SCATTERING OF PROTONS WITH ENERGIES OF 460 AND 660 MEV BY PROTONS AND DEUTERONS

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Experiments devoted to the study of nucleon scattering by nucleons and deuterons are the first stage in implementing the programme of experiments dealing with the investigations of interaction between high-energy nucleons and nucleons and nuclei.

This paper is devoted to experiments on studying elastic p-p and p-d scattering of protons with the energies of 460 and 660 Mev, as well as the quasi-elastic scattering of protons by nucleons contained in the deuteron. The experiments were conducted on a non-polarized proton beam ejected from the USSR Academy of Sciences, Institute of Nuclear Problems synchrocyclotron. The proton energy in the ejected beam was determined by measuring the angle of Čerenkov radiation of protons and amounted to 460 ± 1 and 657 ± 2 Mev. The energy non-uniformity was equal to ± 4 and ± 8 Mev, respectively[1]. Scintillation-counter telescopes were used to record the scattered protons and deuterons. The scattered particles were detected either by two telescopes connected to the coincidence circuit or by each telescope separately. Ionization chambers filled with helium or argon were used as monitors.

Previous experiments [2, 3, 4] on investigating elastic p-p scattering in the energy region of 460 to 660 Mev were conducted in the range of angles of 30 to 90° in c.m.s. (centre-of-mass system). These experiments revealed qualitative changes in the pattern of p-p scattering: deviation from isotropy in scattering, which developed into a clearly pronounced anisotropy, and a change in the magnitudes of differential cross-sections of p-p scattering with an increase of energy. Experiments dealing with the study of elastic p-p scattering at the energies of 460, 560 and 660 Mev in the region of angles down to 5° in c.m.s. ($\sim 2.2°$ in a laboratory system) have now been completed. In these experiments the scattered protons were recorded by a single telescope. The charged products of inelastic p-p collisions (π^+ mesons, protons and deuterons) were separated from elastically scattered protons by means of absorption filters. The experiments were performed with a liquid hydrogen target[5].

The absolute values of differential cross-sections were determined by normalizing the relative cross-sections with the help of the data obtained from previously performed work[2, 3, 4]. The results of the measurements are given in Table 1.

TABLE 1

Differential cross-section of p-p scattering at the energies of 460, 560 and 660 Mev in the small-angle region (in units of 10^{-27} cm^2 × sterad^{-1}).

Angle θ in c.m.s.	Energy in the lab. system (Mev)		
	460	560	660
5°	33 ± 6	26 ± 5	18.9 ± 1.1
10°	5.91 ± 0.46	8.04 ± 0.78	11.0 ± 0.7
15°	4.69 ± 0.38	6.78 ± 0.63	8.67 ± 0.53
20°	—	6.29 ± 0.58	7.75 ± 0.48
25°	—	5.70 ± 0.53	6.56 ± 0.40

Measurements of the p-p scattering cross-sections at the energy of 650 Mev in the angular region of 10° to 90° were also made on the Birmingham accelerator by means of a diffusion chamber[6]. Considering the relatively poor statistical data as well as the energy distribution in the proton beam used in Birmingham, it can be said that the results of the present experiments agree fairly well with the results obtained in Birmingham.

As shown in Table I, at all the energies investigated in the region of small angles there occurs a further increase in the cross-section of the p-p scattering with a decrease of the angle. At an angle of 5° in c.m.s. a particularly marked influence of Coulomb scattering and its interference with the nuclear scattering is observed. For this reason measurements at the angle of 5° were not taken into account when the total cross section of elastic p-p scattering was computed, and the function $\sin\theta \frac{d\sigma(\theta)}{d\omega}$ in

the angular range from 0° to 10° was extrapolated to zero according to the linear law. The total cross-sections of elastic scattering of protons by protons are given in Table 2.

TABLE 2

Total cross-sections of elastic and inelastic processes in p-p interaction (in units of 10^{-27} cm^2)

Energy in Mev	Elastic	Total	Inelastic
460	24.0 ± 0.6	27.6 ± 0.4	3.6 ± 0.7
560	25.2 ± 0.8	34 ± 0.5*	8.8 ± 0.9
660	24.7 ± 1.0	41.4 ± 0.6	16.7 ± 1.2

* Obtained trough interpolation of the data given in reference[8]).

At an energy of 560 Mev the value of the total cross-section of the elastic p-p scattering was determined from the data presented in the papers [4, 7]) and the results of the present experiments. Table 2 also contains the total cross-sections of p-p interaction measured elsewhere[8]). These data and our results on the total cross-sections of elastic p-p scattering allow us to obtain the total cross-sections of inelastic collisions of protons with protons, which are also given in Table 2.

The data presented in Table 2 demonstrate that the total cross-section of elastic p-p scattering in the energy range of 460 to 660 Mev remains constant within the experimental errors. Consequently, the increase in the total cross-section of p-p interaction [8, 9]) in the energy interval of 460 to 660 Mev can only be accounted for by the processes of meson production.

The investigation of elastic p-d scattering and quasi-elastic p-p and p-n scattering at the energies of 460 and 660 Mev were carried out by means of equipment similar to that used for investigating elastic scattering of protons by protons in the region of large angles[2, 3, 4]).

In order to distinguish the processes of elastic p-d and quasi-elastic p-p scattering one of the telescopes was fixed at a predetermined angle, while the second one, connected in coincidence with the first, was set at various angles on the opposite side of the proton beam. Fig. 1 shows a typical curve of the coincidence count in such experiments as a function of the angle between the telescopes. The curve distinctly shows two maxima : one of them belongs to the elastic p-d scattering, and the other, located in the region of the maximum of elastic scattering of protons by free protons, is accounted for by the quasi-elastic scattering of protons on protons bound in deuterons.

Measurements of the differential cross-section of elastic p-d scattering were made in the ranges of angles 40 to 130° and 40 to 150° in c.m.s. at the energies of 460 and 660 Mev, respectively. To obtain better selection of the elastic p-d scattering events a filter absorbing deuterons was set up behind the deuteron telescope, as well as a scintillation counter connected in anti-coincidence with the deuteron telescope. The cross-section of elastic p-d scattering at the energies of 460 and 660 Mev is given in Table 3.

These data together with the results presented in other papers [10-13]) relating to smaller energies demonstrate that in the region of angles less than 110° in c.m.s. the differential cross-sections of elastic p-d scattering decrease with the increase in the angle and the energy.

The elastic scattering of protons by deuterons at large angles attracts particular attention. In this case the forward-moving deuteron takes up most of the momentum and receives an energy exceeding hundreds of times the binding energy of a nucleon in the deuteron. A large transfer of energy to the deuteron (up to 560 Mev) appears to take place at such a moment of collision, when the nucleons in the deuteron are at relatively small distances. This means that proton scattering by deuterons accompanied by a considerable momentum transfer to the deuterons results from interaction between the incident proton and both nucleons of the deuteron.

TABLE 3

Differential cross-sections of elastic p-d scattering at the energies of 460 and 660 Mev (in units of 10^{-27} cm^2 sterad^{-1})

Angle of scattering in c.m.s.	Energy in the laboratory system (Mev)	
	460	660
39°	0.47 ± 0.20	
40°		0.124 ± 0.015
49°	0.31 ± 0.14	0.067 ± 0.013
58°	0.09 ± 0.09	
60°		0.035 ± 0.012
67°	0.09 ± 0.02	0.030 ± 0.008
78°		0.033 ± 0.016
92°		0.011 ± 0.009
112°		0.000 ± 0.025
126°		0.034 ± 0.017
128°	0.021 ± 0.016	
140°		0.047 ± 0.016
150°		0.063 ± 0.027

Elastic scattering of protons by deuterons at large angles is characterized by an increase in the differential cross-section in the angular range from 110° to 150° in c.m.s. Relative contribution of the back-scattering of protons increases with a rise of the energy of incoming protons. The preservation of deuterons intact at high momentum transfers may be caused by the same mechanism as that causing the emission of H^2, He^2, Li, Be etc. from nuclei bombarded by fast nucleons.

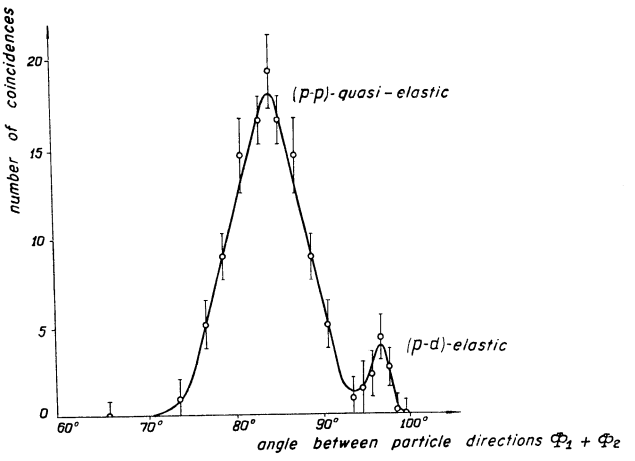

Fig. 1. The number of coincidences as a function of the angle between the telescopes

Measurements of differential cross-sections of quasi-elastic p-p scattering at the energies of 460 and 660 Mev were made at angles ranging from 50° to 90° in c.m.s. of two nucleons. The cross-sections of quasi-elastic p-p scattering differ little from those of elastic proton scattering by free protons at the corresponding angles. Nevertheless with a decrease in the angle of scattering the cross-section of the quasi-elastic p-p scattering becomes somewhat smaller than the corresponding cross-section of the elastic scattering of protons by free protons.

At the energy of 460 Mev a single telescope was used to measure the cross-sections of quasi-elastic p-n scattering in the angular region ranging from 20° to 150° in c.m.s. of two nucleons (see fig. 2). The differential cross-sections of quasi-elastic p-n scattering at the energy of 460 Mev is also in agreement with the neutron elastic scattering cross-sections at the energies of 380 and 580 Mev by free protons[14, 15]. It is worth mentioning that the differential cross-sections of quasi-elastic p-n scattering so obtained for small angles might prove exaggerated because of the interference effects.

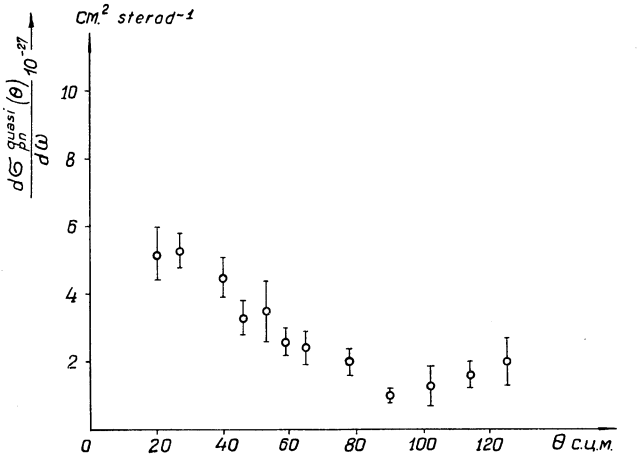

Fig. 2. Differential cross-section of quasi-elastic p-n scattering at the energy of 460 Mev

A comparison of the cross-sections of p-n scattering at various energies is of certain interest. Measurement of quasi-elastic p-n scattering by a single telescope at the energies of the order of 600 Mev proves to be impossible because of the considerable contribution made by the processes of meson production. For this reason when the energy dependence of quasi-elastic p-n scattering of two nucleons at the angle of 90° in c.m.s. was measured, one of the two telescopes, connected in coincidence, was replaced by a highly effective neutron detector[16]. Differential cross sections of quasi-elastic p-n scattering at 90° c.m.s. slightly decrease with a rise of energy in the interval 460-660 Mev.

LIST OF REFERENCES

1. Zrelov, V. P. (Instruments and experimental technique.) (to be published.)
2. Meshcheriakov, M. G., Bogachev, N. P., Neganov, B. S. and Piskarev, E. V. (Elastic scattering of 460 Mev protons by protons.) Doklady Akad. Nauk SSSR, *99*, p. 955-8, 1954.
3. Bogachev, N.P. and and Vzorov, I.K. (Elastic scattering of 660 Mev protons by protons.) Doklady Akad. Nauk SSSR, *99*, p. 931-3, 1954.
4. Meshcheriakov, M. G., Neganov, B. S., Soroko, L. M. and Vzorov, I. K. (Anomalous variations in cross-section for elastic scattering of protons by protons in the 460 to 660 Mev region.) Doklady Akad. Nauk SSSR, *99*, p. 959-61, 1954.
5. Sidorov, V.M., Frolov, N.I., Nozdrin, I. Kh. and Kavaliova, N.M. RINP, 1952.
6. Riddiford, L. (Study of the p,p interaction at about 650 Mev using protons accelerated in the Birmingham Synchrotron.) A paper presented at the Physical Society's Summer Meeting on "High-energy nuclear physics" at Liverpool, 1955. Also a private communication.
7. Selektor, Ia. M., Nikitin, S. Ia., Bogomolov, E. G. et Zombkovski, S. M. (Diffusion des protons d'énergies 460-660 Mev par les protons.) Doklady Akad. Nauk SSSR, *99*, p. 967-9, 1954.
8. Dzhelepov, V. P., Moskalev, V. I. and Medved, S. V. (Total cross-section of p-p interaction in the energy intervals of 410 to 660 Mev.) Doklady Akad. Nauk SSSR, *104*, p. 380-3, 1955.
9. Shapiro, A. M., Leavitt, C. P. and Chen, F. F. The total p-p cross section above 400 Mev. Phys. Rev., *95*, p. 663, 1954.

10. Stern, M. O. and Bloom, A. L. Elastic d-p scattering at 190 Mev. Phys. Rev., *83*, p. 178, 1951.
11. Cassels, J. M., Stafford, G. H. and Pickavance, T. G. Scattering of 146 Mev protons by deuterons. Nature, *168*, p. 556-7, 1951.
12. Schamberger, R. D. 240 Mev proton-deuteron scattering. Phys. Rev., *85*, p. 424-6, 1952.
13. Clark, D. D. and Chamberlain, O. Elastic scattering of 340 Mev protons by deuterons. Bull. Amer. phys. Soc., *29*, (1), p. 48, 1954.
14. Dzhelepov, V. P. and Kazarinov, Iu. M. (Elastic scattering of neutrons of energy 380 Mev by protons.) Doklady Akad. Nauk SSSR, *99*, p. 939-42, 1954.
15. Kazarinov, I. M. and Simonov, I. N. Zh. eksper. teor. Fiz. SSSR. (in the press.)
16. Akimov, I. K., Kuznetsov, A. S. and Leksin, G. A. (Instruments and experimental technique.) (in the press.)