

## IS THERE AN ANOMALY IN THE BACKWARD CROSS SECTION OF N-T SCATTERING AROUND 14 MEV?

G. PAIĆ, D. RENDIĆ and V. PEČAR

*Institut Ruđer Bošković, Zagreb*

*and*

*Institut de Physique Corpusculaire, Université de Louvain, Louvain-la-Neuve, Belgique*

Received 3 February 1976

*Abstract:* The differential cross sections for n-T elastic scattering stemming from different experiments are reviewed and compared with data at 6, 9, 18, 19.5, 21 and 23 MeV. It is found that the 14 MeV data do not follow the trend suggested by the data at other energies. To check whether we are facing an anomaly in a narrow energy range as suggested by some data we undertook a measurement in the energy range 14 to 15 MeV. The results of the measurement suggest that the anomaly is not confined to such a small energy interval.

### *1. Introduction*

The scattering of 14 MeV neutrons on tritium has been measured repeatedly, but after more than 25 years and eight measurements it is still very difficult to deconvolve a convergence of the results. However we shall try to make an evaluation of the data in order to be able to incorporate them in the body of data at other energies.

### *2. Evaluation and review of n-T elastic scattering data*

Coon *et al.*<sup>1)</sup> The experiment has been done at 14.3 MeV. The results of this experiment as quoted in Ref.<sup>1)</sup> should be renormalized as suggested by Desreumaux<sup>2)</sup> since the normalization was made using a cross section of 50 mb/sr

for the n-p elastic scattering at  $180^\circ$ . Using the Hopkins-Breit<sup>3)</sup> value at 14.3 MeV of 57.2 mb/sr it is necessary to increase the data of Coon by 14%. It has to be pointed that the energy is determined only to  $\pm 0.2$  MeV.

*Blanc et al.*<sup>4)</sup>. The experiment was done at 14 MeV. At  $180^\circ$  the points are somewhat lower than Coon's. No data on normalization cross sections do exist so it is difficult to ascertain the real measured cross section.

*Basar*<sup>5)</sup>. The experiment was done at 14.4 MeV. This experiment has yielded differential cross sections much lower than ever measured before. A correct n-p elastic cross section was used but the results at very large angles ( $> 160^\circ$ ) were about 2 times smaller than those measured by Coon. The fact that the ratio of disagreement decreases going to lower angles has precluded to explain the disagreement on the ground of an error in the tritium content of the target.

*Kootsey et al.*<sup>6)</sup>. Done at  $E_n = 14.1$  MeV the experiment distinguishes itself with good statistics and careful tritium content measurement. Although not stated it is reasonable to expect that the right n-p elastic scattering cross section was used. The results match very well the renormalized Coon's data.

*Fuschini et al.*<sup>7)</sup>. To prolong the suspense, in a measurement done at  $E_n = 15.2$  MeV they have measured cross sections in two points (at  $\sim 180^\circ$  and  $150^\circ$  c. m. angles) in agreement with the values of Basar. Though it is expected that the 15.2 MeV should be lower (following the  $1/E$  law for instance as suggested by Seagrave<sup>8)</sup> the disagreement with measurements<sup>1,4,6)</sup> is striking.

*Debertin et al.*<sup>9)</sup>. Measured at 14.1 MeV this experiment situates itself right in between the extremes with 72 mb/sr at  $175^\circ$ .

*Shirato et al.*<sup>10)</sup>. Measured at 14.1 MeV the differential cross sections are generally lower than in the experiments<sup>1,6,11)</sup>. At  $150^\circ$  c. m. they agree well with Basar's and Fuschini's data. The error in the number of tritium atoms is quoted to be 10% but no details are given as to how this assesment was made.

*Desreumaux et al.*<sup>11)</sup>. The experiment was done at 13.85 MeV with a good angular distribution, good statistics, special precautions to determine the tritium content via the p-T elastic scattering. The results of this experiment should be heavily weighted in the evaluation of data around 14 MeV. The results agree very well with the data of experiments<sup>1,6)</sup>.

If the results are summarized we see that two distinct groups can be formed — a »high« group including expts<sup>1,6,11)</sup> partially expt<sup>4)</sup> and somewhat lower expt<sup>9)</sup> and a »low« group including expt<sup>5,7,10)</sup>. Looking at the energy at which these measurements were made it is visible that the »high« group corresponds to energies grouped around 14 MeV (including here the rather undefined energy of expt<sup>1)</sup>), the »low« group with exception of expt<sup>10)</sup> was measured at higher energies. We were therefore considering the possibility of an energy anomaly around 14 MeV that could perhaps explain the discordance in the results.

In view of that hypothesis we have plotted the results of the high group in Fig. 1 with a reference line representing the most probable values as obtained from the experiments<sup>1,6,11</sup>).

Having thus an assumed value of the n-T differential cross section for scattering we wish to compare it with the data measured at other energies. The measurements at other energies are rather scarce. The review by Seagrave et al.<sup>8)</sup> lists data at 6; 9; 18; 19.5; 21 and 23 MeV. In Fig. 2a. we show the 149° c. m. differential cross section from the present evaluation alongside the values from expt<sup>5,7)</sup> and the data from Ref. <sup>8)</sup>. It seems apparent that the 14 MeV points do not lay on a smooth curve linking the other points but rather higher.

The same behaviour appears if other backward angles are taken.

In Ref.<sup>8)</sup> it was pointed that a satisfactory fit was achieved at large angles with p-<sup>3</sup>He angular distributions measured at the same incident energy. A systematical difference was however observed in that the minima of the n-T elastic angular distributions were, at all energies reviewed in Ref.<sup>8)</sup>, inferior to the p-<sup>3</sup>He minima.

The 14 MeV data are compared to the p-<sup>3</sup>He data at 13.6 MeV<sup>12)</sup> and it is visible that the criteria of Ref.<sup>8)</sup> do not apply. The proposed n-T differential cross sections are always superior to p-<sup>3</sup>He data, as shown in Fig. 1. The different behaviour of the 14 MeV backward differential cross section compared to the points below and above it may suggest two different things:

- there is a systematic error in the set of cross sections from Ref.<sup>8)</sup>, and
- a possible anomaly in the excitation function in the range  $9 < E_n < 18$  MeV.

The first hypothesis would imply the cross section of Ref.<sup>8)</sup> to be consistently lower by a constant factor. This is however not likely because the excitation function of the total cross section presented in Fig. 2b. does not exhibit marked irregularities at 14 MeV.

Therefore the second hypothesis seems worth investigating. The cross sections of experiment<sup>7)</sup> suggests that perhaps such an anomaly occurs in a very short energy interval between 14. and 15.2 MeV.

This has prompted us to attempt a measurement aimed at measuring the energy behavior of the n-T differential cross section in the backward hemisphere.

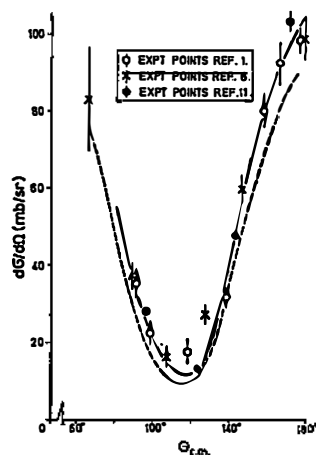


Fig. 1. Experimental points from the experiments most heavily weighted in the present analysis.

The solid line represents a guide to the eye through the points. The dashed curve represents the p-He data of Ref.<sup>12)</sup> at 13.6 MeV in the same angular range.

### 3. Experiment

The differential cross section for the n-T elastic scattering has been measured at three different neutron energies with a charged particle counter telescope arrangement.

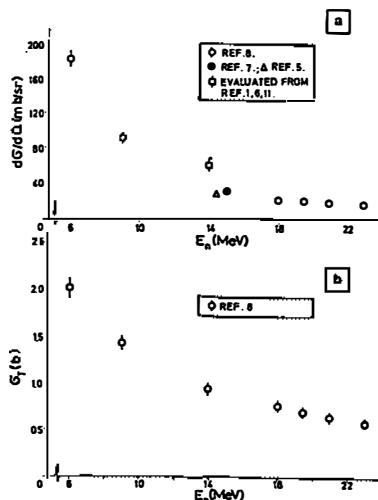


Fig. 2. a) Experimental points for the n-T differential cross section at  $149^\circ$  c. m. in the energy range under study.

b) Total cross sections for n-T interaction as reported in Ref. <sup>8)</sup> on the basis of Refs <sup>13,14)</sup>.

A TiT target on copper backing was bombarded with neutrons from a d-T neutron generator with an analyzed beam of 160 keV deuterons. The elastically scattered tritons were detected in a charged particle telescope consisting of 3 surface barrier detectors.

The energy of the neutrons was changed by placing the target + detector assembly at different angles with respect to the deuteron beam in the neutron generator. The angles were chosen to be  $0^\circ \pm 1^\circ$ ;  $67^\circ \pm 2^\circ$  and  $96^\circ \pm 4^\circ$  with respect to the incident deuteron beam. The target 5 mm in diameter was placed 11.2; 13.8 and 13.8 cm from the neutron source, respectively. Taking into account the energy loss in the neutron generating target the kinematical spread and the uncertainty in the telescope's angular setting the energies of the neutrons are the following:

$$14.94 \pm 0.08 \text{ MeV};$$

$$14.4 \pm 0.10 \text{ and}$$

$$13.94 \pm 0.12 \text{ MeV.}$$

The silicon detectors used were 75, 200 and 400  $\mu\text{m}$  thick. The signals from the three detectors were fed in a triple coincidence with 1  $\mu\text{s}$  resolving time. The coincidence output triggered the gates for the  $\Delta E$  signal derived from the 200  $\mu\text{m}$  detector and for the sum of the signals of all three detectors representing the  $E$  signal. These two signals were stored in a  $64 \times 64$  channel two dimensional analyzer.

The relative normalization of the cross section was done using a 4  $\text{mg}/\text{cm}^2$   $\text{CH}_2$  target in front of the tritium target therefore recording simultaneously elastic protons and elastic tritons.

The total thickness of silicon is not sufficient to stop elastic protons produced in this experiment but they were visible and well separated in the spectra exhibiting a peak at the location corresponding to the energy loss in the total thickness of detectors. The angular opening of the telescope was  $22^\circ$  corresponding to a mean angle of  $12.5^\circ$ . The opening was deliberately chosen large because the objective was not to measure the differential cross section but rather to measure the energy behavior of a large part of the backward cross section for elastic scattering. The energy behavior was obtained dividing the number of tritons by the number of elastic protons obtained in the same measurement. The ratios found were as follows:

$$\begin{aligned} & \text{at } 14.94 \text{ Mev} - 0.0176 \pm 0.0010, \\ & \text{,, } 14.4 \text{ Mev} - 0.0213 \pm 0.0011, \\ & \text{,, } 13.94 \text{ Mev} - 0.0190 \pm 0.0010. \end{aligned}$$

The ratio listed above is given by the relation

$$R = \frac{(\frac{d\sigma}{d\Omega})_{n-T} \times N_T^{\#}}{(\frac{d\sigma}{d\Omega})_{n-p} \times N_p^{\#}}$$

$(\frac{d\sigma}{d\Omega})_{n-T}$  and  $(\frac{d\sigma}{d\Omega})_{n-p}$  are the differential cross sections at given angles for the elastic scattering of neutrons on tritons and protons respectively.  $N_T^{\#}$  and  $N_p^{\#}$  are the numbers of tritium and hydrogen atoms in the target. To obtain values which are proportional, to a constant, to the differential cross section of n-T scattering we multiplied the value  $R$  with the magnitude of  $(\frac{d\sigma}{d\Omega})_{n-p}$  at the given energy. Multiplying by the respective value of  $(\frac{d\sigma}{d\Omega})_{n-p}$  at  $180^\circ$  c. m. we obtain the following values:

$$\left(\frac{d\sigma}{d\Omega}\right)_{n-T}^{14.94 \text{ MeV}} = K \cdot 0.970 \pm 0.055,$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{n-T}^{14.4 \text{ MeV}} = K \cdot 1.127 \pm 0.058,$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{n-T}^{13.94 \text{ MeV}} = K \cdot 1.108 \pm 0.058.$$

The cross section for the n-T elastic scattering as measured in the present experiment does not exhibit any sharp variation in the region of 14 to 15 MeV. Therefore the possibility we considered that the discrepancies in measured cross sections are due to differences in neutron energy should be discarded.

#### 4. Conclusion

The possibility that the wide discrepancies in n-T differential cross sections are due to a resonant behavior in a narrow energy region has been considered. The experiment covered the energy range 14 to 15 MeV. The result indicates to a flat behavior of the differential cross section with energy. Therefore the scatter in reported differential cross sections should be blamed on errors rather than on a physical phenomenon.

If maximum credibility is given to experiments<sup>1,6,11)</sup> it is still pertinent to point out the discrepancy of the n-T and p-<sup>3</sup>He data at 14 MeV compared to the agreement achieved at 6, 9, 18, 19.5, 21 and 23 MeV. However if there is a resonant behavior in this energy region it should be much broader than the energy region accessible in the present measurement.

#### Acknowledgements

We wish to acknowledge the stimulating discussions with Prof. R. Bouchez. We thank Dr. Đ. Miljanić and K. Kovačević, A. Miran and S. Vidić for their help in preparing and running the experiment.

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## POSTOJI LI NEPRAVILNOST U RASPRŠENJU NEUTRONA NA TRITONIMA NA VELIKIM KUTEVIMA U BLIZINI 14 MeV?

G. PAIĆ, D. RENDIĆ i V. PEČAR

*Institut »Ruđer Bošković«, Zagreb*

i

*Institut de Physique Corpusculaire, Université de Louvain, Louvain La Neuve, Belgija*

Do sada izmjereni diferencijalni udarni presjeci za elastično n-T raspršenje kod 14 MeV su ocijenjeni i uspoređeni s postojećim podacima na 6, 9, 18, 19.5, 21 i 23 MeV. Opaženo je da najvjerojatniji podaci za n-T raspršenje kod 14 MeV leže izvan krivulje koju sugeriraju podaci na obližnjim energijama.

Isto tako diferencijalni udarni presjeci za elastično n-T raspršenje kod 14 MeV leže iznad odgovarajućih podataka za p-<sup>3</sup>He raspršenje, što nije slučaj kod drugih energija.

Da provjerimo radi li se o nepravilnosti u kratkom energetskom intervalu poduzeli smo mjerenja n-T raspršenja na jednom kutu u intervalu energija od 14 do 15 MeV. Rezultati mjerenja ukazuju da se udarni presjek u mjenom intervalu ne mijenja bitno i stoga zaključujemo, da nepravilnost u ponašanju diferencijalnog udarnog presjeka na velikim kutovima ima blažu energetsku zavisnost.