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IV.

Theorie der Atomkerne und ihre experimentellen Grundlagen

High energy scattering of Neutrons and Protons

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Summary. A summary of the experiments on neutron-proton scattering at 280, 90 and 40 MeV and of proton-proton scattering at 340 and 32 MeV is presented. The measurements, obtained with various techniques, concern the total cross section and the angular distribution of the scattering.

Attempts to interpret the experiments by a nucleon-nucleon potential are described. These attempts are successfull only to a limited degree. The experimental data are incompatible with the hypothesis of the equality of $n-p$ and $p-p$ interaction.

Some of the most instructive experiments on atomic structure were the famous experiments on the scattering of alpha particles, which showed the existence of the nucleus and the coulomb repulsion between an alpha particle and the nucleus itself. By analogy it might be thought that experiments on n—p, p—p and n—n scattering might give us the clue on the law of force between nucleons, and for this reason they have always been in the minds of the physicists as some of the most interesting to perform. We think now that the scattering of neutrons and protons are more complicated phenomena than it was assumed a few years ago, and the hope that their experimental study will give easily interpretable answers is fading. Nevertheless they still remain as important facts that any future theory will have to explain.

It is also clear that as long as the DeBroglie wave length $\lambda/2\pi$ in the center of mass system

$$\left(\frac{9 \times 10^{-13}}{\sqrt{E}},\ E \text{ in MeV in the laboratory system}\right)$$

is large compared to the nuclear dimensions the obtainable information can not reveal details of the short range nuclear forces: only the recent high energy accellerators bring us in the region of interest.

As soon as the new machines of the Radiation Laboratory in Berkeley started to operate, investigation of these scattering problems began and is being actively pursued. This is a report on this work, and more a progress report than a description of finished work.

The experiments concern mainly the measurement of the total scattering cross section σ, and the angular dependence or differential scattering cross section $\sigma(\vartheta)$. The energies and particles used for the experiments are determined by the accelerators available and the whole group of experiments is tabulated in Table 1.

Table 1.

Experiment	Energy (lab syst.) MeV	β (center of mass system)	Particles	Measurement	Technique	Reference
(1)	40	0.14	$n-p$	σ, $\sigma(\vartheta)$	Prop. counters	1)
(2)	90	0.21	$n-p$	σ, $\sigma(\vartheta)$	Prop. counters cloud chamber	1) 2)
(3)	260	0.35	$n-p$	σ, $\sigma(\vartheta)$	Prop. counters crystal counters	3)
(4)	32	0.13	$p-p$	σ, $\sigma(\vartheta)$	Prop. counters phot. plate	4) 5)
(5)	340	0.39	$p-p$	σ, $\sigma(\vartheta)$	Prop. counters crystal counters	6)

References.

1) J. Hadley, E. Kelly, C. Leith, E. Segrè, C. Wiegand, H. York, Phys. Rev., **75,** 351 (1949).

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3) E. Kelly, C. Leith, C. Wiegand, Phys. Rev. **75,** 589 (1949) and private communication.

4) B. Cork, L. Johnston, C. Richman, Phys. Rev. **75,** 1465 (1949) and private communication.

5) W. K. H. Panofsky and F. Fillmore, Phys. Rev. **75,** 1465 (1949) and private communication.

6) O. Chamberlain and C. Wiegand, private communication.

No direct experiment on $n - n$ scattering is contemplated, but it is hoped that a study of $d - p$ scattering and $n - d$ scattering (d = deuteron) combined with the data of the direct $n - p$ and $p - p$ experiments may shed some light on the $n - n$ interaction.

The counter technique used in experiments one, two and three is illustrated in Fig. 1. The neutrons produced in the 184-inch cyclotron by stripping deuterons on beryllium or by collision of protons with beryllium, emerge from the thick concrete shielding of the cyclotron which acts also as a collimator. They are scattered by a polyethylene target and the scattered *protons* are detected by a system of counters in coincidence (counter telescope). The main beam is monitored either by a bismuth fission chamber or by a secondary scatterer. The hydrogen effect is measured as the difference between the effect observed with a polyethylene and a graphite scatterer. With this apparatus one obtains a quantity proportional to $\sigma(\vartheta)$. The proportionality factor is determined by measuring the total cross section of hydrogen in an attenuation experiment and imposing the condition that $\sigma = \int \sigma(\vartheta)\, d\omega$. The absorber A of Fig. 1 limits the smallest energy detected in the telescope and hence since the energy of the protons E_p is approximately $E_n \cos^2 \Phi$, also the energy of the neutrons considered in the experiment.

In experiments one and two the thickness of absorber A is so small that the correction due to nuclear scattering and multiple scattering in the absorber does not constitute a serious problem. At the higher energy of experiment three the thickness of absorber A reaches a maximum of 45 gr/cm² wolfram and introduces a large uncertainty in the result because the correction due to it is about a factor of 2 in the most unfavorable circumstances. It might be added that the neutrons used in experiment three are obtained by bombarding beryllium with 340 MeV protons. Their spectrum is much less known theoretically and experimentally than the spectrum of the stripped neutrons used in experiments one and two and the value of 260 MeV is a rather crude approximation for a broad distribution of which the upper limit is about 310 MeV. The total cross section for $n - p$ scattering at 260 MeV has been measured by an attenuation experiment using crystal counters.

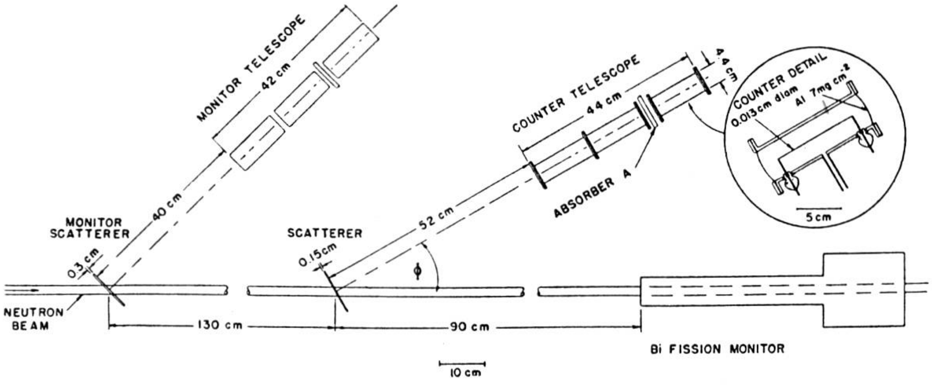

Fig. 1.
Schematic diagram of the scattering apparatus used in experiments (1), (2) and (3).

The cloud chamber used for experiment three had a diameter of 16 in. It was filled with 110 cm of H_2 and saturated with a water alcohol mixture and was placed in a magnetic field of 14,000 gauss.

The stereoscopic pictures were reprojected and reconstructed in space and from the $H\varrho$ of the scattered protons and the angle of scattering one found the energy of the impinging neutrons. The results are in agreement with the ones of the counter experiment and cover approximately the same angular range.

The counter technique used in experiment four is illustrated in Fig. 2. The beam of the linear accelerator (32 MeV) is carefully collimated and enters a chamber full of hydrogen. The counters of a special annular design are closed by a thin window that lets the protons through and absorbers suitable for each angle are used. $\sigma(\vartheta)$ is measured directly and absolutely from the counting rate, the density of the hydrogen in the apparatus, and the current carried by the beam which is integrated and measured in a Faraday cup. The effective volume of the scattering gas is calculated from the geometry and background effects are detected by introducing a shutter around the scattering volume.

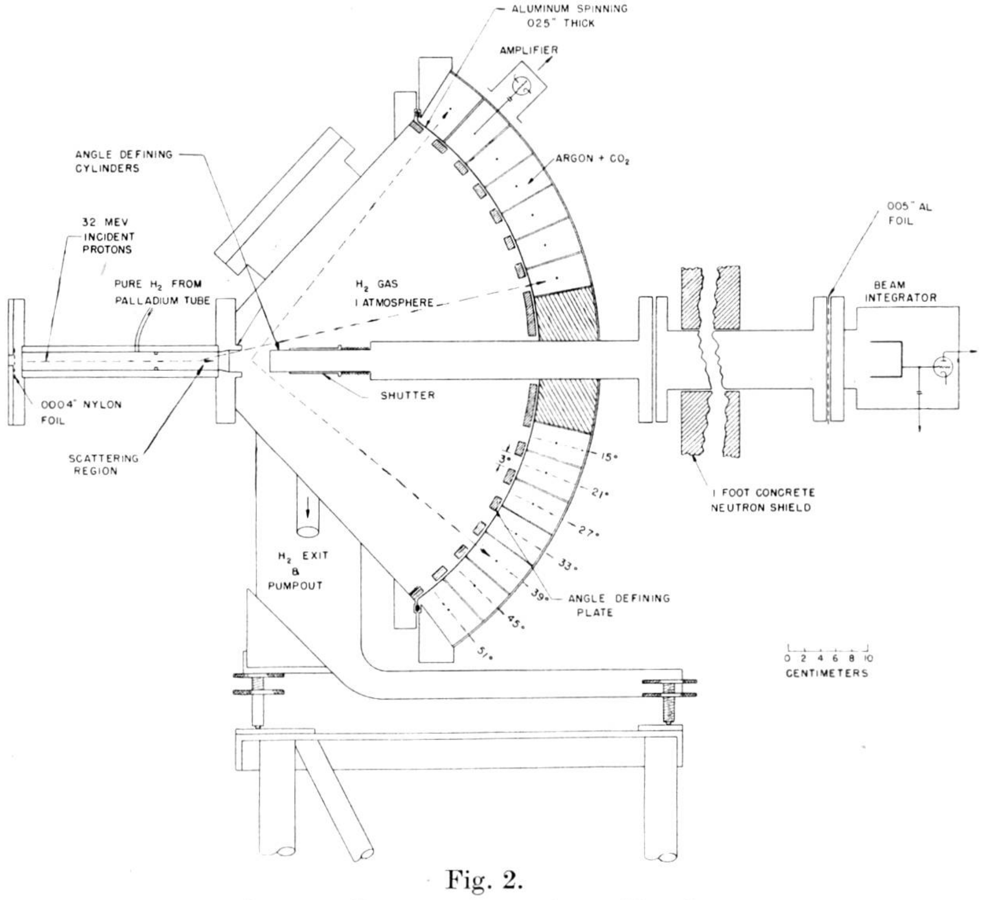

Fig. 2.
Proton—Proton Scattering Chamber
Schematic diagram of apparatus used in experiment (4).

In the same energy range $\sigma(\vartheta)$ for $p-p$ scattering has been investigated by the photographic plate technique as shown in Fig. 3. The scattering volume is here a cylinder and the angle of scattering is read from the angle of the proton track in the emulsion and the geometry of the apparatus. A check on the primary energy is given by the fact that from the range of the scattered particle its energy is determined and the scattering angle ϑ is known ($E_p = E_0 \cos^2 \Theta$). The study of the plates gives directly $\sigma(\vartheta)$. The normalization constant is obtained from the density of the gas, the geometry and the charge collected in a Faraday cup and hence the absolute values of $\sigma(\vartheta)$ in the two $p-p$ scattering experiments at 32 MeV are completely independent. The laboratory scattering angles cover the range of $10^0 < \Theta < 80^0$ so that all data are duplicated about 45^0, serving as a check on gas purity, background and observer reliability.

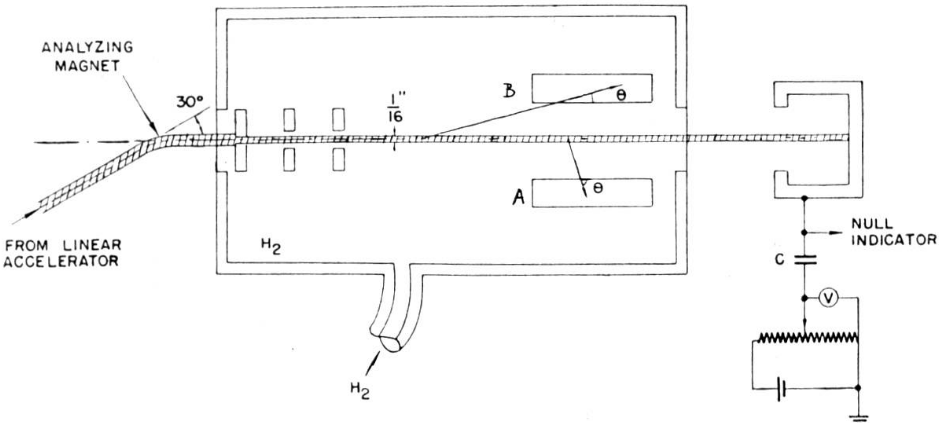

Fig. 3.

Schematic diagram of apparatus used in experiment (4). The planes of the photographic plates *A* and *B* are parallel and equidistant from the beam, and do not contain the beam.

The investigation of $p-p$ scattering at 340 MeV has been carried out by two methods. In the first the apparatus used is practically identical to the one of Fig. 1 except that the proton beam was measured with a Faraday cup. The absolute cross section has been determined by plotting the coincidence counting rate of the telescope as a function of the thickness of absorber *A* and extrapolating to zero thickness, but the procedure is rather inaccurate. Another line of approach is to use 90^0 coincidences between the two protons. In this experiment one telescope of two counters and a single counter at an angle of about 90^0 have been used. Incidentally the angular resolution of the apparatus is about 2 degrees and the relativity effect ($\beta = 0.39$ in the center of mass system) that makes the angle between the 2 protons different from 90^0 is very well visible. The measurements obtained at 340 MeV up to now cover a limited range of angles and will be extended with a different technique using very fast distributed amplifiers and crystals counters.

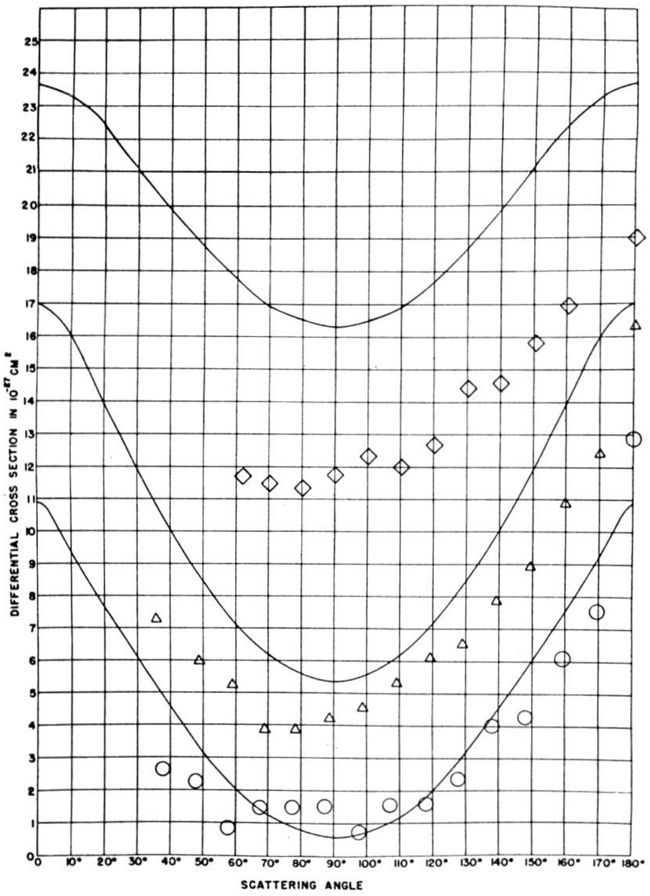

Fig. 4.

Differential neutron-proton scattering cross section in the center of mass system. Squares 40 MeV (lab. system), triangles 90 MeV, circles 260 MeV. In the same figure we have plotted a scattering curve calculated with a Yukawa potential and $R = 1.35 \cdot 10^{-13}$ as indicated in the text. The normalization of the experimental curves depends on measurements of the total cross section and errors of 20% are possible.

The results obtained in experiments one, two and three are summarized in Fig. 4. It must be remembered that there might still be considerable systematic errors in the curve at 260 MeV and the data reported for it are to be considered as provisional.

The results obtained in experiments four are summarized in Fig. 5.

The results on $p-p$ scattering at 340 MeV (experiment five) are given by the following values of $\sigma(\vartheta)$ (cm^2 per steradian in the cm system)*)

$\vartheta =$	41^0	43^0	49^0	60^0	62^0	85^0	90^0
$\sigma(\vartheta) \times 10^{27}$	5.5 ± 0.9	5.2 ± 1.1	5.1 ± 1.1	6.0 ± 0.9	5.3 ± 0.7	6.5 ± 0.9	5.1 ± 0.6

where ϑ is the scattering angle in the center of mass system.

The theoretical interpretation of these experiments is due to the theoretical group of the Radiation Laboratory, directed by Professor R. SERBER. Prof. CHEW, Mr. HART, Mr. CHRISTIAN and Mr. NOYES have been especially concerned with this work.

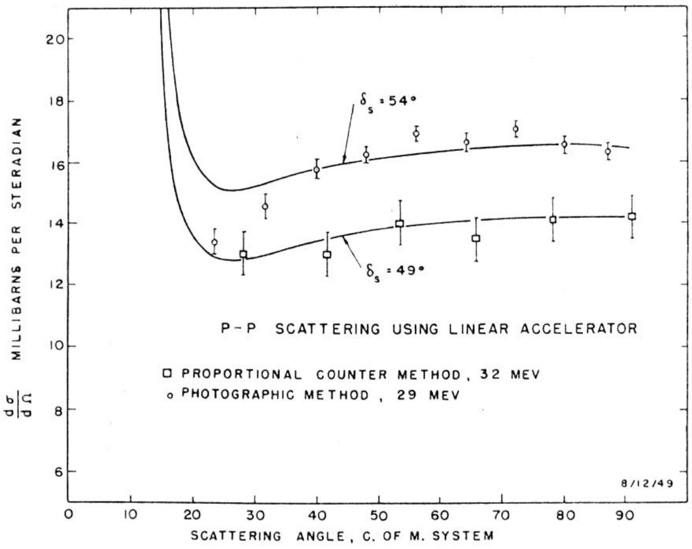

Fig. 5.

Differential proton-proton scattering cross section at 32 and 29 MeV. The theoretical curves are drawn considering the s-wave alone.

A phenomenological approach has been used throughout because it does not seem profitable at the present to try to deduce a potential from meson theory. Rather the attempt was made to fit all data known on the $n-p$ system into a consistent scheme and, if possible, find a potential which when introduced in the SCHROEDINGER equation would fit the data. We shall see in the following to what extent this program has been successful.

We consider first the $n-p$ system. A particularly simple interaction potential was chosen, whereby all the forces had the same

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*) This definition is normalized in the same way as in MOTT and MASSEY, Theory of atomic Collisions, London (1933), page 73 and is valid also for Fig. 5.

radial dependence. The spin dependent interaction potential was written in the form

$$V(r, \sigma) = {}^1/_2 (1 + P_x) (\alpha + \beta\, \sigma_1 \cdot \sigma_2 + \gamma\, S_{12})\, J(r/R),$$

where P_x is an exchange operator acting on the coordinates alone. S_{12} is the tensor operator $3 \frac{(\sigma_1 \cdot r)(\sigma_2 \cdot r)}{r^2} - \sigma_1 \cdot \sigma_2$, and $J(r/R)$ gives the radial form of the potential. The depths α, β and γ as well as the range R are determined by means of the following low energy data: (1) binding energy of the deuteron, (2) singlet scattering length, (3) triplet scattering length and (4) the quadrupole moment of the deuteron. (The magnetic dipole moment was not fitted although the models considered do give reasonable values.)

The ${}^1/_2 (1 + P_x)$ factor was chosen to suppress all the waves of odd angular momentum and make $\sigma(\vartheta)$ symmetrical around 90^0. Although there is no theoretical foundation for this particular form, it has been adopted because (1) the asymmetry around 90^0 in the region thus far explored is relatively small and (2) this gives a minimum total cross section. With the more general exchange interaction $(1 - a + a P_x)$ it was found that the limits on a are between 0.5 and 0.6.

Calculations were then made using various forms for the radial dependence $J(r/R)$. It was found that a potential with a long-tail was necessary to fit the 40 and 90 MeV scattering simultaneously. The most successful models have been the Yukawa, $[\exp(-r/R)]/(r/R)$, and the exponential, $\exp(-r/R)$, with $R = 1.35 \cdot 10^{-13}$ cm and $R = 0.75 \cdot 10^{-13}$ cm, respectively. The fit of the angular distribution as predicted by the Yukawa well is fair, however the total cross section is 20—30% too high. This latter defect can be removed by using the exponential well at the expense of a poorer fit to the angular distribution.

The general degree of agreement of these calculations with the experiments is shown in Fig. 4, where the predicted results for the Yukawa well at 40, 90 and 260 MeV are compared with the experimental data.

A detailed discussion of how the various parameters affect $\sigma(\vartheta)$ is found in a paper by R. CHRISTIAN and E. W. HART, to be published soon. It has been our privilege to have their manuscript available.

Considering next the $p - p$ scattering data we find that only the range and depth of the singlet interaction has been determined from the low energy scattering. The singlet $n - p$ potential can be chosen with the same range and depth (within 1%). This fact has formed the experimental basis of the often assumed "charge independence of nuclear forces".

The 32 MeV $p - p$ experimental data is compatible with an s-wave interaction alone (having a phase shift slightly larger than that predicted by a Yukawa well, adjusted to fit the low energy data). However when a potential model is used a d-wave is automatically predicted that is incompatible with the experimental data. This argument speaks strongly against the "charge independence" hypothesis. The potential model can be made to give agreement by postulating a tensor interaction in the odd (triplet) states which just masks the d-wave effect.

The 340 MeV $p - p$ data shows an anomalously high and flat cross section, which can not be explained by means of s-wave scattering alone, since the cross-section is approximately twice $4 \pi \lambda^2$. Again a tensor interaction may be invoked to obtain agreement when using the potential model.

In all the above calculation relativistic effects have been neglected. Our present ignorance of the whole subject precludes even a valid guess, other than that the corrections are proportional to β^2, and hence at the higher energies may not be inappreciable. It is believed, considering the agreement obtained in the $n - p$ system, that at least in this case, they are not of major importance.

Finally it should be mentioned that the near symmetry of the 90 MeV scattering has shown that the repulsive forces are small between unlike particles. This, coupled with the lack of any repulsive forces in the 32 MeV $p - p$ scattering, is one of the most striking features of the data, since models based on these experiments will not lead to nuclear saturation.