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Radioactive Decay of Nb^{95}†

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The decay of Nb^{95} was investigated in order to check on the unusually short comparative half-life which had been reported for the twice-forbidden ground state to ground state beta transition. It was found that the 0.924-MeV beta group has an abundance of only 0.075% rather than the 1 or 2% reported previously. As a consequence, $\log ft \geq 10.8$ rather than 9.7. The main decay is by a 159.7±0.5-keV beta transition followed by a 764.5±0.5-keV gamma ray. The gamma transition appears to be $E2$ with a $K/(L+M)$ internal conversion ratio of 7.5±0.1 and $\alpha_K = (1.1\pm0.1)\times10^{-3}$. No evidence was found for an additional 752-keV gamma transition.

I. INTRODUCTION

THE highest energy beta transition in the decay of Nb^{95} is of particular interest because the value for the comparative half-life, on the basis of the intensity and end-point energy measurements,[1] is one of the smallest reported for a $\Delta I = 2$, *no* transition of the second-forbidden type. Most well-measured transitions of this kind have comparative half-lives which lie in the range[2] $\log ft = 12.2$ to 13.5. Fe^{59} seems to be an exception. The highest energy 0.3% group of Fe^{59} appears to have the value[3] $\log ft = 10.96$. This is an order of magnitude larger than the value $\log ft = 9.7$ reported for Nb^{95}. Only two attempts to determine the ft value of the highest energy transition of Nb^{95} have been reported.[1,4] Since the experimental measurements yield such an unusually low value for the comparative half-life for this presumably twice-forbidden transition, it seems worthwhile to consider the reasons for supposing that this is such a transition and then to reexamine the measurements of the β decay of Nb^{95} by earlier investigators.[5]

The reasons that the low intensity, highest energy transition of Nb^{95} is interpreted as belonging to the second forbidden class, $\Delta I = 2$, *no* are as follows: This transition is from the ground state of Nb^{95} to the ground state of Mo^{95}. The ground state of Nb^{95} has been assigned[5] the spin and parity $\frac{9}{2}^+$, on the basis of the shell model and in analogy with the better known Nb^{93}. The ground state[5] of Mo^{95} has been measured as $\frac{5}{2}$ and has been assigned a positive parity on the basis that the nuclear magnetic moment belongs to the $d_{5/2}$ Schmidt group.

The experimental results which lead to the unusually low comparative half-life should be reviewed. First, Cork *et al.* reported[4] that although the data points for the highest energy group were "not subject to the best statistics," the high-energy component appeared to comprise about 2% of the total number of electrons in the β decay and that the upper energy limit was 910±30 keV. This would lead to a $\log ft$ value approximately equal to 9.7. A more recent measurement for this transition, reported[1] by Drabkin *et al.*, gives the following values for this group:

$$E_0 = 930\pm20\text{ keV};\quad 1.0\pm0.5\%;\quad \log ft = 9.7.$$

Since there is some disagreement concerning the intensity for this transition and since both measurements lead to the unusually low ft value, it seemed desirable to attempt to establish better the end-point energy and the intensity of this group in order to check on the basis for this apparently short comparative half-life.

It was our original intention to try to determine whether the shape of the beta spectrum was consistent with that expected[6] for a twice-forbidden transition. Our recent success in measuring such a shape for the 0.3% abundant group in the decay[3] of Fe^{59} suggested that such an attempt might be successful in the case of Nb^{95} if the intensity were as much as had been reported.[1,4] As a result of this investigation, however, the intensity turns out to be much lower ($\leq 0.075\%$ of the decays) than the $\sim 1\%$ expected. Because of this low intensity, uncertainty in the treatment of the background and the possibility of small amounts of scattering become serious, and it becomes impossible to make a definite analysis of the detailed shape of this high-energy spectrum. However, it is possible to set an upper limit on the intensity and, thus, set a lower limit on the comparative half-life for this transition. Our analysis yields a value, $\log ft \leq 10.8$, which is closer to the range of values reported for other $\Delta I = 2$, *no* transitions and is about the same as the recent value[3] found for Fe^{59}.

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[1] G. M. Drabkin, V. I. Orlov, and L. I. Rusinov, Izv. Akad. Nauk SSSR, Ser. Fiz. **19**, 324 (1955) [translation: Bull. Acad. Sci. USSR, Phys. Ser. **19**, 298 (1955)].

[2] E. Konopinski, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. 10, p. 310.

[3] D. E. Wortman and L. M. Langer, Phys. Rev. **131**, 325 (1963).

[4] J. M. Cork, J. M. LeBlanc, D. W. Martin, W. H. Nester, and M. K. Brice, Phys. Rev. **90**, 579 (1953).

[5] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC 60–5–120, 121, 122.

[6] See, for example, C. S. Wu, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. 11, p. 347.

II. EXPERIMENTAL PROCEDURE

The experimental factors that might lead to distortion in the measurement of a low relative intensity, high-energy group such as that of Nb^{95} have previously been discussed[3] in conjunction with the measurement of the low relative intensity, highest energy transition of Fe^{59}. The extreme criteria required to measure the 0.3%, highest energy Fe^{59} group were also employed in this work.

Spectrometer

The Nb^{95} beta spectrum was studied in a high-resolution, 40-cm radius of curvature, shaped magnetic field spectrometer.[3,7] Source and detector widths of approximately 4 mm were used, resulting in a resolution of 0.65%.

For all low-energy spectrum measurements, an end-window proportional counter[3] was used. The counter window was an unsupported aluminized Zapon film which had a cutoff for 9-keV electrons. For the higher energy spectrum measurements, an integrally biased solid-state radiation detector,[3] of the silicon surface barrier type, was employed in the magnetic spectrometer. The thin window proportional counter was required to measure the low-energy inner group because the silicon counter is not suitable for such low-energy measurements.[3] The silicon counter, however, because of its inherent low sensitivity for gamma radiation, has a lower background and is more appropriate for measurement on the low-intensity, high-energy group. It has been shown that the solid-state detector has the same energy response as the proportional counter in the energy region in which it was operated.[3] Thus, with proper normalization for gross sensitivity and source strength, the measurements made with both methods of detection were directly comparable.

Measurements on the high-energy spectrum made with the solid-state counter and with a much stronger source were normalized to the intensity of the 159.7-keV inner group detected with the proportional counter from a much weaker and somewhat thinner source. A detailed determination of the internal conversion lines of the 764.5-keV gamma transition under both conditions served as a means of normalization.

Sources

Two shipments of Nb^{95} were obtained from Oak Ridge National Laboratories. Source No. 1 was prepared from a 30 mC shipment, and source No. 2 was prepared from a 1 mC shipment. In each case practically the entire activity was transferred successfully onto the source backing.

The Nb^{95} came carrier-free in the form of an oxalate and was said to have a contamination of less than 1% Zr^{95}. In order to prepare thin sources, the oxalate solution was concentrated to a few drops and the excess oxalic acid was destroyed with concentrated HNO_3. The resulting solution was brought to dryness in a platinum crucible. A few drops of $6N$ HNO_3 and a few drops of $25N$ HF were added in order to pick up the activity from the crucible.

Source No. 1 was liquid-deposited with the aid of insulin[8] onto a thin, $\sim 20\ \mu g/cm^2$, Zapon film which was supported by a 0.9 mg/cm^2 aluminized Mylar film. The 4 mm×25 mm source of thickness $\sim 0.1\ mg/cm^2$ was then covered with an $\sim 20\ \mu g/cm^2$ Zapon film. Source No. 2 was similarly deposited onto an $\sim 20\ \mu g/cm^2$ self-supporting Zapon film, and this, too, was covered with an $\sim 20\ \mu g/cm^2$ Zapon film. Source No. 2 was approximately 4 mm×25 mm and was thinner than source No. 1. To reduce the possibility of contamination of the spectrometer from accidental breakage of the source, the thickness of the backings and cover films were somewhat greater than have been used in other spectrum shape measurements. However, it is felt that these source thicknesses and backings had negligible distorting effects on the interpretation of the data in the proper regions of interest.

The decay of each source was followed over a period of at least 15 days and the half-life used (35.5 days) was in agreement with that reported[9] as 35.58 ± 0.42 days. No evidence was found for any short half-life contaminants.

III. DATA AND RESULTS

Source No. 1 was used to measure the internal conversion lines following the main inner beta group and the low relative intensity, $\sim$925-keV outer group. Source No. 2 was used to measure the high relative intensity $\sim$160-keV inner group and the internal conversion lines. Several runs were made through the respective regions of interest with each source. The intensity of the internal conversion lines served to normalize measurements made with source No. 1 and the solid-state detector to those made with source No. 2 and the proportional counter. Thus, the relative intensity of the outer group with respect to the inner group was determined.

Figure 1 shows the momentum distribution of Nb^{95} with the data all normalized to the same intensity. The solid curve represents an allowed statistical shape spectrum determined from the straight line Fermi-Kurie (F-K) plot fitted to the undistorted part of the intense low-energy spectrum as shown in Fig. 2. The effect of source thickness and backing and the onset of absorption by the counter window are clearly evident. These occur at sufficiently low energies so as not to influence the interpretation of the spectrum.

Because of the presence of intense gamma radiation, it was felt that the energy region below that correspond-

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[7] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 257 (1948).

[8] L. M. Langer, Rev. Sci. Instr. **20**, 216 (1949).

[9] A. Pierroux, G. Gueben, and J. Govaerts, Bull. Soc. Roy. Sci. Liege **28**, 180 (1959).

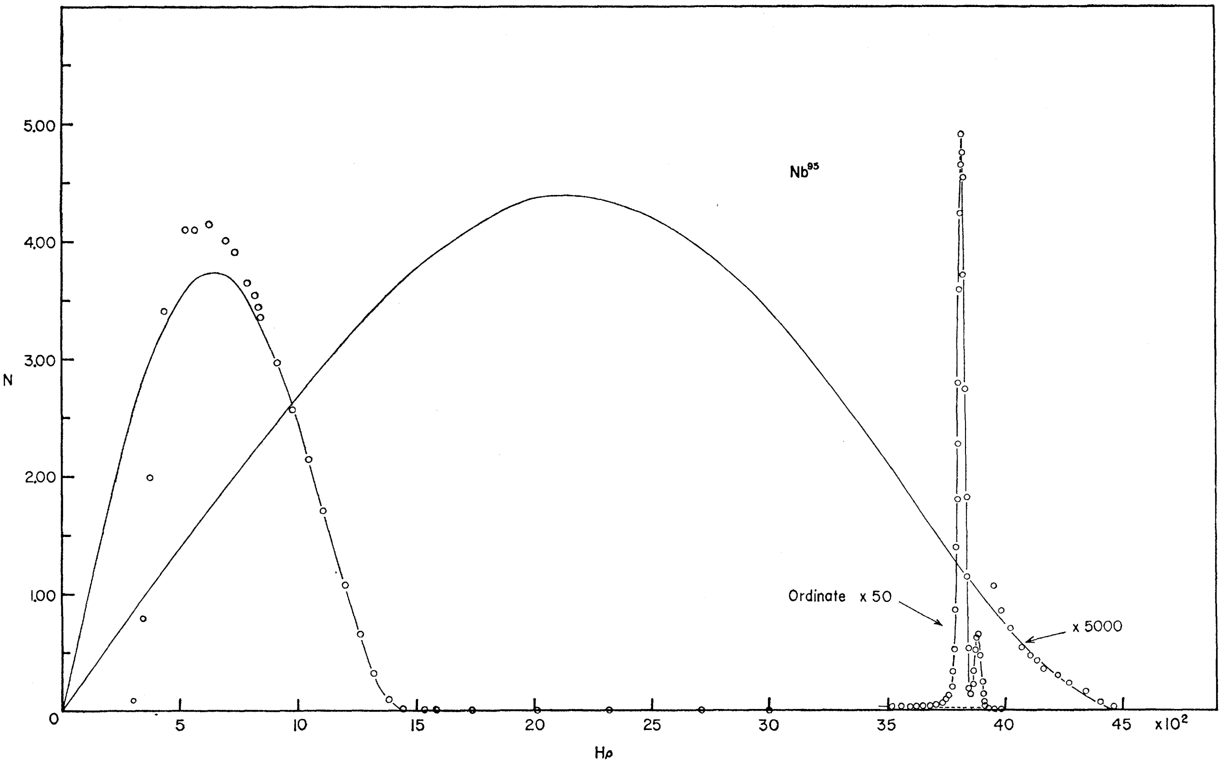

FIG. 1. Electron momentum distribution in the decay of Nb^{95}. The analysis into beta groups is based on statistical F-K plots.

ing to the internal conversion lines would be distorted by some contribution of Compton electrons. Therefore, only the data at energies higher than 765 keV were used in order to determine the contribution of the ground state to ground state transition. Uncertainties in the treatment of the background and the interpretation of the small residual scattering in the spectrometer preclude making any meaningful shape factor analysis of the data. Therefore, the shape was treated as if it were that of a statistical distribution and a straight line F-K plot was extrapolated back to the lower energy region. The spectrum corresponding to this F-K plot is shown in Fig. 1 as a solid curve. This gives an upper limit on the intensity of the transition since the extrapolation may be influenced on the high side by any small amount of scattering. The treatment of the shape as statistical rather than twice forbidden would not have any appreciable effect on the value of log *ft*.

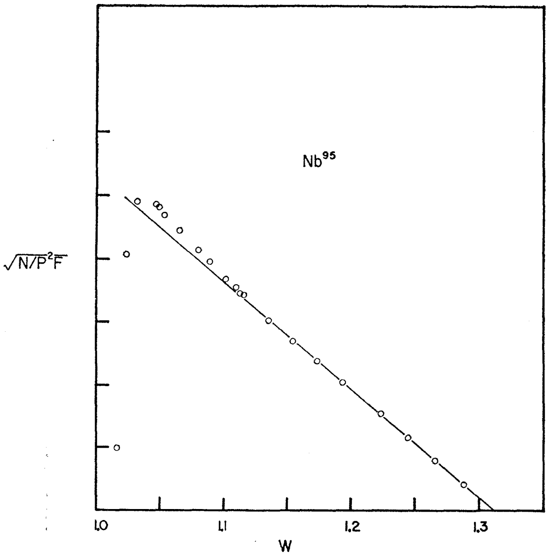

FIG. 2. F-K plot for the lower energy inner group in the decay of Nb^{95}.

Figure 2 is an F-K plot of the high relative intensity inner group after subtracting the high-energy group and the background from the total spectrum. At energies beyond $W=1.12$, the experimental shape factor is indistinguishable from the allowed shape. The extrapolated end point for this group is 159.7±0.5 keV.

Figure 3 is an enlarged plot of the region containing the conversion lines. From the K internal conversion line, the energy of the gamma transition was determined to be 764.5±0.5 keV. Because one expects that the outer group has a nonstatistical shape, and since the intensity is so low that one cannot determine the details of the shape, it is more meaningful to take for the maximum energy of the high-energy group the sum of the end point of the inner beta group and the energy of the cascading gamma ray. This value of 924 keV is consistent with a least-square straight line drawn through the data on the F-K plot.

Acording to Fig. 3, the energy region just below the K line shows a small peaking and this region is further enlarged to determine the energy of a possible gamma transition. The line is at 706 keV and would correspond to a 725-keV gamma ray in Nb^{95}. Such a gamma ray has been reported following the decay of Zr^{95}. Moreover, the decay of the data points in this region was found to be consistent with the 65 day half-life reported[5] for Zr^{95} rather than the 35.5 day half-life of Nb^{95}. Thus, the peak apparently is because of the small Zr^{95} contaminant.

According to the decay scheme of Nb^{95}, as reported[4] by Cork *et al.*, one might expect to find a 752-keV gamma ray. Although they may have seen evidence for such a gamma ray by using the integration property of photographic detection in a fixed-magnetic-field spectrometer, no evidence for such a transition is found in the present investigation. The arrow in Fig. 3 indicates the energy at which an internal conversion line associated with such a gamma ray would occur. Our detection of the weak 725-keV transition permits our setting a limit on the amount of any 752-keV gamma-ray activity.

On the assumption that the Zr^{95} contamination in our source is $\sim 1\%$ and that the intensity of the 725-keV gamma transition in Zr^{95} represents $\sim 55\%$ of the decays,[5] one can make an estimate of the relative intensity of any 752-keV gamma-ray transition. If such a transition were of the same character as the detected 725-keV transition, it should have been observed if its intensity were as much as 1% of the Nb^{95} decays.

The ratio of internal conversion in the K shell to that in the $L+M$ shells could be determined with some precision and was found to be 7.5 ± 0.1. This is to be compared with the theoretical values[10] of 7.6 expected for a pure $E2$ transition and 8.71 for an $M1$ transition. The determination of the conversion coefficient in the K shell, α_K, is subject to greater error since it involves the comparison of the intensity of a relatively weak line with that of the high-intensity, low-energy beta group. The result obtained, $\alpha_K = (1.1 \pm 0.1) \times 10^{-3}$, is in better agreement than the estimates reported[11] previously with the value 1.30×10^{-3} expected theoretically[10] for a pure $E2$ transition. In any case, the agreement is such as to give added confidence to our determination of the intensity of the high-energy beta group and the consequent estimate of the comparative half-life.

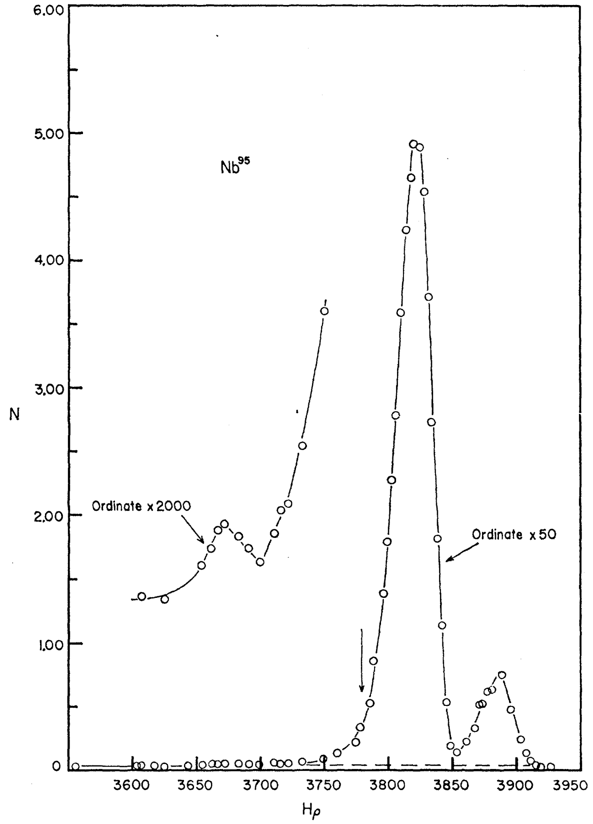

FIG. 3. Internal conversion lines of Nb^{95}. The very weak line shown in the enlarged plot arises from the small amount of Zr^{95} contamination. The arrow indicates the location at which the K line of a 752-keV transition would be expected to appear.

IV. DISCUSSION OF RESULTS

The primary reason for this investigation was to obtain measurements for the low relative intensity, highest energy beta transition of Nb^{95} in order to check upon the comparative half-life which has been reported[1,4] to be shorter than that of any other well measured $\Delta I = 2$, *no* transition. The results of this investigation indicate that the intensities reported[1,4] by Cork *et al.* and by Drabkin *et al.* are much too large. A possible explanation for this might be that the Compton electrons and some possible scattered electrons were considered in the earlier studies as belonging to the spectrum of the high-energy transition.

The results of this investigation allow an upper limit of 0.075% to be set for the intensity of the transition. This, in turn, leads to the assignment of a lower limit for the comparative half-life ($\log ft \geq 10.8$) that is closer to the range of values reported for other $\Delta I = 2$, *no* transitions. This value is of the same order as the value ($\log ft = 10.96$) reported[3] for the similar low intensity ($\sim 0.3\%$), highest energy beta group of Fe^{59}.

Incidental to our main objective, which was to reevaluate the $\log ft$ value for the twice-forbidden transition, several other aspects of the decay scheme were

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[10] L. A. Sliv and I. M. Band, *Coefficients of Internal Conversion of Gamma Radiation* (Academy of Science of the USSR, Moscow, Leningrad, 1956); issued in USA as Rept. 57 ICC KI and Rept. 58 ICC Ll, Department of Physics, University of Illinois, Urbana, Illinois.

[11] P. P. Zarubin, Izv. Akad. Nauk SSSR, Ser. Fiz. **18**, 563 (1954).

determined. The main inner group was found to have an energy of 159.7±0.5 keV with a relative intensity of ~99.92% ($\log ft=5.1$). The cascading gamma ray following the inner group was found to have an energy of 764.5±0.5 keV. The $K/(L+M)$ ratio for the gamma transition is 7.5±0.1, which is in close agreement with the theoretical value predicted for a pure $E2$ transition. The internal conversion coefficient was found to be $\alpha_K=(1.1\pm0.1)\times10^{-3}$. This is somewhat lower than values which have been reported[5,11] previously and is also in closer agreement with the value predicted[10] by theory for a pure $E2$ transition. No evidence was found for an intensity of as much as 1% for an additional 752-keV gamma transition as reported[4] by Cork *et al.*

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Beta Decay of Li^9†

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A beryllium "rabbit" irradiated with neutrons from the $t+d$ reaction was transferred repeatedly to remote scintillation detectors by means of a timed pneumatic system. The spectrum of beta rays emitted by the Be sample and detected by means of a Pilot-B scintillator displays a strong component with a half-life of ~1 sec and $\beta_{\max}\sim3.5$ MeV and a weaker component with a half-life of 0.19±0.03 sec and $\beta_{\max}=13.5\pm0.3$ MeV. These activities are identified as He^6 from the $Be^9(n,\alpha)He^6$ reaction and as Li^9 from the $Be^9(n,p)Li^9$ reaction, respectively. A much weaker component is assigned to N^{16} resulting from oxygen in the sample. Beta rays in coincidence with neutrons detected in a second Pilot-B crystal have an end-point energy of 11.0±0.4 MeV. The coincidence spectrum from the neutron-detecting crystal displays a principal component corresponding to a neutron energy of 0.7±0.2 MeV and gives some evidence for neutrons having an energy of 3–4.5 MeV. From these data, together with a shape analysis of the beta-ray singles spectrum, it is deduced that Li^9 decays with a 25% branch to the ground state of Be^9($\log ft=5.5\pm0.2$) and with a 75% branch mostly to the known 2.430-MeV level ($\log ft=4.7\pm0.2$). Both $\log ft$ values require allowed transitions and are compatible with a probable shell-model spin-parity assignment of $\frac{3}{2}-$ to Li^9 and with the tentative assignment of $\frac{5}{2}-$ given previously to the 2.430-MeV level. The cross section for forming Li^9 with neutrons of about 15.5 MeV is ~0.7 mb.

INTRODUCTION

It is known[1] that Li^9 will decay to Be^9 with the emission of beta rays and delayed neutrons having a half-life of 0.169±0.003 sec. When the present work was begun the only information on the decay energy of this nuclide came from a measurement[2] of the threshold for the $Be^9(d,2p)Li^9$ reaction. This predicted a Li^9-Be^9 mass difference of 14.1±1 MeV. During the course of the present experiments it was learned that a magnetic-spectrograph analysis of the $Li^7(t,p)Li^9$ reaction had been carried out by Middleton.[3] He obtained a ground-state Q value of −2.397±0.020 MeV for this reaction which establishes the Li^9 mass excess as 27.624±0.022 MeV and the Li^9-Be^9 mass difference as 13.614±0.022 MeV. It had been reported[4] that Li^9 is formed in the $Be^9(n,p)Li^9$ reaction using $t+d$ neutrons and that beta rays of >4 MeV are emitted. More recently Nefkens[5] has found several beta-ray activities in the 320-MeV photon irradiation of B^{11}. All of these have end-points of 13.1±0.5 MeV and one is assigned to Li^9. Based on cross-section arguments Nefkens finds that Li^9 decays 50–70% to the ground state of Be^9.

According to shell-model considerations[6] the most likely spin-parity assignment to Li^9 is $\frac{3}{2}-$. In his study of the $Li^7(t,p)Li^9$ reaction Middleton[3] found that the angular distribution of the ground-state proton group is characteristic of double stripping and can be fitted by assuming a mixture of $L=0$ and 2. This is expected if Li^9 is $\frac{3}{2}-$. Such an assignment would imply that Li^9 should decay by an allowed beta-ray transition to the $\frac{3}{2}-$ ground state of Be^9. Another possible decay mode would be to the 2.430-MeV level in Be^9 which has been given a tentative assignment[1] of $\frac{5}{2}-$ and which is in the position expected[6] for a $\frac{5}{2}-$ level. Further confirmation of this assignment has been obtained recently by Edge and Peterson[7] who showed from electron scattering experiments that the 2.430-MeV level is connected to the ground state by a magnetic transition, probably $M1$.

Earlier work[8] carried out in this laboratory on the

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[1] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

[2] W. L. Gardner, F. N. Knable, and B. J. Moyer, Phys. Rev. **83**, 1054 (1951).

[3] R. E. Middleton (private communication).

[4] D. E. Alburger, A. Elwyn, A. Gallmann, J. V. Kane, S. Ofer, and R. E. Pixley, Phys. Rev. Letters **2**, 552 (1959).

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