*KNOCKOUT OF DEUTERONS FROM Li, Be, C, AND O NUCLEI BY PROTONS OF ENERGY 675 MEV**

L. S. AZHGIREI, I. K. VZOROV, V. P. ZRELOV, M. G. MESCHERIAKOV, B. S. NEGANOV, and A. F. SHABUDIN

Joint Institute for Nuclear Research, Academy of Sciences, U.S.S.R.

Submitted to JETP editor July 1, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 1185-1195 (November, 1957)

A study is made of the momentum spectra of charged particles emitted in the bombardment of deuterium, lithium, beryllium, carbon, and oxygen by 675-Mev protons. The investigation was carried out by the method of magnetic analysis at an angle of 7.6° to the proton beam. A group of deuterons of energy about 600 Mev is found to be emitted for all elements. In the case of deuterium the source of fast deuterons is elastic (p-d) scattering; in the remaining cases, deuterons are emitted in the reaction $p + (Z, A) \rightarrow d + p + (Z - 1, A - 2)$, which is proton scattering by quasi-deuteron groups inside the nuclei. With an accuracy of about 20%, the differential cross sections of this reaction are 2.9, 2.2, 3.7, and 4.6×10^{-27} cm^2/sterad for Li, Be, C, and O respectively. For the same nuclei, the mean energy of motion of the quasi-deuteron groups is evaluated at approximately 8, 11, 14, and 14 Mev. In the high momentum part of the spectra, no perceptible quantities of knocked out tritium nuclei have been detected.

The experiments that have been carried out show that in the passage of nucleons of a given energy through light nuclei, an essential role is played by the processes of three-particle interaction which are accompanied by large momentum transfer to the deuteron. The results obtained are in accord with the concept that underlies the high-momentum model of the nucleus.

1. INTRODUCTION

FROM the time of the early attempts to explain characteristics of the interaction of nucleons with nuclei at high energies ($E > 100$ Mev) one usually considers the process of the traversal of the nucleus by a nucleon as a series of successive collisions of the indicent nucleon with the individual nucleons located in its path. Such an approach to the problem of nucleon-nuclei interaction appears reasonable in the framework of the independent-particle model if the wavelength of the incident nucleon and the effective radius of the nucleon-nucleon interaction are small by comparison with the average distance between nucleons in the nucleus.

There is, however, reason to believe that the assumed existence of a cascade of two-particle collisions inside the nucleus give a rather rough approximation to reality. One should first mention that in the energy region from 100 to 1000 Mev the effective radius of the nucleon-nucleon interaction is only approximately one and one-half times less than the average distance between nucleons in densely packed nuclei. This circumstance by itself demonstrates that many-body interactions of nucleons in a cascade process are not rare. Nor should one overlook the fact that in the simplest form of the independent particle model the space correlation of nucleons inside the nucleus is not taken into account. Besides, as has been pointed out by Brueckner, Eden, and Francis,[1] the available experimental data show clearly that in a number of nuclear processes high-energy effects related to the space correlation of the nucleons play an appreciable role. Among these effects are the nuclear photoeffect, successfully described by the quasi-deuteron model of Levinger,[2] the absorption of mesons by nuclei, and the creation of mesons in nucleon-nuclei collision, the scattering of nucleons inside nuclei,[3-6] and also the capture of nucleons from nuclei by the incident nucleons with formation of deuterons.

*Communicated May 17, 1957 at the Second Session of the Scientific Council of the Joint Institute for Nuclear Research.

A particularly noteworthy feature of the last process, formed upon irradiation of different elements by neutrons and protons with energy of around 90 Mev,[7-10] is the emission of deuterons predominantly forward with energies only slightly less than the energy of the incident nucleon. The analysis of this process is based on the premise that the incident nucleon interacts simultaneously in the nucleus, only with one corresponding nucleon that moves approximately with the same momentum as that of the incident nucleon.[11] It was shown that the data obtained near 90 Mev on the angular distribution and yield of deuterons can be explained, at least qualitatively, by using for the nucleons in the nucleus a momentum distribution which extends much farther in the direction of large momenta than the distribution corresponding to the model of the Fermi gas of the non-interacting particles.[12,13] This corresponds to the admission that strong local interactions exist inside nuclei.

The formation of fast deuterons has also been observed under the action of 300-Mev protons and neutrons as the result of the capture of nucleons from nuclei not by directly-incident particles, but rather by relatively slow secondary nucleons which have undergone one or more collisions inside the nucleus.[14]

In this article some results are presented of experiments carried out with the aim of studying the collisions of protons with the tightly-bound strongly-interacting nucleons in the nuclei of Li, Be, C, and O at an energy of 675 Mev and particularly with quasi-deuteron groups. At the same time the results of another experiment on the observation of the elastic scattering of protons by free deuterons, at an energy of 675 Mev, is also presented. The comparison of data obtained under the same conditions on (p–d) elastic scattering, with the ejection of deuterons from light nuclei by protons, permits one to make definite conclusions on the character of the latter process. In the described experiment information was obtained concerning the following: (a) the momentum spectrum of the secondary charged particles emitted in p + Li, p + Be, and p + C collisions at 7.6 degrees relative to the beam of the primary protons; (b) the differential cross section of the processes of the direct ejection of deuterons from the nuclei, Li, Be, C, and O and also the differential cross section of elastic (p–d) scattering; (c) the average kinetic energy of the quasi-deuteron groups in the bombarded nuclei; (d) the upper limit of the value of the contribution of tritium nuclei in the yield of emitted deuterons.

2. METHOD OF INVESTIGATION

To detect the direct knockout of deuterons from light nuclei under the action of fast protons, we carried out experiments in which the momentum spectrum of the secondary particles was determined by the method of magnetic analysis. This method was already used by us in studying the momentum spectrum of the products of the reactions $p + p \rightarrow n + p + \pi^+$, $p + p \rightarrow p + p + \pi^0$, and $p + p \rightarrow d + \pi^+$ (Ref. 15). The placement of the analyzing magnet with poles of 100 cm diameter and with a 10-cm air gap relative to the primary beam and the concrete shield of the synchrocyclotron is shown on Fig. 1. The intensity H of the magnetic field in the gap of the magnet was measured by the method of nuclear absorption with an accuracy of 0.2% and remained constant within 0.2% with the help of an electronic stabilizer. The average radius of curvature, ρ, was 367.6 cm. The angle of deviation of the particles in the magnetic field was 19°.

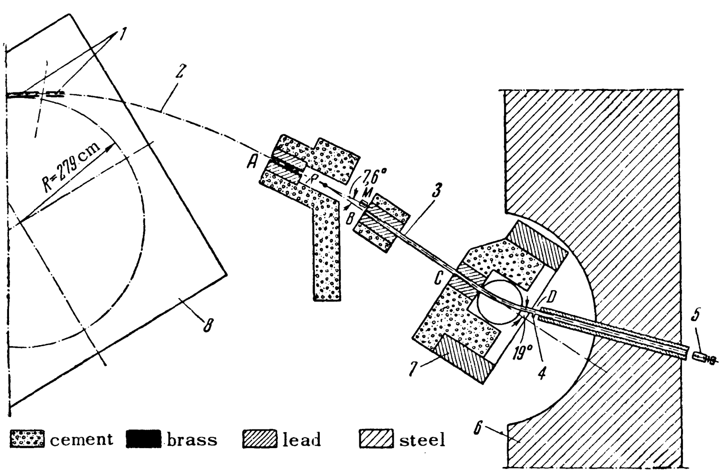

FIG. 1. Experimental setup: 1 — magnetic channel; 2 — proton beam; 3 — vacuum pipe; 4 — vacuum pump; 5 — telescope; 6 — shielding wall; 7 — magnet; 8 — synchrocyclotron chamber; R — target; M — monitor; A, B, C, D — collimators with slits 3 cm high and 1, 2, 3, and 1 cm wide, respectively.

A beam of unpolarized protons of 675 ± 6 Mev energy,* obtained from the 6-meter syn-

*This value of the average energy of the proton in the beam ejected in the atmosphere, after introducing several changes in the setup of the synchrocyclotron, was obtained in our laboratory by L. Soroko, O. Savchenko, and Iu. Akimov from measurements of the proton ranges in copper by a differential method.

chrocyclotron of the Joint Institute for Nuclear Research, was used in our experiment. The beam current at the location of the target was $\sim 3 \times 10^9$ protons/cm^2-sec. The intensity of the beam was controlled by an ionization chamber filled with helium. The brass collimator A determined the dimensions of the proton beam incident on the target. Alignment of the proton beam with the collimator A was attained by shifting the beam in the horizontal and vertical direction by means of an additional magnetic field made up of two movable steel bars, placed in the deflecting field of the accelerator at the point where the proton beam is ejected from the vacuum chamber. Secondary particles emitted from target R at an angle of 7.6° with respect to the primary beam, passed through collimators B and C, the analyzing field, and collimator D, and reached a telescope made up of four scintillation counters arranged for three and fourfold coincidence. The first three counters had as scintillators tolane crystals of dimensions 3 × 3, 2.5 × 2.5, and 4 × 4 cm, respectively, while the fourth counter had a liquid scintillator (a solution of terphenyl and phenylcyclohexane) of 10 cm diamter. The efficiency of the detection of the particles in the momentum interval investigated was approximately constant. The entire path of the particles from their entrance in collimator B until the telescope was in vacuum. Collimator D was used to decrease the importance of effects connected with the scattering and the slowing down of the particles in the walls of collimators B and C. Because of the high level of the irradiation near the synchrocyclotron, it was impossible to separate the beam of secondary particles ahead of the analyzing magnet by means of an array of scintillation counters.

TABLE I

Target	Height, cm	Width, cm	Thickness (g/cm²)	ΔE, Mev	$\overline{<\theta^2>^{1/2}}$, degree.
H_2O	6.0	1.5	1.18	2.78	0.18
D_2O	6.0	1.5	1.30	2.78	0.18
Li	2.5	1.0	1.11	2.30	0.08
Be	2.5	1.0	3.16	6.50	0.18
C	2.5	1.0	3.37	7.52	0.21

Chemically pure targets of Li, Be, and C were used. The elastic (p–d) scattering was observed from the difference in the effects with targets of D_2O (99.93% pure) and H_2O, poured in thin-walled aluminum containers. A target of H_2O was used in the observation on the direct knockout of deuterons from oxygen nuclei. The dimensions of the targets, and also the energy losses and the average angle of multiple scattering of 675-Mev protons in the targets, are displayed in Table I.

The resolving power $\Delta p/p$ of the spectrometer was approximately 3% for the targets used with the dimensions shown and for secondary-particle beam angle of $\sim 0.3°$.

3. ANALYSIS OF THE MEASUREMENT RESULTS

The ordinates of the momentum spectra were computed by dividing $H\rho$ into the number of coincidences corresponding to one and the same number of protons passing through the target. The background in the absence of a target was less than 2%. Upon computing the spectra, corrections were introduced as follows:

1. The absorption of secondary protons and deuterons in the target, in the scintillators, and in the foils covering the entrance and the exist of the vacuum pipe. This correction was at most 4%.

2. Counting errors in the detecting setup. This correction reached an appreciable value only in the narrow region where the peaks of the diffraction scattering of protons were located. When measuring the spectra in this region, the intensity of the beam was decreased sufficiently to keep the counting error below 10%.

The distortion of the forms of the spectra, due to variation of the angle of multiple scattering in the momentum interval examined and to the energy losses of the secondary particles in the target, was within the limits of experimental error.

In order to obtain the absolute value of the differential cross section $d^2\sigma/d\omega\, dp$, separate direct measurements were made of the cross section $d\sigma/d\omega$ of the emission of secondary charged particles with $H\rho > 1100 \times 10^3$ gauss-cm from p + Be and p + C collisions. The area under the curve representing spectra of charged particles with $H\rho > 1100 \times 10^3$ gauss-cm, were normalized to the corresponding experimental value $d\sigma/d\omega$. The accuracy of this procedure was approximately 20%. The ordinate of the spectra obtained with lithium and oxygen were determined by comparison with the yield of the secondary particles from these elements and carbon, and by the use of the known cross section for carbon. The same method was used to compute the ordinates of the peak corresponding to deuteron emissions in elastic (p–d) scattering at an angle of 7.6°.

4. EXPERIMENTAL RESULTS AND THEIR INTERPRETATION

The momentum spectra of the secondary particles from lithium, beryllium, and carbon for the interval from 3600×10^3 to 6200×10^3 gauss-cm are presented on Figs. 2, 3, and 4 together with the statistical errors of the measurements. The section of each spectrum from 4000×10^3 to 4500×10^3 gauss-cm consists of an intense peak, corresponding to protons diffraction-scattered by nuclei, and a closely adjoining projection to the left, corresponding to the lower part of the momentum distribution of the protons from the quasi-elastic scattering by nucleons inside the nucleus. In the case of elastic scattering of 675-Mev protons by nuclei of lithium, beryllium, and carbon, the diffraction peaks should be located at 4355×10^3, 4360×10^3, and 4370×10^3 gauss-cm respectively, while the peak corresponding to protons from elastic (p–d) scattering should be at 4300×10^3 gauss-cm. The experimentally-observed positions of the diffraction peaks differ by less than 0.5% from the computed values. The appearance of the spectra indicates that under the conditions of these experiments the emission of secondary protons is due chiefly to diffraction scattering by the nuclei.

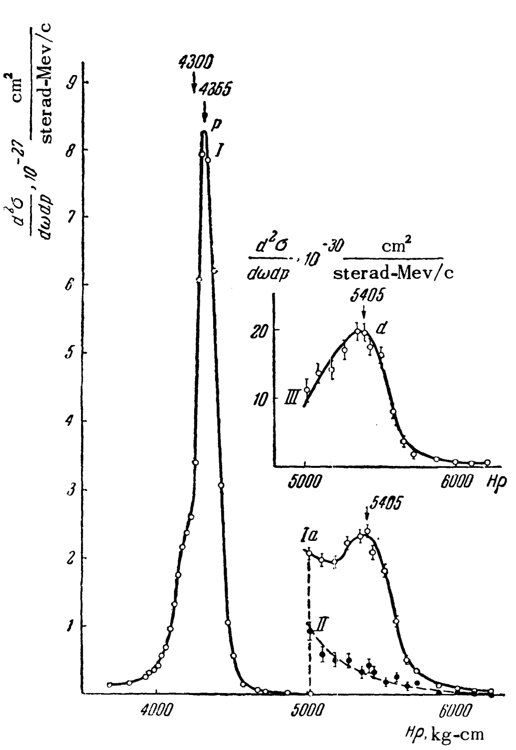

FIG. 2. Momentum spectrum of the secondary charged particles from (p + Li) collisions at an angle of 7.6°. I and Ia — total spectrum of secondary charged particles; II — proton spectrum (the ordinates of Ia and II represent $d^2\sigma/d\omega\,dp$ magnified 100 times); III — spectrum of particles stopped in the absorber.

The experiments in which deuterons were knocked out directly from light nuclei by 675-Mev protons were preceded by the observation of the deuteron yield from elastic (p–d) scattering at an angle of 7.6°. Figure 5 shows part of the spectrum of secondary particles from the (p–d) collision corresponding to this process. The distinct peak observed at 5405×10^3 gauss-cm is due to the recoil deuterons from elastic (p–d) collisions. The shape of this peak represents the experimental resolution curve of the spectrometer. The half width of this peak is approximately 150×10^3 gauss-cm. The value of the differential cross section of the elastic (p-d) scattering with emission of a deuteron at 7.6° to the primary beam is found to be $(0.55 \pm 0.12) \times 10^{-27}$ cm²/sterad.*

Bearing in mind the results of the experiment on the elastic (p–d) scattering, we measured carefully the momentum spectra in the interval from 5000×10^3 to 6200×10^3 gauss-cm. The experiment was carried out with lithium, beryllium, carbon, and oxygen under an 18-cm copper absorber, sufficiently thick to stop the ejected deuterons completely, placed ahead of the fourth counter. The number of particles stopped by the absorber was obtained from the difference between the number of three and four-fold coincidences. At the same time, experimentally-determined corrections were introduced for the absorption and the scattering of the protons in the absorber and in the scintillators. The four-fold coincidences with absorber to the right of the diffraction peak, are due to diffraction-scattered protons subjected to additional scattering along their path in the spectrometer.

The observed results are shown in Figs. 2 — 4 and 6. In the momentum interval studied the ordinates of the spectra are magnified 100 times compared with the ordinates of the remaining part of the spectrum. Well resolved peaks near 5400×10^3 gauss-cm are observed on the spectra of the secondary particles from lithium and beryllium. In the same region of the carbon and oxygen spectra one notices characteristic tails to the right of the diffraction peak. No peculiarities were remarked in the spectra of the particles passing through the copper absorber. The experimentally observed spectra of the particles stopped in the absorber involved in all cases peaks with maxima around 5350×10^3, 5250×10^3, and 5230×10^3 gauss-cm for lithium, beryllium, carbon, and oxygen respectively.

*Results of experiments on the study of (p–d) collisions at an angle of 7.6° will be discussed in another communication.

From the spectra obtained by us it follows that 675-Mev protons interact with light nuclei to cause, with appreciable probability, emission of particles whose momentum is greater than the momentum of the protons diffraction-scattered by the nuclei. The momenta transferred to such particles are grouped around

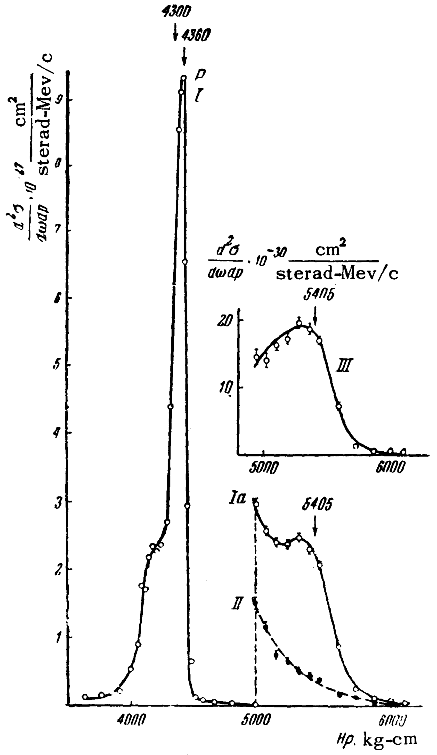

FIG. 3. Momentum spectrum of the secondary charged particles from (p + Be) collisions at an angle of 7.6°. I and Ia — total spectra of the secondary charged particles; II — proton spectrum (the ordinates of Ia and II represent $d^2\sigma/d\omega\, dp$ magnified 100 times); III — spectrum of the particles stopped in the absorber.

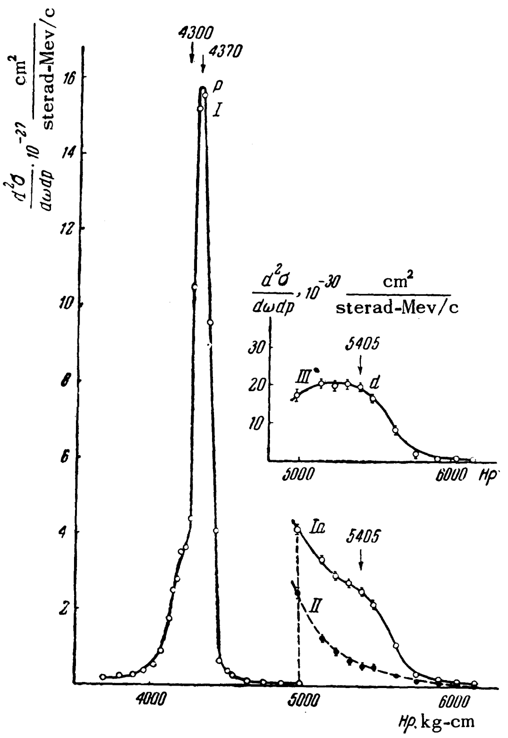

FIG. 4. Momentum spectrum of the secondary charged particles from (p + C) collisions at an angle of 7.6°. I and Ia — total spectrum of secondary charged particles; II — proton spectrum (the ordinates of Ia and II represent $d^2\sigma/d\omega\, dp$ magnified 100 times); III — spectrum of the particles stopped in the absorber.

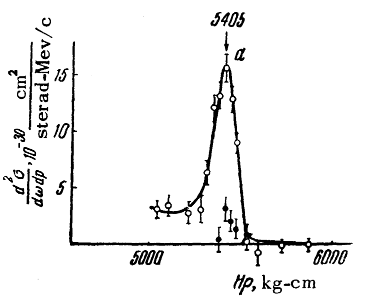

FIG. 5. Part of the momentum spectrum of secondary charged particles from (p + d) collisions with the peak of the elastically-scattered deuterons. ○ — results of measurements without absorber to stop the recoil deuterons; ● — the same with absorber.

values that are only slightly smaller than the momentum of the deuteron emitted in elastic (p–d) scattering. Like the recoil deuterons from elastic (p–d) scattering, the observed group of particles is completely stopped in 18 cm of copper. Under the conditions of these experiments, in the momentum region $H\rho > 5000 \times 10^3$ gauss-cm the only particles heavier than protons that could penetrate were deuterons and tritium nuclei. The latter could be emitted by quasi-elastic collision of the incident proton with a group of three strongly interacting nucleons and would have a momentum of approximately 6000×10^3 gauss-cm, which is appreciably greater than the momentum of the particles in the observed peaks.

The above experimental results evidence that 675-Mev protons sometimes knock out deuterons from light nuclei. This process is kinematically very similar to elastic (p–d) scattering. From the presence of such a correspondence between the two processes one can conclude that deuterons are knocked out as the result of almost elastic collision between the incident protons and quasi-deuteron groups inside the nuclei.

It should be emphasized that the observed group of deuterons could not result from capture of neutrons within the nuclei by the incident protons, i.e., in reactions of the type $p + (Z, A) \rightarrow d + (Z, A - 1)$. Indeed, the

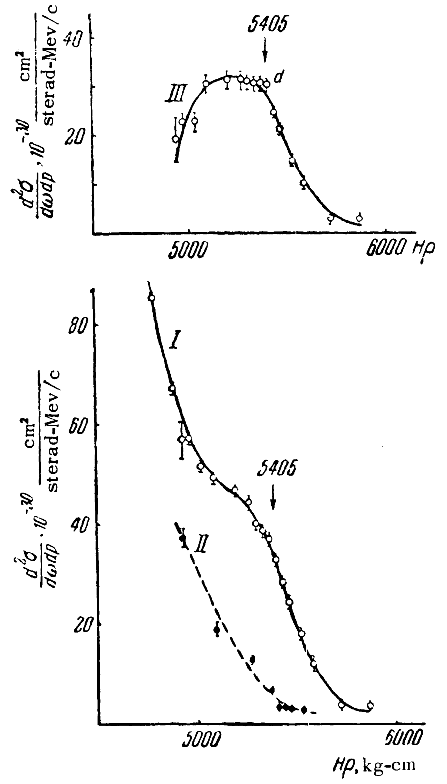

FIG. 6. Momentum spectrum of the secondary charged particles from (p + O) collisions. I — total spectrum of the secondary charged particles; II — proton spectrum; III — spectrum of the particles stopped in the absorber.

TABLE II

Element	$\left(\frac{d\sigma}{d\omega}\right)_t$ $10^{-27}\frac{cm^2}{sterad}$	$\left(\frac{d\sigma}{d\omega}\right)_d$ $10^{-27}\frac{cm^2}{sterad}$	$\left(\frac{d\sigma}{d\omega}\right)_d/Z$ $10^{-27}\frac{cm^2}{sterad}$	ΔE, Mev	Binding energy of the Deuteron, Mev
D	—	0.55±0.12	0.55	—	—
Li	—	2.9 ±0.6	0.97	10	9.5
Be	590±30	2.2 ±0.5	0.55	23	16.7
C	900±50	3.7 ±0.8	0.61	30	25.2
O	—	4.6 ±1.0	0.58	33	20.7

deuterons emitted in this process must have momenta greater than the momentum of the recoil deuterons in elastic (p–d) scattering. For instance, in the case of neutron capture by protons in the C^{12} nucleus without excitation of the residual nucleus C^{11}, deuterons would be emitted with momenta approximately 225 × 10^3 gauss-cm greater than the momentum of the deuterons in elastic (p–d) scattering. Actually, however, the observed peak is below the peak of the elastic scattering of deuterons by ~ 150 × 10^3 gauss-cm. Neither can the observed group of deuterons be identified with the deuterons resulting from capture of nucleons from nuclei by relatively slow secondary nucleons that have become involved in the nuclear cascade by the primary proton. Deuterons emitted in such a process of indirect nucleon capture must have a smeared momentum spectrum without any correlation with the deuteron peak in the elastic (p–d) scattering. The observed peaks cannot furthermore be assigned to the deuterons formed in the reactions $p + p \rightarrow d + \pi^+$ and $p + n \rightarrow d + \pi^0$, which possibly take place inside the nuclei. The deuterons corresponding to these reactions would have to have momenta not more than 4560 × 10^3 gauss-cm, which is approximately 800 × 10^3 gauss-cm less than the studied region of the momentum spectrum. Finally, by virtue of the principle of detailed balance, one would expect to observe the production of deuterons in the reaction $p + n \rightarrow d + \gamma$, the inverse of the photodisintegration of the quasi-deuteron group in the nuclei. At an angle of observation of 7.6° and at a proton energy of 675 Mev, deuterons in this reaction must be emitted with momenta not greater than 4690 × 10^3 gauss-cm, which is almost 500 × 10^3 guass-cm lower than the observed region of the spectrum.

One can say thus that the peaks observed at the upper limits of the momentum spectra correspond actually only to deuterons ejected from nuclei by collision of protons with quasi-deuteron groups. An approximate estimate of the absolute magnitude of the differential cross section of this process was carried out by comparison of the areas, on one hand, under the diffraction and quasi-elastic scattering spectra of the protons and on the other hand under the peaks corresponding to particles with a range less than 18 cm in copper. The numerical values of the differential cross sections $(d\sigma/d\omega)_d$ obtained in such a way for the knock-out of deuterons are given in Table II, together with the corresponding values of the differential scattering $(d\sigma/d\omega)_t$ for the emission of secondary charged particles with $H\rho > 1100 \times 10^3$ gauss-cm from p + Be and p + C collisions.

In the case of Li, Be, and C the spectra were measured up to $H\rho = 6200 \times 10^3$ gauss-cm, which includes the region in which one would expect the occurrence of groups of tritons ejected from the nuclei. A study of the high-momentum component of the spectra showed that if the ejection of tritons from the nuclei occurred at all under the conditions of this experiment, their yield constituted less than 2 to 3% of the deuteron yield.

5. ANALYSIS OF THE DEUTERON PEAKS

A distinguishing feature of the spectra obtained is that the peaks corresponding to the ejected deuterons are appreciably wider than the peak observed in the case of the elastic (p–d) scattering. This difference apparently results to a large extent from the momentum distribution of the quasi-deuteron groups inside the nuclei. The average kinetic energy of the quasi-deuteron groups in the nuclei can be estimated from data on the widths of the experimental peaks and from the resolution curve of the spectrometer, assuming the effect of the scattering of the deuterons as they leave the nuclei to be small. Simple computations have shown that the average kinetic energies of the quasi-deuteron groups are approximately 8, 11, 14, and 14 Mev for Li, Be, C, and O respectively.

The observed peaks are not clearly resolved on the left side. This may be due in part to energy loss of the protons and deuterons in the nuclei and in part to the slowing of the deuterons in the walls of the collimators. Nor can one exclude the possibility that adjacent to the left of the observed peak are smeared deuteron peaks from the possible reactions $p + p \rightarrow d + \pi^+$ and $p + n \rightarrow d + \pi^0$.

The experiment has demonstrated that in the spectra of light elements, the deuteron peaks are shifted slightly to the left of the peaks due to the deuterons from elastic (p–d) scattering. The next to the last column of Table II lists the difference between the energy of elastically-scattered deuterons and the average energy of the deuterons ejected from nuclei corresponding to the observed shift, while the binding energy of the deuterons in the nuclei is given in the last column of Table II. This difference represents principally the binding energy of the deuteron in the potential well due to the remaining nucleons. If the proton, after colliding with the quasi-deuteron group, also leaves the nucleus without further collisions, then the observed process can be envisioned as a reaction of the type $p + (Z, A) \rightarrow d + p + (Z - 1, A - 2)$. According to the data obtained, the recoil energy and the excitation of the residual nucleus $(Z - 1, A - 2)$ must not be large.

TABLE III

Nucleus	Li	Be	C	O
σ_d, 10^{-27} cm^2	~4.5	~6	~9	~12
σ_t, 10^{-27} cm^2	—	272±7	340±10	416±30

It is necessary to mention that the scattering of protons from quasi-deuteron groups with transfer of high momenta to the deuteron represents basically a process connected with three-particle interactions. For a given angle, the cross section of this process, as seen from Table II, increases with increasing dimension of the nuclear target. Normalized to one proton in the nucleus, the differential cross section for the ejection of a deuteron does not differ strongly from the cross section for elastic (p–d) scattering, observed under the same conditions. This fact apparently means that the character of the three-particle interaction is the same both in the collisions of protons with quasi-deuteron groups in light nuclei and in collisions of protons with free deuterons. Such a situation seems possible only if the other nucleons within the nucleus do not participate effectively in the interaction between the incident proton and the tight quasi-deuteron group.

The total cross section for the ejection of deuterons from the nuclei was estimated by assuming that the angular distributions of the recoil deuterons in elastic (p–d) collisions and in collisions of protons with quasi-deuteron groups are the same. The angular distribution of the cross section for elastic (p–d) scattering at an energy of 660 Mev was measured in our laboratory by Leksin[16] in the interval 40 — 150° in the proton-deuteron center-of-mass system. From these data it was estimated that the total cross section of elastic (p–d) scattering is approximately 1.5×10^{-27} cm^2. From this, assuming that the yield of deuterons is proportional to Z, we determined the total cross sections σ_d for the ejection of deuterons. Their values are listed in Table III. For comparison, this table contains also the values of the total cross section σ_t for the interaction of protons with the nuclei of the elements mentioned at an energy of 650 Mev.[17] The contribution of the three-nucleon collisions to the total cross section for the interaction of the protons with the nuclei must apparently be even greater because of the collisions between the protons and quasi pp and nn groups and also with pn groups in states other than $^3S_1$ and $^3D_1$.

6. CONCLUSION

The experiments carried out show that bombardment of Li, Be, C, and O by 675-Mev protons results with appreciable probability, in emission of deuterons with almost the same momentum as in elastic (p–d) scattering. Such a close relation between the processes named leads to the assumption that the deuterons are knocked out from light nuclei by collision of the incident protons with quasi-deuteron groups. Examination of the broadening of the deuteron peaks shows that the average kinetic energy of the quasi-deuteron groups in the potential well of the remaining nucleons in the nuclei is approximately 8, 11, 14, and 14 Mev for Li, Be, C, and O respectively. As suspected, the average kinetic energies of the quasi-deuteron groups are less in lithium nuclei than in the nuclei of the other elements investigated. A similar result was obtained in Massachusetts[18] upon investigation of the photodisintegration of quasi-deuteron groups. From a comparison of the differential cross section of elastic scattering of protons by free deuterons and by quasi-deuteron groups, it follows that the character of the three-nucleon interactions in free (p–d) collisions and in collision of protons with quasi-deuteron groups do not differ in any noticeable way. If under the condition of these experiments, any tritons were knocked out at all by collisions between protons and tight three-nucleon groups, the yield of tritons comprised less than 2 to 3% of the yield of the ejected deuterons.

The results of these experiments can be considered as an important argument in favor of the nuclear model proposed by Brueckner and his colleagues[19–21] and recently analyzed by Bethe.[22] This model is based on the assumption that in nuclear matter strong short-range interactions exist between pairs of nucleons, in consequence of which the wave function of the ground state of the nucleus contains an appreciable admixture components corresponding to large momenta of individual nucleons. This is equivalent to assuming an appreciable correlation in the locations of the nucleons inside the nuclei or, in other words, to assuming short-lived formations of two or more strongly-interacting nucleons.

Within the framework of the high-momentum model of the nucleus, the ejection of deuterons from nuclei by high-energy protons can be considered either as the result of transfer of high momentum to the tight two-nucleon groups as a whole, or as the capture of a neutron from such a group with the formation of a deuteron emitted forward. The fact that the ejected particles do not include many tritons is apparent evidence of the relatively rare event whereby a three-nucleon group, capable of undergoing recoil as a whole, is formed inside the nucleus. An analogous result follows from the high-momentum model of the nucleus.[21,22]

The problem of the transfer of high energy from the incident nucleon to the nuclear fragment was investigated by Blokhintsev[23] under the assumption that short-lived tight clusters of nucleons, which can be ejected from nuclei in the form of separate particles upon collision with nucleons are formed inside the nuclei. Calculations based on such a picture show the dependence of the cross section for ejection of energetic deuterons on the atomic number and on the atomic weight of the nucleus to be of the form $Z^2A^{-1/3}$ for nuclei containing few nucleons, and of the form $ZA^{-1/3}$ for nuclei in which the effect of saturation of nuclear forces is already substantial. The probability of emission of tritons comprises only several percent of the yield of deuterons, which is not in disagreement with experiment. The absolute value of the cross section also appears to be in agreement with the results of these measurements.

It is impossible to say anything definite at this time on the nature of the forces acting between the incident proton and the quasi-deuteron group. At a given energy, the wavelength of the proton, in the center-of-mass system of the two nucleons is $\lambda = 0.35 \times 10^{-13}$ cm, which is only 1.7 times greater than the Compton wavelength of the nucleon, $\hbar/Mc$. The possibility is not excluded that such tight collisions of protons with quasi-deuteron groups are accompanied by a strong deformation of the meson cloud of the three colliding nucleons, and by an interaction which occurs through the simultaneous exchange of pairs of π mesons. From this point of view, the high-energy collisions of nucleons with quasi-deuteron groups, like three-body collisions appear as favorable for the observation of effects connected with three-body forces and therefore warrant further investigation.

In conclusion the authors express their thanks to D. I. Blokhintsev, G. A. Leksin, and V. I. Ogievets for discussions, and also to Iu. N. Denisov for help in the measurements of the magnetic field of the spectrometer.

[1] Brueckner, Eden, and Francis, Phys. Rev. **98**, 1445 (1955).
[2] J. Levinger, Phys. Rev. **84**, 43 (1951).
[3] Claidis, Hess, and Moyer, Phys. Rev. **87**, 425 (1952).
[4] J. Wilcox and B. Moyer, Phys. Rev. **99**, 875 (1955).
[5] P. Cüer and J. Combe, J. Phys. et radium **16**, 298 (1955).
[6] McEwen, Gibson, and Duke, Phil. Mag. **2**, 231 (1957).
[7] H. York, Phys. Rev. **75**, 1467 (1949).
[8] K. Brueckner and W. Powell, Phys. Rev. **75**, 1247 (1949).
[9] J. Hadley and H. York, Phys. Rev. **80**, 345 (1950).
[10] W. Selove, Phys. Rev. **92**, 1328 (1953); **101**, 231 (1956).
[11] Cüer, Morand, and Van Roxsum, Compt. rend. **228**, 481 (1949).

[12] G. Chew and M. Goldberger, Phys. Rev. 77, 470 (1950).
[13] J. Heidman, Phys. Rev. 80, 171 (1950).
[14] W. Hess and B. Moyer, Phys. Rev. 101, 337 (1956).
[15] Mescheriakov, Neganov, Vzorov, Zrelov, and Shabudin, Dokl. Akad. Nauk SSSR 109, 449 (1956), Soviet Phys. "Doklady" 1, 447 (1956).
[16] G. A. Leksin, J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 440 (1957), Soviet Phys. JETP 5, 371 (1957).
[17] V. Moskalev and B. Gavrilovskii, Dokl. Akad. Nauk SSSR 110, 972 (1956), Soviet Phys. "Doklady" 1, 607 (1956).
[18] Wattenberg, Odian, Stein, Wilson, and Weinstein, Phys. Rev. 104, 1710 (1956).
[19] K. Brueckner and C. Levinson, Phys. Rev. 97, 1344 (1955).
[20] K. Brueckner, Phys. Rev. 97, 1353 (1955).
[21] K. Brueckner, Phys. Rev. 100, 36 (1955).
[22] H. Bethe, Phys. Rev. 103, 1354 (1956).
[23] D. Blokhintsev, J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 1295 (1957), Soviet Phys. JETP, this issue, p. 995.

Translated by Fay Ajzenberg-Selove
245

SOVIET PHYSICS JETP VOLUME 6 (33), NUMBER 5 MAY, 1958

*A GROUP-THEORETICAL CONSIDERATION OF THE BASIS OF RELATIVISTIC QUANTUM MECHANICS. II. CLASSIFICATION OF THE IRREDUCIBLE REPRESENTATIONS OF THE INHOMOGENEOUS LORENTZ GROUP**

Iu. M. SHIROKOV

Moscow State University

Submitted to JETP editor December, 11, 1956

J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 1196-1207 (November, 1957)

A classification is obtained for the states of a relativistic quantum system. The irreducible representations of the inhomogeneous Lorentz group are divided into four fundamental classes: P_m, P_{Π}, P_0, O_0. All the representations of classes P_m and P_{Π}, both unitary and non-unitary, are found explicitly.

1. CLASSIFICATION OF THE STATES OF A RELATIVISTIC QUANTUM SYSTEM

We have previously[1] found all the possible invariants of the inhomogeneous Lorentz group, and have noted that the classification of the irreducible representations of the group reduces to finding the eigenvalue spectra of these invariants. However, we as yet do not know the independent variables contained in the wave functions, which transform according to a particular irreducible representation. In order to find these variables and their domain of variation, we must select from among the operators of the group a complete set, i.e., a complete system of operators which commute with one another (but not with all the operators of the group). The choice of such a system of operators is, of course, not unique. This non-

*Notations used without explanation are the same as in Ref. 1. References like (I.8) are to the corresponding formula in Ref. 1.