ELASTIC SCATTERING OF 580 MEV NEUTRONS BY PROTONS AND NEUTRONS

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(presented by V. P. Dzhelepov)

Present-day information concerning the character of elastic scattering of neutrons by protons and neutrons relates to an energy region (100-400 Mev) where the processes of meson production are either entirely absent or where the total meson production cross sections in n-p and n-n collisions form an exceedingly small portion of the respective total interaction cross sections. With the aim of detecting possible changes in the character of neutron scattering by protons and neutrons at nucleon energies markedly exceeding the threshold of pion production, experiments were conducted on the synchrocyclotron of the Institute of Nuclear Problems of the USSR Academy of Sciences. Differential cross sections of elastic scattering of neutrons (with energies close to 600 Mev) by protons and neutrons were measured.

1. *Total n-p interaction cross sections*

The study of the angular dependence of elastic n-p scattering cross sections was preceded by experiments which determined the total n-p interaction cross sections in the energy range of 380-630 Mev. The measurements were carried out in "good geometry" by the attenuation of a beam of neutrons of given energy passing through an absorber. The neutron beam used in the experiments was obtained as a result of the exchange scattering of 680 Mev protons by a beryllium target. The energy distribution of neutrons in the beam is given in fig. 1. In the region adjacent to the upper border of the spectrum, there is a maximum at 600 Mev with a half-width of about 130 Mev [1]*. The intensity of the neutron beam above 450 Mev was 2×10^4 neutrons cm^{-2} sec^{-1}.

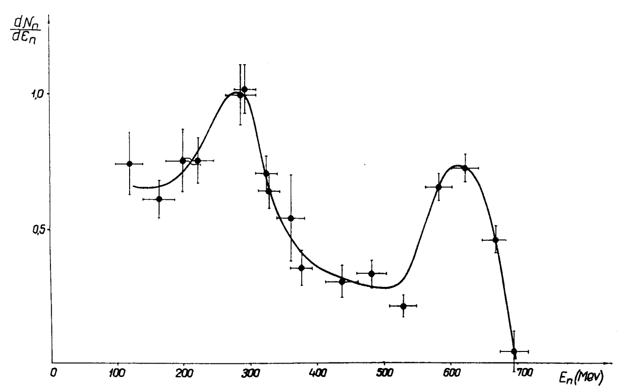

Fig. 1. Neutron energy distribution.

The measurements showed that in the investigated energy region the total cross section of n-p scattering remains constant within the limits of experimental errors and amounts to $(34 \pm 2) \times 10^{-27}$, $(35 \pm 2) \times 10^{-27}$, $(36 \pm 2) \times 10^{-27}$ and $(37 \pm 4) \times 10^{-27}$ cm^2 at E_n equal to 380, 500, 590 and 630 Mev respectively [2].

2. *Elastic scattering of 580 Mev neutrons by protons*

The differential cross sections $\sigma_{np}(\vartheta)$ in the angular range $35{,}5^\circ \leqslant \vartheta \leqslant 180^\circ$ (center-of-mass system) were measured by the method of registering recoil protons from elastic n-p collisions. To do this, the difference in the number of recoil protons from scatterers of paraffin ($CH_{2.09}$) and graphite (C) placed in the neutron beam, was determined at angles $\Phi = 0^\circ \div 70^\circ$ (laboratory system), the scatterers having the same stopping power. When working at various angles, the thickness of the scatterers varied, and for the graphite scatterers in the recoil angle ranges $\Phi = 0 \div 15^\circ$; $25 \div 60^\circ$ and $60 \div 70^\circ$ (laboratory system) it amounted to 5; 3 and 0,5 gm/cm^2, respectively. A diagram of the experiment is shown in fig. 2.

The detector consisted of three scintillation counters (1, 2, 3) connected in coincidence with a resolving time of $5 \cdot 10^{-8}$ sec. The scintillation counters were operated on ФЗУ-19 photomultipliers and tolan crystals. The counting characteristics of the detector had a plateau

* The second maximum observed in the 270 Mev neutron spectrum is due, as an elementary analysis shows, to neutrons that are produced in those collisions of primary protons with nucleons of the beryllium nucleus, which lead to pion production.

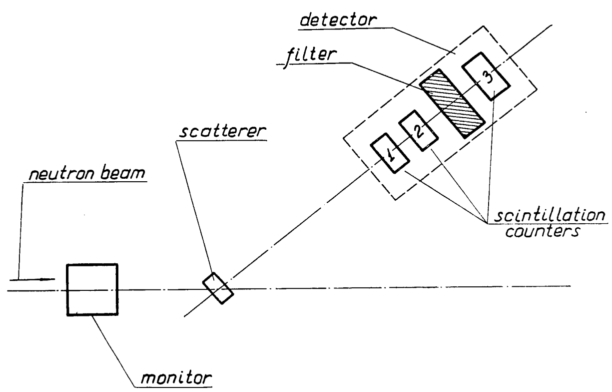

Fig. 2. Experimental arrangement used in the measurement of elastic n-p scattering cross sections.

of 150-200 volts. The selected geometry of the detector provided for an angular resolution of 2°. The energy threshold of the detector was defined by a tungsten or copper filter placed between the last two counters of the detector. The thickness of the filter depended on the scattering angle and was selected in such a way that the detector would operate only when the energy of the neutron entering the scatterer exceeded 450 Mev. This made it possible to exclude the effect produced by lower energy particles which were present in the neutron beam in a sufficiently large quantity. In these conditions, the average energy of the neutrons used in the experiments was 580 Mev.

Measurement of the n-p scattering differential cross sections

The process of measurement of the angular distribution of recoil protons consisted in determining the number of charged particles, which, as a result of n-p collisions, emerged from the scatterer in a given direction, and correcting the result for an admixture of pions and for absorption of protons in the filter of the detector.

The corrections for an admixture of charged π mesons at angles $\Phi \geqslant 60°$ were determined with the aid of a telescope made up of three scintillation counters; this telescope is similar to the detector used in the measurements of the angular distributions of charged particles. Evaluations made on the basis of paper [3] showed that if the threshold of such a detector is raised to the maximum energy of the recoil protons at the given angle $\Phi \geqslant 60°$, it will record 70 to 80% of all the π mesons produced in the n-p collisions and emerging from the scatterer at a given angle. In measurements at angles $\Phi < 60°$, use was made of the selection of particles according to velocity in order to isolate π mesons. To do this, the first counter of the detector was replaced by a Čerenkov counter. Plexiglass was used as a material for the Čerenkov counter at angles $30° \leqslant \Phi \leqslant 60°$, and water at $\Phi < 30°$. The correction was determined by comparing the number of particles recorded by the detector in ordinary conditions (which corresponded to experiments on the measurement of n-p scattering cross sections), with the number of particles which the detector recorded, if the first counter of the detector is replaced by a Čerenkov counter. The efficiency of the Čerenkov counter was considered to be equal to 80% [4]. It should be noted that at angles $\Phi < 45°$, maximum energy recoil protons could likewise be recorded by the Čerenkov counter. Therefore, when measurement were being made at the above-stated angles, a part of the filter was placed in front of the detector in order to reduce the energy of the protons to a value equal to the threshold of the Čerenkov counter. The correction for an admixture of π^+ mesons at angles of $\Phi = 30°$ and $\Phi = 70°$ reached 24% and at the remaining angles it did not exceed 20%.

For determination of corrections due to nuclear absorption of protons in the material of the filter, use was made of the method of conjugated telescopes * which registered p-p collision events taking place in the scatterer placed in the 657 Mev proton beam. The correction was found as the ratio of the number of p-p collisions recorded when the defining telescope was operated without filter, to the number of counts with a filter of a given thickness. The correction factor thus found was close to unity at angles $\Phi \geqslant 60°$ and rose to a value of 2.6 ± 0.2 at $\Phi = 0°$. The geometry of the detector used in these experiments corresponded exactly to the conditions of the experiments for measuring the differential n-p scattering cross sections. The angle at which the defining telescope was placed was selected in such a way that the energy of the scattered protons entering the telescope was equal to the mean energy of the recoil protons at the angle for which the absorption correction was measured.

The absolute values of the differential n-p scattering cross sections were determined by normalizing the obtained angular distribution of recoil protons to the total cross section of elastic scattering of neutrons by protons, making use of the relation

$$\sigma^{\text{elastic}} = 2\pi \int_0^{\pi/2} \sigma_{np}(\Phi) \sin\Phi \, d\Phi \qquad (1)$$

The value of this cross section at 580 Mev was obtained as the difference of the total n-p interaction cross section

$$\sigma^{\text{total}} = (36 \pm 2) \times 10^{-27} \text{ cm}^2$$

and the total cross section for π meson production in n-p collisions

$$\sigma^{\pi} = (10 \pm 2) \times 10^{-27} \text{ cm}^2, \text{ [1]}$$

and comes to $(26.0 \pm 3.0) \times 10^{-27}$ cm^2.

* A method in which two telescopes are connected in coincidence and record simultaneously the scattered particle and the recoil particle.

In normalizing, it was assumed that in the angular region $\vartheta < 35°$ (center-of-mass system) the n-p scattering differential cross section increases monotonically reaching the value 6.10^{-27} cm²/sterad.

This value is the minimum value of $\sigma_{np}(\vartheta)$ at the energy $E_n = 580$ Mev and is obtained on the basis of the inequality

$$\sigma_{np}(0^0) > \left(\frac{k\sigma_{np}^{total}}{4\pi}\right)^2,$$

the correctness of which for nucleon-nucleon interaction was proved by L.I. Lapidus [5], who used the relation

$$\mathrm{Sp\,Im}\,M(0°) = \frac{k\sigma_{np}^{total}}{4\pi}$$

where M(0°) is the amplitude of forward scattering, and k is the wave number. However, it should be noted that a departure of the true distribution from that used during normalization cannot change considerably the obtained results since the total scattering in the angular region $0° \leqslant \vartheta \leqslant 35°$, even if the curve $\sigma_{np}(\vartheta)$ is symmetrical with respect to the angle 90°, amounts to less than 20% of the total cross section of elastic n-p scattering.

The final results of the measurements of the differential n-p scattering cross sections are given in fig. 3 and in Table 1.

TABLE 1

$\vartheta°$ in centre-of-mass system	$\sigma_{np}(\vartheta)$ in 10^{-27} cm²/sterad.
180°	8.4 ± 0.7
169°	5.3 ± 0.5
157°	3.4 ± 0.3
147°	2.1 ± 0.2
135°	1.7 ± 0.13
124°	1.0 ± 0.07
114°	0.78 ± 0.05
103°	0.78 ± 0.05
93°	0.91 ± 0.06
83°	1.1 ± 0.08
73°	1.6 ± 0.13
63°	2.1 ± 0.2
54°	2.3 ± 0.17
45°	3.0 ± 0.3
35°	3.7 ± 0.2

The errors given in the diagram and in the table are standard statistical errors in the determination of the angular distribution of recoil protons. The errors do not include errors in the determination of the elastic n-p scattering total cross section (12%) and a certain indefiniteness in the normalization (about 5%) that is due to the

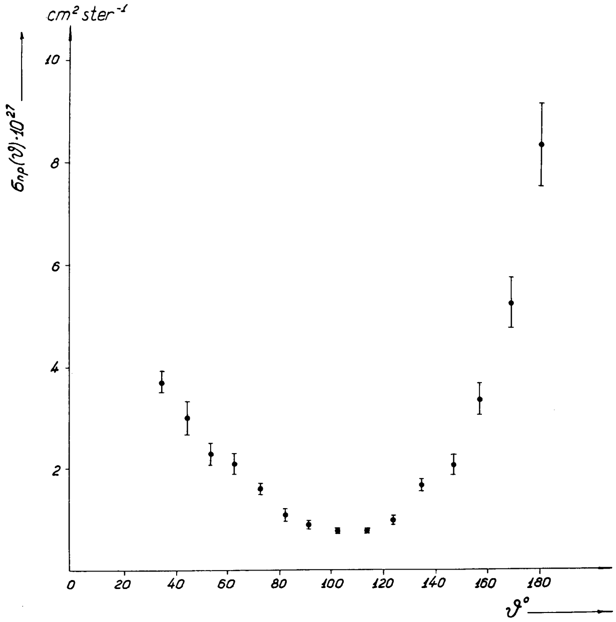

Fig. 3. Differential cross sections for elastic n-p scattering at neutron energy 580 Mev.

lack of precise data concerning the dependence of $\sigma_{np}(\vartheta)$ in the angular region $\vartheta < 35°$.

Discussion of the results of experiments on the scattering of neutrons by protons

The nature of the obtained dependence of the differential cross section upon the scattering angle shows that at 580 Mev, just as in the region of lower energies, exchange forces play a considerable role in n-p interaction. Exchange interaction and ordinary interaction make contributions of the same order of magnitude to the total elastic scattering cross section. The results also show that as the neutron energy rises from 300-400 Mev to 580 Mev the scattering picture also changes. Scattering anisotropy increases; the ratio of the cross sections σ_{np} (180°) to σ_{np} (90°) reaches the value (9 ± 1.2). The asymmetry of the curve $\sigma_{np}(\vartheta)$ with respect to the angle $\vartheta = 90°$ is clearly visible even in the region of angles exceedingly close to $\vartheta = 90°$.

It is of great interest that the energy dependence of n-p scattering cross sections at the angles close to 0° and 180° is different. If $\sigma_{np}(\vartheta \sim 180°)$ decreases with increasing energy (as follows from our measurements at $E_n = 380$ and 590 Mev), $\sigma_{np}(\vartheta \sim 0°)$ increases in this energy range.

(At $E_n = 400$ Mev $\sigma_{np}(15°) = (4.4 \pm 0.5) \times 10^{-27}$ cm²/ /sterad [20]; at 580 Mev, as was shown above, the minimum value of $\sigma_{np}(0°)$ is near 6×10^{-27} cm²/sterad); at 400 Mev $\sigma_{np}(180°) = (13,5 \pm 2.5) \cdot 10^{-27}$ cm²).

Iu. Pomeranchuk and L. Okun [20] indicated the possibility of a decrease in the backward scattering cross section with increasing energy due to the considerable role of meson production processes at nucleon energies higher than 500-600 Mev. In this case there must exist an energy range in which n-p scattering cross sections at 0° and 180° will be again close in magnitude (as it was at about 100 Mev). At still higher energies the scattering will be of a diffraction character (that is it will be mainly in the forward direction). This was brillantly confirmed by Dr. Smith in his report at the Moscow Conference on p-p scattering experiments carried out on the Brookhaven Cosmotron.

Lack of a precise theory of scattering does not permit us to carry out a rigorous analysis of available experimental data concerning the scattering of nucleons by nucleons; nevertheless, an attempt to consider the results obtained on the basis of certain general methods of classification of the states of a system of two nucleons should be of interest. It is undoubtedly of interest, for example, to analyse the obtained results from the standpoint of the charge independence of nuclear forces. It is not difficult to see that the results of our work do not contradict this hypothesis. Indeed, if we make use of the cross sections $\sigma_{np}(\vartheta)$ given in fig. 3 and the cross sections $\sigma_{pp}(\vartheta)$ found [6, 7] for practically the same energy, it may be seen that they satisfy the well-known relation:

$$2[\sigma_{np}(\vartheta) + \sigma_{np}(\pi-\vartheta)] - \sigma_{pp}(\vartheta) = \sigma_{T=0}(\vartheta) > 0 \qquad (2)$$

which is a consequence of the above hypothesis [8].

Assuming the hypothesis of charge independence of nuclear forces to be valid and making use of (2) one can find the differential n-p scattering cross section $\sigma_{T=0}(\vartheta)$ in the isotopic spin state T = 0, as well as determine the total cross section for elastic scattering of nucleons in this state. The latter, as may be clearly seen, is:

$$\sigma^{el}_{T=0} = 2\sigma^{el}_{np} - \sigma^{el}_{pp} \, . \qquad (3)$$

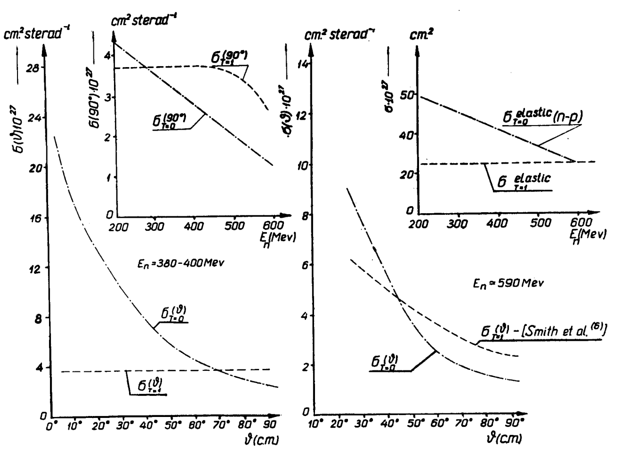

Fig. 4. Dependence on angle and energy of the cross sections $\sigma_{T=0}(\vartheta)$, $\sigma_{T=1}(\vartheta) = \sigma_{pp}(\vartheta)$, $\sigma^{el}_{T=0}$ and $\sigma^{el}_{T=1}$

Fig. 4 gives the angular and energy dependence of the scattering cross sections for nucleons in states with different T (T = 0 and T = 1) for two nucleon energies E_n = 380-400 Mev and 590 Mev, as well as the energy dependence of the total cross sections for the elastic scattering of nucleons in these states in the energy range of 200-600 Mev.

The curves of fig. 4 were plotted according to the data of the present work, the previously measured n-p scattering cross sections, the results of Smith [6] and Meshcheriakov [7] and to the Beretta survey [9].

Calculations show that the angular distributions $\sigma^{el}_{T=0}(\vartheta)$ and $\sigma^{el}_{T=1}(\vartheta)$ for lower nucleon energies are similar to those for E_n = 380 – 400 Mev.

As shown by Lapidus [10], a relation similar to (3) is valid also for the total cross sections for nucleon-nucleon interaction including both elastic scattering and meson production, that is

$$\sigma^{total}_{T=0} = 2\sigma^{total}_{np} - \sigma^{total}_{pp} \qquad (4)$$

From (3) and (4) one may find the total cross section for pion production $\sigma^{\pi}_{T=0}$ in the state with T = 0. Table 2 gives the corresponding data for E_n = 380 and 580 Mev.

TABLE 2

E, Mev	σ^{el}_{np}	$\sigma^{el}_{T=1}=\sigma^{el}_{pp}$	$\sigma^{el}_{T=0}$	$\sigma^{\pi}_{T=1}$ **)	$\sigma^{\pi}_{T=0}$
	in 10^{-27} cm²				
380	33±2[1])	24±1*	42 ± 3	1,5±1	0,5±4
580	26±3	25±1*	27±4	11±1$_1$	9±4

* These data were obtained by interpolation of the total cross sections for elastic p-p scattering foun d in[7]) and[12]) for nearly the same energies.

** $\sigma^{\pi}_{T=1}$ is the cross section for pion production in p-p collisions.

The curves in fig. 4 and the data of Table 2 allow us to draw the following conclusions:

1. In a broad energy range the angular and energy dependence of the differential cross sections for nucleon-nucleon scattering in the states T = 1 and T = 0 are sharply different. As the energy rises to 580 Mev, there is a tendency towards a reduction of the difference between the two states. However, it manifests itself clearly at this energy as well.

2. The total cross sections for elastic n-p scattering in the states T = 0 and T = 1 varies differently with energy. While $\sigma^{el}_{T=1}$ does not depend upon the energy in a broad energy range, $\sigma^{el}_{T=0}$ systematically decreases with increase

in the energy and at 580 Mev (within experimental errors) becomes equal to $\sigma^{el}_{T=0}$. According to the hypothesis of charge independence this decrease of $\sigma^{el}_{T=0}$ may account for the fact that in spite of the increase in meson production cross section the total n-p interaction cross section in the indicated energy range remains constant.

3. Both states of the n-p system (T = 0 and T = 1) give a comparable contribution to the elastic scattering cross section at angles around 90°.

4. The probabilities of meson production at 580 Mev for nucleon-nucleon collisions in the states T = 0 and T = 1 do not differ very greatly. One must keep in mind, however, that the errors in the cross section $\sigma^{\pi}_{T=0}$ are still large.

A sharp difference in the behaviour of nucleon-nucleon scattering in the states T = 0 and T = 1 indicates that the interaction of nucleons in these states is different. It was also shown [8] that only the interaction in the state T = 1 is anomalous. The scattering cross section in the state T = 0 is reminiscent of that calculated in the Born approximation. A potential well is assumed to be matched for the scattering in this state.

At present, one cannot say with confidence whether these conclusions contradict the relatively intensive pion production (experimentally observed at about 600 Mev) and the significant cross section for elastic nucleon-nucleon scattering in the state with T = 0 at angles close to 90°.

It is possible that the correlation experiments on polarization in nucleon-nucleon scattering and triple scattering, and a corresponding analysis of the total sum of experimental data, would be of great value in determining the cause of the differences in the interaction of two nucleons in the states with different T *.

The marked asymmetry (observed in experiments for 580 Mev neutrons) of the curve $\sigma_{np}(\vartheta)$ with respect to an angle of 90° is, as an analysis shows, a result of the interference of waves that correspond to scattering in the states T = 0 and T = 1. In this light, the curve $\sigma_{np}(\vartheta)$, which was found at 90 Mev [13] and is nearly symmetrical, indicates that if at this energy there is wave interference from scattering in the above-mentioned states, its role is very small. On the other hand, since scattering at 90 Mev is described only by S, P and D-waves[14], it may be assumed, apparently, that asymmetry of the curve $\sigma_{np}(\vartheta)$ at 580 Mev is a result of the interaction of two nucleons in states of a system with orbital moments $l > 2$.

We attempted to evaluate the magnitude of the maximum moment that plays a marked part in neutron-proton scattering at 580 Mev. It is known that the highest order of the Legendre polynomials that enters into the expression for the angular distribution of scattered nucleons (when considering the problem of scattering in a nonrelativistic approximation) is equal to 2 l_{max}, where l_{max} is the maximum value of the orbital angular momentum that corresponds to the highest state in which marked interaction takes place at a given nucleon energy [15].

Calculations showed that the angular distribution $\sigma_{np}(\vartheta)$ (at E_n = 580 Mev) may be approximated by the expression ** :

$$\sigma_{np}(\vartheta) = \lambda\!\!\!^{-2} [|1,29 \pm 0,05| + |0,24 \pm 0,13| \cdot P_1 + |1,42 \pm 0,2| P_2 - |0,87 \pm 0,24| \cdot P_3 + |0,28 \pm 0,22| \cdot P_4 - |0,5 \pm 0,16| P_5 + |0,14 \pm 0,1| \cdot P_6 - |0,33 \pm 0,1| \cdot P_7 + |0,19 \pm 0,18| P_8 - |0,2 \pm 0,24| \cdot P_9 + |0,39 \pm 0,26| \cdot P_{10} + |0,10 \pm 0,19| P_{11} + |0,25 \pm 0,15| \cdot P_{12}]$$

where P_i is Legendre's polynomial and $\lambda\!\!\!^{-}$ is the wavelength that corresponds to the relative velocity of the nucleons.

Thus, the maximum value of the orbital angular momentum is equal to $l \simeq 6$. If we now make use of the concept of a collision parameter, it is possible to make a rough estimate of the effective dimensions of the region of interaction r. The evaluation gives for r the value of 2.2×10^{-13} cm.

3. *Elastic neutron-neutron scattering at 590 Mev*

In the low-energy region, the main source of information concerning neutron-neutron interaction is an analysis of data dealing with the coupling energies of mirror nuclei and the results of investigations of nuclear reactions which are accompanied by the production, in the final state, of two neutrons with small momenta of relative motion. At high energies, data on neutron-neutron interaction may be obtained from experiments in which the angular distribution of neutrons, scattered by deuterons and protons, are measured in identical conditions.

With the aim of justifying the possibility of determining elastic n-n scattering cross sections from experiments in n–d scattering, a preliminary analysis was made of the processes of interaction of high-energy neutrons and deuterons, and formulae were found that connected the total

* The above measurements apparently allow us to distinguish between interactions for different total spins S of the system with given T. A marked difference in the behaviour of nucleon-nucleon interaction cross sections in the states T = 0 and T = 1 is observed, and at the energies of 800-1000 Mev, as was shown by Dr. Bruckner at the Moscow Conference, it falls gradually (in agreement with the predictions of theory) in the energy range of 1.5-3 Bev when the elastic nucleon-nucleon scattering acquires purely diffraction character.

** The coefficients in this expansion are determined by the method of least squares.

probability of emergence during such collisions of the neutron at an angle θ (θ is the scattering angle in the laboratory system) to the direction of the primary beam, with the scattering cross sections of neutrons by free neutrons and protons. Calculations conducted in a nonrelativistic impulse-approximation showed that there exists an angular range where the total cross section of n-d scattering at a given angle practically coincides with the sum of the cross sections of the scattering of neutrons by free neutrons and protons [16].

The present-day state of the theory and the available experimental data allows only approximate estimations of the value of the interference term. In this connection, an attempt was made to determine experimentally the angular range where nucleon-deuteron scattering is of an additive character. Measurements were made of the relative values of the differential cross sections of p-d and p-p scattering, and the ratios

$$\frac{\sigma_{pd}(\vartheta) - \sigma_{pp}(\vartheta)}{\sigma_{pp}(\vartheta)} = \frac{\sigma_{np}(\vartheta) + \sigma_{interf}(\vartheta)}{\sigma_{pp}(\vartheta)}$$

were found. A comparison of these relations with the ratios of the cross sections of n-p and p-p scattering make it possible to find the region of scattering angles where

$$\sigma_{interf}(\vartheta) \ll \sigma_{np}(\vartheta)$$

Experiments conducted with 300 Mev and 400 Mev protons showed that at least in the angular range ϑ (ϑ is the scattering angle in the center-of-mass system)

$30° \leqslant \vartheta \leqslant 90°$ for $E_p = 300$ Mev
and $25° \leqslant \vartheta \leqslant 90°$ for $E_p = 400$ Mev

the total cross sections of p-d scattering at a given angle, coincide with the sum of the cross sections of p-p and p-n scattering to an accuracy of a few percent. Measurements of this type with high-energy protons were not made. However, the evaluations made by the authors showed that the region of scattering angles where the cross section of interference processes in n-d collisions forms a considerable portion of the nucleon-nucleon scattering cross sections at the same angle, decreases with an increase in the energy. Thus it may be considered that with the effective energy of the neutrons at 590 Mev, the region of additive scattering will be at least not narrower than in the case of 400 Mev neutrons, and consequently, the n-n scattering cross sections may be determined in the above-mentioned angular range ($30° \leqslant \vartheta \leqslant 90°$) as the differences between the cross sections of neutron scattering by deuterons and free protons.

Determination of n-n scattering cross sections

The cross sections were determined by comparison of the yields of high-energy neutrons from n-d and n-p collisions not accompanied by meson production. To do this, scatterers of D_20, H_20, CH_2 and C were placed in the neutron beam in succession (without turning off the accelerator) with the aid of a special remote control arrangement. The scattered neutrons were registered by a neutron telescope (fig. 5). This instrument consisted of a converter, four scintillation counters placed behind the converter for registration of charge-exchange protons, and one counter placed in front of the converter. The counter in front of the converter was connected in anti-coincidence with the remaining ones (which were connected in coincidence) and was used to exclude the charged particles emerging from the scatterer. The energy threshold of the neutron telescope was given by an absorber placed in the path of the charge-exchange protons, and was selected so that the effective energy of the primary neutrons equalled 590 Mev *.

When measuring the differential cross sections of n-d and n-p scattering, the neutron telescope was placed at given angles to the axis of the neutron beam, and for each of the scatterers a determination was made of the difference in the counting rates with the converter placed in its working position and removed from the path of the neutrons being registered. The difference in the effects produced by the polyethylene and carbon scatterers is proportional to the n-p scattering cross section:

$$N_{CH_2}(\vartheta) - N_C(\vartheta) = B(\vartheta)\,\sigma_{np}(\vartheta) \qquad (5)$$

A similar difference obtained with scatterers of D_20 and H_20 is proportional to the difference between the cross sections of neutron scattering by deuterons and protons:

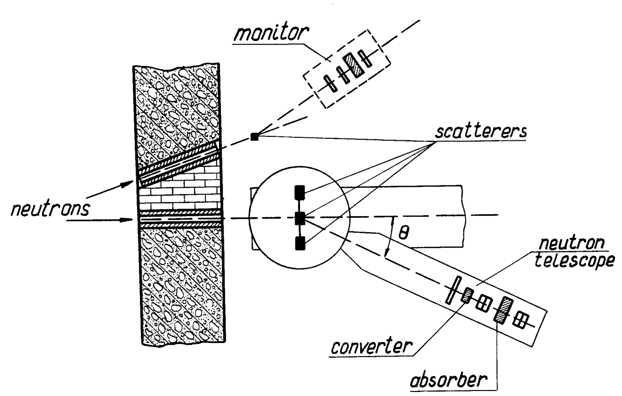

Fig. 5. Measurement of elastic n-n-scattering cross sections (experimental arrangement)

* With the given thickness of the absorber, the telescope recorded the effect only from incoming neutrons of more than 470 Mev.

$$N_{D_2O}(\vartheta) - N_{H_2O}(\vartheta) = B(\vartheta)[\sigma_{nn}(\vartheta) + \sigma_{interf}(\vartheta)] = B(\vartheta)S(\vartheta) \qquad (6)$$

The constants of proportionality in both cases are equal and depend on the geometry of the experiment, the effectiveness of the neutron telescope, and the intensity of the neutron beam.

In order to escape the difficulties connected with a precise determination of the values of these constants, in the present work measurements were made of the ratio of values (5) and (6) :

$$A(\vartheta) = \frac{\sigma_{nn}(\vartheta) + \sigma_{interf}(\vartheta)}{\sigma_{pp}(\vartheta)} = \frac{S(\vartheta)}{\sigma_{np}(\vartheta)} \qquad (7)$$

and then with the aid of the ratios found the unknown values $S(\vartheta)$ were determined from the known differential cross sections of elastic n-p scattering (obtained from the experiments [17]) described in section 2).

The measurements were made in the range of scattering angles ϑ from 30° to 90° in the center-of-mass system. The results obtained are given in fig. 6 and in Table 3.

TABLE 3

ϑ° in center-of-mass system	$\sigma_{nn}(\vartheta)$ in 10^{-27} cm²/sterad.
30°	5.8 ± 0.8
49°	4.7 ± 0.5
55°	3.8 ± 0.4
67°	2.9 ± 0.35
78°	2.3 ± 0.30
89°	2.5 ± 0.25

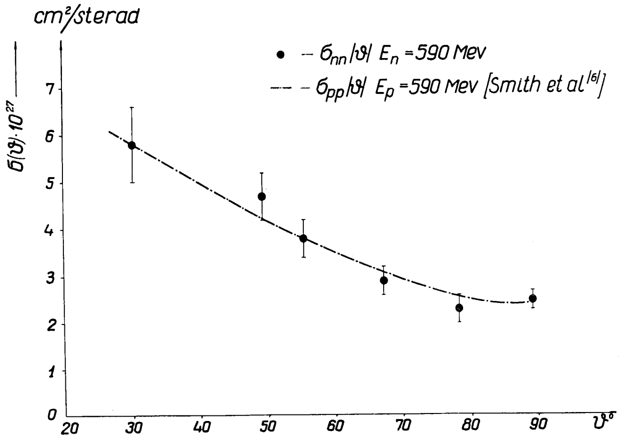

Fig. 6. Differential cross sections for elastic n-n scattering at neutron energy 590 Mev.

Due to the fact that the data of experiments conducted on a proton beam, as well as the results of our calculations, testify to the additive character of (n-d) scattering at energies $E_n \geqslant 300$ Mev and at scattering angles $30^\circ \leqslant \vartheta \leqslant 90^\circ$, it may be asserted that the cross section $S(\vartheta)$ found by us for 590 Mev coincides with the cross section of elastic scattering of neutrons by free neutrons $\sigma_{nn}(\vartheta)$.

Discussion of the results of experiments on neutron-neutron scattering

The most outstanding peculiarity of elastic neutron-neutron scattering, which is manifested when passing from 300 Mev to 590 Mev, is that, similar to p-p scattering, it becomes strongly anisotropic. Whereas for 300-Mev neutrons the ratio of cross sections $\sigma_{nn}(30^\circ) / \sigma_{nn}(90^\circ)$ was close to unity [18]), at 590 Mev the n-n scattering at an angle of 30° exceeds by 2.3 times the scattering cross section at 90°. The considerable anisotropy in n-n scattering at this energy testifies, apparently, to the increased role of the interaction of nucleons in states with high values of the angular momentum.

It is also possible that the reason for the anisotropy is the considerable increase in the cross sections of inelastic neutron-neutron interaction as the energy increases from 300 to 590 Mev. The following is a convincing indication of the large contribution of inelastic processes to n-n interaction. According to the data obtained by us, the difference of the total cross sections of n-d and n-p interaction (which difference characterizes the n-n interaction cross section with sufficient accuracy) varies in this energy range from $(23 \pm 3) \times 10^{-27}$ cm² to $(36 \pm 3) \times 10^{-27}$ cm² [(1)].

At the same time, evaluations show that the total cross section of elastic n-n scattering in this energy range practically does not vary at all and remains equal to (23-25) × × 10^{-27} cm². Thus, at 590 Mev, the cross section of the inelastic interaction of two neutrons forms about 40% of the elastic scattering cross section.

As may been seen from fig. 6, throughout the investigated region of scattering angles, the differential cross sections of elastic n-n scattering at 590 Mev coincide, in magnitude (within the limits of experimental error), with the corresponding cross sections of p-p scattering at the same energy [6]). This fact, together with the results of similar experiments we have made with 300 Mev neutrons[18]), prove directly the existence of the charge symmetry of nuclear forces at high energies.

An indication of the nuclear interaction of two neutrons and two protons being identical is given also by the equality (accurate within experimental error and effects of an electromagnetic character) of the total cross sections of n-d and p-d interactions at high energies.

To illustrate this fact, Table 4 gives the corresponding data obtained mainly in our laboratory and relating to the energy range 300-590 Mev.

TABLE 4

* E Mev	σ_{nd}^{total}	σ_{pd}^{total}
	in 10^{-27} cm^2	
315	—	56.8 ± 5 [12]
380	57 ± 2.5 [1]	—
400	—	58.9 ± 1.6 [19]
500	65 ± 2.5 [1]	61.7 ± 3.0 [19]
590	72 ± 2.5 [1]	66.8 ± 2.3 [19]

* The accuracy of the E-values given is in the order of 2-2.5%.

As a result of a comparison made earlier between the obtained differential cross sections of elastic n-p scattering and the cross sections of proton-proton scattering, it was established that these data do not contradict the hypothesis of the charge independence of nuclear forces. The results of the experiments with neutrons just described permit us to extend this conclusion also to neutron-neutron scattering.

Conclusion

The total and differential cross sections of elastic scattering of neutrons by protons and neutrons were determined at an energy close to 600 Mev. At this energy, the contributions of inelastic processes (meson production) to the total cross sections of n-p and n-n interaction amount already to about 30%.

The character of the obtained dependence of the differential cross sections upon the scattering angle shows that as the nucleon energy rises from 300-400 Mev to 580 Mev, the picture of nucleon-nucleon scattering varies considerably. The anisotropy of n-p scattering increases. The ratio of the cross sections σ_{np} (180°)/σ_{np} (90°) reaches a value of (9 ± 1.2). Neutron-neutron scattering also becomes sharply anisotropic : $\theta_{nn}(30°)/\sigma_{nn}(90°) = 2.3$.

Marked asymmetry of the curve $\sigma_{np}(\vartheta)$ is observed with respect to an angle of 90°, even in the angular region close to 90°. It should, however, be noted that the contributions made to neutron-proton interaction by ordinary and exchange forces remain of the same order.

An analysis of the experimental results lead to the following conclusions :

1. The total sum of the data obtained concerning the scattering of neutrons by nucleons does not contradict the hypothesis of the charge invariance of nuclear forces.
2. The equality of the differential cross sections of elastic n-n scattering, found in the experiments, with the cross sections of p-p scattering at the same energy is a direct indication of the charge symmetry of nuclear forces in the high-energy region. The equality of the total cross sections of n-d and p-d interactions at the same nucleon energy is an added proof of this fact.

3. A qualitative analysis of the experimental data carried out on the basis of the hypothesis of charge invariance showed that the sharp difference (observed at the energies of 300-400 Mev) between the angular and energy dependence of nucleon-nucleon scattering cross sections in states with different total isotopic spins decreased considerably as the energy increased to about 600 Mev.

4. The character of the dependence of the n-p scattering differential cross section upon the scattering angle makes it possible to assume that at an energy close to 600 Mev a marked interaction in the system of two nucleons is present in states with orbital moments up to $l \simeq 6$.

In conclusion, the authors wish to thank M. G. Meshcheriakov, corresponding Member of the USSR Academy of Sciences, and R. M. Ryndin, Scientific Worker of the Institute of Nuclear Problems of the USSR Academy of Sciences, for a discussion of the results of the work, We are also extremely indebted to G. N. Tentiukova, I. V. Popova, and L. A. Kuliukina, Engineers of the Calculation Bureau, for making the necessary calculations.

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DISCUSSION

A. Roberts inquired about the origin of the second maximum around 300 Mev of neutron spectrum at 580 Mev (fig. 1 of the article).

V. P. Dzhelepov: We think that this maximum is caused by neutrons obtained in nucleon-nucleon reactions inside the beryllium nucleus, accompanied by meson production, such as the following reactions:

1. $p + p \rightarrow \pi^+ + n + p$
2. $p + n \rightarrow \pi^0 + p + n$
3. $p + n \rightarrow \pi^+ + n + n$

The arguments in favour of this explanation of the second maximum are the following:

1. At energies around 700 Mev the total cross section for production of high-energy neutrons by the above inelastic reaction is close to the n-p elastic cross section,

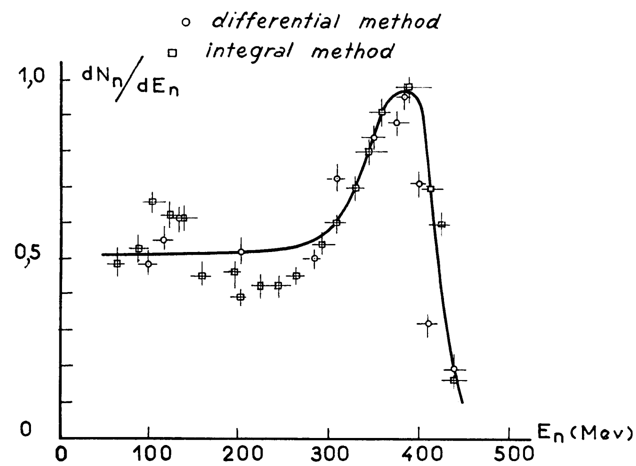

Fig. 1a. Energy spectra of neutrons. $\Theta = 0°$ $E_p = 480$ Mev

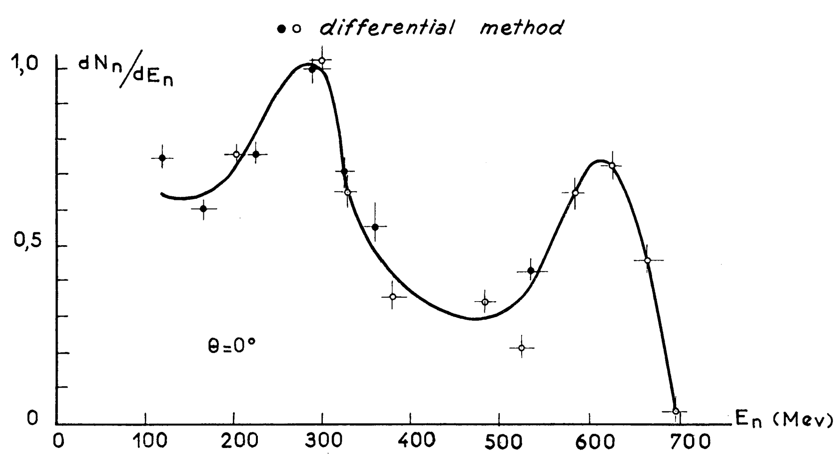

Fig. 1b. Energy spectra of neutrons. $\Theta = 0°$ $E_p = 680$ Mev

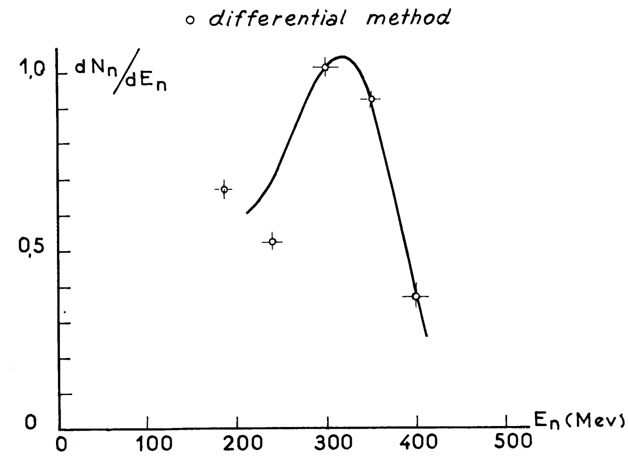

Fig. 1c. Energy spectra of neutrons.
$\Theta = 18°$ $E_p = 480$ Mev

and consequently the inelastic and elastic processes will contribute in comparable amounts to the neutron yield.

2. The position of the second maximum in the spectrum of neutrons emitted in the forward direction coincides within the experimental errors with the position of the peak in the energy spectrum of protons emitted in the forward direction as a result of the reactions :

$$p + p \rightarrow \pi^+ + n + p$$
and $$p + p \rightarrow \pi^0 + p + p$$

The proton spectra from these reactions have been investigated for an incoming energy of 660 Mev by M.G. Meshcheriakov and his collaborators.

3. As we go to an angle of the emitted neutrons of 18° the second maximum in the neutron spectrum is shifted somewhat towards lower energies (from 270 to 230 Mev). This is shown by the accompanying figs. 1a and 1b showing the neutron spectra at 0° and 18° for bombarding proton energies of 480 Mev, as measured by V. B. Fliagin, V. P. Dzhelepov and Iu. M. Kazarinov, and at 680 Mev, as measured by V. B. Fliagin and W. S. Kiselev (figs. 1c and 1d). The low energy part of the spectrum is visibly decreased.

4. At the lower bombarding energy of 480 Mev, where the cross section for meson production is much smaller compared to the elastic cross section, the low energy peak in the neutron spectrum is seen to be absent within the experimental errors.

The above arguments also indicate that the mechanism of nucleon emission in conjunction with pion production inside a complex nucleus has to some degree the same features as the elementary nucleon-nucleon process.

E. McMillan inquired about the construction of the neutron detector used by Prof. Dzhelepov.

V. P. Dzhelepov described in some detail the neutron telescope shown in fig. 5 of the preprint, which consists of an anticoincidence scintillation counter, a converter, and a telescope for measuring the recoil protons from the converter. The proton telescope required the protons to penetrate an absorber so that only neutrons of more than 460 Mev were detected.

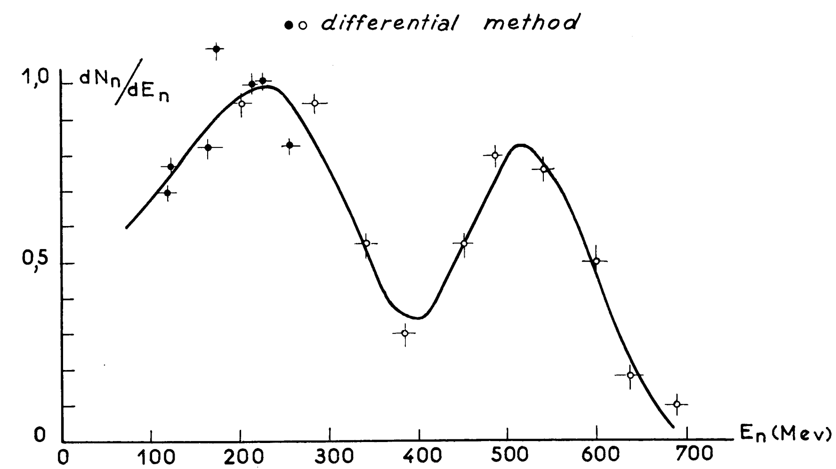

Fig. 1d. Energy spectra of neutrons.
$\Theta = 18°$ $E_p = 680$ Mev