written:

$$\varphi_i(\text{Sc}^{47})=[f_{7/2}^6(n)]_0 f_{7/2}(p),$$
$$\varphi_g(\text{Ti}^{47})=[f_{7/2}^5(n)]_{5/2}[f_{7/2}^2(p)]_0,$$
$$\varphi_e(\text{Ti}^{47})=[f_{7/2}^5(n)]_{7/2}[f_{7/2}^2(p)]_0.$$

Here φ_g and φ_e represent the wave functions for the ground state and excited state of Ti^{47}, respectively. If the calculation is carried out assuming that one of the neutron pairs of the parent is broken to form a proton pair in the product, it turns out that the transition to the excited state is allowed and that to the ground state is forbidden. On the other hand, if the ground-state configuration is used to calculate the magnetic moment of Ti^{47}, one obtains -1.67 instead of -0.787 nm. It is presumed that the "almost allowed" transition to the ground state (log $ft=6.0$) has its explanation in a certain amount of configuration mixing in the ground state which is at the same time responsible for the low value of the magnetic moment.

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Alpha-Particle Bombardment of A^{36} and A^{40}†*

R. B. Schwartz,‡ J. W. Corbett,§|| and W. W. Watson
Sloane Physics Laboratory, Yale University, New Haven, Connecticut
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Gas targets (130-kev thick) of natural argon (99.6% A^{40}; 0.34% A^{36}) and of argon enriched in A^{36} (97.4% A^{36}; 2.5% A^{40}) have been bombarded with 7.4-Mev alpha particles from the Yale cyclotron. Protons and neutrons at 90° to the incident beam have been studied by means of 50μ Ilford *C*-2 emulsions, placed 16 cm from the target. The ground-state *Q*-value for the $A^{36}(\alpha,p)K^{39}$ reaction is -1.28 Mev, with excited states at 2.50 and 2.87 Mev. The ground state *Q* for $A^{40}(\alpha,p)K^{43}$ is -3.36 Mev, with excited states at 0.65 and 1.18 Mev. The cross sections for these two reactions, as well as for the $A^{40}(\alpha,n)Ca^{43}$ reaction, have been measured and are found to be in general agreement with the predictions of simple compound-nucleus theory.

INTRODUCTION

IN 1924, Rutherford and Chadwick[1] reported particles emitted from argon under alpha bombardment. This reaction was then reinvestigated by Pollard and Brasefield,[2] Buchanan,[3] and others using natural argon (99.6% A^{40}, 0.34% A^{36}) and argon considerably enriched in A^{36}. However, since no protons were ever observed in these later experiments, this is the only part of Rutherford's early work in this field which has not been verified by later, more exact, measurements. Our present work, then, in addition to obtaining *Q*-value information in the currently important region around $Z=20$, indicates why the earlier investigators failed to detect any protons from these reactions. The explanation lies in a combination of circumstances: (1) the difficulty in handling gas targets, (2) the low alpha-beam currents available, (3) the fact that the most abundant isotope (A^{40}) has a low cross section, (4) the negative *Q*-values for these reactions, resulting in low-energy protons which were difficult to detect.

ALPHA-PARTICLE BOMBARDMENT

Argon gas targets were bombarded with 7.4-Mev alpha particles from the Yale cyclotron. The target chamber had a 0.87-mg/cm² mylar entrance window, and a 6.9-mg/cm² aluminum exit window. The chamber was initially pumped down through the main cyclotron vacuum, and the argon was then admitted at 15 cm pressure, making a target about 130-kev thick. Two different targets were used: one was natural argon (99.6% A^{40}; 0.34% A^{36}) and the other was argon enriched to 97.4% A^{36}. The enriched sample had been previously prepared by Anderson[4] using thermal diffusion methods and the procedure described by Zucker and Watson.[5]

Protons and neutrons at 90° to the alpha beam were studied by means of 50μ Ilford *C*-2 emulsions placed 16 cm from the chamber. The plates were allowed to fade for about 12 hours after bombardment, then

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‡ Now at Brookhaven National Laboratory, Upton, New York.
§ Now at General Electric Research Laboratory, Schenectady, New York.
|| General Electric Charles A. Coffin Fellow.

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processed, and examined under a Bausch and Lomb microscope fitted with a 45× objective and 15× eyepieces.

The cyclotron beam energy calibration was in terms of the ground-state group from the $N^{14}(\alpha,p)O^{17}$ reaction, taking the Q-value for this reaction to be -1.198 Mev.[6] The bombardments ranged from 3000 to 5000 microcoulombs of alphas at an average beam current of 0.3 microampere. Two plates were exposed with the chamber filled with enriched A^{36}, four each with natural argon and with air (i.e., N^{14}), and three with the chamber evacuated. Two observers measured a total of about 2700 tracks for each of the $A^{36}(\alpha,p)K^{39}$ and $A^{40}(\alpha,p)K^{43}$ reactions, and 1100 tracks for the $N^{14}(\alpha,p)O^{17}$ calibration.

RESULTS

Typical histograms for the $A^{36}(\alpha,p)K^{39}$ and $A^{40}(\alpha,p)$-K^{43} reactions are shown in Figs. 1 and 2, respectively, with the results shown in Table I. It is important to note that the histograms are plots of dn/dl *vs* l—the number of tracks per unit track length in the emulsion, plotted against the length. A more usual way of presenting this type of data would be a plot of dn/dE *vs* E—the number of tracks per unit energy interval, against energy. Because of the nonlinearity of the range-energy relationship (range is approximately proportional to $E^{\frac{3}{2}}$),[7] the peaks in the histograms of Figs. 1 and 2 are distorted with respect to a dn/dE *vs* E plot. For the poorly resolved first and second excited states of both reactions, the peaks must be located by fitting Gaussians; hence one is interested in the true shape of the peak. Since most of the contributions to peak width (cyclotron beam energy spread, target thickness, and range straggling in the emulsion) are symmetric with respect to energy, the plot must be transformed to a dn/dE *vs* E plot. Gaussian curves of width approximately equal to the calculated width (knowing all of the above factors) were thus fitted on a transformed histogram, with results as indicated in Figs. 1 and 2. This gives the mean proton energy for each energy level as measured in the emulsion itself. In order to compute the Q-values, it is necessary to know the mean

TABLE I. Energy levels in Mev.

Reaction	Level	E_p	Q	Excitation
$A^{36}(\alpha,p)K^{39}$	0	5.25	-1.28 ± 0.03	0
	1	2.83	-3.78 ± 0.06	2.50
	2	2.45	-4.15 ± 0.04	2.87
$A^{40}(\alpha,p)K^{43}$	0	3.29	-3.36 ± 0.03	0
	1	2.66	-4.01 ± 0.04	0.65
	2	2.15	-4.54 ± 0.07	1.18
$N^{14}(\alpha,p)O^{17}$	0	4.22	-1.198	0

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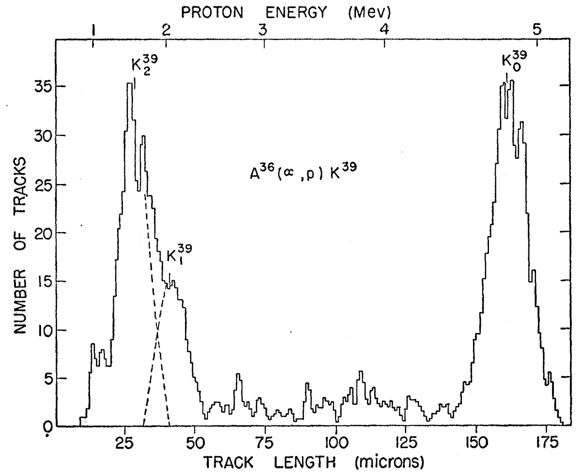

FIG. 1. Proton spectrum from the alpha-particle bombardment of the sample containing 97.4% A^{36} and 2.5% A^{40}.

proton energies at the center of the target, which means correcting for the loss of proton energy in the aluminum exit window of the bombardment chamber[8,9] and in the target gas.[10] These corrections give E_p of Table I—the mean proton energy at the center of the target in the laboratory system. Because of these corrections, the proton energies as read directly off the histograms are all lower than the values listed under E_p. Further, since dE/dx is a decreasing function of energy (varying) roughly as $E^{-\frac{1}{2}}$), the level spacings on the histograms appear greater than the true spacings as given in Table I.

The low-intensity group at about 4.8 Mev in Fig. 2 is the ground-state group from the $A^{36}(\alpha,p)$ reaction:

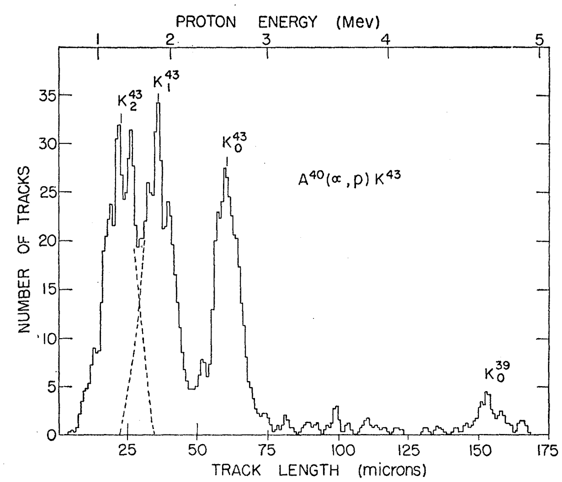

FIG. 2. Proton spectrum from the alpha-particle bombardment of natural argon—99.6% A^{40} and 0.34% A^{36}.

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TABLE II. Ground-state Q-values in Mev.

Reaction	This work	Mass spectroscopy	Other nuclear reactions
$A^{36}(\alpha,p)K^{39}$	-1.28 ± 0.03	-1.23 ± 0.07	-1.04 ± 0.52
$A^{40}(\alpha,p)K^{43}$	-3.36 ± 0.03	-3.37 ± 0.07	-3.49 ± 0.27

Although A^{36} is present to only 0.34% in the A^{40} sample, as will be shown later, the cross sections are such that this group appears.

It should be noted that the rather high energy of the first excited state in K^{39} follows the trend of the first excited states in the other 20-neutron nuclei whose $d_{\frac{3}{2}}$ proton shell is being filled.

Table II compares the ground-state Q-values obtained in this work with those computed from mass-spectroscopic data[11] (together with the $K^{43}-Ca^{43}$ beta energy[12]), and with the Q's computed from other nuclear reaction data.[12–14] The "other nuclear-reaction" Q's were computed from the following chains:

$$A^{36}(\alpha,p)K^{39}: A^{36}(d,p)A^{37}; A^{37}(K)Cl^{37}; Cl^{37}(d,p)Cl^{38}; Cl^{38}(\beta^-)A^{38}; K^{38}(\beta^+)A^{38}; K^{39}(\gamma,n)K^{38},$$

$$A^{40}(\alpha,p)K^{43}: A^{40}(d,p)A^{41}; A^{41}(\beta^-)K^{41}; K^{41}(\alpha,p)Ca^{44}; Ca^{43}(d,p)Ca^{44}; K^{43}(\beta^-)Ca^{43}.$$

It will be seen that the ground-state Q's agree with each other to well within the experimental error. Our value for the $A^{36}(\alpha,p)K^{39}$ Q-value is also in perfect agreement with the value of 1.28 Mev recently reported for the ground-state group from the $K^{39}(p,\alpha)A^{36}$ reaction.[15]

CROSS SECTIONS

The cross sections for the $A^{36}(\alpha,p)$, $A^{40}(\alpha,p)$ and $A^{40}(\alpha,n)$ reactions were measured by counting the number of events on the plate and dividing by the geometry, and, in the case of the (α,n) reaction, also dividing by the efficiency of the emulsion for neutron capture. It should be pointed out that simply dividing by the geometry tacitly assumes an isotropic angular distribution; an investigation of this particular point is planned. The results of the cross-section measurements are:

Reaction	Cross section (millibarns)
$A^{40}(\alpha,p)K^{43}$	0.26
$A^{36}(\alpha,p)K^{39}$	8.5
$A^{40}(\alpha,n)Ca^{43}$	33.0

The (α,p) cross sections are accurate to within 35 percent, but the (α,n) cross section may be in error by as much as a factor of two.

The magnitudes of these cross sections are in semiquantitative agreement with the predictions of the compound nucleus theory. We assume that the cross section $\sigma(a,b)$ for a reaction of the general type $X(a,b)Y$ is of the form $\sigma(a,b)=\sigma_c(a)G_c(b)$, where $\sigma_c(a)$ is the cross section for the formation of a compound nucleus c by capture of a particle a, and $G_c(b)$ is the probability that the compound nucleus, once formed, decays by emission of a particle b. If we ignore individual properties of the nuclei and consider that the quantities of interest are primarily functions of Z and A, we can say that σ_c is about the same for A^{36} and A^{40}. Therefore, the total alpha-bombardment yield from A^{36} should be the same as from A^{40}. Since we are below the threshold for the $A^{36}(\alpha,n)Ca^{39}$ reaction, and since inelastic alpha-scattering makes a negligible contribution to the total yield, the sum of the $A^{40}(\alpha,p)$ and $A^{40}(\alpha,n)$ cross sections should equal the $A^{36}(\alpha,p)$ cross section. They actually differ by a factor of four, which is not unreasonable considering that the $A^{36}(\alpha,p)$ reaction goes by way of the doubly magic compound nucleus Ca^{40}.

Because of the Coulomb barrier, neutron emission from the compound nucleus should be highly favored, and hence one expects the $A^{40}(\alpha,n)$ cross section to be much higher than that for $A^{40}(\alpha,p)$. As shown in Blatt and Weisskopf,[16] $G_c(b)$ is proportional to

$$\int_0^{\epsilon_{bY}} \epsilon_\beta \sigma_c(\epsilon_\beta) w_Y(\epsilon_{bY}-\epsilon_\beta) d\epsilon_\beta,$$

where ϵ_{bY} is the energy of the ground-state group, ϵ_β is the energy of the outgoing particle, $\sigma_c(\epsilon_\beta)$ is the cross section for the *inverse* process (i.e., formation of the compound nucleus by collision between b and the product nucleus), and w_Y is the energy-level density. We assume that for our case

$$w(\epsilon)=0.4\exp[2(0.8\epsilon)^{\frac{1}{2}}],$$

and numerically integrate the expression for the $A^{40}(\alpha,p)$ and $A^{40}(\alpha,n)$ reactions. The result indicates that the cross sections should be in the ratio of 1:300. The measured cross sections are in the ratio 1:130, which if felt to be satisfactorily close.

Finally, from the cross-section table given in Blatt and Weisskopf,[12] the absolute cross section for the $A^{40}(\alpha,n)Ca^{43}$ or $A^{36}(\alpha,p)K^{39}$ reactions is expected to be about 11 millibarns. This is in reasonable agreement with our measured values of 8.5 mb for $A^{36}(\alpha,p)K^{39}$ and 33 mb for $A^{40}(\alpha,n)Ca^{43}$.

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