Decay of Na^{26}†

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The bombardment of high-purity natural magnesium targets with fast neutrons from the $Li^7(d,n)Be^8$ reaction ($E_n \lesssim 24$ Mev) yielded, in addition to activities associated with well-known isotopes, an activity having an experimental half-life of 1.03±0.06 sec. Scintillation spectrometer measurements showed a (1.82± 0.03)-Mev gamma ray and a (6.7±0.3)-Mev beta group decaying with the 1.03-sec half-life. The 6.7-Mev beta group was found to be in coincidence with the 1.82-Mev gamma ray. The assignment of the (1.03±0.06)-sec half-life to Na^{26} produced in the reaction $Mg^{26}(n,p)Na^{26}$ and the proposed decay scheme are supported by internally consistent arguments based on the known characteristics of the reaction products and their decay modes; the half-life studies using both beta and gamma radiation; the features of experimental beta and gamma spectra; and nuclear systematics. The decay of the ground state of Na^{26} takes place in part by a (6.7±0.3)-Mev beta transition to the (2+) first excited state of Mg^{26}. The intensities of the beta transitions to the (2+) second excited state and (0+) ground state are less than 0.1 of the intensity of the (6.7±0.3)-Mev transition. The possible ground-state spin and parity assignment for Na^{26} is either 1+, 2+, or 3+. A weak theoretical argument against spin 1 is presented. The present experimental measurements alone will not reduce the ambiguity in the spin assignment. A Na^{26}—Mg^{26} mass difference of 8.5±0.3 Mev is derived from the known level structure of Mg^{26} and the beta transition energy measured in the present investigation.

I. INTRODUCTION

IN an investigation of the radioactivities following the bombardment of high-purity natural magnesium targets with fast neutrons from the $Li^7(d,n)Be^8$ reaction ($E_n \lesssim 24$ Mev), an activity was observed which we have ascribed to the decay of Na^{26}. After the completion of the measurements and reduction of the experimental data, it was found (in connection with the preparatory literature search for the writing of this report) that the observation of an activity assigned to Na^{26} had been published.[1] This report had been overlooked in the preliminary literature search. These experimenters reported that the irradiation of natural magnesium metal and MgO highly enriched in Mg^{26} with 14.8-Mev neutrons produced a new activity with a half-life of 1.04±0.03 sec which is assigned to Na^{26} produced by the $Mg^{26}(n,p)Na^{26}$ reaction. The activity was reported to "consist mainly of high energy (>5 Mev) beta particles." The present results are in agreement with these conclusions and include further experimental information concerning the new isotope Na^{26} and its decay modes.

II. EXPERIMENTAL APPARATUS

The experimental apparatus, circuit configurations, and some of the experimental techniques used in the present investigation have been described elsewhere.[2,3] There are some important points of difference and additions which will be discussed below.

The lead cave and graded absorber which had formerly housed the gamma-ray detector, a 3×3-in. NaI(Tl) crystal mounted on a 6363 DuMont photomultiplier, were removed. The graded collimator between the source and counter was also removed. The pulses from the gamma-ray detector were passed through a gain-one-or-ten preamplifier to either the half-life measuring system or the multichannel pulse-height analyzer.

The beta detector consisted of a cylindrical ($1\frac{1}{2}$-in. height ×$2\frac{1}{2}$-in. diameter) Pilot-*B* plastic phosphor optically coupled to a 6363 DuMont photomultiplier tube. The phosphor was covered with an aluminum light shield. The window through which the beta particles entered the phosphor was 1-mil aluminum foil. The pulses from the beta detector were amplified by a gain-of-ten preamplifier and fed into either the half-life measuring system or the multichannel pulse-height analyzer. The resolution obtained for the 0.624-Mev internal conversion line of Ba^{137m} was 15%. The beta spectrometer was calibrated using well-known internal conversion lines and/or beta-spectra end points.

Target carriers made from several different plastic materials (Lucite, Araldite, and polystyrene) were used during the course of these measurements. It was found that both Lucite and Araldite were unsatisfactory because of the N^{16} activity produced by the reaction $O^{16}(n,p)N^{16}$ in the target carrier itself. For the counting programs and procedures required in these measurements, activity from polystyrene carriers made no detectable contribution to the experimental beta or gamma spectra.

The magnesium targets were cylinders ($\frac{3}{4}$-in. diameter ×$\frac{7}{16}$-in. height) of vacuum distilled magnesium metal.[2,4] Four similar targets, short bombardments, and scheduled measurements were used to avoid the accumulation of the longer lived activities. The targets, carriers, and carrier hardware could be interchangeably assembled so that the contributions to the total spectrum of each, if any, could be systematically studied.

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[1] N. J. Nurmia and R. W. Fink, Nuclear Phys. **8**, 139 (1958).

[2] E. L. Robinson and O. E. Johnson, Phys. Rev. **120**, 1321 (1960).

[3] R. P. McLean, Master of Science thesis, Purdue University, Lafayette, Indiana, August, 1958 (unpublished).

[4] D. Geiselman and A. G. Guy, Trans. Am. Inst. Mining Met. Petrol. Engrs. **215**, 814 (1959).

The beta spectrum in coincidence with energy-selected gamma radiation was measured by positioning a gamma-ray detector coaxially with the beta detector and on the opposite side of the cylindrical source from the beta detector. The pulses from the beta detector were delayed and passed to the multichannel analyzer. The pulses from the gamma detector were amplified and pulse-height analyzed in a single-channel differential discriminator. The output of the discriminator was shaped, delayed, and passed into the prompt coincidence gate of the multichannel analyzer. The resolving time of this coincidence system was ~ 1.5 μsec.

The neutrons used in the irradiations were produced using the reaction $Li^7(d,n)Be^8$. The 9.7-Mev external deuteron beam of the Purdue University 37-in. cyclotron was focussed by a set of quadrupole magnets; collimated; and passed through a 1-mil aluminum window, $\frac{3}{8}$ in. of air, and a second 1-mil aluminum window before striking a $\frac{1}{16}$-in. thick lithium target. The nominal deuteron current and energy at the lithium target were ~ 0.5 μa and ~ 8.8 Mev. The bombardment position for the magnesium cylinders was $\frac{1}{4}$ in. directly behind the lithium target. The Q value for the reaction $Li^7(d,n)Be^8$ is ~ 15 Mev, and the reaction neutron spectrum is known to be complex. A maximum neutron energy of ~ 24 Mev could be expected.

III. MEASUREMENTS, RESULTS, AND DISCUSSION

Many nuclear reactions are energetically possible when natural magnesium is irradiated with neutrons from the Li^7-d reaction. The identification of the unstable reaction products was accomplished using measurements of the half-lives of various portions of the gross beta and gamma spectra as well as measurements of the beta and gamma spectra proper.

The gamma spectra were measured using a series of bombardment and counting programs such that the components of the gross spectra due to isotopes having different half-lives could be studied. A gamma spectrum was measured using 60-sec counting periods starting 20 sec after a 30-sec irradiation. A background correction was made. The photopeaks and general features of this spectrum could be consistently interpreted by assuming that Mg^{27}, ~ 9.5 min; Na^{25}, ~ 60 sec; Na^{24}, ~ 15 hr; Ne^{24}, ~ 3.4 min; and Ne^{23}, ~ 38 sec were produced in the irradiation.[5] This particular program was intended to reduce the contribution of the shorter lived isotopes. A second type of measurement of the gamma spectrum was made which would tend to enhance the net contribution of the shorter lived isotopes. In these measurements the target was irradiated T_B sec; the beginning of the counting period was delayed T_{D1} sec after the end of irradiation; the spectrum was measured for T_{C1} sec; after a time interval T_{D2} sec, a second measurement of the spectrum was made for T_{C2} sec. A difference-spectrum was formed from the two individual spectra thus obtained. A series of similar measurements was made and the difference-spectra obtained after each bombardment were summed to form the final spectrum. A number of such difference-spectra were formed with various combinations of time intervals. The resulting gamma spectra were used in the identification and assignment of the observed activities. In Fig. 1 a gamma spectrum obtained using a program in which $T_B=2.2$ sec, $T_{D1}=0.21$ sec, $T_{C1}=T_{C2}=3.0$ sec, and $T_{D2}=5$ sec (this will be referred to as the short program). The peak at 1.82 ± 0.03 Mev and the less prominent one at 0.520 ± 0.015 Mev are the only indications of gamma-ray full-energy peaks in the spectrum. The peak at 0.520 ± 0.015 Mev was attributed to annihilation radiation associated with the positron decay of Mg^{23}, ~ 12 sec, produced by $Mg^{24}(n,2n)Mg^{23}$

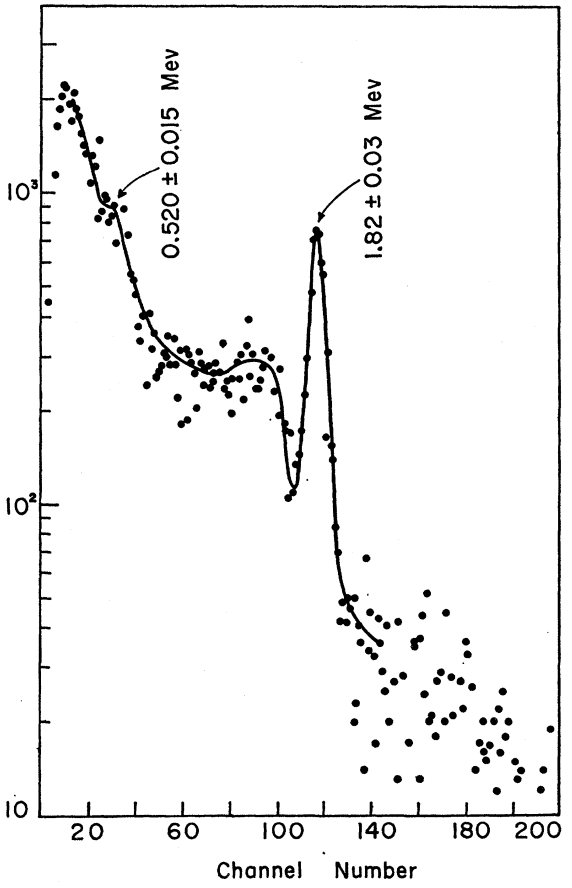

FIG. 1. A gamma-ray spectrum from neutron-irradiated natural magnesium targets formed from the difference of two spectra: the first measured over a 3-sec time interval 0.21 sec after a 2.2-sec bombardment; the second measured over a 3-sec interval 8.21 sec after the bombardment.

[5] It may be generally assumed, unless otherwise specified, that the values for various nuclear properties referred to in this report have been taken from one or more of the following compilations of nuclear data: P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957); D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958); *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington 25, D. C., 1958–1960).

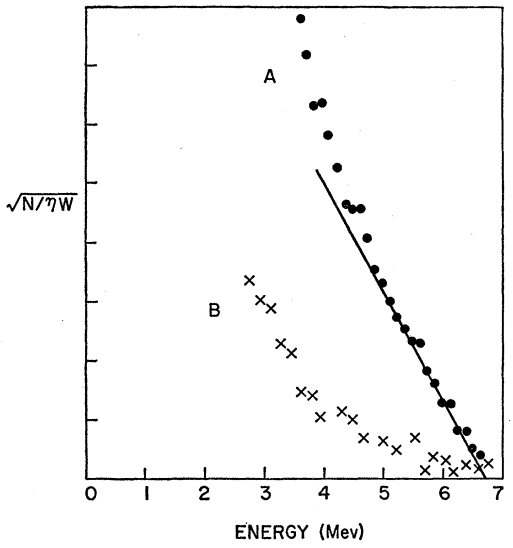

FIG. 2. Fermi plots of the beta spectra associated with the decay of isotopes produced by neutron irradiation of thick natural magnesium targets. The points labelled *A* correspond to the gross beta spectrum with the short program (see text). The points labelled *B* correspond to the beta spectrum in coincidence with the 1.82-Mev gamma ray using a short program. The Fermi function was assumed to be constant.

and the annihilation of positrons from external pair production. Comparison with gamma spectra obtained with other programs indicated that the contribution of the long-lived components had been effectively reduced. Using an identical program, the gamma spectrum up to an energy of 9 Mev was measured and no evidence was found for other gamma rays.

Half-life determinations were made by counting the gamma radiation in a 0.180-Mev energy interval centered at 1.82 Mev a period of 0.21 sec after a 2.2-sec neutron irradiation. The half-life associated with the 1.82-Mev photopeak was found to be 0.97±0.10 sec. A second series of half-life measurements were made in which all the pulses from the beta detector corresponding to pulses above a given energy were used. The energy-bias and experimental half-life for the short-lived component were: 1.1 Mev; 1.01±0.05 sec; 1.4 Mev, 1.06±0.05 sec; 1.8 Mev, 1.06±0.05 sec; 2.4 Mev, 1.06±0.06 sec; 3.0 Mev, 1.07±0.08 sec; 4.1 Mev, 1.11±0.10 sec; 4.7 Mev, 0.97±0.10 sec. The average experimental half-life resulting from all such measurements is 1.05±0.03 sec which is the same, within experimental errors, as that found for the 1.82-Mev gamma radiation. From these measurements it was concluded that the beta radiation with an energy greater than 4.7 Mev is associated with the 1-sec activity and the high-energy radiation (>4.7 Mev) has only a single short half-life associated with it, 1.05±0.03 sec. A half-life of 1.03±0.06 sec, based on all experimental measurements, is assigned to Na^{26}. The error was determined from statistical considerations as well as an appraisal of the various experimental measurements and the methods used in the analysis of the data.

The same program and procedure used in measuring the gamma spectrum described previously (the short program) was used to measure the beta spectrum. The neutron-irradiated magnesium targets constituted extremely thick beta sources since the radioisotopes were produced more or less uniformily through the body of the target. The experimental beta distribution extended to 6.6±0.3 Mev. In Fig. 2 (points labelled *A*) is a Fermi plot resulting from this beta distribution assuming the Fermi function to be energy independent. The maximum beta energy obtained by a linear extrapolation of this Fermi plot is 6.7±0.3 Mev. Also in Fig. 2 (points labelled *B*) is shown a Fermi plot made from the experimental beta spectrum in coincidence with the 1.82-Mev gamma radiation. The counting statistics in the coincidence spectrum were very poor. However, a linear fit of the points corresponding to energies greater than ~4 Mev yields an end point which within statistical and experimental errors is in agreement with that obtained without the coincidence requirement. The Fermi plots were utilized only as an aid in obtaining the end-point energy. The measurements of the beta distribution support the conclusion that there is a 6.7±0.3-Mev beta transition in coincidence with the 1.82-Mev gamma ray.

Subsidiary measurements were made which proved conclusively that the 1.03-sec activity arises from the magnesium target and not other materials in either the experimental area or the pneumatic transfer system proper. The chemical analysis of the magnesium[2,4] used,

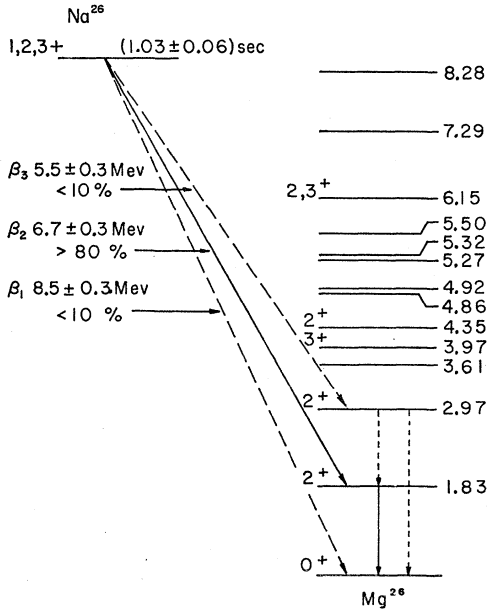

FIG. 3. The level structure of Mg^{26} as taken from recent compilations of nuclear data (see reference 5). The proposed decay scheme of Na^{26} is that resulting from the present investigation.

and the investigations reported elsewhere[2] constitute strong evidence for the purity of the target material. The 1.03-sec activity is therefore assigned to an isotope produced by the reaction of neutrons with one of the stable isotopes of natural magnesium.

Consideration of each nuclear reaction (involving neutrons up to an energy of ~24 Mev and any one of the stable isotopes of magnesium) which is energetically possible results in the conclusion that there is no known product isotope with a 1-sec half-life except Na^{26}(1.04±0.03 sec).[1] Assuming the correct assignment to be Na^{26}, there would be beta decay to one or more of the states of Mg^{26}. The level structure of Mg^{26} is well known and is shown in Fig. 3 as taken from recent compilations of nuclear data.[5] The remainder of Fig. 3 is the proposed decay scheme of Na^{26} as deduced from the results of this investigation. The 1.82-Mev gamma ray observed in this investigation would then correspond to the de-excitation of the (2+) first excited state which is presumably populated by the 6.7-Mev beta transition from the ground state of Na^{26}. The assignment of 2+ for the second excited state of Mg^{26} suggests the possibility of a 5.56-Mev beta transition. If this beta transition did occur, the subsequent depopulation via a direct 2.97-Mev gamma transition to the ground state (14%) or a 1.14-Mev gamma transition (86%) to the 1.82-Mev state would be expected. Analysis of the gamma-ray spectra obtained using the short program yielded the result that the intensity of the 1.14-Mev gamma is less than 0.1 that of the 1.82-Mev gamma. This implies that the beta branching to the 2.97-Mev state is less than ~12% of that to the 1.82-Mev state. Analysis of the various measurements of beta spectra indicate that the beta transition between the ground states of Na^{26} and Mg^{26} is less than 0.1 the intensity of the 6.7-Mev group.

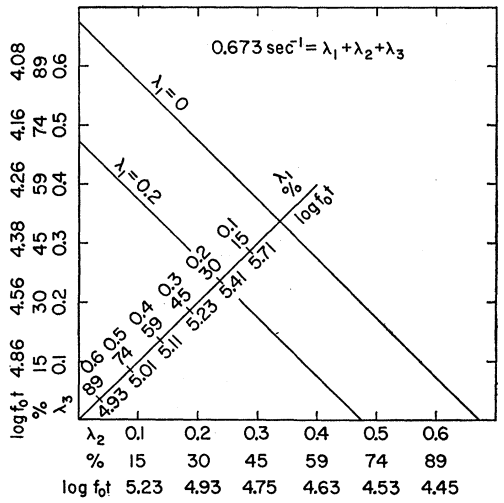

FIG. 4. Plot of the intersection of the plane $0.673=\lambda_1+\lambda_2+\lambda_3$ with the $\lambda_2-\lambda_3$ plane for various values of λ_1, where λ_1, λ_2, and λ_3 are the partial transition probabilities of the beta groups which may possibly be associated with the decay of Na^{26}. The text should be consulted for assumptions and details related to the construction and significance of this graph.

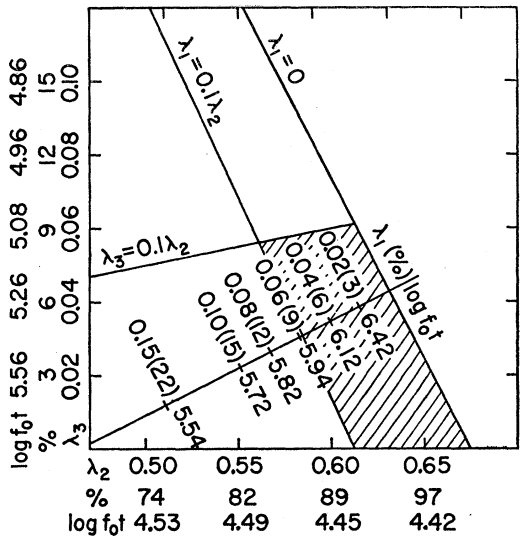

FIG. 5. An expanded portion of the graph in Fig. 4 with the experimental limits shown. The cross-hatched region corresponds to those points whose coordinates (λ_1, λ_2, λ_3) are consistent with the transition probabilities allowed by the experimental results.

A direct application of the shell model yields the alternative spin assignments 1, 2, 3, 4, or 5 and even parity for the ground state of Na^{26}. In the discussion to follow the spins of 4 and 5 are ruled out because of the allowed character of the 6.7-Mev beta group. A weak argument for eliminating spin 1 as a possibility will be presented leaving either 2 or 3 as the more probable spin of the Na^{26} ground state.

In the following discussion it will be assumed that only three beta groups are associated with the ground state of Na^{26}: β_1 to the ground state of Mg^{26}, 8.5 Mev; β_2 to the first excited state, 6.7 Mev; and β_3 to the second excited state, 5.5 Mev. The sum of the three partial transition probabilities λ_1, λ_2, and λ_3 corresponding to the beta branches β_1, β_2, and β_3 is equal to 0.673 sec^{-1}. Figure 4 is a graph of the family of straight lines in the λ_2-λ_3 plane corresponding to the various values of λ_1. The scales on the λ_2 and λ_3 axes indicate the partial transition probability, $\log f_0 t$ values, and branching percentages. The spin assignments for the first and second excited states of Mg^{26} are both 2+; therefore, the orders of forbiddenness of the corresponding beta branches would be the same. In particular, if the ground-state spin of Na^{26} is 1, 2, or 3, both β_2 and β_3 would be allowed transitions and would be expected to have log $f_0 t$ values in the range from ~4 to ~7. It has been established experimentally that $\lambda_3<0.1\lambda_2$ while λ_1 is definitely less than 0.1 λ_2 and is most probably *much less* than λ_2. Figure 5 is an expanded portion of the graph of Fig. 4 with the experimental limits clearly indicated. The cross-hatched region corresponds to those points whose coordinates (λ_1, λ_2, λ_3) are consistent with the experimental results. It should be noted that unless the branching of β_1 is substantially less than 3%,

the range of log f_0t values for this transition falls within that normally associated with allowed transitions and an assignment of 1+ for the Na^{26} could be inferred. It then follows that both β_2 and β_3 would be allowed transitions of the Gamow-Teller type. The classification of β_1 as a forbidden transition on the basis of its log f_0t value, with any certainty, requires that the intensity of β_1 be shown experimentally to be much less than 3%. Though this may indeed be the case, the present measurements neither exclude nor support such a conclusion. If β_1 is a first forbidden transition, implying a ground-state spin of 2+ or 3+ for Na^{26}, then β_2 and β_3 would still be allowed transitions consistent with the experimental implications.

Making the plausible assumption that the first excited state and the ground state of Mg^{26} are the same shell-model configuration, an assignment of 1+ for the ground-state spin appears unlikely because the log f_0t for the ground-state group must be greater than ~5.9 and that of the first excited state must be less than ~4.5. (See Fig. 5). Under the weak assumption concerning the similarity of the shell-model configurations for the two final states of the beta transitions, the log f_0t values would be expected to be more nearly equal.

IV. CONCLUSIONS

In the preceding sections arguments and supporting experimental evidence have been presented for the following conclusions: (1) A radioisotope with a half-life of 1.03±0.06 sec is produced in the bombardment of pure magnesium targets with Li^7-d neutrons (neutron energy up to ~24 Mev). (2) The observed half-life is that of Na^{26} produced in the reaction $Mg^{26}(n,p)Na^{26}$. (3) The decay of the ground state of Na^{26} takes place in part by a beta transition ($E_0=6.7\pm0.3$ Mev, an allowed transition) to the first excited state of Mg^{26}. (4) The Na^{26}-Mg^{26} mass difference is 8.5±0.3 Mev. (5) The intensity of a beta transition to the second excited state of Mg^{26} is less than 0.1 that of the first excited state transition. (6) A ground-state to ground-state beta transition definitely is less than 0.1 the intensity of the first excited state beta transition and is probably much weaker. (7) The possible spin and parity assignment for the Na^{26} ground state is 1+, 2+, or 3+ with a weak argument against 1. These conclusions are summarized graphically in Fig. 3.

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