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DIFFERENTIAL ELASTIC SCATTERING CROSS SECTIONS OF 14.4 MeV NEUTRONS BY HYDROGEN ISOTOPES

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Abstract: The differential cross section for n-p, n-d and n-t elastic scattering have been measured at the neutron energy of 14.4 MeV with a relative error of 2%. The absolute error obtained has been for n-p and n-d data 12%, for n-t data 20%. The value for the anisotropy in n-p scattering has been determined as 1.10 ± 0.03.

1. Introduction

Very accurate data on the elastic scattering of fast neutrons from hydrogen isotopes are highly desirable for manifold reasons. The n-p elastic differential cross section is used as a standard for the normalization of the differential cross sections of fast neutron induced reactions. Measurements of n-p scattering in the region of incident neutron energies from 10 to 50 MeV, performed with an accuracy better than 5% could significantly contribute to our present understanding of nucleon-nucleon interaction. Accurate n-d elastic scattering data combined with p-d data could help to improve the present phase shift analysis[2)] and might possibly shed light on the problem of $T = 1/2$ states in the $A = 3$ system. Theoretical models for the three nucleon systems based on the exact treatment of Faddeev face their first test in comparison with n-d elastic data. The four nucleon system is still not adequately understood, and the study of n-t elastic scattering could yield valuable information on the trion wave function and on levels in the $A = 4$ system.

At the beginning of the present investigation the experimental information on neutron scattering at the energy around 14 MeV from hydrogen isotopes consisted of the data accumulated by the Los Alamos group[3, 4, 5)] in the years 1950–55, with the exception of the measurement of n-p elastic scattering by Nakamura[6)] in 1960. Allred *et al.*[3)] from the group measured the n-p and n-d

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elastic scattering at $E_n = 14.1$ MeV by the use of the nuclear emulsion technique, while Seagrave[4] performed these measurements by the use of counter telescopes. The only information on n-t elastic scattering around 14 MeV represented the measurement of Coon *et al.*[5] at $E_n = 14.3$ MeV.

In the last decade counter telescope techniques have been appreciably improved, particularly by the use of multidimensional analysis in (neutron, charged particle) reactions (refs. [7, 8]). Thus it seemed worthwhile to undertake a new investigation of elastic scattering of 14.4 MeV neutrons from hydrogen isotopes.

2. *Measurements*

A flux of 2×10^9 neutrons/s of $E_n = 14.4$ MeV was produced by a Cockcroft–Walton accelerator. The neutron flux was determined by detecting the alpha particles associated with the neutron generating process $T(d, n)^4He$ additionally by a BF_3 counter.

Charged particles were identified using a counter telescope which consisted of two proportional counters, yielding information on energy loss and a scintillation counter in coincidence giving the remaining energy of the charged particle. In order to reduce the background, an anticoincidence proportional counter was inserted between the neutron source and the target irradiated by neutrons. This system has been in operation for about seven years and has demonstrated high particle discrimination (1 in 10^3–10^4) and good relative cross section accuracy (3–5%), with low inherent background (for a more detailed account of the system see refs.[7, 8]).

The most difficult problem lies in the absolute determination of the 14.4 MeV neutron flux. It was assumed that the number of the incident 14.4 MeV neutrons was given by the total yield of T-D neutrons determined by the associated particle method and corrected for the loss of 14.4 MeV neutrons. The loss of neutrons resulted from the absorption in the material between the source and the target and from the scattering from the surrounding material. An estimate of the correction factor was obtained by determining the number of neutrons degraded in energy and/or impinging obliquely into the target and studying the 0^0 proton and deuteron spectra from n-p and n-d elastic scattering. The correction factor was determined to be 0.90 ± 0.06.

An unpleasant characteristic of measurements in fast neutron physics is the poor angular resolution. In the case of rather sharply varying angular distribution the actual cross section differs from the measured one in such a way as to decrease the minima and raise the maxima. In particular, the geometry used in the present experiment smeared the n-d and n-t angular distribution

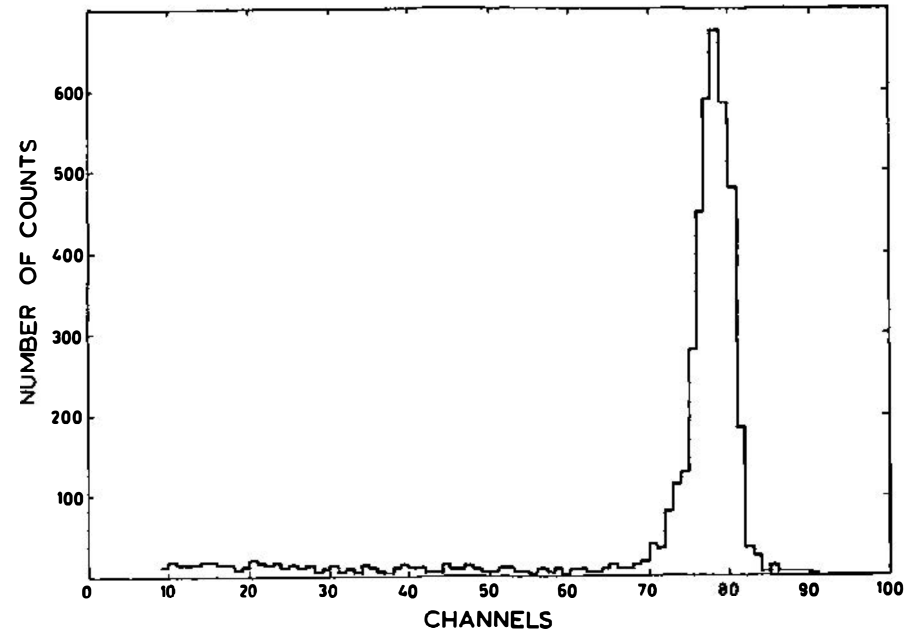

Fig. 1. The proton energy spectrum.

and thus decreased σ (Θ = 180°) by 10% and σ (Θ = 160°) by 7%. The effect on the n-p angular distribution, which is almost isotropic, is considerably smaller.

All hydrogen targets were solid. The proton target was a polyethylene foil 2.7 mg/cm² thick. The deuterium target was a circular layer of deuterated paraffin $(CD_2)_n$ deposited on a gold backing. The thickness of the layer was 1.07 mg/cm². For tritium measurements two targets were used. The first was a ZrT target on a tungsten backing having an activity of 15.04 Ci. The second target was a TiT on a copper backing with an activity of 1.47 Ci. The uncertainty in the amount of the target atoms in polyethylene and deuterated paraffin is due to uncertainties in the weight measurement. The determination of the tritium content is considerably more difficult.

The total uncertainty of the absolute measurements of the n-p and n-d elastic scattering cross section was estimated to be 12%, while the total uncertainty of the n-t elastic scattering cross section was 20%. The relative differential cross section was measured to an accuracy of about 2%.

A typical energy spectrum is shown in Fig. 1. The intense peak is due to recoil protons from n-p elastic scattering, while the flat part below the channel 70 is associated with degraded neutrons.

The differential cross section was measured at 11 angles. The results in the centre of mass system are summarized in Tables 1 to 4. The errors quoted are relative errors.

3. Discussion

Figure 2 shows the present n-p elastic scattering data (solid circles) as well as the data obtained by Allred *et al.*[3] (open circles), by Seagrave[4] (open triangles) and by Nakamura[6] (crosses). The agreement between the data is remarkably good. The differential cross section can be fitted with the expres-

Table 1

n–p elastic scattering differential cross section

$\Theta/1^{\circ}$		$\sigma/\mathrm{mb\ sr^{-1}}$	
169.5	$^{+8.3}_{-7.2}$	59.5	±1.1
165.7	$^{+9.9}_{-9.2}$	57.6	±1.0
157.5	$^{+11.7}_{-11.5}$	56.9	±1.0
148.0	$^{+11.8}_{-11.7}$	58.6	±1.0
138.4	$^{+11.5}_{-11.5}$	56.4	±1.0
128.9	$^{+11.5}_{-11.5}$	52.9	±1.1
119.1	$^{+11.4}_{-11.4}$	53.3	±1.1
109.3	$^{+10.6}_{-10.6}$	52.4	±1.2
99.6	$^{+9.9}_{-9.9}$	52.8	±1.1
89.8	$^{+9.4}_{-9.4}$	47.6	±1.1
79.9	$^{+9.2}_{-9.2}$	51.4	±0.9

Table 2

n–d elastic scattering differential cross section

$\Theta/1^0$		σ/mb sr^{-1}	
169.5	$^{+8.3}_{-7.2}$	92.4	±2.3
165.7	$^{+9.9}_{-9.2}$	79.9	±1.5
157.5	$^{+11.7}_{-11.5}$	50.7	±1.0
148.0	$^{+11.8}_{-11.7}$	29.0	±0.9
138.4	$^{+11.5}_{-11.5}$	16.0	±0.7
128.9	$^{+11.5}_{-11.5}$	10.2	±0.5
119.1	$^{+11.4}_{-11.4}$	8.4	±0.3
109.3	$^{+10.6}_{-10.6}$	11.9	±0.5
99.6	$^{+9.9}_{-9.9}$	18.6	±0.8
89.8	$^{+9.4}_{-9.4}$	31.4	±0.8
79.9	$^{+9.2}_{-9.2}$	36.8	±1.1

sion $A + B \cos \Theta_{CM}$ with $A = 58.1$ and $B = 5.7$ in mb sr^{-1}. The anisotropy ratio obtained from the present data is 1.10 ± 0.03, while the average value from refs.[3, 4, 6] is 1.05 ± 0.03.

Figure 3 shows the present n-d elastic scattering data (solid circles) together with the data of Allred *et al.*[3] (open circles) and the data of Seagrave[4] (crosses). The experimental data are compared with five theoretically predicted angular distributions. Two solid curves result from the calculations of Buckingham, Hubbard and Massey[9] performed in the framework of the resonating group structure method using central forces only. The nuclear potential had an exponential form

$$V(r) = -A \exp(-2r/a)$$

with $A = 242 m_e c^2$, and $a = 1.73$ fm. The solid curve (1) ($\sigma(0^0) = 58$ mb/sr) was obtained using the symmetric exchange type force, while the solid curve (2) is due to the ordinary type force (Wigner + Bartlett). The dashed curve (3) was obtained by de Borde and Masey[10] using Serber forces. The results of the calculations of Christian and Gammel[11] are given as a dashed curve (4).

According to the optical theorem the differential cross section for elastic scattering at $\Theta = 0^0$ cannot be smaller than

$$\sigma_{el}\,(\Theta = 0^0) \geqq \left(\frac{k}{4\pi}\,\sigma_{total}\right)^2 .$$

Table 3

n–t elastic scattering differential cross section using the ZrT–W target

$\Theta/1^0$		σ/mb sr^{-1}	
170.6	$^{+6.8}_{-5.9}$	43.7	±0.6
166.5	$^{+8.1}_{-7.5}$	42.7	±0.6
158.0	$^{+9.5}_{-9.2}$	33.7	±0.6
148.3	$^{+9.7}_{-9.5}$	26.9	±0.5
138.7	$^{+9.4}_{-9.3}$	20.5	±0.4
129.1	$^{+9.3}_{-9.3}$	12.0	±0.3
119.3	$^{+9.2}_{-9.2}$	6.0	±0.3
109.4	$^{+8.6}_{-8.6}$	6.4	±0.3
99.6	$^{+8.1}_{-8.1}$	14.5	±0.5
89.8	$^{+7.7}_{-7.7}$	22.2	±0.4
79.9	$^{+7.5}_{-7.5}$	34.3	±0.8

Table 4

n–t elastic scattering differential cross section using the TiT–Cu target

$\Theta/1^0$		σ/mb sr^{-1}	
167.0	$^{+9.5}_{-8.2}$	44.5	±3.1
165.1	$^{+11.2}_{-10.5}$	42.3	±2.6
157.2	$^{+13.3}_{-13.0}$	37.6	±2.6
147.7	$^{+13.5}_{-13.3}$	25.9	±2.5
138.2	$^{+13.4}_{-13.3}$	18.3	±2.3
128.7	$^{+13.0}_{-13.0}$	13.9	±2.0
119.0	$^{+13.0}_{-13.0}$	9.3	±1.1
109.2	$^{+12.0}_{-12.0}$	10.6	±1.9
99.5	$^{+11.2}_{-11.2}$	16.3	±2.0
89.7	$^{+10.8}_{-10.8}$	24.2	±4.0
79.9	$^{+10.5}_{-10.5}$	34.7	±2.4

This lower limit of σ_{el} ($\Theta = 0^0$) is known as Wick's limit[12]. Using $\sigma_{total} = 0.805$ b for $E_n = 14$ MeV one obtains 124 mb/sr for Wick's limit, which rules out the theoretical curves (1) and (4).

An extensive review on n-d elastic scattering has been given recently by Seagrave[13] in which he compares the older Los Alamos data with the present data and with the p-d elastic scattering data of Kikuchi *et al.*[14] All data around 14 MeV are consistent among themselves as well as with the data at neighbouring energies, as is shown in the complex phase shift analyses of Van Oers and Brockman[2]. Only the very recent measurements of Berick using the

C_6D_6 scintillator and time-of-flight technique[15] gave larger cross section values, particularly at forward angles where actually no n-d data have been found as yet.

Amado[16] and A. C. Phillips[17] performed the calculation of n-d elastic scattering in the framework of Faddeev's approach using the nonlocal separable nucleon-nucleon interaction. The prediction of Amado (dashed-dotted curve (5) in Fig. 3) comes out rather low in the absolute cross section, and that of Phillips gives too shallow angular distribution.

Figure 4 shows the present n-t elastic scattering data for TiT_2-Cu (open triangles and for ZrT_2-W (open circles) targets together with the data of Coon *et al.*[5] (crosses). The solid curve was calculated by Bransden *et al.*[18] using Serber forces. The internal consistency of the present data is quite good, but the disagreement between the present data and the earlier measurement of Coon *et al.*[5] could not be explained by the inaccuracy in the H_2–T_2 amount in the target nor by the lack of discrimination of deuterons from the T(n, d)2n reaction from recoil tritons. The total n-t cross section at $E_n = 14.1$ MeV known to be 0.965 b determines Wick's limit as 225 mb/sr[13]. The integration of our angular distribution extending the data to $\Theta = 0^0$ to meet Wick's limit

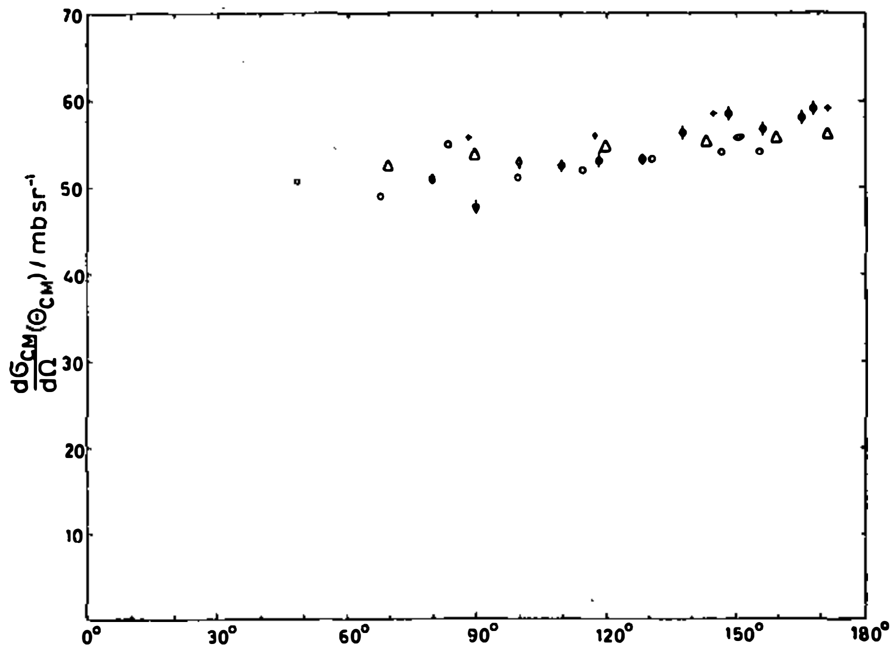

Fig. 2. The differential cross section of n-p elastic scattering data. Present data (solid circles), Allred *et al.*[3] (open circles), Seagrave[4] (open triangles), and Nakamura[6] (crosses).

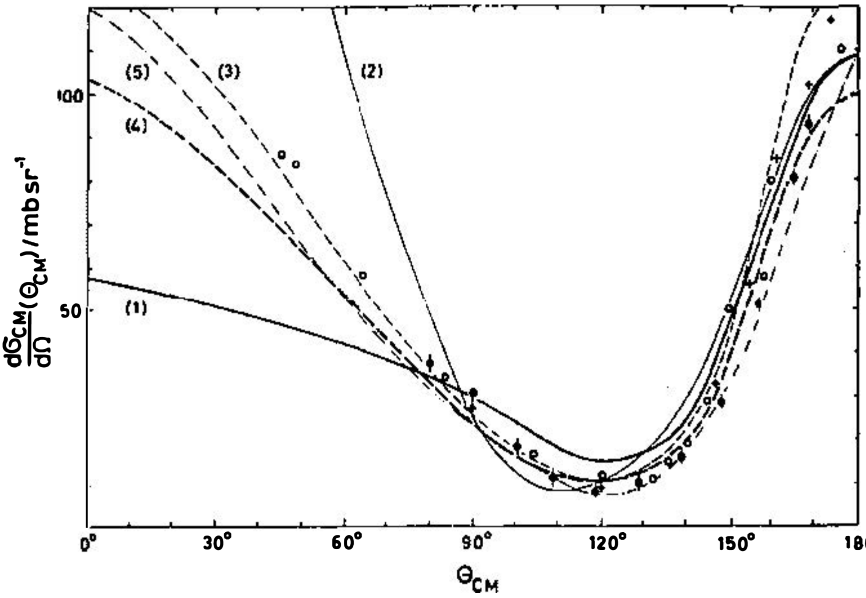

Fig. 3. n-d elastic scattering data. Present data (solid circles), Allred *et al.*[3] (open circles) and Seagrave[4] (crosses). Curves (1) and (2) are the calculations of Buckingham *et al.*[9]. Curve (3) is due to de Borde and Massey[10], and curve (4) to Christian and Gammel[11]. The dashed-dotted curve (5) is from ref.[16].

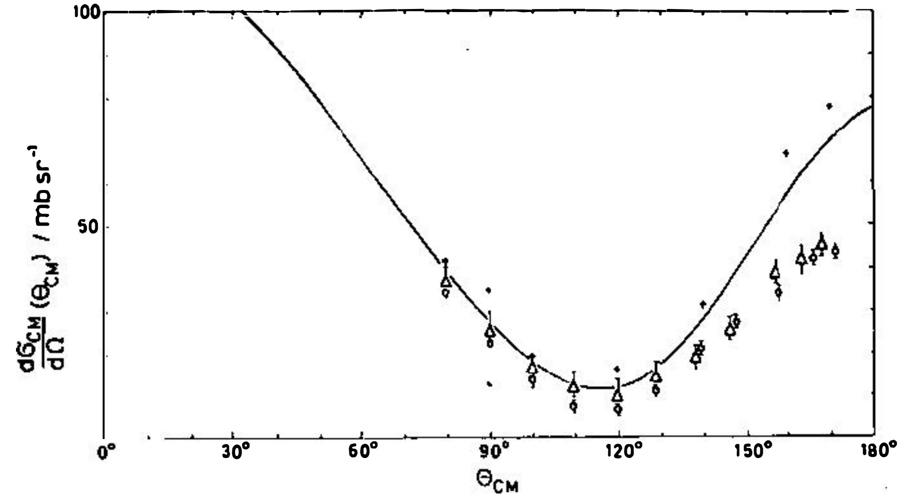

Fig. 4. Angular distribution of n-t elastic scattering. Present data using a TiT_2-Cu target (open triangles) and a ZrT_2W target (open circles) together with the data of Coon *et al.*[5] (crosses). The solid curve is the calculation from ref.[18].

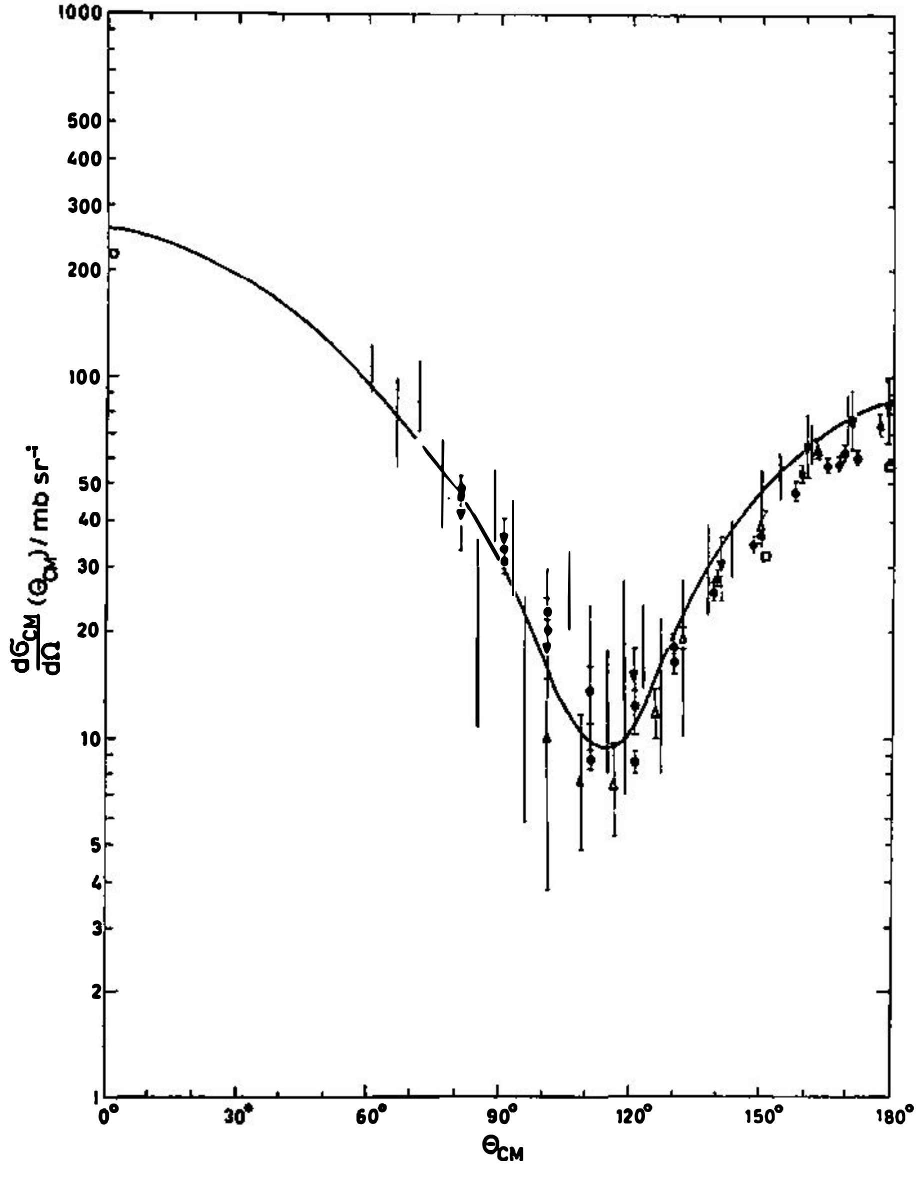

Fig. 5. Angular distribution of n-t elastic scattering. Our normalized data (solid circles), Coon *et al.*[5] (solid triangles), Debertin *et al.*[21] (open triangles), Fuschini *et al.*[22] (open square) and Blanc *et al.*[23] (bars). The open circle is Wick's limit. The solid curve represents the average through the p-^{3}He elastic scattering data of Leland and Rosen for $E_p = 14.5$ MeV[24].

gives the total elastic cross section of 0.620 b. The total cross sections for the T(n, 2n)d and T(n, 3n)p processes are[19] 45 ± 5 and 0 ± 1 mb, respectively. These values were obtained by the use of an yttrium tritide sample, in the presence of an Y(n, 2n) cross section of 900 ± 45 mb. The deuteron and proton spectra from the T(n, d)2n and T(n, p)3n reactions investigated[20] at $\Theta = 0^0$ yielded differential cross sections of 40 ± 10 and 12 ± 6 mb/sr, respectively. The deuteron spectra were also investigated[1] at a number of small angles, and it was observed that the cross section rapidly decreases as the angle increases. Although the precision for the total inelastic cross section as quoted in ref.[13], might be too optimistic, the value of 95 ± 60 mb was accepted as a fair estimate. Thus the total elastic cross section amounts to 870 ± 60 mb as compared with our integrated value of 620 mb. In view of the large uncertainty in the amount of tritium atoms in the target the data from the present measurements were normalized on the value of 870 mb for the total elastic cross section. In Fig. 5 our normalized data (solid circles) are compared with the data of Coon *et al.*[5] (solid triangles), of Debertin *et al.*[21] (open triangles), of Fuschini *et al.*[22] (open squares) and of Blanc *et al.*[23] (bars). The open circle is Wick's limit. The solid curve represents the average through the p-^{3}He elastic scattering data of Leland and Rosen for $E_p = 14.5$ MeV[24].

The data on n-t and p-^{3}He elastic scattering around 14 MeV seem to be consistent. The remaining differences can be accounted for by finite geometry corrections due to the difference between the present data and p-^{3}He and by the particle discrimination leading to the difference between the data of Coon and the present data. The normalization factor 1.4, as discussed above, is subject to an uncertainty of 20% which is within the uncertainty in the amount of tritium in the target employed in the present experiment.

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DIFERENCIJALNI ELASTIČNI UDARNI PRESJECI KOD RASPRŠENJA 14.4 MeV NEUTRONA NA IZOTOPIMA VODIKA

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Sadržaj

Pomoću brojačkog teleskopa izmjereni su apsolutni diferencijalni udarni presjeci za n-p, n-d i n-t elastično raspršenje kod energije upadnih neutrona $E_n = 14.4$ MeV. Relativna pogreška mjerenja iznosi oko 2%. Apsolutna pogreška za n-p i n-d podatke iznosi oko 12%, a za n-t podatke oko 20%.

Za anizotropiju kutne raspodjele n-p raspršenja nađena je vrijednost 1.10 ± 0.03.