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(n,t) Cross Sections for B^{10}, B^{11}, and Be^9†

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A measurement of the (n,t) cross sections for Be^9, B^{10}, and B^{11} is described. The tritium yield was determined by absolute counting of the beta activity. Neutron fluxes were measured by standard techniques. The following values were obtained for the (n,t) cross sections at the indicated neutron energies: Be^9 at 14.1 Mev, 18±1.5 mb; B^{10} at 4 Mev, 95±10 mb; B^{10} at 5.6 Mev, 230±25 mb; B^{10} at 9.6 Mev, 125±15 mb; B^{10} at 14.1 Mev, 85±6 mb; B^{10} for fission spectrum, 30±2 mb; B^{11} at 14.1 Mev, 15±5 mb.

INTRODUCTION

One way of determining the cross section for (n,t) reactions is to measure the tritium activity produced by a known number of neutrons. Since the half-life for the beta decay of tritium is 12.262±0.004 years,[1] 10^9 tritons are needed to produce about two counts per second. The end-point energy of the tritium beta is 18.0 kev,[2] requiring that it be detected inside a counting system.

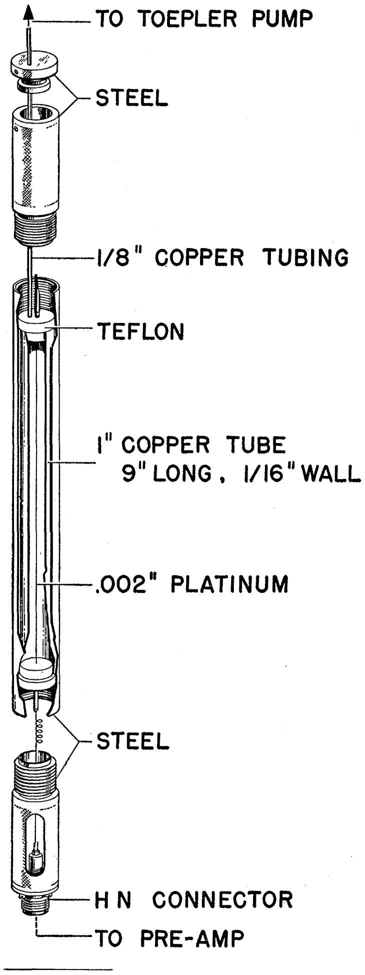

Fig. 1. Teflon-ended counter for counting the tritium beta activity.

EXPERIMENTAL TECHNIQUES

A low-background system was built using an ethane proportional counter. Figure 1 is a schematic sketch of this counter. By the use of Teflon plugs on the ends of a copper tube 9 in. long and 1 in. o.d., counting losses in the end regions were minimized. The center wire (0.002-in. platinum wire) was threaded through the $\frac{1}{8}$-in. copper tubes held in the Teflon plugs and crimped. The steel ends were screwed down tight against the Teflon plugs, producing a vacuum seal for the counter. The platinum and copper materials were chosen because they have lower solution rates for hydrogen than most structural materials. Hence, the increase in counter background due to internal contamination could be reduced to a minimum. The counter had a volume of 80 cm^3 and was filled with ethane to a pressure of 20-cm Hg. The counter proved to be about 95% efficient by comparison with a counter that had a known efficiency.[3,4]

An anticoincidence counter surrounded the tritium counter and was built as an annular ring containing ten 0.003-in. Kovar wires. The counter and anticoincidence counter were placed in a 3-in. thick steel sleeve and then surrounded by 2 tons of lead, as shown in Fig. 2.

The signals from each of these two counters were fed into amplifiers which had been modified to accept pulses thirty times greater than normal saturation without blocking. The amplifier gains were set at about 10^4. By feeding the outputs of these amplifiers into the anticoincidence circuit with the discriminators set at about 4 volts, it was possible to get voltage plateaus for each counter with less than 1% change in 100 volts at 2000 volts. The plateau characteristics were not altered by the addition of hydrogen up to 25% of the

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[1] W. M. Jones, Phys. Rev. **100**, 124 (1955).

[2] L. M. Langer and R. J. D. Moffat, Phys. Rev. **88**, 689 (1952).

[3] Engelkemier, Hamill, Inghram, and Libby, Phys. Rev. **75**, 1825 (1949).

[4] A. G. Engelkemier and W. F. Libby, Rev. Sci. Instr. **21**, 550 (1950).

counter filling. The tritium counter had a background counting rate of about 55 counts/min but when used with the anticoincidence circuit, the rate was reduced to about 2.5 counts/min.

The materials used for samples were heated in a vacuum to remove all traces of tritium. These materials were loaded into copper capsules in a dried helium atmosphere and sealed by soldering.

The samples were irradiated in monoenergetic neutron fluxes supplied by the Cockcroft-Walton accelerator, the P-9 Van de Graaff accelerator, and the P-3 Van de Graaff accelerator, all at the Los Alamos Scientific Laboratory. The Van de Graaff fluxes were determined by counter telescope techniques.[5] The Cockcroft-Walton *d*-T neutron flux was measured by detecting the associated α particle in the neutron-producing reaction. A few small B^{10} samples were irradiated in a fast-fission neutron flux created by a U^{235} radiator in the thermal column of the LASL Water Boiler reactor, the flux being determined by measuring the fission yield of some U^{235} monitor foils.

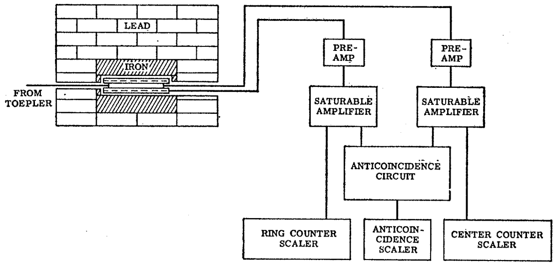

FIG. 2. The shield and anticoincidence circuit.

ANALYSIS

The irradiated samples were placed in a quartz firing tube and connected to a vacuum circuit (Fig. 3). The air was pumped out and the sample heated inductively (breaking the solder seal). The evolved gases were collected in a Toepler pump and added to the ethane of the counter. Succeeding additions of the evolved gases to the counter with the Toepler pump caused the measured activity to increase and reach a limiting value, indicating that all the tritium had been evolved. A small amount of hydrogen was added to the system before the evolution to act as a carrier. This prevented any loss of tritium in the transfer.

In order to identify the activity as that due to tritium, the tritium and carrier were passed through a palladium window. The counter filling including the evolved tritium was transferred by the hand Toepler pump to the automatic Toepler pump loop. A liquid-nitrogen trap condensed the ethane, leaving the tritium (and hydrogen carrier) to pass through the heated palladium (500°C). The counter was refilled with new ethane and the gases which had passed through the palladium were added to the counter. Normally all the original activity could be removed in 1 to 2 hr. If some of the tritium was collected as water vapor, it condensed in the liquid-nitrogen trap. When this trap was replaced with a dry-ice trap, the water vapor was held but the ethane released. Permitting the remaining water vapor to pass over uranium at 900°C released the hydrogen and tritium. These gases could be passed through the heated palladium and added to the counter to check for the remaining activity. No unknown activities were found and each sample was verified to better than 98%.

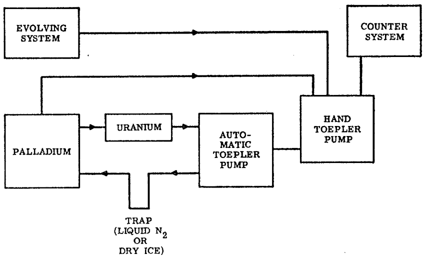

FIG. 3. The analysis system.

RESULTS

$B^{10}+n \rightarrow H^3+2\ He^4+0.23$ Mev

Two 1-gram samples of enriched B^{10} (95.5%) were irradiated by 4.0-Mev neutrons from the *d*-D reaction at the P-3 Van de Graaff. A flux of 2.5×10^{11} neutrons/cm^2 produced a tritium activity of about 135 counts/min in the samples. The $B^{10}(n,t)$ cross section was measured as 95±10 mb. The two samples gave results which differed by 7%.

Three 1-gram samples of B^{10} were irradiated by 5.6-Mev neutrons from the *p*-T reaction at the P-9 Van de Graaff. A flux of 1.8×10^{11} neutrons/cm^2 produced about 240 counts/min in the samples, yielding an (n,t) cross section of 230±25 mb. The three samples showed a variation of 10%.

Two 1-gram samples were irradiated by 9.6-Mev neutrons from the *d*-D reaction at the P-9 Van de Graaff. A flux of 2.4×10^{11} neutrons/cm^2 produced about 165 counts/min in the samples, yielding an (n,t) cross section of 125±15 mb. The two samples gave results which differed by 8%.

Nine 1-gram samples were irradiated by 14.1-Mev neutrons from the *d*-T reaction at the P-4 Cockcroft-Walton accelerator. A flux of 1.8×10^{12} neutrons/cm^2 produced about 830 counts/min in the samples, yielding an (n,t) cross section of 85±6 mb. The samples gave results which had an over-all spread of 15% but had an average deviation of 5%.

Five samples of B^{10} (0.15 g) were irradiated in a flux of fission-spectrum neutrons in a U^{235} radiator located in the Water Boiler reactor. U^{235} foils were placed on either side of the samples and the total

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[5] Bame, Haddad, Perry, and Smith, Rev. Sci. Instr. **28**, 997 (1957).

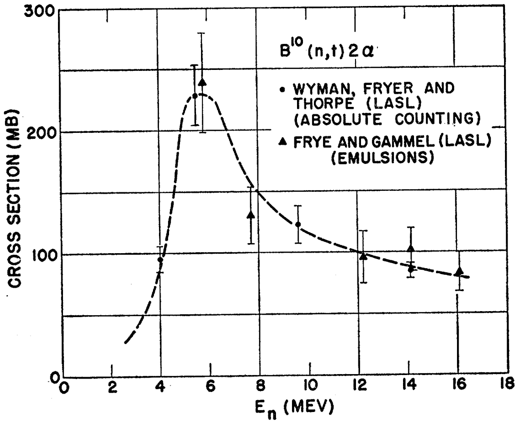

FIG. 4. A plot of the $B^{10}(n,t)2\alpha$ reaction cross section as measured by absolute counting and emulsion techniques.

fissions determined by LASL radiochemists. The flux was determined by using the fission cross section for U^{238} in a fission-neutron spectrum[6] and the ratio of U^{235} to U^{238} fission cross sections as measured in the radiator. The samples produced activities of about 1000 counts/min. The average (n,t) cross section was 30±2 mb. The total spread in the five results was 10%, with an average deviation of 2%.

$B^{11}+n \rightarrow H^3+Be^9-9.55$ Mev

A 0.264-gram sample of normal boron was irradiated by 14.1-Mev neutrons at the P-4 Cockcroft-Walton accelerator. A flux of 7.28×10^{12} neutrons/cm^2 gave a tritium activity of 340 counts/min in the sample. A 1-g sample of normal boron was exposed to a flux of 1.06×10^{12} neutrons/cm^2 of the same energy neutrons. It showed a tritium activity of 200 counts/min. From the value of 85 mb for the $B^{10}(n,t)$ cross section, these two samples would predict an (n,t) cross section for B^{11} of 15±5 mb. The error in this case is an estimate.

$Be^9+n \rightarrow H^3+Li^7-10.4$ Mev

Six 1-gram samples of Be^9 were irradiated by 14.1-Mev neutrons from the d-T reaction at the P-4 Cockcroft-Walton accelerator. A flux of 1.8×10^{12} neutrons/cm^2 produced about 210 counts/min tritium activity. The average value for the (n,t) cross section was 18±1.5 mb, with a spread of 20% and an average deviation of 7%.

These results are listed in Table I.

TABLE I. The (n,t) cross sections for B^{10}, B^{11}, and Be^9.

Kind of sample	No. of samples analyzed	Neutron energy (Mev)	Typical activity (counts/min)	$\sigma(n,t)$ (mb)
B^{10}	2	4.0±0.2	135	95±10
B^{10}	3	5.6±0.05	240	230±25
B^{10}	2	9.6±0.15	165	125±15
B^{10}	9	14.1±0.1	830	85±6
B^{10}	5	fission spectrum	1000	30±2
B^{11}	2	14.1±0.1	200	15±5
Be^9	6	14.1±0.1	210	18±1.5

RELIABILITY

The neutron flux at 4 Mev had a reliability of ±10%, at 5.6 Mev, ±7%, at 8 Mev, ±8%, at 9.6 Mev, ±7%, and at 14.1 Mev, ±4%. A measure of the other uncertainties was the spread of the results from the individual samples. In general, the evolution system and the counting system seemed to have reliabilities of ±5%.

The B^{11} measurement has a greater uncertainty since it was determined by two subtractions (background and the B^{10} activity).

INTERPRETATION AND COMPARISON

Comparison of the cross section for $B^{10}(n,t)$ by the absolute counting techniques as compared to emulsion techniques[7] is shown in Fig. 4. The dotted line is merely a connection of the points to indicate a reasonable variation in the cross section. The increase in the value of the cross section at a neutron energy of 5.6 Mev corresponds to a level in the compound nucleus of B^{11} at about 16.6 Mev which had been observed to decay by triton emission.[8]

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[6] R. B. Leachman, Nuclear Energy 4, 38 (1957).

[7] G. M. Frye, Jr., and Juanita H. Gammel, Phys. Rev. **103**, 328 (1956).

[8] R. W. Gelinas and S. S. Hanna, Phys. Rev. **89**, 483 (1953).