INTERACTIONS BETWEEN 630 Mev PROTONS AND He^4 *NUCLEI*

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A high-pressure diffusion cloud chamber was employed to study the scattering of 630 Mev protons on helium nuclei. The total, elastic, and inelastic cross sections were measured and found to be equal to $(150 \pm 13) \times 10^{-27}$ cm^2, $(24 \pm 5) \times 10^{-27}$ cm^2, and $(126 \pm 14) \times 10^{-27}$ cm^2, respectively. The angular distribution for the elastic scattering can satisfactorily be described in terms of the optical model using a complex potential with $V_R = 30$ Mev, $V_I = -(34 \pm 4)$, and $R = 1.45 \times 10^{-13}$ cm. Quasi-elastic proton-proton scattering and quasi-free proton-neutron interaction events were singled out. The cross sections for these reactions are $(15 \pm 2) \times 10^{-27}$ cm^2 and $(24 \pm 2) \times 10^{-27}$ cm^2 per nucleon, respectively. It is demonstrated that, in 20% of the events, either a cascade develops or the primary particle experiences a collision with a group of nucleons. Events involving π^- meson production in pn collisions were treated separately, and it was established that the cross section for this process is $(1.3 \pm 0.5) \times 10^{-27}$ cm^2 per neutron.

INTRODUCTION

A series of investigations devoted to the interaction of nucleons with the helium nucleus is being carried out at present. These experiments progress along two main directions. The first of these is related to the study of the structure of the He^4 nucleus. Among the structural properties, main attention is paid to the study of the nuclear size and the intranuclear nucleon motion,[1] as well as to a search of excited states.[2-4] Among research along this same direction belong also the experiments of Blankenbecler and Hofstadter on the charge distribution in the nucleus.[5] For research along the second direction, one should refer to the experiments devoted to the study of the mechanism of interaction of fast particles with the He^4 nucleus.[6,7] This nucleus has a sufficiently complex structure to exhibit the main features of interactions of fast particles with a complex nucleus in scattering processes and, at the same time, possesses a not too large number of nucleons, which makes it possible to discern easily the details of the observed events. Information obtained in such experiments can serve for creating a basis for the momentum-approximation method and for the optical model, which describe the interaction of fast particles with nucleons.

Although a large number of experiments have been devoted to the study of the interactions between nucleons and He^4 nuclei, only fragmentary data are available in the high-energy range (above 300 Mev). In this energy range, only two experiments have been carried out, those of Chamberlain et al.[6] and of Moulthrop.[7] In the first of these, the polarization and the elastic scattering of 315-Mev protons were investigated, while the second dealt only with the processes of π^--meson production in collisions of 300-Mev neutrons with He^4 nuclei.

It should be noted that investigations involving He^4 are more difficult as compared to those involving other light nuclei, since it is not always a simple problem to produce a target of liquid helium. Up to now, only two experiments[1,6] have used a liquid helium target.

In the present experiment, measurements on 630-Mev protons were carried out using a diffusion chamber. The method chosen made it possible to study both the processes of elastic scattering and the inelastic interactions in the same experiment. In connection with the latter, the possibility of studying the quasi-free scattering, and also of obtaining data on the multiple-interaction processes in a light nucleus, is of greatest interest.

EXPERIMENTAL METHOD

Proton scattering was studied by means of a diffusion chamber which, together with the auxiliary apparatus, has been described in detail in reference 8. The diameter of the working volume amounted to 30 cm. The height of the sensitive layer was 5 — 7 cm. The chamber was filled with helium to a pressure of 15 — 20 atmospheres.

A schematic diagram of the position of the apparatus during the experiment is shown in Fig. 1.

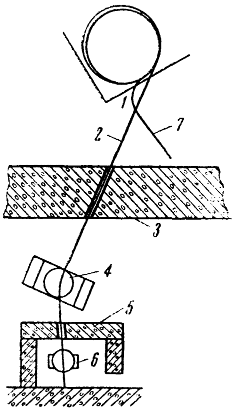

FIG. 1. Schematic diagram of the apparatus: 1 – accelerator chamber, 2 – proton beam, 3 – 4 m shielding wall, 4 – magnetic filter, 5 – additional chamber shield, 6 – diffusion chamber, 7 – π^--meson beam.

The protons were obtained by means of the synchrocyclotron of the Joint Institute for Nuclear Research. The particles were taken out of the accelerator chamber by means of an internal target. In this way, it was possible at the same time to work with another array placed in the π^--meson beam emerging from the same target. However, the proton energy was somewhat lower than the maximum obtainable in the accelerator and amounted to (630 ± 15) Mev, taking ionization losses into account.

The proton beam intensity was attenuated in an appropriate way so that a few tens of particles impinged upon the diffusion chamber during one cycle. The protons emerging from the accelerator were deflected at an angle of 19° by a deflecting magnet, and then directed through a 3 × 10 cm collimator to the diffusion chamber. The chamber was placed in a concrete hut with walls of 0.5 m thickness and which was, in addition, shielded by lead bricks to decrease the background of spurious radiation. A photograph was taken every 15 — 20 sec. The stereoscopic camera used had a basis of 120 mm, and the pictures were taken from a distance of 800 mm on Panchrom-X film with sensitivity $S_{0.85}$ = 1000 GOST units.

IDENTIFICATION OF INTERACTION EVENTS

About 20,000 stereograms were taken during the whole period of chamber exposure. Interaction events were selected by triple scanning through a stereoscopic magnifier. As the result of the scanning, 444 events of scattering of protons on helium nuclei were found. This number does not contain six events which were considered as interactions with C or O nuclei contained in methyl alcohol. The number of interactions with the nuclei of the admixture is roughly in agreement with the estimated expected number of such events.

The distribution of the interaction events of protons with helium nuclei, according to the number of prongs, is as follows:

Number of prongs	1	2	3	4	5
Number of events	0	204	228	8	4

Better sections of the film were used to obtain the total interaction cross section. The number of tracks in these was counted. Taking the necessary corrections into account, the value σ_t = (150 ± 13) × 10^{-27} cm^2 was obtained for the total cross section.

The measurement of the spatial angles and also of the length of the tracks was carried out by means of a projector described earlier.[9] In several cases, the specific ionization of the particles was estimated by photometering the tracks by means of the MPH-4 microphotometer.[10]

A large number of reactions can occur on helium nuclei in the scattering of 630-Mev protons. For convenience of identification, they can be subdivided into separate groups according to the criterions for selection and analysis (see Table I).

Reactions of the first group, with the exception of reaction 4, represent coplanar two-prong stars, and are recognizable from kinematic conditions of the decay.

The second group of reactions also includes two-prong stars. The majority of events in this group consist of the quasi-elastic scattering of protons or neutrons (reaction 1). Other events, with the exception of reactions of types 2 and 4, refer to quasi-free interactions of protons. In the present experiment, it has not been possible to distinguish between reaction 1 and other reactions of this group.

The third group of reactions consists of three-prong stars, and includes not only the cases of quasi-free interactions of protons with protons, but also other processes in which a great number of nucleons take part in the interaction.

The quasi-elastic proton-proton scattering (reaction 1) was singled out from the reactions of this group. The selection of quasi-elastic scattering events was effected using the corresponding correlation of the emission angles of the particles, and also their momenta in the final state. The selection procedure of such events is analogous to that which has been used in the identification of quasi-elastic scattering of π mesons on protons, and which was described in detail in reference 16.

TABLE I

Reaction group	Serial Number	Reaction	Number of events
I	1	$p+He^4 \rightarrow p+He^4$	66
	2	$p+He^4 \rightarrow d+He^3$	(1)*
	3	$p+He^4 \rightarrow \pi^+ + He^5$	0
	4	$p+He^4 \rightarrow \pi^0 + Li^5$	0
II	1	$p+He^4 \rightarrow p+n+He^3$	136
	2	$p+He^4 \rightarrow \pi^+ + n + He^4$	
	3	$p+He^4 \rightarrow \pi^+ + 2n + He^3$	
	4	$p+He^4 \rightarrow \pi^0 + p + He^4$	
	5	$p+He^4 \rightarrow \pi^0 + (p, n) + He^3$	
III	1	$p+He^4 \rightarrow p+p+H^3$	88 (19)*
	2	$p+He^4 \rightarrow \pi^+ + (3n, 2p)$	124
	3	$p+He^4 \rightarrow \pi^0 + (2n, 3p)$	
	4	$p+He^4 \rightarrow p + (2n, 2n)$	
VI	1	$p+He^4 \rightarrow \pi^- + p + p + He^3$	7 (3)**
	2	$p+He^4 \rightarrow \pi^- + p + p + p + d$	4

Note: Brackets with one star give the number of not completely certain events out of the total number of identified events. Brackets with two stars give the number of events which can be interpreted as production of a π^0 meson with consecutive decay into an electronic pair and a γ ray.

The fourth group of reactions consists of events referring to the production of π^0 mesons in p-n collisions. These events, in contrast to the reactions discussed above, represent four- and five-prong stars. The results for singled-out reactions of this group are given below.

In the interaction of 630-Mev protons with helium nuclei, the paired π-meson production can also occur, which can contribute to the number of four- and five-prong stars. However, it follows from the experiments of Block and others[12] that the cross section for processes of that type is very small even at the energy of 800 Mev, and is not greater than 0.8 mb per nucleon. One can assume that the contribution of paired production at 630 Mev is negligibly small, and it can be neglected in the above classification of reaction groups. Only one event which could be interpreted as a probable case of paired meson production was found in analyzing the five-prong stars. A picture of this event is shown in Fig. 2

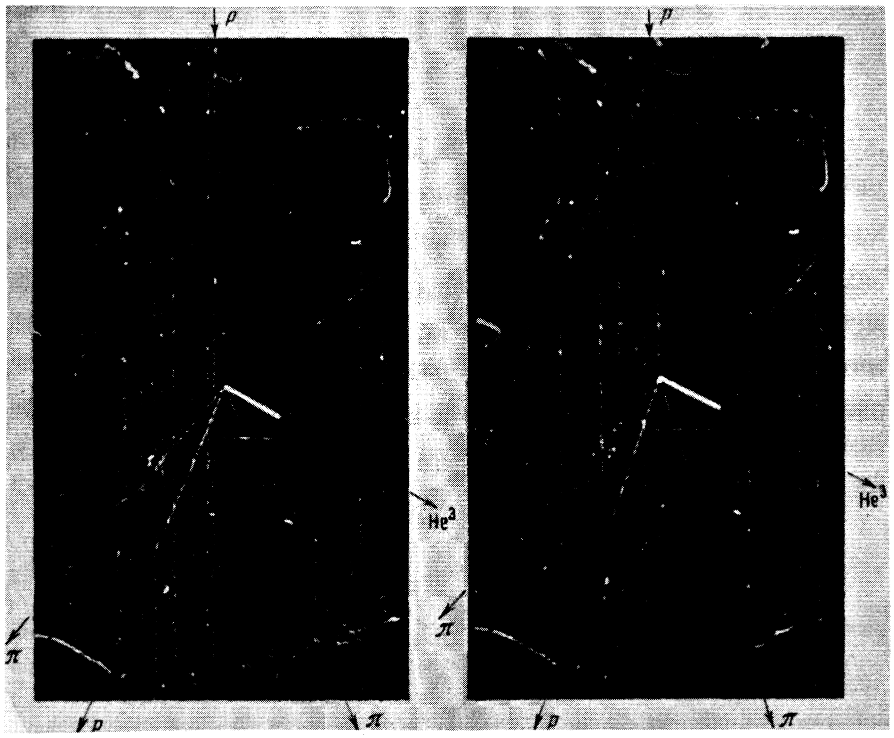

FIG. 2. Photograph of probable event of paired π-meson production.

ELASTIC SCATTERING

The angular distribution of elastic scattering is shown in Fig. 3. The minimum detection angle amounted to 5° in the c.m.s. Without a correction for the range of small angles, the following value was obtained for the total cross section for elastic scattering:

$$\sigma_{el} = (22.0 \pm 4.5) \cdot 10^{-27} \text{ cm}^2$$

From the optical theorem,[13] one can estimate the minimum correction to the cross section for the range of small angles. With the correction, the cross section amounts to $\sigma_{el} = (24.0 \pm 5.0) \times 10^{-27}$ cm^2, or 0.16 of the total cross section for the pHe interaction. This result shows that the cross section of elastic scattering remains practically constant from 315 to 630 Mev. (The integration of the angular distribution obtained by Chamberlain et al.[6] for 315 Mev gives $\sigma_{el} = 19 \times 10^{-27}$ cm^2.)

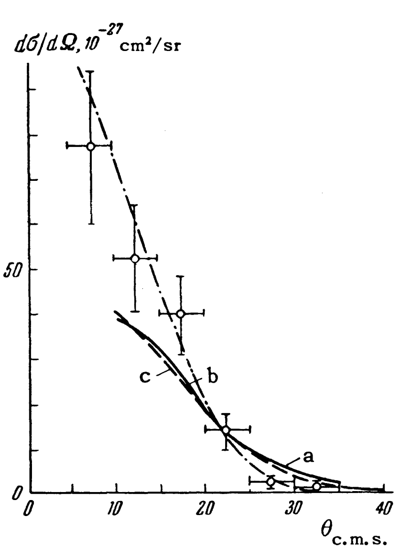

FIG. 3. Angular distribution of elastic scattering of proton on helium. The points represent the experimental distribution at 630 Mev; curve a – experimental distribution at 315 Mev;[6] b – angular distribution at 630 Mev, calculated according to the optical model with the parameters V = 45 Mev, R = 1.45 × 10^{-13} cm; c – angular distribution at 315 Mev calculated according to the optical model with parameters V = 17 Mev, R = 1.90 × 10^{-13} cm.

Estimates of the Coulomb scattering have shown that it is mainly concentrated in the range of angles 0 – 5° and, therefore, its contribution to the angular distribution given above is negligibly small.

Calculations of the angular distribution of the elastic scattering have been carried out within the framework of the optical model, using the Born approximation, and neglecting the spin-orbit and Coulomb interactions.

The scattering potential was taken as a rectangular well with radius R and depth $V = \sqrt{|V_R|^2 + |V_I|^2}$. The form of the angular distribution, consistent with the experimental data, is very sensitive to the value of the radius and to the potential. Acceptable distributions are obtained for radii in the range $(1.3 - 1.55) \times 10^{-13}$ cm. The possible values of the depth of the potential well amount to 40 – 50 Mev. A best fit with experimental points is obtained for the curve for which V = 45 Mev and R = 1.45 × 10^{-13} cm (Fig. 3).

If we use the value of the cross section for inelastic processes, then, for R = 1.45 × 10^{-13} cm, we obtain the value $V_I = -(34 \pm 4)$ Mev for the imaginary part of the potential. The real part of the potential is then equal to $V_R = 30$ Mev.

Analogous calculations were carried out for a proton energy of 315 Mev. The same figure (Fig. 3) shows the results of measurements of the elastic scattering of polarized protons on He^4 nuclei, obtained by Chamberlain et al.,[6] as well as the distribution calculated for R = 1.9 × 10^{-13} cm, and V = 17 Mev, which represents the best fit with the experimental points. If we assume R = 1.9 × 10^{-13} cm and set the Goldberger factor $\gamma = 0.8$, then, from the total pp and pn scattering cross section at 315 Mev, we obtain for the imaginary part of the potential $V_I = -18$ Mev; i.e., V_I is almost equal to the absolute value of the total potential.

A certain ambiguity is present in the choice of γ, since there is no information on the cross section for inelastic scattering at 315 Mev. This ambiguity, however, cannot affect the conclusion about the small value of the real part of the potential at this energy. This result is in agreement with calculations of the real part of the central potential carried out by Riesenfeld and Watson[14] from a phase-shift analysis of nucleon-nucleon scattering. The consistency of the results at 615 Mev may, within the framework of the accepted scheme, indicate that at 630 Mev the picture is sufficiently correct. Hence, we can conclude that the real part of the potential increases with increasing energy.

It should be mentioned that, within the framework of the above analysis, it is impossible to describe the angular distribution at the energies of 315 and 630 Mev with the same radius for the potential well.

INELASTIC SCATTERING

Multiple collisions inside the helium nucleus. The representation of cascade processes developed by Goldberger[15] can be applied to the He^4 nucleus. Cascade development at the energy under consideration can be due to recurring collisions both of nucleons and mesons produced in the first collision. The incident nucleons can also collide with a group of nucleons of the nucleus. The ejected nucleons are then found to be in both bound and free final states. In the latter case, the event can appear in such a way that it will be impossible to determine whether a cascade has developed, or whether a collision with a complex of nucleons has taken place. The term plural interaction will, in the following, be applied to processes of single or recurring interactions of the incident particle with several nucleons. From the data given above, one can estimate the contribution of such processes.

If we denote the total number of collisions between the incident proton and the neutrons of the nucleus by N_{pn}^{nuc}, we can write

$$N_{pn}^{nuc} = N_{pn} + N_{pn}^{pl} = N_2' + N_4 + N_5 + N_{pn}^{pl},$$

where N_{pn} is the number of cases of quasi-free interactions, N_2' is the number of two-prong stars including the elastic scattering events, N_4 and N_5 is the number of four- and five-prong stars, and N_{pn}^{pl} is the number of cases in which a multiple interaction has occured. This method of writing N_{pn}^{nuc} is possible only because of the fact that, among the two-prong stars, events related to multiple interaction processes are practially absent. Any repeated collisions will lead to an increase in the number of prongs, as a result of which a three-prong star will be detected. Exceptions to these are the reactions

$$p + He^4 \rightarrow \pi^0 + p + He^4, \qquad p + He^4 \rightarrow \pi^+ + n + He^4,$$

in which the development of the cascade may not lead to an increase in the number of prongs. However, it we use the results of Moulthrop,[7] it can be seen that the contribution of such reactions is small.*

The number of three-prong stars N_3 contains not only the events of quasi-free interactions between protons and protons N_{pp}, but also the events of plural interactions N_{pp}^{pl} and N_{pn}^{pl}. Therefore, the number of collisions between protons and protons N_{pp}^{nuc} can be written in the form

$$N_{pp}^{nuc} = N_{pp} + N_{pp}^{pl} = N_3 - N_{pn}^{pl}.$$

It is reasonable to assume that the cross sections for quasi-free scattering of nucleons have a ratio similar to that of the corresponding cross sections for free nucleons. Taking this into account, it is possible to estimate the contribution of the processes of plural interaction in the scattering of protons on He^4 as follows:

$$\varepsilon = \frac{(N_{pn}^{pl} + N_{pp}^{pl})}{(N_{pp}^{nuc} + N_{pn}^{nuc})} = \frac{N_3 - N_2' - N_4 - N_5}{N_3 + N_2' + N_4 + N_5} = 0.22 \pm 0.07.$$

The result obtained shows the considerable role of the plural interaction processes, even for such a light nucleus as He^4. The considerable role of such processes has also been established in the study of the scattering of fast π mesons on He^4.[16]

Quasi-free scattering of protons. The cross sections for various reactions singled out in the identification of interaction events are given in Table II. A comparison of the total cross section for inelastic processes with the sum of nucleon-nucleon cross sections results in a value of 0.82 for the quantity γ. These results indicate that, even for the energy of incident particle equal to ~ 600 Mev and for light nuclei, it is necessary to know the value of γ in order to estimate the value of the mean free path using the sum of the nucleon-nucleon cross sections. For 970 Mev protons, the value of γ still does not attain one, even for the deuteron, and amounts to 0.91.[11]

In row 7 of Table II, the data on the quasi-free scattering of neutrons on the neutrons of the helium nucleus are given. The total cross section for the quasi-free scattering amounts only to 0.65 of the corresponding cross section for free nucleons, without taking into account the processes of plural interaction. An analogous result has also been obtained for the quasi-elastic scattering of protons on protons (row 8). Introducing the corresponding correction for plural interaction, we obtain for γ roughly the same value as that obtained from the total cross section of inelastic scattering.

As can be seen from rows 5 and 6 of the same table, the cross section for meson production in collisions of protons with bound neutrons amounts to $(1.3 \pm 0.5) \times 10^{-27}$ cm^2, which is approximately equal to the cross section obtained in reference 17 for free neutrons.*

The angular distribution of protons emitted in quasi-elastic scattering is shown in Fig. 4. For a comparison, the angular distribution of elastic scattering of protons on protons at 660 Mev is also given in the same figure. The comparison of the distributions shows that, in quasi-elastic scattering, a certain number of nucleons are ejected both at small and large (close to 90°) angles. The observed difference is probably due mainly to the Pauli principle.

The form of the angular distribution of protons

*At 300 Mev, the output of π mesons from the $n + He^4 \rightarrow \pi^- + P + He^4$ reaction amounts to less than 6% of the total cross section for meson production.

*The results obtained are in agreement with the data of Dzhelepov, Kiselev, Oganesyan, and Flyagin, reported at the 1959 Kiev Conference in the paper of B. M. Pontecorvo.

TABLE II

	Reaction	Cross section per nucleus 10^{-27} cm^2	Cross section per nucleon 10^{-27} cm^2	$\frac{\sigma}{\sigma_{NN}}$	Cross section per nucleon with correction for plural processes, σ'	$\gamma=\frac{\sigma'}{\sigma_{NN}}$
1	**Inelastic scattering**	126±14	—	—	—	—
2	$p+n+He^3$					
3	$\pi^+ + n + n + He^3$	46±4	23±2	—	—	—
4	$p + He^4 \rightarrow \pi^0 + (p, n) + He^3$					
5	$\pi^- + p + p + He^3$	1.3±0.7	1.3±0.5	—	—	—
6	$\pi^- + p + p + p + d$	1.3±0.7				
7	**Total quasi-free pn interaction**	48±4	24±2	0.65	29±3	0.78
8	$p + He^4 \rightarrow p + p + H^3$	29±3	15±2	0.6	18±2	0.73

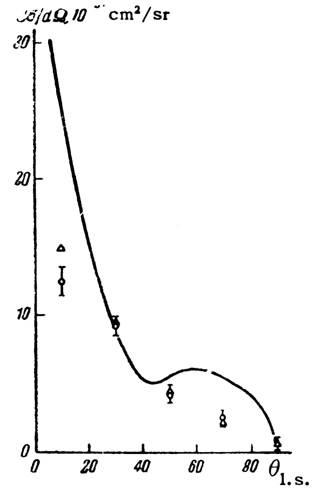

FIG. 4. Angular distribution of quasi-elastic scattering of protons on protons: o – experimental distribution, Δ – distribution calculated by the Monte-Carlo method, solid line – angular distribution of scattering of protons on free protons.

was calculated by the Monte Carlo method, taking the bond into account. In the calculation, the intranuclear momentum distribution of nucleons was taken as a Fermi distribution with a limiting momentum of 220 Mev/c. Plural interaction processes were not taken into account. Results of the calculation are also shown in Fig. 4. It can be seen that the angular distribution obtained experimentally is in satisfactory agreement with the calculated distribution. Such a fit indicates that the plural interaction processes which occur in helium do not, in the majority of cases, strongly distort the form of the distribution, but lead to a practically proportional ejection of protons at all angles.

In conclusion, the authors express their thanks to A. G. Potekhin and V. F. Poenko for help in setting up the experiment, and also to E. A. Shvanev for help in reducing the experimental data.

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