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(d, t) REACTIONS ON Li^6, Li^7, *AND* Be^9 *NUCLEI*

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The spectra of tritons emitted at various angles in the (d, t) reactions on Li^6, Li^7, and Be^9 have been studied for 20-Mev deuterons. The probability of formation of excited states in the final nucleus decreases sharply with increasing excitation energy. Angular distributions have been obtained for triton groups corresponding to the formation of Li^5 in the ground state, Li^6 in the ground and in the first two excited states, and Be^8 in the ground and in the first excited state. The angular distributions are in good agreement with those computed from the Butler formula for (d, t) reactions, but the radius increases with the level energy.

INTRODUCTION

DEUTERON reactions are widely used in nuclear spectrometry in connection with the possibility established by Butler[1] of determining characteristics of nuclear levels from the angular distributions of the reaction products. By now a large amount of data have been accumulated concerning the (d, p) and (d, n) stripping reactions.

The inverse pickup reactions — (p, d), (n, d), (d, t), etc., have been studied much less extensively, although they allow one to obtain the same kind of spectrometric data as do the stripping reactions. The few available experimental results[2,3] confirm the agreement of the angular distributions in pickup reactions with Butler's theory. However, with respect to the probability of excitation of various levels of the final nucleus, the pickup reactions must differ significantly from the stripping reactions. In a stripping reaction, the nucleon from the deuteron is captured with the greatest probability into a single particle level of the nucleus, whereas the probability of excitation of other levels associated with a readjustment of the nucleus itself is small. In pickup reactions from a target nucleus in the ground state, one of its nucleons is removed. If in this case the probability of readjustment of the remaining nucleus is also small, then one should expect that in pickup reactions the greatest probability corresponds to the excitation of hole levels whose structure is compatible with the ground state of the target nucleus.

Consequently, a study of pickup reactions might give rise to the possibility of picking out a specific class of nuclear levels which is different from that observed in stripping reactions, and it is from this point of view that such a study is apparently of greatest interest.

The experimental study of pickup reactions presents certain difficulties, since these reactions in the majority of cases have a negative value of Q, and the particles produced in these reactions have to be recorded in the presence of a strong background of high-energy primary particles. Therefore until now pickup reactions have not been studied sufficiently well. The available data refer only to one or two lowest states of the final nucleus.[2,3] The probability of excitation over a wide energy range has not been investigated.

The method of studying nuclear reactions accompanied by the formation of tritium which has been developed in our laboratory[4] enables us to investigate one type of pickup reactions — the (d, t) reaction — under conditions in which we are entirely free from the background of other particles. The study of the spectra and of the angular distributions of tritons at a deuteron energy of approximately 20 Mev enables us to investigate the probability of excitation of levels of final nuclei over a wide energy range from 0 to 15 or 20 Mev. In this paper we present the first results of such an investigation concerning the (d, t) reaction on Li^6, Li^7, and Be^9.

Deuterons were accelerated to an energy of 20 Mev by means of a cyclotron. The tritons produced in a thin target were caught by stacks of aluminum foil situated at a distance of 15 cm from the target at different angles in the range 7 — 150°. After irradiation tritium was extracted from the foils by means of heating and was introduced into a Geiger counter. A measurement of the tritium activity contained in each individual foil enabled us to determine the distribution of tritons with respect to range at different angles.

For the calculation of angular distributions we used Butler's formula modified by Newns[5] for the case of the (d, t) reactions. The triton form factor was taken from French's article:[6]

$$G^2(k) = 113/(1+2.4k^2)^2 \quad \text{for } k \leqslant 0.7.$$

In evaluating this factor, French utilized the triton wave function proposed by Irving.[7]

THE Li^7 (d, t) Li^6 REACTION

The target of 2.5 or 3 mg/cm^2 thickness was prepared from natural metallic lithium by sputtering onto a zapon film (~ 0.01 mg/cm^2). The transfer of the target from the sputtering apparatus into the apparatus where the irradiation occurred took place without interrupting the vacuum. In order to obtain the absolute value of the cross section we used a target of LiF sputtered onto an aluminum foil.

Figure 1 shows the triton spectrum obtained at an angle of 7°. Spectra obtained at other angles have approximately the same form. Three triton groups may be clearly seen corresponding to the formation of Li^6 in the ground and the first two excited states (2.19 and 3.58 Mev), and also a continuous triton spectrum. The levels with energies of 4.5 and 5.3 Mev are much less clearly pronounced. Since the shape of the continuous spectrum in this range of triton energies is not known, it is not possible to estimate in any reliable fashion the magnitude of the cross section for the formation of Li^6 in these states. No levels of Li^6 with a higher excitation energy were observed at any angle. The upper limit on the cross section for their formation is equal to 1.5 mbn/sterad at small angles.

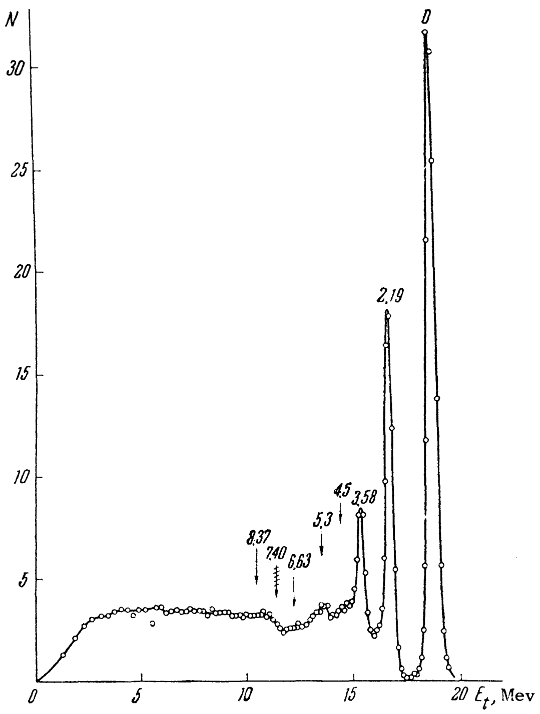

FIG. 1. The triton spectrum in the Li^7 (d, t) Li^6 reaction at an angle of 7°. Arrows indicate the known levels[8] of Li^6. The hatched arrow corresponds to a broad level.

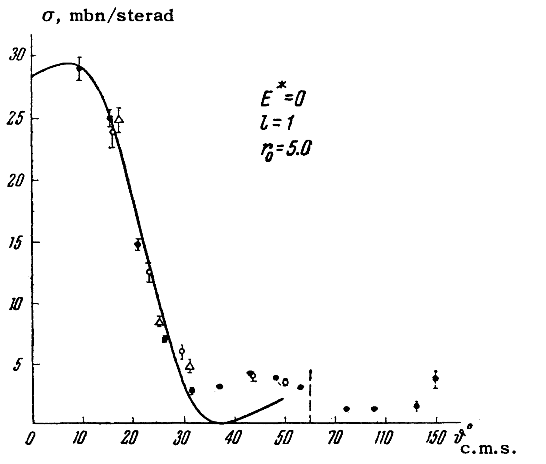

FIG. 2. The angular distribution of tritons in the Li^7 (d, t) Li^6 reaction with the formation of Li^6 in its ground state ($E^* = 0$; $l = 1$, $r_0 = 5.0$). Dots, circles, and triangles indicate results of different irradiations. The solid curve has been calculated on the basis of Butler's theory.

The observed continuous triton spectrum is formed, apparently, as a result of the decay of residual excited nuclei in the reactions

$$Li^7(d,n)Be^{8*} \to Li^5 + t \quad \text{or} \quad Li^7(d,d')Li^{7*} \to He^4 + t.$$

Figures 2 and 3 give angular distributions for three triton groups which agree well with those calculated on the basis of Butler's theory (solid curves). In all three cases the value of the angular momentum transferred is $l = 1$, which agrees

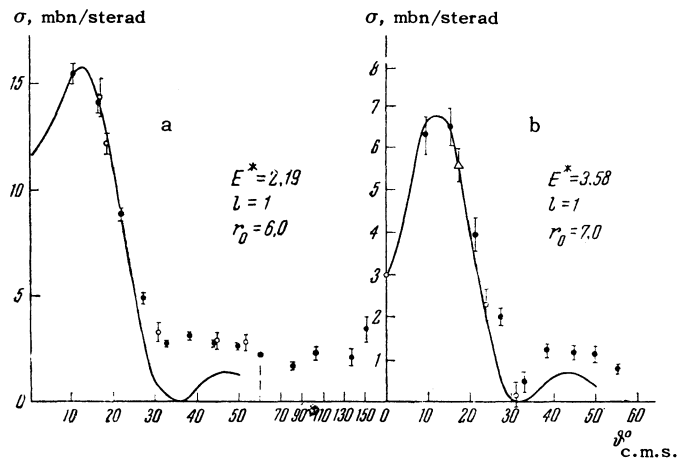

FIG. 3. Angular distributions of tritons in the Li^7 (d, t) Li^6 reaction with the formation of Li^6: a) in the first, b) in the second excited states. Dots, circles, and triangles indicate results of different irradiations. The solid curves have been calculated on the basis of Butler's theory.

Residual nucleus	Level energy, Mev	σ_{max} in c.m.s., mbn/sterad	$r_0 \times 10^{-13}$ cm	l	θ^2 from present work	θ^2 from other work
Li^5	0	52.3 (9.5°)	5.5	1	0.24	0.05[1]
Li^6	0	29.0 (9.5°)	5.0	1	0.11	0.11[2] 0.05[3]
	2.19	15.5 (10°)	6.0	1	0.061	0.061[2] 0.035[3]
	3.58	6.5 (16°)	7.0	1	0.083	0.055[4]
	5.3					0.017[4]
	other levels in interval 5.5—15 Mev	<1.5				
Be^8	0	17.9 (9.5°)	4.0	1	0.086	0.024[3]
	2.9	19.8 (9.5°)	5.0	1	0.082	
	4.2	~1 (15°)				
	4.9	~0.7 (15°)				
	5.3	~0.5 (15°)				
	6.0	~0.3 (9,5°)				
	other levels in interval 5.5—17 Mev	<0,1				
	17	~0.2 (18°)				

[1]From the reaction He^4 (d, p) He^5 at E_d = 14 Mev.[11]
[2]From the reaction Li^7 (d, t) Li^6 at E_d = 14.3 Mev.[3]
[3]From the reaction (p, d) at E_p = 18 Mev.[2]
[4]From the reaction Li^7 (d, He^3) He^6.[3]

with the well-known[8] level scheme for Li^6. The values of the radius r_0 adopted in calculating the curves, and also the values of the reduced widths obtained from the magnitude of the maximum cross section are given in the table.

THE Li^6 (d, t) Li^5 REACTION

The target was prepared in the form of a foil of 4 mg/cm^2 thickness from enriched metallic lithium (Li^6 content — 90%) by rolling in oil. Before being set up for irradiation the target was washed in CCl_4. The absolute value of the cross section was obtained on the basis of measurements with a target of natural LiF.

Figure 4 gives the triton spectrum obtained at an angle of 6.5°. One can clearly see the broad triton group which corresponds to the formation of the Li^5 nucleus in its ground state. The width of this level is equal to 1.3 ± 0.2 Mev. In the measured spectra one may also easily see two groups of tritons originating in the (d, t) reaction in the 10% admixture of Li^7 and corresponding to the formation of Li^6 in the ground and the first excited states. If the peak corresponding to the level of the Li^5 nucleus of energy ~ 2 Mev [the possibility of whose existence was indicated by our experiments[4] with the Li^7 (p, t) Li^5 reaction] does exist, then at all angles it is masked by the triton group corresponding to the ground state of Li^6.

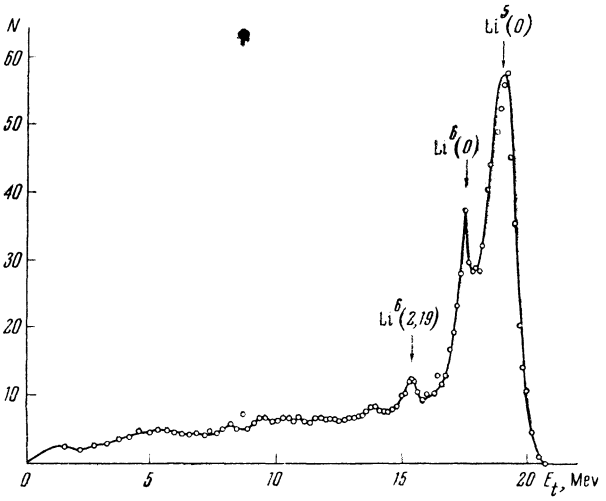

FIG. 4. The triton spectrum in the Li^6(d, t)Li^5 reaction at 6.5°.

The observed continuous triton spectrum may be formed in different ways, for example, as a result of the reaction

$$Li^6(d,\,p)\,Li^{7*} \rightarrow He^4 + t.$$

The angular distribution of the tritons from the Li^6 (d, t) Li^5 reaction with the formation of Li^5 in the ground state is shown in Fig. 5. The solid curve is calculated on the basis of Butler's theory with l = 1 and r_0 = 5.5.

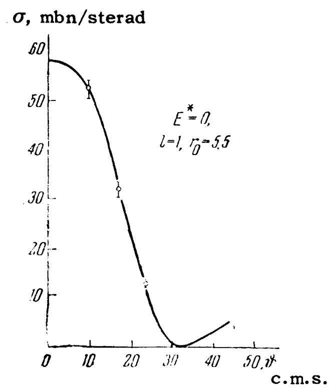

FIG. 5. The angular distribution of tritons in the Li^6(d,t) Li^5 reaction with the formation of Li^5 in the ground state. The solid curve was calculated on the basis of Butler's theory.

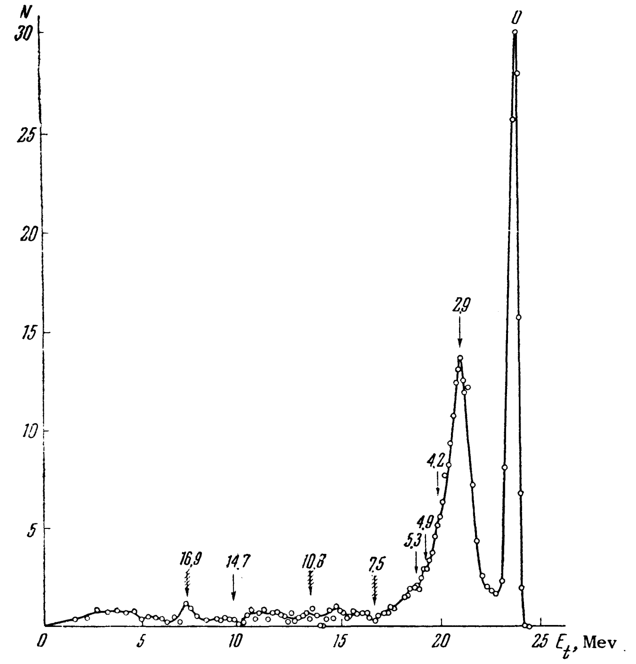

FIG. 6. The triton spectrum in the Be^9(d, t)Be^8 reaction at at 11.5°. Arrows show the known levels[8] of Be^8.

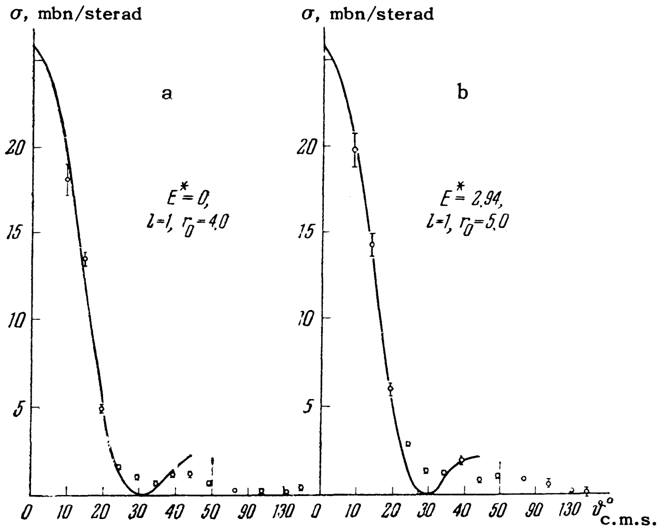

FIG. 7. Angular distributions of tritons in the Be^9(d, t)Be^8 reaction with the formation of Be^8: a) in the ground, b) in the first excited states. The solid curves were calculated on the basis of Butler's theory.

THE Be^9(d, t)Be^8 REACTION

A beryllium foil of 4-mg/cm² thickness prepared by means of electrolysis from molten BeF_2 salt[9] served as the target. In order to remove fluorine impurities the foil was heated in vacuo at a temperature of approximately 1000° C.

Figure 6 shows the triton spectrum obtained at an angle of 11.5°. The spectra obtained at other angles are of the same nature. Arrows show the positions of the Be^8 levels known from other work.[8] In addition to the ground state of Be^8, the 2.9-Mev level is also strongly excited. According to our measurements, the width of this level amounts to 1.35 ± 0.15 Mev. Possibily there is also an indication of levels of energies 4.2, 4.9, 5.4, and 6.0 Mev. The peaks which correspond to these values of excitation energy of Be^8 were observed at several angles; however they are of very low intensity. The high lying levels of Be^8, just as in the case of the Li^7(d, t)Li^6 reaction, are practically not observed. The only exception is the level which has an energy of approximately 17 Mev which is apparently excited by the removal of one of the strongly bound neutrons. This level is observed fairly clearly at several angles. It is of interest to note[10] that in the Be^9(p, d)Be^8 reaction at a proton energy of 95 Mev, the formation of Be^8 in this state occurs with a higher probability than in the ground and the first excited states.

Figure 7 shows angular distributions of tritons in the Be^9(d, t)Be^8 reaction for transitions to the ground and the first excited states of Be^8. In both cases the transferred orbital angular momentum is $l = 1$, which is in agreement with the known values of the spin and parity of the corresponding states of Be^9 and Be^8.

The observed continuous triton spectrum is formed apparently as a result of the reaction Be^9(d, α)$Li^{7*} \rightarrow He^4 + t$. The total cross section for the formation of the tritons in the continuous spectrum amounts to 50 mbn.

The principal results of this work are summarized in the table. The reduced widths θ^2 are given in dimensionless Wigner units ($\theta^2 = 3\mu n\gamma^2/2\hbar^2$). In the last column of the table we have given the reduced widths obtained in other papers for comparison.

The experimental error in the measurements of the absolute values of the cross sections in the present work amounts to ± 20%.

DISCUSSION OF RESULTS

The measured angular distributions of the monoenergetic triton groups agree satisfactorily with those calculated on the basis of Butler's theory which allows us, as in the case of stripping reactions, to determine the spins and the parities of the corresponding levels. This has already been demonstrated in previous work on (d, t) reactions.[3,5,12] All the characteristics of the Li^5, Li^6, Be^8 levels obtained by us agree with those known from other work.

However, it should be noted that the most suitable value of the radius r_0 (see table) increases monotonically as the level energy increases. The

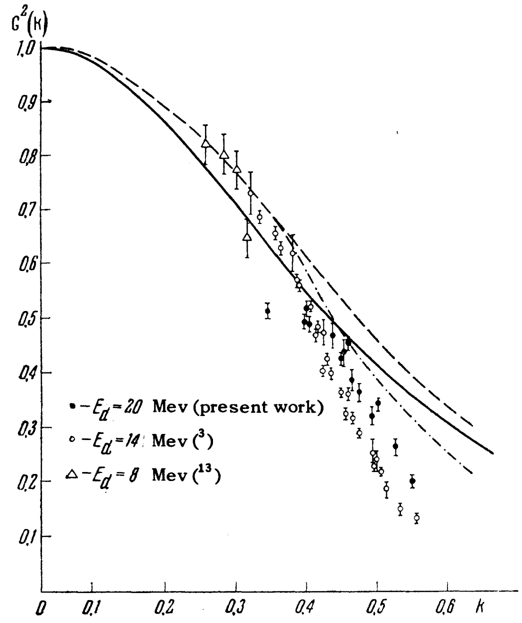

FIG. 8. Neutron momentum distribution in the triton obtained from the angular distributions of the tritons in the Li^7 (d, t) Li^6 reaction. The value of the nuclear radius was chosen equal to 5.5×10^{-13} cm. The curves represent the calculated momentum distributions with approximations being made to the triton wave-function: solid line – by means of the Irving function (French[6]); dotted line – by means of the Irving function (Newns[5]); dash-dotted line – by means of the Gauss function (Newns[5]).

same tendency of an increase in r_0 was observed in the (d, t) and (d, He^3) reactions on Li^7 at an energy of 14.4 Mev.[3] It is difficult to assume that the nuclear radius actually varies so strongly from level to level, particularly since this is not observed in the (d, p) and (p, d) reactions. It appears more natural to assume that the use of the simplest approximations for the triton wave function does not give the correct expression for the triton form factor.

Figure 8 shows the momentum distribution in the triton obtained from the angular distributions of the Li^7 (d, t) Li^6 reaction on the assumption that the nuclear radius r_0 has the same value in all the lower states and is equal to 5.5×10^{-13} cm. In addition to the data from the present work, we have also made use of the angular distribution of the tritons from the Li^7 (d, t) Li^6 reaction obtained at energies of $E_d = 14.4$ Mev,[3] and $E_d =$ 8 Mev.[13] The relative values of the form factor obtained from the angular distributions of the different groups were matched at the overlapping intervals. It can be seen from Fig. 8 that the triton form factor obtained in this fashion falls off at large values of neutron momentum considerably more rapidly than the form factor obtained from the Irving or the Gauss functions.

The determination of the triton form factor from the angular distributions in the Be^9 (d, t) Be^8 reaction does not give a clear result, since it is difficult to choose some one definite value for the interaction radius r_0 because of its dependence on the energy in the pickup reactions in Be^9.

As may be seen from the table, the reduced widths obtained from the (d, t) reactions are larger than those obtained from the (p, d) reactions in the same nuclei. The reduced width for the Li^6 (d, t) Li^5 reaction also turns out to be considerably larger than the reduced width for the definitely single-particle reaction He^4 (d, p) He^5. Apparently this also shows the necessity of obtaining a more accurate triton wave function.

The most significant feature of the measured triton spectra is the strong dependence of the intensity of the individual groups on the excitation energy of the corresponding levels of the residual nucleus. The probability of excitation is high only for the ground and for one or two lower excited states. The probability of excitation for higher lying states over the whole rather wide energy range that has been investigated turns out to be smaller by one or perhaps even by two orders of magnitude. The preliminary data obtained by us in the case of the F^{19} (d, t) F^{18} reaction also confirm this behavior.

Such a strong dependence cannot be explained by an increase in the transferred angular momentum l. Thus, for example, in the Be^9 (d, t) Be^8 reaction several of the higher lying levels of Be^8 could be excited by transferring the same angular momentum $l = 1$, as in the case of the lower levels, while the cross section for their excitation is less by a factor of more than 10. As is well-known, in stripping reactions the energy range for strongly excited levels is considerably wider. This confirms the hypothesis stated at the beginning of this paper on the essential difference between pickup reactions and stripping reactions with respect to the probability of excitation of different states of the final nucleus, and this has great significance for the classification of nuclear levels and for the investigation of their structure.

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