Violation of the Isotopic Spin Selection Rule in the $Ca^{40}(d,\alpha)K^{38}$ Reaction*

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Alpha particles leading to the ground state and first excited state of K^{38} in the $Ca^{40}(d,\alpha)$ reaction have been observed and the excitation energy of the first excited state of K^{38} has been determined as 123 ± 8 kev. The relative intensities of the groups has been measured for incident deuteron energies between 3.2 and 4.1 Mev. Over this range the average intensity of the ground-state group is about 10 times that of the group to the first excited state and it is concluded that the latter is the 0^+ $T=1$ analog of the A^{38} ground state.

Even in the absence of isotopic spin selection rules, the alpha transition to the 0^+ state is expected to be inhibited appreciably by selection rules on angular momentum and parity. A calculation using the statistical model of the nucleus indicates that these decrease the cross section for the $0^+ \rightarrow 0^+$ transition by a factor of about 5 relative to that for the ground-state transition. It thus appears that the isotopic spin selection rule inhibits the transition only by a factor of about two. This breakdown of the isotopic spin selection rule can probably be attributed to Coulomb effects in the compound state. The reduction of the cross section as a result of angular momentum selection rule is probably equally important in other (d,α) reactions that have so far been used to study isotopic spin selection rules. It appears that further experimental results are needed for an understanding of the "isotopic spin forbidden" (d,α) reactions on light nuclei.

INTRODUCTION

A NUMBER of measurements have now been reported[1-3] in which nuclear transitions violating isotopic spin selection rules[4,5] are observed. Particularly simple examples of a selection rule and its violation are provided by the (d,α) reactions proceeding from the ground state of even-even self-conjugate nuclei to low-lying $T=1$ states in odd-odd nuclei with $A=4n+2$. Browne[1] has made a careful study of the $O^{16}(d,\alpha)N^{14}$ reaction with incident deuterons in the energy range from 5.5 to 7.5 Mev. The forbidden group is observed with an average intensity of about 5% of that of the allowed group proceeding to the ground state of N^{14}. The forbidden group has also been observed with low intensity in reactions leading to the first $T=1$ state in Al^{26} [6] and P^{30}.[7] The observed violation of the selection rule is attributed to the effect of the Coulomb interaction in mixing states of different T, and it is to be expected that the breakdown of the rule would be more severe in heavier nuclei. The present measurements of the $Ca^{40}(d,\alpha)K^{38}$ reaction were undertaken on the heaviest stable self-conjugate nucleus in an effort to obtain further information on the usefulness of the isotopic spin in characterizing states in heavier nuclei.

EXPERIMENTAL

The deuteron beam from the University of Rochester variable-energy cyclotron was used in these measurements. After analysis by a double-focusing wedge magnet, beam currents of 0.1 μa with an energy resolution of 0.2% were available over the energy range from 3.3 to 4.1 Mev. Measurements of the (d,α) cross section were carried out in a 10-in. diameter scattering chamber, to which a spectrometer magnet could be attached at 15° intervals. The beam was collected in a lead-lined Faraday cup and could be monitored by a CsI crystal and photomultiplier which detected the deuterons elastically scattered at 90° to the beam direction.

A magnetic spectrometer was used to observe the weak alpha groups of interest. This was a 16-in. radius double-focusing instrument similar to those described by Snyder *et al.*[8] or by Malm and Inglis.[9] The magnetic field of the spectrometer was measured by a rotating coil system similar to that described by Hedgran.[10] This system was stable to within 0.15% over periods of several hours. From day to day, however, mechanical instabilities, thermal effects, and brush noise gave rise to uncertainties of about 1% in the calibration of particle momentum *vs* field meter reading, and the calibration was regularly checked against that of the analyzer magnet by observing elastically scattered particles of known energy.

Two types of particle detectors were used with the spectrometer. Initially a thin CsI crystal mounted on a well-shielded photomultiplier was used. With a beam spot on the target 0.22 in. wide, and a $\frac{1}{4}$-in. exit slit, the momentum resolution was $\Delta p/p=0.43\%$. Later, the exit slit was removed and a small camera for 1-in.×3-in. nuclear track plates mounted in place of the photomultiplier. This system had a momentum resolution $\Delta p/p=0.3\%$. The range of momenta accepted on a single plate was about 2%, allowing simultaneous observation of both groups of interest in the present measurements. The relative transmission of the spectrometer as a function of focus position along the plate

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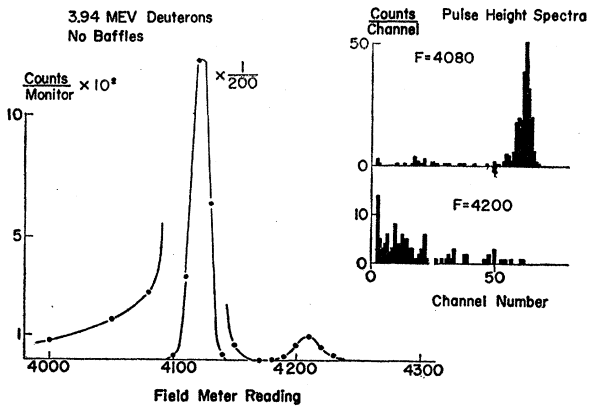

FIG. 1. Spectrum of deuterons elastically scattered from gold. Pulse-height spectra from the scintillation detector at field meter settings of 4080 and 4200 are shown in the insets.

was determined by observing the apparent intensity of a group of elastically scattered particles focused to different positions on the plate.

Because of the very low intensities of the alpha groups relative to that of the elastically scattered deuterons, it was necessary to minimize the scattering of particles from the walls of the spectrometer vacuum chamber. A series of baffles at the entrance to the spectrometer ensured that no particles were scattered from the top and bottom of the vacuum chamber. It was found, however, that particles could still be scattered from the walls in the vicinity of the exit slit. Figure 1 shows a spectrum as measured by the spectrometer when 3.94-Mev deuterons were scattered from gold. The pulse-height spectra from the CsI crystal show that the small peak at a field meter reading of 4200 arises from particles which have been scattered inside the spectrometer. After adding baffles in the exit tube of the spectrometer, this spurious peak no longer appears, as shown in Fig. 2. The measurements of Fig. 2 actually were extended over a much wider range than is shown, and the background intensity was found to be never greater than 0.02% of that of the elastic peak.

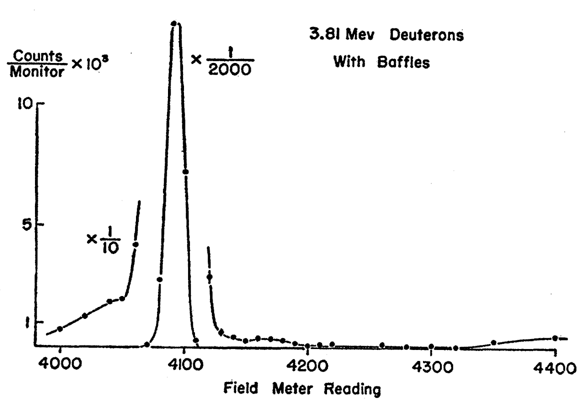

FIG. 2. Spectrum of deuterons elastically scattered from gold after installing antiscattering baffles near the spectrometer exit port.

Targets were prepared by evaporating natural calcium metal onto a gold leaf backing. A spectrographic analysis[11] of the calcium used showed less than 0.5% Mg impurity, and no significant amounts of other metals. The thickness of the backing was determined by weighing to be about 0.2 mg/cm². The thickness of the calcium was measured by comparing the elastic scattering in the forward direction from the Ca and the gold backing. Typical targets were about 0.1 mg/cm² in thickness.

IDENTIFICATION OF THE GROUPS

For these measurements a thin (0.001-in.) CsI crystal covered by a 0.0003-in. Al foil was used to detect the particles focused through the spectrometer. With this crystal, alpha particles in the energy range from 4 to 8 Mev gave pulses two to three times as large as those from protons or deuterons of the same magnetic rigidity, and no trouble was experienced in distinguishing alphas from these other particles. With a calcium target, two prominent alpha groups were observed. The variation of alpha particle energy with angle

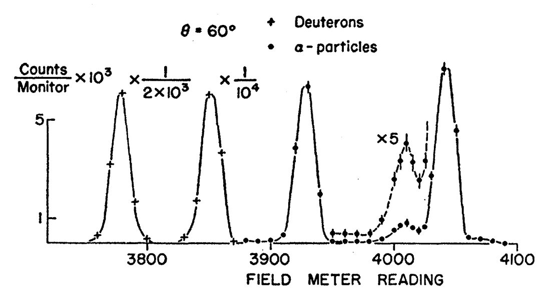

FIG. 3. Alpha-particle groups to the ground and first two states of K^{38}. Elastic deuteron groups from Au and Ca are also shown.

identified them as arising from the (d,α) reaction on Ca^{40}. Q values of the groups were 4.65 and 4.21 Mev, in satisfactory agreement with the values of 4.650 and 4.20 Mev reported by Braams,[12] for this reaction. Strong alpha groups at lower energies were also observed coming from oxygen and carbon contamination on the target. In addition to the above, a weak group was observed at an energy slightly below that of the strong group of highest energy. A typical measurement is shown in Fig. 3 in which the weak group is observed with an intensity of about 10% of that of the strong group. The differences in Q values for this weak group are shown in Table I as a function of angle. From these measurements it is concluded that the weak group arises from a (d,α) reaction on a nucleus of $A=40\pm1$. The possibility that the group arises from one of the other stable Ca isotopes is definitely excluded. Possible potassium impurity in the target is much too small to give rise to the group, and it was concluded that it does

[11] We are indebted to Professor W. Walters of the University of Rochester Chemistry Department for this anslysis.

[12] C. M. Braams, thesis, Utrecht, 1956 (unpublished).

in fact come from the $Ca^{40}(d,\alpha)K^{38}$ reaction leading to the $T=1$ first excited state of K^{38}. As a byproduct of these measurements the excitation energy of this state was determined to be 123±8 kev.

MEASUREMENTS AND RESULTS

For measurements of the relative intensities of the groups leading to the ground state and first excited state of K^{38}, the nuclear plate camera was used in place of the scintillation detector. 1-in.×3-in. Kodak NTA emulsions 50 microns in thickness were used in the camera. These plates were sensitive to protons, deuterons, and alpha particles. Protons were easily distinguished by their track densities. Deuterons and alpha particles could be distinguished from each other this way, by careful scanning, but usually alphas were identified on the basis of track length. Exposures were made at 15° intervals between 15° and 135° at incident deuteron energies of 3.30, 3.69, and 4.09 Mev. In addition, cross sections were measured every 0.1 Mev from 3.3 to 4.1 Mev at angles of 30° and 105°. After processing, the plates were scanned in strips of 260 μ width, over a distance of about 2 cm, in which both groups of interest were focused. A background of tracks arising from deuterons scattered inside the spectrometer was observable in the scanning. These could be distinguished from alphas by the wide variation in track lengths, and by the fact that such tracks generally entered the emulsion at a different angle than those produced by particles focused through the spectrometer. Well away from the alpha peaks a small background of tracks which could not be distinguished from true alpha tracks was observed. This background amounted to about $\frac{2}{3}$ track per scanning strip on each side of the alpha peaks, and it was assumed that the same background contributed to the measured peaks.

TABLE I. Q values for $Ca^{40}(d,\alpha)K^{38}$ reaction calculated from measured alpha groups.

θ	Ground state group Q_0 (Mev)	First exc. group Q_1 (Mev)	Q_0-Q_1 (kev)
30°	4.662±0.017	4.547±0.020	123±18
45°	4.655±0.017	4.528±0.020	127±18
60°	4.634±0.017	4.511±0.020	123±18
90°	4.561±0.017	4.528±0.040	123±40
105°	4.656±0.017	4.531±0.040	125±40
120°	4.650±0.017	4.530±0.024	120±22
135°	4.668±0.017	4.547±0.024	121±22

After subtraction of background and correction for spectrometer transmission, the results shown in Figs. 4, 5, and 6 for the angular distributions and in Fig. 7 for the excitation functions of the two groups were obtained. At the two higher energies the alpha groups were focused to the same spot as the elastic deuterons at certain angles. Although the alpha tracks could still be seen, the heavy exposure made accurate counting impossible. From these results, total (d,α) reaction cross sections $\sigma=\int(d\sigma/d\omega)d\omega$ were calculated for both groups at each energy. The ratio of the cross section for the group to the excited state relative to that to the ground state is shown in Table II at the three energies. The quoted error is an estimate of the uncertainty introduced by the statistical errors in the measured cross sections and by the interpolation and

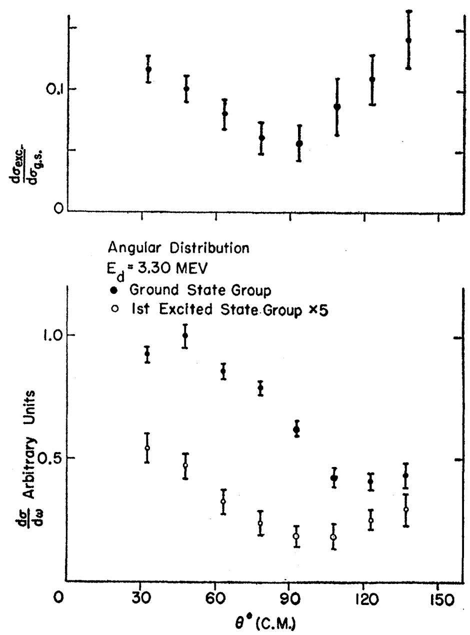

FIG. 4. Angular distributions and relative intensity of alpha groups to the ground and first excited states of K^{38}. $E_d=3.30$ Mev.

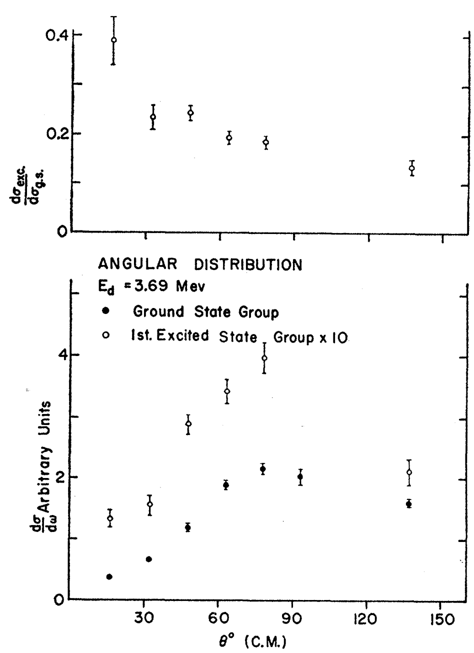

FIG. 5. Angular distributions and relative intensity of alpha groups to the ground and first excited states of K^{38}. $E_d=3.69$ Mev.

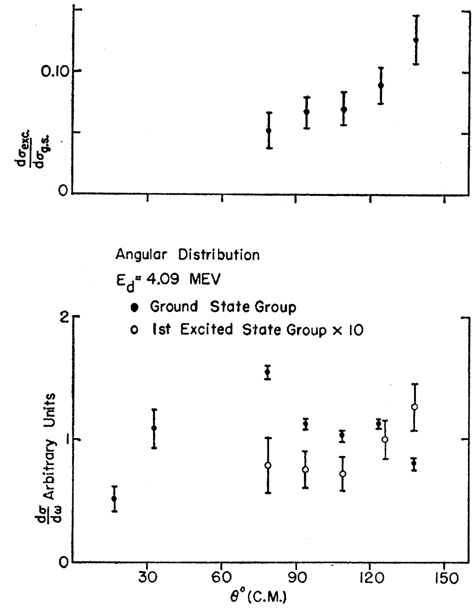

FIG. 6. Angular distributions and relative intensity of alpha groups to the ground and first excited states of K^{38}. $E_d=4.09$ Mev.

extrapolation involved in the calculation. The mean of these three values, $r=0.11\pm0.01$, is in agreement with the mean value of 0.12 for the ratio of the differential cross sections at 30° over this energy range.

DISCUSSION

In the $j-j$ coupling shell model, the states of the lowest configuration in K^{38} have spins, parities, and isotopic spin $(0^+,2^+)$ $T=1$ and $(1^+,3^+)$ $T=0$. From the β^+ decay of K^{38}, it is concluded that the lowest two states are the 3^+ $T=0$ and 0^+ $T=1$ though the order of the levels is not completely certain.[13]

This measurement of the energy difference of 123 kev between these levels establishes the 3^+ state as the ground state. If this were the higher level, it should show appreciable beta decay to the ground state of A^{38} via the K^{38} ground state, and this is not observed.[14] The assignment of $T=1$ to the first excited state would also be reasonable in view of the low intensity of the alpha group going to that state.

At first sight it would appear that the isotopic spin selection rule inhibits the forbidden transitions by a factor of about ten, but it is now necessary to consider the conservation of angular momentum and parity also. With a target nucleus of zero spin and even parity, deuterons of angular momentum will form compound states of spin $j=l$, $l\pm1$ and parity $(-)^l$. Alpha emission to a 0^+ state is only possible, however, from states of spin J, parity $(-1)^J$. Hence it appears that only about one-third of the states formed in the compound nucleus will be able to decay by alpha emission to the 0^+ state in K^{38}. To make a more quantitative estimate of this effect, a calculation of the ratio of the total cross sections for the two states of interest was made using the statistical theory of the nucleus in the form given by Hauser and Feshbach.[15] The reaction cross section is

TABLE II. Measured ratio of (d,α) cross sections to first excited state and to ground state of K^{38}.

E_d (Mev)	3.30	3.69	4.09
$r=\sigma_{\text{exc.}}/\sigma_{\text{g.s.}}$	0.09±0.02	0.17±0.02	0.08±0.02

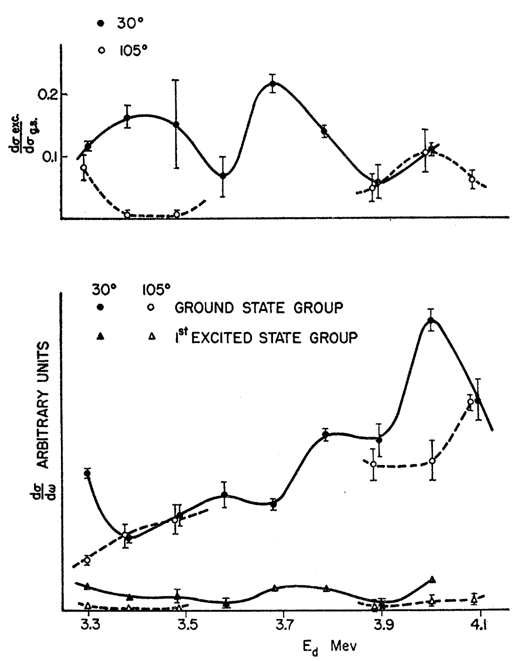

FIG. 7. Excitation functions for the alpha-particle groups to the ground and first excited states of K^{38}.

$$\sigma(i|i')=\frac{\pi\lambda\!\!\!^{-2}}{(2s+1)(2i+1)}\times\frac{\sum_l T_l(E)\sum_{jJ}\epsilon_{lj}{}^J(2J+1)\sum_{j'l'}\epsilon_{j'l'}{}^J T_{l'}(E')}{\sum\epsilon_{j''l''}{}^{J''}T_{l''}(E'')}.$$

The transmission coefficients T_l were calculated from the graphs given by Morrison.[16] The use of these graphs implies a "black" nucleus or a sticking probability of unity for the deuterons and alphas. This assumption is probably well justified in this case because of the strong absorption of these particles in nuclear matter. It was necessary to consider partial waves up to $l=4$ for the deuteron and $l=7$ for the alphas. The sum appearing in the denominator is to be taken over all open channels for each value of J. It was assumed that

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this sum was independent of J because of the very large number of channels open, not only for (d,α) reactions but for (d,p) and (d,n) reactions also. The ratio of the (d,α) cross sections going to the 0^+ and 3^+ states is then easily evaluated with the result:

$$\sigma(0^+|0^+)/\sigma(0^+|3^+)=0.17, \quad E_d=3.3 \text{ Mev}$$
$$=0.19, \quad E_d=4.1 \text{ Mev.}$$

Thus it appears that the transition to the 0^+ $T=1$ state is inhibited by a factor of about 5 by angular momentum and parity selection rules and only by a factor of about two by the isotopic spin selection rule.

Shell model calculations indicate that the admixture of $T=1$ states in the ground state of Ca^{40} and K^{38} should be about 5% in intensity.[17] Hence, for a direct transition the isotopic spin selection rule would be expected to reduce the cross section by a factor of about 20 rather than the observed factor of 2. It seems likely that this breakdown of the isotopic spin selection rule comes about by the mixing of states of different isotopic spin in the compound nucleus. In the present measurements the compound states involved in Sc^{42} are at an excitation energy of about 15 Mev. While nothing is known of the structure of this nucleus, the level spacing for states of a given spin and parity may be estimated[18] probably to within a factor of 3, to be 1.5 kev. It would be expected that the Coulomb matrix element between two such states would be considerably larger than this, implying that these states can no longer be characterized by a definite isotopic spin.

It is interesting to note that all (d,α) measurements which have so far been interpreted as indicating the validity of the isotopic spin selection rule have been 0^+ $T=0 \rightarrow 0^+$ $T=1$ transitions in which conservation of angular momentum will be an important factor in diminishing the cross section. In the most carefully studied of these, $O^{16}(d,\alpha)N^{14}$, the ratio of the cross section to the first $T=1$ state to that to the ground state was $r=\sigma(0^+|0^+)/\sigma(0^+|1^+)\simeq 0.05$. This result is an average taken over a range of 2 Mev in incident deuteron energy, and hence represents an average over many compound states. A calculation similar to that for Ca^{40} using the statistical model predicts a ratio $r=0.14$, indicating that even in this light nucleus the isotopic spin selection rule inhibits the "forbidden" transition only by a factor of about 3. In addition to the isotopic spin impurity in the nuclear states involved, another factor which has been suggested as contributing to the violation of the selection rule is the polarization of the deuteron in the Coulomb field of the nucleus. The resulting space asymmetry in the deuteron wave function would imply a mixing of $T=1$ states in the deuteron ground state. A calculation suggested by French[19] was made to estimate an upper limit for this effect. Assuming the deuteron to be completely polarized (i.e., that the proton in the deuteron traverses a Coulomb trajectory), the relative intensity of $T=1$ states was given by $|\psi(T=1)|^2/|\psi(T=0)|^2 \leqslant 0.1$. An effect of this magnitude would be too small to account for the observed violation of the selection rule but might show up in a careful comparison of the inelastic scattering of deuterons and alpha particles. Such measurements have been made on N^{14},[20,21] and it is found that the group to the lowest $T=1$ state is very weak in both cases. In fact, the isotopic spin selection rule appears to be even more effective than might be expected. It is not clear at present why the selection rule should have such a large effect in the inelastic deuteron and alpha scattering and such a small one in the (d,α) reactions.

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[21] W. D. Ploughe *et al.*, Bull. Am. Phys. Soc. Ser. II, 4, 17 (1959).