^{36}K Decay and $T=1$ Analog in ^{36}Ar†

R. E. Berg,* J. L. Snelgrove,‡ and E. Kashy
Cyclotron Laboratory, Michigan State University, East Lansing, Michigan
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The 23-MeV proton beam from the Michigan State University sector-focused cyclotron was used to produce the ^{36}K isotope by means of the ^{36}Ar$(p,n)^{36}$K reaction. From measurements of γ rays following the positron decay of ^{36}K, the half-life of ^{36}K was measured to be 0.265 ± 0.025 sec, and energy levels in ^{36}Ar were measured at 1.9701 ± 0.0007, 4.1779 ± 0.0007, 4.4401 ± 0.0012, and 6.6119 ± 0.0009 MeV. The 6.6119-MeV level is identified as the $T=1$ analog of the ground states of ^{36}Cl and ^{36}K. Branching ratios for the positron decay of ^{36}K were obtained and the $\log ft$ values computed for each branch, using the observed partial half-life and a computed value of the ^{36}K mass. Spin and parity assignments of 2+ have been made for the ground state of ^{36}K and the $T=1$ level of ^{36}Ar, in agreement with the expectation from the previously measured 2+ value of the ^{36} Cl ground-state spin.

INTRODUCTION

There has been considerable interest recently in the Coulomb systematics of analog states.[1] Among such experiments has been the precise determination of excitation energies of $T=1$ analogs in the $T=0$ members of several isotopic spin triplets.[2–4] In the present investigation, properties of the $A=36$ triplet were measured, where neither the $T=1$ level of ^{36}Ar nor the isotope ^{36}K had been previously observed. The (p,n) reaction on ^{36}Ar was used to produce ^{36}K, which then decays with a high probability to its $T=1$ analog in ^{36}Ar, since the transition is superallowed. From the measured $T=1$ energy level, we have calculated, on the basis of Coulomb systematics, a value for the mass of ^{36}K, using a uniform charge model. Such a model is shown to yield, in the case of the $A=40$ isotopic spin triplet, a value for the mass of ^{40}Sc in reasonable agreement with the measured value. An experimental determination of the ^{36}K mass from (He^3,t) measurements on ^{36}Ar has been reported in progress.[5]

EXPERIMENTAL PROCEDURE

Negative hydrogen ions were accelerated to 23 MeV in the Michigan State University cyclotron and extracted by stripping the orbital electrons in a 700 μg/cm^2 aluminum foil. A $\frac{1}{8}$-in.-diam hole following the stripping foil served as the object aperture for the beam-focusing system shown in Fig. 1. The beam was focused into a cylindrical aluminum gas cell, $\frac{3}{4}$ in. in diam. by 5-in. long, containing argon gas enriched to over 99% ^{36}Ar; entrance and exit windows for the proton beam were constructed of 0.001 in. Kapton. A 3-cc Ge(Li) detector positioned two in. from the center of the cell was used to detect the γ radiation.

In order to insure that no beam hit the walls of the gas cell, a thin piece of plastic scintillator with a $\frac{1}{4}$-in. hole was periodically inserted in the beam path immediately before the cell with the $\frac{1}{4}$-in. hole centered on the axis of the cell. The scintillator was viewed by remote TV and the beam focused to go entirely through the $\frac{1}{4}$-in. hole. This procedure eliminated the need of having a defining aperture close to the cell, which would have increased the γ-ray background.

The principal background radiation observed consisted of the well-known 1.369- and 2.754-MeV γ rays from the decay of ^{24}Na, the latter resulting from the interaction of neutrons with the aluminum in the gas cell and the beam pipe system. These γ rays provided ideal calibration data, since their energies are known to a high degree of accuracy.

The proton beam was turned on and off with a period of about 1.5 sec by pulsing the cyclotron rf voltage. While the beam was on (0.75 sec), the data were accumulated in the first 1024 channels of a 4096-channel analyzer, and while the beam was off, the data were routed successively into the remaining three quadrants, with data accumulated for approximately 0.25 sec in each quadrant. The time span for each of the quadrants was carefully calibrated for use in the determination of the ^{36}K half-life.

HALF-LIFE OF ^{36}K

Figure 2 shows three successive 1024-channel γ-ray spectra obtained during a 12-h run with an average beam current of 15 nA.

The attenuation of the 5.588-MeV peak from the de-excitation of the $T=1$ level of ^{36}Ar is apparent in Fig. 2. Values of the ^{36}K half-life were calculated from such data by comparing the yield in successive spectra of each γ ray identified as a transition in ^{36}Ar. The resulting value for the ^{36}K half-life after correction for the decrease in analyzer dead time in successive spectra was 0.265 sec, with a standard deviation of 0.025 sec.

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* National Science Foundation Cooperative Graduate Fellow.
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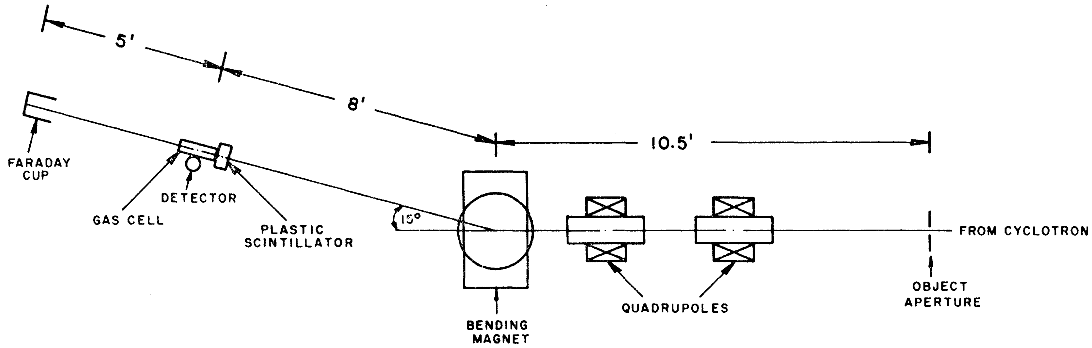

FIG. 1. Beam transport system used in the $^{36}Ar(p,n)^{36}K$ experiment.

ENERGY LEVELS OF ^{36}Ar

Previous experiments have established energy levels of ^{36}Ar at 1.973±0.007, 4.17±0.03, 4.45±0.05, 4.94 ±0.03, 5.85±0.03, and 6.85±0.03 MeV.[6] Preliminary analysis of inelastic scattering of protons from ^{36}Ar shows strong excitation of levels at 1.97 and 4.17 MeV, while less strongly excited levels were observed at 4.41, 5.15, and 5.88 MeV.[7] On the basis of the inelastic scattering data, spin and parity assignments of 2+ to the 1.97-MeV level and 3− to the 4.17-MeV level are indicated, in agreement with previous assignments obtained from $^{35}Cl(p,\gamma)^{36}Ar$ experiments.[8]

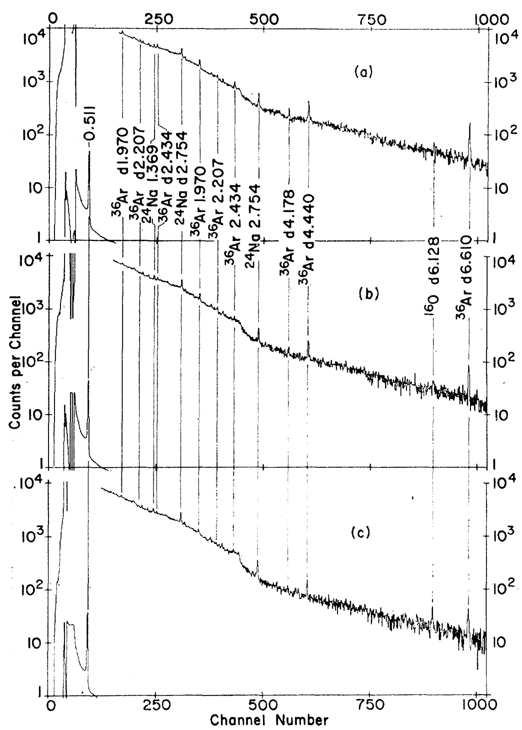

FIG. 2. γ-ray spectra obtained in successive time intervals of approximately 0.25 sec following the 0.75-sec beam pulse. Attenuation of the prominent ^{36}Ar γ rays resulting from the short half-life of ^{36}K is clearly apparent. Energies of the peaks are given in MeV; double-escape peaks are marked *d*.

Each of the three spectra in Fig. 2 was analyzed to obtain the energies of levels in ^{36}Ar. Standard γ rays used for calibration are given in Table I.[9,10] Energies of γ rays from ^{36}Ar are given in Table II, along with their relative strengths. Correcting for the recoil of the nucleus, the resulting ^{36}Ar energy levels are shown in Table III. The existence of two decay branches for the 4.178- and the 6.612-MeV levels allows extremely precise determination of the energy of these levels. Figure 3 shows energy levels of ^{36}Ar obtained from the positron decay of ^{36}K.

Branching ratios for the positron decay of ^{36}K to ^{36}Ar, determined to about ±5% accuracy on the basis of γ-ray yields, are shown in Fig. 3. Absolute efficiency curves for the detector used are shown in Fig. 4. Photopeak efficiencies were obtained experimentally by comparison to a NaI(Tl) detector, and double-escape peak efficiencies were computed.[11] No evidence was found for a β^+ branch to the 4.178-MeV level; on the basis of spin selection rules, the possibility of a sizable branch to the ground state of ^{36}Ar was excluded. From the branching ratios of the positron decay, partial lifetimes were computed and log*ft* values obtained, using a calculated value for the ^{36}K mass.[12] (See discussion below.)

TABLE I. Standard γ rays used for calibration.

E_γ (MeV)	ΔE_γ (MeV)
0.511006	±0.000005[a]
1.36853	±0.00004[a]
2.75392	±0.00012[a]
5.1058	±0.0012[b]

[a] See Ref. 9. [b] See Ref. 10.

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[12] A. H. Wapstra, G. J. Nijgh, and R. van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

TABLE II. Observed γ rays from transitions in ^{36}Ar. Relative strength is normalized such that the total number of β^+ decays to ^{36}Ar levels is 1.000.

E_γ (MeV)	ΔE_γ (MeV)	Relative strength
1.9700	±0.0007	0.887±0.020
2.2067	±0.0010	0.185±0.020
2.4344	±0.0007	0.230±0.050
4.1783	±0.0009	0.020±0.005
4.4398	±0.0012	0.045±0.010
6.6096	±0.0020	0.023±0.005

γ-ray branching ratios in the de-excitation of the 6.612- and the 4.178-MeV levels are also given in Fig. 3. The branching ratios for de-excitation of the 4.178-MeV level agree, within the accuracy of the measurements, with previously published results.[8,13] However, no transition was observed between the 4.440- and the 1.970-MeV level, as had been previously reported.[8]

The existence of an allowed positron decay branch to the 1.970-MeV 2+ level of ^{36}Ar suggests spin-parity of 1+, 2+, or 3+ for the ground state of ^{36}K; the observed superallowed positron decay branch to the 6.612-MeV level establishes this level as the analog to the ground state of ^{36}K, also with spin 1+, 2+, or 3+. Of these, an assignment of spin and parity of 2+ can be made for the 6.612-MeV level on the basis of the strong transitions observed to the ground and 3− levels. This yields a spin and parity assignment of 2+ to the ground state of ^{36}K. These results are expected, since the $T_z=+1$ member of the isospin triplet, ^{36}Cl, has a ground-state spin and parity of 2+ and its first excited state lies at 788 keV.

The positron decay branch to the 4.440-MeV level of ^{36}Ar suggests spin and parity of 1+, 2+, or 3+ for that level. A 3+ assignment is unlikely, since no decay branch is observed to the 1.970-MeV 2+ level.

MASS OF ^{36}K

With the measured energy of the $T=1$ analog level in ^{36}Ar, the ^{36}Ar-^{36}K mass difference was computed using Coulomb systematics. Table IV gives a comparison of measured β^+ decay energies[14,15] to values for several $T=1$, $T_z=-1$ nuclei computed using the relation

$$M(Z+1)-M(Z)=E_x(Z,\,T=1)-M_n+M_p+\Delta E_c\,,$$

TABLE III. Energy levels of ^{36}Ar with spin-parity assignments.

E_x (MeV)	ΔE_x (MeV)	$J\pi$
1.9701	±0.0007	2+
4.1779	±0.0007	3−
4.4401	±0.0012	(2+)
6.6119	±0.0009	2+

[13] R. Berenbaum and J. H. Matthews, Proc. Phys. Soc. (London) **A70**, 445 (1957).

[14] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 1 (1965).

[15] M. E. Rickey, P. D. Kunz, J. J. Kraushaar, and W. C. Anderson, Phys. Letters **17**, 296 (1965).

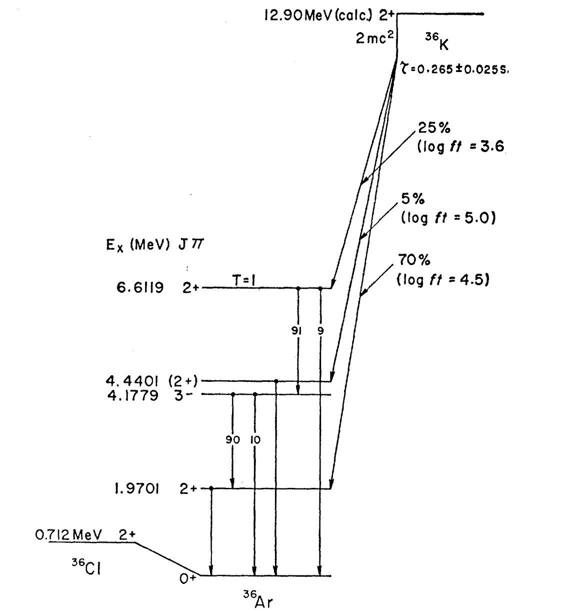

FIG. 3. Energy-level diagram for levels of ^{36}Ar populated by the decay of 0.265-sec ^{36}K. Branching ratios are given to within about ±5% and spin-parity assignments are indicated.

where

$$\Delta E_c=\frac{6}{5}\frac{e^2}{r_0}\frac{Z}{A^{1/3}}.$$

The constant r_0 is obtained in a similar way from the known mass differences between the $T_z=+1$ and $T_z=0$ members of the triplet, and the excitation energy of the lowest $T=1$ level in the $T_z=0$ nucleus. Of particular significance is the accuracy with which this uniform charge model predicts the mass of ^{40}Sc. Using the recent

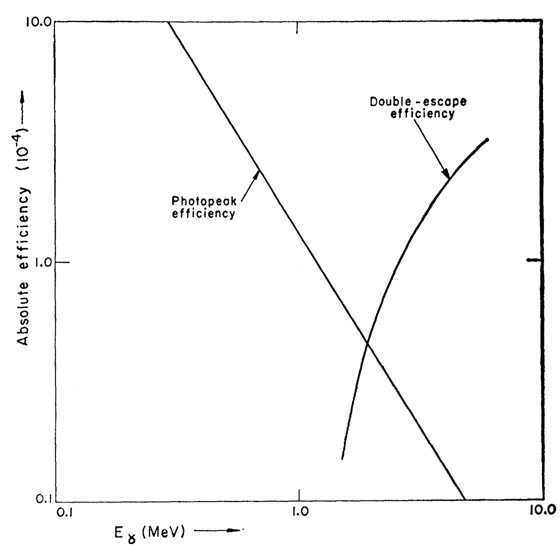

FIG. 4. Absolute efficiency curves for Ge(Li) detector. Photopeak efficiencies were obtained by comparison with a NaI(Tl) crystal, and double-escape efficiencies were computed.

TABLE IV. Comparison of measured β^+ decay energies with calculated values obtained using the uniform-charge model from measured β^- decay energies and measured values for the excitation energy of the $T=1$ level of the $T_z=0$ nucleus.

A	$E_x(T=1)$ (MeV)	Measured β^- decay energies (MeV)	r_0(F)	Calculated β^+ decay energies (MeV)	Measured β^+ decay energies (MeV)
40(K-Ca-Sc)	7.661±0.001(Ca)	1.314±0.003[a]	1.346	14.38	14.47±0.06[b]
36(Cl-Ar-K)	6.612±0.001(Ar)	0.712±0.004[a]	1.331	12.90	...
32(P-S-Cl)	7.002±0.008(S)	1.710±0.002[a]	1.343	12.70	13.20±0.38[a]

[a] See Ref. 14. [b] See Ref. 15.

value of 7.661±0.001 MeV for the energy of the $T=1$ level of ^{40}Ca,[3] the computed ^{40}Sc–^{40}Ca mass difference differs from the measured value by about 1.5 times the error in the experimental measurement,[15] as shown in Table IV.

A simple picture can be employed to explain the accuracy of this procedure in the case of ^{40}Sc and to justify its use in predicting the mass of ^{36}K. The wave functions for the members of the $A=40$ isotopic spin triplet can be written on a simple shell-model basis as

$$\psi(^{40}\mathrm{K})=[d_{3/2}^{-1};\, T=\tfrac{1}{2},\, T_z=+\tfrac{1}{2}]\,[f_{7/2}^{1};\, T=\tfrac{1}{2},\, T_z=+\tfrac{1}{2}],$$

$$\psi(^{40}\mathrm{Ca})=\tfrac{1}{2}\sqrt{2}[d_{3/2}^{-1};\, T=\tfrac{1}{2},\, T_z=-\tfrac{1}{2}]\,[f_{7/2}^{1};\, T=\tfrac{1}{2},\, T_z=+\tfrac{1}{2}] -\tfrac{1}{2}\sqrt{2}[f_{7/2}^{1};\, T=\tfrac{1}{2},\, T_z=-\tfrac{1}{2}]\,[d_{3/2}^{-1};\, T=\tfrac{1}{2},\, T_z=+\tfrac{1}{2}],$$

$$\psi(^{40}\mathrm{Sc})=[f_{7/2}^{1};\, T=\tfrac{1}{2},\, T_z=-\tfrac{1}{2}]\,[d_{3/2}^{-1};\, T=\tfrac{1}{2},\, T_z=-\tfrac{1}{2}].$$

The transition from $T_z=+1$ to $T_z=-1$ occurs smoothly by mixing of $d_{3/2}$ and $f_{7/2}$ shell wave functions in the $T_z=0$ member; such systematic behavior yields smooth Coulomb energy differences between adjoining members of the triplet. On this basis, the calculation of the ^{36}K mass should perhaps be even more accurate than that of ^{40}Sc, since in the case of the $A=36$ triplet the transition from $T_z=+1$ to $T_z=-1$ occurs entirely within the $d_{3/2}$ subshell. A value of 12.90 MeV for the ^{36}K–^{36}Ar mass difference has been obtained in the present calculation. It is also worth noting the constancy of the value of r_0 given in Table IV for $A=32$, 36, and 40.

Note added in proof. New data on the "measured β^+ decay energies" for ^{40}Sc and ^{32}Cl (Table IV) have been reported in D. A. Bromley, J. C. Overley, and P. D. Parker, Phys. Rev. Letters **17**, 705 (1966) as follows:

^{40}Sc 14.325±0.007 MeV
^{32}Cl 12.755±0.013 MeV.

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