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 ${}^2\text{H}(d, n){}^3\text{He}$  FROM  $E_d = 3$  TO 6 MeV.

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G. Galeazzi<sup>(x)</sup>, P. Pavan, D. Toniolo, G. Zago and R. Zannoni  
Istituto di Fisica dell'Università di Padova, and INFN, Sezione di Padova  
<sup>(x)</sup> INFN, Laboratori Nazionali di Legnaro.

SUMMARY.

The zero degree differential cross section of the reaction  ${}^2\text{H}(d, n){}^3\text{He}$  was measured, by means of a proton recoil neutron counter telescope, with an accuracy of 2%, in the incident deuteron energy interval from 3 to 6 MeV.

1. - INTRODUCTION.

The  ${}^2\text{H}(d, n){}^3\text{He}$  reaction, largely used in the past as a monoenergetic source of few MeV neutrons, is now used, with cyclotrons and tandem accelerators, to produce neutrons with energy of some tens of MeV, in controlled thermonuclear fusion researches, for medical and biological applications and in fast neutron activation<sup>(1)</sup>.

The reaction cross section was measured by several authors, reviewed up to 1973 by F. Ajzenberg-Selove<sup>(2)</sup>.

In 1974 M. Drogg published the results of a systematic measurement, performed at Los Alamos with the time-of-flight technique, of the cross sections of the (d, d), (p, t) and (d, t) reactions, for incident particle energy  $E_i$  from 6 to 17 MeV, together with an evaluation of results previously obtained by various authors, starting from  $E_i = 3$  MeV<sup>(3)</sup>.

Some differences, not larger than 4%, but larger than the individual errors in some measurements (1.6% at 6 and 7 MeV in the Los Alamos experiment) are apparent between the evaluations of Drosch and of Liskien and Paulsen<sup>(4)</sup>, regarding the zero degree cross section of the (d, d) reaction between about 4 and 10 MeV (Fig. 11 of Ref. (3)).

This difference and the importance of the forward yield of the reaction as neutron source induced us to remeasure  $\sigma_{dd}(0^\circ)$  in the deuteron energy interval 3 - 6 MeV, where the discrepancy is larger, using a different technique.

The measurement here described was performed by using a proton recoil telescope as absolute neutron counter. The accuracy and reliability of this instruments in measuring forward neutron yields have also recently been demonstrated<sup>(5)</sup>. On the other hand, although in principle the associated particle technique is very precise, it is not suited for measuring forward neutron yields for kinematical reasons<sup>(3)</sup>.

## 2. - EXPERIMENTAL METHOD.

A deuteron beam with energy from 3 to 6 MeV, produced by the CN Van de Graaff at Legnaro, collimated by a tantalum diaphragm with 2.5 mm diameter, entered a deuterium gas target 5 cm long, having a pressure of about 2 atmospheres and a temperature of 20°C, closed between two Havar windows 4  $\mu$ m thick. The exit window, backed by an evacuated chamber ending with a tantalum plate cooled by an air jet, was used in order to reduce the local heating of the deuterium, which with deuteron currents around 1  $\mu$ A would generate not negligible thermal gradients<sup>(5, 6)</sup>.

A suppressor of secondary electrons located in front of the entrance window was maintained at a potential of -300 V with respect to the target. The deuteron current charge was measured by an integrator.

The forward emitted neutrons were counted by a proton recoil telescope of known efficiency, described in Ref. (7), whose main characteristics are the following.

A thin circular polyethylene radiator of about 10 mg/cm<sup>2</sup> and 0.9 cm in diameter, located 8 cm from the center of the deuterium target, was followed by a silicon solid state transmission detector 150  $\mu$ m thick with an area of 150 mm<sup>2</sup> and by a 5 mm thick plastic scintillator NE 102 A (sufficient to stop the recoil protons) with a diameter of 30 mm, located at 15 cm from the radiator, and viewed by a photomultiplier 56AVP.

The recoil protons were counted by the pulses of the transmission counter, whose amplitude was analyzed using a multichannel analyzer, in fast coincidence with pulses from the plastic scintillator. The coincidence had a resolution of about 5 ns.

The zero degree differential cross section  $\sigma_{dd}(0^\circ)$  of the (d, d) reaction was measured by the counts F of the telescope by the formula<sup>(7)</sup>:

$$F = N_d \frac{\sigma_{dd}(0^\circ) n_d}{d_o^2} N_p 4\sigma_{np}(180^\circ) \left( \frac{\pi r^2}{d^2} \right) (1 + c) \quad (1)$$

where :

- $d_o$  = effective distance of the radiator from the target (5.01 cm long). The effective distance is equal to the square root of the product of distances  $d_1$  and  $d_2$  of the radiator from the extremes of the target ( $d_1 = 5.80$  cm,  $d_2 = 10.81$  cm).
- $N_d$  = number of deuterons incident on the deuterium target.
- $n_d$  =  $2pt N_{AV}/RT$  = number of deuterons per  $cm^2$  of the target, at pressure  $p$  ( $\sim 2$  bar), temperature  $T$  ( $\sim 290$  K), thickness  $t = d_1 - d_2 = 5.01$  cm.  $N_{AV}$  is the Avogadro number and  $R$  the gas constant.
- $N_p$  = number of protons in the polyethylene  $(CH_2)_n$  radiator of known mass. Two radiators were used having masses of 7.20 and 13.14 mg.
- $r$  = radius of the diaphragm at the front of the plastic scintillator (1.41 cm).
- $d$  = distance between the radiator and the diaphragm of the scintillator.
- $\sigma_{np}(180^\circ)$  = differential cross section of n-p scattering at  $180^\circ$  in the center of mass system, taken from Ref. (8).
- $c$  = correction term, see the next paragraph.

### 3. - RESULTS.

The results of the measurements are given in Table I. The two groups of data were taken respectively with two polyethylene target thicknesses. The experimental data have been corrected for several effects.

The attenuation of the incident neutron beam due to the materials present between the deuterium target and the radiator, 1.0 mm of iron and 1.0 mm of tantalum, was calculated by considering that the effective attenuation lengths of neutrons with a mean energy of 8 MeV are 3.6 cm for the iron and 3.9 cm for the tantalum. The attenuation lengths have been deduced from the total Fe and Ta cross sections diminished by the elastic cross sections for scattering angles smaller than  $6^\circ$ , which is the half-aperture of the mean solid angle subtended between the radiator and the iron and tantalum plates.

The calculated attenuation is  $(4.5 \pm 0.5)\%$ ; the error is essentially due to the uncertainty of the fraction of the forward elastic scattering subtracted from the total cross section. The cross section have been taken from Ref. (9).

TABLE I - Zero degree differential cross section of the reaction  ${}^2H(d, n){}^3He$ , in the laboratory system.

$E_D$ MeV	$\Delta E_D$ MeV	$E_n$ MeV	$\sigma(0^\circ)$ mb	$\pm \Delta\sigma$ mb
3.26	0.18	6.53	58.2	1.3
3.40	0.18	6.66	60.7	1.4
3.53	0.18	6.80	62.5	1.0
3.67	0.17	6.93	64.0	1.4
3.80	0.17	7.06	65.4	1.4
3.93	0.16	7.19	64.7	1.4
4.07	0.16	7.33	66.6	1.5
4.20	0.16	7.45	67.1	1.5
4.34	0.15	7.59	68.7	1.5
4.47	0.15	7.71	66.9	1.5
4.61	0.14	7.85	69.9	1.5
4.87	0.14	8.11	71.3	1.0
4.87	0.14	8.11	72.2	1.5
5.12	0.13	8.36	73.7	1.5
5.39	0.13	8.61	76.5	1.5
5.65	0.12	8.87	80.7	1.3
5.92	0.12	9.12	78.5	1.3
6.08	0.12	9.28	81.0	1.3

$E_D$ , incident deuteron energy.  
 $\Delta E_D$ , energy spread of the incident deuterons.  
 $E_n$ , mean neutron energy.  
 $\sigma(0^\circ) \pm \Delta\sigma$ , differential cross section and total error.

Two factors contributed to the background of the experiment: the one due to charged particles not coming from the polyethylene radiator ( $f_1$ ) and the other due to neutrons not coming directly from the deuterium ( $f_2$ ). The first contribution was measured by removing the radiator from the neutron beam, having previously verified that the contribution due to the carbon present on the radiator was absolutely negligible. It was found that  $f_1 = (1.0 \pm 0.2)\%$  and was practically energy independent. The background  $f_2$ , measured by substituting the deuterium on the target with hydrogen, was found to be  $(1.1 \pm 0.2)\%$  and was also practically energy independent.

Other possible sources of background were considered as negligible on the basis of the extremely low number of counts outside the peak of foreground pulses.

Nuclear reaction of the recoil protons on the radiator and on the silicon of the transmission counter gave rise to a negligible ( $< 0.2\%$ ) loss of counts, owing to the thinness of both<sup>(10)</sup>.

No loss of counts was due to nuclear reactions in the plastic scintillator because it was used only for the timing.

According to the supplier, the purity of the deuterium was greater than 99.6%. No correction was therefore applied.

The ratio between the number of H and C atoms of the polyethylene was taken as equal to  $1.98 \pm 0.5\%$  on the basis of informations given by the supplier.

It was finally supposed, as in Ref. (11), that the Coulomb inscattering of protons in polyethylene and silicon compensates outscattering within 0.1% and the multiple scattering on the scintillator diaphragm was negligible. The correction due to the finite solid angle of the telescope calculated by the method described in Ref. (12) was 1.5%.

The total value of the corrections here considered (c of formula (1)) was  $(4.8 \pm 0.8)\%$ .

The statistical error was typically 1.5% and in a few cases was 1%. Other errors are due to uncertainties in the pressure and temperature of the deuterium target (0.3%), in the telescope geometry (0.5%), in the n-p cross section (0.5%). The errors of the deuteron charge collected by the target and of the radiator masses are negligible.

The total uncertainty of the single cross section value is 1.1% plus the statistical error (1.5% or less), that is  $< 1.9\%$ .

The experimental results given in Table I are reported in Fig. 1 as a function of the incident mean neutron energy. The figure also reports the results of Thornton<sup>(13)</sup> and Drogg<sup>(3)</sup>, and the two evaluation curves of Drogg<sup>(3)</sup> and Liskien and Paulsen<sup>(4)</sup>.

The  $\chi^2$  of our data relative to the Drogg evaluation is 18.2 being 16 the freedom degrees, confirming the recommended data.

#### 4. - CONCLUSION.

The zero degree differential cross section values of the  ${}^2\text{H}(d,n){}^3\text{He}$  reaction, measured by means of a proton recoil telescope in the deuteron energy interval 3 to 6 MeV, with a total uncertainty of less than 2% per point confirmed the results obtained by Drogg<sup>(3)</sup> and Thornton<sup>(13)</sup>.

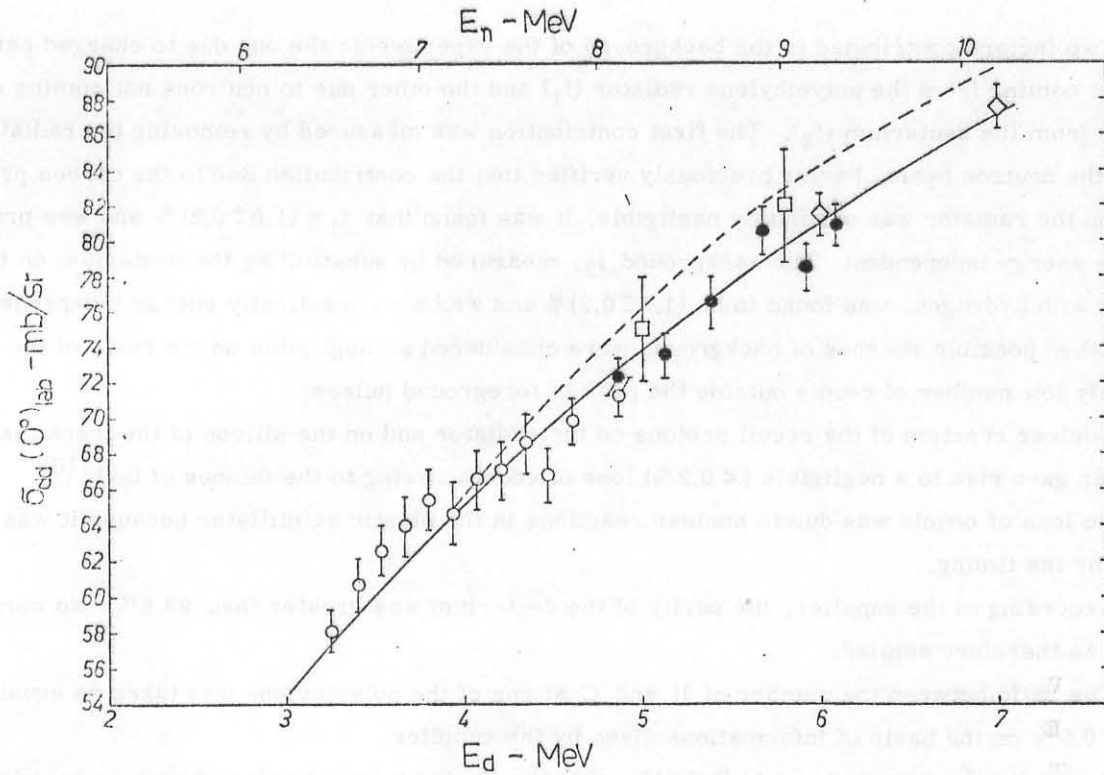


FIG. 1 - Differential zero degree cross section for the reaction  ${}^2\text{H}(d,n){}^3\text{He}$  as a function of the incident deuteron energy  $E_d$ . Full and open circles, results of the present work relative to two polyethylene radiators with different thickness. Square, results of Thornton<sup>(13)</sup>; diamonds, results of Drogg<sup>(3)</sup>. Continuous and broken lines, recommended data respectively of Drogg<sup>(3)</sup> and Liskien and Paulsen<sup>(4)</sup>.  $E_n$  is the zero degree neutron energy.

This work also confirmed the reliability of the proton recoil telescope in measurements of the forward neutron yields which, for kinematical reasons, are very difficult to perform with the associated particle technique.

In respect to the neutron time-of-flight technique the telescope presents greater simplicity which, in measurements of large neutron intensities, compensates the low, but easily and precisely calculable, efficiency.

The efficiency of the telescope, for a given energy resolution increases with increasing neutron energy<sup>(7)</sup>, therefore it would seem useful also at larger energies and in the study of other neutron source reactions.

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