Small-Angle Scattering of 3.27-Mev Neutrons by Deuterons

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THEORETICALLY calculated angular distributions of neutrons elastically scattered by deuterons show a marked dependence on the assumed type of forces between two nucleons.[1-4] In view of the experimental difficulties in determining the angular distribution, there are discrepancies among the various data obtained by different experimenters.[5-7] However, for neutrons of a few Mev, the data show, in common, a strong maximum of the distribution at $\theta=180°$, a minimum around 90°, and a tendency to form another maximum at 0°, where $\theta=$ the neutron-scattering angle in the c.m. system. Although the shape of the distribution at small scattering angles seems very important for the comparison with the theory, the experimental data were, to our knowledge, not extended far enough into this region to allow for reliable extrapolation of the value of the differential cross section at 0°, nor to show whether the pronounced maximum of the distribution lies at 0° or at 180°.

In an earlier published experiment[7] we measured the angular distribution of 3.27-Mev (d, d)-neutrons scattered by deuterons in a cloud chamber. The investigation covered the range of $\theta=50°$–$180°$, and the distribution was then extrapolated for smaller scattering angles. However, it seemed desirable to extend the measurements as low as possible beyond 50° in order to obtain the shape of the distribution in this region.

With the same experimental procedure used in the former experiment, we studied the angular distributions of the neutron-proton as well as the neutron-deuteron scattering. In this case, the incident neutron beam was made to penetrate perpendicularly into the cloud chamber through its upper glass cover. This arrangement was chosen to facilitate the photographing and measuring of recoil tracks projected at large angles from the neutron beam. Four thousand proton recoils and four thousand deuteron recoils lying in the angular range between 18° and 70° have been photographed and measured. The angular distribution of the neutron-proton scattering was found to be isotropic throughout the investigated angular range, which suggested the reliability of the measurements in the case of the neutron-deuteron scattering. In Fig. 1, we have plotted the intensity of scattered neutrons *versus* angle of scattering in the c.m. system. The curves represent the data of the two experiments which were made to join at about 60° and so represent the angular distributions throughout the range from 18° to 180°.

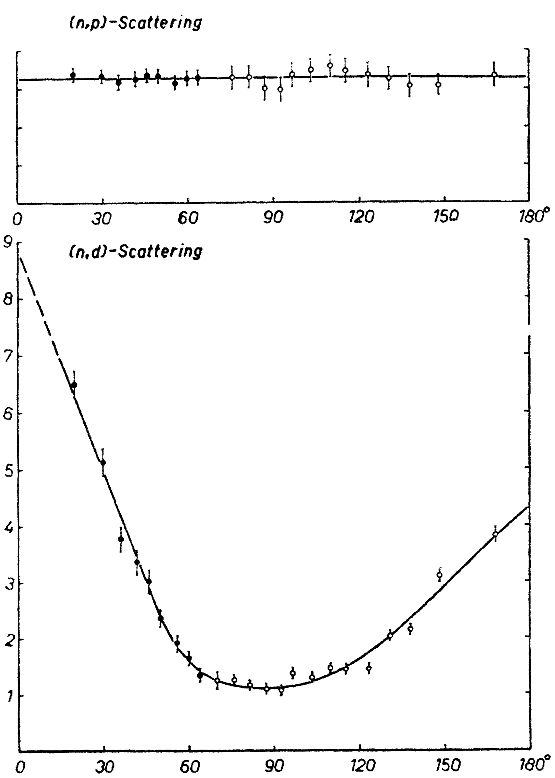

FIG. 1. Intensity of scattered neutrons *versus* angle of scattering in c.m. system. The open circles represent the data of the former experiment; the closed circles represent the data of the present experiment.

Our data were extended far enough into the region of small scattering angles, and they show clearly that more neutrons are scattered forward than backward. This distribution with its pronounced maximum at 0° does not agree qualitatively with either of the two theoretical distributions at 2.5 Mev calculated by Massey and Buckingham.[2] The disagreement is more marked in the case of the exchange force distribution, especially as Buckingham[8] points out that a refinement of the exchange force theory (by taking into account the contribution of d-angular momentum state) tends to enhance backward scattering at the expense of forward scattering of the neutrons. Verde[3] has given numerical calculations of the angular distributions at 20 Mev, and he states generally that a pronounced maximum at 0° disagrees with the "characteristic feature" of the symmetrical theories. We believe that it is rather early to draw theoretical conclusions from the experimental data because the spin-orbit coupling is not taken into consideration in any theory of this process.

We wish to express our sincerest gratitude to Professor P. Scherrer for his continuous encouragement and valuable advise.

The detailed experiment will be published in *Helvetica Physica Acta.*

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On the Nuclear Scattering of Negative Pi-Mesons*

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THE analysis of the interactions of artificially produced pi-mesons of well-known energy has yielded direct evidence of the anticipated nuclear scattering. Although the number of scatterings detected and studied in detail is not very large, evidence collected to date eliminates any doubt as to the real existence of some rather peculiar features of these meson-nuclear phenomena.[1] These features are (1) the relatively high probability for very large angle scatterings, (2) the existence of inelastic scatterings with exceedingly large energy losses, (3) the dependence of these peculiar scatterings on the incident meson's energy.[2]

These conclusions are based on the results of combined plural scattering and grain density measurements made upon tracks of incident and scattered particles in Ilford G5 plates. Figure 1 illustrates a typical plot of these measurements. This figure represents the inelastic scatterings ($\Delta E/E>0.15$) suffered by mesons of 70–110 Mev. The energy values were deduced from the Snyder and Scott formula,[3] recently checked very satisfactorily by Bramson and Havens.[4] The precision of the measurements depends on

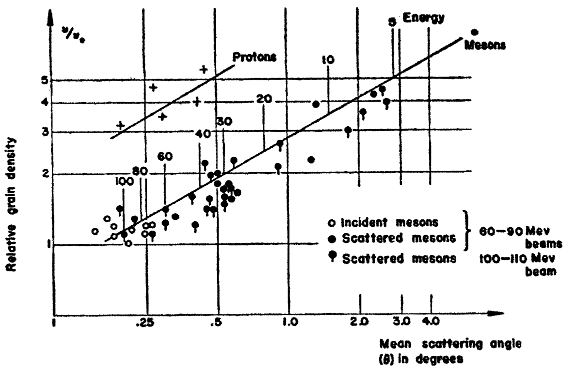

FIG. 1. Grain density *vs* multiple scattering angle of π^--mesons incident and scatttered in Ilford G5 emulsion. The noise level is included. Angles are measured by successive chords.

E_2 and the lengths of the tracks. All cases in which the measure of $\langle\theta\rangle$ would have a statistical error greater than 20 percent were considered as doubtful and not plotted.

The frequency and angular distribution of all measured scatterings at various incident energies are given in Fig. 2. To render the contribution of coulomb and shadow scatterings negligible, the elastic scatterings are plotted only for angles $>30°$. Shrinkage effects limit the precision of space angles in the emulsion to $\pm 5°$. As a check on the scanning efficiency, all the elastic scatterings $>10°$ for mesons of 30–50 Mev, and scatterings $>5°$ for mesons of 70–110 Mev were also considered. The results were very consistent with the numbers expected from the Rutherford law and the composition of the emulsion supplied by the manufacturer.

Figures 1 and 2 form the basis of the conclusions stated above. Some remarks remain to be added. The large angle events are rather frequent both in the inelastic and in the elastic scatterings, and we believe that they are correlated with some unknown process occurring in the interaction of pi-mesons with nuclear matter. Cloud-chamber experiments[5] now in progress indicate that a similar effect takes place in carbon; and, thus, the backscattering appears to be independent of nuclear size.

The frequency of strongly inelastic scatterings, $\Delta E = E_2 - E_1 > E_1/2$ Mev, has already been shown[6] to cast doubt upon a model based on single elastic pi-nucleon collisions in nuclear matter. The possibility of multiple elastic collisions inside the nucleus can probably also be ruled out by the results of Chedester *et al.*,[7] which give a very small cross section for pi-proton scattering. An alternative model is suggested to us by the grouping of the E_2's (Fig. 1) independently of incident energy and by the strong energy dependence of these scatterings. The mesons apparently are capable of raising nuclear matter to some excited state in a sort of mesic Raman effect. This means that in complex nuclei, the

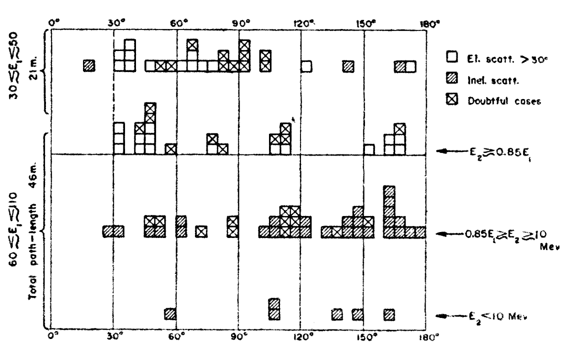

FIG. 2. Angular distribution of elastic and inelastic scatterings of π^- at various incident energies.

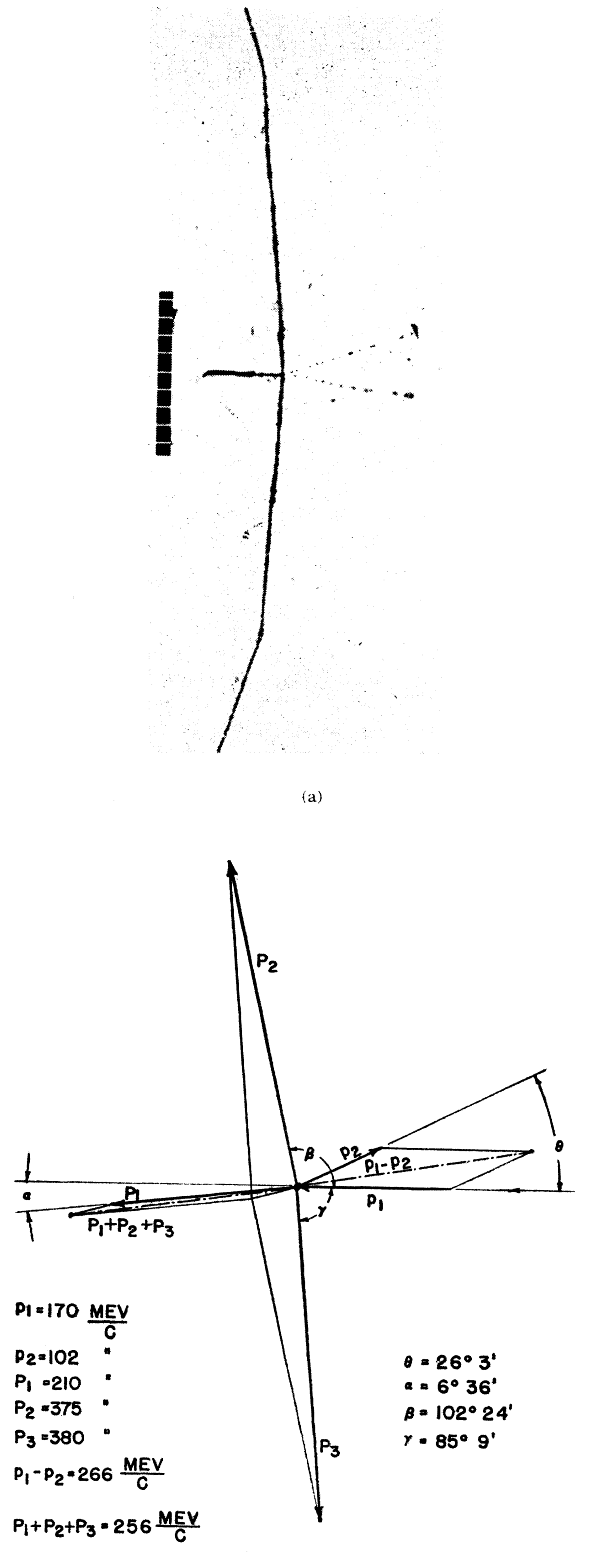

FIG. 3. Inelastic scattering of an 82-Mev π^- on a C_6^{12} nucleus (observed by Mrs. E. Wimmer). Each division of the scale in Fig. 3(a) is equivalent to 5 microns. Figure 3(a) is a photomicrograph of the event. Figure 3(b) is the corresponding momentum diagram.

scattering as well as the absorption is a many-body process. This probably naive picture of the nuclear scatterings is, to some extent, supported by some particular cases which are especially difficult to reconcile with a single pi-nucleon encounter. One of these cases is shown in Fig. 3(a). A meson of $E_1=82\pm5$ Mev (track length 2400μ) is scattered through 157°. The scattered meson (track length 8400μ) energy $E_2=33\pm3$ Mev. At the vertex, the three heavy prongs all end in the emulsion and have ranges, $R_1=21\mu$, $R_2=138\mu$, $R_3=145\mu$. If these are assumed to be 3 α-particles, the reaction would be $\pi_1^-+{}_6C^{12}\rightarrow3\alpha+\pi_2^-$. The α's are practically coplanar. The energy balance is

$$Q=(82-33)-(6+18.5+19)=5.5\pm6 \text{ Mev},$$

and the Q of the process ${}_6C^{12}\rightarrow3\alpha$ is 7.2 Mev. Figure 3(b) illustrates the consistency of the momentum balance. In another case, the meson has $E_1=73\pm10$ Mev, and the scattered meson, $E_2=2.2\pm0.2$ Mev. At the vertex, a proton track is found to have an energy $E_p=80\pm10$ Mev. No correlation of momenta is observed. These and other similar cases give us the impression that it will be difficult to explain the scattering of mesons and its energy dependence with any simple model based on the known properties of nuclei and conventional meson-nucleon interactions.

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The Mean Square Angle of Emission of Nucleons in High Energy Nucleon-Nucleus Collisions

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In previous work[1,2] we consider the problem of finding the mean square angle of emission of nucleons in high energy nucleon-nucleon collisions. In the present case we are concerned with obtaining the mean square angle of emission of nucleons resulting from a collision of a high energy nucleon with a nucleus using the results obtained in references 1 and 2.

Let $n(U, C, z)dUdC$ be the probability of finding a nucleon at a depth z in homogeneous nuclear matter with energy in the interval U, $U+dU$ and making an angle with the downward vertical whose cosine lies in the interval C, $C+dC$. Further, let $W(U, c)dUdc$ be the probability of finding a nucleon with energy in the interval U, $U+dU$ and scattered at an angle whose cosine lies in the interval c, $c+dc$. Denote by ω the angle between the plane containing the vertical and the direction of motion of a scattered nucleon and the plane passing through the directions of motion of both the incident and scattered nucleons.

The fundamental equation for $n(U, C, z)$ is

$$C[\partial n(U, C, z)/\partial z]+n(U, C, z) =2\int_U^\infty\int_{c0}^1\int_0^{2\pi} n(U', Cc+Ss\cos\omega, z) \times W(U, U', c)dU'dcd\omega/2\pi, \quad (1)$$

where

$$S=(1-C^2)^{\frac{1}{2}} \quad\text{and}\quad s=(1-c^2)^{\frac{1}{2}}.$$

The mean square angle of scatter of nucleons at a depth z in homogeneous nuclear matter is given by

$$\langle\theta^2(U_0, U, z)\rangle=\left\{\int_{-1}^1 n(U, \cos\theta, z)\sin^2\theta d(\cos\theta)\right\} \times\left\{\int_{-1}^1 n(U, \cos\theta, z)d(\cos\theta)\right\}^{-1}. \quad (2)$$

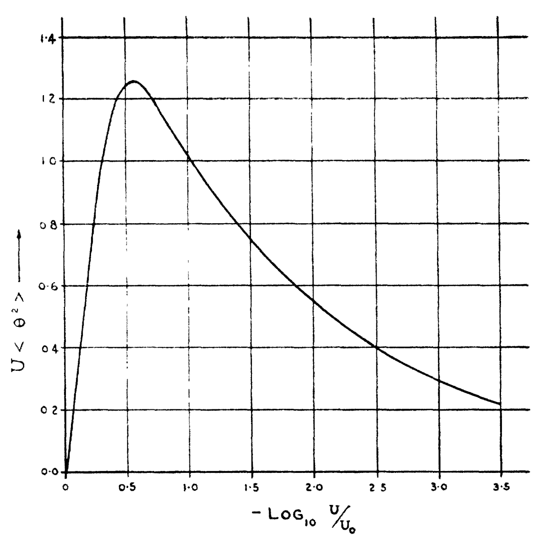

FIG. 1. A plot of $U\langle\theta^2(U_0, U)\rangle$ against the logarithm of the ratio of the energy U above which particles are emitted from a nucleus, to the primary energy U_0. The energies are measured in proton mass units. $\langle\theta^2(U_0, U)\rangle$ gives the mean square angle of emission in radians squared of nucleons resulting from a nucleon-nucleus collision. The curve is valid for nitrogen and oxygen nuclei.

Using the solution we have found for Eq. (1) and assuming that the nuclei are spherical in shape, we can show that the mean square angle of emission of nucleons with energies greater than U, resulting from a nucleon-nucleus collision is equal to

$$\langle\theta^2(U_0, U)\rangle=I_1/I_2, \quad (3)$$

where

$$I_1=\frac{1}{2\pi i}\frac{1}{2U}\int_{s_0-i\infty}^{s_0+i\infty}\left(\frac{U}{U_0}\right)^{-s}\left\{\frac{2-\alpha(s)-\alpha(s+1)}{\alpha(s)}\right\}f[D_A\alpha(s)]\frac{ds}{s+1} \quad (4)$$

and

$$I_2=\frac{1}{2\pi i}\int_{s_0-i\infty}^{s_0+i\infty}\left(\frac{U}{U_0}\right)^{-s}\frac{1-f[D_A\alpha(s)]}{s}ds. \quad (5)$$

Both the primary energy U_0 and the secondary energy U are measured in proton mass units. In the above expressions

$$f(x)=1-2[1-(1+x)e^{-x}]/x^2, \quad (6)$$

$$\alpha(s)=1-240\{(s+2)(s+3)(s+4)(s+5)\}^{-1}, \quad (7)$$

and D_A is the average number of collisions suffered by a primary nucleon in making a diametrical passage through a nucleus whose atomic weight is A.

The result of a calculation for light nuclei using Eq. (3) (D_A was taken equal to 3·7 and hence should be valid for nitrogen and oxygen nuclei) is given in Fig. 1. The apparent approach to zero in the limit $U\rightarrow U_0$ may be fallacious, since the method for evaluating the integrals becomes precarious for $U/U_0>\frac{1}{3}$, i.e., to the left of the maximum. However, this region has little physical significance.

These results ought to enable us to estimate the energy of the primary nucleon from a statistic of the angles of secondary nucleons in high energy photographic plate stars.

We shall present the details of the above work and a comparison with experiments in a subsequent publication. Results will also be presented for the heavy nuclei, silver and bromine.

We are indebted to Professor E. Schrödinger for many stimulating discussions throughout the course of the above work.

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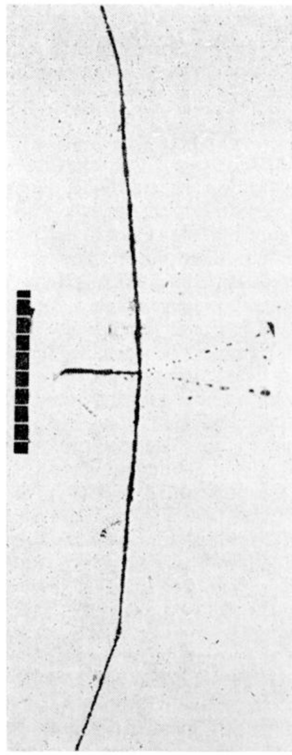
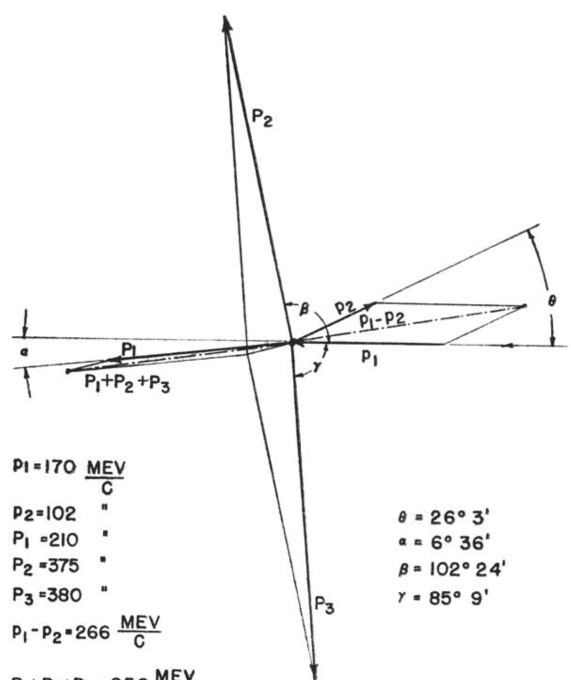


(a)



(b)

FIG. 3. Inelastic scattering of an 82-Mev π^- on a C_6^{12} nucleus (observed by Mrs. E. Wimmer). Each division of the scale in Fig. 3(a) is equivalent to 5 microns. Figure 3(a) is a photomicrograph of the event. Figure 3(b) is the corresponding momentum diagram.