POLARIZATION IN p-n AND n-p SMALL ANGLE SCATTERING AT ABOUT 600 MeV †

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As is known, results of all experiments on elastic nucleon-nucleon scattering may be expressed as different combinations of five complex scattering amplitudes. The determination of these in the general case requires nine independent experiments [1].

Due to the unitarity of the scattering matrix in the energy region below the threshold of mesons production, the number of the necessary experiments reduces to five [2]. In the energy region above 300 MeV, the number of experiments necessary for the determination of the amplitudes increases to 9; that is to 18 if both amplitudes (A_{pp} and A_{np}) are determined in separate analysis of the data. It may be shown that the charge independence of nuclear forces allows one to decrease the number of independent experiments necessary for the determination of *n-p* and *p-p* amplitudes to 13, provided one carries out a joint analysis of *n-p* and *p-p* data.

It also follows from charge independence that both *n-p* and *p-p* scattering are described by 10 complex functions. These functions are connected with the nucleon interaction in the different isotopic spin states and defined in the angular interval ($0 \leqslant \theta \leqslant \pi/2$). Therefore, every pair of similar experiments with *p-p* system (in the angular interval ($0 \leqslant \theta \leqslant \pi/2$)) and *n-p* system (in the interval ($0 \leqslant \theta \leqslant \pi$)) gives information about 3 real functions describing the scattering. Two functions are determined by nucleon interactions in the states with $T = 0$ and $T = 1$. The third function is the interference between these states. Therefore six pairs of identical experiments with *n-p* and *p-p* systems and one additional experiment with the *n-p* or *p-p* system should be done to determine completely (except for a phase factor common for the *p-p* and *n-p* amplitudes) the *n-p* and *p-p* amplitudes.

In order to make a combined analysis along the lines proposed above, a system of five experiments discussed by Putzikov et al. [2] must be partly carried out. Furthermore, the other experiments must be chosen carefully, so as to yield a unique solution for the scattering amplitude.(*)

Possibility of using data from p-d-scattering

In a number of papers proton scattering by neutrons in *p-d* collisions has been investigated. Here, however, the question about the validity of using the obtained results instead of the data on free *n-p* scattering arises. We have considered earlier the conditions under which the data on *n-d* scattering may be used for obtaining cross-sections for elastic neutron-neutron scattering [3]. We have made an attempt to obtain nucleon polarization in different types of nucleon-deuteron collisions with a non-relativistic impulse approximation and to determine their connection with the polarization in free *n-p* scattering, using a method similar to that applied by Tamor [4].

For the case of the incident nucleon being scattered into the angle θ of the lab. co-ordinate system and the states of the other two nucleons remaining undetermined, the following expression for the polarized cross-section PQ obtains:

$$(PQ)_{pd}(\theta) = (PQ)_{pp}(\theta) + PQ_{np}(\theta) + PQ_{\text{interf.}}(\theta) \cdot I(\theta).$$

Here $I(\theta)$ is a function, equal to unity at $\theta = 0°$ and rapidly decreasing with the scattering angle.

From this expression one can see that in the angular interval where the integral of $I(\theta)$ is small the polarized cross-section for *p-d* collisions coincides with the sum of the polarization cross-section for *p-p* and *n-p* collisions (**).

In concluding we may remark that in approximate reconstruction of the nucleon-nucleon scattering amplitudes, the other data on nucleon-deuteron collisions may also be useful, as the corresponding expressions contain combinations of amplitudes that enter only in the most complicated experiments with free nucleons. In particular, the expression for the polarized *p-d* elastic cross-section obtained contains beside the usual terms Re ae^* also terms of the type Re be^*, which enter only into the expression describing the correlation of the polarization in the scattering of the polarized beam.

† Appendix to Session 2. — Experimental I.

(*) The discussion of a system of experiments for a combined analysis as well as the relevant analytical expressions will be given in our paper submitted to JETP.

(**) The measurements performed by us show that at 635 MeV the interference term is already small at $\theta \geqslant 8°$.

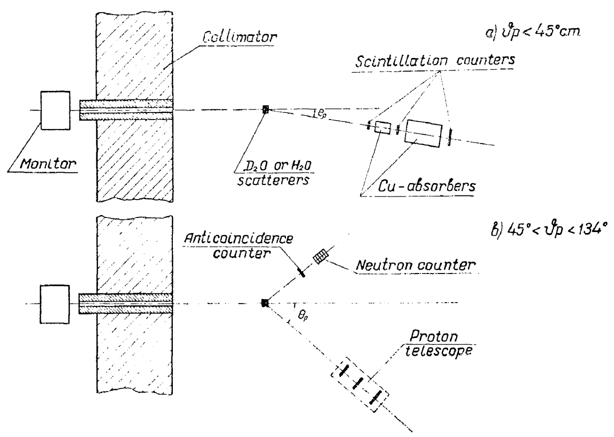

Fig. 1. *Experimental arrangements used in measurements of polarization in p-n scattering.*

Results of the experiments and related discussion

In the experiments performed at the Laboratory for Nuclear Problems, at energies in the neighbourhood of 600 MeV, the total *n-p* [5] and *p-p* [6] collision cross-sections, the differential cross-section for *n-p* [7] and *p-p* [8] elastic scattering and the polarization in the elastic *p-p* scattering [9] were measured. During the last year we studied the angular dependence of polarization in *p-n* scattering in *p-d* collisions ($E_p = 635$ MeV) and the differential cross-sections for elastic scattering of neutrons by free protons at small angles ($E_n = 600$ MeV).

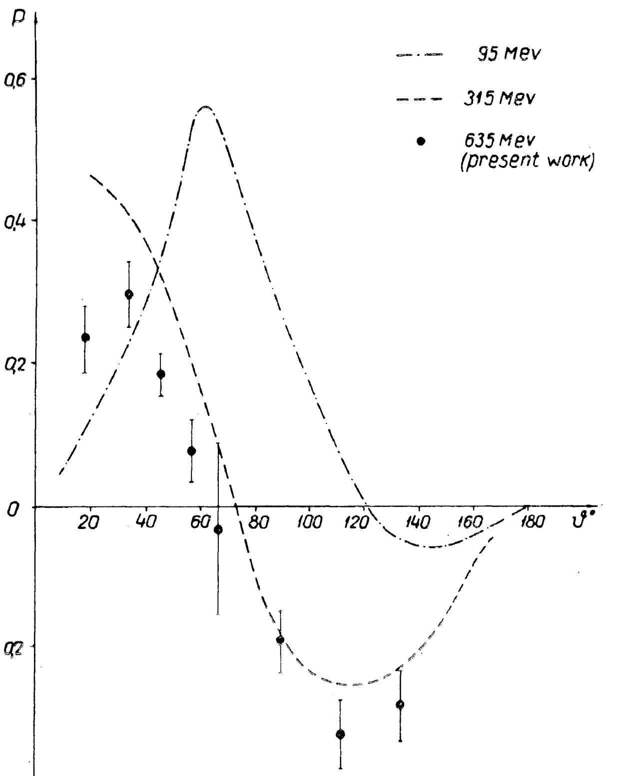

Fig. 2. *Polarization for n-p scattering as a function of c.m. scattering angle at 95, 315 and 635 MeV.*

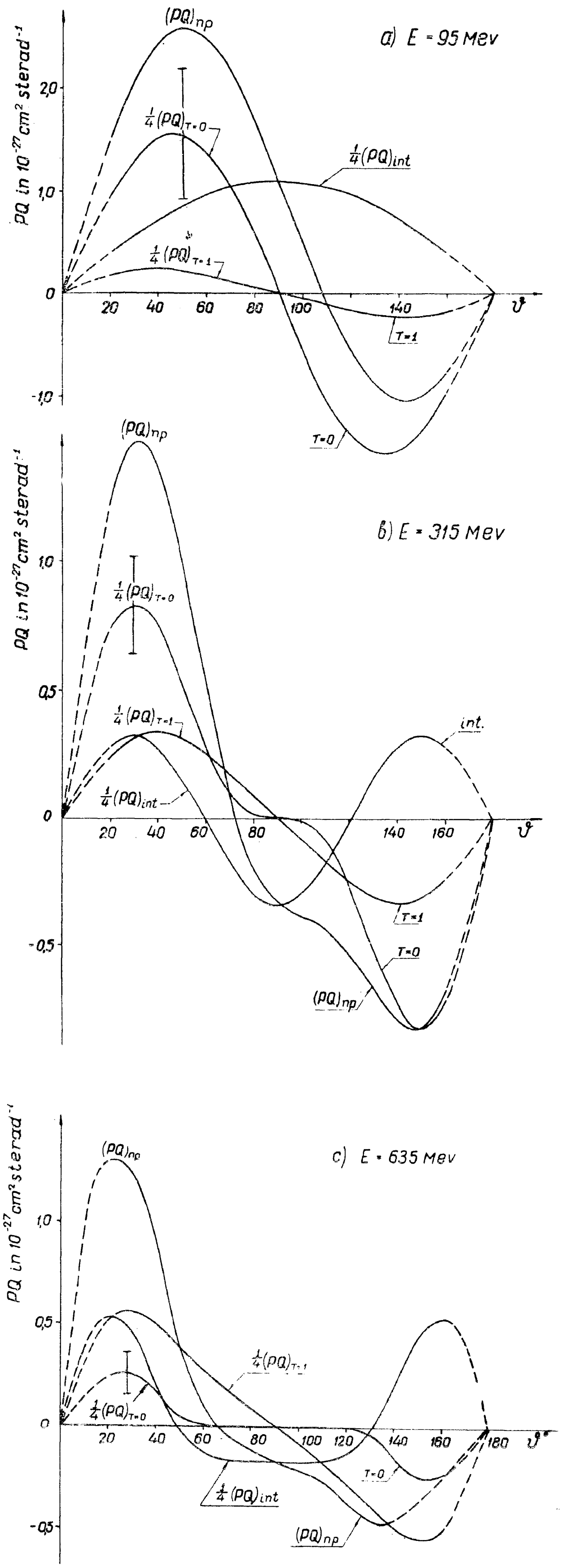

Fig. 3. *Polarization cross-sections PQ as a function of scattering angle θ.*

1. Fig. 1 gives the scheme of the experiments on the polarization in *p-n* collisions at 635 MeV. Simultaneously with the measurements of the asymmetry in *p-n* scattering, the asymmetry in quasi free or free *p-p* scattering were measured. The agreement of the values obtained with the asymmetry in free *p-p* scattering at the same energy as in [9] served as a criterion that in our experiments there was no spurious asymmetry.

The results on the angular dependence of the polarization in *p-n* scattering are given by Fig. 2 (*) together with results obtained by the authors at smaller energies [10, 11]. It is to be noted that in the energy interval 100-300 MeV, the dependence quoted changes sharply. In the energy interval 300-635 MeV the change of that dependence is not so drastic. Although the polarization data in *n-p* scattering have a relatively low accuracy, it may be useful to extract from them the polarized cross-sections of the nucleons interacting in different isotopic spin states. The results obtained for three energies of the nucleons are given by Fig. 3. All the " partial " cross-sections are given with the weights with which they enter in the polarized *n-p* scattering. It may be seen that the relative contributions of the " partial " polarized cross-sections in PQ_{np} depend considerably on energy, and that these cross-sections vary differently with energy for $T = 1$ and $T = 0$ states. $PQ_{T=1}$ rises with the energy, $PQ_{T=0}$ drops considerably when the energy rises. The fact that the polarized cross-section for $T = 0$ is fairly large at 635 MeV reveals a considerable amount of non-central interactions in these states. The same conclusion for energies 100-300 MeV was made by Wolfenstein [12, 20].

The drop of the polarization cross-sections $PQ_{T=0}$ together with the previously obtained data on the angular dependence of the elastic scattering in $T = 0$ states, and the data on the decrease of the total nucleon cross-sections in these states with the rising energy [13] may serve as an additional argument in favour of the possibility of a qualitative description of the nucleon interaction in $T = 0$ states by the Born approximation [14].

2. The small angle *n-p* scattering at $\sim$ 600 MeV was observed in our laboratory in two different ways. In the first experiments [15] the neutrons were registered by a neutron telescope and cross-sections at $\theta = 11^\circ$ and 23° were obtained. The second group [16] designed and used for this purpose a ring scatterer, containing 100 times more of scattering matter than used in conventional targets. The experimental scheme is shown in Fig. 4. This method allowed us to go into the region of smaller angles and to determine the cross-sections down to $\theta = 5^\circ$ (see Table).

θ C. of M.	5°	8°	11.5°	23°	35° *matching point*
$Q_{np}(\theta)$ in 10^{-22} cm²/sterad	10 ± 2	8.2 ± 1.4	6.4 ± 0.9	4.3 ± 0.5	3.7 ± 0.2 [7]

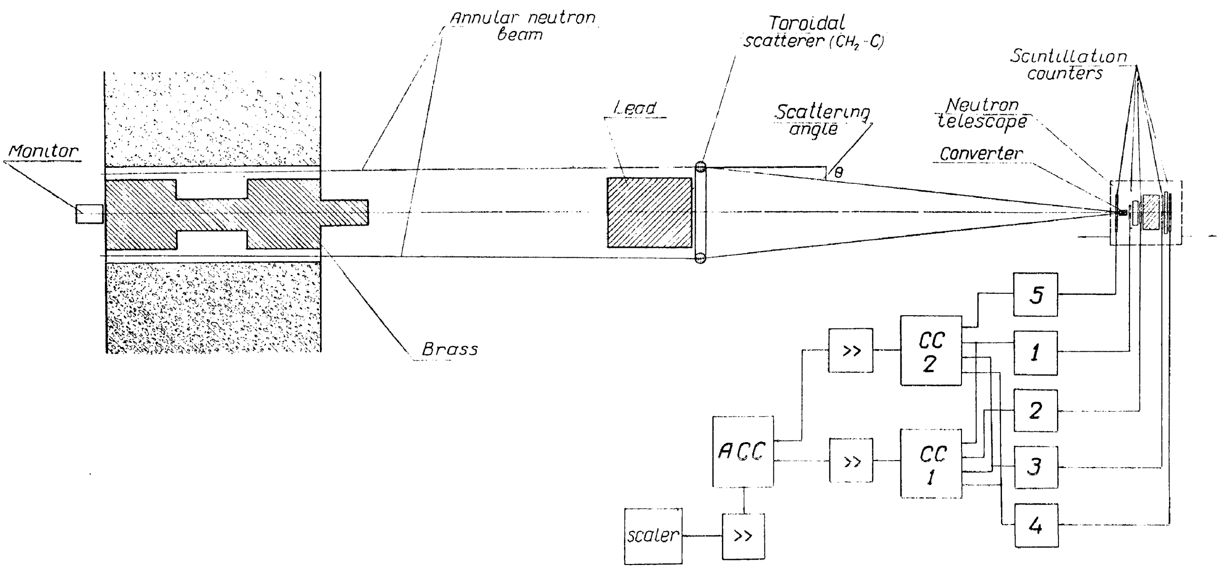

Fig. 4. *Experimental arrangements used for measurements of cross-section for n-p scattering at small angles.*

(*) When calculating the polarization in *p-n* collisions for 635 MeV, the value of the polarization of the primary proton beam equal to $P = (58 \pm 3)\%$ [9] was used.

In the overlapping angular regions the results of these two papers are in good agreement. It can be seen from the data that the n-p scattering cross-section rises rapidly at small angles and already for $\theta = 5°$ the cross-section exceeds the value for zero angle, predicted by the optical theorem for the opaque sphere, which for 600 MeV is 5.8×10^{-27} cm²/sterad.

This gives us strong indications to believe that besides the imaginary part of the spin independent term of the neutron-proton scattering amplitude at $\theta = 0°$ there is also a large contribution from the real part of the spin independent term, as well as non-vanishing spin dependent terms of the amplitude.

This circumstance, together with the considerable polarization in n-p scattering observed by us, leads to the conclusion that it is not possible to consider the neutron-proton scattering at 600 MeV with the black sphere model for the nucleons, as this model does not give the polarization, while the complete forward scattering amplitude is given by the imaginary part of the spin independent part [17]. The same conclusion may be drawn also for p-p scattering at these energies.

3. From the above it may be seen that in spite of some difficulties appearing in the analysis of n-p scattering, at present there is data showing some peculiarities of the n-p interaction. In this connection it is useful to compare the data obtained at various energies. As an example of such a comparison we consider the polarization cross-section for n-p scattering at 90° c.m. At this angle only one term remains in the expression for PQ_{np}, which is determined by the interference between the states with different isotopic spin. Fig. 5 gives the present data on PQ_{np} (90°) for a variety of energies. It is remarkable that this quantity changes its sign, becoming zero near 200 MeV. From the paper of Signell and Marshak [18] it follows that at 150 MeV both the s-phases decrease, and the phases of all the other waves rise with energy. Comparison of these results with the phase-analysis of the p-p scattering at 300 MeV [19] shows that the ^1S-phase changes its sign in the interval 150-300 MeV. On the other hand, according to Wolfenstein [20] the main contribution to the polarization in n-p scattering near 100 MeV is due to the interference of ^3S - ^3D - waves. If one assumes that also at higher energies there is a considerable contribution from the interference of different waves with the ^3S-waves, one may come to the conclusion that the phase of the ^3S-wave changes its sign near 200 MeV; this means that the phases of both S-waves behave similarly in this energy region.

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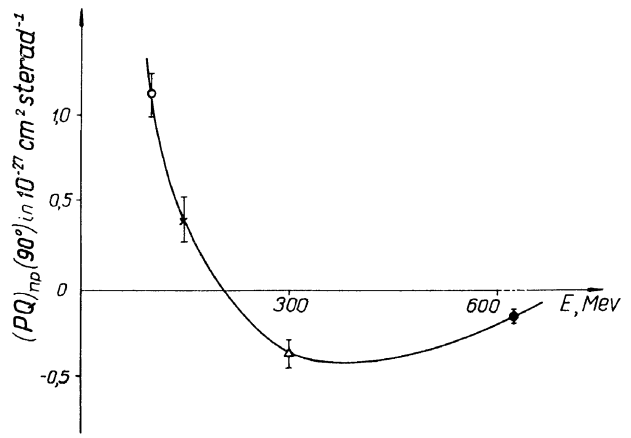

Fig. 5. *Polarization cross-section for n-p scattering at $\theta = 90°$ as a function of nucleon energy*: ○ - [10]; × - [18]; △ - [11]; ● - *the present work.*

LIST OF REFERENCES

1. Oehme, R. Phys. Rev., *98*, p. 216, 1955.
2. Puzikov, L., Ryndin, R. and Smorodinskij, Ya. Zh. eksper. teor. Fiz., SSSR, *32*, p. 592, 1957.
3. Golovin, B. M. Dissertation. LYAP OIYAI No. 510, 1955.
4. Tamor, S. Phys. Rev., *97*, p. 1077, 1955.
5. Dzhelepov, V. P., Satarov, V. I. and Golovin, B. M. Doklady Akad. Nauk SSSR, *104*, p. 717, 1955.
6. Dzhelepov, V. P., Moskalev, V. I. and Medved', S. V. Doklady Akad. Nauk SSSR, *104*, p. 380, 1955.
7. Kazarinov, Yu. M. and Simonov, Yu. N. Zh. eksper. teor. Fiz., *31*, p. 169, 1956. Trans. Sov. Phys. JETP, *4*, p. 161, 1957.
8. Bogachev, N. P. and Vzorov, I. K. Doklady Akad. Nauk SSSR, *99*, p. 931, 1954.
   Bogachev, N. P. Doklady Akad. Nauk SSSR, *108*, p. 806, 1956.
9. Meshcheryakov, M. G., Nurushev, S. B. and Stoletov, G. D. Zh. eksper. teor. Fiz., *33*, p. 37, 1957.
10. Stafford, G. H., Whitehead, C. and Hillman, P. Nuov. Cim., *5*, p. 1589, 1957.
11. Chamberlain, O., Segrè, E., Tripp, R. D., Wiegand, C. and Ypsilantis, T. J., Phys. Rev., *105*, p. 288, 1957.
12. Wolfenstein, L. Phys. Rev., *101*, p. 427, 1956.
13. Dzhelepov, V. P., Golovin, B. M., Kazarinov, Yu. M. and Semenov, N. N. CERN Symposium 1956, *2*, p. 115.
14. Smorodinskij, Ya. A. Prob. sovrem. Fiz. No. *7*, 1954.
15. Amaglobeli, N. S. and Kazarinov, Yu. M. Zh. eksper. teor. Fiz., *34*, p. 53, 1958.
16. Golovin, B. M., Dzhelepov, P. V., Katyshev, Yu. V., Konin, A. D., Medved', S. V. (to be published)
17. Lapidus, L. I. (to be published in Zh. eksper. teor. Fiz.)
18. Signell, P. S. and Marshak, R. E. Report NYO 2100. Univ. of Rochester 1957. (to be published in Phys. Rev.)
19. Stapp, H. P., Ypsilantis, T. J., Metropolis, N. Phys. Rev., *105*, p. 302, 1957.
20. Wolfenstein, L. Ann. Rev. nucl. sci., *6*, p. 43, 1956.