THE (d, t) REACTION IN C^{12}, F^{19}, *AND* Al^{27} *NUCLEI*

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The spectra and angular distributions of tritons produced at 20 Mev deuteron energies in the reactions $C^{12}(d, t)C^{11}$, $F^{19}(d, t)F^{18}$, and $Al^{27}(d, t)Al^{26}$ were measured on the basis of the β radioactivity of tritium. The spins and parities of a number of states of F^{18} and Al^{26} were derived by comparing the obtained triton angular distributions with those obtained from Butler's theory. The probability of excitation of levels of the residual nucleus drops sharply with increasing level energy.

THE investigation of (d, t) reactions in Li^6, Li^7, and Be^9, which was begun in the preceding work,[1] has disclosed a characteristic feature of this reaction — a strong decrease in the excitation probability with increasing level energy of the final nucleus. This feature is apparently connected with the fact that in pickup reactions, particularly in the (d, t) reaction, only the hole levels corresponding to the stripping of a neutron from the external shell of a target nucleus in the ground state have a high excitation probability. In (d, p) and (d, n) stripping reactions, as is known, the levels with the greatest excitation probability are the single-particle levels of the nucleon captured by the nucleus, and the spectral distribution of the emitted nucleons has an entirely different character.

In the present paper we report on an investigation of the (d, t) reaction in F^{19} and Al^{27}. It is natural to expect the spectrum of the excited levels to be more complicated even when only hole levels are excited, since a neutron can be extracted not only from the 2s and 1d outer shells, but also from the filled 1p shell.

The triton spectra were obtained on the basis of the β activity of the resultant tritium. The tritons emitted from the thin target were trapped in stacks of aluminum foils, arranged 15 cm away from the target at various angles, starting with 7°. After irradiation, the tritium was extracted from the foils by heating and was introduced into the Geiger counter. Measurement of the activity of the tritium contained in each individual foil has made it possible to determine the distribution of the tritons by ranges at various angles. To study the $F^{19}(d, t)F^{18}$ reaction we used a 2.97 mg/cm^2 MgF_2 target sputtered on an aluminum foil 0.4 mg/cm^2 thick, and also a teflon (CF_2) target 8.2 mg/cm^2 thick. The deuteron energy was 20 Mev. The $Al^{27}(d, t)Al^{26}$ reaction was investigated at a deuteron energy of 19 Mev. The target was made of aluminum foil 2.15 mg/cm^2 thick.

Figure 1 shows the triton spectrum, measured at an angle of 11°, due to deuteron bombardment of a MgF_2 target. The contribution from the (d, t) reaction on magnesium isotopes at triton energies greater than 9 Mev was negligibly small. The dotted line shows the contribution from the (d, t) reaction on an aluminum base. Analogous spectra, but with worse resolution, were obtained in the bombardment of the teflon target. Furthermore, these spectra show clearly a group of tritons from the $C^{12}(d, t)C^{11}$ reaction (ground state).

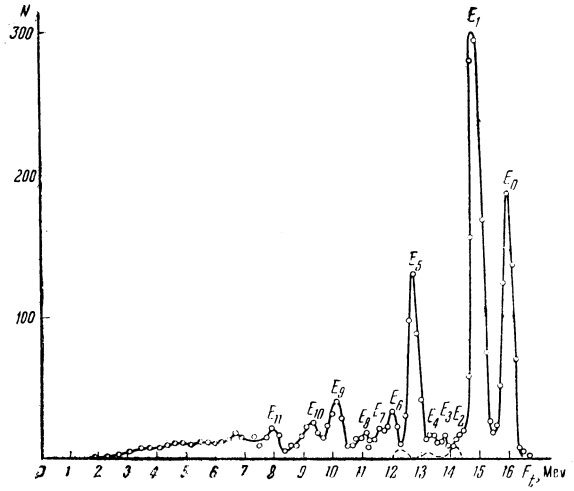

FIG. 1. Triton spectrum in the $F^{19}(d, t)F^{18}$ reaction at angle of 11°. The dotted line shows the contribution from the $Al^{27}(d, t)Al^{26}$ reaction.

The angular distributions of various groups of tritons formed in the $F^{19}(d, t)F^{18}$ reaction are shown in Fig. 2. The solid curves were calculated by the Butler theory[2] for the (d, t) reactions, and the triton form factor suggested by French[3] was

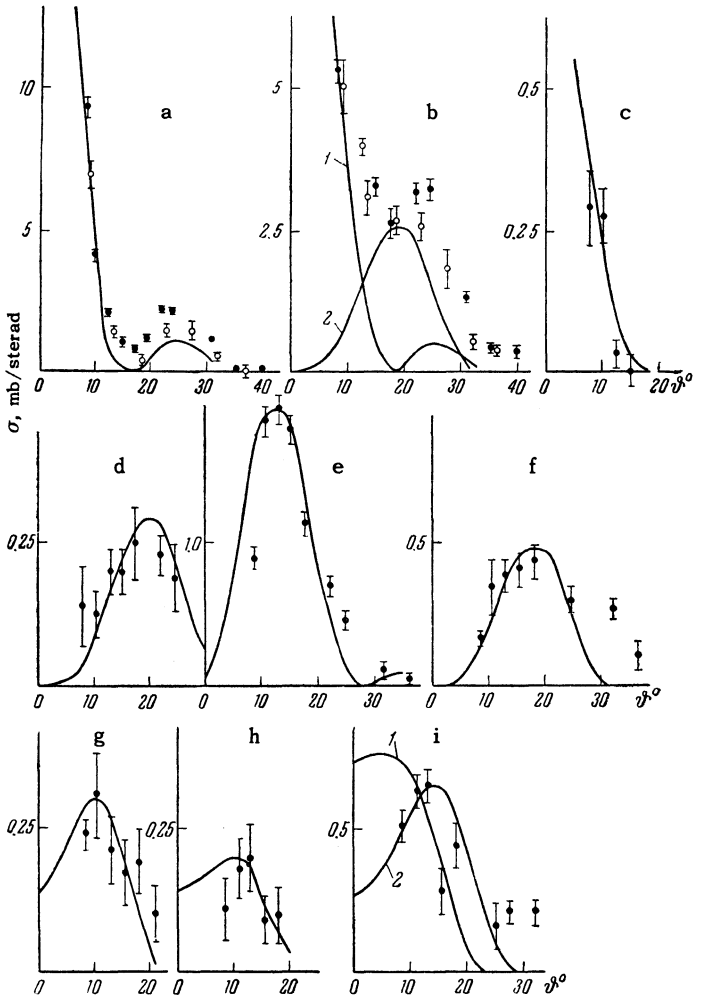

FIG. 2. Angular distributions of tritons in the $F^{19}(d, t)F^{18}$ reaction. The solid curves were calculated by Butler's theory, while the full and open circles denote the results of various types of irradiation (for groups E_0 and E_1). a) ground state, $l = 0$, $r_0 = 7.0$; b) 1.0 Mev, $l = 0$ (curve 1), $l = 2$ (curve 2), $r_0 = 7.0$; c) 1.8 Mev, $l = 0$, $r_0 = 7.0$; d) 2.6 Mev, $l = 2$, $r_0 = 7.0$; e) 3.3 Mev, $l = 1$, $r_0 = 7.0$; f) 3.9 Mev, $l = 2$, $r_0 = 8.0$; g) 4.4 Mev, $l = 1$, $r_0 = 8.0$; h) 5.0 Mev, $l = 1$, $r_0 = 8.0$; i) 5.9 Mev, $l = 1$, $r_0 = 8.0$ (curve 1), $l = 2$, $r_0 = 9.0$ (curve 2).

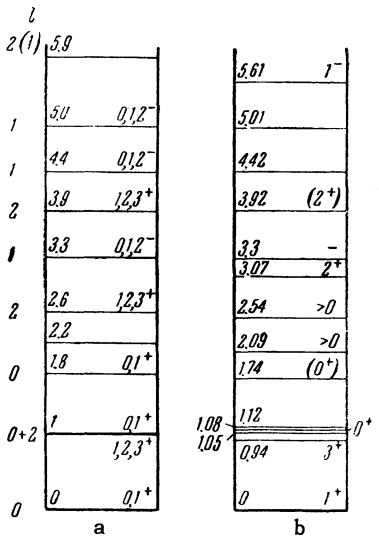

FIG. 3. Level scheme of F^{18}. a) from the (d, t) reaction, b) from the $O^{16}(He^3, p\gamma)F^{18}$, $Ne^{20}(d, \alpha)F^{18}$, $N^{14}(\alpha, \gamma)F^{18}$, and $F^{19}(p, d)F^{18}$ reactions.

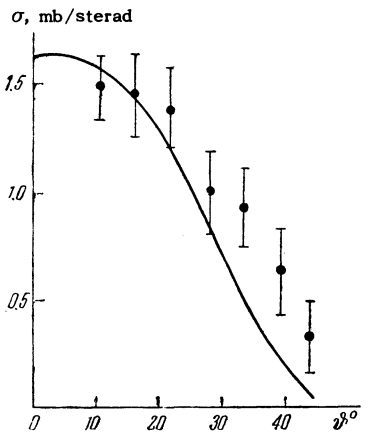

FIG. 4. Angular distribution of the tritons in the $C^{12}(d, t)C^{11}$ reaction with formation of C^{11} in the ground state ($l = 1$, $r_0 = 4.5$)

used. The parameters l and r_0 are indicated in the diagram. The angular distribution of group E_1 ($E^* = 1.0$ Mev) contains two components corresponding to $l = 0$ and $l = 2$. This is apparently connected with the fact that the E_1 group corresponds not to one but to several levels, known to be located near 1 Mev for F^{18} (reference 4). The presence of a component with $l = 1$ in the angular distribution of group E_1 is not completely excluded, but if it does exist, its intensity is several times smaller than the intensity of the components with $l = 0$ and $l = 2$.

The level scheme we obtained for F^{18} (Fig. 3) is in good agreement with the results of other experiments.[4-8] However, certain neighboring levels (for example, near 1 Mev) have not been resolved in our experiments. The values of the parities of levels 2.6, 4.4, and 5.0 Mev were determined here for the first time.

Figure 4 shows the angular distribution of the tritons from the $C^{12}(d, t)C^{11}$ reaction (ground state).

Figure 5 shows the triton spectrum of the $Al^{27}(d, t)Al^{26}$ reaction, measured at an angle of 7°. The level scheme of Al^{26}, which is known from other investigations,[9] is shown in Fig. 6 together with the transitions we observed. The angular distributions of the groups E_0, E_1, E_2, and E_8 are shown in Fig. 7. For groups E_4 and E_5 we were able to determine the values of l from the change in the form of the unresolved peak near 11 Mev.

The principal results of the work are listed in Table I. The reduced widths θ^2 are given in percentages of the single-particle width [$\theta^2 = 3\mu_n/2\hbar^2)\gamma^2 \times 100$, where μ_n is the reduced mass of the neutron, and γ^2 is the width in the usual units].

It is seen from the spectra and from Table I

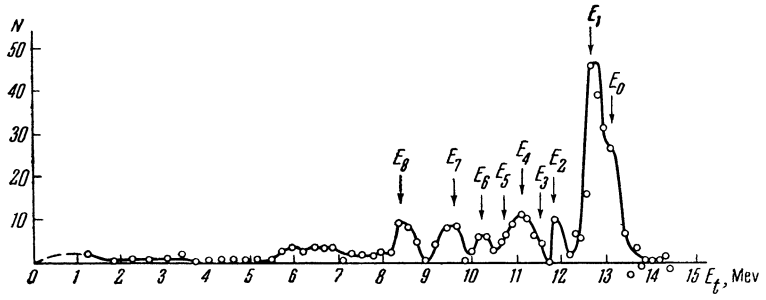

FIG. 5. Triton spectrum in the Al^{27} (d, t) Al^{26} reaction at an angle of 7°.

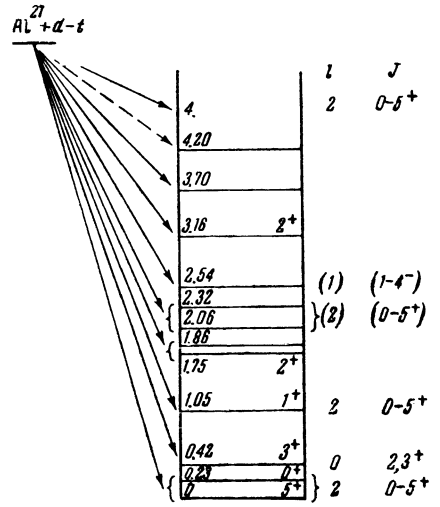

FIG. 6. Level scheme of Al^{26} (reference 9). The arrows indicate the transitions observed in the (d, t) reaction.

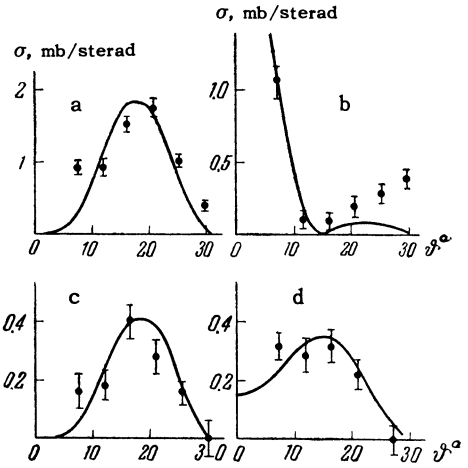

FIG. 7. Angular distributions of tritons in the Al^{27} (d, t) Al^{26} reaction. The solid curves have been calculated by the Butler theory. a) E_0, $l = 2$, $r_0 = 7.5$; b) E_1, $l = 0$, $r_0 = 8.0$; c) E_2, $l = 2$, $r_0 = 7.5$; d) E_8, $l = 2$, $r_0 = 8.0$.

TABLE I

Residual nucleus	Triton group	Excitation energy of the residual nucleus, Mev	l	$r_0 \cdot 10^{13}$, cm	$\sigma_{max}(\vartheta)$ in c.m.s., mb/sterad	θ^2, %	Error $\Delta(\theta^2)$, %
C^{12}	E_0	0	1	4.5	1.50 (11°)	1.3	±12
	E_1	1.85			<0.4 (11°)		
F^{18}	E_0	0	0	7.0	9.4 (8°)	1.5	± 4
	E_1	1.0	2	7.0	2.5 (20°)	1.6	±10
			0	7.0	5.0 (8°)	0.6	±10
	E_2	1.8	0	7.0	0.26 (10°)	0.05	±25
	E_3	2.2			0.15 (12°)		±50
	E_4	2.6	2	7.0	0.25 (17.5°)	0.2	±25
	E_5	3.3	1	7.0	1.95 (12.5°)	0.73	± 5
	E_6	3.9	2	8.0	0.44 (18°)	0.37	±10
	E_7	4.4	1	8.0	0.32 (10°)	0.1	±25
	E_8	5.0	1	8.0	0.20 (13°)	0.08	±30
	E_9	5.9	2(1)	9.0—8.0	0.65 (13°)	{0.4 (l=2) 0.3 (l=1)	±10
Remaining levels in the excitation energy interval 7–13 Mev					<0.1 (8—20°)		
Al^{26}	E_0	0÷0.23 *	2	—	1.7 (21°)	1.1	±10
	E_1	0.42 *	0	—	1.1 (7.5°)	0.11	±10
	E_2	1.1	2	—	0.40 (17°)	0.28	±15
	E_4	2.2	(2)	—	0.5 (15—23°)	0.35	±20
	E_5	2.6	(1)	—	0.5 (11°)	0.15	±20
	E_8	4.7	2	—	0.32 (16.5°)	0.23	±15
Remaining levels in the excitation energy interval 5–11 Mev					<0.05 (7—17°)		

*Indicated level energy from reference 9.

TABLE II

Final nucleus	$r_0 \cdot 10^{13}$, cm		Final nucleus	$r_0 \cdot 10^{13}$, cm	
	Reaction (p, d)	Reaction (d, t)		Reaction (p, d)	Reaction (d, t)
Li^5	4.5*	5.5	C^{13}	5.4****	5.0—5.9
Li^6	5.5	5.0—7.0	F^{18}	5.0	7.0—8.0
Be^8	3.0	4.0—5.0	Na^{22}		6.5—7.0
C^{11}	4.?**	4.5	Al^{26}	5.0	7.5—9.0
C^{12}	4.0***	6.5			

*For He^5 from the Li^6(n, d)He^5 reaction (reference 15).
**For B^{11} from the (d, p) reaction.
***From the (d, p) reaction.
****For N^{13}.

that in the (d, t) reactions in F^{19} and Al^{27}, as in the reactions on Li^7 and Be^9, a strong decrease is observed in the probability of excitation of the levels of the residual nuclei with increasing level energy. Levels with energies 3 — 4 Mev correspond to reduced widths that are 3 — 10 times smaller than those corresponding to the ground state. If levels with energies above 5 — 7 Mev are excited at all, their probability is $1/20$th or $1/30$th that of the ground state. This confirms the hypothesis that in the (d, t) reactions it is the hole levels that are predominantly excited, corresponding to the stripping of the outer nucleon.

The lower levels F^{18} are excited with approximately equal probability as a result of the stripping of a neutron with orbital momentum 0 and 2 from the F^{19}. This denotes that the s and d states of outer nucleons of F^{19} are greatly mixed.

The 3.3-Mev level, the parity of which is negative, is excited with a relatively greater probability. Apparently this level is excited by stripping of a neutron from the p shell. It is interesting to note that the neighboring nucleus, O^{17}, also has a first level with negative parity at an energy of approximately 3 Mev, the excitation probability of which is small in the O^{16}(d, p)O^{17} reaction,[10] as is to be expected for a hole level.

The investigation of the Al^{27}(d, t)Al^{26} reaction did not make it possible to refine greatly the level scheme of Al^{26}, owing to insufficient resolution. There is no doubt however that the stripping of the neutron with $l = 2$ is one order of magnitude more probable than that with $l = 0$. Consequently, the outer neutrons of Al^{27} are predominantly in the d state, and the admixture of s state is small.

In the investigation of the (d, t) reaction in Li^7 and Be^9 we noted[1] a systematic increase in the most suitable value of r_0 with a decreasing energy of the corresponding level, indicating an inaccuracy in the simplest expressions for the triton form factor. The tendency of increasing r_0 with increasing level energy is observed also for the reaction F^{19}(d, t)F^{18}. The absolute values of r_0, obtained from the reactions (d, t) in our investigations and in others,[11-13] are found to be as a rule greater than those from (p, d)[14] and (d, p) reactions (Table II). This discrepancy can also naturally be ascribed to the inaccuracy in the triton form factor employed.

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