Neutron-Induced Charged Particle Reactions in Potassium-39†*

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Thin thallium-activated potassium iodide crystals were exposed to monoenergetic neutrons ranging in energy from 2.0 to 5.5 Mev. Pulse-height spectra were taken of the scintillations in the crystal. Five charged particle groups were observed, three (n,p) reactions leading to states in A^{39}, and two (n,α) reactions leading to states in Cl^{36}. A new level was discovered at 2.46±0.1 Mev in A^{39}, and the level at about 1.25 Mev in A^{39} confirmed. Yield curves were measured for three of the groups.

INTRODUCTION

THE interaction of fast neutrons with nuclei has been the subject of considerable investigation in recent years. The majority of this work has been concerned with either neutron scattering or the measurement of gamma radiation from neutron-irradiated targets. Comparatively little is known, however, about the charged particles resulting from neutron irradiation. Few investigations have been made in this area because of the low yield necessarily resulting from targets sufficiently thin to allow the charged particles to emerge. In the present experiment, this difficulty was circumvented by combining the target with the charged particle detector.

By observing the resultant charged particle groups, it is possible to detect states in the residual nuclei which are difficult to observe when other methods of excitation are used.

The yield for the various groups, as a function of neutron energy, is also of interest. Information of this kind is of considerable value in attempting to understand the mechanisms of these reactions. In the present study, yield curves are obtained for three of the groups.

EXPERIMENTAL ARRANGEMENT

Thin chips of thallium-activated potassium iodide were cleaved from commercially grown crystals. The chips were about $\frac{1}{2}$ mm thick, $\frac{1}{2}$ cm wide, and 1 cm long. These crystals were only a few hundred kev thick to electrons, which greatly reduced the gamma-ray background. The crystals were mounted, with gelva resin or silicone oil for optical coupling, on Dumont (6292) or R.C.A. (6199) photomultiplier tubes, and backed with aluminum reflectors. Amplified output signals from the phototube were displayed on a multichannel analyzer. The crystal was exposed to neutrons obtained by bombarding a thin deuterium gas target with deuterons. A description of the gas target is given elsewhere.[1] The neutron energy was varied by varying the angle between the direction of observation and that of the incident deuteron beam. The phototube was so placed that the crystal was 8 cm from the target. Crystal dimensions limited the neutron energy spread due to the acceptance angle of the counter to 3% or less.

RESULTS

The pulse-height spectra observed for various incident neutron energies are shown in Fig. 1. The six observed peaks must be due to heavy charged particles since gamma rays of an equivalent energy would not produce peaks in a crystal of this thickness. The approximate proton energy calibration of the counter was found by exposing the crystal to protons produced by the $C^{12}(d,p)C^{13}$, $H^2(d,p)H^3$, and $N^{14}(d,p)N^{15}$ reactions. The counter calibration for alpha particles was found by using a polonium alpha source. The proton pulse height was approximately 1.5 times the alpha pulse height for particles of the same energy.

The high Coulomb barrier which a proton would need to penetrate in order to emerge from an iodine nucleus renders it unlikely that any of the peaks are due to reactions in iodine. To confirm this deduction, a NaI(Tl) crystal of similar dimensions was substituted for the KI(Tl) crystal. The lack of peaks in the spectrum indicated that the peaks in the KI(Tl) spectra, as expected, are due to reactions in potassium and not in iodine.

One would expect most of the spectrum to be due to K^{39} since natural potassium consists of 93.2% K^{39} and 6.8% K^{41}. A survey of the possible reactions[2] showed that $K^{39}(n,p)A^{39}$ ($Q_{max}=0.20$ Mev) and $K^{39}(n,\alpha)Cl^{36}$ ($Q_{max}=1.36$ Mev) are the only reactions which are energetically possible when K^{39} is bombarded with neutrons having an energy of a few Mev. The reactions $K^{41}(n,p)A^{41}$ ($Q_{max}=-1.80$ Mev) and $K^{41}(n,\alpha)Cl^{38}$ ($Q_{max}=-0.09$ Mev) are also possible at these energies. The Q values for these reactions are taken from the recent nuclear mass compilation of Wapstra.[3] Comparison of the spectra with those obtained using protons of known energy indicates that the highest peak is due to the $K^{39}(n,p)A^{39}$ reaction. The energy calibration was not sufficiently precise to allow the measurement of the Q

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[1] P. R. Chagnon, dissertation, The Johns Hopkins University, 1955 (unpublished).

[2] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. 26, 95 (1954).

[3] A. H. Wapstra, Physica 21, 385 (1955).

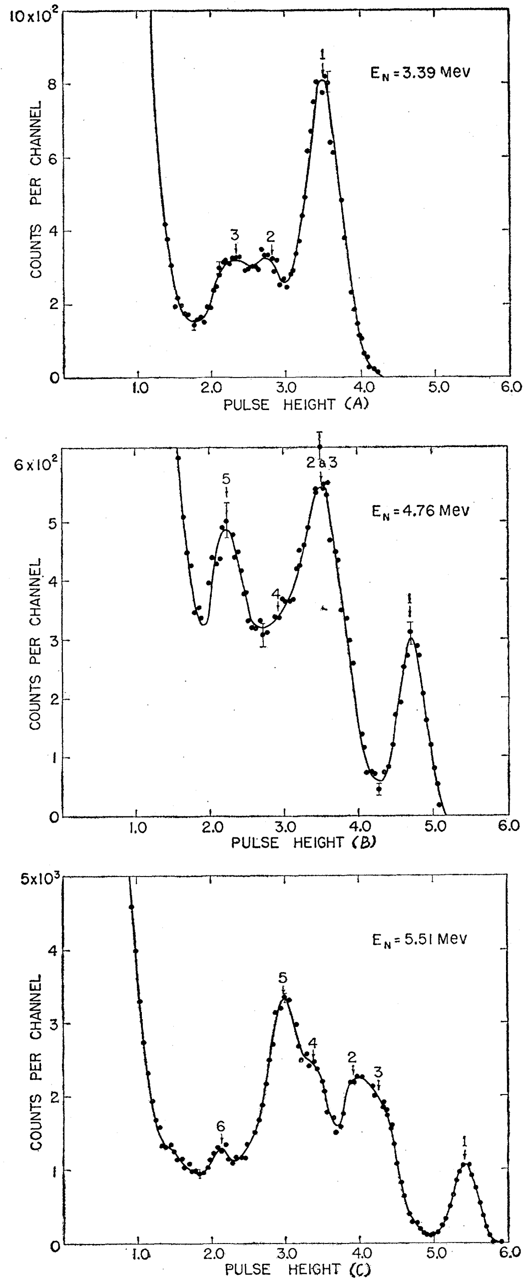

FIG. 1. Three of the pulse-height spectra observed when KI(Tl) crystals are bombarded with neutrons. E_n is the neutron energy, the abscissa is the pulse height in units of equivalent proton energy in Mev; the ordinate is the actual number of counts per channel.

value for this reaction as accurately as it can be determined from the nuclear masses. A Q of 0.20 Mev was therefore assumed and used in conjunction with the pulse height of this peak to establish an energy calibration for the spectra.

Pulse-height spectra were taken at a total of ten different incident neutron energies ranging from 2.0 to 5.5 Mev, including the three spectra shown in Fig. 1. The peak position as a function of neutron energy is shown in Fig. 2 for five of the peaks seen in these spectra. A sixth peak was identified as being due to background neutrons from the $C^{12}(d,n)N^{13}$ reaction.

DISCUSSION OF RESULTS

The fact that more and more peaks are discernible in the pulse-height spectra as the neutron energy is increased may be explained by two reasons:

(1) The Coulomb barrier inhibition of the outgoing particles favors the more energetic particles.

(2) The lower energy pulses are masked by the approximately isotropic gamma-ray background in the low pulse-height region.

Because some of the peaks are due to alpha particles and others are due to protons, their relative positions on the pulse-height spectra vary with incident neutron energy. Peaks No. 2 and No. 3 can be seen to exhibit this effect. These peaks are well resolved at low incident neutron energies (Fig. 1, $E_n = 3.39$ Mev), merge together and cross as the energy is increased (Fig. 1, $E_n = 4.76$ Mev), and start to separate again at the highest neutron energy (Fig. 1, $E_n = 5.51$ Mev).

Each group reported here was seen as a resolved peak in at least two of the spectra and the Q values were determined and the particles identified from these peaks. All the energies quoted are corrected for the transformation to and from the center-of-mass system of coordinates. The average energy in the laboratory system was used in all cases.

As stated previously, peak No. 1 is due to the $K^{39}(n,p)A^{39}$ reaction leading to the ground state in A^{39}. Peaks No. 3 and No. 5 were identified as also being due to protons from the slopes of the corresponding peak position *vs* neutron energy lines (Fig. 2). These groups correspond to states in A^{39} whose excitation energies are 1.24 ± 0.05 and 2.46 ± 0.1 Mev, respectively. The state in A^{39} which had been reported previously at 1.33 Mev[4,5]

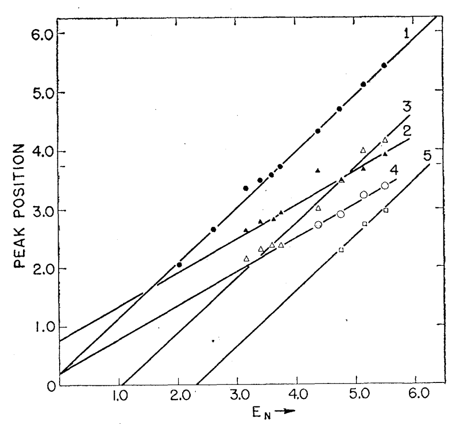

FIG. 2. Peak position in units of equivalent proton energy *versus* incident neutron energy, both given in Mev.

[4] Haslam, Katz, Moody, and Skarsgard, Phys. Rev. **80**, 318 (1950).

[5] Nussbaum, Lieshout, and Wapstra, Phys. Rev. **92**, 207 (1953).

is doubtless the 1.24-Mev state found here. No state in the vicinity of 2.5 Mev is mentioned in the literature. However, the only previously published investigation of A^{39} was done by means of the β decay of Cl^{39}.[4] The β particle to this state would have a maximum energy of about 0.5 Mev and therefore would have been difficult to detect in the presence of the allowed 1.65-Mev β particle to the first excited state.

Endt and Kluyver[2] report a possible level in A^{39} at 1.68 Mev, but no evidence for such a level was seen in the present work. The pulse height *vs* neutron energy lines for peaks No. 2 and No. 4 have smaller slopes than those for protons and therefore these peaks are due to alpha particles. The slope of the line representing peak No. 2 in Fig. 2 gives a value of 1.51 ± 0.15 for the ratio of proton pulse height to alpha pulse height for particles of the same energy, in agreement with the directly measured ratio of 1.5. Using this value a Q_{max} of 1.25 ± 0.20 Mev was obtained for the reaction $K^{39}(n,\alpha)Cl^{36}$, which is in agreement with that obtained from the nuclear masses.[3] Peak No. 4 is due to the reaction $K^{39}(n,\alpha)Cl^{36*}$ leading to the first excited state in Cl^{36}. An excitation energy of 0.87 ± 0.1 Mev was found for this state, in agreement with the previously reported value of 0.78 Mev.[6]

Yield curves were obtained in units of particles per incident neutron using the d-d neutron angular distributions of Hunter and Richards.[7] The yield curve for the highest energy proton group is shown in Fig. 3. For comparison, the calculated Coulomb barrier penetrability ($\times 4\pi\lambda^2$) is also shown with a nuclear radius of $(1.2A^{\frac{1}{3}}+0.5)\times 10^{-13}$ cm assumed in the calculation. Rough yield curves were also obtained for the second highest energy proton group and for the long-range alpha group. These curves had qualitatively the same shape as the curve for the ground-state proton group but appeared to be displaced upward in energy by 1–1.5 Mev. The other groups were not resolved over a wide enough range of neutron energies to draw meaningful yield curves for them. In all three observed cases the curves have a maximum at an energy well below the Coulomb barrier seen by the outgoing particle. No reasonable adjustment of the nuclear radius would be sufficient to account for this behavior. The strong positive slope of the yield curves at low incident neutron energies is at least partially due to increasing barrier penetrability. The negative slope at higher energies is perhaps due to the presence of competing reactions.

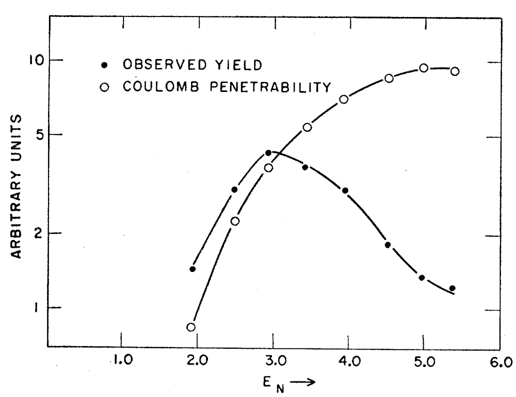

FIG. 3. Observed yield curve for the ground state proton from the reaction $K^{39}(n,p)A^{39}$. For comparison, the Coulomb barrier penetrability calculated using a nuclear radius $r_0=(1.2A^{\frac{1}{3}}+0.5)\times 10^{-13}$ cm.

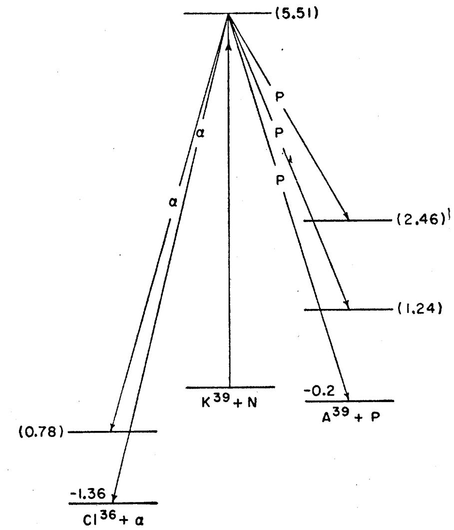

FIG. 4. Energy level diagram showing the observed reactions for an incident neutron energy of 5.51 Mev.

CONCLUSIONS

An energy level diagram showing the transitions observed when K^{39} is irradiated with 5.5-Mev neutrons is shown in Fig. 4. The numbers in parentheses next to the energy levels indicate their excitation energies in the daughter nuclei. The values shown for the two excited states in A^{39} are those obtained in this experiment. No evidence was found for a state in the region of 1.68 Mev, which had been reported previously.[2,5,8]

The yield curves for the three groups for which yield curves were measured all rose sharply with energy until reaching a maximum and then decreased as the neutron energy was increased further. The shape of the yield curves can be explained only partially by Coulomb effects.

ACKNOWLEDGMENTS

The authors wish to thank Dr. S. S. Hanna for his many helpful suggestions during the course of this work.

[6] B. Hamermesh and H. Hummel, Phys. Rev. **88**, 916 (1952).

[7] G. I. Hunter and H. T. Richards, Phys. Rev. **76**, 1445 (1949).

[8] *Note added in proof.*—Penning, Maltrud, Hopkins, and Schmidt (Bull. Am. Phys. Soc. Ser. II, **1**, 162 (1956)) have recently investigated the β decay of A^{39}. They find β particles having end-point energies of 3.43 and 1.90 Mev and gamma rays of 1.52, 1.27, and 0.246 Mev, with coincidences observed between the 1.27- and the 0.246-Mev gamma rays. The 1.27-Mev gamma ray very probably corresponds to a transition to the ground state from the 1.24-Mev state reported here. The yield of protons from the (n,p) reaction leading to the 1.52-Mev state must be at least a factor of three lower than that leading to the 1.24-Mev state or the former reaction would have been observed in the work reported here.