Decay of A^{41}†

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(Received June 7, 1956)

The beta and gamma radiations from 110-min A^{41} were investigated with a 180° and a lens-type magnetic beta spectrometers and a NaI(Tl) scintillation spectrometer. Two beta groups are observed with end points of 2.48±0.04 Mev and 1.199±0.008 Mev with relative intensities of 0.88% and 99.1%, respectively. The beta spectrum of the upper energy group exhibits an α shape in agreement with shell model predictions for the spins of the involved levels. The $\log f_1 t$ of this transition is 8.50. The gamma-ray energy is 1.290±0.005 Mev. This results in a mass difference of 2.489±0.010 Mev between the ground states of A^{41} and K^{41}. A procedure is described for determining the background contribution in the region of the very weak, high-energy group due to the scattering of beta and gamma radiation.

INTRODUCTION

THE complex decay of A^{41} has been investigated with two magnetic beta-ray spectrometers and a NaI(Tl) scintillation spectrometer. Previous measurements[1] have been reported in which the radiations were measured by cloud chamber and absorption techniques. Brown and Perez-Mendez[2] have measured the intense, low-energy beta spectrum with a 180° spectrometer. No measurements of the shape of the beta spectrum of the forbidden ground-state to ground-state transition have been reported.[3]

Since the spin of K^{41} is known[4] to be $\frac{3}{2}$, the degree of forbiddenness of the beta transition to the K^{41} ground state can yield information on the spin of A^{41}. The simple shell model prediction in this region of 21 to 27 odd-nucleon number is $f_{7/2}$ for the A^{41} ground-state configuration. Within this subshell, all the nuclei whose spins are known have this spin except ${}_{25}Mn_{30}$. If the prediction of the simple shell model that the three odd neutrons in the $f_{7/2}$ shell couple to give a spin of 7/2 is correct, then the high-energy beta spectrum of A^{41} should have the unique α shape characteristic of first forbidden transitions with $\Delta J=2$, yes.

The abundant low-energy spectrum was measured with a 180° and a thin-lens-type beta-ray spectrometer. The end points obtained from both of these measurements are in excellent agreement. This newly determined maximum energy, however, is different from the previously reported end point,[2] which is probably in error.

During the course of this research, Kluyver and Van der Leun[5] reported measurement of the A^{41} gamma-ray energy and inferred the $A^{41}-K^{41}$ mass difference from this measurement and the low-energy beta end point of Perez-Mendez and Brown. The A^{41} decay energy is the only measured mass connection from A^{41} to a series of measured masses in this region. Our gamma-ray energy measurement is in agreement with that obtained by Kluyver and Van der Leun; however, because of the previously reported incorrect low-energy end point, their $K^{41}-A^{41}$ mass difference must be revised.

PRODUCTION OF A^{41}

A^{41} was produced by neutron irradiation of natural argon (99.6% A^{40}) in the Brookhaven reactor. Tank argon (99.5% pure) was passed over hot calcium, through a dry ice trap, and collected in an evacuated quartz ampoule. For each of the spectrometer runs, 10 cc of argon (N.T.P.) were irradiated for 5 hours at a flux of 2×10^{12} neutrons/sec cm². For the gamma-ray measurements, 1 cc (N.T.P.) was irradiated for 10 seconds. It was unnecessary to remove the gas from the quartz irradiation tube during the gamma measurements since the very weak Si^{31} activity from the quartz contains no gamma rays in the energy region of concern. The logarithmic decay curve of the active gas was linear for 4 half-lives with a half-life of 111±1 min. This is in agreement with the value of 109±1 min reported previously by other experimenters[1]; and, therefore, confirms the purity of the activity.

GAMMA-RAY ENERGY MEASUREMENTS

A NaI(Tl) crystal, 2 inches in diameter and 2 inches thick, was used to measure the gamma-ray energy. A DuMont 6292 photomultiplier tube, an Atomic linear amplifier, and an Atomic 20-channel pulse-height analyzer were the main components of the gamma-ray spectrometer.

The pulse-height distribution of the gamma photopeaks of A^{41}, Co^{60}, and Na^{22} are shown superimposed in Fig. 1. The A^{41} gamma energy lies in the 0.055-Mev interval between the 1.277-Mev gamma ray[6] of Na^{22} and the 1.332-Mev gamma ray[7] of Co^{60}. Since this energy difference is so small, it is possible to obtain very high accuracy for the energy of the A^{41} line by measuring

† This work was partially supported by the U. S. Atomic Energy Commission.

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[2] H. Brown and V. Perez-Mendez, Phys. Rev. **78**, 649 (1950).
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[5] J. C. Kluyver and C. Van der Leun, Physica **21**, 604 (1955).
[6] D. E. Alburger, Phys. Rev. **76**, 435 (1949).
[7] Lind, Brown, and DuMond, Phys. Rev. **76**, 591 (1949).

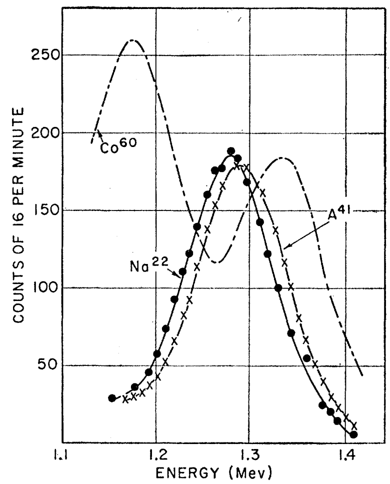

FIG. 1. Scintillation spectra of the photopeaks due to the gamma rays from Co^{60}, Na^{22}, and A^{41}. The three spectra have been superimposed on a common energy scale determined by using the two Co^{60} lines for calibration.

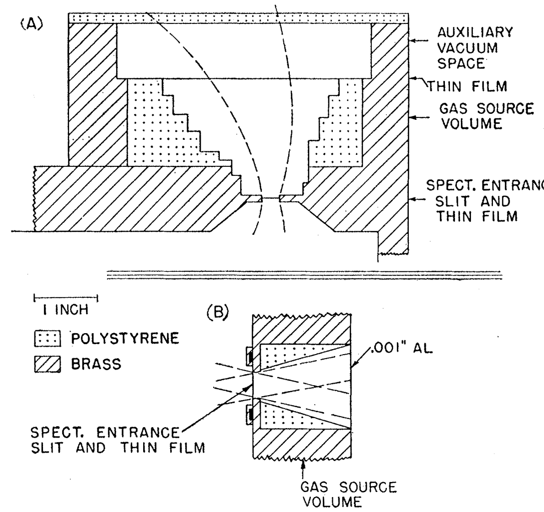

FIG. 2. Radioactive gas source volumes: (A) for the 180° spectrometer; (B) for the lens type spectrometer. The dashed lines indicate the envelope of the accepted trajectories.

only the difference between the Na^{22} and the A^{41} gamma energies. Because of the resolution width (9% at 1.3 Mev) of the scintillation spectrometer, it was impossible to resolve the lines of Na^{22}, A^{41}, and Co^{60} when all these sources were placed simultaneously in the spectrometer. Therefore, the three sources were measured separately. In such a procedure, it is important to determine if there exists a rate dependent calibration shift[8] of the phototube for the different measurements. The phototube was selected for rate-independent gain, and tests showed no detectable shift of the A^{41} energy for a factor of 10 change in source intensity. As a further precaution, sets of curves of the gamma spectra from A^{41}, Co^{60}, and Na^{22} were taken with different total counting rates. A typical set is shown in Fig. 1. For each set of curves, a calibration line was drawn on the basis of the 1.172-Mev and 1.332-Mev lines[7] of Co^{60}. In all the sets, the value of 1.277 for the Na^{22} gamma-ray energy agreed within 0.004 Mev with the calibration curve. For each set, the energy difference between the A^{41} and Na^{22} lines was calculated; and from the seven sets of curves, a value of 0.013 Mev for this difference was determined. The probable error of these seven measurements is ± 0.0006 Mev. Because of the possibility of systematic error in location of the Na^{22} and A^{41} peaks, the final spacing error is estimated at less than 0.002 Mev.

The A^{41} gamma-ray energy is 0.013 ± 0.002 Mev higher in energy than the gamma ray of Na^{22}. The value 1.277 ± 0.004 Mev for the Na^{22} gamma-ray energy was measured by Alburger[6] using photoelectric conversion with a magnetic spectrometer. Thus, the A^{41} gamma energy is 1.290 ± 0.005 Mev, in agreement with the recent measurement of 1.298 ± 0.010 Mev obtained by Kluyver and Van der Leun.[5]

BETA SPECTROMETERS

The 180°, uniform-field beta spectrometer was of conventional design. The magnetic field was measured by determining the induced voltage in a coil which rotated in the spectrometer gap. Extensive measurements of the field shape, the efficiency characteristics, and the calibration of this spectrometer have been previously reported.[9] The known spectra of Au^{198}, P^{32}, In^{114}, and Cu^{64} were measured. Each showed allowed shape and are in excellent agreement with accepted end points. A thin-lens spectrometer was kindly lent to us by Dr. D. E. Alburger. For the purpose of spectral shape measurements, a new baffle system was constructed to reduce scattering effects.[10]

Both spectrometers were calibrated with the 0.9759 Mev[11] and the 0.477-Mev internal conversion lines of Bi^{207}. Tests showed that the calibration of the spectrometers for gaseous sources is the same as for a thin source placed at the gas volume aperture. The resolution of both spectrometers was adjusted to 2.8%.

SPECTROMETER SOURCE VOLUMES

Schematic drawings of the gaseous source volumes for the 180° and thin-lens spectrometers are shown in Figs. 2(A) and 2(B), respectively. Each had a defining aperture, which formed the virtual source for the spectrometer, and a thin film for the rear wall of the volume. The volumes were lined with polystyrene machined in such a way that beta particles which had scattered from the polystyrene walls could not enter a trajectory of the spectrometer which terminated at the counter. This can be seen in the figure from the dashed envelope of the accepted rays. In both source volumes, accepted rays can originate from the back surface of the

[8] Bell, Davis, and Bernstein, Rev. Sci. Instr. 26, 726 (1955).

[9] A description of these measurements is given in the Pupin Cyclotron Laboratories progress reports CU-143, CU-134, and CU-131 (unpublished).

[10] A description of this baffle will be presented by Kistner, Schwarzschild, and Rustad (to be published).

[11] D. E. Alburger, Phys. Rev. 92, 1257 (1953).

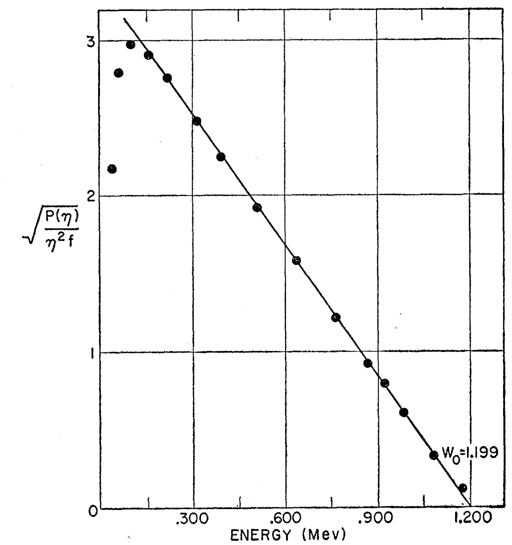

FIG. 3. Kurie plot of 1.2-Mev beta spectrum of A^{41}. The very small contribution due to the high-energy group has been subtracted.

volume. For high-energy measurements taken with the lens spectrometer, this surface consisted of a 0.001-inch sheet of aluminum backed finally by air. For the 180° spectrometer, the backing was 1 mg/cm² aluminized Mylar film which itself was backed by an auxiliary vacuum space and finally a polystyrene cover. This construction reduced backscattering, which becomes increasingly important at low energies.

In the 180° spectrometer, the source and counter windows were 0.5 mg/cm² rubber hydrochloride. The spectrum of the high-energy group was measured with the thin lens because of its higher transmission. The source window was 0.85 mg/cm² Mylar and the counter window was 3.5 mg/cm² mica. The active A^{41} was transferred from the quartz irradiation ampoules to the source volume of the spectrometer and adjusted to a pressure of 10 cm Hg. The maximum gas density was 0.8 mg/cm² in the direction of the trajectories for both spectrometers.

BETA SPECTRA

The low-energy spectrum was measured with the 180° iron core spectrometer which had thinner windows on the counter and source. Analysis of this group can be shown to be virtually independent of the shape of the very weak, upper energy beta group. The upper energy group, which affects the low-energy end point by less than 0.002 Mev, and the background from the gamma ray, which amounted to less than 1% of the spectrum peak rate, were subtracted from the data. After correction for source decay, a Kurie plot of the resulting spectrum was constructed. This plot is shown in Fig. 3. The Kurie plot has an end point of 1.199±0.008 Mev (estimated maximum error). The spectrum has an allowed shape down to 0.150 Mev where the counter and source windows begin to attenuate the low-energy electrons. Kurie analysis of the upper end of the low-energy group as measured in a similar manner with the lens spectrometer yielded an end point of 1.196 Mev.

The momentum plot of the A^{41} spectrum taken with the thin lens spectrometer is shown in Fig. 4. The data have been corrected for source decay, and the small natural background has been subtracted. It can be seen that there is a large "background" past the end of the spectrum. This background extends below the end point; and in order to subtract it properly, its shape as a function of energy must be determined.

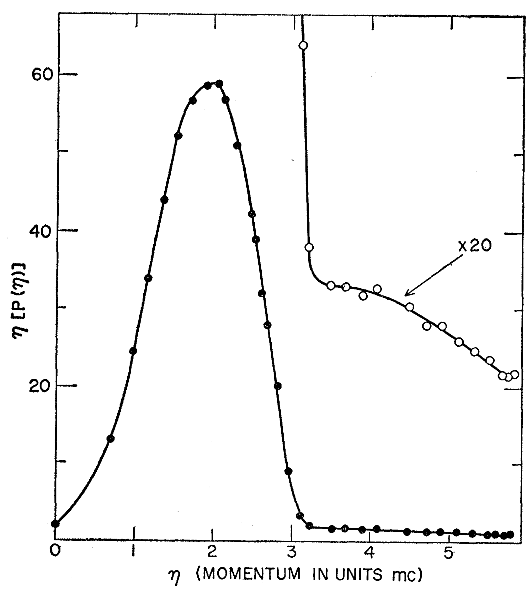

FIG. 4. The beta spectrum of A^{41} as measured with the lens spectrometer. The scale has been enlarged by a factor of 20 in the region of analysis of the high-energy group.

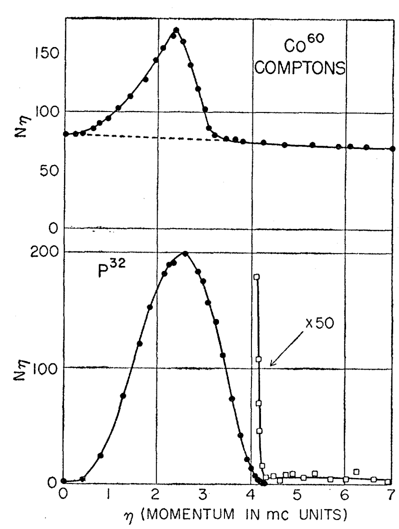

FIG. 5(a). Beta spectrum of P^{32} including the region above the P^{32} end point. (b). Spectrum due to a Co^{60} source placed in the source volume of the magnetic spectrometer. A small natural background has been subtracted from both curves.

It was assumed that this "background" may be attributed to two distinct sources: (1) the scattered beta particles from the intense, low-energy group; and, (2) Compton electrons produced in the walls of the gas source volume and the baffle system, as well as scattered gamma rays. Sources of P^{32} and Co^{60} were used to simulate these two sources of background separately. By measuring the effect of these two sources in the spectrometer, information can be obtained of the shape of the "background" under the A^{41} spectrum. A 1.5-mC source of P^{32}, a pure beta emitter, was deposited on a thin film which was placed in the median plane of the gas source volume. The spectrum was measured with special attention paid to the region above the end point. This spectrum is shown in Fig. 5(a) and indicates that the "background" of scattered beta particles above the spectrum end is only 0.05% of the peak rate for P^{32}. To determine the second contribution to the background, a 10-mC source of Co^{60} was covered with a sufficient thickness of aluminum foil to stop its beta rays and placed in the gas source volume. The spectrum of the Compton electrons and gamma rays as a function of the magnetic field is shown in Fig. 5(b). It should be noted that the aluminum cover on the source used to eliminate beta particles represents only a very small proportion of the total surface from which Compton electrons can originate. The Co^{60} gamma rays have an energy very close to that of the A^{41} gamma ray. The curve shows that the region of interest of the high-energy A^{41} beta spectrum, above 1.3 Mev, does not include the Compton peak and that the "background" to be subtracted from the A^{41} spectrum is almost linear.

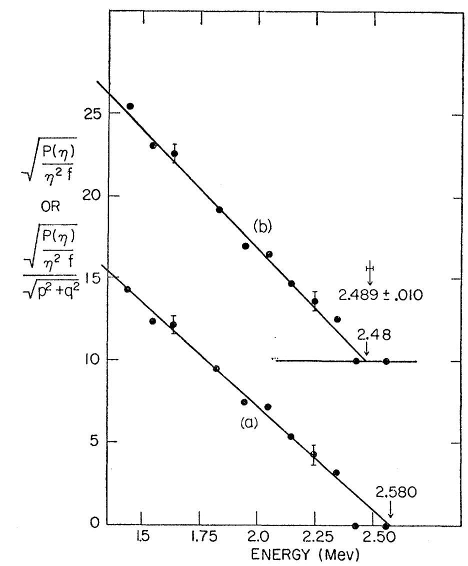

FIG. 7. Kurie plots of the beta spectrum of the high-energy group of A^{41}. (a) Uncorrected spectrum. (b) Spectrum corrected for α-shape. The upper curve has been corrected by the unique first forbidden correction factor and normalized in slope. The arrow and bars marked 2.489±0.010 Mev indicate the end point and its error expected for this group from the sum of E_{max} for the low-energy beta group and the gamma-ray energy

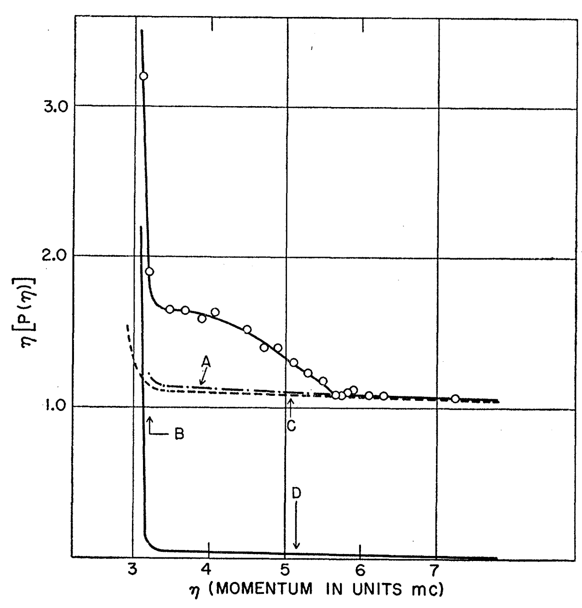

FIG. 6. The "background" subtracted from the spectrum of the A^{41} upper energy group. The circles indicate the counts recorded in the spectrometer with the natural room background subtracted. The energy indicated by the arrow at B is the end point of the low-energy group. The curve D is the normalized P^{32} curve and indicates the "background" resulting from scattering of low-energy beta particles from the intense, low-energy group of A^{41}. The curve C is the normalized Co^{60} Compton curve and indicates the "background" due to the gamma rays of A^{41}. Curve A, the final background subtracted from the experimental points, is the sum of curves C and D.

These curves, representing the "background" resulting from the gamma rays and scattered beta rays, were normalized to the A^{41} data in the following manner. The P^{32} spectrum was contracted in the momentum scale to correspond to a spectrum with a 1.2-Mev end point, and then was normalized in area to the low-energy group of A^{41}. The resulting spectrum gives the contribution to the "background" due to the low-energy beta group both at zero field and beyond the end of this group. The Co^{60} gamma-Compton curve was normalized to account for the remainder of the background in the region above the end point of the high-energy group. The validity of this procedure was checked at zero magnetic field, where the counting rate actually observed from the A^{41} source was found to agree within a few percent with the sum of the two normalized "backgrounds." A curve showing the relative contributions of these backgrounds to the actual A^{41} spectrum is shown in Fig. 6.

After the subtraction of these backgrounds, as indicated in Fig. 6, a conventional Kurie plot was constructed which is shown in the lower half of Fig. 7. It may be seen that this curve approximates a straight line; however, the end point is much higher (6 times probable error) than that indicated by the sum of the low-energy beta and end point and the gamma-ray

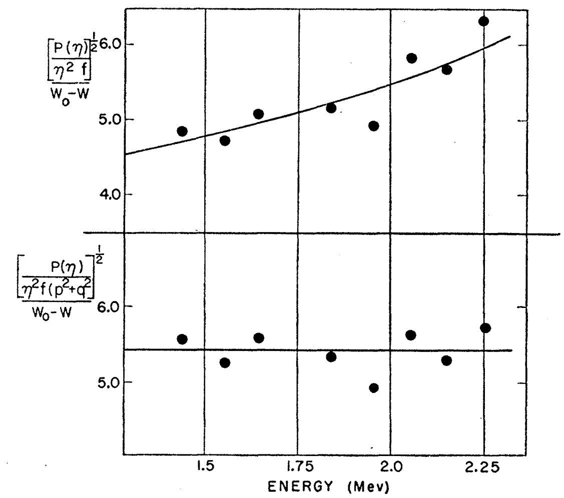

FIG. 8. Fierz plots of the upper energy group. The upper points are the uncorrected data, and the lower points have been corrected for α-shape. The energy W_0 has been taken as 2.489 Mev; i.e., the sum of $E_{\max}$ for the low-energy beta group and the gamma-ray energy.

energy. Also, one may note that the two highest-energy points on this plot are low, a typical characteristic of unique first forbidden, α-shape spectra. A plot of the higher energy beta spectrum corrected for the α shape is also shown in Fig. 7. The end point is now in excellent agreement with the value, 2.489±0.010 Mev, obtained from spectrum of the lower group and the gamma-ray energy. This spectrum is weak, statistical fluctuations are high, and only a small portion of the spectrum is available for analysis. However, since the end point is known from other parts of the decay scheme, a Fierz plot of

$$\left[\frac{P(\eta)}{\eta^2 fC}\right]^{\frac{1}{2}} \Big/ (W_0-W)$$

versus W may be much more useful than the conventional Kurie analysis for determining its shape; this quantity should be a constant independent of energy if C is the properly chosen shape factor.

In Fig. 8, these plots are shown for $C=1$ (allowed or nonunique first forbidden) and $C=p^2+q^2$ (unique first forbidden). On this type of plot, the points very near the end point of the spectrum become unusually sensitive to the choice of W_0. Since their statistical errors are also relatively large, they are not useful to interpret the spectrum shape and are not shown on the curves. An α shape for the spectrum is clearly indicated by these curves.

CONCLUSION

The decay scheme for A^{41} is shown in Fig. 9. The relative intensities of the two beta groups are 0.88% and 99.1% for the high- and low-energy groups, respectively. These were determined by extrapolation of high-energy group to low energies assuming an α shape for this group. The value of $\log f_0t$ for the low-energy group is 5.00, and for the upper energy group $\log f_0t = 8.34$ and $\log f_1t = 8.50$, where[12]

$$100 f_1/f_0 = 5.1(\epsilon_0^2-1) - 5.2(\epsilon_0-1) = 1.46.$$

A tabulation of the $\log f_1t$ values for a ($\Delta J=2$, yes) transition[13] shows that the average value is 8.53 for odd-A nuclei with only two of the nine known cases having $\log f_1t$ outside the limits $8.1 < \log f_1t < 8.6$. The ft values of nonunique first forbidden transitions are from one to two orders of magnitude lower. This confirms the degree of forbiddenness of the high-energy spectrum as determined from its shape. It is concluded from this evidence and from the Fierz plots that the ground-state transition is an unique first forbidden type ($\Delta J=2$, yes).

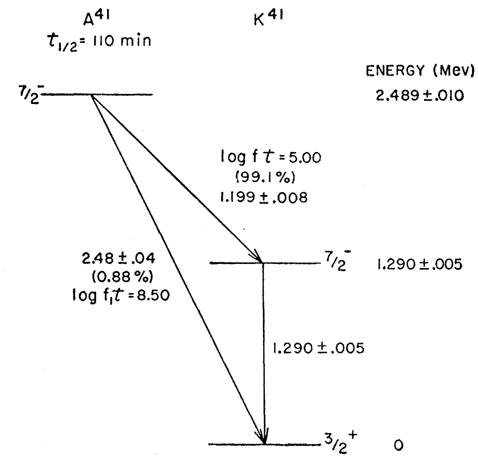

FIG. 9. Decay scheme of A^{41}.

The spin of the K^{41} ground state has been measured directly by molecular-beam techniques.[4] The parity is inferred from the shell model configuration of $d_{\frac{3}{2}}$ for this state. From the ($\Delta J=2$, yes) nature of the beta decay, the spin and parity of the ground state of A^{41} is inferred to be (7/2−) in agreement with the simple shell model prediction for an $f_{7/2}$ configuration. The spin of the excited state of K^{41} has been determined by Engelder[14] and by Elliot[15] from the multipolarity ($M2$) of the gamma-ray transition which they deduced from the 6.6×10^{-9}-sec half-life of this state. This spin assignment is consistent with the ft value of the beta transition to this state.

The mass difference between A^{41} and K^{41} on the basis

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[13] C. S. Wu in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 333.
[14] T. C. Engelder, Phys. Rev. **90**, 259 (1953).
[15] L. S. Elliott, Phys. Rev. **85**, 942 (1952).

of the sum of the 1.199-Mev beta end point and the 1.290-Mev gamma energies is 2.489±0.010 Mev or 2.673±0.011 mMU.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Dr. D. E. Alburger for kindly lending them his thin-lens spectrometer and associated circuitry and to Mr. Ottmar Kistner for his help in adapting this spectrometer for use with gaseous sources. We would also like to thank Dr. M. Fox and the members of the Brookhaven Reactor Department for their aid in the irradiation of the argon ampoules. The constant interest of Professor W. W. Havens, Jr., is appreciated.

PHYSICAL REVIEW VOLUME 103, NUMBER 6 SEPTEMBER 15, 1956

Coulomb Excitation of Elements of Medium and Heavy Mass*

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(Received April 2, 1956; revised version received June 21, 1956)

Yields of gamma rays from thick targets of In, I^{127}, Ta^{181}, $Re^{185,187}$, $Ir^{191,193}$, $Hg^{198,199,200,202}$, Th, and U were investigated under proton or alpha-particle bombardment in the energy range 2 to 4 Mev. By using the theory for electric excitation, reduced matrix elements for all electrically excited radiations were computed and compared with single-particle estimates. The results are interpreted in terms of the strong-coupling collective model of Bohr and Mottelson and compared with the systematic trends in the region of the closed shell at 126 neutrons.

A 512-kev gamma ray excited in In by proton bombardment must result from a nuclear reaction. From excitation curves, gamma rays in I^{127} at 60, 208, 392, 438, 631, 751, and 941 kev appear to arise from Coulomb excitation. No cascade radiations are observed. The radiations from Ta, Re, Ir, and Hg show the effects of a transition from the strong collective rotational motion to a collective vibrational nuclear motion or single-particle excitation as one approaches the closed neutron shell. Only the first excited states of Th^{232} and U^{238} were excited with alpha particles. No evidence for other levels was observed with proton excitation. The results agree within experimental error with other excitation measurements and with radiative lifetime measurements.

INTRODUCTION

COULOMB excitation has recently been exploited to produce a large volume of experimental data on the properties of low-lying excited states of nuclei throughout the mass table.[1] Because the nature of the electromagnetic interaction is well understood, one can make quantitative deductions of the magnitudes of radiative matrix elements from the experimental data. These results may then be compared with the same quantities deduced from direct radiative lifetime measurements. The theory of Coulomb excitation has been treated semiclassically[2] as well as rigorously.[3] The semiclassical approximation developed by Alder and Winther[2] is sufficiently accurate for the work reported here. Coulomb excitation studies have provided a striking confirmation of the predictions of the unified nuclear model of Bohr and Mottelson.[4] That model is most successful in the regions between closed shells where the collective effects in the nucleus produce large distortion, enhanced quadrupole moments, and enhanced radiation matrix elements.

Some of the experiments reported here were undertaken to supplement investigations of level properties by inelastic neutron scattering.[5] At the present time, inelastic neutron scattering cannot be used to determine spins and parities, although it can excite a much wider variety of states than can electric excitation. I^{127} was selected because the results from (n,n') scattering were quite ambiguous and it was hoped that Coulomb excitation would clarify the problem.

Verifications of the theory for excitation had been made[6] for some medium-mass elements and it was generally assumed that the direct nuclear interaction would not play any appreciable role in nuclei as heavy as In when bombarded with protons in the energy range 2–3 Mev. After startling deviations from theory were observed in indium, excitation studies were made

*Supported by the U. S. Atomic Energy Commission and the Wisconsin Alumni Research Foundation.

† Now at the Rice Institute, Houston, Texas.
‡ Now with Department of Atomic Energy, Government of India, Bombay, India.
§ Now with Lockheed Aircraft Corporation, Van Nuys, California.

[1] A review paper by Alder, Bohr, Huus, Winther, and Zupancic Revs. Modern Phys. (to be published) summarizes the experimental results. See also summary papers by G. Temmer and N. Heydenburg, Phys. Rev. **100**, 150 (1955) and Huus, Bjerregaard, and Elbek, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 17 (1956). P. H. Stelson and F. K. McGowan, Phys. Rev. **99**, 112 (1955) and McClelland, Mark, and Goodman, Phys. Rev. **97**, 1191 (1955).

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