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INVESTIGATION OF THE $K^{39}(d, p)K^{40}$ AND $Ca^{40}(d, p)Ca^{41}$ REACTIONS

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Nuclear emulsions were used to study the angular distributions of three groups of protons from the K^{39} (d, p) K^{40} reaction for a deuteron energy of 4 Mev, and also the angular distribution of the long-range proton group from the Ca^{40}(d, p)Ca^{41} reaction with 1.3, 2.2, and 4.0 Mev deuterons. The measured angular distributions do not agree with those calculated from the Butler theory. Comparison of the results obtained for the two reactions enables us to draw some conclusions concerning the low-lying states of the K^{40} nucleus.

THE (d, p) stripping reaction has been investigated for the principal isotopes of all elements with Z ≤ 20. The only exception is the K^{39}(d, p)K^{40} reaction; no data have been published concerning the angular distribution of the protons formed in this reaction.

In 1954 one of the authors[1] studied this reaction for the purpose of assigning quantum numbers to the low-lying states of K^{40}. However it appeared that the angular distributions could not be interpreted uniquely using the Butler theory.[2] It was necessary to assume configuration mixing or to suppose that the Butler theory is not applicable to this case. The latter appeared quite probable, since the Butler theory does not take account of the Coulomb or the nuclear interaction between the particles participating in the reaction. At the same time, such interactions are important in this case because the energy of the bombarding deuterons (4 Mev) is below the Coulomb barrier (5.65 Mev).

In order to find the cause of the discrepancy between the experimental results and the theory, we first made some additional studies of the K^{39}(d, p)K^{40} reaction, and also measured the angular distribution of the protons which are produced in the Ca^{40}(d, p)Ca^{41} reaction when the Ca^{41} nucleus is formed in the ground state. The latter reaction was selected because there are the same number of neutrons in the K^{39} and Ca^{40} nuclei and their charges are almost the same. In addition, the calcium reaction had already been studied for a deuteron energy of about 8 Mev (Ref. 3) and good agreement with the Butler theory had been obtained in this case.

In order to understand the changes in shape of the angular distribution with changing deuteron energy, the Ca^{40}(d, p)Ca^{41} reaction was also studied for deuteron energies of 2.2 and 1.3 Mev.

EXPERIMENTAL METHOD

The experiments were carried out at the 72 cm cyclotron of Moscow State University. The required changes in deuteron energy were achieved by changing the mode of operation of the cyclotron. Consequenly the beam intensity was practically unchanged when the deuteron energy was lowered. The extracted, focused beam of particles passed through a collimator into a special cylindrical chamber, 26 cm in diameter, placed at a distance of about 5.5 meters from the accelerator. The energy spread of the deuterons traversing the collimator did not exceed ± 40 kev. A thin target was placed at the center of the chamber, with nuclear plates at various angles around it for recording the reaction products. Aluminum or silver absorbers were placed in front of the plates to cut out elastically scattered deuterons and long-range protons.

Thin targets containing potassium were prepared by evaporation of potassium iodide onto a gold foil backing, followed by admission of iodine vapor into the vacuum system.[4] Calcium targets were obtained by evaporating metallic calcium. Immediately after preparation, such a target changes its color as the calcium oxidizes, but then over a long period no noticeable changes occur in the target. The amount of material deposited on the backing was determined by weighing the target after irradiation. In this way the thickness of the layer was measured to an accuracy of ± 0.05 — 0.08 mg/cm^2 (for a total layer thickness of 0.2 — 0.9 mg/cm^2).

The current integrator which was used to measure the deuteron beam current was calibrated in terms of the elastic scattering of deuterons on gold, where it was assumed that the scattering is pure Rutherford scattering. The accuracy of this calibration, including errors in measurement of the thickness of the gold target and the energy of the bombarding particles, does not exceed 12 — 15%. Consequently the possible overall uncertainty in determining the absolute cross section of the reaction is 30 — 40%. The accuracy of the determination of relative cross sections for the $Ca^{40}(d, p)Ca^{41}$ reaction with different energies of the deuterons is considerably higher, since the same target was used in all the experiments. In addition, after carrying out the main irradiations at 4, 2.2, and 1.3 Mev, a check run was made at 4 Mev. The ratio of the differential cross sections measured at several angles in the check run to the cross sections at the same angles in the main run was 0.99, which showed that the calcium content of the target was practically unchanged.

TABLE I. Excitation Energy (Mev) of Low-Lying Levels of K^{40}

Reference 6	Reference 4	Reference 7	Our Results	Proton Group
0, 0.03	0	0	0	p_{01}
0.80, 0.89	0.81	0.76	0.82	p_{23}
	2.01	2.06		
		2.28	2.08	p_4
		2.40		
	2.56	2.56		
		2.77		

In studying the reaction products from bombardment with moderate energy deuterons of any but the very lightest nuclei, the problem of impurities in the target is important. Light element impurities are especially harmful, since their reactions occur with a considerable probability even for low bombarding energies. Since purified reagents were used for the targets, the only substances which can appear in significant amounts in the targets are oxygen, carbon, and nitrogen, which are hard to get rid of. However, only those protons which come from the $C^{13}(d, p)C^{14}$ and $N^{14}(d, p)N^{15}$ reactions, in which the final nucleus is formed in its ground state, have sufficient energy to pass through the absorbers placed in front of the plates. The small number of proton tracks from the nitrogen reaction, which were observed in the measurements with 2.2 and 1.3 Mev deuterons, did not interfere with the measurements since their length is much greater than that of the true tracks. The protons from $C^{13}(d, p)C^{14}$ have an energy close to that of the particles formed in the potassium and calcium reactions, and can therefore be a serious contamination. Experiment showed that the proton group from the reaction on C^{13} is noticeable only for the $Ca^{40}(d, p)Ca^{41}$ reaction with 1.3 Mev deuterons. Using data from the literature on the $C^{13}(d, p)C^{14}$ cross section,[5] we can compute that there is little carbon in the calcium target, and that the target consists mainly of calcium oxide (approximately 9 CaO molecules per $CaCO_3$ molecule). At angles of emergence below 50° we were unable to resolve the proton groups from C^{13} and Ca^{40}.

NIKFI Ia-2 plates with an emulsion thickness of 100 μ were used in the experiments. The number of plates used in the various experiments ranged from 21 to 32. In order to speed up the search, in most cases the energy spectrum was taken for each plate with low statistics. Then the limits of a particular proton group were found from the histogram, and the number of tracks belonging to this group was counted in a definite area of the plate.

The accuracy of the angular distributions is determined, aside from statistical fluctuations, by many other factors (such as the accuracy in alignment of plates, target, collimator, etc.) which are difficult to estimate. However, the comparison of the angular distribution of elastic scattering of deuterons on gold with the Rutherford formula, and the comparison of the results obtained in the various experiments for plates placed at the same angle to right and left of the beam, show that the rms spread in the individual points does not exceed 8 — 10% (while the statistical errors are 5 — 6%). We may therefore assume that the errors in the measurements of angular distributions, which are not due to statistical fluctuations, are surely less than 10%.

EXPERIMENTAL RESULTS

The $K^{39}(d, p)K^{40}$ reaction was studied for a deuteron energy of 4 Mev. Since the normal mixture of potassium isotopes was used in the present work, the only proton group which could be selected with certainty is that from the most abundant isotope K^{39} (93.3%). Table I gives the available data on the lowest excited levels of K^{40}, as obtained by Sailor[4] using proton absorption in Al, by Buechner et al.[6] from magnetic analysis of the protons, and by Adiasevich, Groshev, et al.[7] from the spectrum of γ rays emitted by K after thermal neutron absorption. Figure 1 shows the energy spectrum which we found for protons emitted at an angle of 41° with respect to the incident beam. Three proton groups are clearly visible on the histrogram. As was to be expected, we could not resolve close levels with the plates, so that the group p_{01} contains protons which are emitted when K^{40} is produced in its ground and first excited states, and the group p_{23} contains protons corresponding to the levels at 0.80 and 0.89 Mev. The group p_4 is also apparently an unresolved doublet or triplet.

The angular distributions obtained for the proton groups p_{01}, p_{23}, and p_4 are shown in Figs. 2, 3, and 4 respectively. The abscissa is the angle of emergence of the proton in the c.m. system, and the ordinate is the differential cross section in mbarn/sterad. The statistical errors are shown on the figures. The angular distributions for the proton groups p_{01} and p_{23} were found from three independent experiments carried out at different times. The results coincided within the limits of error. Figures 2 and 3 show the angular distributions for the series in which the plates were set at a large number of angles.

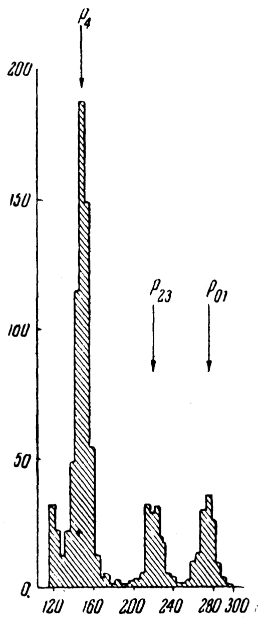

FIG. 1. Spectrum of protons from $K^{39}(d, p)K^{40}$. The abscissa is the number n of divisions on the microscope ocular scale (1 division = 1.41 μ).

The angular distribution of the proton group p_0, which corresponds to formation of Ca^{41} in its ground state in the $Ca^{40}(d, p)Ca^{41}$ reaction, was measured for deuteron energies of 4.0, 2.2, and 1.3 Mev. The experimental results are shown in Figs. 5 — 7. For 1.3 Mev deuterons, the angular distribution could only be measured with very poor statistics, and as already mentioned, only in the angular range above 50°.

Table II gives the values of the total cross section for the various proton groups. In the case of the groups p_{01} and p_{23} from the $K^{39}(d, p)K^{40}$ reaction, the averages of the results of the three sets of experiments are given; the rms fluctuation of individual measurements is 30%.

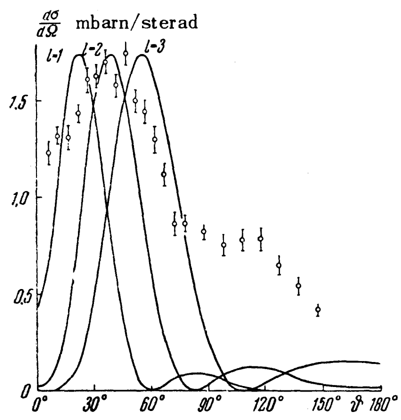

FIG. 2. Angular distribution of the group p_{01} from K. The solid curves are computed from the Butler formula.

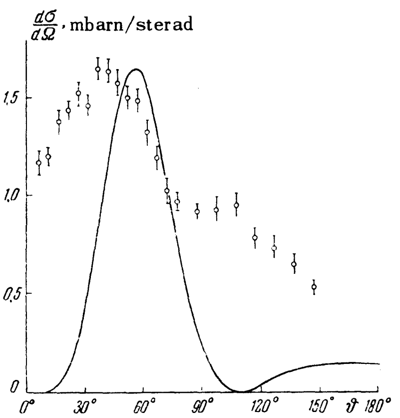

FIG. 3. Angular distribution of the group p_{23} from K. The solid curve is computed from the Butler formula with $\ell = 3$.

DISCUSSION OF RESULTS

In Fig. 2, which shows the angular distribution of the proton group p_{01} from the $K^{39}(d, p)K^{40}$ reaction, we give the curves calculated from the Butler[2] formula for orbital angular momentum of the captured neutron equal to $\ell = 1, 2, 3$ (the nuclear radius is set equal to 5.8×10^{-13} cm in the computations). Comparison of the shapes of these curves with the measured angular distribution shows that even moderately satisfactory agreement can be obtained only by assuming either that $\ell = 2$ or that the angular distribution is determined by the sum of $\ell = 1$ and $\ell = 3$ (with relative contributions of 1 and 8 respectively). The first assumption contradicts the single-particle model, ac-

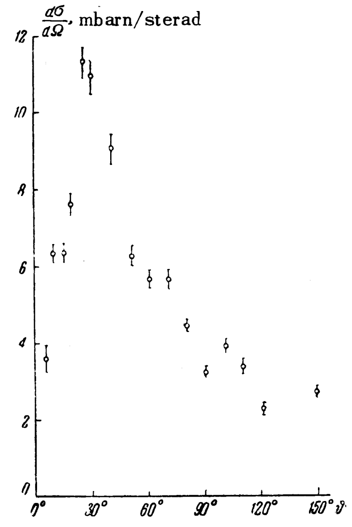

FIG. 4

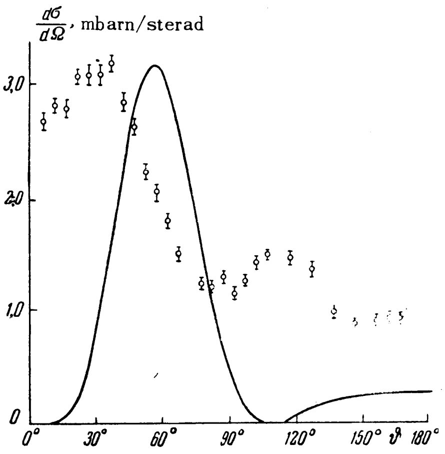

FIG. 5

FIG. 4. Angular distribution of group p_4 from potassium.

FIG. 5. Angular distribution of group p_0 from calcium for 4.0 Mev deuterons. The solid curve is computed from the Butler formula with $\ell = 3$.

TABLE II. Total Cross Sections

Reaction	Deuteron Energy, Mev	Proton Group	σ, mbarn
$K^{39}(d, p)K^{40}$	4.0	p_{01}	12
	4.0	p_{23}	13
	4.0	p_4	58
$Ca^{40}(d, p)Ca^{41}$	4.0	p_0	21
	2.2	p_0	2.2
	1.3	p_0	0.04

cording to which the odd neutron in the K^{40} nucleus should be in the 1 $f_{7/2}$ state. It is true that for the first excited level (0.03 Mev) the neutron might be in some other state, but according to the shell model this state should be either 2 $p_{3/2}$ or 1 $f_{5/2}$. So if we assume that the Butler calculation is applicable to the present case, the shell model requires the assumption of a mixture of $\ell = 1$ and $\ell = 3$.

However, the very great similarity between the results obtained in the present work, at a deuteron energy of 4.0 Mev for the angular distributions of the proton groups p_{01} from the $K^{39}(d, p)K^{40}$ reaction (Fig. 2) and p_0 from $Ca^{40}(d, p)Ca^{41}$ (Fig. 5), indicate that the orbital angular momentum of the neutron captured by potassium is 3. On the one hand the angular distribution of the group p_0 from the $Ca^{40}(d, p)Ca^{41}$ reaction, as measured by Holt and Marsham,[3] agrees with the calculated curve for $\ell = 3$. Since they used deuterons with an energy of 8 Mev, which is above the top of the Coulomb barrier, there is no reason in their case for doubting that the Butler theory is applicable. On the other hand, the neutron number is 20 in both K^{39} and Ca^{40}, so that the neutron states in the final nuclei should be the same (1 $f_{7/2}$).

Thus the comparison of the angular distributions for the proton groups p_{01} and p_0 leads to the conclusion that in the ground and first excited states of K^{40} the neutron has an orbtial angular momentum of 3. The assumption of a mixture of $\ell = 1$ and $\ell = 3$ is therefore obviously incorrect.

The angular distribution of the group p_{23} (Fig. 3) coincides almost exactly with that of the group p_{01}, so that the captured neutron should here be assigned to $\ell = 3$. This result is in complete agreement with the assumption that the quantum numbers of the odd neutron are the same (1 $f_{7/2}$) in the four lowest states of K^{40}, and that the existence of these four states is caused by different relative orientations of the angular momenta of the proton and neutron. From the measured relative intensities of the respective proton groups,[6] it has been possible to make assignments of all four levels, giving 4^-, 3^-, 2^-, and 5^-, in order of increasing energy.[8] This is confirmed by our re-

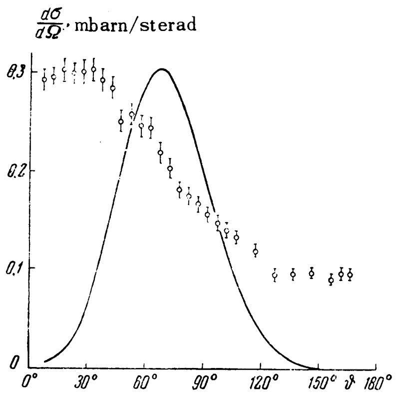

FIG. 6

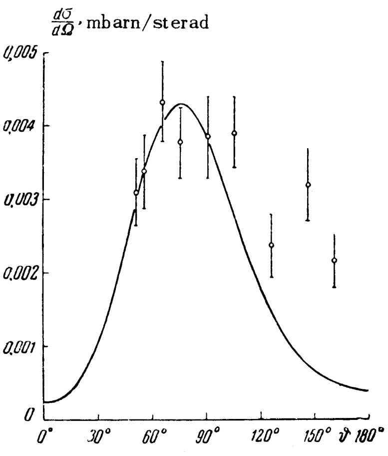

FIG. 7

FIG. 6. Angular distribution of group p_0 from calcium for 2.2 Mev deuterons. The solid curve is computed from the Butler formula with $\ell = 3$.

FIG. 7. Angular distribution of group p_0 from calcium for 1.3 Mev deuterons. The solid curve is computed from the Butler formula with $\ell = 3$.

sults, since the average of the intensity ratio for groups p_{23} and p_{01} for all angles was equal to unity (more precisely, 0.97). If we assume that the cross section is proportional to $(2I_f + 1)$, where I_f is the spin of the final state, the equality of the intensities requires that levels with spins of 4 and 3 contribute to the one group, and levels with spins 2 and 5 to the other.

We should mention that the differential cross sections for the group $p_0(Ca^{40})$ and the sum of the differential cross sections for groups p_{01} and p_{23} (K^{39}) are practically the same at the peak of the angular distribution. Since the statistical factors $(2I_f + 1)/(2I_i + 1)$ are the same in both cases, this indicates that the reduced widths of the final states are equal, which once again confirms the validity of our conclusions concerning the low-lying excited states of K^{40}.

The differential cross section for formation of group p_4 (Fig. 4), both at the maximum and at large angles, is several times greater than the cross section for formation of groups p_{01} and p_{23}. This is still another indication that this group corresponds to several levels in the K^{40} nucleus. The maximum in the angular distribution of this group is considerably sharper, and is at a smaller angle, than that of the longer range protons. It is therefore reasonable to assume that the angular distribution is mainly determined by $\ell = 1$ or 2, and that $\ell = 1$ is more probable, since the large differential cross section is evidence that the corresponding level is a single-particle level and according to the shell model d-states should not appear at low excitations. So apparently among the levels corresponding to the group p_4 there are one or more in which the neutron is in a $2p_{3/2}$ state.

By using the results for the $Ca^{40}(d, p)Ca^{41}$ reaction with 4.0 Mev deuterons, we have succeeded in getting some information about the low-lying excited states of K^{40}. In addition, from these same results it follows that the Butler[2] theory, as usually stated, is not applicable to the description of angular distributions of protons produced in reactions of 4 Mev deuterons with nuclei having Z around 20. The main difference between the experimental angular distributions and those calculated from this theory is that the maximum in the differential cross section, which is a characteristic feature of the stripping reaction, is shifted toward smaller angles and is broadened. This fact was already pointed out in our paper[9] on the $S^{32}(d, p)S^{33}$ reaction. The displacement and broadening of the maximum is considerably greater for calcium and potassium than for sulfur. This may be explained first of all by the difference in nuclear charge, and secondly by the difference in orbital angular momentum of the captured neutron ($\ell = 2$ for sulfur and $\ell = 3$ for calcium and potassium). The results found for the $Ca^{40}(d, p)Ca^{41}$ reaction with 2.2 Mev deuterons (Fig. 6) show that for this case the maximum of the differential cross section is close to 0°, i.e., the difference between the experimental and theoretical distributions increases with decreasing deuteron energy. At 1.3 Mev (Fig. 7) the cross section apparently becomes more isotropic; if there is a rise at low angles, it starts at angles below 50°. Despite the fact that its position is close to the calculated location, the maximum, of which there is a hint around 80 – 90°, can hardly be the principal maximum which is characteristic for the stripping process. In any case, the results found with 4.0 and 2.2 Mev deuterons make this unlikely. If this maximum is not caused by a chance fluctuation of the points because of the poor statistics, then it is more likely that it is the secondary maximum associated with the stripping process (cf. for example, Fig. 5), or is caused by the symmetry of the differential cross section about 90° which occurs when the reaction goes primarily via the compound nucleus. In the latter case, as shown by calculation of Pratt[10] based on the statistical theory of Wolfenstein,[11] if the final nucleus is formed in a $7/2^-$ state, the cross section has a maximum around 90°.

Since a considerable difference between experimental angular distributions and those calculated from Butler's formula appears at deuteron energies less than or equal to the height of the Coulomb barrier, and since this difference increases with increasing nuclear charge and decreasing deuteron energy, it is obvious that for a correct description of the experimental results we must include both the Coulomb interaction and the nuclear interaction between the particles participating in the reaction. The fact that the maximum is shifted toward 0° shows that the nuclear interaction is very important at low deuteron energies, since the Coulomb interaction by itself shifts the peak toward larger angles,[12] i.e., in the opposite direction.

In conclusion, it is a pleasure to express our thanks to S. S. Vasil'ev for his interest in the work, and to the operating crew of the cyclotron, in particular to G. V. Kosheliaev, A. A. Danilov, and V. P. Khlapov.

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273

SOVIET PHYSICS JETP VOLUME 6 (33), NUMBER 6 JUNE, 1958

DISSOCIATION OF C^{12} INTO THREE ALPHA PARTICLES INDUCED BY FAST NEUTRONS

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The energy dependence of the effective cross-section for the neutron-induced disintegration of C^{12} into three α particles was investigated for neutron energies between threshold and 19 Mev. Information about the mechanism by which this reaction goes (in the indicated energy range) was obtained from calculations of the excitation energy of intermediate nuclei formed during the decay, and also from the distributions of the reaction products in space and energy.

MANY authors have studied the disintegration of C^{12} into three α particles as induced by fast neutrons. The most detailed examination of this reaction was carried out by Frye, Rosen, and Stewart,[1] whose work extends the data given by earlier workers (Ref. 2, and others). However, several points remained unclear, in particular the energy dependence of the effective cross section near the threshold and the maximum, how the mechanism of the reaction depended on the energy of the incident neutrons, and the question of whether direct interaction processes occurred at neutron energies of 18 to 20 Mev.

In this paper we investigate the energy dependence of the effective cross section for the decay of C^{12} into three α particles from threshold ($Q = -7.28$ Mev) to 19 Mev, and try to see how the mechanism of the decay depends on the energy of the incident neutrons.

Decay stars were observed both in NIKFI-Ia-2 emulsions and also in specially prepared layered emulsions loaded with a powder of spectroscopically pure carbon, the grain size being about 1 μ. The carbon powder enabled us to distinguish between three-pronged stars corresponding to the decay $C^{12} \rightarrow 3\alpha$ and three-pronged stars due to the reaction $N^{14}(n, 2\alpha)Li^7$, and also enabled us to take into account decays which looked like two-pronged stars because the third α particle had too little energy to make a track in the emulsion, thus giving a better value for the effective cross section.

The plates were exposed to neutrons from a thick lithium target bombarded by deuterons accelerated to 4 Mev in a cyclotron. Before hitting the emulsion, which was inclined at an angle of 6° to the incident current, the neutrons passed through a system of collimators. The cassettes containing the emulsions were shielded from scattered neutrons.