"radium fork" (see Fig. 4). Judging by the latest published decay scheme for RaC[7], the total energy of the RaC″ – RaD transition is 5.4 Mev. It is obvious that the sum of the energy of the partial β spectrum and the kinetic energy of a neutron is 0.2 or 0.6 Mev, if the magnitude of the binding energy is respectively 5.2 or 4.8 Mev.

According to our data, the probability of neutron emission due to the β disintegration of RaC″ is ~ 2×10^{-2}%. A partial β spectrum is also predicted with an end-point energy of ~ 100 kev and a relative transition probability of $10^{-1} - 10^{-2}$%. When the energy of the basic β transition is ~ 2 Mev, the existence of this transition is possible. The neutron kinetic energy in this case should be no more than 0.5 Mev.

The authors are deeply grateful to the now deceased Academician P. I. Lukirskii for his fruitful discussion of this paper. We should also like to express our gratitude to M. I. Sergeev for his help in taking the measurements and preparing the apparatus and to V. M. Permiakov and O. M. Nechaeva for their help in obtaining and purifying the radon.

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109

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Elastic and Quasi-elastic Scattering of 660 Mev Protons by Deuterons *

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The differential elastic $p-d$ scattering cross sections at angles of 40° to 150° and the differential quasi-elastic $p-p$ scattering cross sections at angles of 50 to 90° of the two nuclei were measured in the center of mass system by the ganged-telescope method. The experimental data point to the existence of a predominant interaction between the incident proton and the separate nucleons in the deuteron and also to the existence of collective interactions between the three nucleons. The energy dependence of the differential cross section of quasi-elastic $p-n$ scattering into an angle of 90° in the c. m. s. of the two nucleons was also measured in the 460 to 660 Mev range.

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1. A study of the interaction of fast protons with the simplest nucleus–the deuteron–leads to several conclusions concerning the elementary nucleon-nucleon interactions and concerning the character of the motion of the nucleons in the deuteron, and also permits an approach to the study of the collective interaction of nucleons at high energies.

This article describes the experimental results of $p-d$ elastic and of $p-p$ and $p-n$ quasi-elastic scattering of 657 ± 2 Mev protons by deuterons. The proton beam was generated in the synchrocyclotron of the Institute for Nuclear Problems of the Academy of Sciences of the U.S.S.R. The method of ganged telescopes[1] was used to separate the above processes from the variety of meson-producing proton–deutron interactions. The twice-collimated proton beam from the accelerator passed through a monitor, before striking the target. An ionization chamber filled with helium was used as a monitor in the

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present experiments. Aluminum cylindrical containers filled with equal numbers of nuclei of heavy and ordinary water were used throughout as targets. The targets enveloped the beam and the errors caused by scattering in the side walls of the containers were thus eliminated. Two telescopes were used to detect the charged particles, each telescope consisting of three scintillation counters (photomultiplier and toluene crystal). The dimensions of the toluene crystals were selected so that the system registered coincidence if a scattered proton passed throught the crystal which determined the solid angle. To decrease the background count the crystals of the photomultipliers were chosen to be only 3 to 6 mm thick. The resolution time of the coincidence counts from the scintillation counters in the telescope was 4×10^{-8} sec. The resolution time of the coincidence counts from the telescopes was 8×10^{-8} sec. The number of accidental coincidences was measured by including a delay line of suitable length in one of the coincidence channels and also by uncoupling the telescopes. The individual telescopes and the entire system had a counting plateau 200 to 300 V wide at a working voltage on the photomultipliers of 1500 V.

2. The laws of conservation of momentum and energy make it possible to distinguish between the scattering processes of the two particles in accordance with the angle $\theta = \theta_1 + \theta_2$ subtended by the two particles for given divergence angle θ_1 of one of the particles. To distinguish elastic and quasi-elastic scattering of protons by deuterons, the dependence of the coincidence counting rate N on the angle θ subtended by the telescopes was therefore studied for three values of angle θ_1 of the fixed telescope relative to the direction of the proton beam. The three "divergence curves" obtained for the angles of the scattered protons in the laboratory coordinate system $\theta_1 = 24$, 36 and 41° are given in Figure 1 (all three curves a, b, c are plotted in a single

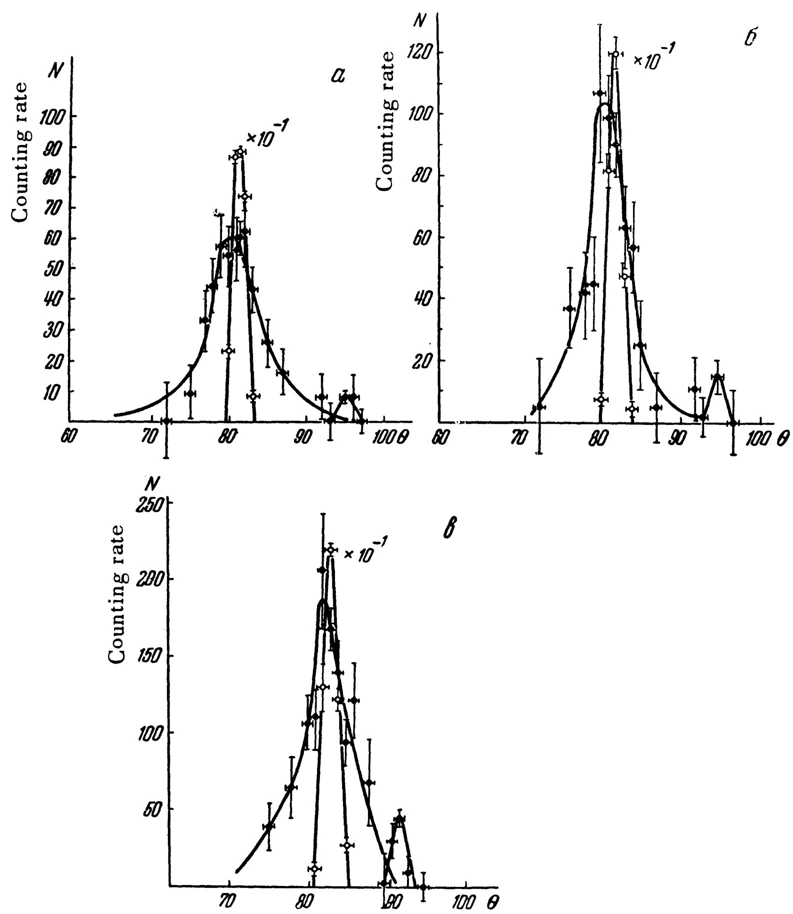

FIG. 1. Dependence of the coincidence count rate on the evergence of particles; $\theta = \theta_1 + \theta_2$, curve a for $\theta_1 = 41°$, b for $\theta_1 = 36°$, c for $\theta_1 = 24°$ in the laboratory system of coordinates.

scale). Each point on a divergence curve represents the difference between the counting rates obtained with D_2O and H_2O targets, after a correction for chance coincidence counts. The effect of the H_2O target, measured by the ganged telescopes, made it possible to determine, the contribution from processes originating from the oxygen nuclei outside the narrow range of angles comprising the peak of elastic p–p scattering. It also made possible measurement of the peak of the elastic scattering of protons by protons under identical conditions. To evaluate the magnitude of the cross section, and to show the characteristic resolution of the apparatus, the peak of elastic p–p scattering is shown in Figure 1 with the ordinate scale reduced by ten times.

The comparatively small cross section of the studied processes and the differential character of the experiment resulted in large statistical errors in the determination of the divergence curves. However, the divergenge curves obtained for deuterium and their comparison with the peak p–p elastic scattering permit the following conclusions:

a) Each divergence curve has two maxima. The position of the smaller of these two maxima corresponds to a divergence angle for elastic proton-deuteron scattering. The width of this maximum, as well as the equal width of the peak for elastic p–p scattering, is not connected with the properties of the nuclear interaction and characterizes the angular resolution of the apparatus. Thus the presence of a smaller maximum in the divergence curves points to the existence of elastic scattering of protons by deuterons in the range of angles studied.

b) The existence and the position of the second maximum near the peak of the elastic proton-proton scattering allows this maximum to be considered as the result of quasi-elastic scattering of the bombarding proton by individual protons in the deuteron.

c) The motion of protons in deuterons leads to a blurring of the maximum of the quasi-elastic scattering. The width and the shape itself of the maximum can be calculated from one of the momentum distributions of the nucleons in the deuteron. Ryndin[2] calculated the scattering of 460 Mev protons by deuterons assuming Hulthen and Bethe-Peierls deuteron. wave functions. The shape of the maximum depends weakly on the energy of the bombarding nucleon at very high energies. Therefore the calcuations agree well with the available experimental data.

d) The maximum of the quasi-elastic p–p scattering is observed to be shifted relative to the peak of elastic p–p scattering. This shift is explained by the effect of the binding of proton in deuteron.

The "divergence curves" obtained in the present work do not differ significantly from those obtained previously for lower energies of bombarding protons[3,4], and show the predominance of the interaction of the bombarding nucleon with one of the nucleons in deuteron. More detailed quantitative comparisons of the parameters of the maximum of p–p quasi-elastic scattering with theory[2] do not allow, within the present experimental accuracy, to shed any light on the character of the wave function of the deuteron at small distances.

3. Principal attention was paid in this work to the measurement of the differential elastic scattering cross section of protons by deuterons in the range of proton emission angles 40 to 150° in the center of mass system (c. m. s.) of the colliding particles. The elastic p–d scattering was separated by ganged telescopes set at the elastic-scattering divergence angles of the proton and deuteron. An additional selection of the elastic p–d scattering events and a decrease in the number of counts in the deuteron-counting telescope were accomplished by placing behind the telescope a deuteron-absorbing copper filter together with a scintillation counter set for anti-coincidence. Except for accidental coincidences, this system registered only elastic p–d scattering events. This was verified for each proton scattering angle by uncoupling the telescopes. The number of accidental coincidences varied together with the number of total counts, ranging from 5 to 40% of the measured effect and reaching 40% in the measurement of the cross section of elastic scattering of protons by deuterons at angles $\gtrsim 90°$ in the laboratory system of coordinates. Therefore, as a control experiment filters absorbing protons of the corresponding energy were inserted in the path of protons scattered into these angles and caused complete cessation of the counting of the elastic p–d scattering events. The presence of elastic p–d scattering was thus verified over the entire range of emission angles of the scattered protons in which the present measurements were carried out.

To obtain the absolute values of the differential cross sections of elastic p–d scattering in the range of angles 40 to 70° in the c. m. s., the counting rates at the peaks of elastic p–d and p–p scattering were measured under identical conditions and compared. The comparative character of the measurement allowed elimination of a series of errors connected with the absolute measurements.

The values of the differential cross sections of elastic scattering of 660 Mev protons by protons were reported previously[5]. The measured differential cross sections for elastic p–d scattering are shown in Table I in units of 10^{-27} cm^2/sterad for 10 values of the proton emergence angle θ^* in the c. m. s. The last line of the table shows the standard statistical deviations.

TABLE I.

θ^*	40,5°	49°	59,5°	67°	78,5°	92,5°	111,5°	126,5°	139,5°	150°
$d\sigma_{pd}^{el}/d\omega$	0,124	0,067	0,035	0,030	0,033	0,011	0,000	0,034	0,047	0,063
$\pm\Delta$	0,015	0,013	0,012	0,008	0,016	0,009	0,025	0,017	0,016	0,027

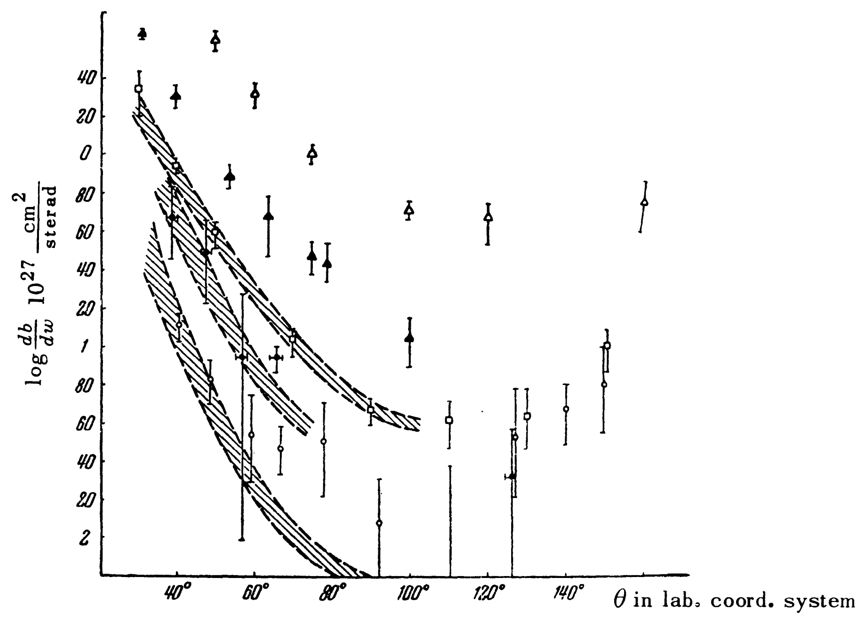

FIG. 2. Differential elastic p–d scattering cross section at various energies. △ – 146, ▲ – 240, □ – 340, ● – 460, ○ – 660 Mev.

Figure 2 compares the data obtained in the present work with the results of previous experiments[3,4,6-8] on elastic p–d scattering at lower energies of the bombarding protons. The abscissa gives the proton emission angle in the c. m. s. of the colliding particles while the ordinate gives, on a logarithmic scale, the differential cross section in units of 10^{-27} cm^2/sterad. The angular dependence of the differential elastic scattering cross section of 660 Mev protons by deuterons is given by an asymmetrical curve with a minimum in the range of angles 100 to 110° in the c. m. s. The differential cross sections increase, starting with 110° in the c. m. s. of the colliding proton and deuteron.

For all of the studied energies, a decrease in the differential cross section was observed with an increase in the emission angle of the scattered protons. In the range of angles $\theta^* < 100°$ in the c. m. s. a decrease in the cross section of the elastic p–d scattering is observed with an increase in the energy of the bombarding proton.

The concept of independent interaction between the bombarding proton and one of the nucleons in the deuteron makes it possible to correlate the peculiarities of the angular dependence of the differential cross section in elastic p–d scattering with the change in the partial proton-nucleon scattering cross sections and with the decrease in the probability of the deuteron remaining whole upon increase in the momentum transferred to the deuteron. This concept was the basis of the impulse approximation for the theoretical analysis of the elastic scattering of fast protons (energy $\geqslant$ 100 Mev) by deuterons[9,10]. Of course, the amplitudes of the proton interaction with the nucleons should agree with the experimental data on elastic p–p and p–n scattering. As a condition of applicability of the impulse approximation, the wave length of the bombarding particle must be small compared with the distance between nucleons in the deuteron. A condition connected with this requirement is that the time of the interaction of the nucleons is comparable with the characteristic "inversion" time of the system. Both conditions are satisfied in the case of elastic scattering of protons by deuterons in the range of angles studied herein (<100° in the c. m. s.). Therefore, there is a qualitative and a definite quantitative agreement between the experimental data[3,4,6-8] and the theoretical calculations[9,10]. By way of an example, Figure 2 shows such a comparison for the 340 and 460 Mev bombarding protons.

A comparison of the results of the present experiment was carried out by calculations quite analogous to those made by Golovin[10] for 660 Mev protons. The differential elastic p–d scattering cross section $d\sigma^{pd}(\theta^*_{pd})/d\omega$ at an angle θ^*_{pd} in the c. m. s. of the colliding proton and deuteron was found from the expression

$$\frac{d\sigma^{pd}(\theta^*_{dp})}{d\omega} = \frac{16}{9}(A+B)T_1^2 + \frac{16}{9}CT_1^2. \qquad (1)$$

Here A, B and C are functions that can be evaluated from the data on elastic scattering of protons and neutrons by protons:

$$\frac{2}{3}\frac{d\sigma^{pp}(\theta^*_{pp})}{d\omega} \leqslant A \leqslant \frac{d\sigma^{pp}(\theta^*_{pp})}{d\omega};$$

$$\frac{2}{3}\frac{d\sigma^{pn}(\theta^*_{pn})}{d\omega} \leqslant B \leqslant \frac{d\sigma^{pn}(\theta^*_{pn})}{d\omega};$$

$$|C| \leqslant \frac{d\sigma^{pp}(\theta^*_{pp})}{d\omega} + \frac{d\sigma^{pn}(\theta^*_{np})}{d\omega}.$$

T_1 is the same as the "sticking" factor evaluated by Chew[9] and depends on the momentum transferred to the deuteron and on the deuteron wave function.

The scattering angle θ^*_{pd} of the protons in the p–d center of mass coordinate system is related to the scattering angles $\theta^*_{pp} = \theta^*_{pn}$ of protons in the center of mass system of two nucleons by the expression

$$\sin\frac{\theta^*_{pp}}{2} = \frac{4}{3}\sin\frac{\theta^*_{pd}}{2}.$$

The coefficient C and the corresponding second terms of Eq. (1), expressing the interference of the waves scattered by the proton and the neutron in deuteron, was set equal to zero in the calculations. Discarding this term is in agreement with the results of previous calculations[6-10]. The calculated curve obtained in this manner describes well the angular dependence of the differential cross section of elastic p–d scattering at angles <100° in the c. m. s. It is evident from Figure 2 that the qualitative agreement is as good as could be expected with the calculation method employed.

In agreement with the results analogous experiments, the deuteron wave function for lower proton energies is written in the form $\varphi_0(r)=A(e^{-\alpha r}-e^{-\beta r})/r$, where $\beta=6\alpha$. This function (proposed by Hulthen) describes the deuteron better than the wave function $e^{-\alpha r}/r$. The presence of protons scattered at angles 60 to 100° in the c. m. s. already shows that at the moment of collision the nucleons in the deuteron are closely packed. This observation was previously made by Bogachev and Vzorov[5]. However, particular attention should be given to the group of protons elastically scattered backward at angles >110° in the c. m. s. The forward scattered deuterons assume thereby the greater part of the momentum and acquire an energy 100 times greater than the binding energy of the nucleons in deuteron. Such transfer of momentum and energy (up to 560 Mev) can take place only at the instant when the neutron and proton are separated by a distance on the order of the wavelength of the bombarding nucleon. This circumstance may mean that scattering of protons by deuterons at large angles takes place through the interaction of the bombarding proton with both nucleons in the deuteron.

A simultaneous interaction of three particles centered in a region having linear dimensions on the order of the wave length of the bombarding particle or smaller makes the impulse approximation inapplicable. At the present time there is no other theory applicable to a calculation involving a strong interaction of three particles, and capable of determining how much the non-additive terms due to the collective interaction of particles contribute to the scattering.

The experiment shows that following features of three-nucleon interaction manifest themselves in elastic backward scattering of protons by deuterons: a) An increase in the differential elastic p–d scattering cross section is observed with an increase in the proton emission angle from 110 to 150° in the

c. m. s., i.e., with an increase in the momentum of the scattered deuteron; b) A relative increase in the magnitude of the cross section of elastic backward $p-d$ scattering is observed with an increase in the incident proton energy from 100 to 660 Mev.

A comparison of elastic $p-d$ backward scattering with the know facts about the emission of "fast" (with energy exceeding the repulsion energy of a particle in the Coulomb field of the remaining nucleus) deuterons, α-particles, Li, Be etc. from nuclei interacting with high-energy nucleons[11-13] shows a close relationship between these phenomena. In particular, the emission of fast fragments from nuclei can be considered a result quasi-elastic interactions between the bombarding nucleon with a group of nucleons in the nucleus that are strongly bound at the time of the collision. The question concerning the mechanism of the collective interaction still remains open. True, a hypothesis has been advanced[14] concerning the presence of multiple forces, apparently connected with a simultaneous exchange of the nucleons with several mesons. If such forces do exist and are responsible for the large transfer of momentum to the forward deuteron emitted in elastic $p-d$ scattering, then the radius of interaction of the multiple forces should be small compared with the radius of ordinary nuclear forces. The facts and comparisons given above are necessarily skethy and skimpy, and therefore it is necessary to emphasize the necessity of a more detailed experimental and theoretical study of this interesting phenomenon.

4. A comparison of the yield of protons elastically scattered by free protons and quasi-elastically scattered by protons bound in deuterons permits determination of the differential cross section of the latter process. The resultant date are given in Table II. The differential quasi-elastic $p-p$ scattering

TABLE II.

θ	54,5°	67,5°	80,5°	90°
$d\sigma_{pp}^{ge}/d\omega \cdot 10^{27}$ cm^2/ sterad $\pm\ \Delta$	3,05 0,55	2,51 0,58	2,19 0,35	2,09 0,17

cross sections differs only slightly from the differential cross section of elastic scattering of protons by free protons at the corresponding angles. This fact again gives evidence that for a given energy $p-d$ scattering results fundamentally in an interaction of the bombarding nucleon with individual nucleons in the target deuteron. More accurately, the differential cross section of elastic $p-p$ scattering should be compared with the quantity

$$d\sigma_{pp}^{ge}(\Phi)/d\omega + d\sigma_{pd}^{el}(\Phi)/d\omega,$$

since the elastic scattering of protons by deuterons is a process competing with the quasi-elastic scattering of protons by nucleons. Figure 3 is a plot the quantity

$$\{d\sigma_{pp}^{ge}(\Phi)/d\omega + d\sigma_{pd}^{el}(\Phi)/d\omega\}/d\sigma_{pp}^{el}(\Phi)/d\omega$$

as a function of the angles Φ of the emission of protons in the laboratory system of coordinates. Disregarding the large statistical errors, a systematic deviation of the curve from unity can be noticed with a decrease in the proton scattering angle. Analogous results were obtained in a study of scattering of deuterons by 460 Mev protons[4]. These data are also shown in Figure 3. It is evident that the deviation

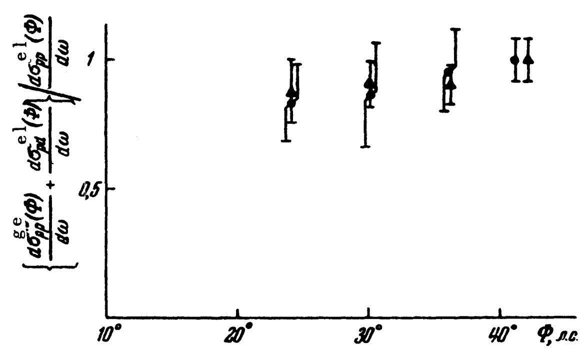

FIG. 3. Dependence of the quantity $[d\sigma_{pp}^{ge}(\Phi)/d\omega + d\sigma_{pd}^{el}(\Phi)/d\omega]/d\sigma_{pp}^{el}(\Phi)/d\omega$ on the scattering angle of proton in the lab. system of coordinates. ● — 660, ▲ — 460 MeV

should be attributed to the unaccounted competeing process, namely non-coplanar scattering, in which all three nucleons assume large energies, again giving evidence of the presence of collective interaction.

5. The present experiments show that the differential quasi-elastic and elastic $p-p$ scattering cross section at an angle of 90° in the c. m. s. are approximately equal to each other. Therefore, it should be expected that the differential elastic and quasi-elastic $p-n$ scattering cross sections at a 90° angle would also be equal to each other. If this is so, measurement of the quasi-elastic $p-n$

scattering at 90° in the c. m. s. can yield some evidence on the differential elastic scattering cross section of protons by free neutrons at that angle.

Great interest is centered about the comparison of the $p-n$ scattering cross sections measured under the same conditions for different energies. The measurement of the quasi-elastic $p-n$ scattering with a single telescope by counting the scattered protons is impossible for energies exceeding 600 Mev because of the large contribution of processes connected with meson production. Therefore, method of the ganged-telescope method was used to solve such a problem with one telescope employed as a highly effective neutron detector[14]. The energy of the protons was reduced with a series of polyethylene filters placed in the path of the proton beam. The beam intensity was maintained constant for all energies The cross sections measured at 460, 560, 590, and 660 Mev were in the ratios of 1.2 : 1.1 : 1.1 : 1. The relative statistical measurement error was 15%.

The data on the elastic $n-p$ scattering cross sections at 580 Mev[15], and also the corresponding data on elastic $p-p$ scattering[16], permit determination of the cross section connected with $p-n$ interaction in states with isotopic spin $T=0$. The data obtained are:

E (MeV) =	460	560	590	660
$\sigma_{T=0}(90°)$ =	$0,8 \pm 0,6$	$0,8 \pm 0,4$	$0,8 \pm 0,4$	$1,3 \pm 0,4$

6. The experimental results and their evaluation lead to the following conclusions:

1. At 660 Mev, the most important process in proton-deuteron collisions is the elementary nucleon-nucleon interaction between the bombarding proton and one of the nucleons in the deuteron.

2. The observed elastic $p-n$ scattering cross section at the proton-emission angles $<110°$ in the center of mass system of the colliding particles agrees with the cross section calculated in the impulse approximation using the Hulthen deuteron wave function for the ground state of the deuteron.

3. The differential $p-n$ quasi-elastic scattering cross section at 90° in the c. m. s. decreases slightly with increasing energy. That part of the cross section due to interaction in the state $T=0$ remains unchanged in the energy interval of 460 to 660 Mev within the limits of experimental error.

4. The elastic forward scattering of deuterons with energy up to 560 Mev can apparently be considered as evidence that in some cases a proton-deuteron collision at energies of 660 Mev results in an interaction between all three nucleons.

5. The presence of such collective interaction between nucleons agrees with many other experimental data, but any detailed determination of the properties of collective interaction necessitates new experimental and theoretical investigations.

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109