SOVIET PHYSICS

JETP

A translation of Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki.

Vol. 13, No. 5, pp 871-1080 (Russ. orig. Vol. 40, No. 5, pp 1237-1535, May 1961) November, 1961

NEUTRON YIELD OF THE REACTION BETWEEN TRITONS AND FLUORINE AND ALUMINUM NUCLEI

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Submitted to JETP editor July 22, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **40**, 1237-1243 (May, 1961)

The neutron yields from the $F^{19}(t,n)$ and $Al^{27}(t,n)$ reactions were studied for triton energies up to 2.4 Mev. The dependence on triton energy of the differential cross section for neutron emission at an angle of 0° was derived. Resonance of the differential cross section for the $F^{19}(t,n)$ reaction was used to determine excited levels of the intermediate nucleus Ne^{22} (Table 1). The symmetrical neutron distribution around 90° in the c.m.s. at five triton energies indicates that up to 2.1 Mev the $F^{19}(t,n)$ reaction proceeds mainly via formation of an intermediate nucleus. The total cross section for the $F^{19}(t,n)$ reaction was determined for several energies (Table II).

1. INTRODUCTION

NUCLEAR physics has obtained much valuable information by investigating the reactions of light nuclei with bombarding protons and deuterons. Reactions with tritium can undoubtedly be just as fruitful. However, the difficulty of producing tritium and certain special conditions for working with it can account for the fact that relatively few investigations have been published[1-10] concerning reactions between tritons and light nuclei.

The nucleus investigated in the present work was F^{19}. Since the solid target consisted of AlF_3 the neutron yield from the reaction $Al^{27}(t,n)$ also had to be investigated.

Neutron-producing reactions between tritons and light nuclei are characterized by the positive reaction energy Q and the appreciable excitation energy of intermediate nuclei. The following reactions of tritons with fluorine and aluminum are possible:

$$F^{19} + H^3 \to Ne^{22} \to Ne^{21} + n, \quad Q = 11.145 \text{ Mev}, \quad (1)$$

$$F^{19} + H^3 \to Ne^{22} \to Ne^{20} + 2n, \quad Q = 4.388 \text{ Mev}; \quad (1a)$$

$$Al^{27} + H^3 \to Si^{30} \to Si^{29} + n, \quad Q = 11.578 \text{ Mev}, \quad (2)$$

$$Al^{27} + H^3 \to Si^{30} \to Si^{28} + 2n, \quad Q = 3.104 \text{ Mev}. \quad (2a)$$

The minimum excitation energies of the intermediate nuclei Ne^{22} and Si^{30} are 21.510 and 22.188 Mev, respectively.[11] The present work was intended to study the neutron yields from the $F^{19}(t,n)$ and $Al^{27}(t,n)$ reactions and the excited levels of the intermediate nuclei.

2. EXPERIMENTAL PROCEDURE

The targets were prepared by evaporating aluminum fluoride on platinum disks and were weighed on a microbalance. The weights of the AlF_3 targets were 0.179, 0.200, 0.211, and 0.280 mg/cm^2. For 1.4-Mev tritons these thicknesses corresponded to energy losses of 60, 67, 70, and 92 kev, respectively. The Al^{27} target was 0.67-mg/cm^2 alumi-

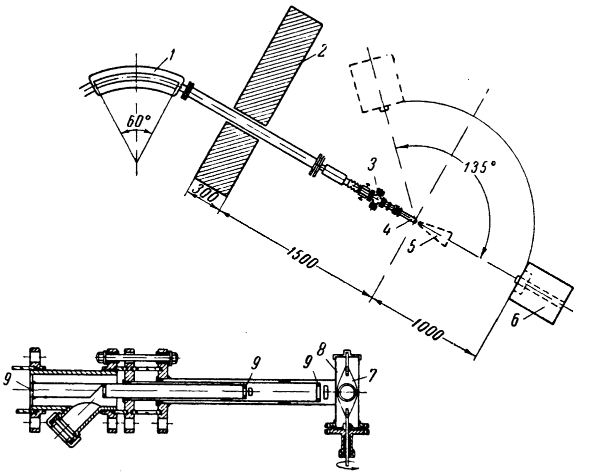

FIG. 1. Diagram of apparatus. 1 – magnetic analyzer, 2 – paraffin-borax shield, 3 – closure, 4 – target, 5 – 30-cm copper cone, 6 – neutron counter, 7 – target holder, 8 – T tube 0.2 mm thick, 9 – collimator diaphragms.

num foil in which 1.8-Mev tritons lost 170 kev. Target weights were checked by the relative neutron yield per unit weight.

Tritons were accelerated in the horizontal electrostatic generator at a pressure permitting energies up to 2.5 Mev. The generator voltage was stabilized by a corona triode. Stabilization was monitored by 60° ion-beam deflection in the magnetic analyzer. The generator voltage was measured from the current supplied to the magnetic analyzer. The voltage was calibrated from the thresholds of the T(p, n) and Li(p, n) reactions on ions of atomic and molecular hydrogen, with errors not above 0.5%.

Tritium diluted with helium in the ratio 1 : 12 was fed into the ion source through a bimetallic leak. The intensity ratio of the beams with masses 1 (H^+), 2 (HH^+, D^+), 3 (T^+), 4 (He^+), and 6 (TT^+) was 0.1 : 0.2 : 1 : 110 : 10. Since tritium and He^4 were admitted to the ion source, with hydrogen, deuterium, and He^3 comprising only a small amount of contamination, it was assumed that the beams with masses 3 and 6 were practically uncontaminated. The purity of these beams was confirmed by comparing the neutron yields in the Li(t, n) reaction using tritons with 0.5 Mev effective energy. In the neutron yield measurements the mean beam current for mass 3 was ~ 0.2 μa.

The number of tritons striking the target was determined by means of a sensitive current integrator giving 40.19 counts per microcoulomb.

The apparatus is represented schematically in Fig. 1. The target 4 was positioned in the beam path in a special holder 7. The beam was collimated by diaphragms 9 with 6 mm × 3 mm apertures. A light T tube 8 with 0.2-mm wall thickness was highly transparent to neutrons leaving the target in all directions. The target was rotated 180° by remote control employing selsyns. The triton beam could therefore be directed against either the front or back of the target.

The neutron flux was measured by a long proportional boron counter 6 rotated on a circle of one-meter radius around a vertical axis passing through the center of the target. The neutron counter was calibrated against a standard Ra + Be neutron source yielding 4.8×10^5 neutrons/sec, that was substituted for the target.* Counter efficiency was 1.008×10^4 neutrons/sr per count. The sensitivity of the neutron counter[12] was within ± 3% for neutrons from 25 kev to 5 Mev and dropped 11% for 14-Mev neutrons.

Background neutrons were taken into account in measurements of the neutron yield from the target. The diaphragms located before the magnetic analyzer 1 and the walls of the analyzer were strong sources of background neutrons generated in "spurious targets." In order to prevent direct entrance of these neutrons into the neutron counter a 30-cm shield 2 made of paraffin with an admixture of borax was set up at the exit of the triton beam from the magnetic analyzer. Under the given experimental conditions (Fig. 1) the neutron background consisted of a) neutrons generated in the "spurious targets" and collimator diaphragms, b) neutrons from the T(t, n) and C(t, n) reactions occurring in tritium impacted into the target by the beam, and in carbon deposited in small amounts on the target during bombardment by accelerated ions, and c) neutrons from all targets, scattered by the surroundings (floor, walls, ceiling etc.).

3. MEASUREMENTS

For the purpose of taking the background neutrons into account while measuring the neutron yield from the F^{19}(t, n) and Al^{27}(t, n) reactions, four measurements were obtained. In the first and second measurements the ion beam struck the face of the target without and with the presence of the cone 5; the third and fourth measurements were analogous for the back of the target. Each measurement corresponded to the same number of counts from the current integrator, the number depending on the neutron yield from the given target. From the four measurements obtained in this

*The background of neutrons scattered by the surrounding medium was 8% when the neutron counter was calibrated. For background measurements the counter was covered with a copper cone 30 cm high.

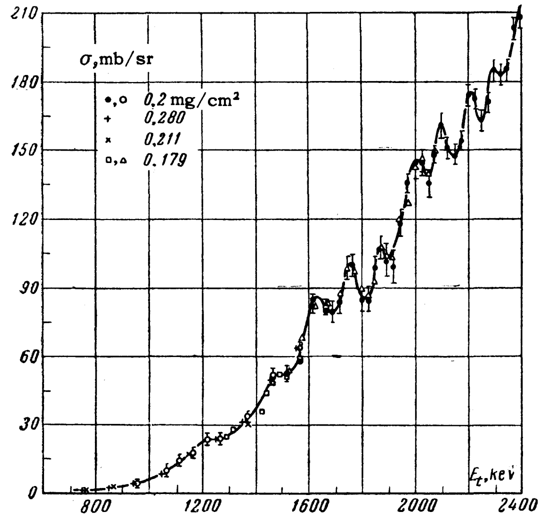

FIG. 2. Differential cross sections for neutron yield at 0° angle from triton reactions with aluminum fluoride targets of different thicknesses. E_t is triton energy.

manner the number of counts of the neutron counter induced by neutrons from the investigated reaction can be expressed by

$$N = N_1 - N_2 - N_3 + N_4 (t_2 + t_3 - t_1)/t_4, \qquad (3)$$

where t_1, t_2, t_3, t_4 are the respective times of the four measurements. Consideration of the measurement times is associated with the fact that the neutron background from the diaphragms and magnetic analyzer walls was essentially a function of time, since the current of the undivided beam did not vary with time, while the background of all other neutrons was a function of the triton beam intensity. The total neutron background was easily estimated by analyzing the four measurements with identical times.

With increasing triton acceleration the total background was observed to increase, reaching 30 – 40%. The difference between the third and fourth measurements, amounting to 6 – 10%, indicated the background due to neutrons from the T(t, n) and C(t, n) reactions. Because of the smallness of this quantity we neglected the neutron background from these reactions that was scattered by the surroundings. Periodic purification of the diaphragms in front of the magnetic analyzer reduced the total neutron background considerably.

4. RESULTS

The reaction of a triton with a fluorine or aluminum nucleus can produce a single neutron [Eqs. (1) and (2)] or two neutrons [Eqs. (1a) and (2a)]. Our technique did not distinguish between these reactions but determined only the total cross section $\sigma(t, n) + \sigma(t, 2n)$. This total cross section will hereafter be understood when we refer to neutron yields.

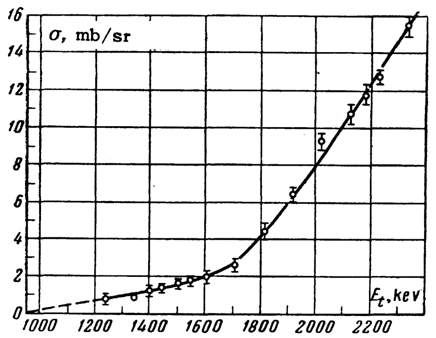

FIG. 3. Differential cross section for neutron yield from $Al^{27}(t, n)$.

Figures 2 and 3 show the differential cross sections for neutron production at 0° in interactions of tritons with aluminum fluoride and aluminum, as a function of triton energy. From these data we obtained the differential cross section at 0° for $F^{19}(t, n)$ vs triton energy, which is shown in Fig. 4.

From the resonances observed on the excitation curve of $F^{19}(t, n)$ the excited levels of Ne^{22} above 22.510 Mev were determined; these are given in Table I. Only two levels, 22.7 and 23.1 Mev, were previously[9] discovered in this excitation region of Ne^{22} from the excitation function of $F^{19}(t, \alpha)$. The 23.1-Mev level agrees with 23.128 Mev within the limits of error.

The angular distribution of neutrons from the AlF_3 target gave the angular distribution for the reaction $F^{19}(t, n)$ (Fig. 5).

Since the neutron yield from $Al^{27}(t, n)$ comprises 6 – 8% of the yield from the AlF_3 target, a correction for neutrons from $Al^{27}(t, n)$ introduced no appreciable error if the angular distributions of neutrons in the $Al^{27}(t, n)$ and $F^{19}(t, n)$ reactions were similar.

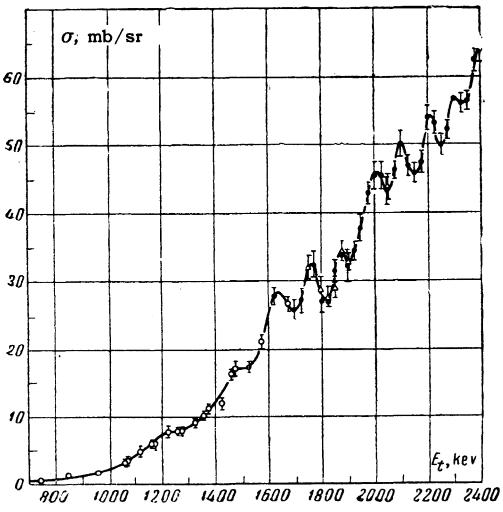

FIG. 4. Differential cross section for neutron yield at 0° angle from F^{19} (t, n) vs triton energy.

Table I. Levels of compound nucleus Ne^{22}*

No.	E_t, Mev	Energy level, Mev	Level width, kev
1	1.215	22.558±0.018	300
2	1.470	22.778±0.018	150
3	1,635	22,921±0,019	100
4	1.760	23.029±0.020	100
5	1.875	23.128±0.020	80
6	2.010	23.245±0.021	130
7	2.100	23.322±0.021	90
8	2.210	23.419±0.022	70
9	2.300	23.495±0.022	50

Table II. Total cross section for $F^{19}(t, n)$

E_t, Mev	σ_{tot}, mb
1,066	36.11±2.13
1.218	77.08±4.24
1.370	95,92±4.80
1,572	203,46±9.56
2.123	442,50±20.35

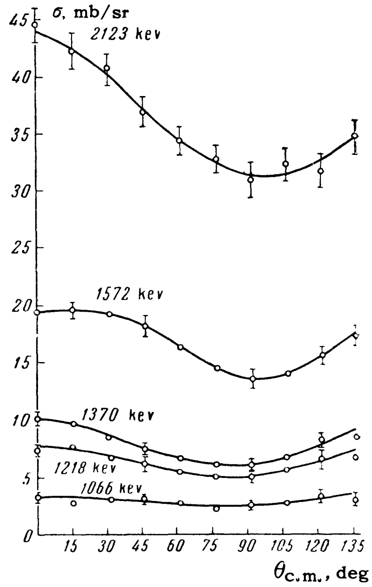

FIG. 5. Angular distributions of neutrons from $F^{19}(t, n)$ for different triton energies.

The angular distributions of neutrons are symmetrical around 90° in the c.m. system. This shows that the $F^{19}(t, n)$ reaction mainly involves the formation of a compound Ne^{22} nucleus. Table II shows the total cross sections for $F^{19}(t, n)$ calculated from the angular distributions assuming symmetry around 90°.

In calculating the absolute errors of the neutron yields we assumed ±3% error in determining the number of nuclei in AlF_3, ±1% for the number of Al nuclei, and ±1% for the number of tritons. The strength of the constant Ra + Be source was known to within ±3%.

Weisskopf's statistical formula[13] can be used to obtain a very rough estimate of the two-neutron contribution to the total cross section. We have

$$\sigma(t, 2n)/[\sigma(t, n) + \sigma(t, 2n)] \approx 1 - (1 + \varepsilon/T)\, e^{-\varepsilon/T}, \quad (4)$$

where $\epsilon = E_{max} - E_n$ is the maximum energy of the second neutron (E_{max} is the maximum excitation energy of the residual nucleus following ejection of the first neutron, and E_n is the neutron binding energy in the residual nucleus), T is the temperature of the residual nucleus determined from $T = \sqrt{4E_{max}/a}$, and a is a constant depending on the atomic weight A.

Heidmann and Bethe[14] give $a = 0.14\,(A - 12)$ Mev^{-1} for mass numbers $15 < A < 70$. Therefore for the excitation energy of Ne^{21} (E_{max} = 13.15 Mev, a = 1.26 Mev^{-1}) and Si^{29} (E_{max} = 13.6 Mev, a = 2.38 Mev^{-1}) the temperatures will be of the orders 6.5 and 4.8 Mev, respectively. With increasing excitation energy the ratio in Eq. (4) can increase approximately from 0.14 to 0.26 for $F^{19}(t, n)$, and from 0.14 to 0.3 for $Al^{27}(t, n)$.

On the other hand, using the experimental temperatures obtained by Gugelot and by Graves and Rosen[15] we obtain T ≈ 1.3 Mev for Ne^{21} and T ≈ 1.2 Mev for Si^{29}. In this case the ratio (4) can increase from 0.86 to 0.96 for $F^{19}(t, n)$, and from 0.73 to 0.93 for $Al^{27}(t, n)$.

The foregoing results show that reactions producing two neutrons make a considerable, if not the principal, contribution to the neutron yield from reactions of tritons with F^{19} and Al^{27}.

It must be emphasized, however, that we have obtained only very approximate cross section ratios.

In conclusion the authors wish to thank M. T. Dorofeev, and also the electrostatic generator group, for experimental assistance. The members of the group were V. I. Petran', I. G. Losev, Yu. K. Panteleev, V. M. Khurgin, N. S. Zlishchev, V. I. Krivoruchko, and G. E. Klitsenko.

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Translated by I. Emin
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