels at 2.10, 2.37, 2.69, 3.01, 3.70, 3.92, and 4.45 Mev all ±0.04 Mev (St 52). A level at 3.67 Mev has also been found by an absorption method at $E_p=7.4$ Mev (Co 52). See also Ha 52c.

For resonances see Mg^{24}.

X. $Na^{23}(d,d')Na^{23}$

At $E_d=14$ Mev levels in Na^{23} are found from this reaction at 1.9, 2.6, 3.75, 4.45, 5.5, 6.3, and 7.2 Mev (Bo 50).

XI. $Na^{23}(\alpha,\alpha')Na^{23}$

At $E_\alpha=3$ Mev a γ ray of 430 kev is observed by scintillation spectrometer, probably resulting from inelastic scattering (Te 54).

XII. $Mg^{23}(\beta^+)Na^{23}$ See Mg^{23}

XIII. $Mg^{25}(d,\alpha)Na^{23}$ $Q_m=7.031$

By use of enriched targets and magnetic analysis ($\vartheta=90°$) at $E_d=1.8$ Mev the ground-state Q value has been measured as 7.019±0.013 Mev and levels in Na^{23} are found at 0.427±0.018 and 2.073±0.015 Mev (En 52a). See also Le 33, Li 37, Al 49b, Va52a.

XIV. $Mg^{26}(p,\alpha)Na^{23}$ $Q_m=-1.848$

Not observed.

Mg^{23}

(not illustrated)

Mass defect: 1.353 Mev

I. $Mg^{23}(\beta^+)Na^{23}$ $Q_m=4.095$

Half-life determinations are 11.6±0.5 sec (Wh 39), 11.9±0.3 sec (Hu 43, see also Hu 42), 12 sec (Ba 46), 12.3±0.4 sec (Bo 51), and 11.4 sec (Ed 52).

The maximum β^+ energy is 2.82 Mev (Wh 39) or 2.99±0.09 Mev (Bo 51). No gamma rays are observed with a cloud chamber (Wh 39). The β^+ decay is superallowed as follows from the small ft value ($\log ft=3.7$).

II. $Ne^{20}(\alpha,n)Mg^{23}$ $Q_m=-7.249$

Not observed.

III. $Na^{23}(p,n)Mg^{23}$ $Q_m=-4.877$

The threshold is accurately determined as $E_p=5.091$ ±0.010 Mev (Wi 52). See also Wh 39 and Bl 51.

For resonances in this reaction see Mg^{24}.

IV. $Mg^{24}(\gamma,n)Mg^{23}$ $Q_m=-16.581$

The threshold is measured as 16.4±0.3 Mev (Be 47a), 16.2±0.3 Mev (Mc 49), and 16.55±0.25 Mev (Sh 51a). The yield curve, measured by the activity of the residual nucleus, has a maximum of $\sigma=8.1$ mb at 19.2 Mev with a half-width of 4.7 Mev and an integrated cross section of 45 Mev mb (Ka 51b).

The photoneutron cross section for natural magnesium measured by the neutron intensity has a maximum of 11 mb at $E_\gamma=18.8$ Mev. The half-width is 3.9 Mev and the integrated cross section is 48-Mev mb. The difference with the proceeding values may be attributed to Mg^{25} and Mg^{26} (Mo 53a).

Another value for the integrated cross section is 72-Mev mb (Ed 52). See also Wa 48, Mc 50.

V. $Mg^{24}(n,2n)Mg^{23}$ $Q_m=-16.581$

Not observed.

Na^{24}

Mass defect: −1.333 Mev

I. $Na^{24}(\beta^-)Mg^{24}$ $Q_m=5.531$

The half-life is given as 14.96±0.10 hr (Wi 49, Bi 50, Sr 51), 15.04±0.06 hr (So 50), 15.10±0.04 hr (Co 50a), 15.0±0.1 hr (Si 51), 15.060±0.039 hr (Sr 51), 15.28±0.19 hr (Bl 52) and 14.97±0.02 hr (Lo 53). See also Am 35, La 35, Va 36.

The decay scheme of Na^{24} has been very thoroughly investigated. The β^- decay goes predominantly to the 4.12-Mev level in Mg^{24} and is followed by two γ rays in cascade through the 1.37-Mev level (La 39, Ma 43a, Co 46, Sa 47, Si 47a, Ba 47, Wi 47). The β^- ray end point and the energies of the two γ rays have been accurately measured (Table IV). See also Ri 36, Ku 36,

TABLE IV. Na^{24} beta decay.

Author	Method	β^- ray endpoint in Mev	$E_{\gamma 1}$ in Mev	$E_{\gamma 2}$ in Mev
Mo 40	ion. ch.	1.36 ±0.05		1.38 ±0.02
It 41	spectrom.		2.80 ±0.02	1.38 ±0.03
El 43	spectrom.		2.76 ±0.06	1.38 ±0.03
Ma 43	spectrom.		2.94 ±0.06	
Go 44	(γ,n)		2.87 ±0.05	
Si 46	spectrom.	1.390±0.005	2.758	1.380
Wa 47	$Be(\gamma,n)$		2.75	
Wa 47	$D(\gamma,n)$		2.72	
Hi 48	abs.	1.41		
Ro 49	spectrom.		2.765	1.380
Wo 50	spectrom.		2.755 ±0.005	
He 52	spectrom.		2.7535±0.0010	1.3680±0.0010
Ki 53d	pair spectrom.		2.753 ±0.005	

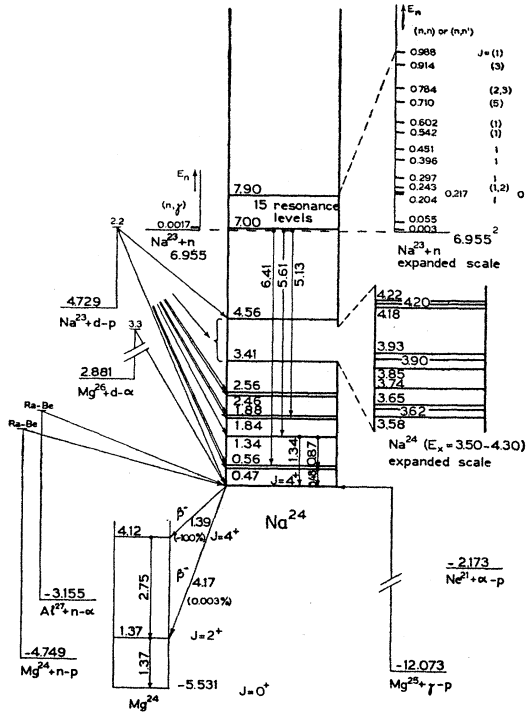

FIG. 6.

Ri 38, Fe 38, La 39a, Cu 40, Kr 45. A weak high-energy β^- component, going to the 1.37-Mev level, has also been found with an endpoint of 4.17 Mev and an intensity of 0.003 percent ($\log ft=12.7$) (Tu 51). See also Gr 50a. A weak crossover γ ray of about 4 Mev and intensity 0.05 percent has been observed (Tu 51) although others report its intensity as lower than 0.005 percent (Bi 50). A reported γ ray of 3.62 ± 0.05 Mev and intensity 0.04 percent (Be 51) could perhaps be an indication of a weak β^- transition to a Mg^{24} level at 4.99 Mev.

There are strong arguments that both the 2.75- and 1.37-Mev γ rays are electric quadrupole. This follows from $\gamma-\gamma$ angular correlation measurements (Wa 41, Ki 42, Br 50a, Ch 50) and from measurements of the internal pair-formation coefficients. For the 2.75-Mev γ ray the latter has been given as $(1.16\pm0.10)\times10^{-3}$ (Ra 49), $(7.6\pm1.9)\times10^{-4}$ and $(8.25\pm1.05)\times10^{-4}$ (Mi 50), $(6.7\pm1.0)\times10^{-4}$ (Cl 51), 8.0×10^{-4} (Sl 52) and $(7.1\pm0.2)\times10^{-4}$ (Bl 52), while for the 1.37-Mev γ ray has been found 0.3×10^{-4} (Sl 52) and $(0.6\pm0.1)\times10^{-4}$ (Bl 52). Also the shape of the internal pair spectrum (Bl 52) and the angular correlation between e^+ and e^- indicate the $E2$ character of the 2.76-Mev γ ray.

The internal conversion coefficient of the 2.75-Mev γ ray is 3×10^{-6} (Si 50), which also points to a quadrupole transition. From delayed $\beta-\gamma$ coincidence measurements an upper limit for the lifetime of the 1.38-Mev level is found of 2×10^{-9} sec, from which it follows that the multipole order of the 1.38-Mev γ ray is smaller than 3 (En 53). On the other hand, the multipole order of this γ ray must be larger than 1 because of the failure to detect resonant nuclear scattering of Na^{24} γ rays in magnesium (Po 48). The most probable spin and parity assignments for the 4.12- and 1.37-Mev level and ground state in Mg^{24} are then: 4^+, 2^+, and 0^+, which is the general rule for even-even nuclei (Sc 53). The β^- decay to the 4.12-Mev level is then allowed because the Na^{24} spin has been measured as $J=4$ (Sm 51, Be 53). The allowed character of the β^- decay has been confirmed experimentally by the shape of the β^- spectrum (Si 46) and by the absence of $\beta-\gamma$ angular correlation (Be 50a, St 51a). The ft value is rather large ($\log ft=6.1$).

For a theoretical discussion of the Na^{24} spin see De 53a.

II. $Ne^{21}(\alpha,p)Na^{24}$ $Q_m=-2.173$

Not observed.

III. $Na^{23}(n,\gamma)Na^{24}$ $Q_m=6.955$

Recent measurements of the thermal neutron capture cross section are 0.47 ± 0.04 b (Co 46a), 0.63 ± 0.13 b (Se 47), 0.52 ± 0.03 b (Ha 50), 0.50 ± 0.015 b (Co 50), 0.47 ± 0.02 b (Po 51), and 0.53 ± 0.03 b (Ba 53c). See also La 40, Ra 40, On 41, Si 41a, Vo 43.

For $E_n\approx1$ Mev the capture cross section is 0.26 mb (Hu 53a). See also Hu 49.

A resonance in the Na^{24} activation cross section has been found at $E_n=1.71$ kev by a boron absorption method (Li 47).

The thermal neutron capture γ rays measured by pair spectrometer (Ki 51) are given in Table V. Lines A, B, C, and I can be explained by transitions to the Na^{24} levels at 0.56, 1.34, 1.84, and 3.41 Mev. Lines F, G, and H could correspond to transitions from the levels at 3.93, 3.86, and 3.58 Mev to ground.

Gamma rays of 2.0, 1.66, 1.34, 0.86, and 0.48 Mev have been found with a two-crystal scintillation spectrometer (Br 53a) and γ rays of 0.877 ± 0.010 and 0.475 ± 0.010 Mev with a lens spectrometer (Mo 53). The 1.34- and 0.47-Mev lines are probably transitions from the corresponding Na^{24} levels to ground, and the 0.87-Mev line the transition from the 1.34 Mev to the 0.47-Mev level.

Thermal neutron capture γ rays have also been detected with deuterium-loaded nuclear emulsions. The following γ-ray energies were found (relative intensities

TABLE V. $Na^{23}(n,\gamma)Na^{24}$ γ rays (Ki 51).

γ ray	Energy in Mev	Intensity in photons per 100 captures
A	6.41 ± 0.03	20
B	5.61 ± 0.03	7.5
C	5.13 ± 0.03	1.8
F	3.96 ± 0.03	20
G	3.85 ± 0.05	11
H	3.60 ± 0.03	10
I	3.56 ± 0.05	20

TABLE VI. Levels in Na^{24} from $Na^{23}(n,n)Na^{23}$ (St 52b).

Resonance energy in kev	Na^{24} level in Mev	Width in kev	σ_{res} in barns	J	l_n
204	7.150	5	5.2	1	(1)
217	7.163	14	~1.3	0	(1)
243	7.188	7	5.9	1 or 2	(1)
297	7.240	4	...	1	0
396	7.335	23	2.1	1	(1)
451	7.387	9	2.5	1	(1 or 2)
542	7.474	39	...	(1)	(0)
602	7.532	6	1.4	(1)	...
710	7.635	72	...	(5)	...
784	7.706	38	...	(2 or 3)	...
914	7.831	36	...	(3)	...
988	7.902	24	...	(1)	...

in brackets): 2.79 (45), 3.05 (61), 3.25 (56), 3.55 (70), 3.92 (39), 4.35 (89), 4.82 (100), and 5.37 Mev (31) (Mi 50a). The first γ ray results from the Na^{24} β^- decay. The γ rays at 3.55 and 3.92 Mev check with Kinsey's lines I and F (see Table V).

See also Bj 34a, Am 35.

IV. $Na^{23}(n,n)Na^{23}$ $E_b=6.955$

Measurements up to 1950 of total cross section *vs* neutron energy have been reviewed by Adair (Ad 50). The cross section is constant (3 b) below $E_n=1$ kev (Hi 50a, Ho 52).

In the $E_n=1-100$ kev region resonances are found at 3.0 ± 0.6 kev ($J=2$) (Hi 50a, Hi 52, Ho 52) and at 55 kev (Ad 49, Hi 52). Twelve resonances (Table VI) were found in the $E_n=0.12-1.0$ Mev region which has been explored at high resolution with $Li(p,n)$ neutrons (St 52b). See also Ad 49. Resonances found with $D(d,n)$ neutrons at 30–50 kev resolution have been reported at $E_n=1.97$, (2.07), 2.10, 2.17, 2.21, 2.29, 2.42, (2.46), 2.55, 2.65, 2.73, 3.26, 3.36, 3.54, and 3.68 Mev (Me 53).

At $E_n=14$ Mev the total cross section is 1.71 ± 0.03 b (Co 52a). See also Ma 40, Hi 50, Dv 53.

V. $Na^{23}(d,p)Na^{24}$ $Q_m=4.729$

The ground-state Q value has been measured by magnetic analysis as 4.731 ± 0.007 Mev (Sp 52) and 4.723 ± 0.008 Mev (Mi 52). Eighteen levels in Na^{24} have been found by high-resolution magnetic analysis at deuteron energies between 1.5 and 2.2 Mev (Sp 52). They are collected in Table VII together with the levels found by an absorption method at $E_d=3$ Mev (Wh 50). See also La 35, La 35a, Li 37, Mu 39, Ba 42, Cl 44, Cl 46a, Ne 50b, St 51.

The angular distribution of the secondary protons has been measured at $E_d=1.15$ Mev with nuclear emulsions both for the ground-state group and for groups leading to the Na^{24} excited states at 0.47 and 0.56 Mev (unresolved). Butler analysis yields $l_n=2$ for the ground-state group in agreement with known spins and parities of Na^{23} and Na^{24} (Ta 53). The angular distribution of the secondary protons at $E_d=3$ Mev gives also $l_n=2$ for the ground-state group, $l_n=0$ and 2 for the unresolved groups to the 0.47- and 0.56-Mev levels, and $l_n=0$ for the group to the 1.34-Mev level, indicating $J=1^+$ or 2^+ for this level (Sh 54).

VI. $Mg^{24}(n,p)Na^{24}$ $Q_m=-4.749$

The cross section of this reaction for $Be(d,n)$ neutrons ($E_d=15$ Mev) is 39 ± 4 mb (Co 51). At $E_n=14.5$ Mev, the cross section is 191 ± 35 mb (Pa 53). See also Am 35.

VII. $Mg^{25}(\gamma,p)Na^{24}$ $Q_m=-12.073$

The cross section shows a maximum of 14.8 mb at $E_\gamma=21.7$ Mev with 6.0-Mev width and the integrated cross section is 100-Mev mb (Ka 51b). From enriched target bombardments a maximum of 13.7 mb is found at 20.5 Mev with an integrated cross section of 56-Mev mb (To 51). See also Ba 46, Hi 47. The threshold has been measured as 11.5 ± 1.0 Mev (Mc 49).

VIII. $Mg^{26}(d,\alpha)Na^{24}$ $Q_m=2.881$

The Na^{24} activity has been measured as a function of deuteron energy up to 14 Mev (He 35, Cl 46, Cl 46a). At $E_d=8.7$ Mev the cross section for this reaction has a maximum of 95 mb (Cl 46). See also Al 49, Al 49b.

IX. $Al^{27}(n,\alpha)Na^{24}$ $Q_m=-3.155$

At $E_n=14$ Mev the cross section is 135 ± 10 mb (Fo 52a) and 79 ± 16 mb (Pa 53). See also Kl 34, Am 35, Po 36, Po 38.

X. $Al^{27}(d,\alpha p)Na^{24}$ $Q_m=-5.381$

The absolute cross section for this reaction has been measured from the threshold $E_d=11.0\pm0.5$ Mev to 190 Mev. A sharp maximum of 53 mb exists at approximately 22 Mev followed by a broad minimum of

TABLE VII. Levels in Na^{24} from $Na^{23}(d,p)Na^{24}$.

Group	Q values (Mev) (Sp 52)	Na^{24} levels (Mev) (Sp 52)	Na^{24} levels (Mev) (Wh 50)
(0)	4.731 ± 0.007	0	...
(1)	4.259 ± 0.007	0.472 ± 0.008	...
(2)	4.167 ± 0.007	0.564 ± 0.008	0.54
(3)	3.390 ± 0.006	1.341 ± 0.008	1.32
(4)	2.887 ± 0.006	1.844 ± 0.008	1.83
(5)	2.847 ± 0.006	1.884 ± 0.008	...
(6)	2.267 ± 0.006	2.464 ± 0.008	...
(7)	2.170 ± 0.006	2.561 ± 0.008	2.55
(8)	1.322 ± 0.005	3.409 ± 0.008	3.44
(9)	1.149 ± 0.006	3.582 ± 0.009	...
(10)	1.108 ± 0.006	3.623 ± 0.009	...
(11)	1.083 ± 0.006	3.648 ± 0.009	...
(12)	0.993 ± 0.005	3.738 ± 0.008	3.81
(13)	0.881 ± 0.005	3.850 ± 0.008	...
(14)	0.832 ± 0.005	3.899 ± 0.008	...
(15)	0.802 ± 0.005	3.929 ± 0.008	3.99
(16)	0.547 ± 0.005	4.184 ± 0.008	...
(17)	0.529 ± 0.005	4.202 ± 0.008	4.27
(18)	0.512 ± 0.005	4.219 ± 0.008	...
(19)	0.173 ± 0.005	4.558 ± 0.009	4.64

18 mb near 60 Mev and a gradual rise to 22 mb at 190 Mev (Ba 53a). See also Cl 46, Cl 47.

GENERAL REMARKS

For a theoretical discussion regarding doublet levels in Na^{24} see In 53.

Mg^{24}

Mass defect: -6.864 Mev

I. $Ne^{20}(\alpha,\alpha)Ne^{20}$ $E_b=9.332$

With α particles from RaC′ and ThC′ and mica absorbers a resonance has been observed at $E_\alpha=5.9$ Mev indicating a level in Mg^{24} at 14.7 Mev (Br 38a). Thirteen sharp resonances (half-width, $\Gamma\leq 10$ kev) have recently been observed in the neon elastic cross section at four different scattering angles for $E_\alpha=2-4$ Mev. Eleven of these are assigned to Ne^{20} (compound nucleus Mg^{24}) and two to Ne^{22} (compound nucleus Mg^{26}). Spins and parities are found from partial wave analysis. The resonances in Mg^{24} occur at E_α (in Mev) = 2.488 ($J=1^-$), 2.573 (0^+), 2.652 (2^+), 2.903 (0^+), 3.062 (1^-), 3.184 (2^+), 3.548 (3^-), 3.780 (1^-), 3.801 (2^+), 3.839 (4^+), and 3.923 (2^+), corresponding to Mg^{24} levels between 11.4 and 12.6 Mev. The resonances in Mg^{26} are found at $E_\alpha=3.245$ (3^-), and 3.418 Mev (3^-) corresponding to Mg^{26} levels at 13.388 and 13.543 Mev (Go 53e).

IA. $Ne^{21}(\alpha,n)Mg^{24}$ $Q_m=2.576$

Not observed.

TABLE VIII. Resonances in the proton bombardment of Na^{23}.

Author:	Cu 39	Bu 41	Ta 46	Fr 48
Detection:	G.M. counter (γ rays)	G.M. counter (γ rays)	G.M. counter (γ rays)	Ion. chamber (α particles)
E_{res} in kev	...	...	255±3	...
	...	310	310±3	...
	...	...	375±4	...
	425	...	445±5	...
	525	515	510±5	...
	...	576	...	...
	590	598	...	590
	690	...	...	...
	755	735	...	740
	...	...	...	800
	875	867	...	...
	...	...	...	920
	...	1006	...	...
	...	1080	...	...
	...	1159	...	...
	...	1206	...	...
	...	1255	...	...
	...	1281	...	...
	...	1324	...	...
	...	1392	...	...
	...	1412	...	...
	...	1454	...	...
	...	1638[a]	...	...
	...	1732	...	...
	...	1795	...	...
	...	1829	...	...
	...	1930	...	...

[a] Width 70 kev, probably unresolved doublet.

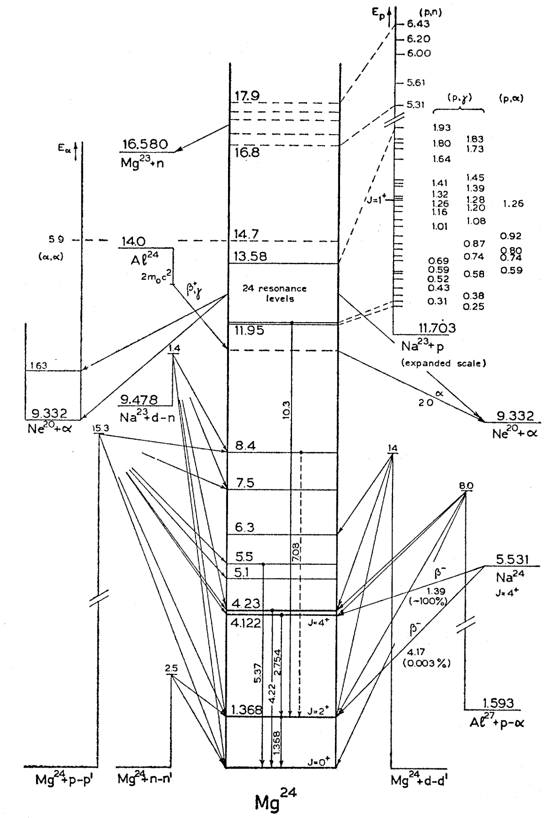

FIG. 7.

II. $Na^{23}(p,\gamma)Mg^{24}$ $Q_m=11.703$

The resonances observed in the proton bombardment of sodium are collected in Table VIII.

The region from $E_p=0.8$ to 1.7 Mev has also been explored by Teener *et al.* (Te 53) who find the same thirteen resonances as given in Table VIII (Bu 41). In the region from $E_p=1.0$ to 2.6 Mev thirty-seven resonances are observed (St 52a). No specific resonance energies are reported in these latter two investigations.

The following γ-ray energies have been determined by absorption: 6.8 Mev (Ta 46) and 8.3 Mev (Ge 37) for the resonance at $E_p=310$ kev, 9.0 Mev for the resonance at 510 kev (Ta 46), and 11.2 Mev for the resonance at 750 kev (Cu 39). Gamma-ray energies and relative intensities determined by scintillation spectrometer at the 310 kev resonance are given in Table IX. Lines A and E can be explained as a cascade through the Mg^{24} level at 1.37 Mev, line D corresponds to a transition from the resonance level to the doublet level around 4.2 Mev (Ca 53). At the resonances above $E_p=1.0$ Mev mainly two γ rays of $E_\gamma=0.45\pm0.01$ and 1.63 ± 0.02 Mev are found by scintillation spectrometer. The first results from the $Na^{23}(p,p')$ reaction and the second from the $Na^{23}(p,\alpha')Ne^{20*}$ reaction leading to the 1.63-Mev level in Ne^{20}. Only at the $E_p=1.415$ Mev resonance is hard capture radiation observed (St 52a). In more recent

TABLE IX. Gamma rays from $Na^{23}(p,\gamma)Mg^{24}$ at $E_p=305$ kev (Ca 53).

Line	Energy (Mev)	Rel. intensity
A	1.38±0.04	28
B	(3.6 ±0.2)	···
C	6.84±0.24	20
D	7.50±0.20	
E	10.3 ±0.3	11

work 52 $(p,p'\gamma)$ resonances are found in the $E_p=1.01-2.43$ Mev region, of which 35 are resonant for hard capture γ rays (St 53d). See also He 37, Ho 41.

III. $Na^{23}(p,n)Mg^{23}$ $E_b=11.703$ $Q_m=-4.877$

Resonances in the Mg^{23} activity yield are observed at $E_p=5.31$, 5.61, 6.00, 6.20, and 6.43 Mev (Bl 51). For threshold determinations see Mg^{23}.

IV. $Na^{23}(p,p')Na^{23}$ $E_b=11.703$

For resonances in the inelastic scattering leading to the 0.44-Mev level in Na^{23} see Mg^{24} reaction II.

For Na^{23} levels found from inelastic scattering see Na^{23}.

V. $Na^{23}(p,\alpha)Ne^{20}$ $E_b=11.703$ $Q_m=2.372$

Resonances in the ground-state transition of this reaction are given in Table VI, last column (Fr 48). For resonances in this reaction leading to the 1.63-Mev level in Ne^{20} see Mg^{24} reaction II. The $\alpha-\gamma$ angular correlation of this transition has been measured at the $E_p=1.255$ Mev resonance in planes parallel and perpendicular to the proton beam. The result can be explained by taking $J=2^+$ for the Ne^{20} 1.63-Mev level and $J=1^+$ for the Mg^{24} resonance level (Se 53). Angular distributions of α particles leading to the Ne^{20} ground state and first excited state have been measured at six resonances in the $E_p=1$ to 2 Mev region (St 53a). Of 52 $Na^{23}(p,p'\gamma)$ resonances in the $E_p=1.01-2.43$ Mev region 17 are resonant for the $Na^{23}(p,\alpha)$ reaction (St 53d).

VI. $Na^{23}(d,n)Mg^{24}$ $Q_m=9.478$

In the bombardment of sodium with 1.4-Mev deuterons several neutron groups are observed by their recoil protons in nuclear emulsions. The reported Q value of the ground-state transition is 9.23 Mev. The other Q values indicate levels in Mg^{24} at 0.83, 1.24, 1.66, 4.16, 7.70, and 8.64 Mev (Ma 49). The levels at 0.83 and 1.66 Mev have not been observed in other reactions. At $E_d=3.7$ Mev a γ ray of $E_\gamma=8.8\pm0.6$ Mev is found, which might also belong to $Na^{23}(d,\alpha)Ne^{21}$ (Al 49b). See also La 35, Hu 51.

VII. $Na^{24}(\beta^-)Mg^{24}$ See Na^{24}

Precision measurements of the γ rays in this decay ($E_\gamma=2.7535\pm0.0010$ and $E_\gamma=1.3680\pm0.0010$ Mev) constitute the most accurate determination of the excitation energies of the two lowest levels in Mg^{24}, *viz.*, 1.3680±0.0010 Mev and 4.1215±0.0014 Mev (He 52).

VIII. $Mg^{24}(n,n')Mg^{24}$

Inelastic scattering of 2.5-Mev neutrons has been investigated by several authors. Observation of the recoil protons in a cloud chamber yields a level at 1.30 Mev (Li 46). The energy of the γ rays has been determined by an absorption method as $E_\gamma=1.4\pm0.1$ Mev (Gr 51) and by scintillation spectrometer as $E_\gamma=1.365\pm0.02$ Mev (Da 53) and $E_\gamma=1.40$ Mev (Ga 53). The inelastic scattering cross section is measured as 0.75 ±0.23 b (Gr 51) and 0.6 b (Li 46) and the elastic cross section as 1.6 b (Li 46).

IX. $Mg^{24}(p,p')Mg^{24}$

Inelastically scattered protons have been observed by numerous authors using bombarding energies from 2.4 to 15.3 Mev. Only Mooring *et al.* (Mo 51) have worked with enriched targets. The 1.37-Mev level has been observed by all (Wi 41, Di 43, Rh 49, Fu 48, Mo 51, Ba 52, Ha 52, and St 52) and is most accurately determined as 1.371±0.002 Mev by electrostatic analysis of the scattered protons (Do 53). A level near 4.17 Mev has been found by Wi 41, Fu 48, and Ba 52, whereas Hausman *et al.* (Ha 52), using magnetic analysis, proved it to be a doublet of 4.13±0.02 and 4.24±0.02 Mev. All other levels reported below 4 Mev (Wi 41, Di 43, Fu 48) can be assigned to Mg^{25} or Mg^{26}. The levels at 5.10 Mev (St 52), 5.51±0.3, 7.32±0.3, 8.30±0.4 Mev (Fu 48), and 6.38±0.08 Mev (Ba 52) may belong to Mg^{24}, but are possibly due to Mg^{25} or Mg^{26}.

The angular distribution of elastically scattered protons and of inelastically scattered protons corresponding to transition to the 1.37 Mev Mg^{24} level has been measured at $E_p=4.5$ Mev (Rh 50), at 6.9 Mev (Wi 41, Wr 43), at 7.3 Mev (Go 52), and at 9.6 Mev (Ba 52). See also Wi 40a, Ha 52c.

The $p-\gamma$ angular correlation (transitions to the 1.37 Mev Mg^{24} level) has been measured at $E_p=7.3$ Mev (Go 52a).

See Al^{25} for resonances in the elastic scattering cross section.

X. $Mg^{24}(d,d')Mg^{24}$

The 1.37-Mev level is observed from the inelastic scattering of deuterons of bombarding energy 6 Mev (Gr 49), 7.5 Mev (Ho 49), and 14 Mev (Bo 50). Moreover, levels at 4.4 and 6.3 Mev are found at $E_d=14$ Mev (Bo 50).

The angular distribution of the inelastically scattered deuterons ($E_d=7.5$ Mev) shows maxima at 35° and 80°, and minima at 60° and 120° (Ho 49). This indicates $l_n=2$ and $y=(1, 2 \text{ or } 3)^+$ for the 1.37-Mev level (Hu 51a).

XI. $Mg^{24}(\alpha,\alpha)Mg^{24}$

See Si^{28} for resonances in the elastic scattering cross section.

XII. $Mg^{25}(\gamma,n)Mg^{24}$ $Q_m=-7.324$

The threshold is $E_\gamma=7.25\pm0.20$ Mev (Sh 51a). See also Mg^{23} reaction IV.

XIII. $Al^{24}(\beta^+)Mg^{24}$ See Al^{24}

XIV. $Al^{27}(p,\alpha)Mg^{24}$ $Q_m=1.593$

Recent determinations of the Q value are:

$Q=1.585\pm0.015$ Mev (magnetic analysis, $E_p=0.94$ Mev) (Fr 50b);

$Q=1.595\pm0.007$ Mev (magnetic analysis, $E_p=1.8$ Mev) (Va 52a);

$Q=1.594\pm0.002$ Mev (electrostatic analysis, $E_p=1.2$ Mev) (Do 53);

$Q=1.61\pm0.02$ Mev (magnetic analysis, $E_p=0.5-0.7$ Mev) (Ru 53a).

See also Fr 48, Ka 52.

Transitions to the 1.38, 4.11, and 4.21 Mev levels are observed by magnetic analysis at $E_p=8$ Mev (Re 52). An accurate determination by electrostatic analysis at $E_p=2.7$ and 3.4 Mev gives a mean value of 1.366 ± 0.004 Mev for the first level in Mg^{24} (Do 53). See Si^{28} for resonances. See also Sh 51.

Al^{24}

(not illustrated)

Adopted mass defect: 7.1 Mev (Bi 52)

I. $Al^{24}(\beta^+)Mg^{24}$ $Q_m=14.0$

The half-life is given as 2.3 ± 0.2 sec (Bi 52), 2.10 ± 0.04 sec (Gl 53) and 2.0 ± 0.1 sec (Br 53c). Gamma rays observed by scintillation spectrometer are listed in Table X.

The 1.39-, 4.22-, and 5.36-Mev γ rays correspond probably to de-excitation of known levels in Mg^{24} to the ground state, the 2.72- and 7.08-Mev γ rays to transitions from the 4.122- and 8.4-Mev level to the 1.368-Mev level. It is noteworthy, that whereas the 4.12-Mev level decays by a cascade through the 1.37-Mev level (as in the decay of Na^{24}), the 4.23-Mev level is de-excited by a direct transition to the ground state.

TABLE X. Gamma rays in the decay of Al^{24}.

Author	Gl 53, Ri 53	Br 53c
E_γ in Mev	1.39 ± 0.03	1.38 ± 0.04
	2.73 ± 0.06	2.70 ± 0.06
	4.22 ± 0.10	4.21 ± 0.12
	5.35 ± 0.10	5.37 ± 0.14
	(6.4)	(5.66 ± 0.18)
	7.12 ± 0.10	7.02 ± 0.20

One per several thousand disintegrations proceeds through an excited level in Mg^{24}, which emits α particles of $E_\alpha=2\pm0.5$ Mev (Bi 52, Gl 53, Gl 53b, Ri 53).

For a theoretical prediction of the Al^{24} spin see De 53a.

II. $Mg^{24}(p,n)Al^{24}$ $Q_m=14.8$

The Al^{24} activity has been discovered in the bombardment of magnesium with protons of a 30-Mev linear accelerator. The threshold is determined as $E_p=15.4\pm0.3$ Mev (Bi 52).

Na^{25}

(not illustrated)

Adopted mass defect: -2.1 Mev (Mc 49, Bl 47).

I. $Na^{25}(\beta^-)Mg^{25}$ $Q_m=3.7$

The half-life has been determined as 61.3 ± 2.4 sec (Hu 44), 60.0 ± 1.2 sec (Ri 44), 62.5 sec (Ba 46), 58.2 ± 1.3 sec, and 62.0 sec (Pe 48). See also Hu 43 and Hu 43a. The maximum β^- energy is about 3.4 Mev (Hu 44, Ri 44, and Mc 49). Bleuler and Zünti suggest a mixture of two β transitions with maximum energies 2.7 and 3.7 ± 0.3 Mev and relative intensities of 45 percent and 55 percent, as they have detected low-energy γ radiation of an intensity less than one γ per β transition (Bl 47). Both transitions are allowed as follows from the ft values ($\log ft=4.8$ and 5.3).

II. $Ne^{22}(\alpha,p)Na^{25}$ $Q_m=-3.4$

Na^{25} activity has been found by the bombardment of neon with Po α particles (Ol 51).

III. $Mg^{25}(n,p)Na^{25}$ $Q_m=-3.0$

At $E_n=14.5$ Mev the cross section is 45 ± 18 mb (Pa 53). See also Hu 44, Ri 44.

IV. $Mg^{26}(\gamma,p)Na^{25}$ $Q_m=-14.0$

By this reaction Na^{25} has been discovered (Hu 43, Hu 43a, and Hu 44) with γ's from the proton bombardment of lithium ($E_\gamma=14.8$ and 17.6 Mev). The cross section at these γ energies is 1.9 mb (Hi 47, Wa 48). The threshold is at $E_\gamma=14.0\pm1.0$ Mev (Mc 49). A detailed study of the cross section as a function of E_γ shows a maximum ($\sigma=19.3$ mb) at $E_\gamma=22.6$ Mev with a half-width of 3.3 Mev and $\int\sigma dE=0.085$ Mev b (Ka 51b). With the x-rays of a 70 Mev synchrotron $\int\sigma dE=0.092$ Mev b has been found (Ed 52). See also Ba 49.

Mg^{25}

Mass defect: -5.824 Mev

I. $Ne^{22}(\alpha,n)Mg^{25}$ $Q_m=-0.462$

Two neutron groups are reported from this reaction with Q values: -0.916 ± 0.07 Mev and -1.71 ± 0.08

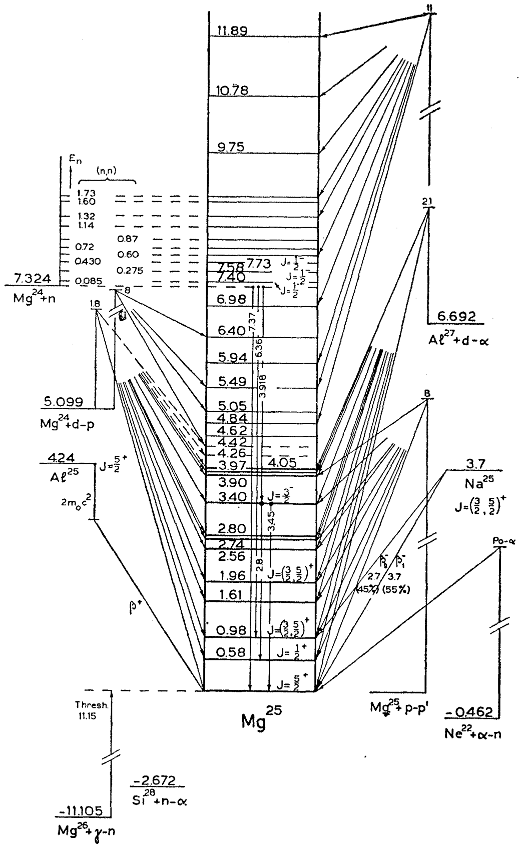

FIG. 8.

Mev. Po$-\alpha$'s and photographic emulsion technique (Ol 51) were used.

II. $Na^{25}(\beta^-)Mg^{25}$ See Na^{25}

III. $Mg^{24}(n,\gamma)Mg^{25}$ $Q_m=7.324$

The thermal neutron capture cross section of isotopic Mg^{24} has been determined as 33 ± 10 mb (Po 52a). For natural magnesium values have been reported of 60 ± 3 mb (Ha 50), 57 ± 6 mb (Co 50), and 60 ± 6 mb (Po 51). See also Ra 42, Vo 43, Co 46a.

By high-resolution pair spectrometer thirteen γ rays have been found resulting from the capture of thermal neutrons in natural magnesium (see Table XI) (Ki 51, Ki 53a). Nine of these might be ascribed with more or less certainty to capture in Mg^{26} although in principle some of them might also be due to captures in Mg^{25} or Mg^{26}. Line C almost certainly corresponds to transitions leading to the ground state of Mg^{25}; lines E, F_2, and G could lead to known levels at 0.58, 0.976, and 1.61 Mev. Lines J and K form a cascade to the ground state through the 3.405-Mev level, which level is also de-excited by line L to the first level. Finally, lines H and I might also be fitted into the Mg^{25} level scheme. The 2.8-Mev line, in addition to one more line at $E_\gamma=1.9$ Mev, has also been observed with a two-crystal scintillation spectrometer (Br 53b). The great intensity of line J (from the capture state to the p level at 3.405 Mev in Mg^{25}) is explained in a natural way as being the most energetic $E1$ transition. Since this level is de-excited by γ rays K and L to the ground state (spin $5/2^+$) and the first level (spin $\frac{1}{2}^+$), both these competing transitions must be $E1$, and the spin of the 3.405 level is uniquely determined as $\frac{3}{2}^-$ (Ki 53e).

A recalculation of the intensities of some lines in photons per 100 captures in Mg^{24} is given in (Ki 53e).

IV. $Mg^{24}(n,n)Mg^{24}$ $E_b=7.324$

The earlier data on neutron cross sections of natural magnesium have been compiled by Adair (Ad 50). Up to $E_n=400$ ev no resonances are observed (Ra 48, Hi 49a), whereas some broad resonances have been found between 0.1 and 2.0 Mev (Fr 50, Fi 47) indicating levels in Mg^{25} at 0.58, 0.69, 1.09, 1.27, 1.60, and 1.66 Mev above the neutron binding energy (Fr 50).

The cross section is about 2 b at $E_n\simeq2.5$ Mev (Ao 39, Zi 39, Ma 40) and 1.75 ± 0.03 b at $E_n=14$ Mev (Go 52a). See also Am 46, Am 46a.

Fields and Walt (Fi 51) have observed resonances at $E_n=85$, 275, and 430 kev, which are attributed to Mg^{24} and indicate $J=\frac{1}{2}^-$, $\frac{1}{2}^-$, and $\frac{3}{2}^-$ for corresponding levels in Mg^{25} at 7.40, 7.58, and 7.73 Mev. Also broad resonances were found at $E_n=560$ and 680 kev and a weak narrow resonance at 22 kev, which might be due to one of the less abundant magnesium isotopes.

V. $Mg^{24}(d,p)Mg^{25}$ $Q_m=5.099$

The most accurate Q value obtained by magnetic analysis for the ground-state transition is 5.097 ± 0.007 Mev (En 52b). This figure supersedes an earlier value given by the Massachusetts Institute of Technology group of 5.094 ± 0.010 Mev (St 51). Ten levels in Mg^{25} (see Table XII) have been found from the magnetic analysis work using natural magnesium targets (En 52b). Assignment of proton groups to $Mg^{24}(d,p)Mg^{25}$ was done by comparison with Mg^{25} levels found from

TABLE XI. Gamma rays found from capture of thermal neutrons in natural magnesium (Ki 51, Ki 53a).

γ ray	Energy in Mev	Intensity in photons per 100 captures	Final nucleus
A	$9.26\ \pm0.04$	1	Mg^{26}
B	$8.16\ \pm0.03$	9	Mg^{26}
C	$7.37\ \pm0.08$	0.5	Mg^{25}
D	$7.15\ \pm0.04$	1	Mg^{26}
E	$6.75\ \pm0.04$	2.5	Mg^{25}, Mg^{26}
F_1	6.440 ± 0.008	1.3	Mg^{27}
F_2	6.358 ± 0.007	3.5	Mg^{25}
G	$5.73\ \pm0.04$	1	Mg^{25}
H	$5.50\ \pm0.04$	7	(Mg^{25}), Mg^{26}
I	$5.05\ \pm0.07$	9	(Mg^{25})
J	3.918 ± 0.004	70	Mg^{25}
K	$3.45\ \pm0.07$	16	Mg^{25}
L	$2.83\ \pm0.05$	39	Mg^{25}

TABLE XII. Energy levels in Mg^{25} from $Mg^{24}(d,p)Mg^{25}$.

Author:	Al 49	En 52b, En 53a	Am 52	Ho 53c
E_d in Mev:	0.93	1.8	1.9	8
Method:	Al absorption	Magnetic analysis	Nuclear emulsions	Al absorption
Q_0 (Mev):	5.03	5.097±0.007	4.99±0.10	...[a]
Levels in Mg^{25} in Mev	0.58	0.582±0.006	0.58±0.10	
	0.98	0.976±0.006	0.94±0.10	
		1.612±0.006	1.62±0.10	
		1.957±0.006		
		2.565±0.006		
		2.742±0.008		
		2.806±0.007		
		3.405±0.007		
		3.899±0.008		
		3.972±0.010		
		(4.052±0.010)		
		(4.265±0.007)		
		(4.421±0.010)		
				4.62±0.05
				5.05±0.07
				5.47±0.05
				6.40±0.05

[a] A ground-state Q value of 5.097 Mev has been assumed.

TABLE XIII. Energy levels in Mg^{25} from $Al^{27}(d,\alpha)Mg^{25}$.

Author:	Po 49	Fr 50a	Sc 50	To 52	En 52b, En 53a
E_d in Mev:	3.79	0.93	11.1	10.8	2.1
Method:	Al absorption	Air absorption	Al absorption	Nuclear emulsions	Magnetic analysis
Q_0 (Mev):	6.52±0.06	6.62±0.05	6.58±0.03	...[a]	6.694±0.010
Levels in Mg^{25} in Mev		0.58±0.05	0.57±0.05	0.58±0.02	0.584±0.006
	0.81±0.07	0.94±0.05	0.96±0.05	0.93±0.04	0.977±0.010
	1.58±0.07	1.54±0.05	1.63±0.04	1.62±0.03	1.610±0.010
		1.87±0.05	1.97±0.05	2.09±0.05	1.958±0.010
	2.54±0.07				2.558±0.010
			2.74±0.04	2.74±0.03	2.729±0.010
					2.791±0.015
			3.36±0.04	3.36±0.03	3.404±0.012
					3.896±0.015
				3.96±0.04	3.960±0.015
			4.01±0.05	4.12±0.04	4.057±0.015
			4.81±0.05	4.87±0.03	
			5.48±0.05	5.56±0.03	
			5.95±0.05	5.93±0.03	
				6.98±0.03	
				7.85±0.04	
				8.62±0.05	
				9.06±0.04	
				9.75±0.04	
				10.78±0.04	
				11.89±0.05	

[a] A ground-state Q value of 6.694 Mev was assumed.

$Al^{27}(d,\alpha)Mg^{25}$ and by comparison with proton groups found from targets enriched in Mg^{25} or Mg^{26} content. The lower levels are in good agreement with other authors using enriched targets (Al 49, Am 52). Four levels above 4.6 Mev have been observed by Holt and Marsham (Ho 53c). See also Al 46, Al 48, Ne 48, Ne 50b, Va 52a.

In the bombardment of natural magnesium with 3.7-Mev deuterons a γ ray of 5.1±0.3 Mev is observed with an absorber technique (Al 49b). This γ ray may be attributed to $Mg^{24}(d,p)Mg^{25}$, but could also belong to several other reactions.

Angular distribution measurements and Butler analysis yield $l_n=0(J=\frac{1}{2}^+)$ for the level at 0.58 Mev and for one or more of the three levels around 2.7 Mev, $l_n=1(J=\frac{1}{2}^-$ or $\frac{3}{2}^-)$ for the level at 3.40 Mev and $l_n=2(J=\frac{3}{2}^+$ or $5/2^+)$ for the ground state and the levels at 0.98 and 1.96 Mev. The angular distribution of protons associated with transitions to the level at 1.61 Mev is isotropic. From the relative intensities of the proton groups neutron capture probabilities can be deduced which give some more information on the configuration (single particle or multiple excitation) of the level concerned (Ho 53c).

VI. $Mg^{25}(\gamma,p)Na^{24}$ $Q_m=-12.072$

With x-rays from a 61 Mev synchrotron a maximum in the cross section was observed at $E_\gamma=22\pm3$ Mev with a half-width of 12±3 Mev (Sa 51).

VII. $Mg^{25}(p,p')Mg^{25}$

By magnetic analysis of the scattered protons of bombarding energy $E_p=8$ Mev on natural magnesium targets levels are found at 0.61; 1.62; 1.98; 2.56; 2.76 (possibly a doublet); 3.41; and 3.91 all ±0.02 Mev (Ha 52). They agree well with levels in Mg^{25} found from other reactions.

Probably some levels observed by other authors (Wi 41, Di 43, Fu 48, and St 52) in the bombardment of natural magnesium have to be assigned also to this reaction.

VIII. $Mg^{26}(\gamma,n)Mg^{25}$ $Q_m=-11.105$

The threshold of this reaction was measured as 11.15±0.20 Mev (Sh 51a). See also Mg^{23} reaction IV.

IX. $Al^{25}(\beta^+)Mg^{25}$ See Al^{25}

X. $Al^{27}(d,\alpha)Mg^{25}$ $Q_m=6.692$

Table XIII shows good agreement between the level positions found with different bombarding energies and detection methods by different authors and also with the level positions deduced from $Mg^{24}(d,p)Mg^{25}$ studies (Table XII). See also Le 33, Mc 35, Al 49b, En 51, St 51.

The α-particle yield measured at $E_d=11.1$ Mev depends markedly on angle for most groups. Only the α-particle group leading to the 1.61-Mev level is isotropic (Sc 50).

XI. $Si^{28}(n,\alpha)Mg^{25}$ $Q_m=-2.672$

Not observed.

Al^{25}

Adopted mass defect: −1.58 Mev (Go 53)

I. $Al^{25}(\beta^+)Mg^{25}$ $Q_m=4.24$

The half-life has been measured as 7.3 sec (Br 48), and 7.62±0.13 sec (Ch 53).

If it is assumed that the β^+ decay proceeds to the Mg^{25} ground state the log ft value would be 3.5, the

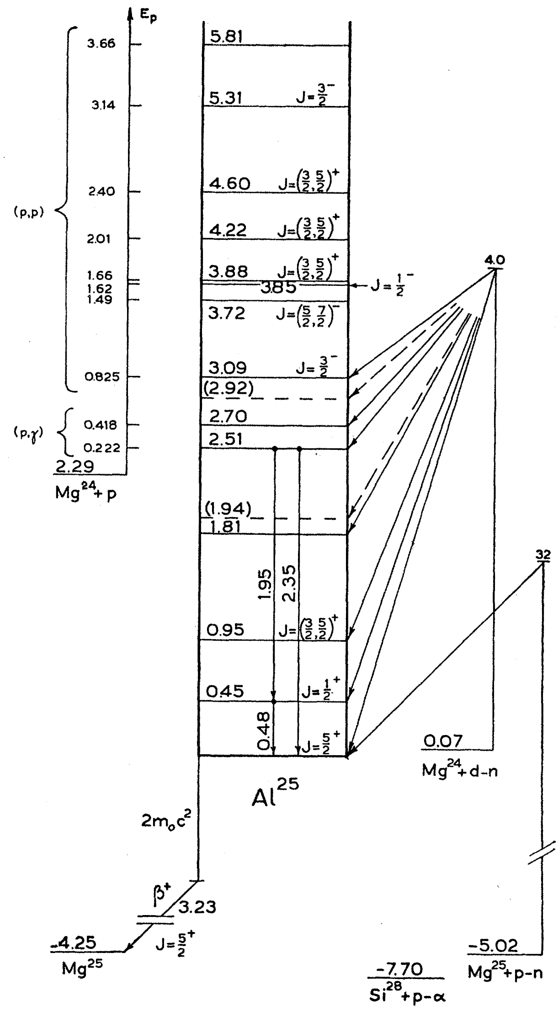

FIG. 9.

usual value for super-allowed transitions between mirror pairs.

II. $Mg^{24}(p,\gamma)Al^{25}$ $Q_m=2.29$

From thin enriched target measurements resonances have been found in the production of radioactive Al^{25} at $E_p=222$ and 417 kev (Gr 50) corresponding to levels in Al^{25} at 2.50 and 2.69 Mev.

High-precision measurement of the energy of the second resonance by electrostatic deflection of the protons and a thin separated Mg^{24} target yields $E_p=418.0 \pm 0.5$ kev (Hu 53).

From thin natural magnesium target bombardments resonances have been found in the γ-ray yield accompanied by β^+ activity at $E_p=222\pm1$, 310 ± 3, 392 ± 4, 417 ± 4, 492 ± 5, 508 ± 5, and 525 ± 6 kev (Ta 46). They might be assigned to levels either in Al^{25} or in Al^{26}. See also Cu 39, and Ho 41.

The following γ-ray energies have been measured at the 222 kev resonance making use of a scintillation-spectrometer: 0.48 ± 0.05, 1.95 ± 0.06, and 2.35 ± 0.1 Mev (Ca 53). They might be interpreted as transitions between the following Al^{25} levels: 0.45 Mev→ground, 2.51 Mev→0.45 Mev, and 2.51 Mev→ground. The thick Mg-target proton capture probability is given as 5×10^{-12} captures/proton.

III. $Mg^{24}(p,p)Mg^{24}$ $E_b=2.29$

The differential cross section at 164° has been determined with thin enriched targets and magnetic analysis of elastically scattered protons for proton-bombarding energies between 0.4 and 3.9 Mev (Mo 51). Partial-wave analysis (Ko 52) of these data yields eight levels in Al^{25} and their width and classification (Table XIV). No resonance has been detected at $E_p=0.417$ Mev as found from the $Mg^{24}(p,\gamma)Al^{25}$ reaction.

TABLE XIV. Levels in Al^{25} from the $Mg^{24}(p,p)Mg^{24}$ reaction (Mo 51, Ko 52).

Bombarding energy in lab. system (Mev)	Level[a] in Al^{25} (Mev)	Width (kev)	Classification
0.825	3.08	1.5	$P_{3/2}$
1.49	3.72	0.3	F
1.62	3.85	36	$P_{1/2}$
1.66	3.88	0.1	D
2.01	4.22	0.15	D
2.40	4.60	0.3	D
3.14	5.31	200	$P_{3/2}$
3.66	5.80		(D)

[a] Using a proton binding energy in Al^{25} of 2.29 Mev.

IV. $Mg^{24}(d,n)Al^{25}$ $Q_m=0.07$

Thin enriched targets were bombarded at $E_d=4.0$ Mev (Go 53). Neutrons were detected with nuclear emulsions at six angles. Q values, levels in Al^{25}, counted number of tracks, maximum value of the differential cross section, and classification of levels (from Butler analysis) are assembled in Table XV. See also Fa 51, Hu 51.

TABLE XV. Levels in Al^{25} from the $Mg^{24}(d,n)Al^{25}$ reaction (Go 53).

Q value (Mev)	Level in Al^{25} (Mev)	Number of tracks counted	Maximum value of $\sigma(\theta)$ (mb/sterad)	Classification
0.07 ± 0.06	0	267	3.0	D
-0.38 ± 0.06	0.45 ± 0.03	1100	57	$S_{1/2}$
-0.88 ± 0.05	0.95 ± 0.03	430	2.5	D
-1.74 ± 0.04	1.81 ± 0.04	103		
-1.87 ± 0.04	(1.94)	14		
-2.44 ± 0.04	2.51 ± 0.05	372		
-2.67 ± 0.04	2.70 ± 0.05	302		
-2.85 ± 0.04	(2.92)	35		
-3.04 ± 0.03	3.09 ± 0.06	750		P

V. $Mg^{25}(p,n)Al^{25}$ $Q_m = -5.02$

The threshold for production of radioactive Al^{25} is given as $E_p = 5.1$ Mev (Bl 51). See also Br 48.

VI. $Si^{28}(p,\alpha)Al^{25}$ $Q_m = -7.70$

Not observed.

GENERAL REMARKS

Excitation energies, spins, and parities of Al^{25} levels agree well with corresponding levels in the mirror nucleus Mg^{25}.

Mg^{26}

Mass defect: -8.565 Mev

I. $Ne^{22}(\alpha,\alpha)Ne^{22}$ $E_b = 10.643$

See Mg^{24} reaction I for resonances.

IA. $Na^{23}(\alpha,p)Mg^{26}$ $Q_m = 1.849$

Several proton groups from this reaction have been reported (Ko 34, Li 37, Ma 36, Me 40, Mo 48, Hj 52). The corresponding Q values and levels in Mg^{26} (average values from different authors) are summarized in Table XVI. Levels are also found at 0.22, 0.60, 1.18, 1.92, and 2.75 Mev (the ground-state Q value is not given) (Hu 41). The agreement between different observers is none too good, but levels at 1.8, 2.7, 3.9, and 4.9 Mev check approximately with the results from the $Mg^{25}(d,p)Mg^{26}$ reaction. A level at 0.4 Mev is not found from $Mg^{25}(d,p)Mg^{26}$ measurements and would be contradictory to the general rule of high first excited states in even-even nuclei. See also Ch 31. Gamma-transitions, in coincidence with the proton groups to the first four excited levels, are established by scintillation spectrometer from the 1.83-Mev level to the ground state, from the 2.97-Mev level to the ground state, but more frequent (6×) to the 1.83-Mev level, from the 3.97-Mev level to the 1.83-Mev level and probably to the ground state, and from the 4.35-Mev level to the 2.97-Mev level. These data combined with the angular distributions of the $Mg^{25}(d,p)Mg^{26}$ reaction (Ho 53c) indicate spins and parities: 0^+, 1^+, 2^+, 2^+, 3^+, for the ground state and the four first excited states in Mg^{26} (Ma 53). See also Ko 46, Al 48a.

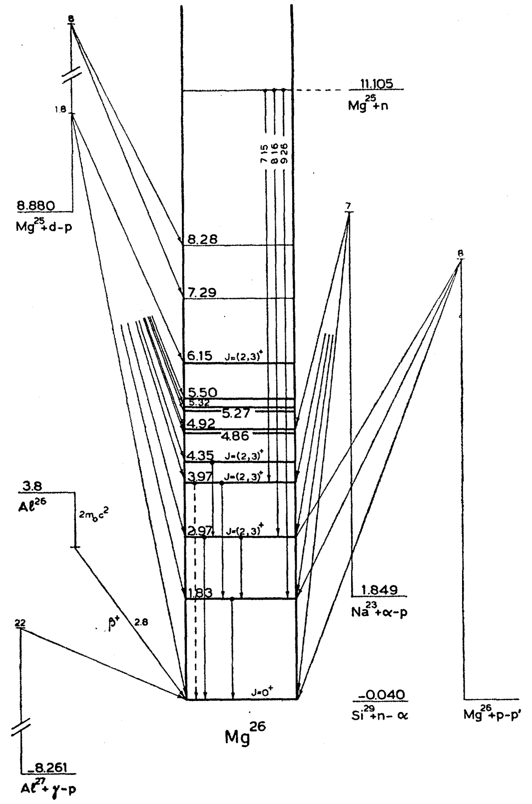

FIG. 10.

II. $Mg^{25}(n,\gamma)Mg^{26}$ $Q_m = 11.105$

The thermal neutron absorption cross section is 0.27 ± 0.09 b (Po 52a).

Twelve different γ rays (see Table XI) were found by pair spectrometer in the region of $E_\gamma = 2.8$ to 12.5 Mev from the capture of thermal pile neutrons in natural magnesium (Ki 51). Only the γ rays A, B, and D may be ascribed with certainty to captures in Mg^{25} (transitions to levels in Mg^{26} at 1.84, 2.94 and 3.93 Mev). Some others (notably lines E and H of Table XI) might be due to capture in Mg^{25}, but could also be ascribed to captures in Mg^{24} or Mg^{26}.

III. $Mg^{25}(d,p)Mg^{26}$ $Q_m = 8.880$ Mev

This reaction has been studied both with natural magnesium targets (Po 41, Al 46, Al 48, Ne 48) and

TABLE XVI. Proton groups from $Na^{23}(\alpha, p)Mg^{26}$.

Author	α source	Energy measurement	Q values (Mev)					
Ko 34, Li 37	Po	Al abs.	1.91		-0.2			
Ma 36, Li 37	Ra($B+C$)	Al abs.			-0.4 ± 0.2		-2.1 ± 0.2	-3.1 ± 0.2
Me 40	Po	nucl. emuls.	1.64		-0.15			
Mo 48	cyclotron (7 Mev)	Al abs.	1.44	1.12	-0.30	-1.3		
Hj 52	Po	nucl. emuls.	1.55	1.15	-0.17	-1.17		
Levels in Mg^{26} (average):			0	(0.36)	1.8	2.7	3.9	4.9

TABLE XVII. Proton groups from $Mg^{25}(d,p)Mg^{26}$.

Author:	Am 52		En 52a	
E_d (Mev):	1.9		1.8	
Method:	Nuclear emulsions		Magnetic analysis	
	Q value (Mev)	Mg^{25} level (Mev)	Q value (Mev)	Mg^{25} level (Mev)
	8.86±0.10	...	8.880±0.012	...
	7.02±0.10	1.84	7.055±0.015	1.825±0.015
	5.86±0.10	3.00	5.908±0.008	2.972±0.010
	4.86±0.10	4.00	4.911±0.007	3.969±0.010
	4.45±0.10	4.41	4.527±0.008	4.353±0.011
	3.95±0.10	4.91	4.017±0.009	4.863±0.011
			3.956±0.007	4.924±0.011
			3.610±0.007	5.270±0.011
			3.558±0.007	5.322±0.011
			3.378±0.007	5.502±0.011
			2.733±0.005	6.147±0.011

enriched targets (Al 49, Am 52, En 52a). In Table XVII are given Q values and Mg^{26} levels reported by the latter two authors. No indication is found of a level at 0.4 Mev.

An angular distribution study at $E_d=8$ Mev indicates that an orbital angular momentum $l_n=0$ is associated with the captured neutron for transitions to the 2.97-, 3.97-, 4.35-, and 6.15-Mev levels ($J=2^+$ or 3^+) and both $l_n=0$ and $l_n=2$ for transitions to the 1.83-Mev level. Moreover, two levels at 7.29±0.06 and 8.28±0.06 Mev are found in this study (Ho 53c).

IV. $Mg^{26}(p,p')Mg^{26}$

Magnetic analysis of scattered protons with bombarding energy $E_p=8$ Mev on natural magnesium confirms the levels at 1.83±0.02 and 2.96±0.02 Mev (Ha 52). The 1.83-Mev level had also been found previously (Rh 49, Rh 50). See also Fu 48.

V. $Al^{26}(\beta^+)Mg^{26}$ See Al^{26}

VI. $Al^{27}(\gamma,p)Mg^{26}$ $Q_m=-8.261$

The threshold is reported as $E_\gamma=8.6\pm0.5$ Mev (Di 50). The cross section has a maximum of 22±6 mb at $E_\gamma=21.2\pm0.5$ Mev with a half-width of 5.4±0.5 Mev and an integrated cross section of 0.12 Mev b (Ha 51). The proton angular distribution is isotropic below $E_\gamma=22$ Mev (Di 50), but anisotropic at $E_\gamma=25$, 40, and 65 Mev (Ho 53h).

VII. $Si^{29}(n,\alpha)Mg^{26}$ $Q_m=-0.040$

Not observed.

Al^{26}

Adopted mass defect: −4.8 Mev

(The adopted mass defect is consistent with determinations of the end point of the Al^{26} β^+ spectrum and with the threshold for the $Al^{27}(\gamma,n)Al^{26}$ reaction determined by Sher *et al.* (Sh 51a). The experimental Q value of the $Mg^{25}(d,n)Al^{26}$ reaction (Sw 50) would lead to a mass defect of −6.0±0.1 Mev and the $Al^{27}(\gamma,n)Al^{26}$ threshold determined by McElhinney *et al.* (Mc 49) to a mass defect of −3.6±0.4 Mev.)

I. $Al^{26}(\beta^+)Mg^{26}$ $Q_m=3.8$

Half-life determinations are 7±1 sec (Fr 34), 7 sec (Ma 37), 7.25±0.2 sec (Hu 43), 6.3 sec (Br 48), 6.49±0.10 sec (Ka 51b), 6.3 sec (Ed 52), and 6.68±0.11 sec (Ch 53). The earlier determinations are subject to doubt because of the approximate equality of the Al^{26} and Al^{25} (7.3 sec) half-lives.

The β^+ end point has been measured by Al absorption as 3.4±0.5 Mev (Fr 34, Bl 46c) and 2.8 Mev (Al 48), and by cloud chamber as 2.99 Mev (Wh 39). See also Ma 37, Br 38, Na 41. No γ rays have been observed (St 53b).

The β^+ decay would be super-allowed because of its low ft value (log ft=3.3).

II. $Na^{23}(\alpha,n)Al^{26}$ $Q_m=-2.7$

A threshold is reported of 3.7 to 4.0 Mev (Sa 35). See also Cu 33, Fr 34, Ma 37, Br 38. See Al^{27} for resonances.

III. $Mg^{25}(p,\gamma)Al^{26}$ $Q_m=6.6$

By the use of thin enriched targets well-resolved resonances were found in the positron yield at $E_p=386$, 489, 508, 586, 650, 680, 722, 777, 812, 880, 924, 980, and 1043 kev (Ru 52a).

Resonances in the γ-ray yield are reported at $E_p=180$, 410, 480, 575, and 825 kev (Cu 39), and at $E_p=310\pm3$,

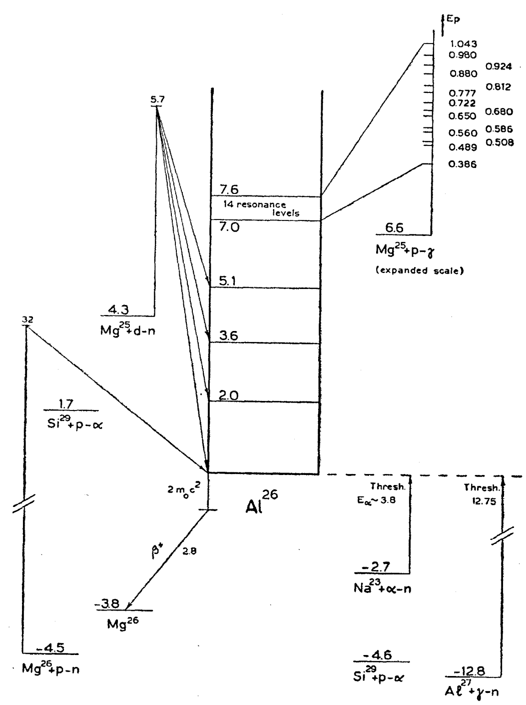

FIG. 11.

392±4, 492±5, 508±5, and 525±6 kev (Ta 46) but the assignment to Mg^{25} is less certain in these cases as targets were used of natural isotopic abundance. See also Ho 41.

IV. $Mg^{25}(p,n)Al^{25}$ $E_b=6.6$ $Q_m=-5.02$

Resonances in the Al^{25} activity yield from natural magnesium targets have been observed at $E_p=5.47$, 5.80, 6.02, 6.31, and 6.49 Mev. They may also be assigned to $Mg^{26}(p,n)Al^{26}$ (Bl 51). See Al^{25} for threshold measurements.

V. $Mg^{25}(d,n)Al^{26}$ $Q_m=4.3$

At $E_d=1.47$ Mev (thick enriched targets, nuclear emulsion technique) a ground-state Q value of 5.58 ±0.10 Mev has been measured. Three more neutron groups were found corresponding to levels in Al^{26} at 2.00, 3.63, and 5.13±0.18 Mev (Sw 50). See also Al 49b.

VI. $Mg^{26}(p,n)Al^{26}$ $Q_m=-4.5$

Production of radioactive Al^{26} has been observed (Br 48). See also Wh 39 and Bl 51. See also reaction IV.

VII. $Al^{27}(\gamma,n)Al^{26}$ $Q_m=-12.8$

The threshold for this reaction has been measured as 12.75±0.20 Mev (Sh 51a) and 14.0±0.4 Mev (Mc 49). The excitation curve (measured by neutron detection) has a peak at 19.7 Mev of 4.0 Mev width. The maximum cross section is 23 mb and the integrated cross section 100 Mev mb (Mo 53a) or 80 Mev mb (Ed 52). The maximum cross section for the production of 6.3 sec Al^{26} is much smaller (8.1 mb). The yield has a peak at 19.2 Mev of 4.7 Mev width and the integrated activity cross section is 45 Mev mb (Ka 51b). See also Hu 42, Be 47a, Wa 48, Pe 48, Di 50, Mc 50.

VIII. $Al^{27}(n,2n)Al^{26}$ $Q_m=-12.8$

Not observed.

IX. $Si^{28}(d,\alpha)Al^{26}$ $Q_m=1.7$

Not observed.

X. $Si^{29}(p,\alpha)Al^{26}$ $Q_m=-4.6$

Not observed.

GENERAL REMARKS

It has been suggested (St 53b, St 53c, see also Mo 53b) that the 6.3 sec activity might have to be assigned not to the Al^{26} ground state but to the level at 2.0 Mev known from the $Mg^{25}(d,n)Al^{26}$ reaction. This excited (isomeric) state might then be the $J=0^+$, $T=1$ analog of the Mg^{26} ground state. The spin of the Al^{26} ground state (about 2.3 Mev above the Mg^{26} ground state) is uniquely fixed as $J=5^+$ through shell-model considerations ($d_{\frac{5}{2}}$ proton, $d_{\frac{5}{2}}$ neutron) and through the fact that no γ rays have been observed in the Al^{26m} decay. The Al^{26} ground state would presumably decay by electron capture to the 1.83-Mev level ($J=2^+$) in Mg^{26} with an estimated half-life of 10^8 years.

An experimental confirmation of the Al^{26} isomerism is found in the fact that the $Al^{27}(\gamma,n)Al^{26}$ cross section is about three times greater if the neutron yield is measured instead of the yield of the Al^{26m} 6.3 sec activity (Mo 53a).

Another indication of a low state in Al^{26} is found in the observation of neutrons (unaccompanied by positrons below $E_p=5.3$ Mev) from $Mg(p,n)Al$ down to proton energies as low as $E_p=3.5$ Mev. From Q-value considerations it may be concluded, that these neutrons cannot result from $Mg^{24}(p,n)Al^{24}$ or $Mg^{25}(p,n)$ Al^{25} (St 54).

For a theoretical prediction of the Al^{26} spin see De 53a.

Mg^{27}

Mass defect: -6.633 Mev‡

I. $Mg^{27}(\beta^-)Al^{27}$ $Q_m=2.612$

Determinations of the half-life are: 10.0±0.1 min (Cr 39), 9.58±0.10 min (Ek 43), 9.45±0.04 min (Sa 53), 9.51±0.03 min (Da 53a) and 9.39±0.03 min (Lo 53). See also Fl 34, He 35.

The β^- decay is complex. The β^- spectrum has three

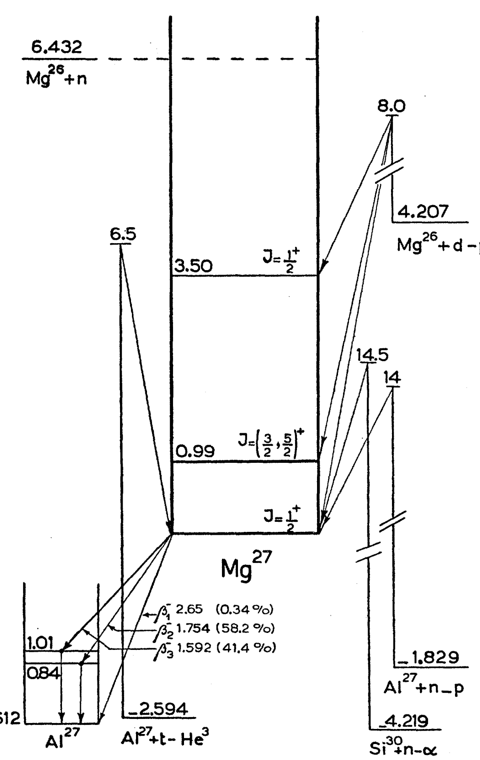

FIG. 12.

‡ The error in the mass defect of Mg^{27} given by Li (Li 52) (-8.633 Mev instead of -6.633 Mev) has here been corrected [Phys. Rev. 90, 1131 (1953)].

TABLE XVIII. Beta decay of Mg^{27}.

Ref.	Method	E_{β_1} (Mev)	E_{β_2} (Mev)	E_{β_3} (Mev)	E_{γ_1} (Mev)	E_{γ_2} (Mev)
He 35	Al abs.		2.05			
Wi 38	Al abs.		1.96 ±0.15			
Ri 38	cl. chamber					0.88 ±0.05
Cr 39	cl. chamber		1.8			
Mo 40	Al abs.		1.74 ±0.05			
It 41	spectrom.				1.02 ±0.02	0.84 ±0.02[a]
Ek 43	cl. chamber		1.77 ±0.09		1.05 ±0.08	
Bl 47	Al abs.		1.78 (75%)	1.32 (25%)	1.1 ±0.1	
Be 48	spectrom.		1.80 (80%)	<0.90 (20%)	1.01 ±0.03	0.835±0.025
Da 53a	Al abs.		1.72 ±0.06 (75%)	1.5 ±0.1 (25%)		0.88 ±0.08
Da 53a	scint. spectrom.				1.00 ±0.03	0.84 ±0.05
Da 53a	spectrom.	2.65±0.14 (0.34%)	1.754±0.004 (58.2%)	1.592±0.005 (41.4%)	1.020±0.008	0.839±0.008

[a] Intensity 45 percent of 1.02 Mev γ ray.

components and two γ rays are observed. Measurements of end points, γ-ray energies, and relative intensities are collected in Table XVIII. A third γ ray of $E_\gamma=0.64\pm0.01$ Mev and an intensity of 30 percent of the 1.02-Mev γ ray (It 41) has later not been confirmed. Because $\gamma-\gamma$ coincidences had been reported (Be 48) it has been assumed until recently that the low-energy β^- component proceeded through a 1.8-Mev level in Al^{27}, which level, however, was not found from other nuclear reactions. It has now been shown that there are no $\gamma-\gamma$ coincidences and that only the well-known Al^{27} levels at 0.84 and 1.02 Mev are involved. Such a decay scheme is strengthened by $\beta-\gamma$ coincidence measurements (Da 53a). See also Bl 45, Va 52c.

The β^- transitions to the 0.84- and 1.02-Mev levels are allowed (both log $ft=4.8$), while the ground-state transition is forbidden (log $ft=7.8$). The latter ($J=\frac{1}{2}^+\rightarrow5/2^+$) would be about 10^5 times faster than is usual for second forbidden transitions.

II. $Mg^{26}(n,\gamma)Mg^{27}$ $Q_m=6.432$

The thermal neutron absorption cross section of isotopic Mg^{26} is 60 ± 60 mb (Po 52a) and the activation cross section 48 ± 10 mb (Se 47). For fission neutrons ($E_n\sim1$ Mev) the activation cross section is 0.60 mb (Hu 49, Hu 53a). See also On 41, Si 41a.

Energies of a number of γ rays from the capture of thermal neutrons in natural magnesium have been determined by pair spectrometer (Ki 51, Ki 53a) (see Table XI). Line F_1 ($E_\gamma=6.440\pm0.008$ Mev) results from capture in Mg^{26} and represents the ground-state transition.

TABLE XIX. Proton groups from $Mg^{26}(d,p)Mg^{27}$.

Author	Am 52	En 52a	Ho 53c	
Method	nucl. emuls.	magn. anal.	Al abs.	
E_d(Mev)	1.9	1.8	8.05	
	Q value (Mev)	Q value (Mev)	Q value (Mev)	Mg^{25} level (Mev)
	4.16±0.10	4.207±0.006	...[a]	0
	3.18±0.2	3.220±0.005	...[a]	0.987±0.006 (En 52a)
			0.71±0.05	3.50 (Ho 53c)

[a] These two proton groups were observed but no Q values are given.

III. $Mg^{26}(d,p)Mg^{27}$ $Q_m=4.207$

Measurements of Q values and Mg^{27} levels from enriched targets are collected in Table XIX. See also He 35, Cr 39, Al 46, Al 48, Ne 48, Al 49b, Va 52a.

Angular distributions of three proton groups from this reaction have been measured at $E_d=8$ Mev. From Butler analysis $l_n=0$ is found for transitions to the ground state and the 3.50-Mev level and $l_n=2$ for transitions to the 0.98 Mev level. This fixes the ground state and 3.50 Mev level as $J=\frac{1}{2}^+$, and the 0.98-Mev level as $J=5/2^+$ or $\frac{3}{2}^+$ (Ho 53c).

IV. $Al^{27}(n,p)Mg^{27}$ $Q_m=-1.829$

The yield has been measured from threshold to $E_n=4$ Mev (Br 49b). The cross section for Be(d,n) neutrons ($E_d=15$ Mev) is 25 ± 2.5 mb (Co 51) and at $E_n=14$ Mev 79 ± 6 mb (Fo 52a) or 52 ± 10 mb (Pa 53). See also Fl 34, Me 34a, Am 35, Kl 35, Hi 40, Go 50a, Ya 52.

V. $Al^{27}(t,He^3)Mg^{27}$ $Q_m=-2.594$

The bombardment of aluminum with 6.5-Mev tritons yields radioactive Mg^{27} (Po 52b).

VI. $Si^{30}(n,\alpha)Mg^{27}$ $Q_m=-4.219$

The cross section at $E_n=14.5$ Mev is 46 ± 23 mb (Pa 53).

Al^{27}

Mass defect: -9.245 Mev

I. $Na^{23}(\alpha,n)Al^{26}$ $E_b=10.110$

Resonances are reported at $E_\alpha=6.2$ and 6.8 Mev with RaC′ α's (thick target) (Br 38). See Al^{26} for threshold measurement.

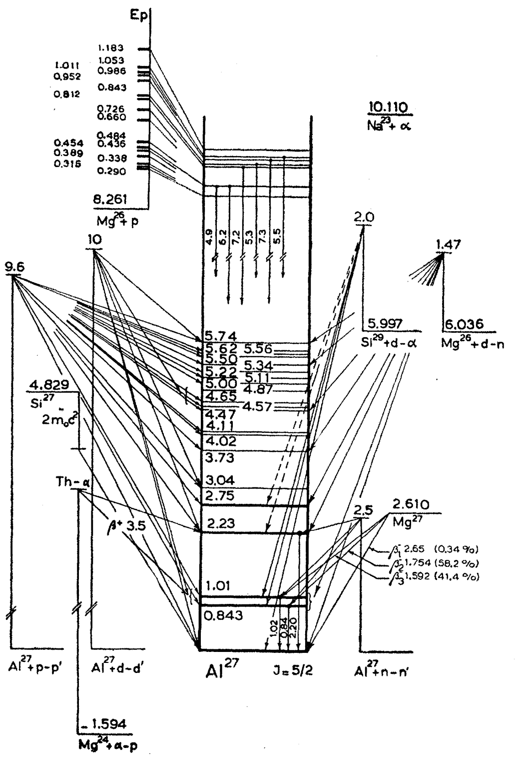

FIG. 13.

II. $Mg^{24}(\alpha,p)Al^{27}$ $Q_m=-1.593$

Early measurements with RaC′ α's (Du 34) and ThC′ α's (Ha 35) indicate levels at 0.8 and 1.7 Mev. See Si^{28} for resonances. See also Li 37.

From a comparison of the resonances in $Mg^{24}(\alpha,p)Al^{27}$ and $Al^{27}(p,\alpha)Mg^{24}$ a Q value of -1.613 ± 0.010 Mev is derived (Ka 52).

III. $Mg^{25}(d,n)Al^{26}$
IV. $Mg^{25}(d,p)Mg^{26}$ } $E_b=17.141$

A resonance is found in both the neutron and proton yield at $E_d=0.965\pm0.015$ Mev from natural Mg-target bombardments. If assigned to Mg^{25}, this would correspond to a level in Al^{27} at 18.07 Mev (Al 48). However, assignment to Mg^{24} seems more probable.

V. $Mg^{26}(p,\gamma)Al^{27}$ $Q_m=8.261$

Resonances observed in the γ-ray yield are collected in Table XX. Only those γ-ray resonances which are not accompanied by β^+ emission are assigned by Tangen (Ta 46) to $Mg^{26}(p,\gamma)Al^{27}$. See also Cu 39, Ho 41.

Gamma-ray energies have been measured at some resonances and are summarized in Table XXI.

The γ ray with $E_\gamma=8.70$ Mev corresponds to the direct de-excitation to the ground state. The greater part of the other γ rays represent cascades through known levels in Al^{27} to the ground state.

VI. $Mg^{26}(p,n)Al^{26}$ $E_b=8.261$ $Q_m=-4.5$

For resonances see Al^{26} reaction IV.

VII. $Mg^{26}(d,n)Al^{27}$ $Q_m=6.036$

Eight neutron groups have been observed with nuclear emulsions from an enriched target at $E_d=1.47$ Mev corresponding to the ground state ($Q_0=5.68\pm0.05$ Mev) and levels at 0.88, 1.92, 2.75, 3.65, 4.33, 5.32, and 5.81 Mev (±0.07 Mev) (Sw 50). See also Al 49b.

VIII. $Mg^{27}(\beta^-)Al^{27}$ See Mg^{27}

IX. $Al^{27}(n,n')Al^{27}$

Inelastic scattering of 2.5-Mev neutrons in aluminum yields a level in Al^{27} at 0.9 Mev. Neutrons were detected by their recoil protons in an anthracene scintillation spectrometer (Po 52, Po 53a).

From 2.5-Mev neutrons on Al^{27} γ-ray energies of $E_\gamma=0.843$, 1.018, and 2.20 Mev (±1.5 percent) have been determined with a scintillation spectrometer (Da 53). These results have later been confirmed by a similar method ($E_\gamma=0.82$, 1.02, and 2.34 Mev) (Ga 53). The observed γ rays represent direct de-excitation of the lowest three excited states in Al^{27} to ground.

The inelastic cross section has been measured at $E_n=14$ Mev (Ph 52).

TABLE XX. Resonances in $Mg^{26}(p,\gamma)Al^{27}$.

Author Target	Ta 46 Natural Mg	Ta 52 Mg^{26}	Hu 53 Natural Mg
E_p (kev)	290±3		
	314±3		314.8±0.5
	336±1.5	339	338.5±0.5
	388±4		389.4±0.5
	430±4		436.5±0.4
	451±2	449	454.2±0.3
	494±5		484.0±1.0
		660	
		726	
		812	
		843	
		952	
		986	
		1011	
		1053	
		1183	
		(all±10)	

TABLE XXI. Gamma-ray energies from $Mg^{26}(p,\gamma)Al^{27}$.

Author	Method	E_p in Mev	E_γ in Mev
Ca 53	scint. spectr.	0.314	4.2 ±0.2
Ca 53	scint. spectr.	0.336	2.83±0.14 and 5.80±0.26
Kl 53	scint. spectr.	0.454	0.81±0.05; (2.28±0.10); 2.80±0.10; (4.10±0.15); (4.58±0.15); 5.74±0.15; 6.54±0.20; 7.86±0.20; 8.70±0.20.
Ru 52	Al absorption	0.454	4.9 and 6.2
Ru 52	Al absorption	0.813	7.2
Ru 52	Al absorption	0.840	5.3
Ru 52	Al absorption	0.954	7.3
Ru 52	Al absorption	1.015	5.5

TABLE XXII. Levels in Al^{27} from $Al^{27}(p,p')Al^{27}$.

Author: E_p (Mev): Angle: Method:	Sh 51 2–4 164° magn. analysis	Ba 52 9.6 30°–120° range in Al	Re 52 8.0 90° magn. analysis	St 52 7.26 50° and 135° scintill. spectrom.	Do 53 2.309 135° electrostat. analysis	Br 53g 6.5–8.4 90° magn. analysis
Levels in Al^{27}	0.82		0.844	0.84	0.843	0.843
(Mev)	1.04	0.99±0.05	1.016	1.01	±0.002	1.013
		1.72±0.15	...[a]	...[a]		
	2.23	2.22±0.08	2.259	2.23		2.211
	2.75		2.782	2.77		2.735
						2.981
		3.00±0.05	3.046	3.03		3.004
		3.63±0.12	3.736	3.71		3.681
		3.93±0.10	4.018	4.00		3.959
			4.115			4.058
		4.39±0.12	4.473	4.47		4.404
			4.575			4.507
		4.66±0.10	4.647	4.60		4.577
			4.875	4.87		4.806
			4.996			
			5.107			
			5.220			5.150
			5.341			5.243
						5.416
		5.46±0.08	5.501	5.43		5.430
			5.565	all ±0.04		5.498
			5.620			5.551
			5.736			5.668
			all ±0.020			5.825
						(5.959)
						all ±0.020

[a] The authors find no indication of a level at 1.8 Mev.

X. $Al^{27}(p,p')Al^{27}$

Levels found from this reaction are represented in Table XXII. The figures given by Browne (Br 53g) must be regarded as preliminary. His levels are consistently lower than those given by Reilly *et al.* (Re 52) by an amount slowly increasing up to 70 kev for the highest levels. No proton groups were found by Browne corresponding to Reilly's level at 4.996 and 5.107 Mev; only a group originating from carbon contamination (inelastic scattering to the C^{12} level at 4.43 Mev) was present in this region. See also Wi 40, Di 43, Fu 48, Br 49, Rh 49, Le 50, Rh 50, Ha 52c, Co 52.

Angular distributions of elastically scattered protons have been measured at $E_p = 4.5$ Mev (Rh 50), 6.9 Mev (Wi 41), 9.6 Mev (Ba 52), 15.5 and 18.3 Mev (Gu 52), and 18.6 Mev (Bu 51). At all these energies the ratio of differential cross section to Rutherford scattering has a maximum at about 90°.

XI. $Al^{27}(d,d')Al^{27}$

Levels in Al^{27} have been found from this reaction with $E_d = 5-6.7$ Mev at 0.85 and 2.13 Mev (Gr 49), with $E_d = 7.5$ Mev at 0.99±0.05 and 2.17±0.05 Mev (Ho 49), with $E_d = 10$ Mev at 0.97, 2.39, 3.17, 4.74, and 5.76 (all ±0.2) Mev (Ke 51) and with $E_d = 14$ Mev at 1.0, 2.3, and 2.9 Mev (Bo 50). The intensity of the inelastic deuteron group leading to the 0.843-Mev level is (at $E_d = 2.1$ Mev and $\vartheta = 90°$) smaller than 1 percent of the elastic group (En 53a).

The differential cross section for elastic scattering at $E_d = 14$ Mev shows maxima at 0°, 70°, and 110° (Go 50).

XII. $Si^{27}(\beta^+)Al^{27}$ See Si^{27}

XIII. $Si^{28}(\gamma,p)Al^{27}$ $Q_m = -11.590$

Not observed.

XIV. $Si^{29}(d,\alpha)Al^{27}$ $Q_m = 5.996$

Magnetic analysis of α particles observed at 90° at $E_d = 1.8$ and 2.0 Mev from targets enriched in Si^{29} content yields a ground-state Q value of 5.994±0.011 Mev and levels in Al^{27} at 0.837±0.016 and 1.007±0.013 Mev and possibly at 2.21±0.03 and 2.74±0.02 Mev. The authors state that no group was found corresponding to a level at 1.8 Mev (Va 52c). See also Va 52a.

XV. $Si^{30}(p,\alpha)Al^{27}$ $Q_m = -2.389$

Not observed.

Si^{27}

(not illustrated)

Adopted mass defect: −4.416 Mev (Ki 53)

I. $Si^{27}(\beta^+)Al^{27}$ $Q_m = 4.829$

The half-life is given as: 3.7 sec (Ku 39), 4.9±1 sec (Cr 40), 4.92±0.1 sec (El 41), 4.5±0.5 sec (Hu 44a), 5.4±0.4 sec (Bo 51), and 4.45±0.05 sec (Su 53).

The β^+ spectrum end-point determinations are 3.74 Mev (Mc 40), 3.54±0.1 Mev (Ba 40) (both measured by cloud chamber), and 3.48±0.10 Mev (Bo 51) (scintillation spectrometer). See also Cu 34. The log *ft* value is 3.6 in accordance with the super-allowed character of this transition between mirror nuclei.

II. $Mg^{24}(\alpha,n)Si^{27}$ $Q_m=-7.205$

Radioactive Si^{27} is produced at $E_\alpha=15$ Mev (El 41). See also Sa 35.

III. $Al^{27}(p,n)Si^{27}$ $Q_m=-5.611$

The threshold for this reaction has been measured as $E_p=5.93$ Mev (Bl 51) and $E_p=5.819\pm0.010$ Mev (Ki 53). See also Ku 39, Mc 40, Ba 40, Gu 51. See Si^{28} for resonances.

IV. $Si^{28}(\gamma,n)Si^{27}$ $Q_m=-17.201$

The threshold has been determined as 16.8 ± 0.4 Mev (Mc 49) and 16.9 ± 0.2 Mev (Su 53). See also Be 47a, Bo 51.

A maximum in the cross section of 21 mb is observed at 20.9 Mev with a half-width of 3.5 Mev and the integrated cross section to 24 Mev is 0.070 Mev b (Su 53). See also Hu 44a, Wa 48.

V. $Si^{28}(n,2n)Si^{27}$ $Q_m=-17.201$

Not observed.

Mg^{28}

(not illustrated)

Adopted mass defect: -6.818 Mev (Ma 53a, Sh 53a)

I. $Mg^{28}(\beta^-)Al^{28}$ $Q_m=1.785$

Mg^{28} has been produced through $Mg^{26}(\alpha,2p)$, $Si^{30}(\gamma,2p)$, $Si^{30}(p,3p)$, and other spallation reactions.

The half-life is given as 21.3 ± 0.2 hr (Sh 53), 21.2 ± 0.2 hr (Li 53, Li 53a), 20.8 ± 0.5 hr (Ma 53a), 22.1 ± 0.3 hr (Jo 53), 21.85 ± 0.32 hr (Iw 53), and 21.4 ± 0.6 hr (Wa 53).

The β^- spectrum is simple and the Kurie plot is straight (Ma 53a). The end point is given as 0.40 ± 0.06 Mev (Sh 53a), 0.3 Mev (Jo 53), 0.39 ± 0.05 Mev (Wa 53) (all by Al absorption), and 0.418 ± 0.010 Mev (Ma 53a, spectrometer). The allowed character of this transition follows also from the *ft* value (log *ft*=4.2).

At least four different γ rays have been found by scintillation spectrometer. Their energies and relative intensities (given between brackets) are $\sim$0.03 Mev, 0.40 ± 0.02 Mev (30 ± 3 percent), 0.95 ± 0.02 Mev (28 ± 3 percent), and 1.35 ± 0.02 Mev (71 ± 5 percent) (Sh 53a). The intensity of the 1.78-Mev γ ray resulting from Al^{28} in equilibrium with Mg^{28} has been taken as unity. A more accurate determination of energy and intensity of the low-energy γ ray is 32.2 kev (70 ± 20 percent) (Wa 53). The three harder γ rays have also been determined by scintillation spectrometer as 0.391 ± 0.005, 0.95, and 1.35 Mev (Iw 53). There may be present more γ rays to at least 2.6 Mev (Jo 53), although this seems difficult to reconcile with the data given above.

The level scheme of Al^{28} up to 6.3 Mev is well known from the $Al^{27}(d,p)Al^{28}$ reaction (En 52c). The γ rays found in the Mg^{28} decay fit well into this level scheme although the γ-ray energies are not accurate enough to decide whether the 0.95- and 1.35-Mev γ rays go to the 0.03-Mev level or partly to the ground state. It seems certain that the 0.391- and 0.95-Mev γ-ray cascade proceeds through the 0.973 and not through the 1.013-Mev level.

II. $Mg^{26}(t,p)Mg^{28}$ $Q_m=6.498$

Radioactive Mg^{28} has been produced from this reaction:

(a) by bombarding $MgSO_4\cdot6D_2O$ with deuterons (production of tritons through the $D(d,t)H$ reaction);
(b) by irradiating Li–Mg alloy with neutrons in a pile (production of tritons through the $Li^6(n,t)He^4$ reaction) (Iw 53).

Al^{28}

Mass defect: -8.603 Mev

I. $Al^{28}(\beta^-)Si^{28}$ $Q_m=4.650$

The most accurate determinations of the half-life are 2.27 ± 0.02 min (Ba 53) and 2.30 ± 0.03 min (Ek 43). Other determinations with 0.1- to 0.2-min errors range from 2.0 to 3.0 min (Cu 34, Cu 34c, Al 35, An 35, Mc 35, Fa 35, El 36, Na 36a, Ec 37, Me 37, Ri 37, He 39, Sz 48, Iw 53, Hu 44a).

The β^- spectrum is simple (Wa 41) and has the allowed shape (Mo 52, Du 47, Ma 53a). The log *ft* value is 4.9. Each β^- particle is followed by one γ ray (Du 47, Bl 45, Bl 47). The ground-state β^- transition is weaker than 2 percent (Mo 52). Determinations of the β^- spectrum end point and of the γ-ray energy are collected in Table XXIII. See also Cu 34, Co 36, Na 36a, Ec 37, Me 37, Ha 51a.

See also the parent nuclide Mg^{28}.

II. $Mg^{25}(\alpha,p)Al^{28}$ $Q_m=-1.196$

Proton groups corresponding to Q values of -1.05, -1.82, and -2.87 Mev, reported from the bombardment of natural magnesium by $Ra(B+C)$ α's (Du 34,

TABLE XXIII. Beta decay of Al^{28}.

Author	Method	$E_{\beta^-\max}$ (Mev)	E_γ (Mev)
Al 35	spectrom.	3.05 ± 0.15	
It 41	spectrom.		1.82 ± 0.02
Ek 43	cl. chamber	2.98 ± 0.18	2.05 ± 0.15
Du 47	abs.	3.10 ± 0.10	2.15
Bl 47	abs.	2.75 ± 0.10	1.80 ± 0.10
Be 48	spectrom.	3.01	1.80
Mo 52	spectrom.	2.865 ± 0.010	1.782 ± 0.010
Ma 53a	spectrom.	2.850 ± 0.050	

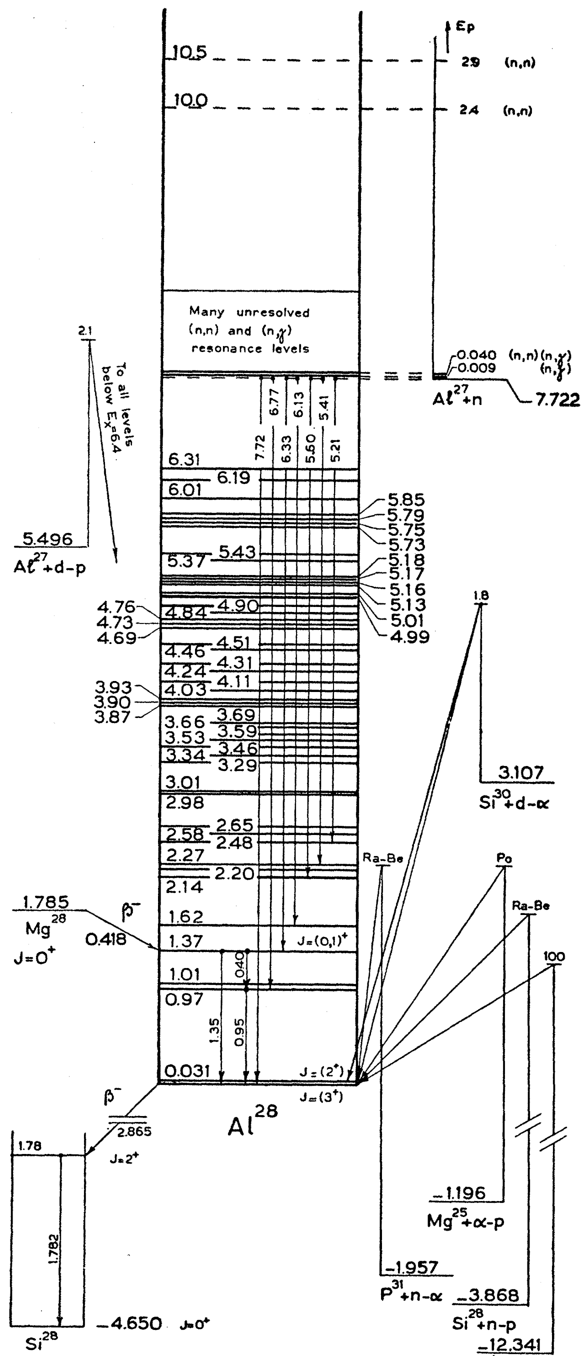

FIG. 14.

Li 37), may also be assigned to the $Mg^{24}(\alpha,p)Al^{27}$ reaction.

The same difficulty exists for the assignment of γ rays of 1.8±0.2 and 4.3±0.3 Mev reported from the bombardment of natural magnesium by 7-Mev α's (Al 48a). They might result from (α,p) but also from (α,n) reactions.

For resonances reported in the Al^{28} yield see Si^{29}. See also Al 34, Ec 35, El 35a, El 36, Sz 44, Sz 48.

III. $Mg^{28}(\beta^-)Al^{28}$ See Mg^{28}

IV. $Al^{27}(n,\gamma)Al^{28}$ $Q_m=7.722$

The thermal neutron capture cross section has been measured as 0.212±0.005 b (Co 50) in good agreement with other determinations (Se 47, Ha 50, Po 51). See also Ra 40, On 41, Si 41a, Ra 42, Vo 43, Co 46a.

The capture cross section at $E_n\approx 1$ Mev (fission neutrons) is 0.37 mb (Hu 53a). See also Hu 49.

Resonances in the Al^{28} yield have been found by a boron absorption method at $E_n=60$ ev with an effective level width of 12 ev (Co 48a) and at $E_n=9.1$ kev (Li 47). See also Gr 43.

With $Li(p,n)$ neutrons a strong resonance in the Al^{28} yield is found at 40 kev and many more partly unresolved resonances between 100 and 550 kev (He 50). Several of those capture resonances notably those at $E_n=40$, 215, and 370 kev coincide with resonances found in the total cross section. See also Si 41, Al 48d, Be 49a.

Twenty-nine γ rays resulting from the capture of thermal neutrons in aluminum have been found by pair spectrometer (Ki 51, Ki 53d). They are collected in Table XXIV. The strong γ-ray A represents the ground-state transition. The great intensity of this line is a notable exception to the rule that only $E1$ ground-state transitions are intense (Ki 52b). It is impossible to fit the other lines uniquely into the complicated Al^{28} level scheme. Lines C, F, G, I', J, L, and all lower energy lines could be transitions from the capturing state to known Al^{28} levels. Lines B, B', D, E, F', G', H, K, and L cannot be explained in this way, but have to be transitions from level to ground or from level to level.

From 14 Mev neutrons on aluminum a continuous spectrum of γ rays up to $E_\gamma\approx 10$ Mev is found by scintillation spectrometer with weak maxima at $E_\gamma=1.7$, 4.5, and 5.4 Mev (Sc 53b). These γ rays may result from

TABLE XXIV. Gamma rays from thermal neutron capture in aluminum (Ki 51, Ki 53d).

γ ray	Energy (Mev)	Intensity in photons per 100 captures	γ ray	Energy (Mev)	Intensity in photons per 100 captures
A	7.724±0.006	35	L	5.21±0.02	3
B	7.34 ±0.04	0.7	M	4.94±0.05	1.4
B'	6.98 ±0.04	0.7	N	4.79±0.02	9
C	6.77 ±0.02	1.4	N'	4.66±0.05	7
D	6.61 ±0.03	0.4	N''	4.45±0.02	3
E	6.50 ±0.03	0.4	O	4.29±0.02	8
F	6.33 ±0.02	2	P	4.16±0.02	6
F'	6.22 ±0.03	0.7	P'	4.06±0.04	3
G	6.13 ±0.02	2	Q	3.88±0.02	8
G'	6.01 ±0.05	0.7	R	3.62±0.02	6
H	5.89 ±0.04	1.0	S	3.46±0.02	4
I	5.78 ±0.03	1.4	T	3.29±0.02	5
I'	5.60 ±0.02	3	U	3.02±0.05	15
J	5.41 ±0.03	3	V	2.84±0.03	13
K	5.32 ±0.03	1.0			

inelastic scattering, capture or other neutron-induced reactions.

See also Fl 36, Ha 50b, Ha 51a, Ya 52.

V. $Al^{27}(n,n)Al^{27}$ $E_b=7.722$

Measurements of the aluminum total cross section have been surveyed by Adair (Ad 50).

The cross section is 1.38 ± 0.01 b from $E_n=2$ to 5000 ev (Me 52). Some ten partly unresolved resonances were found with $Li(p,n)$ neutrons in the $E_n=10-800$ kev region and resonances at $E_n=2.4$ and 2.9 Mev with $D(d,n)$ neutrons (Ad 50).

Recent measurements of the transmission of $D(d,n)$ neutrons through aluminum at 30–50 kev resolution indicate resonances at $E_n=1.90$, 1.95, 2.015, 2.095, 2.17, 2.23, 2.29, 2.34, 2.40, 2.51, 2.57, 2.65, 2.80, 2.90, 3.00, 3.12, 3.37, and 3.57 Mev (Me 53). Measurements of the total cross section up to $E_n=6$ Mev have been performed with $N^{14}(d,n)$ neutrons (St 51d), and with pile neutrons of $E_n=3-12$ Mev (Ne 53). At $E_n=14$ Mev the cross section is 1.73 ± 0.03 b (Co 52a) or 1.86 ± 0.07 b (Ag 53), while 1.84 ± 0.06 b is found at $E_n=19$ Mev (Da 53b).

The angular distribution of elastically scattered neutrons has been measured at $E_n=3.7$ Mev. The total cross section at $E_n=3.7$ is 2.55 b (Wh 53).

VI. $Al^{27}(d,p)Al^{28}$ $Q_m=5.496$

Fifty proton groups from this reaction have been found by high-resolution magnetic analysis ($\vartheta=90°$) at deuteron energies up to 2.1 Mev (En 52c, En 53a). The Q values and corresponding Al^{28} levels are collected in Table XXV. Proton groups have been designated by a capital with an index. The index 1 corresponds to the most intense component of a close doublet or triplet, the index 2 to the next most intense and so on. The first excited state is at 31.2 ± 0.5 kev (En 51, En 53a). The errors associated with the excitation energies of the other levels increase gradually from 4 kev for the levels B_1 and B_2 to 8 kev for the highest levels. The error in the ground-state Q value is 8 kev. For smaller Q values the error decreases to about 3 to 4 kev for $Q<2.5$ Mev. See also St 51.

Older work at much lower resolution has not yielded more Al^{28} levels below 6.3 Mev than those given in Table XXV (La 34, La 35a, Mc 35, Sc 40, Al 46, Al 48, Ne 49a, Ne 50b, Po 49, Wh 50, Ke 51). Above 6.4 Mev levels are reported at 6.9 ± 0.2, 7.4 ± 0.2, and 8.5 ± 0.2 Mev (Ke 51), but it is probable that many more levels exist in this region.

The existence of the first excited state at 31 kev has been confirmed by observation of a 31.4 ± 1.0 kev γ ray following the $Al^{27}(d,p)Al^{28}$ reaction at $E_d=0.7$ Mev both by proportional counter and by scintillation spectrometer. No internal conversion electrons from this γ ray were observed: $\alpha_K<2$ (Sm 51a). See also Al 49b.

TABLE XXV. $Al^{27}(d,p)Al^{28}$ Q values and energy levels in Al^{28} (En 52c, En 53a).

Group	Q value (Mev)	Excitation energy (Mev)	Group	Q value (Mev)	Excitation energy (Mev)
A_1	5.494	—	L_2	1.383	4.111
A_2	5.463	0.031	M_1	1.256	4.238
B_2	4.521	0.973	M_2	1.186	4.308
B_1	4.481	1.013	N_1	1.036	4.458
C	4.128	1.366	N_2	0.982	4.512
D	3.873	1.621	O_1	0.808	4.686
E_1	3.359	2.135	O_2	0.758	4.736
E_3	3.298	2.196	P_1	0.735	4.759
E_2	3.228	2.266	P_3	0.656	4.838
F_2	3.012	2.482	P_2	0.596	4.898
F_3	2.917	2.577	Q_1	0.506	4.988
F_1	2.843	2.651	Q_2	0.486	5.008
G_1	2.513	2.981	R_1	0.366	5.128
G_2	2.487	3.007	R_2	0.337	5.157
H_1	2.202	3.292	R_3	0.324	5.170
H_2	2.152	3.342	R_4	0.312	5.182
I_2	2.034	3.460	S_2	0.124	5.370
I_3	1.961	3.533	S_1	0.060	5.434
I_1	1.907	3.587	T_2	−0.241	5.735
J_2	1.828	3.666	T_4	−0.261	5.755
J_1	1.796	3.698	T_1	−0.298	5.792
K_1	1.621	3.873	T_3	−0.361	5.855
K_2	1.595	3.899	U	−0.519	6.013
K_3	1.563	3.931	V	−0.696	6.190
L_1	1.464	4.030	W	−0.813	6.307

Proton angular distributions have been determined at several deuteron energies and at relatively low-energy resolution (Ne 49b, Ho 50, Go 51, Ho 53b), but no definite spin and parity assignments can be made in view of the great complexity of the Al^{28} levels. The ground-state doublet contains at least one $l_n=0$ component and the angular distribution of the proton group to the doublet around $E_x=1.0$ Mev is represented by a mixture of $l_n=0$ and $l_n=2$ (Ho 53b). The $l_n=0$ assignment to the ground-state doublet has been confirmed (Bl 53).

The excitation curve for the production of the Al^{28} activity has been measured from 1 to 6 Mev (Ri 47).

VII. $Si^{28}(n,p)Al^{28}$ $Q_m=-3.868$

Radioactive Al^{28} is produced by fast neutrons on silicon (Bj 34, Me 34a, Cu 34c, Am 35, Na 36a, Bl 47). The cross section is 45 ± 5 mb for $Be(d,n)$ neutrons ($E_d=15$ Mev) (Co 51) and 220 ± 50 mb for 14.5 Mev neutrons (Pa 53).

VIII. $Si^{29}(\gamma,p)Al^{28}$ $Q_m=-12.341$

Radioactive Al^{28} is found from this reaction (Ba 46, Hi 47).

IX. $Si^{30}(d,\alpha)Al^{28}$ $Q_m=3.107$

A ground-state Q value of 3.120 ± 0.010 Mev has been measured for this reaction with enriched targets and magnetic analysis at $E_d=1.8$ Mev (St 51). An α-particle group leading to the 31 kev level in Al^{28} has also been observed at several deuteron energies up to $E_d=2.0$ Mev, but with insufficient resolution to determine the corresponding excitation energy (En 53a).

X. $P^{31}(n,\alpha)Al^{28}$ $Q_m = -1.957$

Radioactive Al^{28} is produced by fast neutrons on phosphorus (Bj 34, Cu 34c, Am 35). The cross section at $E_n = 14.5$ Mev is 146 ± 30 mb (Pa 53).

GENERAL REMARKS

The Al^{28} ground-state doublet could well consist of the $J = 2^+$ and 3^+ states corresponding to the ($d_{\frac{5}{2}}$ proton, $s_{\frac{1}{2}}$ neutron) configuration predicted by the shell model. The differential cross sections of the $Al^{27}(d,p)Al^{28}$ reaction would thus be identical ($l_n = 0$) for the two components leading to the ground-state doublet, apart from a factor $(2J_f + 1)$. The experimental yield ratio (intensity of excited-state protons over that of ground-state protons) at $\vartheta = 90°$ and $E_d = 2.0$ and 2.1 Mev is 0.70 (maybe somewhat lower at lower deuteron energies and 0.55 at $E_d = 5.16$ Mev (Bu 53b)). This agrees well with the predicted ratio of 0.71 for a ground-state spin $J = 3^+$ and an excited-state spin $J = 2^+$ (En 53a).

From the $Mg^{28}(\beta^-)Al^{28}$ data the spin of the 1.366 Mev level in Al^{28} can be restricted to $J = 0^+$ or 1^+, and the spin of the 0.973 Mev level to $J = 1$ or 2.

For a theoretical discussion regarding doublet levels in Al^{28} see In 53.

Si^{28}

Mass defect: -13.253 Mev

I. $Mg^{24}(\alpha,p)Al^{27}$ $E_b = 9.996$ $Q_m = -1.594$

In experiments with thin separated $Mg^{24}F_2$ targets and magnetic analysis of the protons resonances are observed at $E_\alpha = 2.755$, 2.931, 2.955, 3.002, 3.137, 3.203, 3.280 Mev (center-of-mass system). The same levels have been found in the inverse reaction $Al^{27}(p,\alpha)Mg^{24}$, when a Q value of 1.613 ± 0.010 Mev is taken. Also the intensities of the corresponding peaks are in good agreement, as suggested by the principle of detailed balancing. A weak resonance has been found at $E_\alpha = 2.84$ Mev without corresponding resonance in the (p,α) reaction (Ka 52). See also Du 34, El 36. See Al^{27} for Q values.

II. $Mg^{24}(\alpha,\alpha)Mg^{24}$ $E_b = 9.996$

In the same investigation as quoted for the $Mg^{24}(\alpha,p)Al^{27}$ reaction (Ka 52) resonances in the yield of elastically scattered α particles are observed, again in good agreement with many resonances in the $Al^{27}(p,\alpha)Mg^{24}$ and $Al^{27}(p,p)Al^{27}$ reactions. Partial-wave analysis yields the following spins and parities for the compound nucleus: $J = 0^+$ for the resonances at $E_\alpha = 2.83$ and 3.00 Mev and $J = 2^+$ for the resonances at $E_\alpha = 2.93$ Mev. The S-wave α-scattering resonance at $E_p = 3.07$ Mev corresponds to a S-wave proton scattering resonance at $E_p = 1.45$ Mev. No single J value of the compound nucleus can explain this behavior. No (α,p) nor (p,α) transitions are observed at $E_\alpha = 3.07$

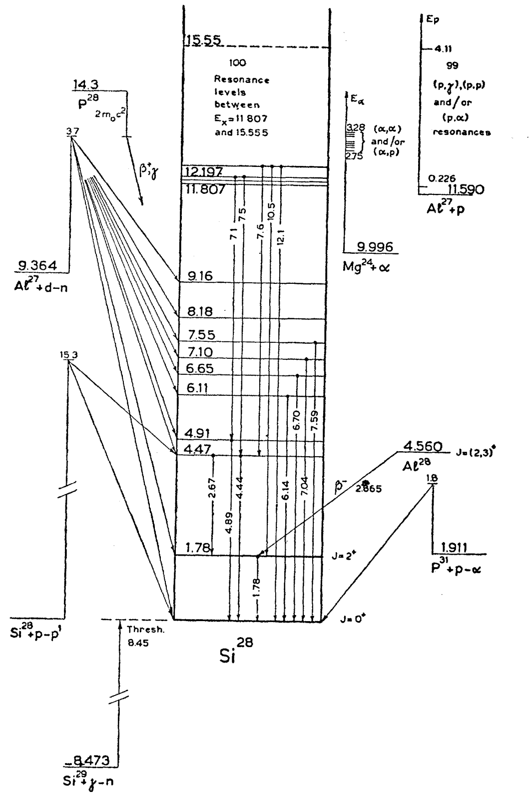

FIG. 15.

Mev. The anomaly near $E_\alpha = 3.25$ Mev is probably caused by two overlapping levels in Si^{28} (Ka 52).

III. $Mg^{25}(\alpha,n)Si^{28}$ $Q_m = 2.672$

Gamma rays observed from the bombardment of magnesium with Po α particles belong possibly to this reaction (Sz 48). See also Ha 49a.

IV. $Al^{27}(p,\gamma)Si^{28}$ $Q_m = 11.590$

Numerous resonances have been observed in this reaction by different authors, and these are summarized in Table XXVI. The six lowest resonances are most accurately measured by Hunt and Jones (Hu 53) in good agreement with earlier measurements, notably those of Tangen (Ta 46), who also measured the relative intensities of these resonances.

Broström *et al.* (Br 47a) measured 29 resonances between 600 and 1380 kev with a precision of 0.2 percent, all with a width of $\leqslant 1$ kev; their relative intensities are given in Table XXVI. Fourteen of the resonances in this region are in good agreement with those found by Plain *et al.* (Pl 40). Moreover the latter authors found 17 resonances in the region 1.4 to 2.6 Mev. The yields of the (p,α) and (p,γ) resonances between 500 and 750 kev have also been measured by Rutherglen and Smith (Ru 53a). The region above 1.4 Mev has also been very thoroughly investigated by Shoemaker

TABLE XXVI. Energies and relative intensities of resonances in Al+p. For authors see text.

E_p in kev	Relative intensity	Secondary particle	E_p kev	Secondary particle	E_p	Secondary particle
226.3±1.5	0.005	γ	1393	$\gamma\ p$	2820	α
294.1±0.5	0.015	γ	1445	α	2849	α
325.6±0.4	0.080	γ	1461	p	2869	p
404.7±0.4	0.30	γ	1508	p	2880	$p\ \alpha$
438.5±0.5	0.050	γ	1523	$\gamma\ p$	2999	p
504.0±0.6	2.0	$\gamma\ \alpha$	1583	$p\ \alpha$	3020	$\gamma\ p\ \alpha$
609	0.4	γ	1593	γ	3045	$\gamma\ \alpha$
630	8.2	$\gamma\ \alpha$	1670	$\gamma\ p$	3070	γ
652	3.3	γ	1688	γ	3080	$\gamma\ \alpha$
677	1.3	γ	1708	p	3106	$\gamma\ \alpha$
728	3.0	$\gamma\ \alpha$	1729	$\gamma\ p\ \alpha$	3185	$\gamma\ p$
733	4.2	γ	1753	$\gamma\ p$	3265	α
738	0.7	γ	1806	$\gamma\ p$	3400	$\gamma\ \alpha$
757	3.8	γ	1910	$\gamma\ \alpha$	3467	γ
764	4.5	γ	1973	$\gamma\ p$	3531	γ
771	11.5	γ	2039	$\gamma\ p\ \alpha$	3552	γ
880	0.5	γ	2051	$\gamma\ p$	3566	$\gamma\ p$
918	4.1	γ	2112	$\gamma\ p$	3599	α
932	3.9	γ	2132	$\gamma\ p\ \alpha$	3623	$\gamma\ p\ \alpha$
986	47.0	γ	2161	$\gamma\ p\ \alpha$	3662	γ
994	2.0	γ	2175	$\gamma\ \alpha$	3705	γ
1018	7.2	γ	2184	γ	3820	γ
1083	1.5	γ	2206	$\gamma\ \alpha$	3850	α
1091	0.8	γ	2288	p	3979	α
1112	13.5	γ	2316	$\gamma\ \alpha$	4055	$\gamma\ \alpha$
1165	2.4	γ	2333	p	4100	$\gamma\ \alpha$
1176	6.5	γ	2365	p	4112	$\gamma\ \alpha$
1192	?	γ	2377	$\gamma\ \alpha$		
1205	11.0	γ	2405	γ		
1255	13.0	γ	2445	$\gamma\ \alpha$		
1268	1.0	γ	2480	$p\ \alpha$		
1309	14.0	γ	2491	p		
1320	10.5	γ	2536	γ		
1355	15.0	γ	2559	p		
1372	105.0	$\gamma\ p$	2578	α		
1379	105.0	$\gamma\ p$	2607	α		

et al. (Sh 51) both for (p,γ), (p,p), and (p,α) resonances. They observed 64 resonances of which 42 are (p,γ) resonances. Only the values of Sh 51 (as reported by Al 50) for the region above 1.4 Mev are listed in Table XXVI. A comparison of the relative intensities (Go 53d), however, makes it probable that the resonances at 1355, 1372, and 1379 kev from Br 47a correspond to the resonances at 1370, 1385, and 1393 kev given by Sh 51, Al 50. It is not possible to decide at present which of the energy scales is the better one. See also He 37, Ge 37, and Ho 41.

An absolute determination of the value of the prominent 985-kev resonance with the Wisconsin electrostatic analyzer yields 993.3±1 kev (He 49).

The shape of the 985 kev resonance has been studied in detail and is in qualitative agreement with the Breit-Wigner theory. When S scattering is assumed, the width is $\Gamma=100$ ev (Be 49).

Gamma ray energies, measured at several resonances, are summarized in Table XXVII. The three γ rays observed in the thick target bombardment at $E_p=750$ kev correspond to transitions to the ground state and the Si^{28} first and second excited states (Ru 51). The gamma rays found at $E_p=325$ and 404 kev may be accounted for by cascades through the 4.91 and 4.47 Mev levels, the latter being de-excited again by a cascade through the 1.80 Mev level (Ca 53).

The angular distribution of γ rays has been measured at the 404-, 503-, 630-, 652-, and 677-kev resonances. The ground-state γ ray is only observed at the 503-kev resonance, while at the other resonances transitions proceed predominantly to the 1.78-Mev level in Si^{28}. The following spins and parities can be assigned to the resonance levels mentioned above: 4^-, 2^+, 3^-, 2^-, and 3^+. The first excited state in Si^{28} has $J=2^+$ (Gr 53). The 1370, 1385, 1393, and 1523 kev (on the Shoemaker scale) resonances are all de-excited by a transition to the first excited state in Si^{28} (Go 53d).

V. $Al^{27}(p,n)Si^{27}$ $E_b=11.590$ $Q_m=-5.611$

Resonances are observed at $E_p=6.17$ and 6.37 Mev by measuring the Si^{27} activity produced (Bl 51). See also Mc 40, Gu 51. See Si^{27} for threshold measurements.

VI. $Al^{27}(p,p)Al^{27}$, $Al^{27}(p,p')Al^{27}$ $E_b=11.590$

The cross section both for elastic and inelastic scattering shows many resonances which are quoted in Table XXVI (Sh 51). See also Al^{27}.

VII. $Al^{27}(p,\alpha)Mg^{24}$ $E_b=11.590$ $Q_m=1.594$

The resonances in this reaction found by Shoemaker *et al.* (Sh 51) are listed in Table XXVI. Alpha particles were also observed at the 503- and 630-kev resonances (Gr 53). See also Mg^{24}.

VIII. $Al^{27}(d,n)Si^{28}$ $Q_m=9.364$

A study of this reaction with nuclear emulsion technique at $E_d=3.68$ Mev reveals 10 neutron groups corresponding to levels in Si^{28} at 1.78±0.13, 4.47±0.10, (4.91±0.21), 6.11±0.10, 6.65±0.14, (7.10±0.12),

TABLE XXVII. Energies of γ rays from $Al^{27}(p,\gamma)Si^{28}$.

Author	Method	E_p kev	E_γ Mev	Relative intensity
Ta 46	absorption	325	5.4	
Ta 46	absorption	404	5.4	
Ta 46	absorption	503	9.2	
Pl 40	absorption	550	6.1	
Pl 40	absorption	700	6.5	
Pl 40	absorption	985	7.7	
Pl 40	absorption	1368	8.2	
Ru 51	pair-spectrometer (thick target)	750	12.12±0.1	
			10.46±0.07	
			7.62±0.1	
Ca 53	scintillation spectrometer	325, 404 }	7.46±0.15 }	(12–16)
			7.12±0.15 }	
			5.04±0.10 }	(5)
			4.65±0.10 }	
			2.82±0.07	12
			1.81±0.04	12

(7.55±0.12), 8.18±0.10, and 9.16±0.17 Mev. The ground-state Q value is 9.08±0.20 Mev (Pe 49).

Gamma rays of $E_\gamma=1.72\pm0.08$ and $E_\gamma=3.0\pm0.2$ Mev are observed with a beta spectrometer connected to the cyclotron and of $E_\gamma=8.5\pm0.5$ with a coincidence absorber technique. They are probably due to this reaction, but might be assigned also to $Al^{27}(d,p)Al^{28}$ or $Al^{27}(d,\alpha)Mg^{25}$ (Al 49b).

The neutron angular distribution has been measured by making use of threshold detectors at deuteron energies of 7.2, 8, 15, and 20 Mev (Ro 47, Hu 51, Fa 51, Sc 51).

IX. $Al^{28}(\beta^-)Si^{28}$ See Al^{28}

X. $Si^{28}(p,p')Si^{28}$

At 15.3 Mev inelastically scattered protons have been observed corresponding to a level at 4.6±0.3 Mev in Si^{28}. Proton energy was measured by deflection in the magnetic field of the cyclotron (Fu 48).

XI. $Si^{29}(\gamma,n)Si^{28}$ $Q_m=-8.473$

The threshold is 8.45±0.20 Mev (Sh 51a).

XII. $P^{28}(\beta^+)Si^{28}$ See P^{28}

XIII. $P^{31}(p,\alpha)Si^{28}$ $Q_m=1.911$

The ground-state Q value has been measured at proton energies from 0.65 to 1.07 Mev as 1.85±0.02 Mev (Fr 51) and at $E_p=1.8$ Mev as 1.909±0.010 Mev (Va 52a) by magnetic analysis of the α particles. For resonances see S^{32}.

P^{28}

(not illustrated)

Adopted mass defect: 0.9 Mev (Gl 53, Br 53c)

I. $P^{28}(\beta^+)Si^{28}$ $Q_m=14.2$

The half-life measurements are 0.280±0.010 sec (Gl 53) and 0.29±0.01 sec (Br 53c). The maximum positron energy is 10.6±0.4 Mev, indicating β^+ transitions to the 1.78 Mev level in Si^{28}. Gamma rays observed by scintillation spectrometer are summarized in Table XXVIII. All the lines found by Richardson *et al.* (Ri 53) can be explained as transitions from known levels in Si^{28} to the ground state but for the 2.66-Mev γ ray which is the transition from the second to the first level in Si^{28}. No delayed α's have been observed i.e., either $E_\alpha<1$ Mev or the α intensity is smaller than 10 percent of the γ intensity (Gl 53, Gl 53a, Gl 53b).

TABLE XXVIII. Gamma rays in the decay of P^{28}.

Author	Ri 53, Gl 53b	Br 53c
E_γ in Mev	1.79±0.02	1.78±0.04
	2.6 ±0.2	2.67±0.08
		(3.01±0.07)
		(4.26±0.12)
	4.44±0.05	4.63±0.10
	(4.93±0.08)	4.89±0.09
		(5.16±0.12)
		(5.46±0.10)
	6.14±0.10	
	6.70±0.12	6.65±0.11
	7.04±0.08	7.10±0.12
	7.59±0.15	(7.44±0.14)
		(7.73±0.14)
		(8.12±0.21)

II. $Si^{28}(p,n)P^{28}$ $Q_m=-14.9$

The threshold is measured by comparison to the $Mg^{24}(p,n)Al^{24}$ threshold measured by Miss Birge (Bi 52) as $E_p=15.6\pm0.5$ Mev (Gl 53) and 15.4±0.5 Mev (Br 53c).

Al^{29}

(not illustrated)

Adopted mass defect: −9.6 Mev (Se 49)

I. $Al^{29}(\beta^-)Si^{29}$ $Q_m=3.8$

Determinations of the half-life are 6.6±0.3 min (Me 37), 6.4±0.1 min (He 39), and 6.56±0.06 min (Se 49). See also Fa 35, Ec 35, Ec 37.

The β^- decay is complex and proceeds to the first and third excited states in Si^{29} (at $E_x=1.28$ and 2.43 Mev), which are de-excited directly to the Si^{29} ground state. No γ ray of 2.03 Mev corresponding to ground-state de-excitation of the second Si^{29} level has been observed (intensity <4 percent) (Ro 53). Determinations of β^- end points, γ-ray energies, and relative intensities are collected in Table XXIX. See also Ec 37.

TABLE XXIX. Beta decay of Al^{29}.

Author	Method	E_{β_1} (Mev)	E_{γ_1} (Mev)	E_{β_2} (Mev)	E_{γ_2} (Mev)
Me 37	Al abs.	2.75			
Be 39	cl. chamber	2.5			
Se 49	Al abs.	2.5 (70%)	1.25±0.2	1.4 (30%)	2.35±0.5
Ro 53	scint. spectr.		1.28 (85%)		2.43 (15%)

Both β^- transitions are evidently allowed as follows from the log *ft* values 5.2 and 4.5 (for transitions to the 1.28, *viz.*, 243-Mev level in Si^{29}).

See Si^{29} "General Remarks" for conclusions about spins and parities.

II. $Mg^{26}(\alpha,p)Al^{29}$ $Q_m=-2.9$

Radioactive Al^{29} has been found from this reaction (Fa 35, El 36, Me 37, Be 39, Se 49). For resonances see Si^{30}.

III. $Al^{27}(t,p)Al^{29}$ $Q_m=8.6$

Radioactive Al^{29} has been produced by bombarding aluminum with 6.5-Mev tritons (Po 52b), and also by bombarding $LiAlD_4$ with deuterons (production of tritons through the $D(d,t)H$ reaction) (Iw 53).

IV. $Si^{29}(n,p)Al^{29}$ $Q_m=-3.0$

The cross section for this reaction is 36±5 mb for Be(d,n) neutrons ($E_d=15$ Mev) (Co 51) and 101±30 mb for 14.5 Mev neutrons (Pa 53). See also Po 37a.

V. $Si^{30}(\gamma,p)Al^{29}$ $Q_m=-13.6$

At $E_\gamma=17$ Mev the cross section is 1.5±0.3 mb (Hi 47, Wa 48). See also Ba 46, Pe 48.

Si^{29}

Mass defect: −13.362 Mev

I. $Mg^{25}(\alpha,p)Al^{28}$ $E_b=11.145$ $Q_m=-1.196$

Resonances in the yield of Al^{28} activity have been found at $E_\alpha=5.4$, 6.2, and 6.9 Mev (Al 35, Fa 35, Ch 37, Me 37). See also Du 34, Ha 35, Sz 44, Sz 48. See Al^{28} for Q value measurements.

II. $Mg^{26}(\alpha,n)Si^{29}$ $Q_m=0.040$

Neutrons have been observed from the bombardment of natural magnesium by Po α's but they may also result from the $Mg^{25}(\alpha,n)Si^{28}$ reaction (Sa 35). See also Ha 49a.

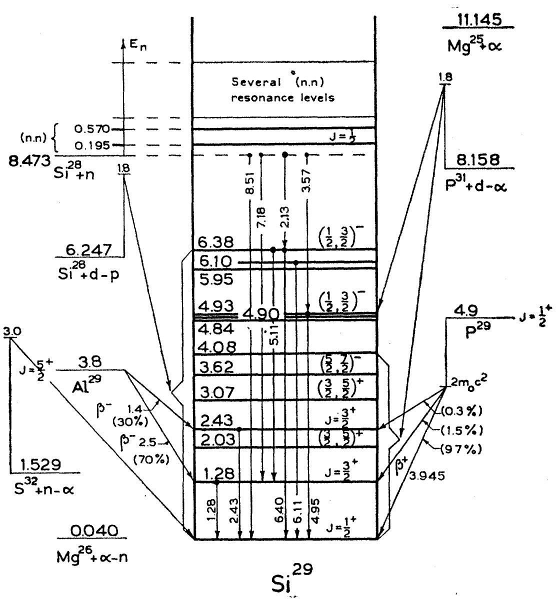

FIG. 16.

III. $Al^{29}(\beta^-)Si^{29}$ See Al^{29}

IV. $Si^{28}(n,\gamma)Si^{29}$ $Q_m=8.473$

The thermal neutron capture cross section for isotopic Si^{28} is 81±24 mb (Po 52a). For natural silicon values are found of 160±10 mb (Co 50), 160±8 mb (Ha 50) and 100±20 mb (Po 51). See also Vo 43.

Energies and intensities of γ rays resulting from the capture of thermal neutrons in natural silicon have been determined by pair spectrometer (Ki 51, Ki 53d). They are collected in Table XXX. A recalculation of the intensities of some lines in photons per capture in Si^{28} is given in (Ki 53e). Line A' certainly results from capture in Si^{29} and represents the transition to the Si^{30} ground state. Lines B, E, G, H, K, and M probably correspond to capture in Si^{28}. Lines B, E, and M check with the ground-state transition and transitions to the levels at 1.28 and 4.93 Mev in Si^{29} and lines K, H, and G with the de-excitation to the ground state of levels at 4.93, 6.10, and 6.38 Mev. None of the other γ rays can be identified with any certainty.

TABLE XXX. Gamma rays from thermal neutron capture in natural silicon (Ki 51, Ki 53d).

γ ray	Energy in Mev	Intensity in photons per 100 captures
A'	10.599±0.011	0.4
B	8.467±0.008	4
C	7.79 ±0.05	1
D	7.36 ±0.08	2
E	7.18 ±0.03	9
E'	6.88 ±0.03	0.7
F	6.76 ±0.04	4
G	6.40 ±0.03	19
H	6.11 ±0.05	4
I'	5.70 ±0.04	2
I	5.52 ±0.05	2
J	5.11 ±0.04	9
K	4.933±0.005	112
K'	4.60 ±0.08	4
L	4.20 ±0.03	19
M	3.540±0.006	94
N	2.69 ±0.05	65

Gamma rays of 2.13 and 2.65 Mev from the capture of thermal neutrons in natural silicon have been found by scintillation spectrometer (Br 53b). The first represents the transition from the capturing state to the 6.38 Mev level, which level is de-excited by line G to the ground state and by line J to the first excited state. These three lines as well as the predominant K, M cascade are all $E1$ transitions (Ki 53e).

V. $Si^{28}(n,n)Si^{28}$ $E_b=8.473$

Data on the silicon total cross section as a function of neutron energy have been reviewed by Adair (Ad 50). The cross section is constant (~2.1 b) below $E_n=200$ ev. Sharp resonances have been found with Li(p,n) neutrons at 195 kev ($J=\frac{1}{2}$) and at 570 kev ($J>\frac{1}{2}$) (Fi 51). Several sharp and several broad resonances exist in the region $E_n=0.8-2.0$ Mev (Fr 50).

From recent measurements of the silicon total cross section with D(d,n) neutrons at 30–50 kev resolution resonances are reported at (≤1.84), 1.93, 1.97, 2.11, 2.18, 2.23, 2.30, 2.38, 2.50, 2.57, 2.62, 2.86, 3.05, 3.12, 3.41, and (3.7) Mev (Me 53). With pile neutrons ($E_n=3-12$ Mev) broad maxima are found at 4.8 and 6.0 Mev (Ne 53). At 14 Mev the cross section is 1.83±0.04 b (Co 52a), while 1.94±0.06 b is found at 19 Mev (Da 53b).

TABLE XXXI. $Si^{28}(d,p)Si^{29}$ Q values and levels in Si^{29}.

Author	Va 52c		Mo 50
Group	$Si^{28}(d,p)Si^{29}$ Q value in Mev	Si^{29} level in Mev	Si^{29} level in Mev
(0)	6.246±0.010	0	0
(1)	4.968±0.008	1.278±0.007	1.29±0.04
(2)	4.219±0.006	2.027±0.007	2.06±0.04
(3)	3.820±0.006	2.426±0.007	2.43±0.04
(4)	3.176±0.006	3.070±0.007	3.08±0.05
(5)	2.623±0.005	3.623±0.007	3.60±0.05
(6)	2.168±0.005	4.078±0.008	4.09±0.06
(7)	1.406±0.004	4.840±0.008	4.87±0.10
(8)	1.349±0.004	4.897±0.008	
(9)	1.312±0.004	4.934±0.008	
(10)	0.300±0.004	5.946±0.009	
(11)	0.141±0.004	6.105±0.009	
(12)	−0.134±0.004	6.380±0.009	

VI. $Si^{28}(d,p)Si^{29}$ $Q_m=6.247$

Twelve proton groups (see Table XXXI) have been found from this reaction by high-resolution magnetic analysis ($\vartheta=90°$) at deuteron energies up to 2.1 Mev (En 51a, Va 52c). Natural silicon targets were used but proton groups due to Si^{29} or Si^{30} could be eliminated by comparison with results obtained from targets enriched in these isotopes. Table XXXI also contains Si^{29} levels obtained by Al absorption at $E_d=3.7$ Mev (Mo 50). There is excellent agreement while also the levels given in Table XXXI agree very well with those found from the $P^{31}(d,\alpha)Si^{29}$ reaction (see Table XXXII). See also Po 41, Al 48, Ne 49a, Ne 50b, St 51.

At $E_d=3.7$ Mev a γ ray of 6.2±0.3 Mev is found by an absorption method (Al 49b).

Angular distributions of the most prominent proton groups have been measured at $E_d=8.2$ Mev. By Butler analysis the orbital angular momentum l_n of the captured neutron has been determined. The ground-state transition corresponds to $l_n=0$ which fixes the Si^{29} ground-state spin and parity as $J=\frac{1}{2}^+$. The levels at 4.93 and 6.38 Mev are reached by $l_n=1$ ($J=\frac{1}{2}^-$ or $\frac{3}{2}^-$), the levels at 1.28, 2.03, and 3.07 Mev by $l_n=2$ ($J=\frac{3}{2}^+$ or $5/2^+$), the level at 3.62 Mev by $l_n=3$ ($J=5/2^-$ or $7/2^-$) while the transition to the level at 2.43 Mev has an isotropic angular distribution. Shell model assignments are discussed on the basis of l_n values and measured neutron capture probabilities (Ho 53a, Ho 53d). The l_n assignments to the ground state and first excited state transitions are confirmed at $E_d=14.3$ Mev (Bl 53).

TABLE XXXII. $P^{31}(d,\alpha)Si^{29}$ reaction (En 51a, Va 52a).

Group	Q value (Mev)	Si^{29} level (Mev)
A	8.158±0.011	0
B	6.885±0.020	1.274±0.010
C	6.126±0.020	2.032±0.014
D	5.727±0.020	2.431±0.015
E	5.086±0.020	3.072±0.016
F	4.539±0.020	3.619±0.017
G	4.080±0.020	4.078±0.018
H	3.221±0.020	4.937±0.020

VII. $P^{29}(\beta^+)Si^{29}$ See P^{29}

VIII. $P^{31}(d,\alpha)Si^{29}$ $Q_m=8.158$

Eight α-particle groups (see Table XXXII) have been found by high-resolution magnetic analysis ($\vartheta=0°$) at $E_d=1.8$ Mev (En 51a). The ground-state Q value given as 8.170±0.020 Mev has later been remeasured as 8.158±0.011 Mev (Va 52a). The excitation energies of Si^{29} levels given in Table XXXII have been corrected by this 12 kev.

In the bombardment of phosphorus with 3.7-Mev deuterons a γ ray of 6.2±0.3 Mev is observed by an absorption method, which might also belong to the (d,n) or (d,p) reaction (Al 49b).

IX. $P^{31}(\gamma,np)Si^{29}$ $Q_m=-17.901$

The yield curve of this reaction has been obtained by subtracting the (γ,n) yield, measured by the P^{30} activity, from the photoneutron yield, measured with BF_3 chambers in paraffin. The integrated cross section is 47 Mev mb (Ha 52a) and 34 Mev mb (Mo 53a).

X. $S^{32}(n,\alpha)Si^{29}$ $Q_m=1.529$

A ground-state Q value of 1.16±0.15 Mev has been measured at $E_n=3.0$ Mev by pulse-height analysis in an SO_2 gas-filled ionization chamber (St 48). The cross section at $E_n=2.8$ Mev is 65 mb (Hu 41a). See also Wi 37.

For resonances see S^{33}.

GENERAL REMARKS

Spins and parities of the Al^{29} ground-state ($J=5/2^+$), of the P^{29} ground-state ($J=\frac{1}{2}^+$) and of the 1.28 and 2.43 Mev levels in Si^{29} (both $J=\frac{3}{2}^+$) are uniquely determined through consideration of the ft values observed in the β decay of Al^{29} and P^{29}.

For a theoretical discussion regarding triple levels in Si^{29} see In 53.

P^{29}

(not illustrated)

Adopted mass defect: −8.395 Mev (Ro 53a)

I. $P^{29}(\beta^+)Si^{29}$ $Q_m=4.967$

The half-life is determined as 4.6±0.2 sec (Wh 41) and 4.45±0.05 sec (Ro 53).

The β^+ decay goes predominantly to the Si^{29} ground state. The β^+ end point is determined by means of a cloud chamber as 3.63±0.07 Mev (Wh 41), with a scintillation counter as 3.9±0.2 Mev (Na 53) and with a magnetic spectrometer as 3.945±0.010 Mev (Ro 53a). Gamma rays of 1.28 and 2.43 Mev in coincidence with positrons have been observed indicating weak β^+ transitions to the 1.28 Mev (1.5 percent) and 2.43 Mev (0.3 percent) levels in Si^{29}. The ground-state β^+ transition is super-allowed ($\log ft=3.7$) and the transitions to the 1.28 and 2.43 Mev levels are allowed ($\log ft=4.7$ and 4.4). No β^+ transition to the 2.04 Mev Si^{29} level and no γ cascades between levels were found (Ro 53, Ro 53a). See Si^{29} "General Remarks" for conclusions about spins and parities.

II. $Si^{28}(p,\gamma)P^{29}$ $Q_m=2.724$

Not observed (see Ta 46).

III. $Si^{28}(d,n)P^{29}$ $Q_m=0.498$

A ground-state Q value of 0.29 ± 0.04 Mev has been reported from bombardment of enriched silicon targets at $E_d=1.4$ Mev and detection of neutrons by nuclear emulsions (Ma 52). From the bombardment of a natural silicon target at $E_d=3.7$ Mev and neutron detection by nuclear emulsions a Q value is found of -0.80 ± 0.10 Mev. The corresponding neutron group was 25 times more intense than any other group from the same bombardment (Pe 48a). It is not impossible that this group results from C^{12} contamination on the target. The next most intense group yields a Q value of 0.71 ± 0.13 Mev. See also Hu 51.

IV. $Si^{29}(p,n)P^{29}$ $Q_m=-5.749$

Radioactive P^{29} has been found from this reaction (Wh 41).

V. $S^{32}(p,\alpha)P^{29}$ $Q_m=-4.220$

Not observed.

Si^{30}

Mass defect: -15.609 Mev

I. $Mg^{26}(\alpha,p)Al^{29}$ $E_b=10.651$ $Q_m=-2.9$

With RaC′ α particles on natural Mg targets resonances in the Al^{29} yield have been observed at $E_\alpha=5.3$ and 6.0 Mev (Me 37).

II. $Al^{27}(\alpha,p)Si^{30}$ $Q_m=2.389$

This reaction has been extensively investigated with natural radioactive α-particle sources. Four proton groups are reported. There is general agreement about the Q values which are: 2.3, 0.0, -1.3, and -2.6 Mev corresponding to levels in Si^{29} at 2.4, 3.7, and 5.0 Mev (Ch 32, St 32, Ha 33, Du 34, Ha 34, Po 35, Me 40a, Me 40, Sl 51, Sl 51a). Angular distributions have been measured (Po α particles, nuclear emulsions) of the two proton groups with highest Q values at the $E_\alpha=4.0$- and 4.44-Mev resonances (Ro 51). More proton groups have been observed at $E_\alpha=22$ Mev with Q values determined by Al absorption of -3.22, -4.96, -5.98, -7.04, -7.65, and -8.64 Mev corresponding to Si^{29} levels at 5.61, 7.35, 8.37, 9.43, 10.04, and 11.03 Mev (Br 49). See also Po 29, Po 30, Ch 31, Di 32, Me 34, Ka 37.

Energies of γ rays in coincidence with selected proton groups at $E_\alpha=7.8$ Mev have been measured by scintillation spectrometer (Al 51, see also La 51, Be 48a). From the first and second (doublet) excited state transitions to the ground state are observed with γ-ray energies of 2.32 ± 0.05 and 3.63 ± 0.15 Mev. The 5.07-Mev level is de-excited either through the second level with γ rays of 1.28 ± 0.06 and 3.55 ± 0.15 Mev or through the first level (less than 15 percent). See also Al 48a, Sz 40.

For resonances see P^{31}.

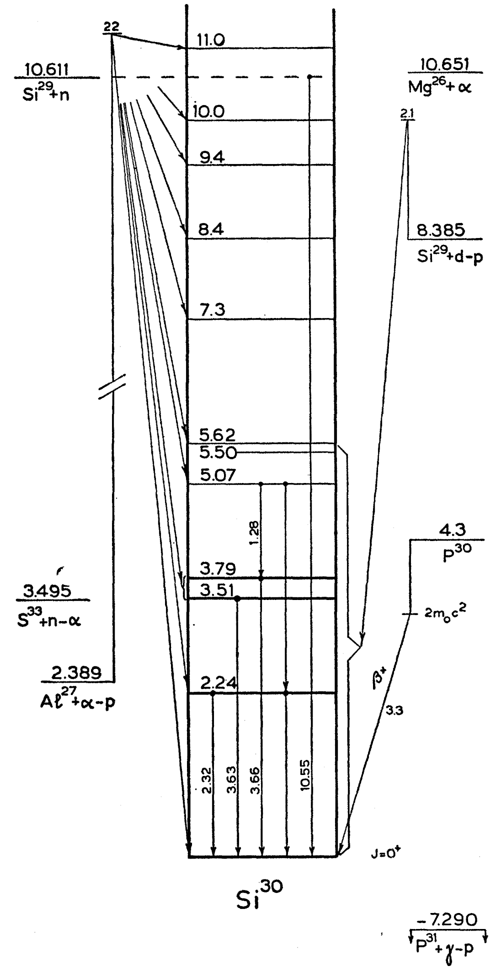

FIG. 17.

III. $Si^{29}(n,\gamma)Si^{30}$ $Q_m=10.611$

The thermal neutron capture cross section of isotopic Si^{29} is 0.27 ± 0.08 b (Po 52a).

The energy of the γ ray corresponding to the ground-state transition after capture of thermal neutrons in Si^{29} has been measured by pair spectrometer as 10.599 ±0.011 Mev (see Table XXX). The transition energy is obtained by adding to E_γ 2 kev, the nuclear recoil energy (Ki 53d).

IV. $Si^{29}(d,p)Si^{30}$ $Q_m=8.383$

Several proton groups from enriched Si^{29} targets have been found by high-resolution magnetic analysis

TABLE XXXIII. $Si^{29}(d,p)Si^{30}$ reaction.

Q value (Va 52c) in Mev	Si^{30} level (Va 52c) in Mev	Si^{30} level (Mo 50) in Mev
8.388±0.013	0	0
6.149±0.015	2.239±0.020	(2.4 ±0.2)
4.873±0.009	3.515±0.016	
4.602±0.015	3.786±0.020	3.91±0.15
	(5.075±0.015)	5.00±0.15
	(5.497±0.015)	
	(5.622±0.015)	5.7 ±0.2

($\vartheta=90°$) at deuteron energies up to 2.1 Mev (Va 52c). Q values and corresponding Si^{30} levels are given in Table XXXIII together with Si^{30} levels obtained by Al absorption at $E_d=3.7$ Mev from enriched targets (Mo 50). See also Po 41, Va 52a.

V. $P^{30}(\beta^+)Si^{30}$ See P^{30}

VI. $P^{31}(\gamma,p)Si^{30}$ $Q_m=-7.290$

Not observed.

VII. $S^{33}(n,\alpha)Si^{30}$ $Q_m=3.495$

Not observed.

P^{30}

Adopted mass defect: −11.3 Mev

(The mass defect has been computed from reactions I, II, V, VII, and IX and the weighted average has been taken.)

I. $P^{30}(\beta^+)Si^{30}$ $Q_m=4.3$

Accurate measurements of the half-life scatter appreciably, possibly because of the presence of an unknown amount of Al^{28} (2.3 min). They are 3.25±0.05 min (Al 35), 2.55±0.05 min (Ri 37), 3.15±0.05 min (Sh 37) and 2.18±0.025 min (Ci 38). Other reported values with larger errors range from 2.3 min to 3.2 min (El 34, Fa 35a, Sa 36, Bo 37a, Me 37, Co 40, St 53b). See also Cu 34, Ba 40, Ta 46.

The β^+-spectrum end point has been determined by spectrometer as 2.8 Mev (El 34), 3.75±0.19 Mev (Al 35), and 3.5±0.3 Mev (Ma 41); by cloud chamber as 3 Mev (Cu 34) and 3.0±0.1 Mev (Ba 40); and by absorption as 2.9±0.1 Mev (El 35), 2.56 Mev (Sh 37), 2.6 Mev (Me 37), and 3.4±0.5 Mev (Fr 34, Bl 46c). See also Cu 34a.

There is no evidence for γ rays (El 35, St 53b).

The $\log ft$ value is 5.0 if the β^+ end point is taken as 3.3 Mev and the half-life as 3.2 min.

See St 53b, St 53c and Mo 53b for isotopic spin assignments in P^{30}.

II. $Al^{27}(\alpha,n)P^{30}$ $Q_m=-2.7$

From bombardments of thick aluminum targets at $E_\alpha=7.6$ Mev and detection of neutrons by nuclear emulsion technique a ground-state Q value of −2.93 ±0.17 Mev has been reported and a level in P^{30} at 1.02±0.12 Mev (Pe 48a). See also Cu 33, Cu 34, Cu 34b, Fr 34, Me 34, Sa 34, Sa 35, Me 37, Ri 37.

See P^{31} for resonances.

III. $Si^{28}(He^3,p)P^{30}$ $Q_m=6.3$

Radioactive P^{30} has been found from this reaction (Al 39, Po 52b, Po 53).

IV. $Si^{29}(p,\gamma)P^{30}$ $Q_m=5.5$

Sharp resonances in the γ ray and P^{30} activity yield have been found at $E_p=326$ and 414 kev. The mean γ-ray energy is measured by Al absorption as 5.2±0.7 Mev (Ta 46). See also Ho 41.

V. $Si^{29}(d,n)P^{30}$ $Q_m=3.3$

By nuclear emulsion technique a ground-state Q value of 3.27±0.04 Mev and levels at 0.75±0.06, 1.46±0.06, and 2.00±0.06 Mev have been determined by bombarding enriched silicon targets at $E_d=1.4$ Mev (Ma 52), and a ground-state Q value of 3.38±0.17 Mev and a level at 1.27±0.48 Mev by bombarding natural silicon targets at $E_d=3.7$ Mev (Pe 48a).

VI. $Si^{30}(p,n)P^{30}$ $Q_m=-5.1$

Radioactive P^{30} has been found from this reaction (Ba 39).

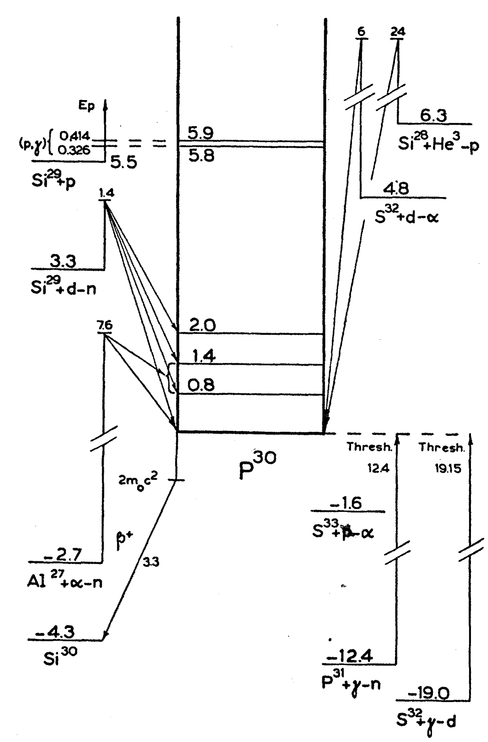

FIG. 18.

VII. $P^{31}(\gamma,n)P^{30}$ $Q_m=-12.4$

The threshold is measured as 12.35±0.2 Mev (Mo 49), 12.4±0.2 Mev (Ka 51a), and 12.05±0.20 Mev (Sh 51a). The cross section has a maximum of 16.7 mb at 19.5 Mev with a half-width of 6.5 Mev and an integrated cross section of 129 Mev mb (Ka 51c) or 99 Mev mb (Ha 52e), as measured by the residual activity. Values found by measuring the neutron intensity with a BF_3 chamber are a maximum cross section of 29 mb at 20.5 Mev, a half-width of 5.7 mb, and an integraded cross section of 140-Mev mb (Mo 53a).

See also Bo 39, Ba 46, Pe 48, Ca 51.

VIII. $P^{31}(n,2n)P^{30}$ $Q_m=-12.4$

Radioactive P^{30} has been found from this reaction (Po 37a). The cross section for $Be(d,n)$ neutrons ($E_d=15$ Mev) is 14.4±1.5 mb (Co 51).

IX. $S^{32}(\gamma,d)P^{30}$ $Q_m=-19.0$

The threshold is found at 19.15±0.20 Mev (Ka 51a). The cross section shows a maximum of 1.8 mb at 23.6 Mev with a half-width of 2.1 Mev and an integrated cross section of 3.9 Mev mb (Ka 51c).

X. $S^{32}(n,t)P^{30}$ $Q_m=-12.7$

Radioactive P^{30} has been found from this reaction at $E_n=24$ Mev but not at 13 Mev (Co 40).

XI. $S^{32}(d,\alpha)P^{30}$ $Q_m=4.8$

Radioactive P^{30} has been found from this reaction (Sa 36, Ho 40b).

XII. $S^{33}(p,\alpha)P^{30}$ $Q_m=-1.6$

Not observed.

Si^{31}

Mass defect: −13.837 Mev

I. $Si^{31}(\beta^-)P^{31}$ $Q_m=1.480$

Accurate determinations of the half-life yield: 157.3±0.5 min (Vr 52), 157.1±0.7 min (We 51), 155.5±1 min (Lu 50), 159±1 min (Mo 52a), and 157.1 ±1.3 min (Ci 38). See also Cu 34c, Ne 37, Wa 37, Al 40, Ru 52b.

TABLE XXXIV. $Si^{30}(d,p)Si^{31}$ Q values and levels in Si^{31}.

Group	$Si^{30}(d,p)Si^{31}$ Q value in Mev Va 52c	Si^{31} level in Mev Va 52c	Mo 50
(0)	4.364±0.007	0	0
(1)	3.607±0.006	0.757±0.007	0.73±0.15
	...	...	1.23±0.15
(2)	2.665±0.006	1.699±0.007	1.73±0.15
(3)	2.045±0.005	2.319±0.008	2.33±0.15
(4)	1.573±0.005	2.791±0.008	...
(5)	1.224±0.005	3.140±0.008	...
(6)	0.825±0.004	3.539±0.008	...
(7)	−0.020±0.004	4.384±0.008	...

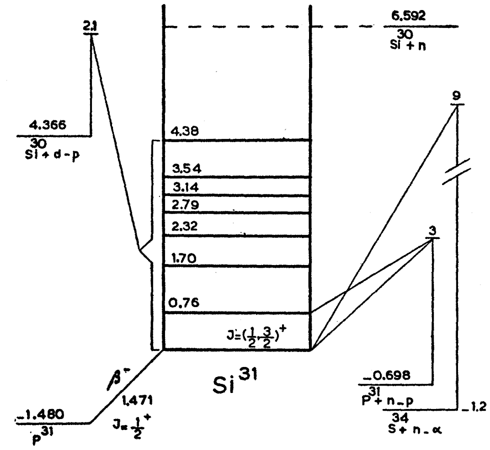

FIG. 19.

The β^- spectrum is simple and has the allowed shape. The end point has been measured by lens spectrometer as: 1.471±0.008 Mev (Mo 52a) and 1.486±0.012 Mev (Wa 52, Wa 53a). The log ft value is 5.5. Recently γ rays have been detected by scintillation spectrometer. Their energy is 1.26 Mev and their intensity 0.07 percent. The corresponding β^- transition is allowed (log $ft=5.6$). There is no indication of γ rays of lower energy (Ly 54). See also Ku 36, Ne 37, Wi 38, We 51.

II. $Si^{30}(n,\gamma)Si^{31}$ $Q_m=6.592$

The thermal neutron capture cross section has been determined by Si^{31} activity measurements as 0.063 b (Si 41a) and 0.116±0.023 b (Se 47), and by the pile oscillator method as 0.41±0.4 b (Po 52a). See also Am 35, Ki 51, On 41.

For fission neutrons ($E_n\approx 1$ Mev) the capture cross section is 1.1 mb (Hu 53a).

II. $Si^{30}(d,p)Si^{31}$ $Q_m=4.366$

Seven proton groups have been found by high resolution magnetic analysis ($\vartheta=90°$) at deuteron energies up to 2.1 Mev using enriched Si^{30} targets (Va 52c). Corresponding Q values and levels in Si^{31} are given in Table XXXIV together with results obtained by Al absorption at $E_d=3.7$ Mev (Mo 50). The proton group corresponding to a level at 1.23 Mev reported by Motz coincides with an intense $Si^{28}(d,p)Si^{29}$ group and might result from incomplete subtraction of the $Si^{28}(d,p)Si^{29}$ contribution to the total proton yield. No corresponding group has been found in the high-resolution work with an intensity (at $E_d=1.8$ Mev and $\theta=90°$) larger than 5 percent of the ground-state group (Va 52c). See also La 35a, Cl 46a, Al 48, St 51.

The excitation curve for production of the Si^{31} activity has been measured from 1 to 6 Mev (Ri 47).

IV. $Si^{30}(He^3,2p)Si^{31}$ $Q_m=-1.127$

Radioactive Si^{31} has been found from this reaction at $E_{He^3}=13$ Mev (Po 53).

V. $P^{31}(n,p)Si^{31}$ $Q_m = -0.698$

By measuring pulse heights from a P_2O_3 gas-filled ionization chamber bombarded by $D(d,n)$ neutrons a Q value of -0.97 ± 0.13 Mev has been found and a level in Si^{31} at 0.7 Mev (Me 48). See also Bj 34, Me 34a, Am 35, Po 37a.

The cross section for $Be(d,n)$ neutrons ($E_d = 15$ Mev) is 120 ± 12 mb (Go 51); for 14-Mev neutrons 91 ± 9 mb (Fo 52a) and 64 ± 8 mb (Pa 53).

See P^{32} for resonances.

VI. $S^{34}(n,\alpha)Si^{31}$ $Q_m = -1.2$

Radioactive Si^{31} has been found from this reaction by bombarding sulfur with fast neutrons (Sa 36, Ci 38). The cross section at $E_n = 14$ Mev is 138 ± 35 mb (Pa 53).

P^{31}

Mass defect: -15.317 Mev

I. $Al^{27}(\alpha,n)P^{30}$ $E_b = 9.679$ $Q_m = -2.7$

Resonances in this reaction have been found both by measuring the yield of radioactive P^{30} and by detection of the neutrons with boron proportional counters. They are listed in Table XXXV. See also El 34, Li 37, Ha 49a.

See P^{30} for Q values.

II. $Al^{27}(\alpha,p)Si^{30}$ $E_b = 9.679$ $Q_m = 2.389$

Resonances in the proton yield observed with natural α-particle sources are at $E_\alpha = 4.0$, 4.44, 4.86, 5.25, 5.75, and 6.6 Mev (Ch 32, Di 32, Du 34, Ha 34, Ka 37, Sz 39, Me 40, Ne 40a, Li 37). See also Ro 51, Ro 53b.

For Q values and observed γ rays see Si^{30}.

III. $Si^{28}(\alpha,p)P^{31}$ $Q_m = -1.911$

From the bombardment of natural silicon with $Th(B+C)$ α particles three proton groups are observed

TABLE XXXV. Resonances in $Al^{27}(\alpha,n)P^{30}$.

Author:	Fa 35a	Wa 36	Sh 37	Fu 38	Sz 39
Source:	Po, $Th(B+C)$	RaC	Rn	$Th(B+C)$	Po
Method:	$P^{30}(\beta^+)$	$P^{30}(\beta^+)$	$P^{30}(\beta^+)$	n	$P^{30}(\beta^+)$
E_α (Mev)		4.0			3.95
		(4.51)			4.53
					4.70
					4.84
	5.1	5.0			5.12
		5.4		5.29	5.3
			5.7	5.64	
		(6.0)		6.01	
				6.38	
	6.5^5	6.7	6.6	6.57	
				7.00	
				7.20	
				7.34	
	7.8			7.60	
				8.04	
				8.24	
				8.42	
				8.62	

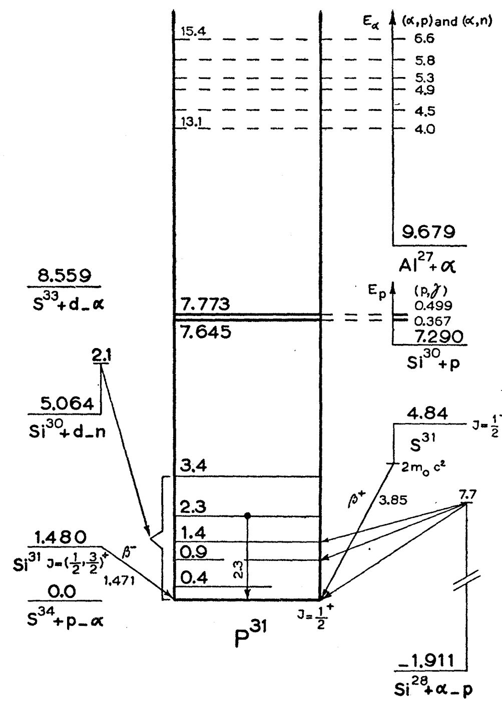

FIG. 20.

corresponding to a ground-state Q value of -2.23 Mev and levels in P^{31} at 1.05 and 1.69 Mev (Ha 35, Li 37). From 7 Mev cyclotron α particles on natural silicon a γ ray is found of 2.3 ± 0.3 Mev as measured by Al absorption (Al 48a).

IV. $Si^{30}(p,\gamma)P^{31}$ $Q_m = 7.290$

From natural silicon bombarded by protons sharp resonances not accompanied by positron emission have been observed at 367 and 499 kev corresponding to P^{31} levels at 7.645 and 7.773 Mev (Ta 46). See also Ho 41.

V. $Si^{30}(d,n)P^{31}$ $Q_m = 5.064$

From natural silicon bombardments at $E_d = 3.7$ Mev and with nuclear emulsion technique for neutron detection Q values are found of 4.56 ± 0.14, 4.12 ± 0.16, 3.57 ± 0.15, and 2.78 ± 0.16 Mev (Pe 48a). By the use of enriched Si^{30} targets at $E_d = 1.4$ Mev and nuclear emulsion technique Q values have been measured of 4.92, 4.59, 3.73, 2.70, and 1.51 Mev all ± 0.04 Mev (Ma 52). If one averages the results of these two investigations (and assumes that in the earlier one the ground-state transition has been missed) the following excitation energies in P^{31} are obtained: 0.4, (0.9), 1.4, 2.3, and 3.4 Mev.

VI. $Si^{31}(\beta^-)P^{31}$ See Si^{31}

VII. $S^{31}(\beta^+)P^{31}$ See S^{31}

VIII. $S^{33}(d,\alpha)P^{31}$ $Q_m=8.559$

Not observed.

IX. $S^{34}(p,\alpha)P^{31}$ $Q_m=0.0$

Not observed.

S^{31}

(not illustrated)

Adopted mass defect: −10.2 Mev

(The adopted S^{31} mass gives a β^+ decay energy which is in good agreement with the value determined by scintillation spectrometer (Bo 51). The agreement with the experimental $S^{32}(\gamma,n)S^{31}$ thresholds is also reasonable. The cloud-chamber determinations of the β^+ endpoint give a lower value, but this method seems to give too low results also in other cases e.g., P^{29}. An estimate of the Coulomb-energy difference with P^{31} taking into account the small systematic oscillation in mass difference between $A=4n+1$ and $A=4n-1$ mirror pairs results in a S^{31} mass defect of -9.9 ± 0.2 Mev.)

I. $S^{31}(\beta^+)P^{31}$ $Q_m=5.1$

The half-life has been measured as 2.9 ± 0.2 sec (Hu 41b), 3.2 ± 0.2 sec (Wh 41), 3.18 ± 0.04 sec (El 41), 2.6 ± 0.2 sec (Mc 49), 3.2 ± 0.3 sec (Bo 51), and 2.66 ± 0.03 sec (Ha 52a). The β^+ spectrum end point has been determined in a cloud chamber as 3.85 ± 0.07 Mev (Wh 41) and 3.87 ± 0.15 Mev (El 41), and with a scintillation spectrometer as 4.06 ± 0.12 Mev (Bo 51). The log *ft* value is 3.6, the usual value for super-allowed transitions between mirror nuclei.

II. $Si^{28}(\alpha,n)S^{31}$ $Q_m=-7.8$

Radioactive S^{31} has been produced by this reaction at $E_\alpha=15$ Mev (El 41).

III. $P^{31}(p,n)S^{31}$ $Q_m=-5.9$

Radioactive S^{31} has been observed from this reaction (Wh 41).

IV. $S^{32}(\gamma,n)S^{31}$ $Q_m=-14.8$

The threshold has been measured as 15.0 ± 0.3 Mev (Be 47a), 14.8 ± 0.4 Mev (Mc 49), and 15.0 ± 0.1 Mev (Ha 52a). The activation cross section has a maximum of 24.6 mb at 20.1 ± 0.5 Mev with a half-width of 4.5 Mev and an integrated cross section of 120 Mev mb (Ha 52a). The photoneutron cross section (for the (γ,n), (γ,np) and $(\gamma,2n)$ reactions together) has a maximum of 13 mb at 19.8 Mev with a half-width of 5.2 Mev and an integrated cross section of 75-Mev mb (Mo 53a). See also Hu 42, Hu 43, Wa 48, Mc 50, Bo 51.

Si^{32}

(not illustrated)

Adopted mass defect: −14.78 Mev (Li 53a)

I. $Si^{32}(\beta^-)P^{32}$ $Q_m=0.10$

Radioactive Si^{32} has been produced from the reaction $Cl^{37}(p,\alpha 2p)Si^{32}$ at $E_p=340$ Mev. From the measured activity and estimated reaction cross section a half-life is calculated between 100 and 710 years. The β^- spectrum end point is ~100 kev. There are no γ rays (Li 53a). See also Li 53.

P^{32}

Mass defect: −14.883 Mev

I. $P^{32}(\beta^-)S^{32}$ $Q_m=1.707$

Accurate determinations of the half-life (differing considerably) are 15.0 ± 0.1 days (Si 36), 14.295 ± 0.005

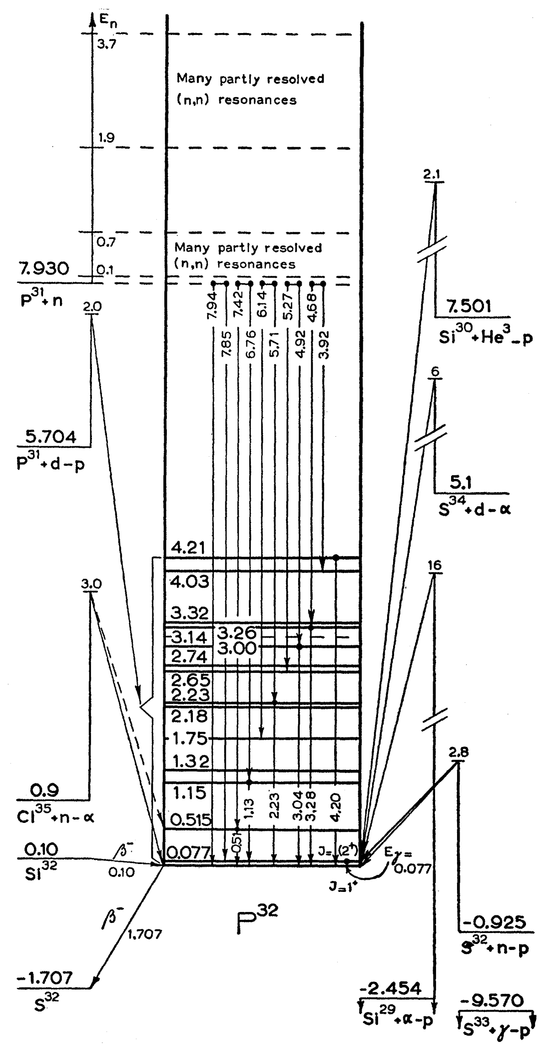

FIG. 21.

TABLE XXXVI. $P^{32}(\beta^-)S^{32}$.

Author	End point (Mev)
Ly 37	1.69 ±0.03
La 39a	1.72 ±0.01
Wi 41a	1.75 ±0.02
Si 46	1.712±0.008
La 49a	1.689±0.010
Ag 50	1.718±0.010
Wa 50	1.708±0.008
Sh 51c	1.695±0.005
Je 52	1.704±0.008
Mo 52a	1.697±0.010

days (Ca 38), 14.35±0.01 days (Mu 40), 14.35±0.05 days (Kl 48), 14.59±0.03 days (Si 51), and 14.50±0.02 days (Lo 53). See also Am 34, Am 35, Pr 35, Fa 35, Sa 36, Ne 37.

The β^- spectrum is simple and has the allowed shape. Determinations of the end point are collected in Table XXXVI. The *ft* value is very large for an allowed transition ($\log ft=7.9$) but this can be explained by *l*-forbiddenness. See also Al 35a, Ku 36, Li 39, Mo 40, Go 40, Hi 48, Ba 50, Ca 52.

The continuous γ radiation (internal bremsstrahlung) has been investigated by numerous authors. Its intensity, energy distribution, and $\beta-\gamma$ angular distribution have been measured (Wu 41, Si 47b, Ma 51, St 51b, No 53, Bo 53, Go 53b, Go 53c, Re 53a).

II. $Si^{29}(\alpha,p)P^{32}$ $Q_m=-2.454$

Radioactive P^{32} has been produced from this reaction (Fa 35, Ki 39a).

III. $Si^{30}(He^3,p)P^{32}$ $Q_m=7.501$

Radioactive P^{32} has been found from this reaction at $E_{He^3}=13$ and 21 Mev (Po 52b, Po 53).

IV. $P^{31}(n,\gamma)P^{32}$ $Q_m=7.930$

The thermal neutron capture cross section has been determined as 0.15±0.015 b (Po 51) and 0.193±0.007 b (Co 50) both by pile-oscillator measurements, and as 0.23±0.05 b by measurement of the yield of radioactive P^{32} (Se 47). See also La 40, Ra 40, On 41, Si 41a, Vo 43.

Twenty γ rays (Table XXXVII) have been found by high-resolution pair spectrometry from the capture of thermal neutrons in phosphorus (Ki 52). In the case of ten of these γ rays (*A*, *A'*, *C*, *D*, *F*, *H*, *J*, *K*, *L*, and *P*) good agreement is obtained if one assumes that transitions take place from the capturing state to the P^{32} ground state and nine excited states. Three other (*O*, *R*, and *S*) may represent transitions from levels to ground.

Three more γ rays of $E_\gamma=0.51$, 1.13, and 2.23 Mev have been found with a two-crystal scintillation spectrometer (Br 53a). They can well be interpreted as ground-state transitions from corresponding P^{32} excited states.

V. $P^{31}(n,n)P^{31}$ $E_b=7.930$

Broad resonances in the phosphorus total cross section (average value about 3.5 b) are found at $E_n=0.22$, 0.38, 0.47, and 0.58 Mev (Sn 53). At high resolution ($\Delta E_n\simeq 2$ kev) 31 resonances are observed between $E_n=125$ and $E_n=830$ kev (Ha 53a). Many incompletely resolved resonances are reported in the region $E_n=1.9-3.7$ Mev (Ri 51). Earlier data have been reviewed by Adair (Ad 50). Below 400 ev the total cross section is essentially constant (3.5 b). The cross section at $E_n=14$ Mev is 1.97±0.04 b (Co 52a) or 2.22±0.05 b (Ag 53).

VI. $P^{31}(n,p)Si^{31}$ $E_b=7.930$ $Q_m=-0.698$

A broad resonance in the production of radioactive Si^{31} has been observed at $E_n=2.9$ Mev (Br 49b). At somewhat higher resolution many incompletely resolved resonances are found in the region $E_n=1.9-3.7$ Mev (Lu 50, Ri 51, Ni 52). See also Bj 34, Me 48.

See Si^{31} for *Q* values.

VII. $P^{31}(d,p)P^{32}$ $Q_m=5.704$

Fifteen proton groups have been found by high-resolution magnetic analysis ($\vartheta=90°$) at deuteron energies of 1.8 and 2.0 Mev (Va 52b). Corresponding *Q* values and P^{32} levels are given in Table XXXVIII together with P^{32} levels obtained by Al absorption at $E_d=3.76$ Mev (Al 51a). See also Po 40a, Cl 46a, Al 49b, St 51, Va 52a.

Angular distributions of transitions to the ground-state doublet level have been measured at $E_d=7.2$ Mev (Pa 52) and at $E_d=14.3$ Mev (Bl 53). It is shown by Butler analysis that these transitions correspond to $l_n=2$ with less than 5 percent $l_n=0$ admixture. The influence of the Coulomb repulsion on stripping has been computed for this case (Bu 54).

TABLE XXXVII. Gamma rays from thermal neutron capture in phosphorus (Ki 52).

γ ray	Energy in Mev	Intensity in photons per 100 captures
A	7.94±0.03	0.5
A'	7.85±0.05	1.5
B	7.62±0.03	2
C	7.42±0.03	7
D	6.76±0.03	24
E	6.33±0.03	0.7
F	6.14±0.03	1.5
G	6.02±0.04	1.5
H	5.71±0.03	6
I	5.41±0.03	2
J	5.27±0.03	8
K	4.92±0.03	4
L	4.68±0.03	26
M	4.49±0.03	4
N	4.38±0.03	11
O	4.20±0.03	7
P	3.92±0.03	25
Q	3.55±0.03	22
R	3.28±0.04	9
S	3.04±0.04	7

TABLE XXXVIII. Q values for $P^{31}(d,p)P^{32}$ groups and energy levels in P^{32}.

Group	Q value (Mev) Va 52b	Levels in P^{32} Va 52b	Levels in P^{32} Al 51a
(0)	5.704±0.008	0	0
(1)	5.627±0.008	0.077±0.002	...
(2)	5.189±0.010	0.515±0.005	0.50±0.05
(3)	4.550±0.007	1.154±0.007	1.10±0.03
(4)	4.388±0.007	1.316±0.008	1.36±0.05
(5)	3.954±0.007	1.750±0.009	1.71±0.04
(6)	3.527±0.008	2.177±0.009	2.22±0.04
(7)	3.477±0.008	2.227±0.009	
(8)	3.054±0.006	2.650±0.008	2.72±0.03
(9)	2.962±0.006	2.742±0.008	
(10)	2.705±0.008	2.999±0.010	...
(11)	(2.563±0.010)	(3.141±0.012)	...
(12)	2.445±0.006	3.259±0.009	3.27±0.04
(13)	2.386±0.006	3.318±0.009	
(14)	1.672±0.005	4.032±0.009	...
(15)	1.497±0.008	4.207±0.010	...

VIII. $S^{32}(n,p)P^{32}$ $Q_m=-0.925$

From pulse-height analysis, bombarding SO_2 gas in an ionization chamber with 2.76 Mev neutrons, a Q value has been measured of -0.93 ± 0.1 Mev (Hu 41a). From sulfur bombarded by 2.5 Mev neutrons γ rays were observed of $E_\gamma=0.077$ and 2.23 Mev by scintillation spectrometer (Da 53). Both were ascribed to inelastic neutron scattering. The second γ ray corresponds to a known level in S^{32}, but the first γ ray is better explained by assuming that it originates from the $S^{32}(n,p)P^{32}$ reaction to the 77 kev level in P^{32}. The cross section for $Be(d,n)$ neutrons ($E_d=15$ Mev) is 285±14 mb (Co 51), and for 14.5 Mev neutrons 369±45 mb (Pa 53). See also Am 34, Am 35, Sa 36, Bo 37, Wi 37.

For resonances see S^{33}.

IX. $S^{33}(\gamma,p)P^{32}$ $Q_m=-9.570$

Not observed.

X. $S^{34}(d,\alpha)P^{32}$ $Q_m=5.1$

Radioactive P^{32} has been found from this reaction (Sa 36).

XI. $Cl^{35}(n,\alpha)P^{32}$ $Q_m=0.9$

From bombardment with 3- to 4-Mev neutrons and pulse-height analysis with ionization chambers Q values of 1.07±0.15 Mev (Fo 52) and 0.97±0.16 Mev (Ad 53) are found. The latter supersedes a previously reported value (Me 47).

The cross section rises from about 10 mb at $E_n=3$ Mev to about 65 mb at $E_n=4$ Mev (Ad 53). The cross section at $E_n=14.5$ Mev is 191±30 mb (Pa 53).

See also Am 34, Am 35.

GENERAL REMARKS

The P^{32} ground-state doublet might well consist of the $J=1^+$ and 2^+ states corresponding to the ($s_{\frac{1}{2}}$ proton, $d_{\frac{3}{2}}$ neutron) configuration predicted by the shell model. The differential cross section of the $P^{31}(d,p)P^{32}$ reaction would then be identical ($l_n=2$) for the two components leading to the ground-state doublet, apart from a factor $(2J_f+1)$.

The experimental yield ratio (excited-state protons over ground-state protons) at $\vartheta=90°$ is 1.7 at $E_d=1.8$ Mev and 1.2 at $E_d=2.0$ Mev (Va 52b). This agrees reasonably with a predicted ratio of 1.67 for a ground-state spin $J=1^+$ and an excited-state spin $J=2^+$ (En 53a).

For a theoretical discussion regarding doublet levels in P^{32} see In 53.

S^{32}

Mass defect: -16.590 Mev

I. $Si^{29}(\alpha,n)S^{32}$ $Q_m=-1.529$

Not observed.

II. $P^{31}(p,\gamma)S^{32}$ $Q_m=8.855$

Sharp resonances in the γ-ray yield have been observed at $E_p=440$, 550, 650, 817, 890, 1067, 1100, 1129, 1162, 1265, 1421, 1458, 1495, 1538, 1583, and 1610 kev (Gr 51a). Tangen reports resonances at 355, 440, and

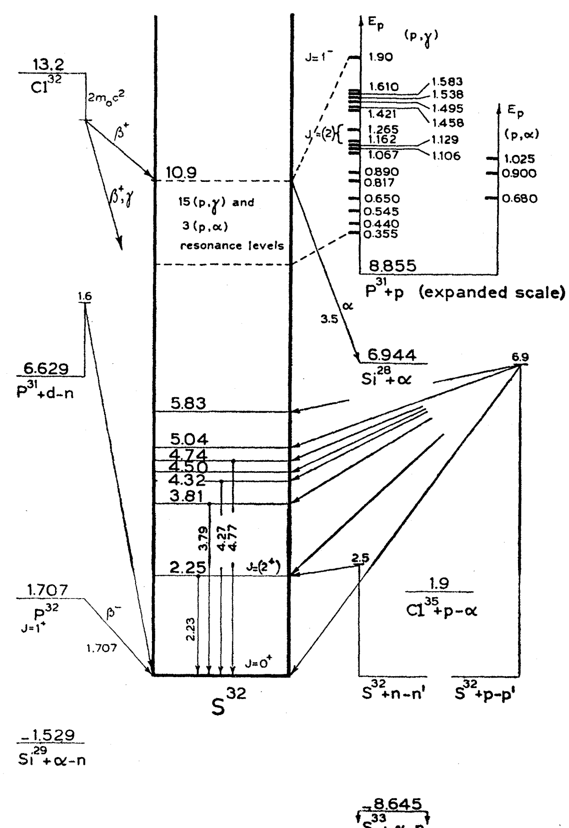

FIG. 22.

540 kev (Ta 46). From relatively thick target measurements resonances are found at 460, 580, 700, and 950 kev (Cu 39). These latter values are probably too high. The region from 1.03 to 2.1 Mev has also been explored by Gove and Paul (Go 53a). Below 1.65 Mev they report the same eleven resonances as found by Grove and Cooper (Gr 51a). There are four more resonances between 1.65 and 2.1 Mev. Gamma-ray angular distributions have been measured at $E_p=1.17$, 1.27, and 1.90 Mev. At the first two resonances there are at least 10 times more transitions to the S^{32} first excited state as to the ground state. If the first S^{32} level is taken as $J=2^+$, the resonance levels at 1.17 and 1.27 Mev have $J=2$. At $E_p=1.90$ Mev at least 7 times more transitions to the ground state than to the first excited state are observed. This resonance level has $J=1^-$ (Go 53a). The γ-ray energy at the 1.27 Mev resonance has been measured by Al absorption as 12 Mev (Gr 51a). See also Ho 41.

III. $P^{31}(p,\alpha)Si^{28}$ $E_b=8.855$ $Q_m=1.911$

Sharp resonances at $E_p=680$, 900, and 1025 kev have been found in the region from 650 to 1070 kev by magnetic analysis of the α particles produced (Fr 51).

See Si^{28} for measurements of the Q value.

IV. $P^{31}(d,n)S^{32}$ $Q_m=6.629$

From bombardments of thick targets at $E_d=1.60$ Mev and detection of neutrons in nuclear emulsions at 0° and 90° a ground-state Q value is reported of 6.2 Mev (error$\geqslant$0.1 Mev) and S^{32} levels at 0.5, 1.5, 2.2, 2.7, 3.3, 3.8, 4.1, 4.5, 4.9, 5.2, and 5.5 Mev, all $\pm$0.1 Mev (Sn 52). At $E_d=8.1$ Mev the ground-state Q value has more accurately been measured as 6.81$\pm$0.08 Mev also by nuclear emulsion technique (El 52).

A γ ray of 6.2$\pm$0.3 Mev has been found by Al absorption from bombardment of phosphorus by 3.7-Mev deuterons (Al 49b). This γ ray may equally well originate from the $P^{31}(d,p)$ or $P^{31}(d,\alpha)$ reaction.

V. $P^{32}(\beta^-)S^{32}$ See P^{32}

VI. $S^{32}(n,n')S^{32}$

From the inelastic scattering of 2.5-Mev neutrons γ rays have been found by Al absorption of $E_\gamma=2.35$ 0.15 Mev (Gr 51, Be 50), and by scintillation spectrometry of $E_\gamma=0.077\pm0.002$ Mev and 2.23$\pm$0.04 Mev (Da 53).

The inelastic scattering cross section at $E_n=2.5$ Mev is 0.38$\pm$0.1 b (Gr 51).

See P^{32} reaction VIII for assignment of the 77 kev γ ray.

VII. $S^{32}(p,p')S^{32}$

From inelastic scattering of 6.9-Mev protons and energy measurement of scattered protons by Al absorption levels in S^{32} are reported at 2.25 and 4.34 Mev (Di 43). At $E_p=8$-Mev levels are found by magnetic analysis at 2.25, 3.81, 4.32, 4.50, 4.74, 5.04, and 5.83 Mev all $\pm$0.02 Mev (Ar 52).

VIII. $S^{33}(\gamma,n)S^{32}$ $Q_m=-8.645$

Not observed.

IX. $Cl^{32}(\beta^+)S^{32}$ See Cl^{32}

X. $Cl^{35}(p,\alpha)S^{32}$ $Q_m=1.9$ Mev

Not observed. See Br 51.

Cl^{32}

(not illustrated)

Adopted mass defect: -3.4 Mev (Gl 53, Br 53c)

I. $Cl^{32}(\beta^+)S^{32}$ $Q_m=13.2$

The half-life has been measured as 0.306$\pm$0.004 sec (Gl 53) and 0.32$\pm$0.01 sec (Br 53c). The maximum positron energy is 9.5$\pm$0.4 Mev, indicating β^+ transitions to the 2.25-Mev level in S^{32}. Gamma-ray energies measured by scintillation spectrometer are collected in Table XXXIX. The 2.77 Mev peak could either be the photopeak of a 2.77-Mev line or the pair peak of a 3.77-Mev γ ray (Ri 53, Gl 53a). The 2.21-Mev and 4.27-Mev γ rays correspond to transitions from known levels in S^{32} to the ground state. In a small percentage, decay to an α-unstable level in S^{32} takes place with $E_\alpha=3.5\pm0.5$ Mev (Ri 53, Gl 53b).

TABLE XXXIX. Gamma rays from $Cl^{32}(\beta^+)S^{32}$.

Author	Gl 53, Ri 53	Br 53c
E_γ in Mev	2.21$\pm$0.03	2.25$\pm$0.04
	2.77 or 3.79	3.79$\pm$0.08
	4.27$\pm$0.08	4.33$\pm$0.09
	4.77$\pm$0.04	4.82$\pm$0.08

II. $S^{32}(p,n)Cl^{32}$ $Q_m=14.0$ Mev

Cl^{32} has been discovered by this reaction and the threshold has been determined [by comparison to the $Mg^{24}(p,n)Al^{24}$ threshold measured by Miss Birge (Bi 52)] as 14.3$\pm$0.5 Mev (Gl 53) and 14.5$\pm$0.6 Mev (Br 53c).

P^{33}

(not illustrated)

Mass defect: -16.606 Mev

I. $P^{33}(\beta^-)S^{33}$ $Q_m=0.265$

The half-life has been determined as: 25$\pm$2 days (Sh 51c), 24.8$\pm$0.5 days (Je 52), and 25$\pm$2 days (We 52). See also Ya 51.

The β^- spectrum end point is measured by spectrometer as 0.27±0.02 Mev (Sh 51c) and 0.26±0.02 Mev (Je 52), and by Al absorption as 0.246±0.005 Mev (We 52). No γ rays have been found (less than 3 percent) (We 52). The β^- transition is allowed (log $ft=5.0$) but l-forbidden.

II. $Si^{30}(\alpha,p)P^{33}$ $Q_m=-2.978$

Not observed.

III. $S^{33}(n,p)P^{33}$ $Q_m=0.517$

The cross section of this reaction for thermal neutrons is 2.3 mb (We 52). See also Je 52.

IV. $S^{34}(\gamma,p)P^{33}$ $Q_m=-10.9$

Radioactive P^{33} has been produced by this reaction (Sh 51c, Je 52).

V. $S^{36}(p,\alpha)P^{33}$ $Q_m=1.3$

Not observed.

VI. $Cl^{35}(\gamma,2p)P^{33}$ $Q_m=-17.2$
$Cl^{37}(\gamma,\alpha)P^{33}$ $Q_m=-\ 7.9$

Radioactive P^{33} has been produced by high-energy γ rays on chlorine (Sh 51c, Je 52, Ho 52a).

S^{33}

Mass defect: −16.871 Mev

I. $Si^{30}(\alpha,n)S^{33}$ $Q_m=-3.495$

Not observed.

II. $P^{33}(\beta^-)S^{33}$ See P^{33}

III. $S^{32}(n,\gamma)S^{33}$ $Q_m=8.645$

The thermal neutron absorption cross section of natural sulfur has been measured by the pile-oscillator method as 0.51±0.03 b (Ha 50), 0.49±0.02 b (Co 50), and 0.47±0.05 b (Po 51). It is unknown how much

TABLE XL. Gamma rays from thermal neutron capture in sulfur (Ki 52, Ki 53e).

γ ray	Energy in Mev	Intensity in photons per 100 captures
A	8.64±0.02	1.2
B	7.78±0.03	1.6
C	7.42±0.03	(0.7)
D	7.19±0.03	(0.5)
E	6.64±0.03	0.25
F	5.97±0.06	(1)
G	5.43±0.02	60
H	5.03±0.06	(5)
I	4.84±0.06	11
J	4.60±0.06	(5)
K	4.38±0.03	7
L	3.69±0.05	4
M	3.36±0.05	7
N	3.21±0.03	20
O	2.94±0.05	20

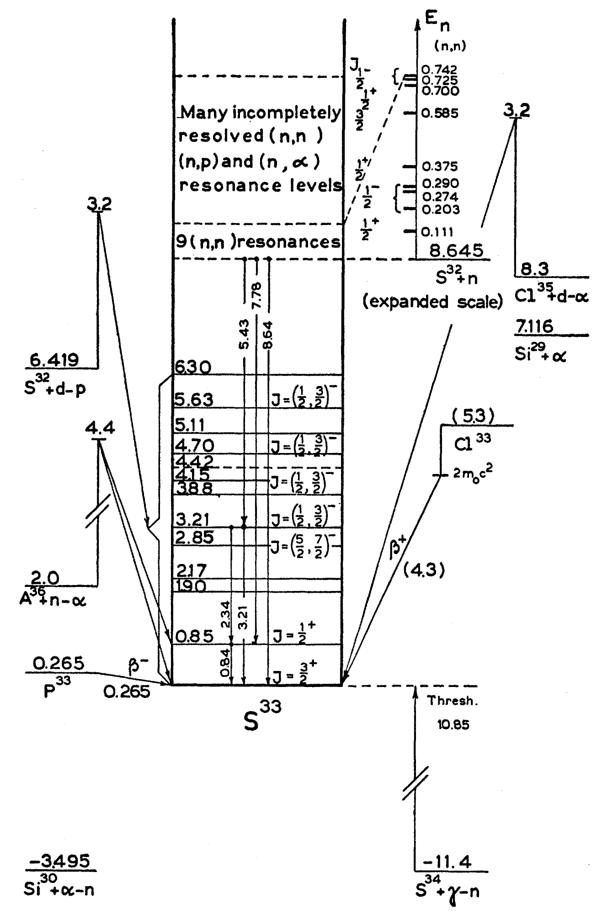

FIG. 23.

the $S^{32}(n,\alpha)Si^{29}$ reaction contributes to the cross section. The contribution of the $S^{34}(n,\gamma)S^{35}$ reaction is 0.011 ±0.002 b (Se 47). See also Vo 43, Co 46a.

Fifteen γ rays have been found by pair spectrometer from the capture of thermal neutrons in natural sulfur (Ki 52, Ki 53e). They are given in Table XL. The intensities are taken from Ki 53e, but those between brackets are from Ki 52. Gamma rays A and B probably represent transitions to the ground state and first excited state of S^{33} and γ rays G and N correspond to a cascade to ground through the level at 3.21 Mev. The identification of the other γ rays is less certain. Gamma rays K, L, and O may be the transitions from the capturing state to the other p states at 4.15, 4.70, and 5.63 Mev (Ki 53e).

Thermal neutron capture γ rays of $E_\gamma=0.84$, 1.52, and 2.34 Mev have been observed with a scintillation spectrometer (Br 53a). The first γ ray corresponds to the de-excitation of the 0.84 Mev level in S^{33}. From the fact that the energies of the first two γ rays add up pretty nearly to that of the third, one would be inclined to assume a S^{33} level at 2.34 Mev, but no such level has been observed from the $S^{32}(d,p)S^{33}$ reaction. A more probable explanation for the 2.34-Mev γ ray is a transition from the strongly excited level at 3.19 Mev to the first level at 0.84 Mev. The 1.52-Mev γ ray then remains unexplained. See also Ku 49.

IV. $S^{32}(n,n)S^{32}$ $E_b=8.645$

Measurements of the sulfur total neutron cross section have been reviewed by Adair (Ad 50). The cross section decreases slowly from 1.6 b at $E_n=0.02$ ev to 1.1 b at $E_n=300$ ev (Ra 48). Below $E_n=750$ kev sharp well-separated resonances are found at 111, 203, 274, 290, 375, 585, 700, 725, and 742 kev. The width of the 111-kev resonance is 18 kev ($J=\frac{1}{2}^+$), of the 375- and 700-kev resonances $\Gamma=12\pm1.5$ kev ($J=\frac{1}{2}^+$), and of the 585-kev resonance $\Gamma=1.5$ kev ($J=\frac{3}{2}$). All other resonances have $J=\frac{1}{2}^-$ (while $J=\frac{3}{2}^-$ is not excluded). Six more sharp resonances are observed in the region from $E_n=750$ to 1100 kev, while from 1100 to 1450 kev the energy resolution (from 9 to 15 kev) was not sufficient to separate the many resonances completely (Ad 49a, Pe 50a). Also in the region from 1.5 to 12 Mev many incompletely resolved resonances were found (Fr 50, Ri 51, Ne 53, St 51d). At $E_n=14$ Mev the cross section amounts to 1.92±0 04 b (Co 52a), while 2.06±0.07 b is found at $\bar{E}_n=13.3$ Mev (Li(d,n) neutrons) (Ag 52, Ag 53).

V. $S^{32}(n,p)P^{32}$ $E_b=8.645$ $Q_m=-0.925$

The cross section increases monotonically from $E_n=1.6$ to 4.0 Mev and is constant (0.3 b) from $E_n=4.0$ to 5.8 Mev (Kl 48). At somewhat better resolution many incompletely resolved resonances are found in the region from $E_n=1.9$ to 3.7 Mev (Wi 37, Bl 47b, Lu 50, Ri 51). See also P^{32}.

VI. $S^{32}(n,\alpha)Si^{29}$ $E_b=8.645$ $Q_m=1.529$

Resonances are reported at 1.77±0.12 and 2.12±0.12 Mev (St 48). See also Wi 37. See Si^{29} for a measurement of the Q value.

TABLE XLI. Levels in S^{33} from $S^{32}(d,p)S^{33}$.

Author	Sm 41	Da 49	Ho 53d	
E_d (Mev)	3.1	3.22	8.0	
Ground-state Q value (Mev)	6.62	6.48±0.11	...	
S^{33} levels (Mev)	0	0	0	$J=(3/2, 5/2)^+$
	1.05	0.79±0.05	0.85	$J=1/2^+$
		1.90±0.05	[a]	
	2.17	2.17±0.05	[a]	
		2.85±0.05	2.90	$J=(5/2, 7/2)^-$
	3.22	3.15±0.05	3.26	$J=(1/2, 3/2)^-$
		3.88±0.05	[a]	
	4.33	4.15±0.05	4.21	$J=(1/2, 3/2)^-$
		4.42±0.05	...	
		4.70±0.05	4.89	$J=(1/2, 3/2)^-$
	5.32	5.11±0.05	[a]	
		5.63±0.05	5.72	$J=(1/2, 3/2)^-$
		6.30±0.05	[a]	

[a] A group leading to this level was present but the Q value has not been determined.

VII. $S^{32}(d,p)S^{33}$ $Q_m=6.419$

The ground-state Q value has been measured by high-resolution magnetic analysis at $E_d=1.8$ Mev as $Q=6.422$ ±0.011 Mev (St 51). Other values for the ground-state reaction energy and S^{33} levels found by range analysis at different deuteron energies are collected in Table XLI. The assignment of the ground-state group is confirmed by the absence of $p-\gamma$ coincidences (Da 49). Spins and parities of S^{33} levels determined from angular distribution measurements and Butler analysis are also given in Table XLI. Shell model assignments have been discussed on the basis of l_n values and measured neutron capture probabilities (Ho 53a, Ho 53d). Angular distribution measurements of proton groups leading to ground state and first excited state have also been performed at $E_d=14.3$ Mev with the same results as given in Table XLI (Bl 53).

VIII. $S^{34}(\gamma,n)S^{33}$ $Q_m=-11.4$

The threshold for this reaction has been measured as 10.85±0.20 Mev (Sh 51a).

The excitation curve is found by subtracting the $S^{32}(\gamma,n)S^{31}$ yield, measured by the S^{31} activity, from the total photoneutron yield, measured by a BF_3 chamber. The values obtained, although subject to large errors, are a maximum cross section of 60 mb at 17 Mev and a half width of 4 Mev and an integrated cross section of 200 Mev mb (Mo 53a).

IX. $Cl^{33}(\beta^+)S^{33}$ See Cl^{33}

X. $Cl^{35}(d,\alpha)S^{33}$ $Q_m=8.3$

An α-particle group from this reaction may have been observed at $E_d=3.2$ Mev. The Q value measured by range analysis is 9.1 Mev (Sh 41).

XI. $A^{36}(n,\alpha)S^{33}$ $Q_m=2.0$

Pulse-height analysis from an argon-filled ionization chamber yields a ground-state Q value of 2.0±0.1 Mev. A second α-particle group is observed corresponding to a Q value of 0.9±0.1 Mev. The excitation curve for these two transitions has been measured from $E_n=2.15$ to 4.40 Mev (To 53). The ground-state group was also observed at $E_n=2.5$ Mev, although it was ascribed to the reaction $A^{40}(n,\alpha)S^{37}$. The measured Q value is 1.8 Mev and the cross section 30 mb (Gr 46).

Cl^{33}

Adopted mass defect: −11.5 Mev

(The adopted mass defect has been calculated from the observed $S^{32}(d,n)Cl^{33}$ Q value. It is in reasonable agreement with the measured Cl^{33} positron decay energy.)

I. $Cl^{33}(\beta^+)S^{33}$ $Q_m=5.4$

The half-life measurements are 2.8 sec (Ho 40b) and 2.8 sec (Sc 48). Other determinations, 2.4±0.2 sec

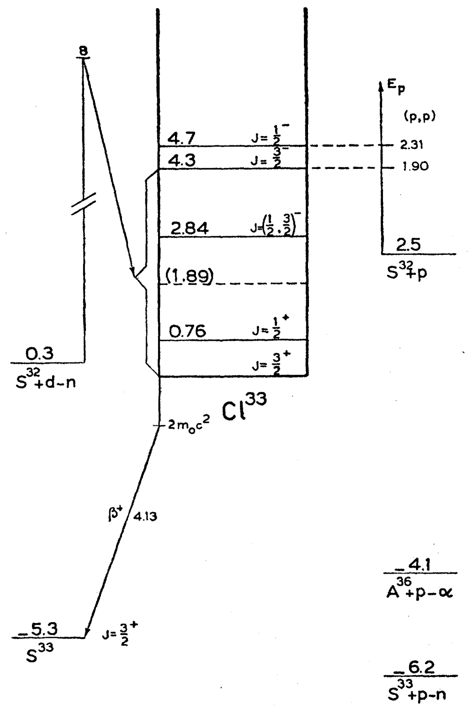

FIG. 24.

(Wh 41) and 1.8±0.1 sec (Bo 51), have to be doubted as probably a mixture of Cl^{33} and Cl^{34} has been studied (St 53).

Possible confusion with the short-lived Cl^{34} also sheds doubt on the measurement of the beta spectrum endpoint: 4.13±0.07 Mev with a cloud chamber (Wh 41) and 4.43±0.13 Mev (Bo 51) and 4.2±0.2 Mev (Na 53) with a scintillation spectrometer. A γ ray of 2.9 Mev is observed in the decay, indicating β^+ transitions to the 2.85 Mev level in S^{33}, with an intensity of 0.3 percent of the ground-state transition (Me 53a). The log ft value of 4.0 suggests even parity for the 2.85 Mev level in contradiction with the results from the $S^{32}(d,p)S^{33}$ reaction.

II. $S^{32}(p,\gamma)Cl^{33}$ $Q_m=2.5$

Not observed. See Ta 46.

III. $S^{32}(p,p)S^{32}$ $E_b=2.5$

With protons of 1.0 Mev$<E_p<$2.8 Mev from an electrostatic generator and a H_2S gas target resonances in the elastic scattering cross section have been observed at $E_p=1.90$ Mev (width <25 kev) and at 2.31 Mev (width ~60 kev). The angular distribution of the scattered protons measured from 50° to 150° indicates that both levels have a negative parity, the 4.3 Mev level a spin $\frac{3}{2}$ and the 4.7 Mev level a spin $\frac{1}{2}$. Above 2.31 Mev and under 1.90 Mev the angular distribution complies with Coulomb scattering (Fe 53).

IV. $S^{33}(p,n)Cl^{33}$ $Q_m=-6.2$

Radioactive Cl^{33} has been produced by this reaction (Wh 41).

V. $S^{32}(d,n)Cl^{33}$ $Q_m=0.3$

Several neutron groups have been observed with nuclear emulsions at $E_d=8$ Mev. The ground-state Q value is 0.25 Mev, and levels are found at $E_x=0.76$ ±0.07, (1.89), 2.84±0.06 and 4.22±0.08 Mev. Several more closely spaced levels are found above 4.22 Mev. From angular distribution measurements and Butler analysis the Cl^{33} ground state can be characterized as $J=(\frac{3}{2},5/2)^+$ $(l_n=2)$, the level at 0.76 Mev as $J=\frac{1}{2}^+$ $(l_n=0)$, while the levels at 2.84 and 4.22 Mev check best with $J=(\frac{1}{2},\frac{3}{2})^-$ $(l_n=1)$ (Mi 53b).

See also Ho 40b, Sc 48, Hu 51.

VI. $Cl^{35}(\gamma,2n)Cl^{33}$ $Q_m=-23.9$

Radioactive Cl^{33} has been produced by the irradiation of NH_4Cl with 70-Mev x-rays (Bo 51).

VII. $A^{36}(p,\alpha)Cl^{33}$ $Q_m=-4.1$

Not observed.

P^{34}

(not illustrated)

Adopted mass defect: −14.8 Mev (Bl 46)

I. $P^{34}(\beta^-)S^{34}$ $Q_m=5.1$

The half-life has been given as 12.7 sec (Co 40), 14.5±1 sec (Hu 45) and 12.40±0.12 sec (Bl 46).

The β^- decay proceeds in two branches. The main branch (75 percent) has an end point measured by Al absorption as 5.1±0.2 Mev, the other branch (25 percent) is in coincidence with γ rays and has an end point of 3.2±0.2 Mev (Bl 46).

The ground-state transition is allowed but l-forbidden (log $ft=5.2$), while the 3.2 transition is allowed (log $ft=4.7$).

The spin and parity of P^{34} are very probably $J=1^+$ (see S^{34} "General Remarks").

II. $P^{33}(n,\gamma)P^{34}$ $Q_m=6.6$

Carrier-free radioactive phosphorus obtained by pile-neutron irradiation of sulfur contains about 2.5 atoms P^{33} per 100 atoms P^{32} (Je 52). If this mixture is again irradiated in a pile a 22±5 sec activity is observed (Ya 51) which may be P^{34} (Je 52).

III. $S^{34}(n,p)P^{34}$ $Q_m=-4.3$

Radioactive P^{34} is produced by fast neutrons on sulfur (Co 40, Bl 46). The cross section at $E_n=14.5$ Mev is 85±40 mb (Pa 53).

IV. $S^{36}(d,\alpha)P^{34}$ $Q_m=5.6$

Not observed.

V. $Cl^{37}(n,\alpha)P^{34}$ $Q_m = -1.3$

Radioactive P^{34} is produced by fast neutrons on chlorine (Hu 45, Bl 46). See also Hu 42a. The cross section at $E_n = 14.5$ Mev is 52 ± 26 mb (Pa 53).

S^{34}

Adopted mass defect: -19.9 Mev (see Introduction)

I. $P^{31}(\alpha,p)S^{34}$ $Q_m = 0.6$

From bombardments with α particles from natural radioactive sources average Q values are obtained of 0.31, -1.0, -2.5, and -4.5 Mev corresponding to S^{34} levels at 1.3, 2.8, and 4.8 Mev (Li 37, Ch 31, Pa 34, Ma 36, Po 36a). In later work Q values were found of 1.3 Mev (very weak and dubious proton group), 0.4, and -1.2 Mev (Me 40).

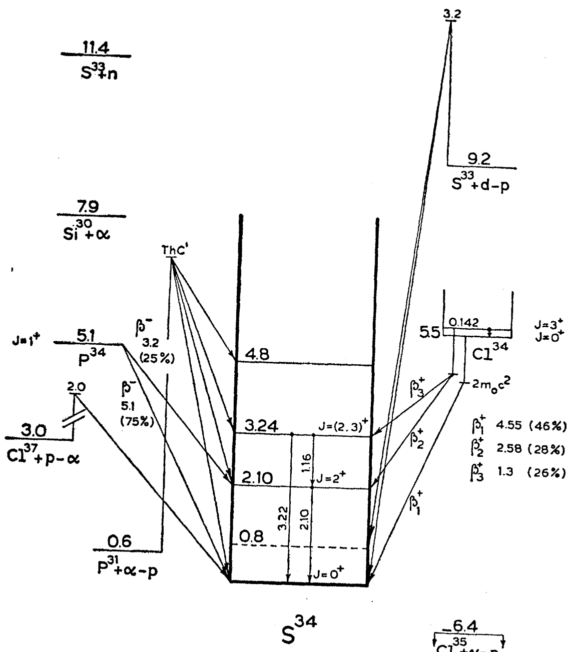

FIG. 25.

Two γ rays were observed from bombardment of phosphorus with 7-Mev α particles. Their energies were $E_\gamma = 2.55\pm0.25$ and 4.1 ± 0.4 Mev as measured by Al absorption (Al 48a). The assignment to the $P^{31}(\alpha,p)S^{34}$ reaction is not unambiguous.

II. $P^{34}(\beta^-)S^{34}$ See P^{34}

III. $S^{33}(n,\gamma)S^{34}$ $Q_m = 11.4$

Not observed.

IV. $S^{33}(d,p)S^{34}$ $Q_m = 9.2$

From bombardments of natural sulfur at $E_d = 3.22$ Mev two weak proton groups were observed which were ascribed to $S^{33}(d,p)S^{34}$. The Q values determined by range analysis are 8.67 ± 0.25 and 7.85 ± 0.25 Mev corresponding to a S^{34} level at 0.82 Mev (Da 49). This level is not found from other reactions and its excitation energy is rather small for a light even-even nucleus.

V. $Cl^{34}(\beta^+)S^{34}$ See Cl^{34}

VI. $Cl^{35}(\gamma,p)S^{34}$ $Q_m = -6.4$

Not observed.

VII. $Cl^{37}(p,\alpha)S^{34}$ $Q_m = 3.0$

Alpha particles are observed from targets enriched in Cl^{37} bombarded by $1.45-2.04$ Mev protons. From proportional counter pulse-height analysis after magnetic deflection a Q value of 3.2 Mev is derived (Br 51).

See A^{38} for resonances.

GENERAL REMARKS

The spins and parities of the P^{34} ground state ($J = 1^+$) and of the S^{34} 2.10-Mev level ($J = 2^+$) are determined uniquely from the fact that the $P^{34}(\beta^-)$ transitions to the S^{34} ground state ($J = 0^+$) and 2.10 Mev level are both allowed, while the β^+ decay from Cl^{34m} ($J = 3^+$) to the 2.10-Mev level is also allowed.

Cl^{34}

(not illustrated)

Adopted mass defect: -14.3 Mev

(The adopted mass defect is based on the S^{34} mass and the $Cl^{34}(\beta^+)S^{34}$ energy release.)

I. $Cl^{34}(\beta^+)S^{34}$ $Q_m = 5.6$

The half-life is 1.58 ± 0.05 sec (St 53b). The half-life of the isomeric state at 142 kev is considerably longer. The more precise determinations are 32 ± 1 min (Ri 37), 33.2 ± 0.5 min (Hu 43), 33.0 min (Pe 48), and 32.5 ± 0.5 min (Hi 52a). See also Fr 34, Po 37a, Br 38, Bo 39, Ed 52.

The energies of the positrons and γ rays present in the decay of Cl^{34} and its isomeric state are listed in Table XLII. Ticho (Ti 51) used in turn a three-, two- and one-crystal scintillation spectrometer in order to

TABLE XLII. The decay of Cl^{34}.

Author: Method:	Ho 46a Cloud chamber	Ru 51a Magnetic lens spectrometer	Ti 51 Scintillation spectrometer
E_{β^+} (max) (Mev)	5.1 ± 0.3 2.4	4.45 ± 0.11 (46%) 2.58 ± 0.26 (28%) $1.3\ \pm0.2$ (26%)	
E_γ (Mev)	3.4 ± 0.3	3.30 ± 0.14 2.13 ± 0.12 0.142 ± 0.003	3.22 ± 0.03 2.10 ± 0.03 1.16 ± 0.03

discriminate between photo-, pair-, and Compton-peaks in his pulse spectrum. See also Sa 36, Bl 46c.

The isomeric state decays in about equal numbers by β^+ emission to excited levels in S^{34} and by γ transitions to the Cl^{34} ground state. It has been shown by means of the Szilard-Chalmers process that Cl^{34} is a daughter of Cl^{34m} (Ar 53a). The conversion coefficient of the 142 kev γ ray (14 percent$\pm$4 percent) indicates it to be $M3$ radiation. According to its log ft value of 3.5, the 4.45 Mev β^+ decay is a super-allowed transition and determines the ground state of Cl^{34} as 0^+.

The β^+ transitions from Cl^{34m} to the S^{34} levels at 2.1 and 3.2 Mev are allowed (log ft=5.8, *viz.*, 4.5). The isomeric state is then 3^+ (Ar 53, St 53, St 53c). Peaslee concludes that the isotopic spin of the ground state is $T=1$ and of the 142 kev level is $T=0$ (Pe 53).

For theoretical discussions of the Cl^{34} ground state see Ku 53, De 53a.

II. $P^{31}(\alpha,n)Cl^{34}$ $Q_m=-5.8$

Radioactive Cl^{34} has been produced from this reaction by α particles from natural radioactive elements (Fr 34, Br 38) and from a 9-Mev cyclotron (Ri 37). No resonances are found.

III. $S^{32}(\alpha,d)Cl^{34}$ $Q_m=-12.4$

This has been the first example of an (α,d) reaction (at $E_\alpha=22$ Mev), although the (α,pn) reaction has not been excluded. The product nucleus was chemically determined as chlorine and an absorption curve of the positrons identified it as Cl^{34} (Sh 40).

IV. $S^{33}(p,\gamma)Cl^{34}$ $Q_m=5.0$

Not observed.

V. $S^{33}(d,n)Cl^{34}$ $Q_m=2.8$

Cl^{34} has been produced by this reaction (Sa 36, Ho 46).

VI. $S^{34}(p,n)Cl^{34}$ $Q_m=-6.5$

Radioactive Cl^{34} has been produced from this reaction, and the excitation curve has been measured to 100 Mev (Hi 52a).

VII. $Cl^{35}(\gamma,n)Cl^{34}$ $Q_m=-12.8$

The cross section at $E_\gamma=17.6$ Mev is 4.4$\pm$1 mb (Wa 48). The integrated cross section is 58 Mev mb (Ed 52). See also Bo 39, Hu 43, Pe 48, Mc 50.

The (γ,n) threshold (9.95$\pm$0.20 Mev) observed in the bombardment of natural chlorine (Sh 51a) should be assigned to $Cl^{37}(\gamma,n)Cl^{36}$.

VIII. $Cl^{35}(p,pn)Cl^{34}$ $Q_m=-12.8$

Cl^{34} has been produced in the bombardment of NaCl with 18-Mev protons (Ru 51a, Ti 51).

IX. $Cl^{35}(n,2n)Cl^{34}$ $Q_m=-12.8$

The bombardment of chlorine with neutrons from Li+d yields Cl^{34} (Po 37a). The cross section at $E_n=14.5$ Mev is 3.5$\pm$1.5 mb (Pa 53).

S^{35}

(not illustrated)

Adopted mass defect: -18.5 Mev

(The mass of S^{35} is very accurately connected to the Cl^{35} mass by means of the β^- spectrum end point.)

I. $S^{35}(\beta^-)Cl^{35}$ $Q_m=0.2$

The half-life has been given as 80$\pm$10 days (An 36), 88$\pm$5 days (Le 40), 88$\pm$3 days (Ka 41), and 87.1$\pm$1.2 days (He 43). Determinations of the β^- spectrum end point are collected in Table XLIII. The Kurie plot is

TABLE XLIII. End point of S^{35} β^- spectrum.

Author	Method	Endpoint (kev)
Li 39	screen-wall counter	107 $\pm$20
Ka 41	Al absorbers	120 $\pm$15
So 47	Al absorbers	167 $\pm$ 4
Ya 48	Al absorbers	169 $\pm$ 5
Al 48c	magn. spectrom.	166
Be 48b	magn. spectrom.	169 $\pm$ 3
Co 48	magn. spectrom.	169.1$\pm$ 0.5
Co 49	prop. counter	168
Gr 50b	electrostat. spectrom.	168.3$\pm$ 4
La 50	magn. spectrom.	167.0$\pm$ 0.5

straight down to the point where source thickness distorts the spectrum (Al 48c, Be 48b, Co 48, La 50, Gr 50b, He 51, Mi 53a) although recent measurements in a diffusion cloud chamber indicate a low-energy cut-off at 10 kev (Pl 53). See also Wu 50.

The log ft value is 5.0. A spin $y=\frac{3}{2}$ for S^{35} is found from microwave experiments (We 51a).

II. $S^{34}(n,\gamma)S^{35}$ $Q_m=7.0$

The thermal neutron capture cross section has been measured by the S^{35} activity produced as 0.26$\pm$0.05 b (Se 47).

III. $S^{34}(d,p)S^{35}$ $Q_m=4.8$

Radioactive S^{35} has been produced from this reaction (Ka 41).

IV. $S^{36}(\gamma,n)S^{35}$ $Q_m=-9.2$

Not observed.

V. $Cl^{35}(n,p)S^{35}$ $Q_m=0.6$

The thermal neutron cross section has been measured by the S^{35} activity produced as 0.169$\pm$0.034 b (Se 47) and as 0.29$\pm$0.07 b (Ma 49a).

The Q value has been determined from ionization-chamber pulse-height analysis both with thermal and with $D(d,n)$ neutrons as 0.52 ± 0.04 Mev (Gi 44).

See also An 36, Le 40, Ka 41, On 41a, Ka 42.

VI. $Cl^{37}(d,\alpha)S^{35}$ $Q_m=7.7$

Radioactive S^{35} has been produced from this reaction at $E_d=14$ Mev (Ka 41).

VII. $A^{38}(n,\alpha)S^{35}$ $Q_m=-0.2$

Not observed.

Cl^{35}

Adopted mass defect: -18.7 Mev (see Introduction)

I. $S^{32}(\alpha,p)Cl^{35}$ $Q_m=-1.8$

With α particles from natural radioactive elements three proton groups are observed with Q values -2.10, -2.7, and -3.6 Mev, indicating levels at 0.6 and 1.5 Mev (Li 37, Ha 35, Br 36). A more recent determination of the ground-state Q value is -2.02 ± 0.11 Mev (Fo 52). With 7 Mev α particles from a cyclotron, a γ ray of $E_\gamma=2.4\pm0.3$ Mev is observed by an Al absorption method (Al 48a), which might also result from $S^{32}(\alpha,\alpha')S^{32}$.

II. $S^{34}(p,\gamma)Cl^{35}$ $Q_m=6.4$

With 1 percent energy resolution, resonances are found in the bombardment of sulfur with protons of 0.9 Mev$<E_p<$1.9 Mev at $E_p=1.37$, 1.61, 1.69, 1.8, and 1.86 Mev. As the target shows no radioactivity these resonances are attributed to S^{34}, but in view of the short half-life of Cl^{33} capture in S^{32} should not be excluded (Ha 51c).

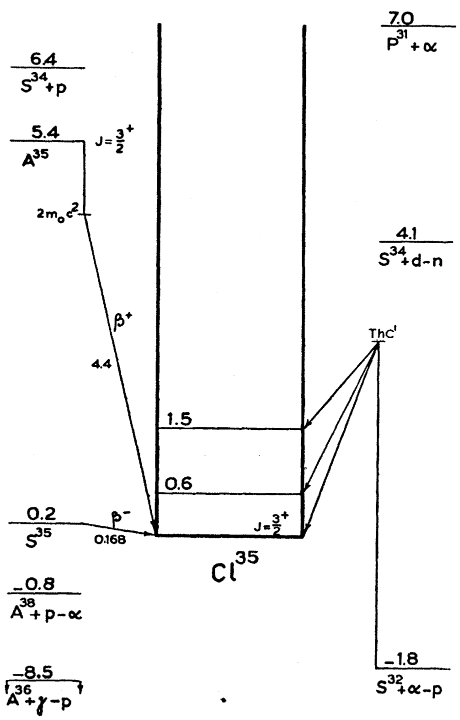

FIG. 26.

III. $S^{34}(d,n)Cl^{35}$ $Q_m=4.1$

Not observed.

IV. $S^{35}(\beta^-)Cl^{35}$ See S^{35}

V. $A^{35}(\beta^+)Cl^{35}$ See A^{35}

VI. $A^{36}(\gamma,p)Cl^{35}$ $Q_m=-8.5$

Not observed.

VII. $A^{38}(p,\alpha)Cl^{35}$ $Q_m=-0.8$

Not observed.

A^{35}

(not illustrated)

Adopted mass defect: -13.3 Mev (Wh 41, El 41)

I. $A^{35}(\beta^+)Cl^{35}$ $Q_m=5.4$

The half-life is given as 2.2 ± 0.2 sec (Wh 41), 1.88 ±0.04 sec (El 41), and 1.84 sec (Sc 48). The β^+ spectrum end point is measured by cloud chamber as 4.38 ±0.07 Mev (Wh 41) and 4.41 ± 0.09 Mev (El 41). The log ft value is 3.5, the usual value for super-allowed transitions between mirror nuclei.

II. $S^{32}(\alpha,n)A^{35}$ $Q_m=-8.1$

Radioactive A^{35} has been found from this reaction (El 41, Sc 48).

III. $Cl^{35}(p,n)A^{35}$ $Q_m=-6.2$

Radioactive A^{35} has been found from this reaction (Wh 41).

IV. $A^{36}(\gamma,n)A^{35}$ $Q_m=-14.7$

Not observed.

S^{36}

(not illustrated)

Adopted mass defect: -19.3 Mev

(The adopted mass defect is based on microwave determinations of the $S^{36}-S^{34}$ mass difference (Lo 49).)

I. $Cl^{37}(\gamma,p)S^{36}$ $Q_m=-9.2$

Not observed.

II. $A^{40}(\gamma,\alpha)S^{36}$ $Q_m=-7.6$

Alpha particles from this reaction have perhaps been observed as a background of large pulses from an argon-filled ionization-chamber bombarded by 17.6-Mev γ rays (Wi 51).

Cl^{36}

Adopted mass defect: −18.9 Mev

(The adopted mass defect is based on the mass of A^{36} and the end point of the $Cl^{36}(\beta^-)A^{36}$ spectrum.)

I. $Cl^{36}(\beta^-)A^{36}$ $Q_m=0.7$

The half-life has been reported as about 10^6 yr (Ov 47a) and $(0.44\pm0.05)\times10^{-6}$ yr (Wu 49). The latter value has been obtained by measuring the absolute decay rate from a NaCl sample, of which the isotopic concentration of Cl^{36} was determined by microwave spectrometry of ClCN. See also On 41a.

The end point of the β^- spectrum is 0.714 ± 0.005 Mev (Fe 52, Wu 49). See also Gr 41, Ov 47a. The shape of the beta spectrum has been investigated extensively with thin sources and is consistent with a $\Delta J=2$, no, transition (Wu 50, Fu 51, Fe 52). The log ft value is 13.4. The number of positrons is less than 10^{-4} times the number of electrons (Wu 49, Jo 49), and no γ rays are present with energy $E_\gamma>20$ kev and an intensity of more than 5 percent (Wu 49).

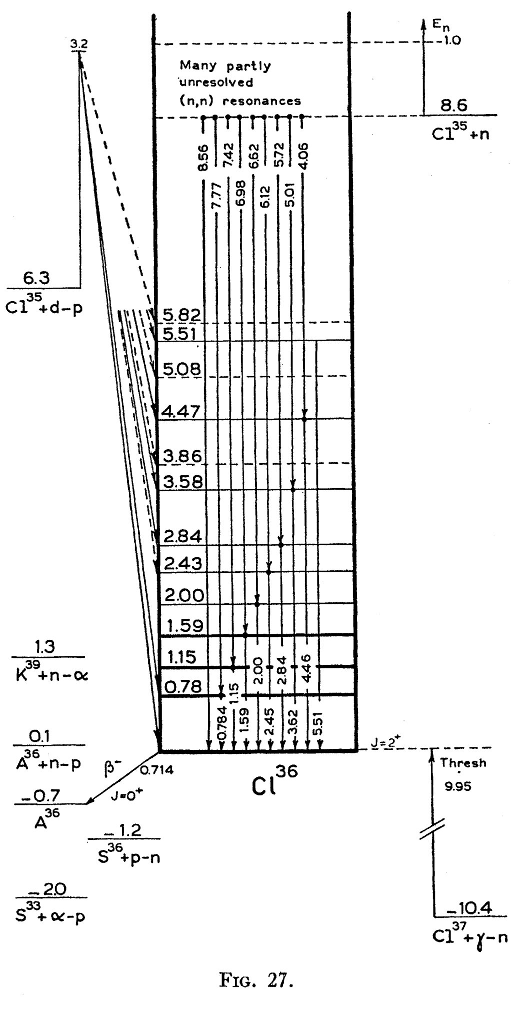

FIG. 27.

TABLE XLIV. Gamma rays from thermal neutron capture in chlorine.

Author	Ki 52		Ha 52b	Re 53		Br 53a
Method	Pair spectrometer		Scintillation spectrometer	Two-crystal scintillation spectrometer		Two-crystal scintillation spectrometer
Line	Energy in Mev	Intensity per 100 captures	Energy in Mev	Energy in Mev	Rel. int.	Energy in Mev
A	8.56±0.03	3				
B	7.77±0.03	10	7.7±0.2			
C	7.42±0.03	8				
D	6.98±0.03	1				
E	6.62±0.06	4				
F	6.12±0.03	6	6.2±0.2			
G	5.72±0.03	2				
H	5.51±0.03	1				
I	5.01±0.03	4				
J	4.46±0.04	2		4.67±0.10		
K	4.06±0.04	3				
L	3.62±0.05	2		3.71±0.10	(23)	
				2.68±0.10	(10)	2.84
				2.40±0.10	(14)	2.45
			2.00 ±0.025	2.03±0.10		
			1.59 ±0.013	1.77±0.10	(19)	
			1.15 ±0.010	1.12±0.10	(29)	1.14
			0.784±0.010	0.70±0.10	(35)	0.75
						0.48

A spin $J=2$ is obtained for Cl^{36} by microwave experiments (To 49, Jo 51, Gi 52a).

For theoretical discussions of the Cl^{36} ground state see Ku 53, De 53a.

In principle the decay Cl^{36}(E.C.)S^{36} with $Q_m=0.4$ Mev is also possible, but this has not been observed.

II. $S^{33}(\alpha,p)Cl^{36}$ $Q_m=-2.0$

Not observed.

III. $S^{36}(p,n)Cl^{36}$ $Q_m=-1.2$

Not observed.

IV. $Cl^{35}(n,\gamma)Cl^{36}$ $Q_m=8.6$

The thermal neutron absorption cross section of natural chlorine is 31.3 ± 0.8 b (Co 50), 31.5 ± 1.6 b (Hu 50), and 32.7 ± 1.6 b (Po 51) as measured by the pile oscillator method. See also La 40, Vo 43, Co 46a. As the Cl^{37} capture cross section is small, this large cross section is mainly due to Cl^{35}.

The γ rays resulting from thermal neutron capture have been extensively investigated by several authors. See Table XLIV and also Ra 35, Ku 49, Mi 50a, Ha 50b. The 8.56-Mev line corresponds to the ground-state transition. Besides the 0.48-Mev line, all other lines can be explained by cascades from the capturing state through one excited state to the ground state. The average Q value of this reaction is 8.57 ± 0.03 Mev (Ha 52b).

V. $Cl^{35}(n,n)Cl^{35}$ $E_b=8.6$

The data on the total neutron cross section of natural chlorine up to $E_n=400$ ev are given by Adair (Ad 50).

In the region from $E_n=0.15$ to 1 Mev resonances are found by use of Li(p,n) neutrons with an average level distance of 14 kev. The average cross section in this region is 2.5 b (Ki 53c). See also Sn 53. In the energy range from 2.2 to 2.85 Mev the cross section is between 2.66 and 2.84 b (Ao 39) or about 3 b (Dv 53). At $E_n=2.85$ Mev $\sigma=3.42\pm0.16$ b has been found (Zi 39) and $\sigma=2.00\pm0.05$ b at 14 Mev (Co 52a).

VI. $Cl^{35}(d,p)Cl^{36}$ $Q_m=6.3$

Q values from bombardment of enriched targets with 3.2-Mev deuterons are 6.31, 5.35, and 1.50 Mev, corresponding to the ground-state transition and transitions to levels at 0.96 and 4.81 Mev (Sh 41). With natural chlorine targets 10 proton groups are observed with $Q=6.26$, 3.94, 3.46, 3.03, 2.76, 2.40, 1.84, 1.18, 0.69, and 0.44 Mev. The 6.26-Mev Q value is the ground-state transition in $Cl^{35}(d,p)Cl^{37}$ (En 51b). The 3.94- and 3.03-Mev Q values have probably to be assigned to $Cl^{37}(d,p)Cl^{38}$ according to the results of Shrader and Pollard. See also Po 40a.

The angular distribution of the ground-state proton group has been measured with nuclear emulsions at $E_d=6.90$ Mev and 7.8 Mev. Butler analysis yields $l_n=2$ in both cases, with less than 4 percent admixture of $l_n=0$ (Ki 52a, Ki 53b).

VII. $Cl^{37}(\gamma,n)Cl^{36}$ $Q_m=-10.4$

The photoneutron threshold of natural chlorine is 9.95 ± 0.20 Mev (Sh 51a). This value should be assigned to the Cl^{37} isotope, as the calculated threshold of $Cl^{35}(\gamma,n)Cl^{34}$ is considerably higher (-12.9 Mev).

VIII. $A^{36}(n,p)Cl^{36}$ $Q_m=0.1$

Not observed.

IX. $K^{39}(n,\alpha)Cl^{36}$ $Q_m=1.3$

Not observed.

A^{36}

(not illustrated)

Adopted mass defect: -19.6 Mev (see Introduction)

I. $S^{33}(\alpha,n)A^{36}$ $Q_m=-2.0$

Not observed.

II. $Cl^{35}(p,\gamma)A^{36}$ $Q_m=8.5$

Eighty-six sharp resonances in the γ-ray yield from targets containing natural chlorine were found for proton energies between 500 and 2150 kev. From targets enriched in Cl^{35} resonances were observed at 858, 888, 1102, 1258, 1484, and 1510 kev (Br 51). See also Cu 39, Ta 46.

III. $Cl^{35}(d,n)A^{36}$ $Q_m=6.3$

Not observed.

IV. $Cl^{36}(\beta^-)A^{36}$ See Cl^{36}

V. $K^{39}(p,\alpha)A^{36}$ $Q_m=2.0$

Not observed.

S^{37}

(not illustrated)

Adopted mass defect: -16.6 Mev (Bl 46)

(The mass of S^{37} is connected to the Cl^{37} mass through the end point of the β^- spectrum.)

I. $S^{37}(\beta^-)Cl^{37}$ $Q_m=4.3$

The half-life is 5.04 ± 0.02 min. The β^- spectrum has been measured by Al absorption. It consists of two components with the following endpoints and relative intensities: 4.3 ± 0.3 Mev (10 percent) and 1.6 ± 0.1 Mev (90 percent). The second component is in coincidence with a 2.7 ± 0.2 Mev γ ray (Bl 46). The β^-ground state transition is evidently forbidden [$\log ft=7.0$ and $\log(W_0^2-1)\ ft=9.0$] while the transition to the 2.7-Mev level in Cl^{37} is allowed ($\log ft=4.2$).

II. $S^{36}(n,\gamma)S^{37}$ $Q_m=5.7$

The thermal neutron activation cross section is 0.14 ± 0.04 b (Hu 52).

III. $S^{36}(d,p)S^{37}$ $Q_m=3.4$

Not observed.

IV. $Cl^{37}(n,p)S^{37}$ $Q_m=-3.5$

The S^{37} activity is produced by fast neutrons on chlorine (Bl 46). The cross section at $E_n=14.5$ Mev is 33 ± 7 mb (Pa 53).

V. $A^{40}(n,\alpha)S^{37}$ $Q_m=-2.0$

In the bombardment of argon gas in an ionization chamber with 2.5 Mev neutrons an α-particle group is observed corresponding to a Q value of 1.8 Mev and a cross section of 0.1 mb (Gr 46). In view of the large discrepancy with the Q value calculated from the S^{37} adopted mass ($Q_m=-2.0$ Mev) it may safely be assumed that the observed α-particle group must be assigned to the $A^{36}(n,\alpha)S^{33}$ reaction ($Q_m=+2.0$ Mev).

Cl^{37}

Adopted mass defect: -20.9 Mev (see Introduction)

I. $S^{37}(\beta^-)Cl^{37}$ See S^{37}

II. A^{37}(E.C.)Cl^{37} See A^{37}

No other reactions have been observed giving information on this nucleus. It can be reached in principle

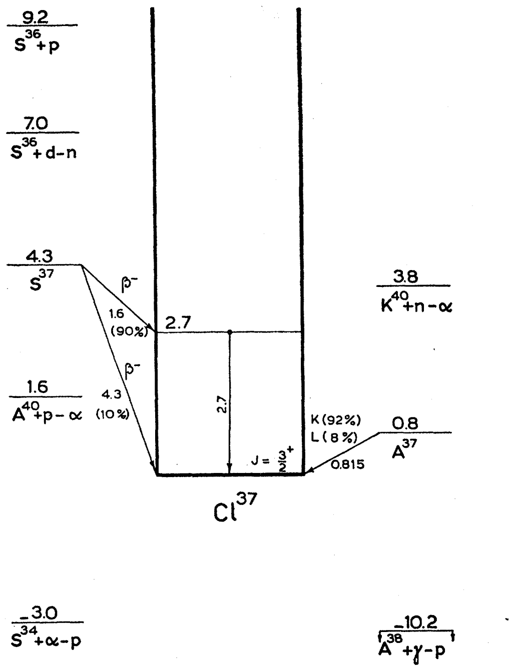

FIG. 28.

by $S^{34}(\alpha,p)Cl^{37}$ ($Q_m=-3.0$), $S^{36}(p,\gamma)Cl^{37}$ ($Q_m=9.2$), $S^{36}(d,n)Cl^{37}$ ($Q_m=7.0$), $A^{38}(\gamma,p)Cl^{37}$ ($Q_m=-10.2$), $A^{40}(p,\alpha)Cl^{37}$ ($Q_m=1.6$), and $K^{40}(n,\alpha)Cl^{37}$ ($Q_m=3.8$).

A^{37}

Adopted mass defect: -20.1 Mev

(The A^{37} adopted mass is based on the $Cl^{37}(p,n)A^{37}$ threshold determinations. It checks very well with the observed K-capture energy release and with the measured $A^{36}(d,p)A^{37}$ Q value.)

I. A^{37}(E.C.)Cl^{37} $Q_m=0.8$

The half-life is given as 34.1 ± 0.3 days (We 44) and 35.0 ± 0.4 days (Mi 52a).

By proportional-counter measurements it has been found that besides K capture also L capture exists with $\lambda_L/\lambda_K=0.08$ to 0.09 (Po 49a). The Auger conversion coefficient of K radiation is given as $W_K=0.96\pm0.03$ (We 44). The energy spectrum of continuous γ radiation (internal bremsstrahlung) has been measured both by Pb absorption and by scintillation spectrometer. The endpoint is at 815 ± 15 kev and the shape of the spectrum agrees with the theory developed for allowed transitions (An 53). These results are confirmed in an independent investigation (Si 54). The K-capture energy release is also found by measurement of the time-of-flight spectrum of Cl^{37} recoil ions. The recoil energy is measured as 9.7 ev, while 9.67 ± 0.08 ev is calculated from the known $Cl^{37}(p,n)$ threshold (Ro 52).

The log ft value is 5.0.

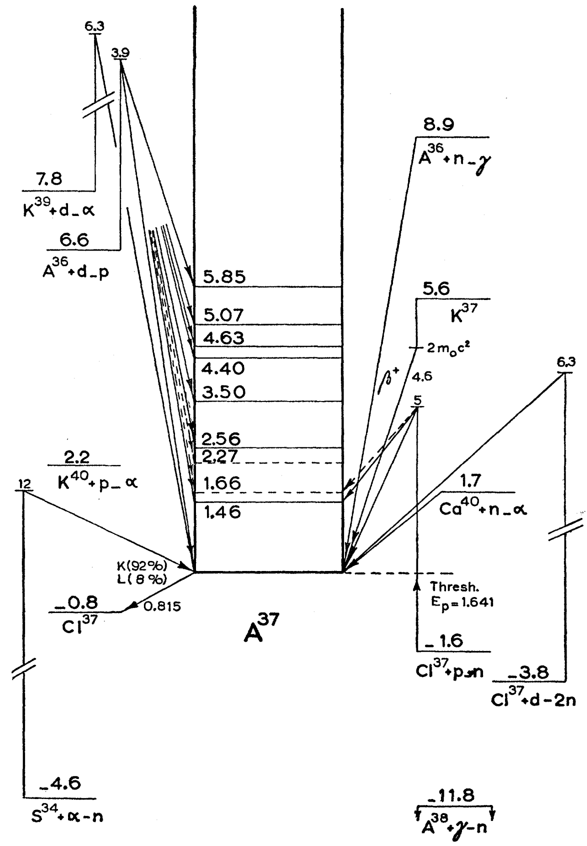

FIG. 29.

II. $S^{34}(\alpha,n)A^{37}$ $Q_m=-4.6$

Radioactive A^{37} has been produced from this reaction (We 44).

III. $Cl^{37}(p,n)A^{37}$ $Q_m=-1.6$

The threshold has been measured as $E_p=1.60$ Mev (Bl 51), 1640 ± 4 kev (Ri 50) and 1641 ± 2 kev (Sc 52a). By nuclear emulsion technique neutron groups have been found with Q values of -1.58 and -2.99 Mev corresponding to a A^{37} level at 1.41 ± 0.05 Mev (St 52c). By the same method A^{37} levels were found at 1.40 and 1.65 Mev (Gr 50c). See also We 44.

See A^{38} for resonances.

IV. $Cl^{37}(d,2n)A^{37}$ $Q_m=-3.8$

Radioactive A^{37} has been found from this reaction (We 44).

V. $A^{36}(n,\gamma)A^{37}$ $Q_m=8.9$

The thermal neutron capture cross section measured by the A^{37} activity produced is 6.5 ± 1.0 b (Mc 50a).

VI. $A^{36}(d,p)A^{37}$ $Q_m=6.6$

In Table XLV Q values and A^{37} levels are given measured from deuteron bombardment of argon gas

TABLE XLV. Levels in A^{37} from $A^{36}(d,p)A^{37}$.

Author	Da 49a		Zu 50	
E_d (Mev)	3.4		3.9	
	Q values (Mev)	A^{37} levels (Mev)	Q values (Mev)	A^{37} levels (Mev)
	6.59±0.03	0	6.49±0.08	0
	5.06±0.03	1.53	5.05±0.05	1.44
	4.92±0.05	1.67	...	...
	4.32±0.05	2.27	...	...
	4.03±0.03	2.56	3.93±0.05	2.56
	3.13	3.46	2.95±0.05	3.54
	...	...	2.09±0.07	4.40
	...	...	1.86±0.07	4.63
	1.58	5.01	1.42±0.03	5.07
			0.64±0.07	5.85

enriched in A^{36} content and from proton energy determinations by Al absorption.

VII. $A^{38}(\gamma,n)A^{37}$ $Q_m=-11.8$

Not observed.

VIII. $K^{39}(d,\alpha)A^{37}$ $Q_m=7.8$

Radioactive A^{37} has been found from this reaction (We 44).

IX. $K^{40}(p,\alpha)A^{37}$ $Q_m=2.2$

Not observed.

X. $Ca^{40}(n,\alpha)A^{37}$ $Q_m=1.7$

Radioactive A^{37} is produced by pile irradiation of calcium (Ro 52). See also We 44.

K^{37}

(not illustrated)

Adopted mass defect: −14.5 Mev

(The adopted mass defect is based on the adopted mass of A^{37} and the $K^{37}(\beta^+)A^{37}$ decay energy.)

I. $K^{37}(\beta^+)A^{37}$ $Q_m=5.6$

The half-life is measured as 1.3±0.1 sec (La 48) and 1.2±0.2 sec (Bo 51). The positron end point has been measured with a scintillation spectrometer as 4.57±0.13 Mev (Bo 51). The log ft value is 3.4 in agreement with other log ft values of super-allowed transitions between mirror nuclei.

The assignment to K^{37} of the half-life and positron end point reported above has recently been made very uncertain by Stähelin's measurements on K^{38} (St 53b). See K^{38} "General Remarks."

II. $A^{36}(p,\gamma)K^{37}$ $Q_m=2.5$

No resonances have been found in the bombardment with protons of $0.5<E_p<1.8$ Mev of silver targets containing separated A^{36} (Br 48a).

III. $A^{36}(d,n)K^{37}$ $Q_m=0.2$

Not observed.

IV. $K^{39}(\gamma,2n)K^{37}$ $Q_m=-24.6$

By this reaction K^{37} has been produced with x-rays from a 70-Mev synchrotron (La 48, Bo 51). See also K^{38} "General Remarks."

V. $Ca^{40}(p,\alpha)K^{37}$ $Q_m=-4.7$

Not observed.

Cl^{38}

Adopted mass defect: −18.6 Mev

(The adopted mass defect is based on the measured Cl^{38} beta-decay energy release and gives good agreement with the measured $Cl^{37}(d,p)Cl^{38}$ Q value.)

I. $Cl^{38}(\beta^-)A^{38}$ $Q_m=4.9$

The half-life is determined as 37.0 min (Va 36), 37.5 min (Hu 37, Cu 40), 37.3±0.3 min (Wa 39), 38.5±0.5 min (Ho 46), and 37.29±0.04 min (Co 50a).

The β^- spectrum is complex and can be analyzed into three branches. Two γ rays are observed. Their energies and relative intensities determined by magnetic spectrometer are given in Table XLVI. The intensity of a potential 3.75-Mev crossover γ ray is less than 0.03 percent per β particle (My 49). The shape of the high-energy β^- spectrum and its ft value [log $ft=7.5$ and $\log(W_0^2-1)\ ft=9.5$] are characteristic for once-forbidden transitions ($\Delta J=2$, yes) (La 50a, Wu 50). The

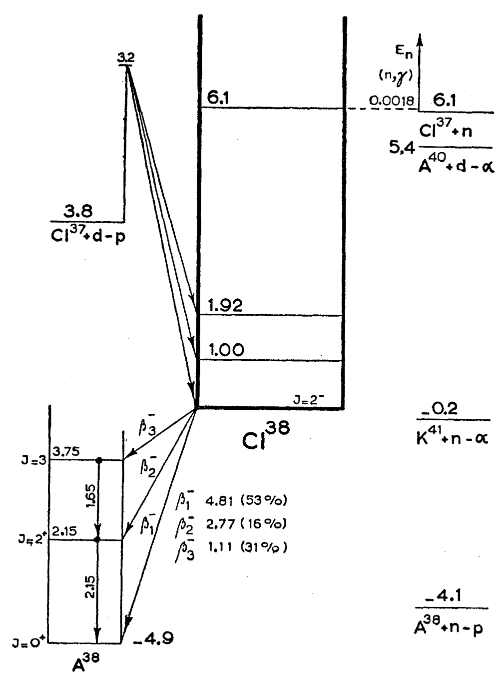

FIG. 30.

TABLE XLVI. Beta decay of Cl^{38}.

Author	Wa 39	Cu 40	It 41	Ho 46	La 50a
$E_{\beta 1}$ (Mev)	4.99±0.06			5.2 (53%)	4.81±0.05 (53.4%)
$E_{\beta 2}$ (Mev)				2.70 (11%)	2.77±0.05 (15.8%)
$E_{\beta 3}$ (Mev)	1.08±0.06			1.19 (36%)	1.11±0.01 (30.8%)
$E_{\gamma 1}$ (Mev)		2.15 (57%)	2.19±0.03 (53%)	2.15 (57%)	
$E_{\gamma 2}$ (Mev)		1.65 (43%)	1.64±0.02 (47%)	1.60 (43%)	

β^- transitions to the 2.15-Mev level are also forbidden (log $ft=6.9$) while those to the 3.75-Mev level are allowed (log $ft=4.9$). From the data given above and from the measured $\gamma-\gamma$ angular correlation (Wa 41, Ki 42, St 50) spins and parities can be assigned as shown in the A^{38} level diagram. The parity of the A^{38} 3.75 Mev level is still in doubt. Odd parity follows from the low ft value (log ft=4.9) of the β^- transition to this level, but the $\gamma-\gamma$ angular correlation measurements would point to even parity. See also Al 35b, Ku 36, Ri 36a, Ak 41.

For theoretical discussions of the Cl^{38} ground state see Ku 53, De 53a.

II. $Cl^{37}(n,\gamma)Cl^{38}$ $Q_m=6.1$

The thermal neutron capture cross section is meassured from the resulting Cl^{38} activity as 0.3 b (On 41), 0.38 b (Si 41a), and 0.56±0.11 b (Se 47). At about 1 Mev the capture cross section is 0.74 mb (Hu 53a). See also Hu 49. A resonance at $E_n=1.8$ kev has been observed by a boron-absorption method (Li 47). See also Am 35, Ke 40, On 41a.

III. $Cl^{37}(n,n)Cl^{37}$ $E_b=6.1$

For resonances in the chlorine total neutron cross section see Cl^{36}.

IV. $Cl^{37}(d,p)Cl^{38}$ $Q_m=3.8$

From enriched target bombardments at $E_d=3.2$ Mev and proton energy measurement by Al absorption Q values are found of 4.02, 3.02, and 2.10 Mev, corresponding to Cl^{38} levels at 1.00 and 1.92 Mev (Sh 41).

See also Va 36, Ku 36, Po 40a, Ak 41, Ho 46, Cl 46a, En 51b.

V. $A^{38}(n,p)Cl^{38}$ $Q_m=-4.1$

Not observed.

VI. $A^{40}(d,\alpha)Cl^{38}$ $Q_m=5.4$

A weak β^- activity with 5-Mev end point observed by cloud chamber after the bombardment of argon with 5.3 Mev deuterons might be ascribed to this reaction (Ku 36, Bl 46a).

VII. $K^{41}(n,\alpha)Cl^{38}$ $Q_m=-0.2$

Radioactive Cl^{38} has been found from the bombardment of potassium by fast neutrons (Hu 37). The cross section at $E_n=14.5$ Mev is 31±11 mb (Pa 53).

A^{38}

Adopted mass defect: −23.5 Mev (see Introduction)

I. $Cl^{35}(\alpha,p)A^{38}$ $Q_m=0.8$

From bombardment of natural chlorine by ThC′ α particles and determination of proton energies by absorption in air Q values are found of 0.1, −2.5, and −4.2 Mev (Po 36a, Li 37). This experiment has been repeated with cyclotron α particles of $E_\alpha=7.45$ Mev and proton energy determination by Al absorption. From targets enriched in Cl^{35} Q values are found of 0.81±0.08, −1.32±0.08, and −2.92±0.08 Mev, corresponding to A^{38} levels at 2.13±0.04 and 3.73±0.04 Mev (Kr 53).

For Q values see A^{37}.

The energies of γ rays from this reaction have been measured by pair formation in a β spectrometer as $E_\gamma=1.7\pm0.2$, 2.7±0.3, and 3.9±0.4 Mev (Ma 37, Ma 41).

II. $Cl^{37}(d,n)A^{38}$ $Q_m=8.0$

Not observed.

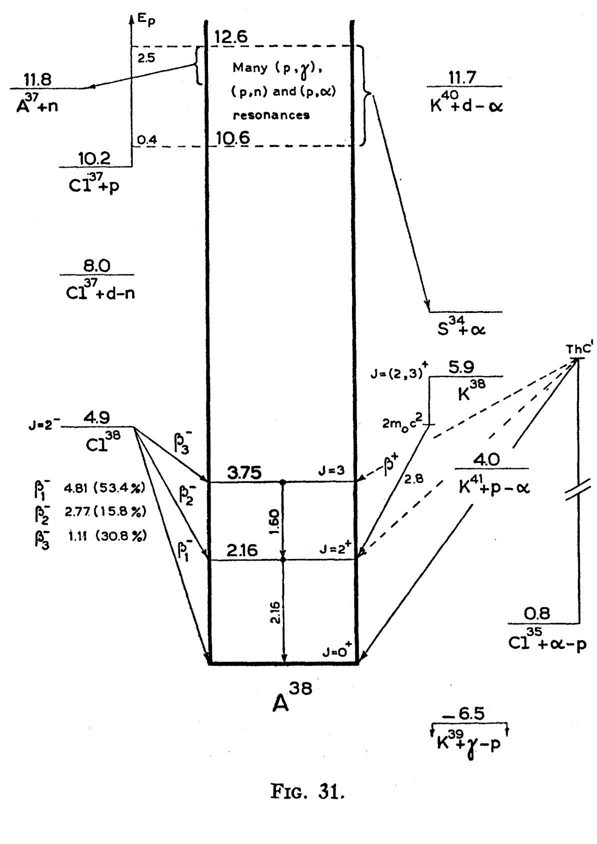

FIG. 31.

III. $Cl^{37}(p,\gamma)A^{38}$ $Q_m=10.2$

Eighty-six sharp resonances in the γ-ray yield from targets containing natural chlorine were found for proton energies between 500 and 2150 kev. From targets enriched in Cl^{37} a resonance was observed at 1090 kev (Br 51). From natural chlorine also resonances were found at 427, 447, 500, and 532 kev (Ta 46) and at 650, 800, and 1000 kev (Cu 39). The maximum γ-ray energy at the last three resonances has been measured by Al absorption as 14.5 Mev (Cu 39).

IV. $Cl^{37}(p,n)A^{37}$ $E_b=10.2$ $Q_m=-1.6$

Some 130 resonances in the neutron yield are found from natural chlorine targets for proton energies from threshold (at 1641±2 kev) to $E_p=2150$ kev (Sc 52a). For a list of resonance energies, relative intensities, and widths one is referred to the original paper. All these resonances can be assigned to Cl^{37} because the $Cl^{35}(p,n)A^{35}$ threshold is at $E_p=6.4$ Mev.

The region from threshold to $E_p=2300$ kev has also been surveyed by Broström *et al.* They reported 47 resonances from natural chlorine targets and resonances at 1928, 1974, 2014, 2028, 2079, and 2108 kev from targets enriched in Cl^{37} (Br 51). The A^{37} yield has been measured from threshold to $E_p=6.2$ Mev and shows many incompletely resolved resonances (Bl 51).

For Q values see A^{37}.

V. $Cl^{37}(p,\alpha)S^{34}$ $E_b=10.2$ $Q_m=3.0$

Ten resonances in the α-particle yield are reported for proton energies between 1450 and 2040 kev. They are assigned to Cl^{37} because the Q value measured by proportional counter pulse-height analysis ($Q=3.2$ Mev) agrees with the Q value expected from masses (Br 51).

VI. $Cl^{38}(\beta^-)A^{38}$ See Cl^{38}

VII. $K^{38}(\beta^+)A^{38}$ See K^{38}

VIII. $K^{39}(\gamma,p)A^{38}$ $Q_m=-6.5$

Not observed.

IX. $K^{40}(d,\alpha)A^{38}$ $Q_m=11.7$

Not observed.

X. $K^{41}(p,\alpha)A^{38}$ $Q_m=4.0$

Not observed.

K^{38}

(not illustrated)

Adopted mass defect: -17.6 Mev

(This mass defect agrees equally well with the energy release in $K^{38}(\beta^+)A^{38}$, as with the threshold of the $K^{39}(\gamma,n)K^{38}$ reaction.)

I. $K^{38}(\beta^+)A^{38}$ $Q_m=5.9$ Mev

The half-life has been measured as 7.75±0.15 min (Hu 37), 7.5±0.1 min (He 37a), 7.65±0.1 min (Ri 37), 7.5 min (Po 37a), 8.0±0.4 min (Hu 43, Hu 42), 7.5 min (Ra 47), 7.6 min (Pe 48), 7.6 min (Wa 50a), 7.7 min (Gr 51b), and 7.5 min (Ed 52).

The positron end point is measured by Al absorption as 2.6±0.1 Mev (He 37a, Hu 37, Bl 46c) and 2.53 Mev (Ra 47), and by a double-lens spectrometer as 2.8 Mev (Gr 51b). Moreover, a γ ray is present of $E_\gamma=2.08$ ±0.08 Mev measured by the Compton electrons from an Al radiator (Ra 47), or 2.16±0.03 Mev measured by scintillation spectrometer (Ti 51). A level in A^{38} at 2.15 Mev is also found in the decay of Cl^{38}. The K^{38} β^+ decay is allowed ($\log ft=5.0$).

For theoretical discussions of the K^{38} ground state see Ku 53, De 53a.

See also K^{38} "General Remarks."

II. $Cl^{35}(\alpha,n)K^{38}$ $Q_m=-5.9$

Radioactive K^{38} has been produced by this reaction by many investigators (He 37a, Hu 37, Ri 37, Ra 47) with $E_\alpha=7$ Mev and higher. The excitation curve for the bombardment of natural chlorine has been measured up to 8 Mev (Po 38a).

III. $A^{38}(p,n)K^{38}$ $Q_m=-6.7$

Not observed.

IV. $K^{39}(\gamma,n)K^{38}$ $Q_m=-13.2$

The threshold is 13.2±0.2 Mev (Mc 49). The cross section at $E_\gamma=17.5$ Mev is given as 5.4±1.4 mb (Wa 48) and as 9 mb (Mc 50) and the integrated cross section as 76-Mev mb (Ed 52). See also Hu 42, Hu 43, Pe 48. See also K^{38} "General Remarks."

V. $K^{39}(n,2n)K^{38}$ $Q_m=-13.2$

The cross section of this reaction for neutrons produced by bombardment of Li with deuterons ($E_n \leqslant 13.8$ Mev) is about 9 mb (Wa 50a); for $T(d,n)$ neutrons ($E_n=14.5$ Mev) 10±5 mb (Pa 53). See also Po 37a, Co 51.

VI. $K^{39}(p,pn)K^{38}$ $Q_m=-13.2$

In the bombardment of KI with 18-Mev protons K^{38} has been produced (Gr 51b, Ti 51).

VII. $Ca^{40}(d,\alpha)K^{38}$ $Q_m=4.5$

The ground-state Q value has been measured by magnetic analysis ($\vartheta=90°$) as 4.650±0.010 Mev (Br 54a). See also Hu 37.

GENERAL REMARKS

Recently an 0.95±0.03 sec activity has been observed (St 53b) from the bombardment of potassium with betatron γ rays. The yield was about equal to that of the 7.7-min activity for betatron energies between 16.5 and 31 Mev. The new activity cannot be assigned to K^{37} because the threshold of the $K^{39}(\gamma,2n)$ reaction is about 25 Mev. It is suggested that the new activity be assigned to the K^{38} ground-state decay, while the 7.7-min activity belongs to K^{38m}. The 1 sec period was also observed earlier, but it was then assigned to K^{37} (La 48, Bo 51). If the observed positron endpoint of 4.57±0.13 Mev (Bo 51) is also assigned to K^{38} the isomeric state comes out at 0.38±0.3 Mev above the K^{38} ground state. From the fact that the β^+ transitions from K^{38} to the A^{38} ground state and from K^{38m} to the $J=2^+$ level in A^{38} at 2.16 Mev are both allowed (log $ft=3.35$ and 5.0) while no γ transitions are observed from K^{38m} to K^{38}, it can be concluded that the K^{38} spin is $J=0^+$ and the K^{38m} spin is $J=3^+$. The K^{38} ground state is then the $T=1$ analog of the A^{38} ground state (St 53b, St 53c). See also Mo 53b.

Cl^{39}

(not illustrated)

Adopted mass defect: −18.8 Mev

(The adopted mass defect is based on the A^{39} mass defect and the Cl^{39} beta-decay energy release. It gives poor agreement with the $A^{40}(\gamma,p)Cl^{39}$ Q value measured by Wilkinson *et al.* (Wi 51).)

I. $Cl^{39}(\beta^-)A^{39}$ $Q_m=3.0$

The half-life is given as 55.5±0.2 min (Ha 50a) and 56.5 min (Ru 52b). By analysis of an Al absorption curve the β^- decay is shown to proceed through two branches with the following end points and relative intensities: 2.96±0.04 Mev (7 percent) and 1.65±0.03 Mev (93 percent). The former transition is forbidden (log $ft=7.6$ and $\log(W_0^2-1)ft=9.3$), while the latter is allowed (log $ft=5.4$). There are γ rays of 0.35±0.05 Mev (conversion coefficient ⩾0.05), 1.35±0.05 Mev and possibly 3.2 Mev (0.11 percent). The 1.65 Mev β^- branch is in coincidence with γ rays and also $\gamma-\gamma$ coincidences have been observed (Ha 50a).

The Cl^{39} decay can best be explained by assuming A^{39} levels at 1.33 and perhaps at 1.68 Mev (Nu 53).

II. $S^{36}(\alpha,p)Cl^{39}$ $Q_m=-4.5$

A 1.1-hr activity has been observed from the bombardment of sulfur by 16-Mev α particles (Ki 39a).

III. $A^{40}(\gamma,p)Cl^{39}$ $Q_m=-12.1$

The threshold for this reaction is reported as 14.2±0.2 Mev (Ha 50a). This value is probably too high because no correction was applied for penetration of the proton through the Coulomb barrier. The Q value at $E_\gamma=17.6$ Mev [Li(p,γ) radiation] has also been measured from proportional counter pulse-height analysis as −10.8 ±0.1 Mev. A second proton group may be present leading to a Cl^{39} level at about 1 Mev (Wi 51).

A^{39}

Adopted mass defect: −21.8 Mev

(The adopted mass defect is based on the K^{39} mass defect and the A^{39} beta-decay energy release.)

I. $A^{39}(\beta^-)K^{39}$ $Q_m=0.6$

The half-life has been measured as 265±30 years by absolute β counting in a lens spectrometer and mass-spectrometric analysis of a radioactive argon gas sample (Ze 52). This is in agreement with measurements of Haslam *et al.* (Ha 50a) who find the half-life to be greater than 5 years, and with measurements of Hälg (Ha 51d) who proves that the half-life cannot be between 1 and 30 min. Formerly half-lives of 4 min (Po 37a), 160±5 sec (Zu 50), and 145±15 sec (Ho 51) were assigned to A^{39}.

The β^- spectrum end point is determined by lens-spectrometer as 565±5 kev. The shape of the spectrum is first forbidden ($\Delta J=2$, yes) which agrees with the high ft value ($\log ft=9.9$ and $\log(W_0^2-1)\ ft=10.4$) (Br 50b). No γ rays are observed (Br 50b, An 52).

The β^- end point of the 160-sec activity observed by Zucker and Watson is determined by Al absorption as about 2.1 Mev (Zu 50).

II. $Cl^{39}(\beta^-)A^{39}$ See Cl^{39}

III. $A^{38}(n,\gamma)A^{39}$ $Q_m=6.7$

The thermal neutron activation cross section is measured as 0.8±0.2 b (Ka 52a).

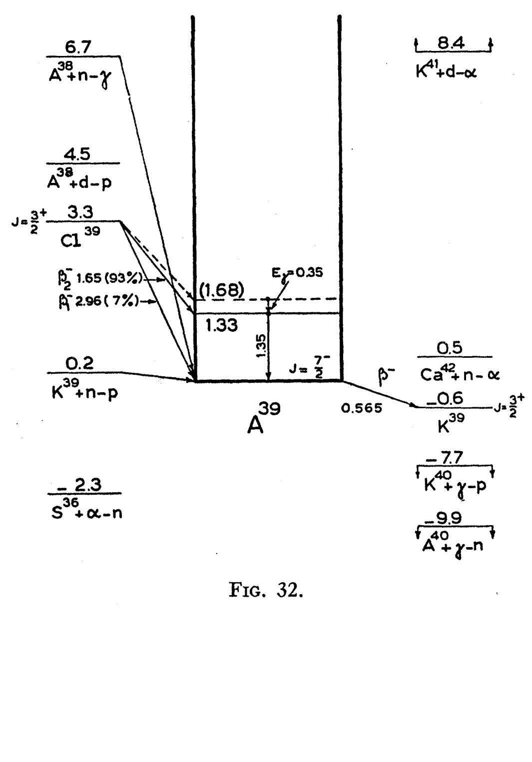

FIG. 32.

IV. $A^{38}(d,p)A^{39}$ $Q_m=4.5$

From bombardments of argon gas enriched to 1.2 percent in A^{38} content with 3.8-Mev deuterons and proton energy measurement by Al absorption, it is deduced that the ground-state Q value is smaller than 5 Mev (An 52). See also Zu 50.

V. $A^{40}(\gamma,n)A^{39}$ $Q_m=-9.9$

A 145±15 sec activity is observed from the bombardment of argon gas with the γ rays of a 70-Mev synchrotron (Ho 51). The assignment is unknown at present.

VI. $K^{39}(n,p)A^{39}$ $Q_m=0.2$

Radioactive A^{39} is produced by pile irradiation of potassium (Br 50b, Ze 52). See also Po 37a, Ha 51c.

VII. The following reactions leading to A^{39} have not been observed:

$S^{36}(\alpha,n)A^{39}$ ($Q_m=-2.3$), $K^{40}(\gamma,p)A^{39}$ ($Q_m=-7.7$), $K^{41}(d,\alpha)A^{39}$ ($Q_m=8.4$), $Ca^{42}(n,\alpha)A^{39}$ ($Q_m=0.5$).

K^{39}

Adopted mass defect: −22.4 Mev (see "Introduction")

I. $A^{39}(\beta^-)K^{39}$ See A^{39}

II. $Ca^{39}(\beta^+)K^{39}$ See Ca^{39}

No other reactions proceeding to K^{39} have been observed. As K^{39} is the most abundant K isotope (93.1 percent) scattering experiments with protons, neutrons, deuterons, and alpha's should be feasible. Other reactions which would yield information on excited states in K^{39} are

III. $A^{36}(\alpha,p)K^{39}$ $Q_m=-1.2$

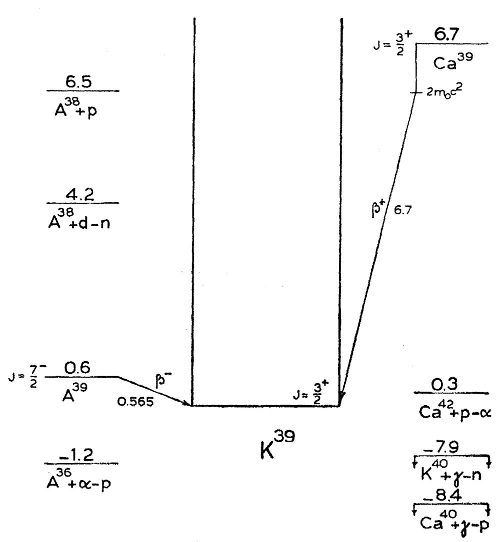

FIG. 33.

IV. $A^{38}(p,\gamma)K^{39}$ $Q_m=6.5$

V. $A^{38}(d,n)K^{39}$ $Q_m=4.2$

VI. $K^{40}(\gamma,n)K^{39}$ $Q_m=-7.9$

VII. $Ca^{40}(\gamma,p)K^{39}$ $Q_m=-8.4$

VIII. $Ca^{42}(p,\alpha)K^{39}$ $Q_m=0.3$

Ca^{39}

(not illustrated)

Adopted mass defect: −15.7 Mev

(The adopted mass defect is in good agreement with the observed $Ca^{40}(\gamma,n)Ca^{39}$ threshold and is about halfway between the values following from the two determinations of the $Ca^{39}(\beta^+)$ decay energy.

An argument against the adopted mass defect would be the resulting high ft value for the Ca^{39} decay ($\log ft=4.0$). A mass defect of −17.1 Mev would yield $\log ft=3.5$ which is the usual value for super-allowed transitions between mirror nuclei.)

I. $Ca^{39}(\beta^+)K^{39}$ $Q_m=6.7$

The half-life is given as 1.06±0.03 sec (Hu 43), 1.1±0.2 sec (Bo 51), 1.00±0.03 sec (Su 53), and 1.00 ±0.05 sec (Br 53). The assignment of a 4.5-min period formerly ascribed to Ca^{39} is unknown at present (Po 37a, Wa 40).

The end point of the positron spectrum is determined by scintillation spectrometer as 5.13±0.15 Mev (Bo 51) and by Al absorption as 6.7±0.5 Mev (Br 53).

II. $A^{36}(\alpha,n)Ca^{39}$ $Q_m=-8.7$

Not observed.

III. $K^{39}(p,n)Ca^{39}$ $Q_m=-7.5$

Not observed.

IV. $Ca^{40}(\gamma,n)Ca^{39}$ $Q_m=-15.9$

The threshold is measured as 15.8±0.1 Mev (Su 53), 15.9±0.4 Mev (Mc 49), and as 16.0±0.3 Mev (Be 47a).

The cross section shows a maximum of 15 mb at 19.3 Mev with a half-width of 4.2 Mev. The integrated cross section is $\int \sigma dE=69$ Mev mb (Su 53).

The cross section for 17.5-Mev γ rays from the $Li(p,\gamma)$ reaction is given as 2.4±0.6 mb (Wa 48) and 1.1 mb (Mc 50).

A^{40}

Adopted mass defect: −23.3 Mev (see "Introduction")

I. $Cl^{37}(\alpha,p)A^{40}$ $Q_m=-1.6$

The yield from this reaction at $E_\alpha=7.45$ Mev was found to be very low, even from targets enriched to 62 percent in Cl^{37} content (Kr 53).

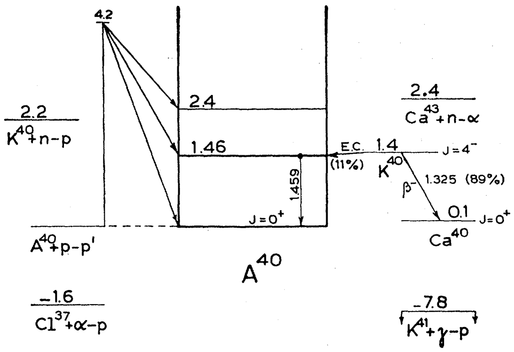

FIG. 34.

II. $A^{40}(p,p')A^{40}$

From proton scattering in argon gas at $E_p=4.2$ Mev and detection of scattered protons in nuclear emulsions placed at several angles between 20° and 70°, levels in A^{40} are found at 1.5 and 2.4 Mev. The angular distribution of elastically scattered protons follows closely the Rutherford law (He 47).

III. K^{40}(E.C.)A^{40} See K^{40}

IV. Other reactions (all unobserved) leading to A^{40} are: $K^{40}(n,p)A^{40}$ ($Q_m=2.2$), $K^{41}(\gamma,p)A^{40}$ ($Q_m=-7.8$), and $Ca^{43}(n,\alpha)A^{40}$ ($Q_m=2.4$).

K^{40}

Adopted mass defect: −21.9 Mev

(This mass defect derived from mass spectrometer data (see "Introduction") is in good agreement with the measured Q values of $K^{39}(n,\gamma)K^{40}$, $K^{39}(d,p)K^{40}$, and $K^{40}(\beta^-)Ca^{40}$ and is in reasonable agreement with the Q values of K^{40}(E.C.)A^{40} and $A^{40}(p,n)K^{40}$.)

I. K^{40}(E.C.)A^{40} $Q_m=1.4$ Mev
$K^{40}(\beta^-)Ca^{40}$ $Q_m=1.3$ Mev

The total half-life of K^{40} is determined by the number of β^-'s emitted per g K, the isotopic concentration of the investigated sample and the branching ratio of electron capture over β^- emission.

The number of β^- particles emitted per sec per g K has been measured as 23 (Mu 30), 26±5 (Br 38b), 26.8±1.2 (Gr 48), 33.5±5.7 (Hi 48), 30.6±2.0 (St 49), 30.5 (Sp 50), 27.1±1.5 (Ho 50a), 31.2±3.0 (Fa 50), 28.3±1.0 (Sa 50a), 22.5±0.7 (Sm 50), 27.1±0.6 (Go 51c), and 32.0±3 (De 51). The average value $N_{\beta^-}=27.6$ yields a decay constant $\lambda_{\beta^-}=4.72\times10^{-10}$ yr^{-1} and a β^- decay half-life $\tau=14.6\times10^8$ yr, based on a natural isotopic concentration of 1.19×10^{-4} K^{40} in potassium (Ni 50, Re 52a). Measurements with enriched targets agree with these values, but have less precision, as the isotopic concentration is not known accurately enough (Bo 48, Fl 49, Sa 50a).

The β^- spectrum end point has been measured by an absorption method as 1.41±0.02 Mev (Hi 46, Hi 48), with scintillation spectrometers as 1.36±0.05 Mev (Be 50b) and 1.28±0.03 Mev (Go 51c), and with magnetic spectrometers as 1.35±0.05 Mev (Dz 46), 1.36±0.03 (enriched sample) (Al 50c) and 1.325±0.015 Mev (Fe 52). See also He 47a, Fr 48a, Bo 48, Al 49c, Fl 49, Sm 50, De 51a. The shape of the spectrum is third forbidden (Wu 50, Al 50c, Be 50b, Go 51c, Fe 52, Ma 53b) in agreement with the spin values $J=4$ of K^{40} (Za 41, Da 49b) and $J=0$ of Ca^{40}. The log ft value is 18.2.

For theoretical discussions of the K^{40} spin see Ku 53, De 53a.

A γ ray occurs in the decay. Its energy has been measured by absorption methods as 1.55±0.05 Mev (Gl 47) and 1.54±0.1 Mev (Hi 48, Hi 46), and by scintillation spectrometer as 1.47±0.03 Mev (Pr 50), 1.46±0.04 Mev (Be 50c), 1.462±0.01 Mev (Be 50d), 1.48±0.02 Mev (Ho 50b) and 1.459±0.007 Mev (Go 51a). See also Be 31, Ce 49.

The number of γ rays emitted per g potassium per sec is 3.6±0.8 (Gl 47), 3.3 (Ah 48), 3.6±0.3 (Sa 49a, Co 51a), 3.0 (Sp 50), 3.6±0.4 (Fa 50), 3.1±0.3

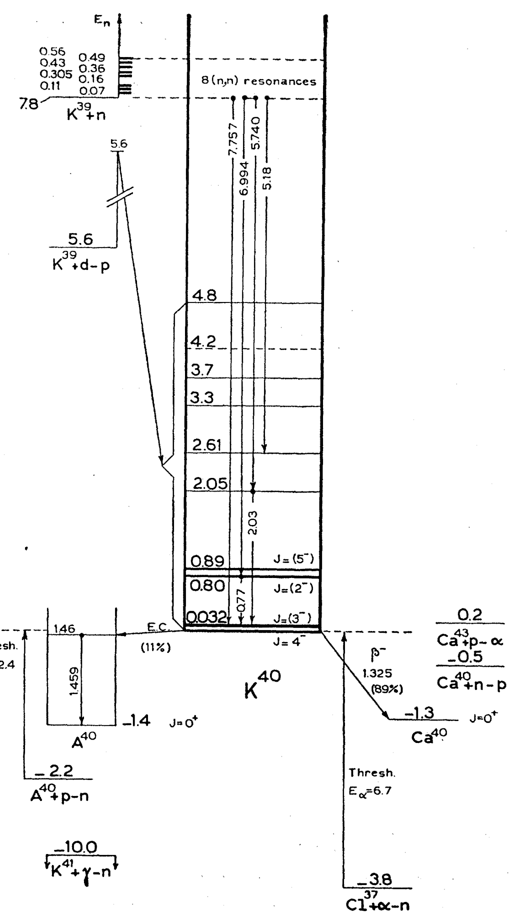

FIG. 35.

(Ho 50a), and 3.37±0.09 (Bu 53). The average 3.4 amounts to 0.123 γ rays per β^- decay. Direct measurements of this ratio are 0.03 (Gr 34), 0.087±0.012 (Hi 48), 0.05 (Fl 49), and 0.05 (Sm 50). No other γ rays are present in a relative intensity of 10 percent or more (Ho 50b).

As the γ-ray energy is larger than the mass-spectroscopic $K^{40}-Ca^{40}$ mass difference, the γ ray evidently belongs to the electron capture branch in the decay and not to $K^{40}(\beta^-)Ca^{40}$. An upper limit of $\beta-\gamma$ coincidences is 1 percent of the number of β's (Me 47a) or 0.6 percent (Ho 50a).

The sequence of K capture and γ ray has been demonstrated by coincidences between γ rays and Auger electrons (Pa 52a, Pa 52b).

The branching ratio (number of electron captures over number of electron emissions) has been the subject of many investigations, as early measurements indicated a total half-life of K^{40} in conflict with geophysical considerations.

Results with screen-wall counters or other G-M counters specially devised to this purpose are $N_K/N_{\beta^-}=1.9\pm0.4$ (Bl 47a), <0.5 (Ho 50a), 0.135±0.040 (Sa 50a), $\leqslant 0.2$ (Gr 51c, Gr 50d) and $\leqslant 0.1$ (Ce 51, Ce 50). Measurements of the amount of argon in potassium containing minerals of known age lead to $N_K/N_{\beta^-}<0.1$ (Ha 47, Su 48), 0.7 (Bo 48) and 1.4±0.2 (Ah 48). Mass spectrometer studies of the K^{40}, A^{40} and Ca^{40} content in minerals lead to $N_K/N_{\beta^-}=0.04$ (Al 48e), 0.126±0.005 (In 50), 0.058 (Mo 52b), and 0.060±0.006 (Ru 53). The high values result in a short total half-life, which has to be rejected on geophysical and geochemical evidence.

There is no evidence for K capture proceeding directly to the ground state of A^{40}. According to the energy available in this decay positron emission would compete with electron capture. Search for positrons results in the following relative intensities: $N_{\beta^+}/N_K<0.01$ (Be 50c), $N_{\beta^+}/N_{\beta^-}<2\times10^{-5}$ (Be 50d), $N_{\beta^+}/N_{\beta^-}<6\times10^{-4}$ (Co 51a) and $N_{\beta^+}/N_K=0.01$ (Go 51b). In view of these data it seems probable, that every electron capture is followed by a γ ray of 1.46 Mev.

The large spread in the experimental values of the branching ratio opposes a definite conclusion, but a lower limit of 0.05 and an upper limit of 0.14 are above dispute. In view of the N_γ/N_{β^-} results a subjective preference to 0.12 is given. This leads to a decay constant $\lambda_K=0.57\times10^{-10}$ yr^{-1} and $\lambda=\lambda_{\beta^-}+\lambda_K=5.29\times10^{-10}$ yr^{-1} or a total half-life of 1.31×10^9 yr.

See also Sm 37, Gr 48a, Fi 49, Rh 50, Mo 51a, Ho 53f.

II. $Cl^{37}(\alpha,n)K^{40}$ $Q_m=-3.8$

The threshold has been determined at $E_\alpha=6.7\pm0.6$ Mev (Po 37c) and the excitation curve up to $E_\alpha=8.6$ Mev has been measured (Po 38a).

III. $A^{40}(p,n)K^{40}$ $Q_m=-2.2$

A threshold of $E_p=2.4$ Mev has been observed (Ri 48).

IV. $K^{39}(n,\gamma)K^{40}$ $Q_m=7.9$

The thermal neutron absorption cross section of isotopic K^{39} has been measured by pile-oscillator as 1.87±0.15 b (Po 52a). For natural potassium values are given of 1.89±0.06 b (Co 50), 2.11±0.1 b (Ha 50), and 2.05±0.1 b (Po 51). See also La 40, Vo 43, Ha 49.

The gamma rays from thermal neutron capture have been investigated by pair spectrometer and are listed in Table XLVII. The assignment of γ rays A'' and A'

TABLE XLVII. Gamma rays from thermal neutron capture in potassium (Ki 52, Br 52b, Ba 53b).

γ ray	Energy (Mev)	Intensity in photons per 100 captures	Assignment (final nucleus)
A''	9.39 ±0.06	0.02	K^{41}
A'	8.45 ±0.02	0.1	K^{41}
B	7.757±0.008	3.5	K^{40}
C	7.34 ±0.02	0.1	K^{42}
D	6.994±0.007	1.3	K^{40}
E	6.31 ±0.06	0.3	
F	5.740±0.012	6	K^{40}
F'	5.66 ±0.02	4	K^{40}
F''	5.50 ±0.02	2.5	K^{40}
G	5.38 ±0.03	6	K^{40}
G'	5.18 ±0.02	2	K^{40}
H	5.06 ±0.02	3	K^{40}
I	4.39 ±0.03	4	K^{40}
J	4.18 ±0.05	(6)	
K	3.92 ±0.05	(5)	
L	3.67 ±0.05	(8)	
	2.80		
	2.03		K^{40}
	1.61		
	1.19		
	0.77		K^{40}

to capture in K^{40} is based on experiments with K^{40} enriched potassium. The γ ray C is produced in the ground-state transition $K^{41}(n,\gamma)K^{42}$.

The γ ray B is the transition from the capturing state to the 32-kev level in K^{40}. Its high intensity is well explained by an $E1$ transition, which would give the 32-kev level $J\leqslant3^-$. Gamma rays D and F are transitions to the 0.80- and 2.01-Mev levels in K^{40}. The assignment of the other γ rays is less certain. The intensities in Table XLVII of lines A'' to I are from Ba 53, of J, K, and L from Ki 52 and should be corrected before being compared to the others (Ba 53b, Ki 52). See also Ku 49, Ha 52b.

Five low-energy γ rays have been found by a two-crystal scintillation spectrometer (Br 53b) and are also listed in Table XLVII.

V. $K^{39}(n,n)K^{39}$ $E_b=7.9$

Maxima in the neutron cross section have been found by transmission measurements at $E_n=70$, 110, 160, 305, 360, 430, 490, and 560 kev. The spread in the neutron energy was 15 kev. The highest value of the cross section was 3.7 b at 70 and 305 kev, between the maxima the cross section was $\leqslant 2$ b (Pe 50b). The cross section at $E_n=2.46$ Mev is 3.44 ± 0.18 b, at 2.88 Mev: 3.13 ±0.15 b (Zi 39) and at 14 Mev: 2.24 ± 0.04 b (Co 52a). See also Ao 39, Ad 50.

VI. $K^{39}(d,p)K^{40}$ $Q_m=5.6$

With an enriched (96.5 percent K^{39}) target and $E_\alpha=3.9$ Mev eight proton groups have been found by an Al absorption method (Sa 50). They are listed in Table XLVIII. The first three groups had been observed before (Po 40a).

TABLE XLVIII. Q values and levels from $K^{39}(d,p)K^{40}$.

Author	Po 40a	Sa 50		Bu 53a	
Energy measurement	Absorption	Absorption		Magnetic analysis	
E_d (Mev)	3.3	3.9		4.76 to 5.65	
	Q value (Mev)	Q value (Mev)	Level (Mev)	Q value (Mev)	Level (Mev)
	5.6 ± 0.3	5.48 ± 0.08	···	5.576 ± 0.010	
				5.544 ± 0.010	0.032 ± 0.002
	4.5 ± 0.3	4.67 ± 0.09	0.81 ± 0.03	4.776 ± 0.010	0.800 ± 0.010
				4.683 ± 0.010	0.893 ± 0.010
	3.4 ± 0.3	3.47 ± 0.09	2.01 ± 0.03		
		2.92 ± 0.10	2.56 ± 0.05		
		2.2 ± 0.1	3.3 ± 0.1		
		1.8 ± 0.1	3.7 ± 0.1		
		(1.3 ± 0.1)	(4.2 ± 0.1)		
		0.7 ± 0.1	4.8 ± 0.1		

By high resolution magnetic analysis the ground-state Q value is determined as 5.576 ± 0.010 Mev and three other levels are measured accurately (Bu 53a). See Table XLVIII.

VII. $K^{41}(\gamma,n)K^{40}$ $Q_m=-10.0$

Not observed.

VIII. $Ca^{40}(n,p)K^{40}$ $Q_m=-0.5$

Not observed.

IX. $Ca^{43}(p,\alpha)K^{40}$ $Q_m=0.2$

Not observed.

GENERAL REMARKS

The shell model would predict in K^{40} low-lying states with $J=2^-$, 3^-, 4^- and 5^- resulting from a $d_{\frac{3}{2}}$ proton and $f_{7/2}$ neutron. The K^{40} spin has been experimentally determined as $J=4$. The excited states at 32, 800, and 893 kev may be the other three members of this quadruplet. The proper spin order may in principle be deduced from the relative intensities of the four proton groups from the $K^{39}(d,p)K^{40}$ reaction observed at $E_d=5.16$ Mev and $\theta=90°$. In first approximation the differential cross section would be the same ($l_n=3$) apart from a factor $(2J_f+1)$. The experimental relative intensities (computed from the proton momentum spectrum given in Bu 53a) are 9, 7.9, 6.0, and 9.7. This would agree best with the relative intensities 9, 7, 5, and 11, to be expected for a spin order 4^-, 3^-, 2^-, and 5^-. Intense γ rays (probably $E1$ radiation) from thermal neutron capture in K^{39} are only observed to the 32 and 800 kev excited states (Ba 53b) which agrees with the assignment given (En 53a).

Ca^{40}

Adopted mass defect: -23.2 Mev (see "Introduction")

I. $K^{39}(d,n)Ca^{40}$ $Q_m=6.2$

Not observed.

II. $K^{40}(\beta^-)Ca^{40}$ See K^{40}

III. $K^{40}(p,n)Ca^{40}$ $Q_m=0.5$

Not observed.

IV. $Ca^{40}(p,p')Ca^{40}$

From inelastic proton scattering at $E_p=7.7$ Mev and energy determination by Al absorption a Ca^{40} level is found at 3.8 Mev. The angular distribution of inelastically scattered protons is nearly isotropic (Ha 52c). From inelastic proton scattering at proton energies between 6 and 8 Mev and magnetic analysis levels in Ca^{40} are found at 3.348, 3.731, 3.900, and 4.481 Mev, all ±10 kev, and at (5.20), 5.24, 5.27, (5.60), (5.62), (5.90), and (6.03) Mev, all ±20 kev (Br 53d, Br 53e).

The proton group leading to the 5.20-Mev level has

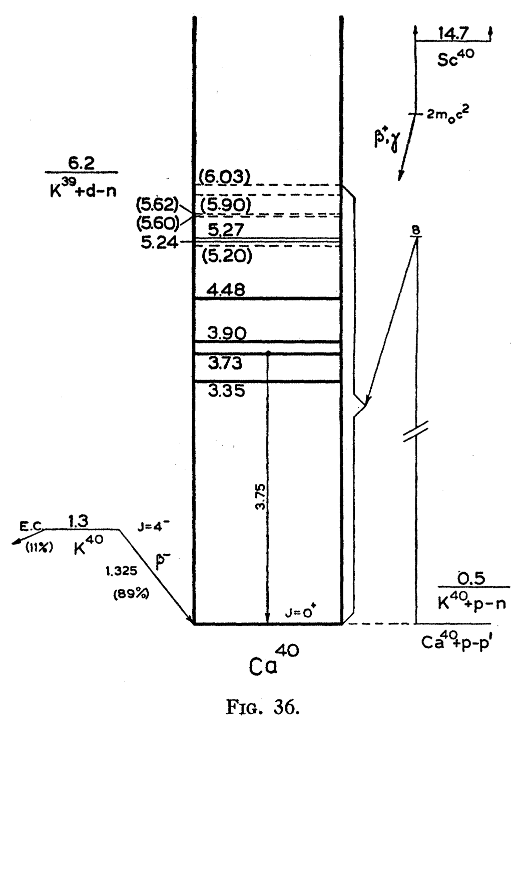

FIG. 36.

recently been shown to be due to some target impurity (Br 54a).

V. $Sc^{40}(\beta^+)Ca^{40}$ $Q_m = 14.7$

Recently Sc^{40} has been discovered from the $Ca^{40}(p,n)Sc^{40}$ reaction. The half-life is 0.22±0.03 sec. The threshold of the $Ca^{40}(p,n)$ reaction is at $E_p = 15.9 \pm 1.0$ Mev, which fixes the mass defect of Sc^{40} as −0.5 Mev. The maximum positron energy is 9.0±0.4 Mev and a γ ray of 3.75±0.04 Mev has been found from the $Sc^{40}(\beta^+)Ca^{40}$ decay by scintillation spectrometer. No delayed heavy particles have been detected (Ri 53, Gl 53a).

A^{41}

Adopted mass defect: −21.0 Mev

(The adopted mass defect gives good agreement both with the observed A^{41} decay energy and with the Q value measured for the $A^{40}(d,p)A^{41}$ ground-state transition.)

I. $A^{41}(\beta^-)K^{41}$ $Q_m = 2.5$

The half-life is given as 110±1 min (Sn 36, Ka 52a), 109.4±1 min (Bl 46a), and 107±3 min (Br 50c).

The β^- decay proceeds by two branches. The ground-state transition is very weak and evidently forbidden (log $ft = 8.6$ and $\log(W_0^2-1)\, ft = 10.1$). The intense low-energy branch is in coincidence with a γ ray (Bl 46a). Determinations of energies and intensities are collected in Table XLIX. The weak β^- branch with 5-Mev end point found from cloud-chamber measurements might be explained by the presence of Cl^{38} contamination (Ku 36, Bl 46a). The Kurie plot of the low-energy β^- transition is straight down to 160 kev. Also the ft value agrees with an allowed transition (log $ft = 5.1$). No γ ray conversion electrons are found (Br 50c). By $\beta-\gamma$ delayed coincidence measurements the half-life of the 1.3-Mev level in K^{41} is established as $(6.7\pm0.5)\times10^{-9}$ sec (El 52a) and 6.6×10^{-9} sec (En 53), which agrees with the theoretical value for $M2$ transitions.

See also Wu 50.

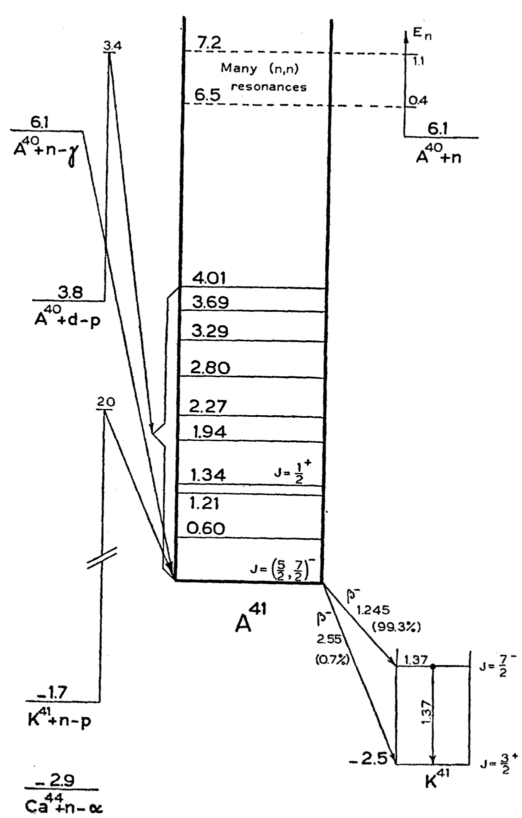

FIG. 37.

TABLE XLIX. Beta decay of A^{41}.

Author	Method	$E_{\beta_1\,max}$ (Mev)	$E_{\beta_2\,max}$ (Mev)	$E\gamma$ (Mev)
Sn 36	Al abs.		1.1	
Ku 36	cl. chamber	~5	1.5	
Ri 36	cl. chamber			1.37±0.06
Bl 46a	Al abs.	2.55±0.2 (0.7%)	1.18 ±0.05 (99.3%)	1.3 ±0.2
Br 50c	spectrom.		1.245±0.005	

II. $A^{40}(n,\gamma)A^{41}$ $Q_m = 6.1$

The thermal neutron absorption cross section is 0.62±0.04 b (Co 50) and the thermal neutron activation cross section is 0.53±0.03 b (Ka 52a). For fission neutrons ($E_n \approx 1$ Mev) the activation cross section is 0.93 mb (Hu 53a).

III. $A^{40}(n,n)A^{40}$ $E_b = 6.1$

The argon total neutron cross section has been measured with $Li(p,n)$ neutrons from 0.4 to 1.1 Mev with 2 kev resolution. The nonresonant total cross section is about 0.7 b. There are resonances of about 3.5 b at $E_n = 580$, 600, and 740 kev and many smaller partly unresolved resonances (Gu 53). There are no resonances beneath 3 kev (Ad 50).

IV. $A^{40}(d,p)A^{41}$ $Q_m = 3.8$

Several proton groups have been observed in the deuteron bombardment of argon. Their Q values and corresponding A^{41} levels are collected in Table L. The

TABLE L. Reaction $A^{40}(d,p)A^{41}$.

Author	Da 40	Da 49a	Sa 49	Gi 52	Da 49a
E_d (Mev)	2.4	3.4	3.9	7.8	
Method	Al abs.	Al abs.	Al abs.	Nucl. emuls.	
	Q values (Mev)	Q values (Mev)	Q values (Mev)	Q values (Mev)	A^{41} levels
	4.37	3.84±0.03	3.80±0.06	3.90±0.08	0
	3.01	3.18±0.05		3.40±0.08	0.66
		2.63±0.04			1.21
	2.23	2.50±0.04		2.56±0.08	1.34
		1.90±0.04			1.94
		1.57±0.05			2.27
		1.04±0.05			2.80
		0.55±0.03			3.29
		0.15±0.05			3.69
		−0.17±0.05			4.01

angular distribution of the ground-state group at $E_d=7.8$ Mev, as measured by nuclear-emulsion technique, corresponds to $l_n=3$ which characterizes the A^{41} ground state as $(5/2 \text{ or } 7/2)^-$. The proton group leading to the 1.34-Mev level corresponds to $l_n=0$ $(J=\frac{1}{2}^+)$ or perhaps $l_n=1$ (Gi 52).

The yield of radioactive A^{41} has been measured up to $E_d=5.1$ Mev (Sn 36).

IV. $K^{41}(n,p)A^{41}$ $Q_m=-1.7$

A weak 1.8-hr activity has been observed from potassium bombarded by fast neutrons (Hu 37, Po 37a). The cross section at $E_n=14.5$ Mev is 81 ± 32 mb (Pa 53).

V. $Ca^{44}(n,\alpha)A^{41}$ $Q_m=-2.9$

Not observed.

K^{41}

Adopted mass defect: -23.5 Mev (see "Introduction")

I. $A^{38}(\alpha,p)K^{41}$ $Q_m=-4.0$

Not observed.

II. $A^{40}(p,\gamma)K^{41}$ $Q_m=7.8$

Thin targets enriched in A^{40} content have been bombarded with protons from 0.5 to 1.8 Mev. Resonances in the γ-ray yield have been found (Br 48a) at

E_p	900	1050	1080	1100	1235 kev
Rel. int.	0.2	0.4	0.5	1.0	0.5

III. $A^{40}(d,n)K^{41}$ $Q_m=5.5$

Neutrons from the bombardment of argon with 3.2 Mev deuterons have been detected by their recoil protons with two proportional counters, separated by absorbing foils, in coincidence. The ground-state Q value has been measured as 5.97 ± 0.25 Mev and levels are observed at 1.34 ± 0.15 Mev, 3.10 Mev and 4.40 Mev (Wo 50a).

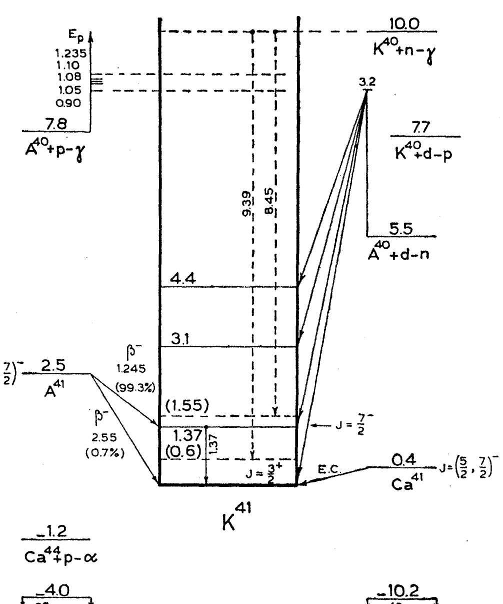

FIG. 38.

IV. $A^{41}(\beta^-)K^{41}$ See A^{41}

V. $K^{40}(n,\gamma)K^{41}$ $Q_m=10.0$

The thermal neutron absorption cross section of isotopic K^{40} measured by the pile-oscillator method is 66 ± 20 b (Po 52a).

Two γ rays A'' and A' of Table XLVII produced by neutron capture in potassium are assigned to K^{41} on account of their energies and from experiments with targets enriched in K^{40}. If originating from the capturing state, they would proceed to K^{41} levels at 0.6 and 1.55 Mev (Ba 53b, Ki 52).

VI. $K^{40}(d,p)K^{41}$ $Q_m=7.7$

Not observed.

VII. $Ca^{41}(E.C.)K^{41}$ See Ca^{41}

VIII. $Ca^{42}(\gamma,p)K^{41}$ $Q_m=-10.2$

Not observed.

IX. $Ca^{44}(p,\alpha)K^{41}$ $Q_m=-1.2$

Not observed.

Ca^{41}

Adopted mass defect: -23.1 Mev

(The adopted mass defect gives good agreement with the observed $K^{41}(p,n)Ca^{41}$ threshold and with the measured Q value of the $Ca^{40}(d,p)Ca^{41}$ reaction.)

I. $Ca^{41}(E.C.)K^{41}$ $Q_m=0.4$

The half-life has been calculated from proportional counter measurements of the intensity of the potassium K_α line in pile irradiated calcium samples (Br 51a, Br 53f). If the Ca^{40} thermal neutron capture cross section is taken as 0.22 b (Po 52a) then the Ca^{41} half-life is equal to $(1.1\pm0.3)\times10^5$ years. The log ft value is 10.8.

From analogous measurements the half-life is concluded to be at least several months (Sa 51a). The assignment of a half-life of 8.5 days to Ca^{41} (Wa 40) is incorrect (Ov 47, Se 47).

II. $K^{41}(p,n)Ca^{41}$ $Q_m=-1.2$

The threshold for neutron emission is at $E_p=1.25$ ±0.02 Mev (Ri 50). See Ca^{42} for resonances.

III. $Ca^{40}(n,\gamma)Ca^{41}$ $Q_m=8.3$

From samples enriched in Ca^{40} content the thermal neutron absorption cross section has been measured by

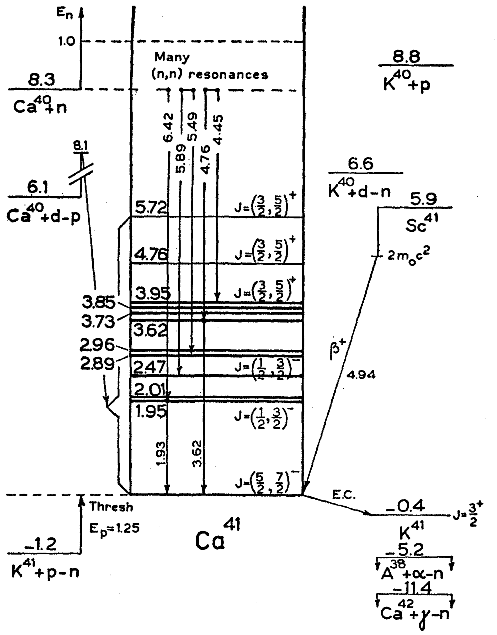

FIG. 39.

pile oscillator as 0.22±0.04 b (Po 52a). For natural calcium values are given of 0.37±0.04 b (Co 46a), 0.40±0.02 b (Co 50), 0.43±0.02 b (Ha 50), and 0.41±0.02 b (Po 51). See also Vo 43, Se 47.

Gamma-ray energies and intensities from thermal neutron capture in natural calcium measured by pair-spectrometer are listed in Table LI (Ki 52). Gamma rays C, D, F, I, and J check well with transitions from the capturing state to known levels in Ca^{41}. Gamma ray L could well represent a transition from the 3.62 Mev level to ground. The assignment of the other γ rays is as yet unknown. The intensities of γ rays C and D characterize them as $E1$ transitions, and the spins and parities of the 1.95 and 2.47 Mev levels as $\frac{1}{2}^-$ or $\frac{3}{2}^-$ (Ki 53e). See also Reaction V.

With a two-crystal scintillation spectrometer a γ ray of 1.93 Mev has been observed (Br 53b). It represents the transition from the first excited state in Ca^{41} to ground.

TABLE LI. Thermal neutron capture γ rays in natural calcium (Ki 52).

γ ray	Energy in Mev	Intensity in photons per 100 captures
A	7.83±0.05	1
B	7.43±0.05	1.4
C	6.42±0.03	83
D	5.89±0.03	11
E	5.66±0.06	3
F	5.49±0.05	4
H	4.95±0.03	8
I	4.76±0.03	6
J	4.45±0.05	30
L	3.62±0.05	16

A recalculated value for the intensity of γ ray C is 80 photons and of γ ray D 12 photons per 100 captures in Ca^{40} (Ki 53e). See also Sa 51a, Br 51a, Ha 52b.

IV. $Ca^{40}(n,n)Ca^{40}$ $E_b=8.3$

For the calcium total neutron cross section see Adair (Ad 50). Many incompletely resolved resonances are found in the region from 30 up to 1000 kev. The cross section at $E_n=14$ Mev is 3.19±0.04 b (Co 52a).

V. $Ca^{40}(d,p)Ca^{41}$ $Q_m=6.1$

In Table LII are collected Q values and corresponding Ca^{41} levels from the $Ca^{40}(d,p)Ca^{41}$ reaction. Natural calcium targets were used in all these investigations. Only the intense groups found by magnetic analysis have been indicated in the Ca^{41} level diagram.

TABLE LII. $Ca^{40}(d,p)Ca^{41}$ reaction.

Author	Da 39	Sa 49	Ho 53e	Br 53e, Br 54
E_d (Mev)	3.1	3.9	8.13	2.5–7.0
Method	Al abs.	Al abs.	Al abs.	Magn. analysis
Ground-state Q value (Mev)	6.30	6.17±0.05	6.14±0.05	6.140±0.010
Ca^{41} levels (Mev)	0	0	0	0
	1.79	1.95±0.07	1.9 ±0.05	1.947±0.010
				2.015±0.010
		2.41±0.07	2.42±0.05	2.469±0.010
				2.582±0.010
				2.611±0.010
				2.675±0.010
			2.9 ±0.1	2.890±0.010
		(3.0 ±0.1)		2.967±0.010
				3.056±0.010
				3.200±0.010
		(3.3 ±0.1)		3.374±0.010
				3.401±0.010
		(3.5 ±0.1)		3.499±0.010
				3.529±0.010
			3.6 ±0.1	3.620±0.010
		(3.7 ±0.1)		3.737±0.010
		3.86±0.07		3.855±0.010
			3.96±0.05	3.950±0.010
			4.76±0.08	
			5.72±0.08	

Angular distributions of six proton groups have been measured. From Butler analysis $l_n=3$ ($J=5/2^-$ or $7/2^-$) is found for the ground-state group, $l_n=1$ ($J=\frac{1}{2}^-$ or $\frac{3}{2}^-$) for transitions to one or both of the doublet levels near 2.0 Mev and to the 2.42-Mev level, and $l_n=2$ ($J=\frac{3}{2}^+$ or $5/2^+$) for transitions to the levels at 3.96, 4.76, and 5.72 Mev. Shell-model assignments are discussed from these data and from the measured neutron capture probabilities (Ho 53c).

VI. $Sc^{41}(\beta^+)Ca^{41}$ $Q_m=5.9$

Radioactive Sc^{41} has been produced by the $Ca^{40}(d,n)Sc^{41}$ reaction at $E_d=8$ Mev. The half-life is 0.87±0.03 sec and the end point of the β^+ spectrum is measured by cloud chamber as 4.94±0.07 Mev (El 41). A recent measurement of the half-life yields 0.873 sec

(Ma 52a). The log *ft* value is 3.4 in agreement with other super-allowed transitions between mirror nuclei.

VII. Not observed are the reactions $A^{38}(\alpha,n)Ca^{41}$ ($Q_m=-5.2$), $K^{40}(p,\gamma)Ca^{41}$ ($Q_m=8.8$), $K^{40}(d,n)Ca^{41}$ ($Q_m=6.6$) and $Ca^{42}(\gamma,n)Ca^{41}$ ($Q_m=-11.4$).

A^{42}

(not illustrated)

This nucleus has been produced by successive capture of two neutrons in A^{40} in a nuclear reactor. Its presence was detected by observation of the 12.5 hr K^{42} daughter activity in milkings from the irradiated argon gas. From the fact that the milkings over a period of 400 days did not show a decrease in activity of more than 20 percent, it is concluded that the half life of A^{42} is longer than 3.5 yr and that the thermal neutron activation cross section of A^{41} is larger than 0.06 b (Ka 52a).

K^{42}

Adopted mass defect: -22.5 Mev

(The adopted mass defect is in agreement with the K^{42} β^- decay energy and with the Q values measured for the $K^{41}(n,\gamma)K^{42}$ and $K^{41}(d,p)K^{42}$ reactions.)

I. $K^{42}(\beta^-)Ca^{42}$ $Q_m=3.6$

The half-life is given as 12.2±0.2 hr (Wa 37), 12.4±0.2 hr (Hu 37), 12.44±0.10 hr (Si 47), 12.5±0.2 hr (Si 51), 12.44±0.08 hr (Ka 53), and 12.516±0.007 hr (Bu 53). See also Am 35, He 35a.

The β^- spectrum is complex. Measurements of the β^- spectrum end points and the γ-ray energy are collected in Table LIII.

The shape of the high-energy β^- spectrum and its *ft* value (log $ft=7.9$ and $\log(W_0^2-1)ft=9.7$) are in agreement with a $\Delta J=2$, yes, assignment which characterizes K^{42} as $J=2^-$ (Si 47, Sh 49). A direct measurement by magnetic resonance in an atomic beam yields also $J=2$ (Be 53). An assignment of $J=2^+$ to the 1.51-Mev level in Ca^{42} is in agreement with the *ft* value of the low-energy β^- branch (Sh 49) (log $ft=7.5$) and with the measured $\beta-\gamma$ angular correlation (Be 50a, St 51c).

No polarization of the γ rays emitted under an angle of the 90° with the β rays has been found, although some polarization is predicted from the measured $\beta-\gamma$ angular correlation (Ha 53b).

For a theoretical discussion of the K^{42} spin see De 53a.

TABLE LIII. Decay of K^{42}.

Author	Method	E_{β_1} (Mev)	E_{β_2} (Mev)	E_γ (Mev)
Ku 36	cl. chamber	4.4	1.4	
Bl 47	Al abs.	3.50±0.12 (70%)	2.1 and 1.4 (30%)	
Si 47	spectrom.	3.58±0.07 (75%)	2.04 (25%)	1.51
Si 47a	$\beta-\gamma$ coinc. spectrom.		1.92 (16%)	
Ka 53	scint. spectrom.			1.51 (20±1)%

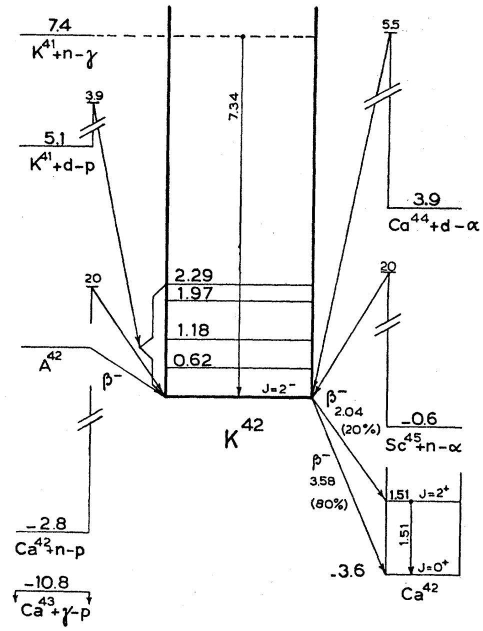

FIG. 40.

II. $A^{40}(\alpha,pn)K^{42}$ $Q_m=-13.1$

Radioactive K^{42} has been found from the bombardment of argon with 40-Mev α particles (Ov 47, Ov 49).

III. $K^{41}(n,\gamma)K^{42}$ $Q_m=7.4$

The thermal neutron absorption cross section of isotopic K^{41} is measured by pile oscillator as 1.19±0.09 b (Po 52a). From the activation of natural potassium samples the thermal neutron activation cross section is measured as ≈1.4 b (Ra 40), ≈1.5 b (On 41), 0.7 b (Si 41a), and 1.0±0.2 b (Se 47). At $E_n\approx1$ Mev (fission neutrons) the activation cross section is 2.9 mb (Hu 49, Hu 53a).

Energies of thermal neutron capture γ rays have been measured by pair spectrometer (see Table XLVII). One weak γ ray (line C) of $E_\gamma=7.34\pm0.02$ Mev could well correspond to the ground-state transition in K^{42} after capture in K^{41}. The intensity is 0.1 photon per 100 captures in natural potassium (Ba 53b, Ki 52). See also Br 53b.

IV. $K^{41}(d,p)K^{42}$ $Q_m=5.1$

From deuteron bombardments (at $E_d=3.9$ Mev) of potassium targets enriched to 87 percent in K^{41} content and range measurements of the resulting protons the following Q values have been found: 5.12±0.10, 4.50 ±0.12, 3.94±0.12, 3.15±0.18, and 2.83±0.12 Mev corresponding to the K^{42} ground state and levels at

0.62±0.07, 1.18±0.07, 1.97±0.15, and 2.29±0.07 Mev (Sa 50).

See also Po 40a, Cl 46a.

V. $Ca^{42}(n,p)K^{42}$ $Q_m=-2.8$

Radioactive K^{42} has been found from the fast neutron bombardment of calcium (He 35a, Wa 37, Hu 37). The cross section for $Be(d,n)$ neutrons ($E_d=15$ Mev) is 120±12 mb (Co 51).

VI. $Ca^{43}(\gamma,p)K^{42}$ $Q_m=-10.8$

Not observed.

VII. $Ca^{44}(d,\alpha)K^{42}$ $Q_m=3.9$

A weak K^{42} activity is found from the deuteron bombardment of calcium (Wa 37).

VIII. $Sc^{45}(n,\alpha)K^{42}$ $Q_m=-0.6$

Radioactive K^{42} has been found from the fast neutron bombardment of scandium (Am 35, He 35a, Hu 37, Wa 37d, Po 38, Wa 40a).

Ca^{42}

Adopted mass defect: −26.1 Mev (see "Introduction").

I. $K^{39}(\alpha,p)Ca^{42}$ $Q_m=-0.3$

From bombardments of natural potassium by ThC′ α particles and range measurements of the resulting protons Q values have been found of −0.89, −2.3, and −3.5 Mev, corresponding to Ca^{42} levels at 3.2 and 4.4 Mev (Po 36a, Li 37).

Recently the ground-state Q value has been remeasured by bombardments with cyclotron α particles of $E_\alpha=7.8$ Mev and range measurements yielding $Q_0=-0.18$ Mev. Several Ca^{42} levels might be present below $E_x=4$ Mev (Sc 53a).

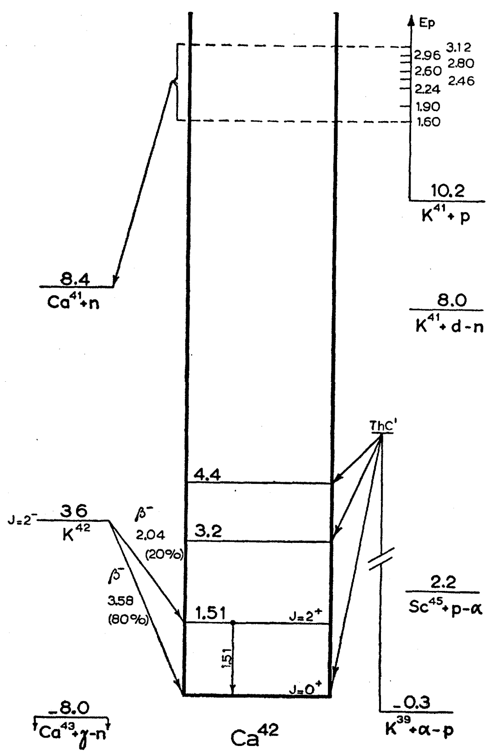

FIG. 41.

II. $K^{41}(p,n)Ca^{41}$ $E_b=10.2$ $Q_m=-1.2$

Incompletely resolved resonances are found between threshold ($E_p=1.25\pm0.02$ Mev) and $E_p=3.5$ Mev at 1.60, 1.90, 2.24, 2.46, 2.60, 2.80, 2.96, and 3.12 Mev (Br 50d, Ri 50).

III. $K^{42}(\beta^-)Ca^{42}$ See K^{42}

IV. The following reactions leading to Ca^{42} have not observed: $K^{41}(p,\gamma)Ca^{42}$ ($Q_m=10.2$), $K^{41}(d,n)Ca^{42}$ ($Q_m=8.0$), $Ca^{43}(\gamma,n)Ca^{42}$ ($Q_m=-8.0$) $Sc^{42}(\beta^+)Ca^{42}$ and $Sc^{45}(p,\alpha)Ca^{42}$ ($Q_m=2.2$).

K^{43}

(not illustrated)

Adopted mass defect: −24.9 Mev

(The adopted mass defect is based on the observed $K^{43}(\beta^-)Ca^{43}$ decay energy.)

I. $K^{43}(\beta^-)Ca^{43}$ $Q_m=0.8$

The half-life is given as 22.4 hr (Ov 49) and 21.5 hr (Ru 52b). The β^- decay is complex. By magnetic spectrometer two branches are found with end points of 0.81 and 0.24 Mev. There is a γ ray with $E_\gamma=0.4$ Mev as measured by Al absorption (Ov 49).

II. $A^{40}(\alpha,p)K^{43}$ $Q_m=-2.4$

Radioactive potassium with a half-life of 22.4 hr has been separated chemically from argon gas irradiated by 40-Mev α particles (Ov 49). No protons were observed from the bombardment of argon gas by ThC′ α particles (Po 37).

III. $Ca^{43}(n,p)K^{43}$ $Q_m=0.0$

Not observed.

IV. $Ca^{44}(\gamma,p)K^{43}$ $Q_m=-11.4$

Not observed.

Ca^{43}

Adopted mass defect: −25.7 Mev (see "Introduction")

I. $A^{40}(\alpha,n)Ca^{43}$ $Q_m=-2.4$

Several neutron groups are observed from the bombardment of argon with ThC′ α particles and detection

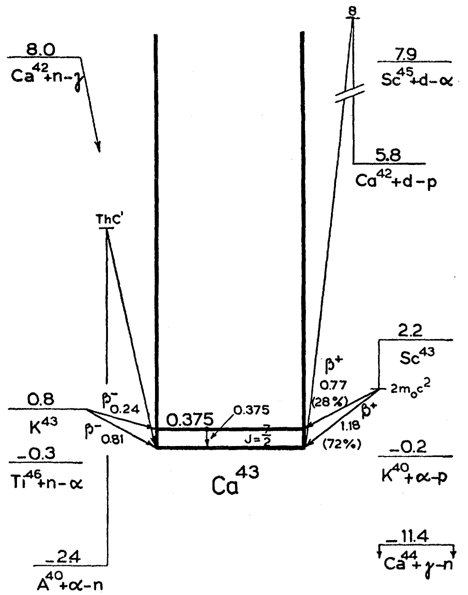

FIG. 42.

of neutrons with a BF_3 ionization chamber. The Q value corresponding to the most energetic neutrons is given as -5.6 ± 1.0 Mev (Po 38a, Po 37c). For resonances see Ca^{44}.

II. $K^{43}(\beta^-)Ca^{43}$ See K^{43}

III. $Ca^{42}(n,\gamma)Ca^{43}$ $Q_m=8.0$

The thermal neutron absorption cross section measured by pile oscillator from samples enriched in Ca^{42} is 39.7 ± 3.2 b (Po 52a).

IV. $Ca^{42}(d,p)Ca^{43}$ $Q_m=5.8$

At proton energies up to 6 Mev the ground-state Q value has been measured by magnetic analysis ($\vartheta=90°$) using enriched targets as $Q=5.70\pm0.02$ Mev (Br 53e). Levels in Ca^{43} are found at 0.38, 0.61, 1.00, and 1.40 Mev, all ±0.02 Mev (Br 54a).

V. $Sc^{43}(\beta^+)Ca^{43}$ $Q_m=2.2$

The half-life is given as 4.4 hr (Fr 35), 4.0 ± 0.1 hr (Wa 37, Wa 37a, Wa 40a), 4.4 hr (Sa 38), 3.92 ± 0.02 hr (Hi 45), 3.9 hr (Ha 52d), and 3.95 hr (Du 53). See also Ba 51.

TABLE LIV. Positron decay of Sc^{43}.

Author	Method	$E_{\beta_1^+}$ (Mev)	$E_{\beta_2^+}$ (Mev)	E_γ (Mev)
Wa 37a	cl. chamber	1.38		
Wa 40a	Al abs.	1.4 ± 0.1		
Hi 45, Bl 46c	Al abs.	1.22 ± 0.05		
Hi 45	spectrom.	1.11 ± 0.05		
Sm 42, Br 50e	spectrom.	1.15		
Ha 52d	spectrom.	1.18 ± 0.02 (72%)	0.77 ± 0.04 (28%)	0.375 ± 0.002
Nu 53	scint. spectrom.			0.375 ± 0.004 (25 ± 2)%

The β^+ decay of Sc^{43} is complex. Observed β^+ spectrum end points, relative intensities, and energies of γ rays are collected in Table LIV. Both β^+ transitions are allowed; log $ft=5.1$ for the 1.18 Mev branch and log $ft=4.7$ for the 0.77-Mev branch.

Several observers (Wa 40a, Hi 45, Pe 46, Ha 52d) report also a γ ray of about 1.1 Mev but this γ ray has to be assigned probably to the Sc^{44} decay (Ha 52d, Nu 53). In recent measurements its intensity is found to be lower than 5 percent (Nu 53).

The spin of Ca^{43} has been measured by magnetic resonance as $J=7/2$ (Je 53).

VI. $Ca^{44}(\gamma,n)Ca^{43}$ $Q_m=-11.4$

The maximum cross section measured by the neutron yield is four times that of the $Ca^{40}(\gamma,n)Ca^{39}$ reaction (Go 54a).

VII. The following reactions leading to Ca^{43} have not been observed: $K^{40}(\alpha,p)Ca^{43}$ ($Q_m=-0.2$), $Sc^{45}(d,\alpha)Ca^{43}$ ($Q_m=7.9$), and $Ti^{46}(n,\alpha)Ca^{43}$ ($Q_m=-0.3$).

K^{44}

(not illustrated)

From calcium targets bombarded by fast neutrons a potassium activity of 18 ± 1 min half-life was chemically separated. This may be K^{44} produced from the $Ca^{44}(n,p)K^{44}$ reaction (Wa 37b, Wa 40). See also Hu 43b.

Ca^{44}

Adopted mass defect: -28.7 Mev (see "Introduction")

I. $K^{44}(\beta^-)Ca^{44}$ See K^{44}

II. $Sc^{44}(\beta^+,E.C.)Ca^{44}$ $Q_m=3.6$

The half-life is given as 4 hr (Po 37a, Po 37b, Co 38, Bo 39), 4.0 ± 0.1 hr (Wa 37, Wa 37d, Br 50e), 4.1 ± 0.1 hr (Wa 37a, Wa 40a), and 3.92 ± 0.03 hr (Hi 45). See also Ge 38.

There exists also an isomeric state (Sc^{44m}) decaying to the Sc^{44} ground state through a 270-kev γ ray with a half-life which has been measured as 48 hr (Po 37a), 52 hr (Po 37b), 52 ± 2 hr (Wa 37, Wa 37a, Wa 37d, Wa 40a), 58.6 ± 0.7 hr (Hi 45, Ba 51), and 57 ± 2 hr (Br 50e).

The Sc^{44} ground state decays through β^+ emission followed by a γ ray of about 1.1 Mev. Measurements of the positron spectrum end point and energies of γ rays are collected in Table LV.

From $\beta^+-\gamma$ coincidence absorption measurements it is concluded that the β^+ spectrum is simple (Cu 50). The Kurie plot of the β^+ spectrum is straight down to 350 kev (Br 50e). The log ft value is 5.3. There is also K capture (Hi 45), about equally strong as β^+ emission (Br 50e). See also Ja 37.

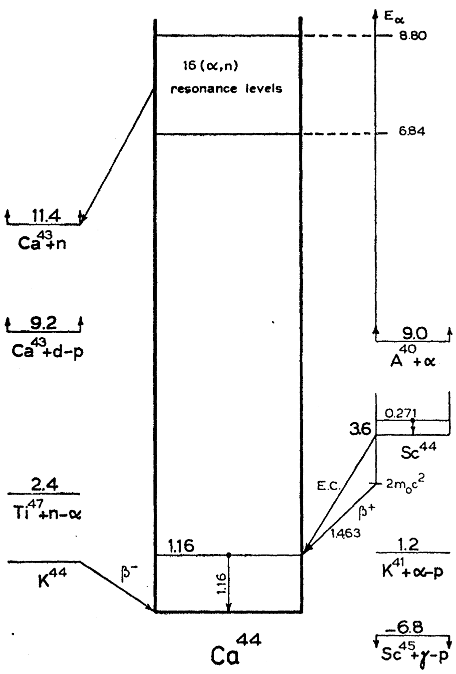

FIG. 43.

The internal conversion coefficient of the Sc^{44m} 270-kev γ ray has been given as $\alpha_K=0.5$ (He 41) and as $\alpha_K=0.070\pm0.012$ with $\alpha_K/\alpha_L=8\pm4$ (Sm 42).

See also Zy 34, He 35a, Wa 37c, Du 38, Bu 38, Ge 38, Wa 40, Ru 52b.

III. $A^{40}(\alpha,n)Ca^{43}$ $E_b=6.0$ $Q_m=-2.4$

Sixteen resonances have been found with ThC′ α particles by varying the gas pressure between source and target and counting the neutrons with a BF_3 counter at $E_\alpha=6.84$, 7.16, 7.35, 7.54, 7.70, 7.81, 7.95, 8.08, 8.17, 8.26, 8.37, 8.50, 8.58, 8.66, 8.75, and 8.80 Mev (Fu 38).

TABLE LV. Decay of Sc^{44} and Sc^{44m}.

Author	Method	Sc^{44} E_{β^+} (Mev)	E_γ (Mev)	Sc^{44m} E_γ (kev)
Wa 37a	cl. chamber	1.63		
Ja 37	cl. chamber	1.1 ±0.1		
Wa 40a	Al abs.	1.50 ±0.05	1.0 ±0.1	250
Wa 40a	spectrom.			255
He 41	spectrom.			260
Sm 42	spectrom.	1.45 ±0.01		269.3±1
Hi 45, Bl 46c	Al abs.	1.43 ±0.05	1.33	280
Pe 46	spectrom.		(1.05)	
Br 50e	spectrom.	1.463±0.005	1.16±0.02	271.3±0.7
Cu 50	Al abs.	1.54	1.2	
Ha 52d	spectrom.		1.15	

IV. The following reactions leading to Ca^{44} have not been observed: $K^{41}(\alpha,p)Ca^{44}$ ($Q_m=1.2$), $Ca^{43}(n,\gamma)Ca^{44}$ ($Q_m=11.4$), $Ca^{43}(d,p)Ca^{44}$ ($Q_m=9.2$), $Sc^{45}(\gamma,p)Ca^{44}$ ($Q_m=-6.8$), and $Ti^{47}(n,\alpha)Ca^{44}$ ($Q_m=2.4$).

Ca^{45}

(not illustrated)

Adopted mass defect: −27.7 Mev

(The Ca^{45} mass defect is derived from the Sc^{45} mass by means of the $Ca^{45}(\beta^-)Sc^{45}$ energy release. It agrees excellently with the mass derived from the $Ca^{44}(d,p)Ca^{45}$ Q value.)

I. $Ca^{45}(\beta^-)Sc^{45}$ $Q_m=0.2$

The half-life is given as 180±10 days (Wa 40), 152 days (Ma 47, Ru 52b), 180 days (Se 47), 150 days (Ba 51), and 163.5±4 days (De 53). See also Po 38.

The β^- spectrum is simple and no γ rays are observed (So 48, Me 49, Ru 52b). The end point is measured by Al absorption as 190 kev (Wa 40), 210 kev (Ma 47), 260±5 kev (So 48), 260 kev (Si 50a), 220±10 kev (Me 49) and 300 kev (Ru 52b), and by magnetic spectrometer as 255±4 kev (Ke 50), 261±4 kev (Ma 53c), and 254±3 kev (Ma 50c). The average β^- ray energy is 74.6±3 kev (Ca 52). The Kurie plot is straight down to 50 kev (Ke 50, Ma 50c). The logft value is 5.7.

II. $Ca^{44}(n,\gamma)Ca^{45}$ $Q_m=7.4$

The thermal neutron activation cross section is 0.63±0.13 b (Se 47). See also Wa 40, De 53.

III. $Ca^{44}(d,p)Ca^{45}$ $Q_m=5.2$

Radioactive Ca^{45} has been produced by deuteron bombardment of calcium (Wa 40).

A preliminary value for the ground-state Q value measured by magnetic analysis (E_d up to 6 Mev, $\vartheta=90°$, enriched targets) is $Q=5.19\pm0.02$ (Br 53e). Levels in Ca^{45} are observed at 0.18, 1.43, 1.89, 2.24, 2.39, and 2.84 Mev, all ±0.02 Mev (Br 54a).

IV. $Ca^{46}(\gamma,n)Ca^{45}$

Not observed.

V. $Sc^{45}(n,p)Ca^{45}$ $Q_m=0.6$

Radioactive Ca^{45} is produced by pile neutron bombardment of scandium (So 48). See also Wa 40.

VI. $Ti^{48}(n,\alpha)Ca^{45}$ $Q_m=-1.9$

The cross section for production of Ca^{45} from bombardment of titanium by epi-cadmium pile neutrons is 3×10^{-32} cm^2 (He 48).

Ca^{46}

(not illustrated)

The mass defect of Ca^{46} is unknown.

I. $Sc^{46}(\beta^-)Ti^{46}$
$Sc^{46}(\beta^+,E.C.)Ca^{46}$

Radioactive Sc^{46} ($\tau=85$ days) decays by β^- emission and not by electron capture (Mi 47) and the β^+ emission is less than 1.6×10^{-5} per β^- (Mi 51), the former in contradiction with early experiments (Wa 39a, Me 45).

II. $Ti^{49}(n,\alpha)Ca^{46}$

Not observed.

Ca^{47}

(not illustrated)

Adopted mass defect: -28.7 Mev

(The Ca^{47} mass is connected to the Ti^{47} mass through the $Ca^{47}(\beta^-)Sc^{47}(\beta^-)Ti^{47}$ decay. The Ca^{47} decay energy (1.76 ± 0.03 Mev) reported by Cork *et al.* (Co 53a) has been used, but for the Sc^{47} decay energy the value (0.622 ± 0.005 Mev) given by Cheng and Pool (Ch 53a) has been prefered.)

I. $Ca^{47}(\beta^-)Sc^{47}$ $Q_m=1.7$

The half-life is given as 5.8 days (Ma 47), 4.8 ± 0.2 days (Ba 51), 4.8 ± 0.5 days (Co 53), 4.3 ± 0.2 days (Ma 53c), and 5.35 ± 0.10 days (Co 53a).

There is general agreement about a γ ray of $E_\gamma=1.3$ Mev (Ma 47, At 53, Co 53a) in the decay, but the problem of the decay scheme is all but solved.

The β^- spectrum end point has been measured by Al absorption as 1.1 Mev (Ma 47) and 1.2 Mev (Ba 51), but recent measurements indicate two branches. By Al absorption end points of $E_{\beta1}=2.0\pm0.2$ Mev (23 percent) and $E_{\beta2}=0.8\pm0.2$ Mev (77 percent) are found (At 53) in agreement with $E_{\beta1}=2.060\pm0.020$ Mev (19 percent) and $E_{\beta2}=0.685\pm0.006$ Mev (81 percent) (Ma 53c). However, an investigation by magnetic spectrometer gives $E_{\beta1}=1.4\pm0.1$ Mev (40 percent, log $ft=7.7$) and $E_{\beta2}=0.46\pm0.02$ Mev (60 percent, log $ft=5.7$). The γ spectrum has also been studied in a magnetic spectrometer (by means of photoelectrons from a Pb radiator and conversion electrons) and by scintillation spectrometer. Gamma rays were found of $E_{\gamma1}=1303\pm40$ kev, $E_{\gamma2}=800\pm25$ kev, $E_{\gamma3}=495\pm15$ kev, $E_{\gamma4}=234.0$ kev and $E_{\gamma5}=149.5$ kev. Conversion electrons are reported from all but the two hardest γ rays. Coincidences are observed between hard γ rays ($E_\gamma>0.25$ Mev) and β particles, and between γ rays of about 0.2 Mev and energetic β particles ($E_\beta>0.6$ Mev). A decay scheme based on these data shows β_1 in triple cascade with γ_4 and γ_5, and β_2 with either γ_1 or with γ_2 and γ_3 (Co 53a).

There is also a controversy about the decay of the 3.4 day Sc^{47} daughter. Whereas on the one hand a γ ray of $E_\gamma=159.5$ kev is reported in cascade with a single β^- spectrum of end point 0.64 ± 0.03 Mev (Co 53a), also a decay scheme is proposed consisting of a branch with $E_{\beta^-}(\max)=0.622\pm0.005$ Mev [(34 ± 4) percent] and a branch with $E_{\beta^-}(\max)=0.435\pm0.008$ Mev followed by a γ ray of $E_\gamma=0.185\pm0.007$ (Mev) (Ch 53a).

II. $Ca^{46}(n,\gamma)Ca^{47}$

Radioactive Ca^{47} has been produced by pile-neutron irradiation of calcium enriched in Ca^{46} content (Co 53a). See also Co 53.

III. $Ca^{48}(d,dn)Ca^{47}$ $Q_m=-9.8$

Radioactive Ca^{47} has been produced by bombardment of calcium with 26-Mev deuterons (At 53).

IV. $Ti^{50}(d,\alpha p)Ca^{47}$ $Q_m=-5.5$

Radioactive Ca^{47} has been produced by this reaction with 26 Mev deuterons (At 53).

V. The following reactions leading to Ca^{47} have not been reported: $Ca^{46}(d,p)Ca^{47}$, $Ca^{48}(\gamma,n)Ca^{47}$ ($Q_m=-9.8$), and $Ti^{50}(n,\alpha)Ca^{47}$ ($Q_m=-3.2$).

Ca^{48}

(not illustrated)

Adopted mass defect: -30.1 Mev (see "Introduction")

I. $Ca^{48}(\beta^-)Sc^{48}$ $Q_m=0.4$

A search for β^- activity of natural calcium has been unsuccessful. It is concluded that the half-life of Ca^{48} is longer than 2×10^{16} yr (Jo 52). No 44 hr Sc^{48} is found in milkings from natural calcium (Ko 48). Theoretical predictions of the Sc^{48} spin are as high as $J=6$ or 7 (Ku 53, see also De 53a). A spin value of at least 6 follows from the Sc^{48} β decay (Ca 53a). See also Fr 52.

The threshold of the $Ca^{48}(p,n)Sc^{48}$ reaction (measured from targets enriched in Ca^{48} content) is smaller than 0.65 Mev. The energy release in the $Ca^{48}(\beta^-)Sc^{48}$ decay is thus at least 0.13 Mev (Tr 53).

II. $Ca^{48}(\beta^-\beta^-)Ti^{48}$ $Q_m=4.3$

A sample of 72 mg Ca enriched to 89 percent in Ca^{48} has been used in a search for double β^- emission. The number of coincidences observed in two scintillation spectrometers would lead to a half-life of $(5\pm2)\times10^{16}$ yr and a β^- end point of 3.7 ± 0.5 Mev (Mc 53).

Ca^{49}

(not illustrated)

Adopted mass defect: -26.8 Mev

(The Ca^{49} mass defect is based on the Ca^{48} mass and the observed $Ca^{48}(d,p)Ca^{49}$ Q value.)

I. $Ca^{49}(\beta^-)Sc^{49}$ $Q_m=5.5$

The half-life of Ca^{49} is 8.5 min (Ma 50b). Previously half-lives were assigned to Ca^{49} of 30 min and 2.5 hr (Wa 40, Hu 43b, Se 47, Co 51).

The 57 min daughter Sc^{49} has been found in milkings from pile-irradiated calcium samples enriched in Ca^{48}.

The Ca^{49} β^- spectrum end point is measured by Al absorption as about 2.7 Mev. Hard γ rays are found in the Ca^{49} decay (Ma 50b).

II. $Ca^{48}(n,\gamma)Ca^{49}$ $Q_m=5.0$

The Ca^{49} activity has been observed in pile-irradiated samples enriched to 62 percent in Ca^{48} content (Ma 50b). The cross section for fission neutrons ($E_n\sim1$ Mev) is 1.9 mb (Hu 53a).

III. $Ca^{48}(d,p)Ca^{49}$ $Q_m=2.8$

The ground-state Q value is reported as $Q=2.8\pm0.3$ Mev (cyclotron deuterons; enriched target; proton scintillation spectrometer) (Wa 53b).

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