Decay of Ca^{39}†

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The "doubly closed shell ± one nucleon" mirror transition, $Ca^{39}(\beta^+)K^{39}$, has been investigated in order to obtain a more precise *ft* value. The beta spectrum was measured with a magnetic, thin-lens spectrometer and has a maximum energy of 5.490±0.025 Mev. A search for gamma rays was made with a NaI(Tl) scintillation spectrometer, and an upper limit of 0.12% was placed on transitions to the lowest known excited levels in K^{39} between 2.5 and 3.5 Mev. A half-life of 0.88±0.01 second was determined. The *ft* value calculated from these results is 4320±100 seconds.

INTRODUCTION

THE decay of Ca^{39} is one of a group of six mirror transitions which have a "doubly closed shell ± one nucleon" nuclear configuration. The comparative half-lives of these transitions, together with those of the 0–0 spin transitions, have been used for determining C_{GT}^2/C_F^2, the ratio of the squares of the coupling constants for Gamow-Teller and Fermi interactions in beta decay.[1–6] Theoretical calculations of the Gamow-Teller matrix elements required for this analysis have been based on the single-particle model. Corrections for coupling of the single particle to the core have been made by considering the deviation of the experimental magnetic moment of the daughter nucleus from the Schmidt limits.[1,2,6,7] For most of this group of mirror transitions, the deviation of the magnetic moments from the Schmidt limits is relatively small. The deviation for K^{39}, however, leads to an appreciable correction for the matrix element of the $Ca^{39}(\beta^+)K^{39}$ transition. The determination of an accurate *ft* value for this decay would permit a comparison to be made of the predictions from the various magnetic moment interpolation methods with an empirical value of the Gamow-Teller matrix element obtained from the other transitions of this group.

The results of previous work[8] on the decay of Ca^{39}, which are listed in Table I, are inconsistent, and no search for gamma rays has been reported. A careful measurement of the beta spectrum, half-life, and gamma spectrum was therefore undertaken to obtain a more precise *ft* value.

PRODUCTION OF Ca^{39} AND THE PNEUMATIC SHUTTLE SYSTEM

The Ca^{39} for this experiment was produced with the Brookhaven 60 inch cyclotron by the reaction, $K^{39}(p,n)Ca^{39}$. The source was made of metallic potassium evaporated onto a 0.0001-inch silver foil to a thickness of 4 mg/cm .

In order to minimize background during the measurements, a pneumatic shuttle system was constructed which transported the source a distance of 55 feet from the target position at the end of the cyclotron beam pipe to a shielded experimental area. The target foil was mounted on a nylon slider which was propelled by differential gas pressure through a rectangular aluminum tube which had inside dimensions of $1\frac{1}{4}$ in. by $\frac{1}{2}$ in. The basic components of the system consisted of a pressure tank and a vacuum tank connected by pneumatically operated valves to one end of the tube, and a ballast volume connected to the other end. The slider was reciprocated by alternately opening the valves to the pressure tank and the vacuum tank. The system was designed so that the pressure differential passed through zero just before the slider reached the end of the tube. The slider was thereby brought gently to rest with a slight back pressure. An initial pressure differential of 10 cm of Hg was sufficient to propel the slider over the distance of 55 feet in 0.8 second. An aluminized 0.8-mg/cm² Mylar window in front of the source posi-

TABLE I. Results of measurements on the decay of Ca^{39}.

E_{max} (Mev)	Method	Half-life (sec)	Reference
5.13 ±0.15	Scin.	1.1 ±0.2	a
6.7 ±0.5	abs.		b
6.10 ±0.15	Scin.	0.90±0.05	c
		0.90±0.01	d
5.58 ±0.4	Scin.	0.97±0.02	e
5.490±0.025	Mag. lens	0.88±0.01	Present work

[a] F. I. Boley and D. J. Zaffarano, Phys. Rev. **84**, 1059 (1951).
[b] R. Braams and C. L. Smith, Phys. Rev. **90**, 995(L) (1953).
[c] W. A. Hunt *et al.*, Phys. Rev. **95**, 611(A) (1954).
[d] R. M. Kline and D. J. Zaffarano, Phys. Rev. **96**, 1620 (1954).
[e] L. S. Ring, Jr., and D. J. Zaffarano, Iowa State College Report ISC-648, 1955 (unpublished).

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[1] A. Winther and O. Kofoed-Hansen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 14 (1953).
[2] O. Kofoed-Hansen and A. Winther, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 20 (1956).
[3] J. B. Gerhart, Phys. Rev. **95**, 288 (1954).
[4] J. M. Blatt, Phys. Rev. **89**, 83 (1953).
[5] J. S. Bell and R. J. Blin-Stoyle, Nuclear Phys. **6**, 87 (1958).
[6] G. L. Trigg, Phys. Rev. **86**, 506 (1952).
[7] G. Mayer and J. H. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley and Sons, Inc., New York 1955), p. 176.
[8] Two independent investigations, which were reported after this work was completed, are in good agreement with the present results. J. A. Welch, Jr., and R. Wallace obtained an end point of 5.43±0.06 Mev with a 180° magnetic spectrometer and a half-life of 0.88±0.05 sec. J. E. Cline and P. R. Chagnon obtained a half-life of 0.876±0.012 sec. Both are reported in Bull. Am. Phys. Soc. Ser. II, **3**, 206 (1958).

tion separated the pneumatic tube system from the evacuated spectrometer tank. The maximum absolute pressure of the system was 18 cm of Hg.

To minimize the production of radioactive contaminants, the entire system was made vacuum tight, and helium was used as the propellent gas. The evaporation of potassium metal onto the target foil was performed in an adjoining volume from which the slider could be transferred to the pneumatic tube without breaking vacuum. The operation of the system was controlled by a cam timer driven by a synchronous motor so that the slider could be cycled automatically.

BETA-RAY SPECTROMETER

The thin-lens spectrometer used for this experment was the same as that described previously for the measurement of the A^{35} beta spectrum.[9] The resolution was 2% with a 1 cm diameter source and with the baffles set for a transmission of 0.25%. A detailed calibration was performed in order to check the instrument for nonlinearity which could possibly have been caused by coil movements arising from cooling-water pressure and field effects. The following well-known internal conversion lines were measured:

976.0 kev, Bi^{207};

624.2 kev, Cs^{137};

$$\left.\begin{array}{r}2526 \text{ kev}\\ 422.8 \text{ kev}\\ 222.2 \text{ kev}\end{array}\right\}, \text{ mesothorium emanation source.}$$

The calibration constants from these lines were consistent within the accuracy of the measurement, which was approximately 0.1%.

HALF-LIFE

For the half-life measurements, a stilbene scintillation counter was placed at the detector position of the beta-ray spectrometer, and the baffle was opened to give a transmission of 0.5%. Bombardments of two seconds duration were made. The scintillation pulses in the narrow energy band transmitted by the spectrometer were selected by a single-channel pulse-height analyzer and recorded on one channel of an Edin, dual-pen, tape recorder. A continuous time calibration was made by recording, with the second channel, the pulses from a 1000-cycle tuning-fork oscillator scaled by a convenient factor. The data from a number of decay runs at a given energy could be superimposed in the analysis in order to obtain sufficient statistical accuracy. This technique minimized the effects due to pulse pileup and dead time in the counter electronics, and reduced background to a very small value.

The half-life of Ca^{39} was measured at beta energies of 2, 3, and 4 Mev. The semilogarithmic decay curves at 3 and 4 Mev are linear for more than five half-lives and give an average half-life of 0.88 ± 0.01 second. At 2 Mev a contaminant with a half-life of the order of ten seconds was observed amounting to about 4% of the total activity. This is attributed to 12-second Mg^{23} produced from small amounts of sodium present in the potassium. In addition, a relatively long-lived activity was found which increased slowly during each run. This was primarily due to N^{13} which has a 1.2-Mev beta group.

BETA SPECTRUM

For the beta spectrum measurements, a Geiger counter, filled to a pressure of 12 cm of Hg with argon-alcohol, was used for the spectrometer detector. The activity in the source was monitored with a Geiger counter which detected positrons emitted through a Mylar window covering the back of the source volume. Because of the relatively large cross section of the $Na^{23}(p,n)Mg^{23}$ reaction and the difficulty of obtaining a target free of sodium, it was not possible to make a source without a significant amount of Mg^{23} contaminant. The beta spectrum was therefore analyzed only above the 3-Mev end point of Mg^{23}.

The following method of taking data was used in order to eliminate the effects of long-lived contaminants. An aluminum absorber was placed in front of the monitor counter in order to reduce the contribution of the relatively low-energy positrons from N^{13} to the monitor count. The detector and monitor counters were each connected to two scalers in parallel. Immediately after the source arrived at the spectrometer, following a two-second bombardment, the gates to one pair of monitor and detector scalers were opened for a period of two seconds. After a four-second delay, the gates to the other pair of scalers were also opened for a period of two seconds, after which time the source was returned for the next bombardment. A complete cycle required 14 seconds and was repeated until a sufficient number of counts was accumulated. The relative intensity of a point on the spectrum was then obtained by taking the ratio of the difference of the counts registered by the two detector and monitor scalers, respectively. The cyclotron beam gate and the counter gates were controlled by the shuttle-system cam timer. The counting periods of the four scalers were made equal to within $\frac{1}{4}$%.

A proton beam of 4 microamperes gave a net detector counting rate of about 120 counts per cycle at the peak of the beta spectrum. This corresponds to a cross section of approximately 2 millibarns for the $K^{39}(p,n)$ reaction at 10 Mev. The intensities at zero field and above the upper end of the spectrum were 1.5% and 0.15% of the peak of the spectrum, respectively. A linear interpolation between these values was subtracted from the spectrum as background. The Kurie plot of a typical spectrum is shown in Fig. 1. Results of the weighted least-squares analysis of 4 Kurie plots are listed in Table II. The average end-point energy is 5.490 ± 0.025 Mev where the stated error is twice the

[9] O. C. Kistner *et al.*, Phys. Rev. **104**, 154 (1956).

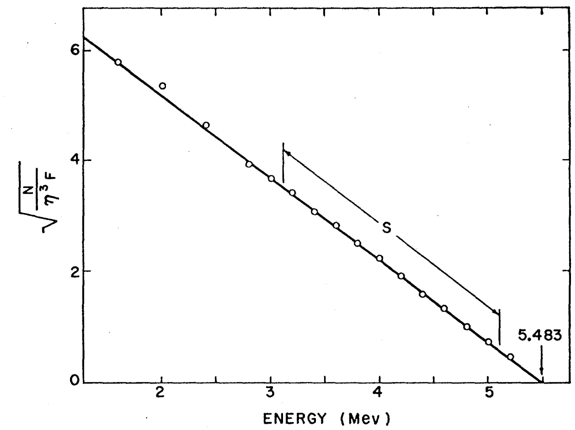

FIG. 1. Kurie plot of a typical Ca^{39} beta-spectrum run. The end point was obtained from a weighted least-squares fit to the points in region S.

combination of the statistical standard deviation and the estimated error of the calibration.

The small-order corrections to the allowed shape of the beta spectrum and the resulting effects on the extrapolated end point were investigated.[10] Inner bremsstrahlung causes an apparent reduction in the maximum beta energy of about 7 kev.[11] The effect of the finite deBroglie wavelength of the leptons causes a shift of the end point of the same magnitude but in the opposite sense.[12] The net effect is therefore small relative to the stated error.

GAMMA SPECTRUM

The gamma spectrum was measured with a 3×3 inch NaI(Tl) scintillation counter and a 100-channel analyzer. No short-lived gamma rays were observed. Relative to the ground-state transition, an upper limit of 0.12% was placed on transitions to the lowest known excited levels in K^{39} between 2.50 and 3.50 Mev.[13–15]

TABLE II. The extrapolated end points obtained from weighted least-squares fits to the Kurie plots of four Ca^{39} beta spectra above 3 Mev. The agreement between the internal and external errors indicates that the Kurie plots are linear within the statistical errors and that instrumental random errors are negligible. The calculation of these errors is discussed by Birge.[a]

E_{max} (Mev)	Standard deviation (Mev) Internal	External
5.503	0.011	0.008
5.465	0.012	0.013
5.483	0.013	0.010
5.504	0.013	0.018

[a] R. T. Birge, Phys. Rev. **40**, 207 (1932).

[10] M. Morita (private communication).
[11] The contribution of inner bremsstrahlung was calculated from curves computed by A. Z. Schwarzschild (unpublished).
[12] The effects of the finite deBroglie wavelength were estimated from tables of L_0 compiled by Rose, Perry, and Dismuke, Report ORNL No. 1459; Oak Ridge National Laboratory.
[13] R. B. Schwartz *et al.*, Phys. Rev. **101**, 1370 (1956).
[14] A. Sperduto and W. W. Buechner, Phys. Rev. **100**, 961(A) (1955).
[15] J. P. Schiffer *et al.*, Phys. Rev. **103**, 134 (1956), have found no levels in K^{39} below 2 Mev.

DISCUSSION

The ft value of the superallowed beta transition, $Ca^{39}(\beta^+)K^{39}$, calculated from the end-point energy of 5.490 ± 0.025 Mev and the half-life of 0.88 ± 0.01 second with the f function tables of Moszkowski and Jantzen,[16] is 4320 ± 100 seconds. From this ft value, together with those of the 0–0 spin transitions and the "doubly closed shell ± one nucleon" mirror transitions of O^{15} and F^{17}, the square of the Gamow-Teller matrix element, $|\int\boldsymbol{\sigma}|^2$, for the Ca^{39} decay is calculated to be 0.38 ± 0.05. This corresponds to a value for C_{GT}^2/C_F^2 of 1.16 ± 0.05. The O^{15} and F^{17} decays were used for this purpose because the magnetic moments of the daughter nuclei for these cases are especially close to the Schmidt limits; and, therefore, the calculation of $|\int\boldsymbol{\sigma}|^2$ from the single-particle model may be expected to be a good approximation. Small corrections were made to the single particle values of $|\int\boldsymbol{\sigma}|^2$ according to the Schmidt-Schmidt interpolation procedure.[1] These corrections were included as estimated errors for the matrix elements in the computation of the stated errors. The single-particle value and the various semiempirical predictions of $|\int\boldsymbol{\sigma}|^2$ for the Ca^{39} decay are listed in Table III. It is interesting to note that $|\int\boldsymbol{\sigma}|^2$ for Ca^{39} must be very close to that for O^{15}, 0.35, almost independently of the ratio of the coupling constants because the ft values of both the transitions are very nearly the same. In view of the possible uncertainties in the estimates of the Gamow-Teller matrix elements[5] of O^{15} and F^{17}, the predictions of both the Schmidt-Schmidt and the Schmidt-Margenau-Wigner interpolation procedures can be considered to be in agreement with the empirical value.

TABLE III. Gamow-Teller matrix element predictions for the $Ca^{39}(\beta^+)K^{39}$ mirror transition.

$\lvert\int\boldsymbol{\sigma}\rvert^2$	Method of calculation	Reference
0.60	Single-particle model	
0.39	Magnetic moment interpolation between the Schmidt limits (odd-particle model)	a
0.33	Magnetic moment interpolation between the corresponding Schmidt and Margenau-Wigner limits (uniform model)	b
0.14	Substitution of experimental magnetic moment in the j-j coupling formula	c

[a] See reference 1.
[b] See reference 6.
[c] See reference 7.

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[16] S. A. Moszkowski and K. M. Jantzen, University of California at Los Angeles U.C.L.A. Technical Report No. 10-26-55 (unpublished).

encouragement. We are indebted to Dr. M. Morita and Dr. J. Weneser for their helpful discussion of the theory. Mr. F. A. Dugan contributed many constructive suggestions to the design of the pneumatic tube system. Finally it is a pleasure to acknowledge the assistance and cooperation of Dr. C. P. Baker and the cyclotron crew during the many cyclotron bombardments.

Note added in proof.—An accurate value for the neutron half-life, 11.7±0.3 minutes, has recently been reported by Sosnovskij *et al.* at the High Energy Conference, Geneva, July, 1958. The resulting *ft* value for the neutron decay is 1187±35 seconds which, when combined with the 0–0 transitions, gives a value for C_{GT}^2/C_F^2 of 1.42±0.06 and leads to an empirical Gamow-Teller matrix element for Ca^{39} of 0.30. We shall discuss this further in a future paper.

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$N^{14}(d,n)O^{15}$ and $N^{15}(d,n)O^{16}$ Reactions*†

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Absolute cross sections for the $N^{14}(d,n)O^{15}$ and $N^{15}(d,n)O^{16}$ reactions have been measured at zero degrees to the incident deuteron beam from 0.6 to 5.3 Mev bombarding energy. Both excitation curves show strong resonance structure and have maximum cross sections of about 6 millibarns per steradian. Eight angular distributions were measured for the $N^{15}(d,n)O^{16}$ reaction at points on and off maxima in the excitation curve. A good fit to the angular distributions is obtained by use of the exchange stripping theory of Owen and Madansky.

I. INTRODUCTION

THE present investigation of the $N^{14}(d,n)O^{15}$ ($Q=5.122$ Mev) and $N^{15}(d,n)O^{16}$ ($Q=9.885$ Mev)[1] reactions was undertaken primarily to ascertain their usefulness as neutron sources in the energy range from 8 to 14 Mev. Reactions which have hitherto been used as neutron sources with Van de Graaff accelerators do not provide neutrons in this energy region. The two reactions are not monoergic sources, but the first excited state is very well separated from the ground state in both O^{15} and O^{16} (5.27 and 6.06 Mev spacings, respectively). A neutron detector with only moderate energy resolution is needed to distinguish the ground state group in either reaction.

If the excitation functions for the $N^{14}(d,n)O^{15}$ and $N^{15}(d,n)O^{16}$ reactions show evidence for compound nucleus formation, information can be obtained on excited states of O^{16} above 20.7 Mev and O^{17} above 14.0 Mev.[1] Angular distribution measurements may help in the determination of reaction mechanisms of deuteron induced reactions in this energy region.

Previous experimental work on the resolved ground state neutron groups from these reactions has not been extensive. Johnston and Bostrom[2] have reported measurements of the excitation curve and angular distributions of $N^{14}(d,n)O^{16}$ for energies below 2.4 Mev. Nonaka *et al.*[3] measured the angular distribution and absolute cross section at 1.96 Mev and Morita[4] has measured relative cross sections at $\theta=0°$, 90°, and 165° from 1.0 to 2.15 Mev bombarding energy. No previous measurements have been reported on the $N^{15}(d,n)O^{16}$ reaction.

II. EXPERIMENTAL METHOD

The deuteron beam from a Van de Graaff accelerator was magnetically analyzed (±0.1% in energy). The beam was then focused and collimated before it entered a gas target. This target was made of 10-mil-wall stainless steel tubing with a gold beam stop and a 0.01-mil nickel entrance window. The target thickness was 20 kev or less in both experiments, with the exception of the $N^{15}(d,n)O^{16}$ data below 1 Mev, where it was as large as 40 kev. The incident deuteron energy was corrected for the energy loss in traversing the nickel foil and one-half the target gas.[5]

Small plastic scintillators were used as proton recoil counters to detect the neutrons.[6] The small size was necessary in order to discriminate against gamma rays. A spheroid 4.90 mm by 2.45 mm, on edge to the beam and backed by an aluminum reflector, was used for the $N^{14}(d,n)O^{15}$ reaction. A right cylinder 5.49 mm long by

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† A preliminary report on this work was given at the Chicago Meetings of the American Physical Society, November 23 and 24, 1956 [Jones, Weil, Kruse, Baicker, and Lidofsky, Bull. Am. Phys. Soc. Ser. II, 1, 326 (1956)].

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[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[2] R. W. Johnston and N. A. Bostrom, Bull. Am. Phys. Soc. Ser. II, **2**, 104 (1957).

[3] Nonaka, Morita, Kawai, Ishimatsu, Takeshita, Nakajima, and Takano, J. Phys. Soc. Japan **12**, 841 (1957).

[4] S. Morita, J. Phys. Soc. Japan **13**, 126 (1958).

[5] J. L. Fowler and J. E. Brolley, Jr., Revs. Modern Phys. **28**, 103 (1956); Reynolds, Dunbar, Wenzel, and Whaling, Phys. Rev. **92**, 742 (1953); Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU-663 (unpublished).

[6] Taylor, Lönsjö, and Bonner, Phys. Rev. **100**, 174 (1955).