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Excited States of K^{40}[†]

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Using a magnetic spectrograph in conjunction with an electrostatic generator, the region of excitation in K^{40} has been studied up to 1 Mev, using the $K^{39}(d,p)K^{40}$ reaction. Excited states in K^{40} have been found at 0.032, 0.800, and 0.893 Mev, the Q value for the ground-state reaction being 5.576×0.010 Mev.

I. INTRODUCTION

INFORMATION regarding the excited states of potassium 40 has been obtained by Sailor,[1] who studied the $K^{39}(d,p)K^{40}$ reaction, and by Kinsey, Bartholomew, and Walker[2] who investigated the capture gamma rays from potassium when bombarded with slow neutrons. The highest-energy gamma ray which was observed in the latter experiments and which could be attributed to capture in K^{39} was 7.757 ± 0.008 Mev.[2,3] This would indicate a Q value of 5.531 for the ground state of the $K^{39}(d,p)K^{40}$ reaction, in reasonable agreement with the value of 5.48 ± 0.08 Mev, found by Sailor. However, it was pointed out[2] that, if this gamma ray did originate in a transition direct to the ground state of K^{40}, its intensity was considerably higher than would be expected on the basis of shell structure theory. According to this model, the odd proton in K^{39} is $d_{3/2}$, while in the ground state of K^{40}, an odd-odd nucleus, the odd proton and odd neutron are in $d_{3/2}$ and $f_{7/2}$ states, respectively. K^{39} in the ground state has a spin of 3/2 and even parity, and capture of a slow neutron should lead to a compound state in K^{40} with spin 1 or 2 and even parity. Since the ground state of K^{40} has a spin of 4 and odd parity, the gamma ray direct to this state involves a change in parity and would be either electric octopole ($E3$) or magnetic quadrupole ($M2$), depending on whether the capturing state had a spin of 1 or 2 units. In either case, such a gamma ray would be relatively low in intensity. Since the 7.757-Mev radiation was among the most intense of those observed, the suggestion has been made[3] that K^{40} may have a low-lying excited state of spin 2 and odd parity and that the gamma ray is associated with a transition to it rather than the ground state. In this case, the radiation would be of the electric dipole type regardless of whether the spin of the capturing state was 1 or 2. $E1$ gamma rays in this energy range are known to be strongly emitted.[4]

As a result of this suggestion, we have studied the region of excitation in K^{40} up to 1 Mev, using the $K^{39}(d,p)K^{40}$ reaction. In this region, both the gamma-ray measurements and the work of Sailor have shown an excited state at 0.80 Mev.

II. EXPERIMENTAL PROCEDURE

For these measurements, we have used the deuteron beam from a large, vertical, pressure-insulated electrostatic generator constructed for the Laboratory of Nuclear Science by Professor Trump and his associates. We have chosen to call this machine the MIT-ONR generator in order to distinguish it from the various other Van de Graaff generators at the Institute, and we wish to acknowledge our indebtedness to the Office of Naval Research which provided the funds necessary for its construction. We have used this generator for various nuclear investigations for somewhat over a year, and it has operated very successfully in the voltage range from 4 to 8.5 Mev.

After emerging from the generator, the ion beam is deflected by a magnet which can be rotated about a vertical axis so as to direct the beam towards a given portion of the target room. For the present measurements, the deuteron beam was deflected through 90 degrees so as to leave the magnet in a horizontal direction, the radius of curvature in the magnetic field being 60 centimeters. By means of adjustable shims at the entrance and exit faces of the magnet, the beam was focused on a set of defining slits placed 185 centimeters from the exit face of the magnet. The slit jaws were insulated and the currents collected on them were used to control a conventional voltage-stabilizing device using corona directed at the generator terminal. During these experiments, a slit opening of $\frac{1}{2}$ mm was used.

After passing through the exit slits of the 90-degree analyzer, the beam struck a target placed in the gap of a 180-degree annular magnetic spectrograph.[5] This spectrograph has been used in conjunction with another electrostatic generator for a number of previous studies of this type. In its new location, the spectrograph has been aligned so that the plane of the magnet gap is accurately at 90 degrees to the direction of the incident beam. Both visual measurements of the shadows cast by fine wires placed in the beam at the entrance and exit faces of the spectrograph and meas-

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[1] V. L. Sailor, Phys. Rev. **77**, 794 (1950).

[2] Kinsey, Bartholomew, and Walker, Phys. Rev. **85**, 1012 (1952).

[3] B. B. Kinsey (private communication).

[4] B. B. Kinsey and G. A. Bartholomew, Physica **18**, 1112 (1952).

[5] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).

urements made on the energies of particles scattered from targets containing nuclei of mass ranging from gold to lithium indicate that, for both proton and deuteron beams with energies between 4 and 8.5 Mev, the 90-degree Q equation for the reaction products can be used without appreciable error.

Power for both the 90-degree deflecting magnet and the 180-degree spectrograph is supplied by stabilized, three-phase, rectifier circuits designed by H. Enge. As measured by nuclear magnetic-resonance fluxmeters, the magnetic field in each analyzer is held constant to approximately 1 part in 100 000. For the field strengths encountered in the present experiments, the signal due to lithium was used.

In these experiments, both the energy of the incident beam and the energies of the reaction products were measured with the spectrograph, the former being determined from observations of the deuterons elastically scattered from various nuclei in the target. Since the values of the proton and lithium magnetic moment have been measured with high precision, it is possible to obtain the particle energies from a direct measurement of the radius of the curvature in the uniform magnetic field. However, a sufficiently accurate and more convenient procedure, using polonium alpha particles, has been employed in these measurements. The details of this calibration procedure and of the conversion of the observed data into nuclear reaction energies have been given in previous publications.[6,7] In the present experiments, the measured deflection of polonium alpha particles from a source placed near the target position has been measured for various values of the magnetic field, the field strengths being determined by the resonance fluxmeter. These measurements were used to determine the distance between the target position and an index mark placed on each plate after it is in position for exposure. The positions of the groups of particles detected on the track plates are measured with respect to the index mark. Since the particles recorded by the spectrograph have approximately the same radius of curvature, the important quantities in the measurements are the relative values of the magnetic fields at which the exposures for the reaction products and for the polonium alpha particles are made, the relative positions of the observed groups on the photographic plates, and the distance between the calibrating alpha-particle source and the position of the beam on the target.

Since the frequencies corresponding to the various magnetic fields used can be measured to a high precision, the principal uncertainties in the measurements arise from the value used for the Hr of polonium alpha particles and from the uncertainity in the determination of the positions of the observed groups. As in our previous work,[7] we have assumed a value of 3.3159×10^5 gauss-centimeters, accurate to one part in 5000, for polonium alpha particles. In general, the locations of the various groups recorded can be determined to within 0.1 mm, the diameter of the path in the magnetic field being approximately 710 mm. The calibration used in this work has been checked by measuring the Q values of a large number of groups which have previously been determined both in this and in other laboratories. In all cases, the agreement has been highly satisfactory.

The targets used in the present work consisted of thin layers of various potassium-containing compounds evaporated onto very thin commercial gold foil. These foils were stiffened with a thin backing of Formvar. The targets appeared stable for beam currents as high as 0.5 microampere. Targets of KI, KBr, and KCN, both with and without the carbon content enriched in C^{13}, were studied.

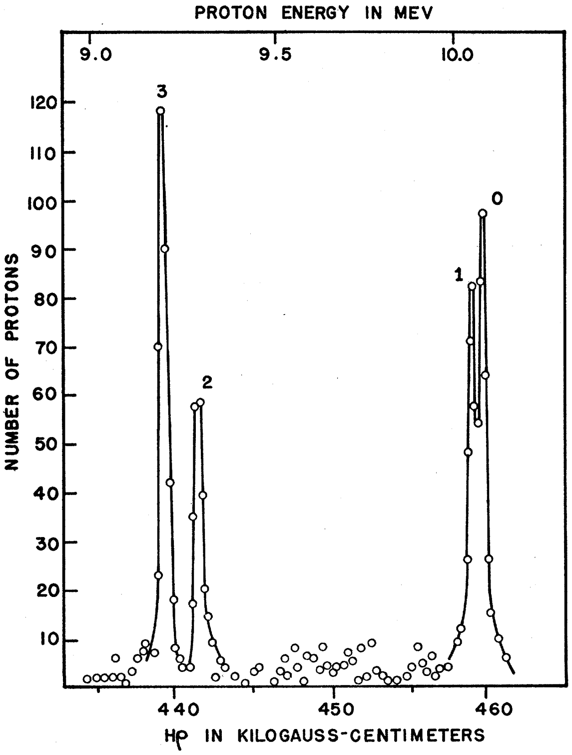

FIG. 1. Proton groups from potassium-iodide target bombarded with 5.00-Mev deuterons.

III. RESULTS

Studies of the proton energy range corresponding to excitations in K^{40} from the ground state up to 1 Mev were made for deuteron energies of 4.76, 5.00, 5.16, and 5.65 Mev. The results of the 5.00-Mev bombardment of a KI target are shown in Fig. 1. The four proton groups shown were found from each of the targests used and at each of the bombarding energies. The con-

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[6] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).

[7] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

TABLE I. $K^{39}(d,p)K^{40}$.

Excitation in K^{40}	Q values[a]		
	Present work	Bartholomew + Kinsey[b]	Sailor[1]
0	5.576±0.010		5.48±0.08
0.032±0.002	5.544±0.010	5.531±0.009	
0.800±0.010	4.776±0.010	4.768±0.008	
0.893±0.010	4.683±0.010		4.67±0.09

[a] 2.226 Mev was used for converting from $K^{39}(n,\gamma)K^{40}$ to $K^{39}(d,p)K^{40}$.
[b] See reference 8.

stancy of the relative intensities of these groups as the target material was varied was used as a check on their assignment to potassium, made on the basis of their shift in energy as the incident deuteron energy was varied. The bombarding energies were purposely kept low in order to bring these groups within the range of the spectrograph. A check on the operation of the spectrograph at these field settings was obtained from measurements on the $C^{13}(d,p)C^{14}$ ground-state group observed from the KCN target enriched in C^{13} and from measurements on the ground state and first excited state from a thin aluminum target. At these bombarding energies, the C^{13} and Al groups occur in the middle of the region shown in Fig. 1. While the precision of the energy measurements made as a function of deuteron energy was not sufficient to determine whether the observed proton groups are due to K^{39} or K^{41}, it is assumed from their intensities and from Sailor's work[1] on normal potassium targets and on targets enriched with K^{41} that the groups originate from $K^{39}(d,p)K^{40}$. The Q values calculated for these groups are tabulated in Table I. Also included are the recent results of Bartholomew and Kinsey,[8] who found in addition to the 7.757-Mev gamma ray another having an energy of 6.994±0.007 Mev, which they ascribed to capture in K^{39}. Also included in the table are the results of Sailor[1] on $K^{39}(d,p)K^{40}$. The excitation energies in K^{40} included in the table are those determined in the present work. One of the advantages of observation at 90 degrees to the incident beam is that, aside from relativistic effects and the effects of the small angle about 90 degrees in which the particles are collected, the energy differences between the groups are independent of the input energy. The energy differences between groups 0 and 1 and between groups 2 and 3 and, hence, the spacings of the corresponding excited states could be determined with a greater precision than could be had by subtraction of the observed Q values.

The Q values listed are each the average of three or more separate determinations, the spread in the individual values in each case being 5 kilovolts or less. Three determinations, agreeing within 1 kev, were used for the spacing of the first level from the ground state. The spacing between the second and third levels was found to be 93±2 kev from four determinations which agreed within 2 kev.

It is clear from the table that, as suggested by Kinsey and his collaborators, the highest-energy gamma ray observed in the $K^{39}(n,\gamma)K^{40}$ reaction proceeds not to the ground state of K^{40} but rather to a low-lying excited state. As has recently been discussed,[8] it is probable that this state has a spin of 2 and odd parity and is analogous to the ground state of K^{42}. Although in both K^{40} and K^{42} the odd proton and odd neutron are in $d_{3/2}$ and $f_{7/2}$ states, respectively, the spin of K^{40} is 4 and K^{42} is 2. It thus appears that, unlike K^{42}, where the total angular momenta of the odd nucleons are antiparallel, the most stable configuration in K^{40} is not the antiparallel condition. It is of interest that the next lowest-energy gamma ray observed in the (n,γ) reaction is associated with the 0.80-Mev level, and no gamma ray was observed which corresponded to a transition to the level at 0.89 Mev.

We have also observed an intense group of lower energy corresponding to a level in K^{40} at approximately 2 Mev. Such a level is indicated both by the gamma-ray work and by the work of Sailor. This group appears to consist of two and possibly three components, but no accurate measurements on it have been made; a similar structure has been found in recent gamma-ray work.[8] In Fig. 1, a considerable background is seen between the pairs of proton groups. This background seems to be mainly due to the gold foil used as a backing material. Elastic-scattering measurements show that there are appreciable amounts of both copper and silver in the gold foil, and such a background has been observed from the foil alone.

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[8] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. (to be published).