Beta Spectrum of Ca^{47}†

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A detailed magnetic spectrometer study was made of the shape of the beta-ray spectrum in the decay of Ca^{47}. It was definitely established that the highest energy transition does not have a once forbidden *unique* shape and, therefore, that a 3/2+ assignment to the ground state of Ca^{47} is not possible. The ground-state to ground-state transition of 1.979±0.005 MeV is probably from a 7/2− initial to a 7/2− final state with an abnormally high comparative half-life ($\log ft=8.5$) possibly resulting from distortion of the Ca^{47} nucleus. Evidence was found for a beta transition to the first excited state of Sc^{47}. This appears to be a twice forbidden transition from 7/2− to 3/2− with an energy of 1.486±0.010 MeV and an intensity of 1.3–1.8%. The comparative half-life for this $\Delta I=2$, *no* transition is relatively short with $\log ft=9.0$. The beta transition to the second excited state of Sc^{47} has an energy of 0.671±0.010 MeV. The relative intensity is 82.4% and $\log ft=6.0$. The observations are consistent with an assignment 7/2− to 5/2−. The energies of the three gamma rays that follow the decay of Ca^{47} were measured with a NaI(Tl) detector and 400-channel analyzer. The energies were found to be 1.308±0.005, 0.815±0.005, and 0.493±0.010 MeV. The half-life for the beta decay was measured in the magnetic spectrometer and found to be 4.7±0.1 days.

I. INTRODUCTION

THIS investigation of the beta disintegration of Ca^{47} was undertaken in an attempt to resolve certain ambiguities which arose as a result of earlier studies[1–3] of this activity. Ca^{47} transforms by negatron emission mainly to either the ground state or to the second excited state of Sc^{47}. A wide range of values, from 4.3 to 5.55 days, has been reported[4] for the half-life. The beta emission is accompanied by three gamma rays[3] of energies 1.3, 0.82, and 0.49 MeV. The 1.3-MeV gamma ray proceeds from the second excited state of Sc^{47} directly to the ground state, or alternatively, the excitation energy is released by the cascade emission of a 0.82-MeV and a 0.50-MeV gamma ray. Previously, no beta-ray emission had been observed[3] to proceed to the first excited state. Therefore, there was some uncertainty about the location of that level and, consequently, about the order of emission of the cascading gamma rays.

A more definitive determination of the shape of the highest energy beta transition from the ground state of Ca^{47} was of particular interest. On the basis of the single-particle shell-model predictions,[4] which one might expect to be quite reliable in this region of the Periodic Table, the ground state to ground state transition was thought to be from an $f_{7/2}$ level to an $f7/2$ level. The 7/2-assignment to the ground state of Sc^{47} is corroborated by the fact that an allowed transition is observed[4] from this level to the stable ground state of Ti^{47}, which has been assigned a spin and parity of 5/2- as the result of nuclear induction and magnetic moment measurements. Because of the unusually long comparative half-life ($\log ft=8.5$), however, it was suggested[4] that perhaps the ground state of Ca^{47} might be 3/2+, resulting from a neutron configuration (16) $(1f_{7/2})^8\,(1d_{3/2})^3$ rather than (16) $(1d_{3/2})^4\,(1f_{7/2})^7$. Hence the transition from such a 3/2+ level of Ca^{47} to the $f_{7/2}$ ground state of Sc^{47} would involve a spin and parity change, $\Delta I=2$, *yes*, which would give rise to a beta spectrum with a *unique* once forbidden shape.

In the present work a detailed study of the Ca^{47} beta spectrum was made with particular emphasis being placed on the shape of the highest energy group. An experimental determination of the shape factor might eliminate one of the alternative spin and parity assignments and, thus, establish the neutron configuration of the ground state of Ca^{47}. In addition, the energy region below 1.5 MeV was examined carefully in search of a possible beta transition to the first excited state of Sc^{47}. A direct determination of the decay rate of Ca^{47} was also made using data obtained in the magnetic spectrometer at energies well above the spectrum of the decaying daughter, Sc^{47}. The gamma-ray spectrum was observed with a scintillation detector and 400-channel pulse-height analyzer.

The general features of the decay scheme, including modifications resulting from this work, are shown in Fig. 1. It was found that although the statistical accuracy and reproducibility of the data were quite adequate to disclose any evidence of a *unique* shape, the distribution of the highest energy beta group was found to be of the statistical form from 1.49 to 1.98 MeV. Definite evidence was also found for a transition from the ground state of Ca^{47} to the first excited state of Sc^{47}.

II. EXPERIMENTAL PROCEDURE

All the precautions previously discussed for making measurements involving low-intensity groups[5,6] were followed in this investigation of the β spectrum of Ca^{47}. This was imperative if a possible β transition of energy

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[1] L. Marquez, Phys. Rev. **92**, 1511 (1953).
[2] W. S. Lyon and T. H. Handley, Phys. Rev. **100**, 1280 (1955).
[3] L. J. Lidofsky and V. K. Fischer, Phys. Rev. **104**, 759 (1956).
[4] *Nuclear Data Sheets*, edited by K. Way *et al.* (Printing and Publishing Office–National Academy of Sciences–National Research Council, Washington 25, D. C.) NRC 60-2-42.
[5] D. E. Wortman and L. M. Langer, Phys. Rev. **131**, 325 (1963).
[6] L. M. Langer and D. E. Wortman, Phys. Rev. **132**, 324 (1963).

between 1 MeV and 1.5 MeV were to exist with measurable intensity. The presence of such a group would distort the shape measurement of the highest energy group unless it was detected and recognized as such. Our recent success[5,6] in measuring the shape of the 0.3% abundant group in the beta decay of Fe^{59} and in measuring the intensity of a 0.075% Nb^{95} beta-ray group suggested that if such a group exists with an intensity in the neighborhood of 1%, it should easily be detected.

The gamma radiation following the beta-decays of Ca^{47} were also observed. These measurements were used to establish more precisely the end point energies of the inner beta groups.

Magnetic Spectrometer

The Ca^{47} beta-spectrum was studied in detail at energies above 600 keV in the high resolution, 40-cm radius of curvature, shaped magnetic field spectrometer.[5,7] The data below 600 keV are distorted because of the beta-radiation from the daughter, Sc^{47}, and are not used in this investigation.

An integrally biased solid-state radiation detector, of the surface barrier type, was used in the magnetic spectrometer throughout this investigation. The sensitivity of the counter is independent of energy over the region of interest.[5] This counter, because of its inherent low sensitivity to gamma-radiation, has a very low background. Any energy dependence of the background, which might otherwise be of importance when considering low intensity effects, was completely negligible in this case since, with the strongest source in place, the background was less than 2.5 counts/min.

The spectrometer was operated at a resolution of about 0.6% with source and detector widths of 0.4 cm.

Gamma Ray Analyzer

The gamma radiation of Ca^{47} was studied with a NaI (Tl) crystal used in conjunction with a 400-channel pulse-height analyzer. A source of intensity approximately equal to that of the calibration sources was used in order that the gain of the phototubes should remain constant. Gamma rays from Cs^{137} (661.6 keV), Bi^{207} (570 keV, 1064 keV), and Co^{60} (1173 keV, 1333 keV) were used for energy calibrations. These calibration sources spanned the energy range of interest and confirmed the high degree of linearity and stability of the apparatus.

Sources

Two beta-ray sources of Ca^{47} were prepared from a shipment of 1 mC from Oak Ridge National Laboratories. Approximately one-tenth of the activity was used to make a relatively thin (1 mg/cm²) source. The remainder of the activity was used to prepare a more intense but somewhat thicker source. Although such a source might be considered thick for detailed spectrum shape measurements designed to explore weak effects, it was anticipated, on the basis of previous experience, that, because of the uniformity of the deposit and the low Z of the material, the thickness might be acceptable for measurements at high energies. The agreement between the energy distributions obtained with the thick and thin sources gave assurance that the spectrum was not being distorted by Compton electrons or by beta rays scattering in the source in the energy regions of interest. Thus it was possible to utilize and have confidence in the statistically more accurate data obtained with the more intense source.

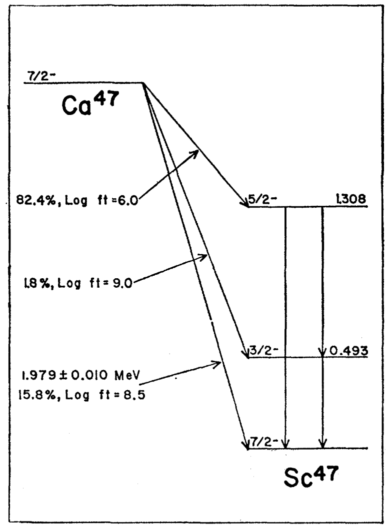

FIG. 1. The decay scheme of Ca^{47}. Modifications resulting from the present investigation are combined with previous results.

The Ca^{47} was received carrier-free in the form of $CaCl_2$ in a dilute solution of HCl. Because some difficulty would be encountered if the deliquescent $CaCl_2$ were used as a source, the $CaCl_2$ was transformed into CaF_2. This was done by adding a few drops of 25 normal HF to the $CaCl_2$ solution, which had been placed in a platinum crucible. The resulting solution was brought to dryness yielding CaF_2 in a finely powdered form. Several drops of H_2O were added to transform the powder into a slurry. A small aliquot (1/10 of the total) of the slurry was quite uniformly deposited onto an $\sim 20\ \mu g/cm^2$ Zapon film which was supported by a 0.9 mg/cm² aluminized Mylar backing. Insulin[8] was used to define the source area. The remainder of the CaF_2 slurry was similarly prepared as source #2. Each CaF_2 source was dried and covered with a thin (20 $\mu g/cm^2$) Zapon film. The thin, weaker source was ~ 1 mg/cm² in thickness and the more intense source was proportionally thicker.

III. DATA AND RESULTS

The decay rate of Ca^{47} was studied in the magnetic spectrometer at energies well above the β spectrum of

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

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

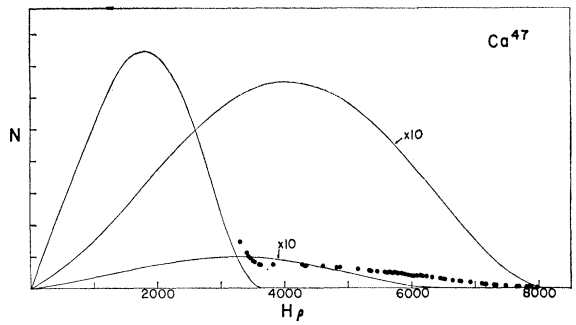

FIG. 2. The beta spectrum of Ca^{47}. The resolution into three groups is on the basis of the analysis of the Fermi-Kurie plot shown in Fig. 3.

the decaying daughter, Sc^{47}. The half-life for such radiations was determined to be 4.7 ± 0.1 days. It should be mentioned that this measurement is in agreement with most other half-life measurements,[4] but definitely does not agree with the values of 5.55 days and 5.35 days which had been reported. No evidence was found for any short half-life impurities in the Ca^{47} source material.

The data obtained with the more intense source were used in the analysis of the β decay of Ca^{47}. Using this source, several runs were made through the spectrum in a period of one week. Points below approximately 600 keV were not used in the analysis of the Ca^{47} β spectrum since they were complicated by the negatron emission from the decaying daughter, Sc^{47}. The data were then corrected for a half-life of 4.7 days. The electron momentum distribution of Ca^{47}, treated in this way, is shown in Fig. 2. The statistical accuracy of each datum point between 600 and 700 keV and of those data points used in the shape factor analysis of the high energy β groups is better than 1%. Several other data points which were taken in search of a possible internal conversion line associated with the 1.3-MeV gamma radiation, though of less statistical accuracy, are also shown. It should be mentioned that no evidence for the internal conversion line was observed. The theoretical internal conversion coefficient for a $\Delta I=1$, *no* gamma transition of 1.3 MeV is only $\sim10^{-5}$. The internal conversion of such a transition would not be measurable in our apparatus.

The three solid curves shown in Fig. 2 represent allowed shape β spectra determined from straight line Fermi-Kurie (F-K) plots fitted to the data shown in Fig. 3. The relative intensities of the 1.979-, 1.486-, and 0.671-MeV β ray transitions were determined to be 15.8%, 1.8%, and 82.4%, respectively.

The F-K plot of the experimental data is shown in Fig. 3. The data points taken with the thin, weaker source were normalized to the intensity of the stronger source and are designated by crosses. Data obtained with the more intense source are designated by circles. Since the more intense source is roughly ten times thicker than the thin, weaker source, distortion effects because of Compton electrons and beta-ray scattering in the finite source material in this energy region should be approximately ten times greater. It is significant to notice, however, that the data obtained with the weaker source follow the same distribution as the data obtained with the stronger source. Thus, distortion effects in the region of interest resulting from the use of the thicker source appear to be negligible.

The solid lines in Fig. 3 correspond to the straight line F-K plots which are consistent with the data after successive subtractions of the outer groups from the spectrum.

The experimental shape factor of the highest energy β group is plotted in Fig. 4. An end-point energy of 1.979 ± 0.005 MeV is obtained by demanding that the shape factor remain finite near the end point. Because of the relatively high comparative half-life of this transition, a deviation from the statistical shape, $S(W)=1$, might be expected. If the transition were from a $3/2^+$ level in Ca^{47} to the 7/2- Sc^{47} ground state, as was proposed,[4] the data points should follow the theoretical *unique* shape factor of the form,[9] $0.975\,p^2+q^2$, which is shown for comparison in Fig. 4. This is obviously not the case. In fact, the data are consistent with the statistical shape from 1.49 to 1.98 MeV. However, there is a deviation from the statistical shape below 1.49 MeV. This rise in intensity is accounted for as the result of a beta transition to the first excited state of Sc^{47}.

Consideration must be given to the possibility that this deviation might be associated with an empirical factor of the form $1+b/W$ which appears to be consistent with the measurements[10] of other beta spectra

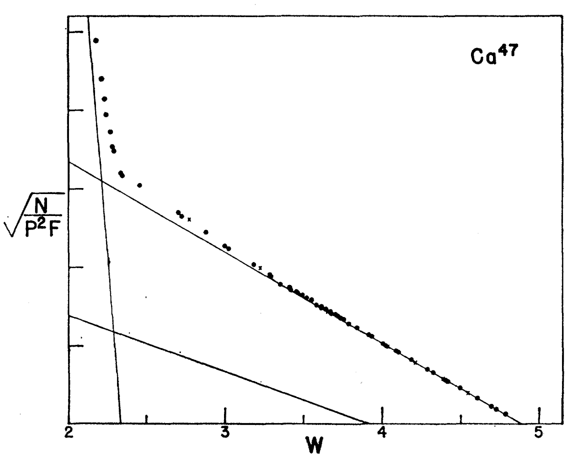

FIG. 3. Fermi-Kurie analysis of the beta spectrum of Ca^{47}. Circles represent data taken with the intense, thicker source. The crosses show that the same general distribution is obtained with the much thinner, weaker source. The three groups were determined by fitting straight lines to the data and successive subtractions.

[9] T. Kotani and M. Ross, Phys. Rev. **113**, 622 (1959).

[10] See references given in D. C. Camp and L. M. Langer, Phys. Rev. **129**, 1782 (1963).

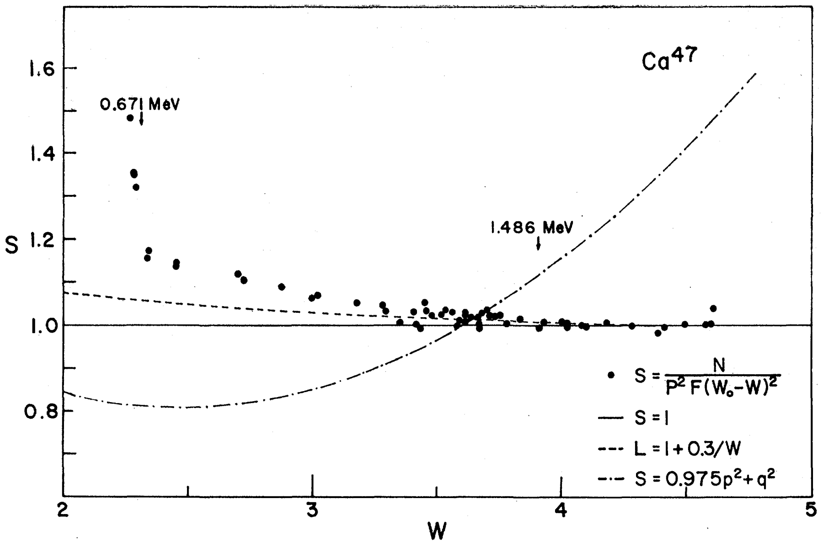

FIG. 4. Shape factor plot of the beta spectrum of Ca^{47}. The data above 1.486 MeV are fitted with the statistical shape. It is clear that the shape factor associated with a *unique* once forbidden transition cannot fit the data. The influence of a possible $1+0.3/W$ empirical correction to the highest energy group is also shown.

shapes. A value of $b=0.3$ is roughly the average value which has been used to obtain the best fit for other spectra. Such a value of b falls far short of accounting for the extent of the deviation in the present case. Furthermore, the agreement with the gamma-ray energy measurements must be regarded as more than fortuitous. The detection of this apparently twice forbidden beta transition establishes the first excited state of Sc^{47} at 0.49 MeV and experimentally removes any ambiguity about the order of emission of the 0.815- and 0.493-MeV gamma rays.

The very intense beta transition to the second excited level of Sc^{47} accounts for the large upward deviation below 0.67 MeV in Fig. 4.

Assuming statistical distributions of the beta groups, the relative intensity of the outer group is 15.8%, that of the first inner group is 1.8%, and that of the second inner group is 82.4%. Although no data were taken below approximately 600 keV, it was possible to obtain accurate estimates of the relative intensities because of the high resolution and because of the excellent statistics of the 9 data points in the 600 to 700-keV energy range. This made it possible to fit these data points with an unambiguous straight line F-K plot, after subtracting the outer two groups from the total spectrum. Although the 1.49-MeV group should not have a statistical shape (since it is probably associated with a twice forbidden transition), uncertainties in subtracting the 1.979-MeV outer group from the total spectrum precludes making a meaningful shape factor analysis of the 1.49-MeV group. Treating the 1.49-MeV group as statistical, however, makes little difference in the determination of the abundance of this group. If a $1+0.3/W$ correction factor is applied in subtracting the outer group from the total spectrum, the intensity of the 1.49-MeV group drops to 1.3%. The intensities of the other groups, in this case, are not significantly changed.

The results of the gamma-ray measurements are shown in Fig. 5. Three gamma rays of energies 1.308 ± 0.005, 0.815 ± 0.005, and 0.493 ± 0.010 MeV were found. A fourth gamma ray, of approximately 0.16 MeV, which is associated with the beta decay of the daughter nucleus, Sc^{47}, was also observed. The end-point energies of the inner beta groups are most accurately determined on the basis of these gamma-ray energies in conjunction with the end-point energy of the outer beta group. The energies of the beta groups determined in this way are 1.979 ± 0.005, 1.486 ± 0.005, and 0.671 ± 0.010 MeV. These end-point energies, the intensity measurements, and the half-life determination,

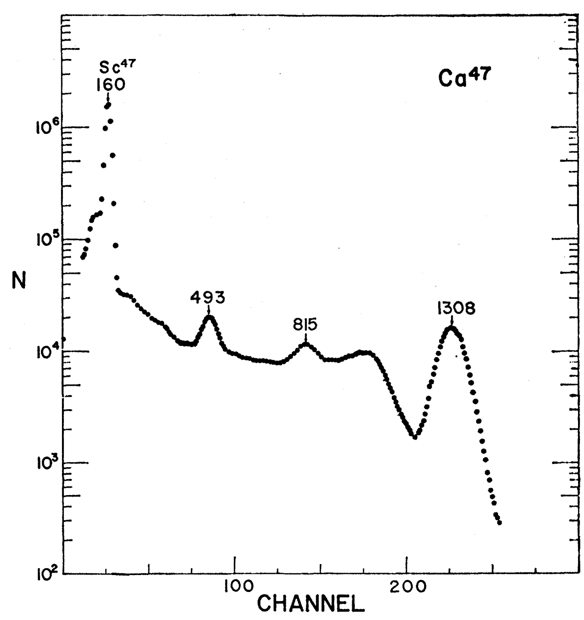

FIG. 5. Gamma-ray spectrum of Ca^{47} obtained with a NaI(Tl) detector and multi-channel analyzer.

allow the comparative half-lives to be determined as follows: $\log ft=8.5$ for the 1.979-MeV group, $\log ft=9.0$ for the 1.486-MeV group, and $\log ft=6.0$ for the 0.671-MeV group.

IV. DISCUSSION

One of the main reasons for interest in the decay of Ca^{47} was an attempt to measure the shape of the beta transition from the ground state of Ca^{47} to the ground state of Sc^{47}. On the basis of the single particle shell model predictions, the transition should be from a $7/2-$ level to a $7/2-$ level. However, a $3/2+$ to a $7/2-$ transition would also be plausible. Because of the relatively high comparative half-life for this presumably allowed beta transition, it was suggested[4] that perhaps the transition was from a $3/2+$ state. Our determination of the experimental shape factor, however, is incompatible with the *unique* shape which is necessarily associated with such a transition. Hence it appears that the correct spin and parity assignment of the ground state of Ca^{47} is indeed $7/2-$.

The experimental shape factor of the 1.979-MeV group is consistent with both the statistical shape and an empirical correction factor of the form $1+0.3/W$. If the statistical shape is used in subtracting the outer group from the spectrum, the relative intensity of this group is found to be 15.8%, yielding a $\log ft=8.5$. The treatment of the outer group using the statistical shape without including the empirical factor does not have any appreciable effect on the value of the $\log ft$. Although this value for the comparative half-life is quite high for an allowed transition, it may possibly be accounted for by a reduction in the size of the nuclear matrix elements because of distortion of the Ca^{47} nucleus.

Subtracting the outer group from the total spectrum, either on the basis of the statistical shape or with the inclusion of the empirical correction factor, establishes the existence of a beta transition to the first excited state of Sc^{47} at 0.493 MeV. The relative intensity of this group is 1.8% ($\log ft=9.0$) if the statistical shape is assumed for the outer group, but is 1.3% ($\log ft=9.1$) if the empirical correction factor is taken into account. The treatment of the 1.486-MeV beta spectrum as statistical rather than as a possible forbidden shape would have no appreciable effect on determining a lower limit on $\log ft$. Thus it is estimated that the relative intensity of this group is in the range 1.3 to 1.8% with a $\log ft$ value of between 9.0 and 9.1. It has been noted[6,11] that such a short comparative half-life may not be too unusual for twice forbidden beta transitions.

The possibility that the 1.486-MeV beta transition is once forbidden rather than twice forbidden cannot be ruled out on the basis of beta spectrum shape measurements alone. Even if this transition were *unique* once forbidden leading to a $3/2+$ first excited state of Sc^{47}, the uncertainties resulting from the low intensity and the subtraction process would preclude distinguishing any uniqueness to the shape. A $3/2+$ first excited state for Sc^{47} is possible on the basis of a strong pairing of $f_{7/2}$ particles which might lead to the configuration $16(1f_{7/2})^2\,(1d_{3/2})^3$. One then has to compare the relative merits of $(5/2-)M1(3/2-)E2(7/2-)$ with $(5/2-)E1(3/2+)M2(7/2-)$ as the proposed sequence of the cascading gamma rays. Theoretically,[12] the first scheme predicts that the 1.308-MeV gamma transition might be expected to be 4.2 times as intense as the 0.815-MeV transition. The scheme involving the positive parity for the first excited level would reduce this intensity ratio to 0.06. The experimental measurement[3] of ~ 13 appears to be in better agreement with the negative parity assignment to the first excited state. The agreement might be made even better if there were some $E2$ mixing; whereas mixing cannot bring the second sequence into agreement. Gamma-gamma angular correlation measurements[13] are not capable of distinguishing between the two proposals but are in agreement with a $5/2\rightarrow 3/2\rightarrow 7/2$ spin sequence.

From the intensity measurements alone, the assignment of negative parity to the first excited state of Sc^{47} appears to be favored. The 1.486-MeV beta transition is, thus, to be interpreted as indeed being twice forbidden with a comparative half-life corresponding to a value of $\log ft$ as low as 9.0.

ACKNOWLEDGMENT

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

[12] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 627.

[13] R. E. Sund, R. G. Arns, and M. L. Wiedenbeck, Nucl. Abst. **13**: 16459 (AECU-4151), and private communication.