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INVESTIGATIONS OF THE REACTIONS (α, α'), (α, p) *AND* (α, t) *ON LITHIUM NUCLEI*

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The angular distribution of the reaction $Li^7(\alpha, \alpha')Li^{7*}$ $(Q = -4.61$ Mev$)$ for the bombarding α-particle energy $E_\alpha = 13.2$ Mev and also the angular distributions of the reactions $Li^7(\alpha, t)Be^8$ $(Q = -2.56$ Mev$)$, $Li^6(\alpha, p)Be^9$ $(Q = -2.13$ Mev$)$, and $Li^7(\alpha, p)Be^{10}$ $(Q = -2.56$ Mev$)$ for $E_\alpha = 10.15$, 11.5, and 13.2 Mev were investigated.

The results can be derived from direct interaction theories. From an interpretation of the experimental angular distribution of the reaction (α, α') within the framework of Butler's theory it follows that the parity of the 4.61 Mev level in the Li^7 nucleus is negative and the spin is equal to one of the following four values: $1/2$, $3/2$, $5/2$, $7/2$.

1. INTRODUCTION

In many papers published in recent years it has been shown that many nuclear reactions proceed without formation of a compound nucleus. This pertains also to reactions due to α particles with energy ranging from several Mev to several times ten Mev, as a result of which the final nucleus remains in the ground state or in a not too excited state.

Symptoms of direct processes in a nuclear reaction are the asymmetry of the angular distribution of the secondary particles with respect to the plane perpendicular to the direction of the beam of bombarding particles (in the center-of-mass system) and relatively weak dependence of the form of the angular distribution on the energy. A characteristic symptom of reactions that proceed via a compound nucleus, to the contrary, is symmetry of the angular distribution relative to the aforementioned plane. An asymmetrical distribution in the case when a compound nucleus is formed is possible only when the reaction goes through a small number of overlapping levels of the compound nucleus of unequal parity, but in this case the form of the angular distribution should be sensitive even to slight changes in the energy.[1]

A simple approximate formula for the differential cross section of direct nuclear reactions was given by Austern, Butler and McManus.[2] The differential cross section was expressed in terms of the linear combination of the squares of spherical Bessel functions $j_l^2(|\mathbf{q}|R)$, where Q is the wave vector of the recoil nucleus, R a certain radius, and l the quantum number of the orbital angular momentum, acquired (or lost) by the nucleus as a result of the collision. Possible values of l are determined by the selection rules

$$|\mathbf{J}_A + \mathbf{J}_B + \mathbf{s}_a + \mathbf{s}_b|_{min} \leqslant l \leqslant J_A + J_B + s_a + s_b \tag{1}$$

and

$$\pi_A \pi_B = (-1)^l, \tag{2}$$

where $\mathbf{J}_A$, $\mathbf{J}_B$, $\mathbf{s}_a$, and $\mathbf{s}_b$ are respectively the spins of the initial and final nucleus and of the incident and emitted particles, π_A and π_B are the parities of the initial and final nucleus. The theory of direct nuclear reactions was later on developed by Butler,[3] who gave a sufficiently general theory (in the Born and plane-wave approximations) of nuclear reactions that occur when bombarding particles interact with weakly bound particles located in the surface region of the nucleus. In particular, it has been shown that in the expression for the differential cross section of direct nuclear reactions, interference terms may appear. Formulas for the differential cross section given by Butler, Austern, et al. were derived specifically for reactions on nuclei which can be described by the nuclear-shell model, but similar formulas can be obtained also when using other nuclear models.[4-6]

The formulas of Butler, Austern, et al. are suitable for describing angular distributions which are directed forward and which have an oscillating structure. Owen and Madansky[7] have considered the mechanism of "stripping of a heavy particle," which produces a peak in the angular distribution at angles close to 180°.

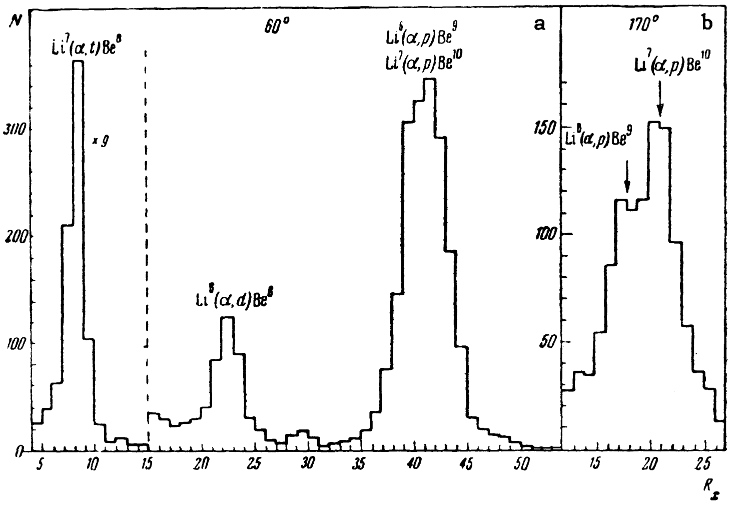

FIG. 1. Track spectra at $E_\alpha = 13.2$ Mev. The abscissas represent the horizontal projection of the track length, a – $\theta_{lab} = 60°$, thickness of aluminum foil in the cassette window $d_{Al} = 62\ \mu$, each division of the horizontal scale corresponds to 5.07 μ; b – $\theta_{lab} = 170°$, $d_{Al} = 8\ \mu$, one division of the horizontal scale = 2.535 μ.

2. MEASUREMENT PROCEDURE

The experiments were performed with the cyclotron of the Leningrad Physico-technical Institute, which produces accelerated particles of different energies (in the experiments reported in this article, α particles of energies 10.15, 11.5, and 13.2 Mev were used). A scattering chamber 50 cm in diameter was attached to the cyclotron. A target was placed in the center of the chamber, surrounded at a radius of 20 cm by special cassettes containing photographic plates (type Ya-2, emulsion thickness 100μ). The average angle between the plane of the photographic emulsion in the cassette and the direction of particle motion from the target was 10°. The scattering chamber and the cassettes employed made it possible to investigate angular distributions in the range from 10 to 170°, in steps of 5 or 10°, but since the particle energy from the Li + α reaction diminishes very rapidly with scattering angle in the laboratory system, in practice only several high-energy particles could be registered at large angles.

The targets were made by rolling metallic lithium of natural isotopic composition in an atmosphere of dry carbon dioxide. The targets employed were 0.75 — 1.1 mg/cm^2 thick.

The plates, exposed and developed in a standard manner, were scanned with a MBI-3 microscope The lengths of the tracks were measured and the energy spectra of the particles and angular distributions of particle groups were determined. The groups of tracks were associated with the different particles produced in the various reactions by studying the changes in the track lengths with scattering angle.

The absolute values of the differential cross sections obtained in different experiments did not deviate from their average values by more than 30 or 40%.

3. RESULTS AND THEIR DISCUSSION

A. Track groups. In scanning the photographic plate under the microscope, many intense track groups were found. Among the short-range tracks (shorter than the tracks of the elastically scattered α particles), the most intense was a group due to the inelastic scattering reaction $Li^7(\alpha, \alpha')Li^{7*}$ (Q = –4.61 Mev). Among the long range tracks, the most intense were groups from the reactions $Li^7(\alpha, t)Be^8$ (Q = –2.56 Mev), $Li^6(\alpha, d)Be^8$ (Q = –1.59 Mev), $Li^6(\alpha, p)Be^9$ (Q = –2.13 Mev), and $Li^7(\alpha, p)Be^{10}$ (Q = –2.56 Mev). The particles from the two last reactions form a single group (see track spectrum at $\theta_{lab} = 60°$ in Fig. 1a) and begin to separate only at large scattering angles (Fig. 1b). What is striking is the large intensity of the triton and deuteron groups.

B. Angular distributions of the reaction $Li^7(\alpha, \alpha')Li^{7*}$ (Q = –4.61 Mev). The angular distribution of the α particles inelastically scattered by Li^7 (Q = –4.61 Mev) at energy E_α = 13.2 Mev, is shown in Fig. 2 (experimental points). The errors indicated are the sum of the corresponding statistical errors, the errors in the determination of the solid angle, and the errors which possibly occurred in the separation of track groups (similar errors are indicated also for the other angular distributions). The transverse cross section of the reaction is very large: the section estimated by integrating the angular distribution from 15 to 90° (in the c.m.s.), is 147 ± 60 mb. In a comparison with the Butler theory,[3] under the assumption that the single-particle level of the unpaired proton from the p shell is excited, it is found that it is impossible to obtain a theoret-

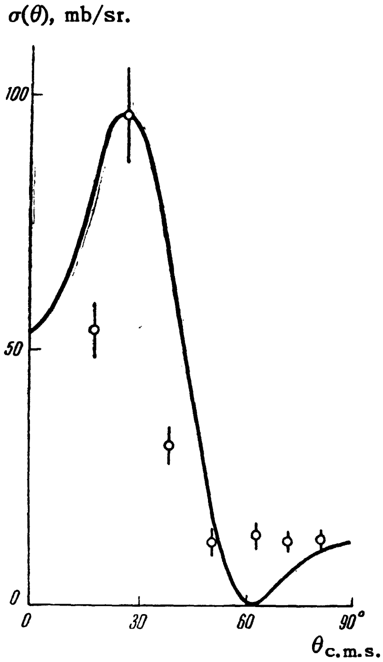

FIG. 2. Experimental and theoretical Butler angular distributions of the reaction $\mathrm{Li}^7(\alpha, \alpha')\mathrm{Li}^{7*}$ (Q = −4.61 Mev) at E_α = 13.2 Mev.

ical curve that fits satisfactorily the experimental one, but the forward peak of the experimental angular distribution can be sufficiently well compared with the peak of the Butler curve with $l = 2$ and radius $R = 5.6 \times 10^{-3}$ cm (curve on Fig. 2). This fact, in accordance with the selection rules (1) and (2) and the known spin and parity of the ground state of the Li^7 nucleus ($3/2^-$),[8] indicates clearly that the 4.61-Mev level of Li^7 has negative parity. The value of the spin can be assumed here to be one of the following four: $1/2$, $3/2$, $5/2$, and $7/2$.

It is seen from Fig. 2 that the experimental peak is narrower than the theoretical one. In explaining this circumstance it must be kept in mind that Butler's theory does not take into account adequately the scattering of the incident and elastically-scattered particles in the field of the nucleus, i.e., the distortions of the plane waves. A refinement of this theory in this sense, as is known, leads indeed to a narrowing of the peaks.[9,10]

C. Angular distributions of the reactions $\mathrm{Li}^6(\alpha, p)\mathrm{Be}^9$ ($Q = -2.13$ Mev) and $\mathrm{Li}^7(\alpha, p)\mathrm{Be}^{10}$ ($Q = -2.56$ Mev). The angular distributions of the protons from these reactions in the laboratory system at $E_\alpha = 10.15$, 11.5, and 13.2 Mev are shown in Fig. 3 [the ordinates represent $0.925\,\sigma_{\mathrm{Li}^7}(\theta) + 0.075\,\sigma_{\mathrm{Li}^6}(\theta)$]. The points with different labels were obtained in different experiments. The same diagram shows curves 1 and 2 corresponding to the isotropic angular distributions of the protons from the reactions $\mathrm{Li}^7(\alpha, p)\mathrm{Be}^{10}$ and $\mathrm{Li}^6(\alpha, p)\mathrm{Be}^9$ in the c.m.s.

Since the groups of protons from the two reactions are not separated, and their c.m.s. are somewhat different, an exact recalculation of the angular distribution to the c.m.s. is impossible. Figure 4 shows as an illustration the approximate angular distribution of the protons in the c.m.s. at $E_\alpha = 11.5$ Mev [the additional errors in the recalculation are $\Delta\theta < 1°$, $\Delta\sigma(\theta) < 5\%$].

It is seen from Figs. 3 and 4 that the angular distributions in the c.m.s. are sharply anisotropic and are asymmetrical with respect to $\theta = 90°$. Their shape changes as the α-particle energy varies from 10.15 to 13.2 Mev, but the similarity between the two is retained, which can be considered as an indication of the important role of the process, which takes place in addition to the production of a compound nucleus. The maximum at angles close to 180° (Fig. 4) is apparently connected with the mechanism of the "stripping of the heavy particle." It is still difficult to say more about the details of the mechanism of the reactions, for it is not known whether both reactions proceed without formation of the compound nucleus, or only one of them.

D. Angular distributions of the reaction $\mathrm{Li}^7(\alpha, t)\mathrm{Be}^8$ ($Q = -2.56$ Mev). The angular distribution of the tritons of the reaction $\mathrm{Li}^7(\alpha, t)\mathrm{Be}^8$ ($Q = -2.56$ Mev) at $E_\alpha = 10.15$ Mev is shown in Fig. 5 (experimental points). At other energies, up to 14.7 Mev, very similar angular distributions are observed.[11] The form and energy dependence of the angular distributions point to the importance of the role of the direct-interaction mechanism.

When a more detailed picture of the direct-interaction mechanism in the $\mathrm{Li}^7(\alpha, t)\mathrm{Be}^8$ reaction is established, it appears more likely to consider the triton produced in this reaction as consisting of nucleons belonging prior to the collision to the Li^7 nucleus rather than to He^4. Actually, the reaction is due to the collision of two light nuclei, which do not differ greatly in their masses, but have substantially different structures: the He^4 nucleus is very strongly bound and compact, while Li^7 is weakly bound and "loose." According to the shell model, the Li^7 nucleus should be considered as consisting of four s-nucleons in the filled shell, forming the α particle, and three outer p-nucleons. Following Brueckner's idea[12] we can assume that the outer p-nucleon can form something by nature of a triton and the Li^7 nucleus can be considered at different times as if consisting of an α particle and a triton. It appears little likely that the $\mathrm{Li}^7(\alpha, t)\mathrm{Be}^8$ reaction is a result of the stripping of a proton from a strong and compact α particle in the field of a loose Li^7 nucleus. A much more probable process is one similar to the knock-out of tritons from Li^7 by α particles, when the tri-

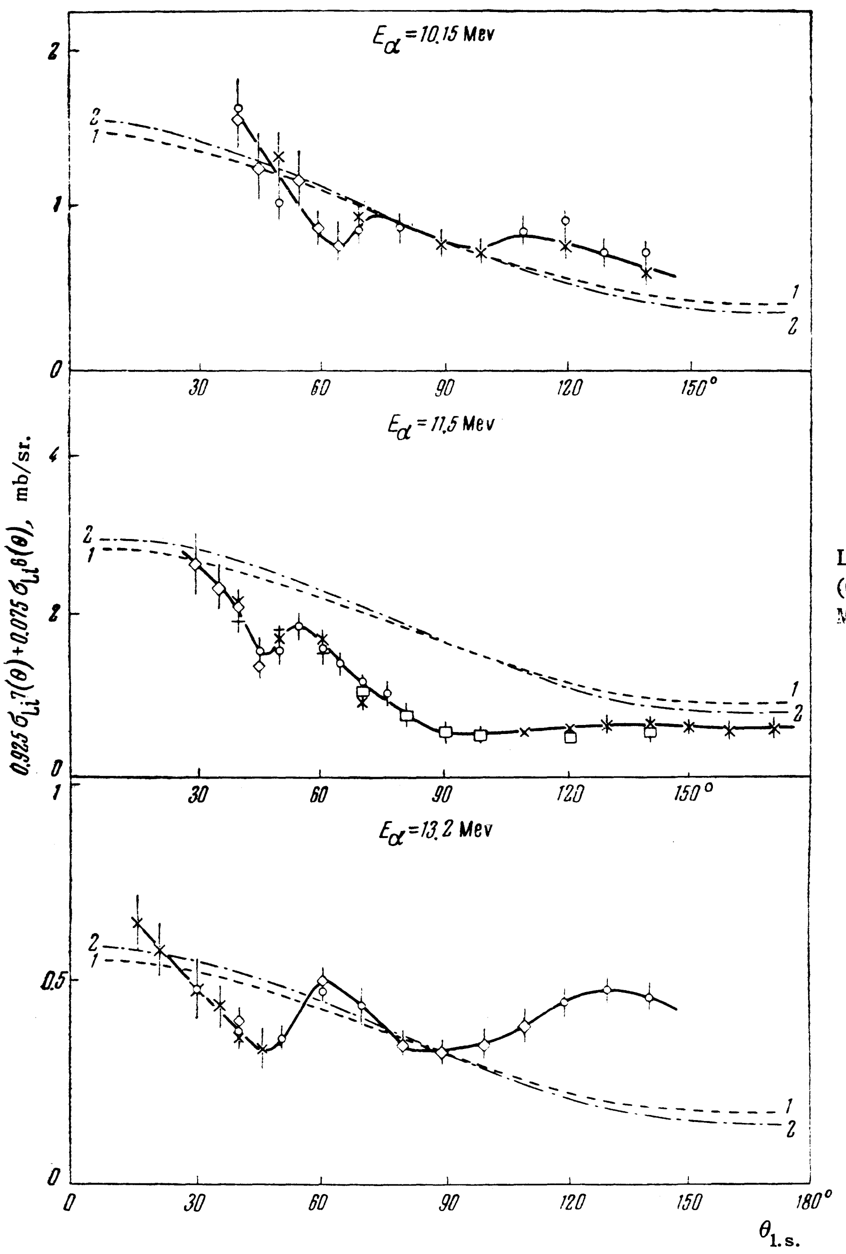

FIG. 3. Angular distribution of the reactions $Li^7(\alpha, p)Be^{10}$ ($Q = -2.56$ Mev) and $Li^6(\alpha, p)Be^9$ ($Q = -2.13$ Mev) at $E_\alpha = 10.15$, 11.5, and 13.2 Mev in the laboratory system.

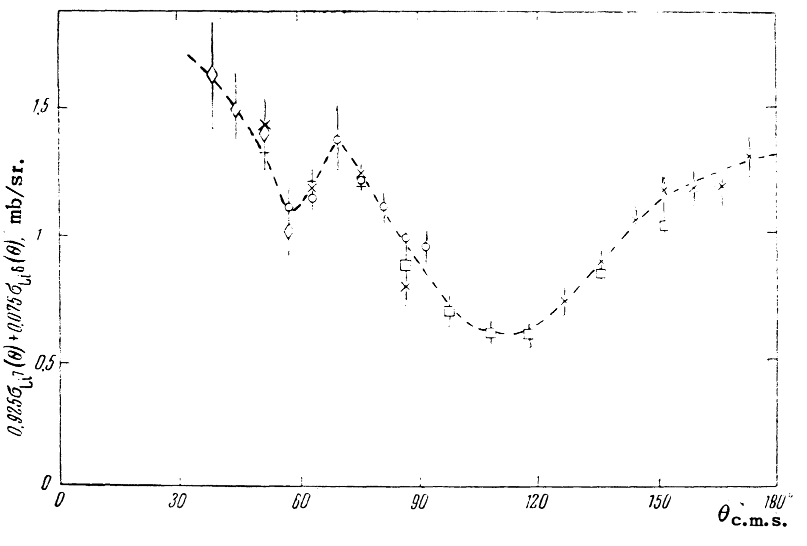

FIG. 4. Angular distribution of the reactions $Li^7(\alpha, p)Be^{10}$ ($Q = -2.56$ Mev) and $Li^6(\alpha, p)Be^9$ ($Q = -2.13$ Mev) at $E_\alpha = 10.5$ Mev in the c.m.s.

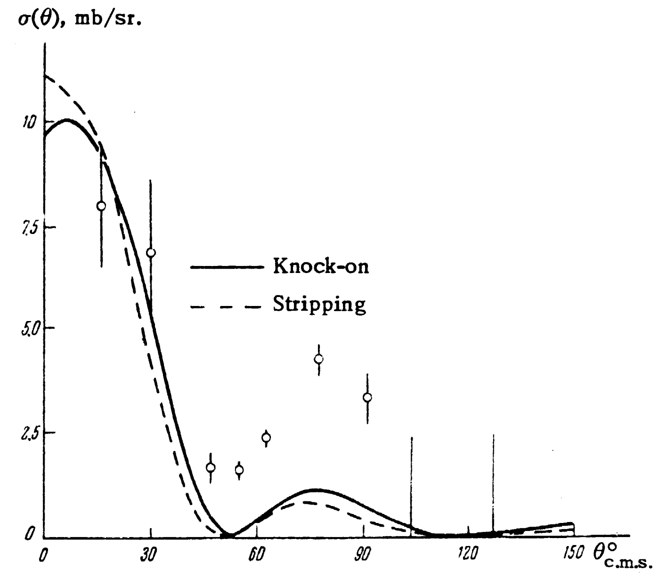

FIG. 5. Experimental and theoretical angular distributions of the reaction $Li^7(\alpha, t)Be^8$ (Q = −2.56 Mev) at E_α= 10.15 Mev.

ton contained in the Li^7 leaves this nucleus as a result of the collision, and the remaining α particle captures the incoming α particle into the Be^8 nucleus. A curve calculated on the basis of such a model with Butler's formula[3] for $l = 1$ (the only possible value compatible with the known values of the spins and parities of the nuclei participating in the reaction[8]), $R = 10 \times 10^{-13}$ cm and $|q| = {}^4\!/_7\, |k_\alpha - {}^7\!/_8 k_t|$ (where k_α and k_t are respectively the wave vectors of the α particle and the triton),[13] is shown in Fig. 5. As can be seen, the positions of the maxima of the theoretical and experimental curves are in fair agreement.

The curve calculated from stripping theory (where the α particle is considered as an antisymmetrical deuteron) for $l = 1$, $|q| = |k_\alpha - {}^7\!/_8 k_t|$ and $R = 5.6 \times 10^{-13}$ cm is shown dotted in Fig. 5. We see that it is similar to the curve calculated by the knock-on theory.

To obtain a satisfactory agreement between the theoretical curves, calculated by the knock-on theory, the "interaction radius" parameter had to be taken very large: $R = 10 \times 10^{-13}$ cm. When R is reduced the maxima of the theoretical curves broaden and creep towards the larger angles, while the distances between them increase. We note that in explaining the experimental angular distributions of other reactions on light nuclei by means of the knock-on mechanism, it is also necessary to take larger values of the parameter R.[14] This is connected with the fact that in the case when a theory similar to that of Butler is used in the analysis of knock-on reactions, R must be interpreted not as a nuclear radius, but as the distance between the center of gravity of the core of the nucleus (in this case the α particle contained in the Li^7) and the center of gravity of the knocked-on particle (in this case the triton) during the instant of collision. For light nuclei this distance may be much greater than the nuclear radius.

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