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SCATTERING OF RELATIVISTIC PROTONS AND DEUTERONS FROM ATOMIC NUCLEI

1985

In honour
of the seventy-fifth anniversary of birth
of Professor M.G.Meshcheryakov

In the last few years the relativistic nuclear physics is going through the stage of impetuous development. Excellent progress in experimental techniques, particularly acceleration of atomic nuclei up to relativistic energy, electron, muon and neutrino high-energy and high intensity beams, the possibility of measuring with a good enough accuracy high momenta transferred to different components of reactions, the observation and measurement of characteristics of multiple, including jet particle production, has made the problem of investigation of the subhadron structure of mesons and nucleons, as well as atomic nuclei, practicable. The principles of theoretical description of observed phenomena are formulated: quantum chromodynamics in spite of serious difficulties (still existing) attempts, in principle, to explain quantitatively all sets of known facts concerning hadron interactions and nuclear matter properties. Intensive searches for hadron and nuclei quark structure are in progress using lepton and hadron interactions. Free quarks are also looked for in accelerator experiments, in cosmic rays and in stable matter (the so-called quark chemistry). These searches are very complicated because of great uncertainties of our knowledge of characteristic signs of objects to be discovered. Unknown is, for example, the mass of free quarks and quark bags as well as the way in which the colour forces manifest themselves. These are no so far, in spite of the remarkable progress achieved lately, the established criteria for observation of phase transition from hadron matter to quark-gluon chromoplasma, and of quark phase admixture into the heterophase state. Therefore, to reveal the intrinsic hadron structure in the hadronic interactions an approach is in good time consisting in the detailed investigation of these interaction first of all within the models not involving the quark concepts. There the difference between experimental data and results of such "classical" analysis would prove that the intrinsic degrees of freedom of interacting particles are revealed [1]. At the same time the efforts of physicists are concentrated on the study of effects which either can't appear in the interactions of hadrons with hadrons on the level of quasiparticles of nuclear matter, or their probability at the experimental conditions achieved nowadays is very low. The idea of the so-called cumulative effect [2] has turned out to be excellent in this regard. However, in both cases the problem is very complicated because of the limitations of existing models and the background effects. In case of the hadron/nucleus-nucleus collisions one has to take into account such effects as, in particular, Fermi motion of intranuclear nucleons, secondary interactions and relativistic effects.

Side by side with new experiments being started, reversion of earlier obtained experimental information is continued, too. At present, when the range of problems in the field as well as difficulties accompanying them is clear enough one can duly appraise at their true worth the first experiments in which the effects attracting nowadays general attention have been observed.

As far as in 1956 M.G.Meshcheryakov et al. have carried out an experiment at the 6 meter synchrotron using the magnetic spectrometer with a telescope of scintillation counters. In this experiment energy spectra of protons with energy 100-700 MeV emitted at the angles of 7°, 12.2°, 18°, 24°, and 30° in the reactions of protons with beryllium, carbon, copper and uranium nuclei at 660 MeV have been studied [3]. The analysis of the experimental data based on impulse approximation and relativistic kinematics shows that the best parametrisation of the momentum distribution of intranuclear nucleons for beryllium and carbon nuclei is the Gaussian function with the value 1/e at the energy of about 20 MeV, or a superposition of two Gaussian distributions which reflects better the high momentum part of nucleon Fermi motion inside a nucleus. The data have been obtained allowing to estimate the momentum distribution of peripheral nucleons of heavier nuclei - copper and uranium. The analysis of these results led to the conclusion which, as it turned out clear latter on, can be related to some of the following experiments. The point is that to explain the high momentum part of experimental distribution of quasielastic scattered hadrons it is necessary to take account of hadron scattering on compact two-nucleon groups and, probables, on heavier intranuclear clusters.

The results concerning the Fermi motion of intranuclear nucleons have been used as a foundation for the intranuclear cascade model very frequently applied in different aspects at experimental data analysis. Later, when the investigation of interactions of relativistic particles and nuclei with atomic nuclei became a unique source of involving short-lived particles as well as local properties of nuclear matter [2], the reliable knowledge of intranuclear nucleon motion as a "classical background" has a factor determining the correctness of these investigations.

In 1957-1958 a number of experiments has been performed in which the energy spectra of π^+ and π^- mesons emitted at an angle of 56° relative to a primary beam of protons with the energy of 670 MeV have been measured [4]. This value of angle in the laboratory reference corresponds to an angle of 90° in the center of mass of nucleon-nucleon system. Carbon nuclei were used as a target. The energy distributions of charged pions obtained in this investigation extend up to a value of 400 MeV and it is not excluded that the upper limit for the energy of these particles reaches as far as 470 MeV, as in the case of $p+{}^{12}C \to \pi^{+} + {}^{13}C$ reaction. The conclusion has been made that to explain the observed high momentum part of the spectra within the intranuclear nucleon-nucleon collision picture, it is necessary to admit the existence of nucleons with a momentum of no less than 350 MeV/c inside a carbon nucleus. This value for a nucleon of a carbon nucleus exceeds by more than 100 MeV/c the upper limit given by the Fermi gas of non-interacting nucleons model. More than ten years later such kind of particle emission in hadron-nucleus interactions where particles emerged off the region allowing for the kinematics of hadron-nucleon collisions began to draw general attention in view of the possibility to study in that way the local properties of nuclear matter [2].

Nevertheless the question under what conditions atomic nuclei properties, nontrivial from nuclear physics point of view can reveal themselves has become more complicated. For example, it has been shown within several model approaches that for emission of secondary particles produced in the hadron-nucleus collisions off the kinematical region allowing for free hadron-nucleon collisions at the same energy and at the scale variable ≤ 2, it is not necessary to use any new concept of the interaction nature [5]. Other criteria, being most likely qualitative, also suffer from shortcoming, for example, the momentum transfer should not be less than ~1 GeV/c, or the effective target mass should exceed the nucleon rest mass, etc. The most argued theoretically as well as experimentally condition is the one proposed recently by A.M.Baldin [6] according to which one can consider that hadrons altogether and nucleons includingly loose their individuality, e.g., they are no more the quasiparticles of nuclear matter when the four-velocity transfer to a secondary particle is not less than 5. In the above experiment [4] this value corresponding to the high-energy part of charged pions emitted in the target nucleus fragmentation region exceeds 5. Thus, as far as in 1957 the effects of qualitatively new kind has been observed the investigation of which has come to be today a basic matter of relativistic nuclear physics. This conclusion is not in contradiction with the fact that the primary energy is far from the energy of limiting fragmentation of target nuclei (≥ 4 GeV). As it follows from the analysis of the process of annihilation $e^{-}e^{+}$ into hadrons, quark degrees of freedom can manifest themselves as early as at an energy value of ~0.6 GeV [7].

The discovery by M.G.Meshcheryakov et al. in 1957 of the effect of direct knocking-out of deuterons from nuclei by protons with an energy of 675 MeV [8] was of great importance. In their experiment a proton beam from the JINR synchrocyclotron incidented with the targets of H_2O , D_2O , Li , Be, and C. Set of collimators extracted the secondary particles, protons mostly, emitted at an angle of 7.6°. At all irradiated targets the maxima of deuterons with a momentum of about 1600 MeV/c, i.e., exceeding approximately by 300 MeV/c the momentum of diffractive scattered protons, have been observed. The analysis of experimental data has shown that the registered deuterons cannot be produced neither in the pick-up reaction of protons from target nuclei by the impinging protons nor in the collisions of primary protons with the neutrons of target nuclei. The possibility of the creation of this deuterons in more complicated processes of the cascade type was also rejected. The authors have pointed out that the peaks in deuteron momentum spectra they have measured are significantly wider than the peaks observed in the elastic pd scattering [8,9]. Supposing this width enlargement being caused mainly by the momentum distributuin of quasideuteron clusters inside the nuclei, the estimations of the average energy of these clusters in lithium, beryllium, carbon and oxygenium nuclei have been obtained: 8, 11, 14 and 14 MeV,respectively. Using the shift of these peaks relatively to the deuteron peak from the pd scattering the binding energy of quasideuteron groups in the studied nuclei was estimated as 9.5, 16.7, 25.2 and 20.7 MeV. The estimation of the total cross-section of deuteron knocking-out from nuclei has been also obtained. Later on, the differential cross-section of deuteron knocking-out at different angles in the interval 6.5°-16° was measured and the dependence of this cross-section on the atomic number of the target nucleus was studied [10]. So, a complete enough and qualitative analysis of the observed effect and, therefore, of the effect of nuclear matter clusterization has been done.

In 1967 G.Palevsky et al. [11] have performed a similar experiment at the Brookhaven cosmotron in which the $p+(A,Z) \to d+p+ +(A-Z, Z-1)$ reaction at 1 GeV/c momentum was studied using a magnetic spectrometer and ^{4}He , ^{6}Li , ^{12}C , ^{16}O and Pb nuclei as targets. The deuteron emission was observed at the angles of 5°, 10°, and 15°. The authors have obtained the estimation of the average kinetic energy of two-nucleon clusters in the studied nuclear targets which turned out to be in good agreement with the earlier JINR data.

The discovery of the effect of direct knocking-out of deuterons by high energy protons from atomic nuclei has stimulated interest to investigation of the structure of atomic nuclei.

After the experiments D.I.Blokhintsev[12] suggested an idea of nuclear matter density fluctuations. This idea was revived as the so-called flucton model of nucleus used for explaining the hard part of momentum spectra of pions produced in the cumulative region in proton-nucleus collisions at the energy of several GeV[13]. It should be noted also that the observed effect pointed out the possibility of experimental investigation of simultaneous hadron interactions at short distances.

The results of M.G.Meshcheryakov et al. attracted attention again in the beginning of 70th when the beams of light relativistic nuclei appeared and, in particular, in view of the investigation of cumulative effect[2].

The following experiments have been done at the JINR synchrophasotron using one-arm magnetic spectrometer with spark wire chambers operating on-line with a computer. The aim of these experiments was a detailed and systematic study of inclusive spectra of fast deuterons and protons, produced in the collisions of deuterons and protons from different targets (p, d, C, Al, Bi) at three values of primary particle momentum: 4.3, 6.3, 8.9 GeV/c[14-18]. Good momentum resolution of the spectrometer ($\Delta p/p \simeq \pm 0.25\%$) and high statistics of experimental data enabled to investigate the details of the structure of high-energy part of secondary proton and deuteron spectra in the interval of transverse momenta $0.2 \leq |t| \leq 0.8$ $(GeV/c)^2$. Set-up of modified version of experiment is shown in Fig.1. At the analysis of experimental information the multiple diffraction scattering model was used because, as is known, with the energy growth from intermediate to higher one the hadron-nucleon scattering at small angles becomes more and more diffractive. At the same time angular particle distributions have maxima sharply expressed in the forward direction. Therefore, when a hadron passes through a nucleus its probability to be scattered at the

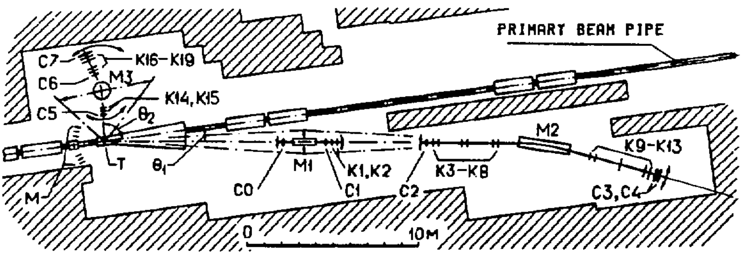

Fig.1. Schematic view of the double-arm magnetic spectrometer placed at the beam of nuclei extracted from the JINR synchrophasotron. T - target, M - beam monitors, K1,...,K9 - proportional chambers, C0,...,C9 - scintillation counters, M1, M2, M3 - magnets.

fixed angle by more than one nucleon can become equal to or even exceeds the scattering probability at the same angle on the single nucleon only [19,20]. Such an approach being rather classical follows from the belief that to study subtle effects caused by the intrinsic degrees of freedom of nucleons inside nuclei it is necessary, in the first place, to have a complete enough information on the nucleus as a multinucleon system. It is of particularly great importance for intermediate interval of four velocity transfer in which parallel with hadron-nucleus interaction on the quasiparticle level the quark effects can manifest themselves.

Let us consider the process of quasi-elastic scattering of the simplest nuclei-deuterons on deuterons involving the target deuteron break-up. In the framework of the multiple nucleon-nucleon scattering model this process is schematically represented in Fig.2. In particular, it is seen from Fig.2 that in quasi-elastic deuteron-deuteron scattering double nucleon-nucleon scatterings of different kinds can occur.

Various kinds of multiple nucleon-nucleon collisions lead to deuteron momentum loss distributions which have maxima at different momentum loss values. The scattering of one (Fig.2a) or both incident nuclei (Fig.2b) on one of the target deuteron nucleons leads to the momentum loss $\Delta \simeq (p_0\theta)^2/2m$, where p_0 is the incident deuteron momentum, θ is the scattering angle and m is the nucleon mass; triple nucleon-nucleon scattering (fig.2e) gives rise to momentum losses distribution smoothly around a value of about $5\Delta/8$; the successive scattering of one

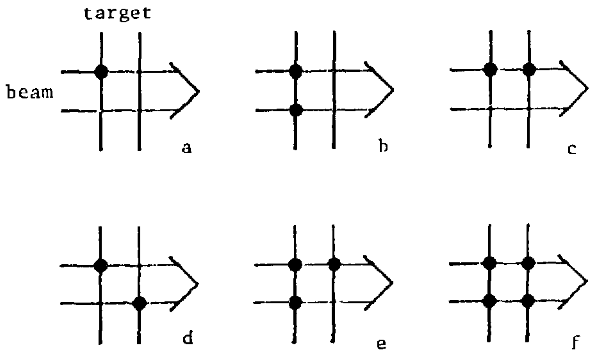

Fig.2. Schematic representation of the multiple nucleon-nucleon scattering processes resulting in the quasi-elastic (with target deuteron break-up) deuteron-deuteron scattering (see text).

of the incident nucleons on both target nucleons (Fig.2c), or the simultaneous scattering of both incident nucleons each on one of two target nucleons (Fig.2d), as well as quadrupole scattering (Fig.2f) lead to a loss of about $\Delta/2$. Therefore the investigation of the high-momentum parts of the spectra of deuterons emitted at small angles in quasi-elastic scattering on deuterons is a spectroscopy of multiple nucleon-nucleon scatterings.

The measured high-momentum parts of the deuteron spectra at an angle of 103 mrd from deuteron-deuteron collisions at 4.3, 6.3 and 8.9 GeV/c are shown in Fig.3[14]. The region of momentum losses investigated corresponds to elastic and quasi-elastic (with target deuteron break-up) deuteron-deuteron scattering. In case of 4.3 GeV/c deuteron scattering there is a peak seen in the spectrum with a bump visible on the right-hand side showing that there is another weak peak, the position of which corresponds to approximately an incident deuteron momentum loss half as large as that for the first peak. At 6.3 and 8.9 GeV/c both peaks are well separated and become comparable in height. In all the spectra the positions of the left-hand peaks correspond kinematically to deuteron scattering on nucleons, and the position of the right-hand peaks correspond to elastic deuteron scattering on deuterons.

The revealed structure of the high-momentum parts of the spectra of the elastic and quasi-elastic scattered deuterons was analysed[14,15] within the framework of the multiple nucleon-nucleon scattering model. In this model the deuteron-deuteron scattering amplitude is expressed through the deuteron form-factor, which characterize its "radius", and elastic nucleon-nucleon scattering amplitudes as a sum of terms corresponding to the different multiplicities of nucleon-nucleon collisions. The elastic nucleon-nucleon scattering amplitude has been taken in the usual form $f(q) = (k\sigma(i+\rho)/4\pi)\exp(-\beta q^2/2)$, where k is the wave number of the incident nucleon, q is the momentum transferred, $\rho = \mathrm{Re}\,f(0)\,\mathrm{Im}\,f(0)$, σ is the total nucleon-nucleon cross-section, and β is the slope parameter for the differential cross-section of elastic nucleon-nucleon scattering. Several versions of calculations with different ρ- and β-values were performed. They are shown as curves 1,2 and 3 in Fig.3. It is seen that calculation results, without any additional assumptions, reproduce qualitatively the main features of the measured deuteron distributions. Therefore, it is natural to interpret the revealed structure as an exhibition of the multiple nucleon-nucleon scattering effect.

The results of calculation depend on used values of the slope parameter for the differential cross-section of elastic N-N scattering: the calculation versions 1 and 2 were distinguished by β-values, which differed in about 20% at 6.3 GeV/c

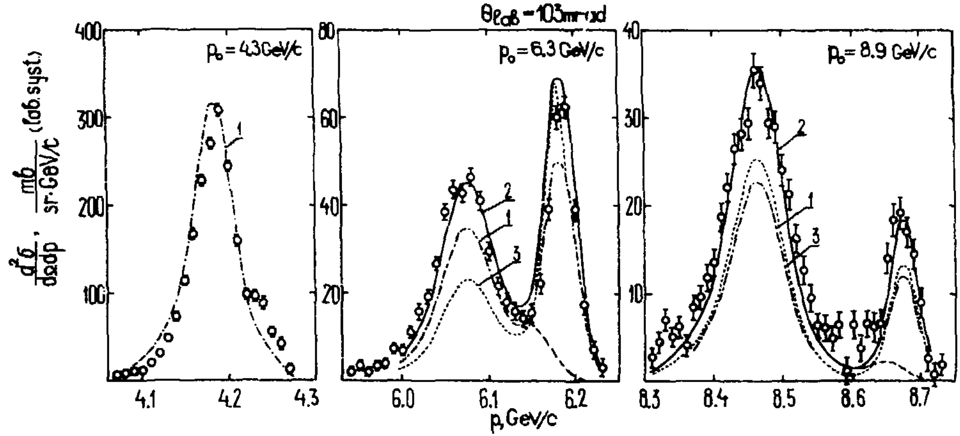

Fig.3. Momentum spectra of deuterons detected at a lab angle of 103 mrd in deuteron-deuteron collisions at 4.3, 6.3 and 8.9 GeV/c. Curves 1,2 and 3 are the versions of the calculations based on the multiple scattering model. The dashed curves show the calculated contributions from the quasi-elastic deuteron scattering to the peaks corresponding kinematically to the elastic d-d *scattering.*

and about 15% at 8.9 GeV/c. It is to be noted that the calculation results are rather sensitive to the value of the ratio of the real and imaginary parts of the elastic nucleon-nucleon scattering amplitude (thus, for calculation versions 2 and 3 the ρ-values were -0.43 and 0, respectively). Because of such a high sensitivity the deuteron-deuteron scattering may be considered as a new independent method of determining the absolute value of the ratio ρ. The method suggested is based on the fact that the differential cross section for $dd \to dnp$ reaction is expressed as a sum of contributions corresponding to the different multiplicities of N-N scattering m, and interference terms, with factors $(1+\rho^2)^m$ /15/. The conventional method of determining the ratio ρ is the analysis of the proton-proton scattering data in the region of Coulomb-nuclear interference.

In these experiments made at the JINR synchrophasotron measurements of the momentum spectra of secondary deuterons emitted at an angle of 103 mrd in the interactions of 8.9 GeV/c deuterons with the hydrogen, deuterium and carbon nuclei include also the interval of the spectra of deuterons having such high momentum losses as 1 GeV/c and even greater. It turnes out to be that such "loose" nuclear system as the deuteron lose their momentum without breaking up into the individual nucleons with a rather great probability. In order to explain these results on a deep-inelastic deuteron-proton scattering it was necessary to take into consideration, besides the contribution of the resonance mechanism of this process when the nucleon resonances are excited in a target proton in consequence of multiple quark-quark scattering, nonresonance quark-parton mechanism that describes the elastic scattering of an incident particle on target quarks. It was shown in that analysis that 5% admixture of six-quark component in the deuteron wave function has improved the agreement of the calculation results with the experimental data on the deep-inelastic deuteron-proton scattering /21/.

An interesting peculiarity that distinguishing the deuteron-deuteron scattering from proton-deuteron scattering at momentum transferred in the region of 0.6-1.5 $(GeV/c)^2$ is the fact that, though the deuteron is a very loose system, under certain conditions the elastic scattering in bombarding deuterons by deuterons proves to be relatively more probable than in bombarding deuterons by protons. This is due to the occurrence of such double collisions in the case of the deuteron-deuteron scattering when both the incident nucleons scatter simultaneously each on one of the two target nucleons (Fig.2e): such a mechanism for the elastic scattering allows rather large momentum to both deuteron nucleons to be transferred without disturbing their relative intranuclear motion. It may be suggested that the existence of multiple collisions of that kind has to

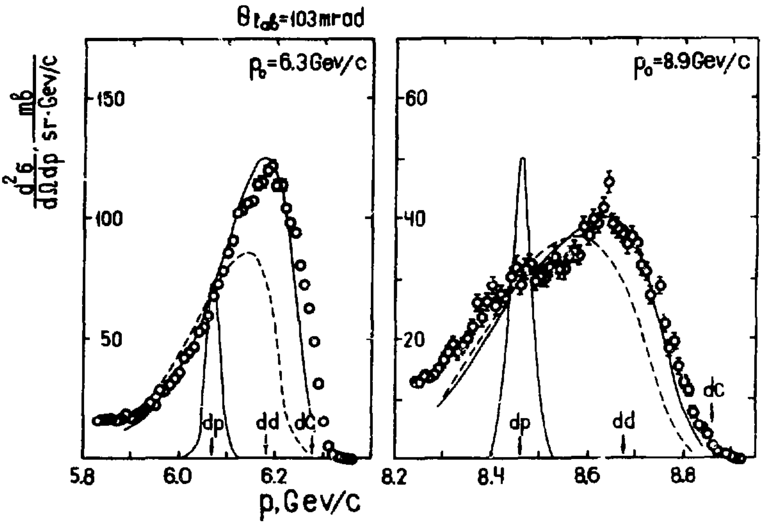

Fig.4. Spectra of deuterons emitted in the collisions of 6.3 and 8.9 GeV/c deuterons with carbon nuclei at a lab angle of 103 mrad. The arrows show deuteron momentum values calculated from the elastic d-p, d-d d-C kinematics. The elastic d-p scattering peaks characterize the spectrometer resolution. The curves represent calculations in the framework of the multiple scattering model made without (dashed curves) and within the assumption that a fraction of nucleons knocked out from the nucleus by deuterons are emitted in the bound state (solid curves).

lead to an enrichment of the upper parts of the deuteron spectra in the case of deuteron-nucleus scattering as well as through the deuteron scattering on nucleon groups inside the nucleus.

The high-momentum parts of the deuteron spectra from the deuteron-carbon scattering at 6.3 and 8.9 GeV/c are shown in Fig.4[17]; the arrows show the deuteron momentum values calculated from the elastic deuteron scattering on the hadrogen, deuterium and carbon nuclei. It is seen, in fact, that the maxima of these spectra are shifted towards larger momentum values as compared with the elastic deuteron-proton peak locations. The dashed curves in Fig.4 represent the results of calculations made in the framework of the multiple scattering model under the assumption that the nucleons knocked out from the nucleus by the incident deuteron do not correlate and do not interact in the final state. It is seen that there is a great discrepancy with the experimental data especially in the range of the small momentum losses.

The observed momentum distributions of deuterons are better reproduced under the assumption that the part of nuclear nucleons involved in interaction with incident deuterons is emitted in the bound states, namely, as nuclei of deuterium, tritium, etc. This calculation version is shown in Fig.4 by solid curves. (It should be noted that the description of the experimental data in case of the deuteron scattering on heavier nuclei (aluminium, bismuth) is less satisfactory, and for a complete interpretation of these results it requires a further development of theoretical concepts about the interactions of multinucleon systems). Some excess of the experimentally observed high momentum parts of the deuteron spectra from the $dC \to dX$ reaction at 6.3 and 8.9 GeV/c over the calculation results may be hoped to compensate both by means of a choice of more realistic nuclear models (and methods taking account of relativistic effects) and by assuming existence of a six-quark admixture in target nucleus [1]. The latter does not contradict to some recent experimental data ([22], for example) and is, in principle, possible according to the four-velocity transfer criterion. Nevertheless definite conclusions may be evidently made on the basis of the further experimental information. In particular the correlation experiments, when kinematical characteristics of hadrons emitted in the broad interval of angles with respect to the primary particle beam and the momentum spectra of relativistic particles emitted in the forward direction are measured simultaneously must be considered as being highly perspective.

At present a number of experiments with such possibilities is planned, including at JINR (Fig.1, for example). It seems that with the help of these experiments some further understanding of questions under consideration may be achieved.

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Рассеяние релятивистских протонов и дейтронов атомными ядрами

Дан краткий обзор экспериментальных работ, в которых изучались спектры пионов, протонов и дейтронов, испускаемых под разными углами в интервале до 30° и при 90° /пионы/, в соударениях протонов с энергией 670 МэВ, а также протонов и дейтронов с импульсом 4,3; 6,3 и 8,9 ГэВ/с с различными ядрами (H, D, Li, Be, C, O, Al, Cu, Pb, Bi, U). В этих исследованиях впервые было обнаружено и проанализировано явление прямого выбивания дейтронов высокоэнергичными протонами. В статье описаны результаты исследования инклюзивных спектров дейтронов и протонов, основные особенности которых удовлетворительно воспроизводятся в рамках модели многократного дифракционного NN-рассеяния. Приведены также результаты анализа спектров неупругорассеянных дейтронов на основании кварк-партонного механизма взаимодействия. Экспериментальный материал получен на 6-метровом синхроциклотроне ОИЯИ при помощи магнитного спектрометра с телескопом из сцинтилляционных счетчиков и на синхрофазотроне ОИЯИ с помощью одноплечевого магнитного спектрометра с проволочными искровыми камерами.

Работа выполнена в Лаборатории вычислительной техники и автоматизации ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1985

Перевод авторов

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Scattering of Relativistic Protons and Deuterons from Atomic Nuclei

The paper reviews briefly the experiments in which momentum spectra of pions, protons and deuterons emitted at different angles in the interval up to 30° and at 90° (pions only) in the collisions of protons with an energy of 670 MeV as well as protons and deuterons with a momentum of 4.3, 6.3 and 8.9 GeV/c from various atomic nuclei (H, D, Li, Be, C, Al, Cu, Pb, Bi, U) are studied. These experiments were the first in which direct knocking-out of deuterons induced by high-energy protons has been found out and analysed. The results of investigation of inclusive proton and deuteron spectra the main features of which are reproduced satisfactorily within the multiple NN diffraction scattering model are described. There are also quoted the results of analysis of inelastic scettered deuteron spectra within the quark-parton interaction picture. The experimental data have been obtained at the JINR 6 meter synchrocyclotron using the magnetic spectrometer with a telescope of scintillation counters and at the JINR synchrophasotron using the one-arm magnetic spectrometer with wire spark chambers.

The investigation has been performed at the Laboratory of Computing Techniques and Automation, JINR.

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