Interaction of neutrons at high energies

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A review is given of problems of the interaction of nucleons. The processes are discussed mainly at energies corresponding to the regions of the minimum and the rise of the total cross sections and to regions covered by the accelerators at Serpukhov and Batavia and the colliding-beam storage rings. Detailed consideration is given to *np* interactions, including the technique for performing experiments in neutron beams. This is done because accurate experiments in neutron beams have been carried out only recently, and the experimental features of these experiments are not widely known. The article discusses total cross sections, forward elastic scattering, backward elastic scattering (*np* charge exchange), and diffraction dissociation of nucleons. The equality of the total *np* and *pp* cross sections (observed experimentally in the energy range of the Serpukhov accelerator), and the near identity of elastic scattering in the diffraction region, mean from the point of view of the optical model that the distributions of nuclear matter in neutrons and protons in the peripheral regions are practically identical. The equality of the total cross sections is in agreement with the prediction of dual models involving degeneracy of the ρ and A_2 trajectories. It is well known that in the *np* charge-exchange reaction there is also observed a long-range interaction which appears in the form of a very sharp peak at $t\approx 0$. The slope of the peak is $\approx 1/m_\pi^2$, where m_π is the pion mass. The existence of this peak and also the simple kinematic law for variation of the cross section with energy: E^{-2} (observed in experiments up to 30 GeV) are due to the dominant role of pion exchange in the charge-exchange reaction. On going to higher energies (the energy range of the Serpukhov accelerator) changes are observed in the energy behavior of the charge-exchange reaction: $E^{-(1.5-1.6)}$. Changes of this type were predicted in Regge models and are due to the increasing role of ρ and A_2 exchanges at high energies. Recently careful studies have been made of the diffraction dissociation of nucleons at high energies (Serpukhov, Batavia, and colliding beams). These studies have revealed a number of features previously unobserved (at energies below 30 GeV), such as the backward peak in the distribution in $\cos\Theta_{GJ}$ in the Gottfried-Jackson coordinate system, the shift of the maximum in the mass spectrum toward higher masses, the approach of the cross section to a constant value at high energies, and other effects. All of the observed effects can be explained with the Deck mechanism if, in addition to one-pion exchange we take into account baryon exchanges and interference.

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CONTENTS

INTRODUCTION

The simplest form of particle interaction is scattering. At high momentum transfers there is a penetration into the deep regions of the particles. In scattering of particles at small angles their structure in the peripheral regions is investigated. In the limiting case of scattering at zero angle we obtain the size of the particles. In fact, according to the optical theorem the imaginary part of the scattering amplitude at zero angle is related to the total cross section for interaction of the particles. The present article will discuss the following subjects:

1. Total cross sections for interaction of neutrons with protons; in this section some attention will be devoted also to the interaction of neutrons with nuclei.

2. Forward elastic scattering of neutrons by protons.

3. Backward scattering of neutrons by protons or so-called elastic *np* charge exchange.

4. Diffraction dissociation of neutrons on protons.

In the last case we are dealing with an inelastic reaction but, in contrast to ordinary inelastic processes in which creation or conversion of particles occurs, this reaction can be discussed as the breakup of the neutron as the result of peripheral interaction with the proton. In this sense we can relate the dissociation reaction, like scattering, to an elementary form of particle interaction.

All of the processes enumerated above will be discussed at high energies. Just what energies are we talking about? Sometime ago we would have been able to attempt a physical definition of the high-energy region as post-resonance, pre-asymptotic, and asymptotic. The transition to this energy region involved hopes that the pattern of interaction of particles at high energies can be simplified as a result of the fact that the particles lose their individuality and the interactions acquire a universal nature.[1] The idea of an asymptote arose as the result of the expectation that with increasing energy, on the one hand, s-channel resonances will disappear (as the result of the increase in width of resonances with increasing mass) and, on the other hand, the cross sections for hadron interaction will reach a constant value. Today the situation has changed. As the result of the recent discovery of "heavy" and "narrow" neutral bosons the idea of the post-resonance region has lost its meaning (or has acquired a new meaning). The hadron total cross sections, passing through a minimum, have begun to increase with increasing energy. We do not know whether this rise of the cross section is transitional or is already an established regime, or just where the asymptotic region is located. However, the characteristic behavior of the total cross sections can serve as a watershed or divide on the energy scale. It is now natural to speak of energy regions before and after the minimum of the total cross sections. In the present article we have devoted the principal attention to discussion of processes at energies corresponding to the regions of the minimum and the rise of the total cross sections and to the regions covered by the accelerators at Serpukhov and Batavia and the colliding beams.

Finally, why does the title refer to the interaction of just neutrons with protons?

The nucleon is an isotopic doublet. A study of the interaction of nucleons implies making measurements in various isotopic states, i.e., investigations of both pp and np interactions. It is very important that the measurements have comparable accuracy. However, the experimental conditions and techniques for study of pp and np interactions are different. Investigation of pp interactions is carried out in monochromatic beams with use of hydrogen targets. The technical problems in carrying out accurate measurements of this type were solved long ago and are well known. The specific feature of np investigations is that there are no pure neutron targets. Of course it is possible to carry out np studies in a proton beam with a deuterium target, using Glauber theory for extraction of the np interaction. However, fundamental difficulties lie in this path if we are discussing an accuracy greater than that of the theory, since the Glauber theory itself in this case must be the subject of experimental study. Therefore only the technique of using neutron beams is promising for development. Historically it turned out that early studies with neutron beams had substantially poorer accuracy than experiments with protons. Neutron experiments were referred to as "experiments of the second kind." Recently, however, a series of studies have been carried out with neutron beams (ITEP-MGU,[2] ITEP-Karlsruhe-CERN,[3-6] FNAL[7-9]), encompassing a broad program of investigations of the interactions of neutrons with protons, in which it was shown that the data obtained are in no way inferior in accuracy to those of proton experiments. In some cases, for example, in study of nucleon-nuclear interactions, neutron experiments have undoubted advantages.

Thus, np investigations are "younger." The experimental features of experiments in neutron beams are not so widely known. For these reasons, in discussing questions of nucleon–nucleon interaction and in carrying out a detailed comparison of np and pp data, we will dwell in more detail on just the np interaction, including questions of technique.

We now turn to the question of how the theory describes the interaction of hadrons. Unfortunately the theory of strong interactions does not exist in general form. The difficulty is that, in contrast, for example, to electrodynamics, in strong interactions the coupling constant is not a small quantity and there is no theoretical apparatus which can take into account the infinite diversity of the interaction. A satisfactory theory can be created for some particular cases. For example, if we consider very remote peripheral interactions, use of the pole model turns out to be successful. In this case a small parameter arises as the result of the exponential decrease of the interaction strength with increase of the impact parameter of the interacting particles. Another approach involves discussion of processes in the very high energy region where, as we have noted, we can expect that the description of the interaction will be simplified.

The best justified theory of the asymptotic interaction of strongly interacting particles is the Regge theory of complex angular momenta.[10] In this theory it is assumed that the main contribution to the interaction is from the exchange of a reggeon—an association of particles which are in a state with definite quantum numbers (baryon charge, isospin, and parity) and variable spin, depending on the square of the momentum transfer. The amplitude of reggeon exchange is proportional to $s^{\alpha(t)}$, where $\alpha(t)$ is the variable spin of the reggeon. At high energies, from an infinite number of singularities characterized by different α_i the principal singularity with the greatest $\alpha(t)$ is separated. This is the essence of the asymptotic discussion. On the other hand, since α depends on t and falls off with increasing momentum transfer, the region of small t turns out to be separated. Thus, the region of applicability of Regge theory is to diffraction processes. The scattering amplitude in the case of exchange of the principal singularity has the form

$$M=\gamma(t)\,\frac{1+\sigma e^{-i\pi\alpha(t)}}{\sin\pi\alpha(t)}\left(\frac{s}{s_0}\right)^{\alpha(t)}, \qquad (*)$$

where $\sigma=\pm1$ is the signature factor and $\gamma(t)$ is the residue, which is a real function of t in the physical region of the s channel.

One of the merits of Regge theory is that it has permitted a relation to be established between previously independent fields—particle scattering at high energies on the one hand, and the spectrum of resonances and elementary particles on the other hand. The amplitude (*) is defined in the physical region of negative t values. In the region of positive t the amplitude (*) has meaning (for bosons) only for integral values of the spin $\alpha(t)$, where it has a pole for a positive signature at $\alpha=0$, 2, 4... and for $\sigma=-1$ at $\alpha=1$, 3, 5... If we associate the poles with real particles and resonances, so-called Regge trajectories are formed. The principal boson trajectory is the Pomeranchuk pole, which has the quantum numbers of the vacuum. This pole assures fulfillment of Pomeranchuk's theorem[11] on the quality of the cross sections for particles and antiparticles in the asymptotic region. The Pomeranchuk pole describes all processes which do not die out with energy, such as forward elastic scattering at zero angle, total cross sections, diffraction dissociation of nucleons, and so forth. The secondary poles f, A_2, ρ, ω with $\alpha_i(0)\sim 0.5$ and π with $\alpha_\pi(0)\approx 0$, at which the corresponding resonances are located, have nonzero quantum numbers and describe exchange processes which fall off with energy, and also the difference in the total cross sections of particles from the same isotopic family. (For example, the ρ and A_2 are responsible for the difference $\sigma_{np}^{tot}-\sigma_{pp}^{tot}$.) Of the secondary poles we should note the pion pole. In spite of the fact that the pion trajectory lies below the others and, consequently, processes described by the pion pole should fall off more rapidly with energy, the fact that the coupling constant for pions is large and that the pole is located very close to the physical region makes the pion singularity dominant in the intermediate energy region. In addition, the closeness of the pole to the physical region leads to characteristic features in the t distributions. The classical example of a process in which the important role is played by pion exchange is elastic np charge exchange.

Pion exchange and the vacuum pole in a unique combination in the Deck mechanism[72,74] determine the behavior of diffraction dissociation of nucleons. In the same process we also have appearance of baryon exchanges, which are usually responsible for backward scattering of pions by nucleons.[12]

Regge poles are not the only singularities. The multiparticle terms in the unitarity condition in relativistic theory lead to appearance of moving branch points. Moving branch points can be considered the result of successive rescatterings by the particles comprising a hadron. A deep analogy exists with the Glauber description of particle scattering by nuclei.[13] Branch cuts in the elastic-scattering amplitude correspond to screening and have a sign opposite to the contribution of the Regge pole. With increasing energy the screening decreases, and this leads to the preasymptotic rise in the total cross sections.[14] For these reasons branch cuts are the cause of the irregularities in the differential cross sections for the scattering and charge-exchange processes. Usually the branch cuts amount to a more or less small correction to the pole picture. However, there are processes in which branch cuts enter as effects of the principal order. One of these processes is np charge exchange. The narrow peak in the differential cross section for np charge exchange in the Regge representation is the result of destructive interference of the pion pole and the pion-Pomeron branch.

1. TOTAL CROSS SECTIONS FOR INTERACTION OF NEUTRONS WITH PROTONS AND NUCLEI

A. Method of measurement

As a rule, measurement of the total cross section for interaction of particles is accomplished by the classical method of removal from the beam. The essence of the method is measurement of the flux of particles which have not interacted with the target material, relative to the total flux. The accuracy in measurement of the cross section is determined by four principal aspects which follow from the basis of the method:

1) Since the flux of particles which have not interacted in the target is measured, there must be a minimal impurity of particles which have interacted in the target but are recorded by the detector. For this reason measurements are made under conditions of so-called good geometry, in which the particle detector has minimal angular dimensions determined by the physical conditions (for example, by Coulomb interaction of the particles in the target if the measurements are made with charged particles). To take into account quantitatively corrections due to scattering of particles in the target, measurements are made of the angular distribution of particles which have interacted in the target.

2) Measurements of the particle flux with target and without target are carried out at different times; hence a requirement for stability of the apparatus with time arises. Drift of the apparatus can be decreased with repeated measurements with target and without target.

3) Measurements with target and without target necessarily are carried out with different loading of the apparatus by beam particles, and therefore strict linearity of the counting characteristics of the apparatus as a function of counting rate is necessary to obtain a correct value of the cross section. Usually effects due to detector loading are taken into account by making cross-section measurements at various beam intensities. Other things being equal, these corrections are smaller, the smaller the absolute beam intensity.

4) Statistics. The choice of the working beam intensity is usually a compromise between the conflicting requirements 3) and 4).

The above features of the method are common for charged particles and neutral particles.

What are the features of total-cross-section measurement in neutron beams? First, neutrons do not undergo Coulomb scattering. This provides the possibility of using the minimum possible detector size, limited only by the beam size, which permits reduction of the correction due to particle scattering in the target at small angles to as low a level as desired (see point 1) above). Second, the absence of Coulomb interaction by neutrons permits use of optimal target thicknesses, i.e., rather thick targets of one to two nuclear lengths. Here a given statistical accuracy (point 4)) is reached in a minimal time or, what amounts to the same thing, a given accuracy can be obtained with a minimal beam intensity (optimization of requirements 3) and 4) above).

However, in working with a neutron beam there are also drawbacks associated with the fact that the neutron beam is nonmonochromatic. Therefore the neutron detector must have the ability to measure the neutron energy. This complication is not fundamental in nature, since the dependence of the total cross sections on energy is very weak and the energy resolution obtained, for example, in a calorimetric measurement of the energy turns out to be sufficient not to introduce additional errors into the measurement of the total cross sections. Since the calorimetric method of measuring neutron energy is universally used in measurements of neutron total cross sections at high energies, we shall dwell briefly on this method.

A calorimeter is device intended to measure the energy of hadrons. It consists of a total-absorption counter containing a large number of layers of dense material with intermediate regions sensitive to ionizing radiation, and with a total amount of material of many nuclear lengths. The calorimeter was invented in 1958[15] and was first used in experiments with cosmic rays. Use of these instruments in accelerators was delayed as the result of the low energy resolution as long as the energy was low (< 10 GeV). In the transition to higher energies the physical principles on which the calorimeter is based have permitted design of instruments with higher energy resolution.

A calorimeter was first used to measure neutron energies in an experiment on total cross sections by Kriesler *et al.*[16] in 1968. In the first measurements of total cross sections (1968–1969) the calorimeters were not perfected and had an energy resolution of ~40–50%. By 1970 a calorimeter had been made at CERN[17] with an improved design which had a resolution of ±15% at 18 GeV.

The best results at the present time have been achieved by the Karlsruhe-ITEP-CERN group[3] working at the Serpukhov accelerator. We shall describe the characteristics of this device, since it has been used in a number of studies[4–6] of the joint ITEP-Karlsruhe-CERN experiment on neutron interaction with protons in the energy range 10–70 GeV, and these studies will be reported in the present article. The calorimeter consisted of forty plates of scintillators (0.7×40×40 cm) from which the light was collected onto a single photomultiplier. The scintillators are interleaved with plates of iron 2 cm thick. The pulse height from the

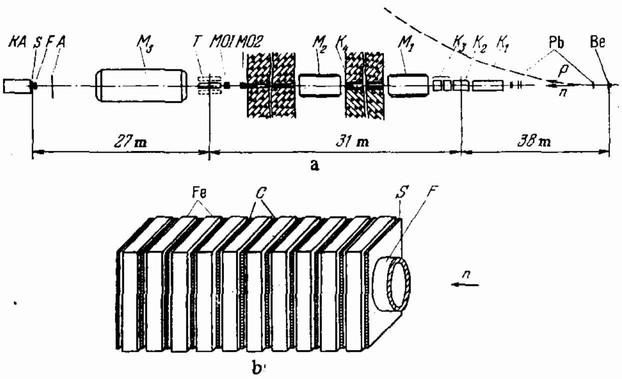

FIG. 1. Arrangement of the ITEP-MGU experiment. a) Apparatus (Be—internal accelerator target, Pb—lead absorbers, K_1–K_4—collimators, M_1–M_3—clearing magnets, MO1 and MO2—beam monitors, T—target, A—anticoincidence counter, S—coincidence counter, F—iron converter, KA—calorimeter); b) arrangement of calorimeter (C are scintillator sheets).

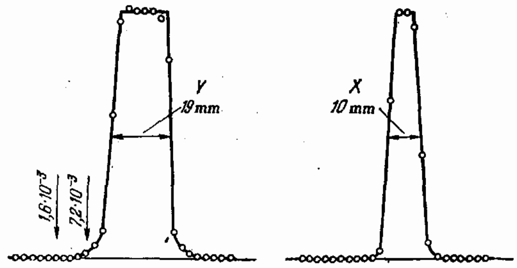

FIG. 2. Profile of neutron beam in two projections.

counter depends linearly on the energy. At 60 GeV a resolution of ±6% is achieved, which is the record resolution at this time for a hadron calorimeter used in experiments.

We now turn to description of experiments on measurement of neutron total cross sections.

B. The ITEP-MGU experiment[2]

The best accuracy in measurement of total cross sections in a neutron beam has been achieved in the work of the group from The Institute of Theoretical and Experimental Physics and Moscow State University, carried out in 1974 at the Serpukhov accelerator.[2]

Figure 1 shows the arrangement of the apparatus. A neutron beam was extracted at 0° to the accelerator orbit. The beam profile in the target region is shown in Fig. 2. It can be seen that the beam had sharp edges, and at a distance of 1–2 cm from the center the intensity amounted to less than 1% of the intensity in the beam itself. This fact was important in taking into account the contribution of scattered particles.

The neutron detector consisted of a calorimeter and a counter in front of it, connected in coincidence. Directly in front of the counter were placed ring-shaped iron converters whose dimensions determined the solid angle of the detector. Only those particles which interacted in the converter were recorded by the detector. The impurity of particles which had undergone scattering in the target and their angular distribution were measured by using converters of different size. The central converter was chosen on the basis of the beam size. With use of this converter only particles scattered with moment transfer of less than 5×10^{-4} $(\mathrm{GeV}/c)^2$ were indistinguishable from particles which passed through the target without interaction. Thus, the correction to the cross section due to neutron scattering in the target was reduced to an extremely small value: ~0.1% for hydrogen and deuterium. It should be noted that this is much less than the correction determined by the Coulomb interaction which exists when a charged-particle beam is used.

The work was performed with targets of statistically optimal length. The frequency of alternation of measurements with target and without target was maximal—interchange of targets was carried out in each accelerator cycle. This reduced to a minimum the effect of the time drift in the apparatus.

Before proceeding to a discussion of the results, let

TABLE I. Comparison of characteristics of various experiments on total cross sections, carried out in neutron beams.

Experiment	CERN,[17] 1970–1971	University of Michigan[19]	ITEP-MGU, 1974[2]	FNAL, 1975,[7]
Neutron energy, GeV	8–21	14–27	26–54	34–273
Beam size, cm	2×2	1×1	1×2	0.4×0.4
Time of alternation of experiments with and without target	5–10 min	—	7 sec	1 min
Sources of error:				
number of H_2 atoms in target	0.7%	1%	0.1%	0.2%
effect of intensity	0.2–0.5%	—	0.1%	0.15%
correction for scattering	0.5%	—	0.1%	0.20%
statistical error with inclusion of apparatus drift	0.7%	—	0.5%	0.40%
total error	1–1.5%	1.5%	0.5%	0.5%

us turn to Table I, taken from Galaktionov,[18] where some comparative data are given for experiments measuring total cross sections carried out recently in neutron beams. The table readily shows what a substantial change has occurred during the last few years in the direction of increased accuracy in measurement of total cross sections in neutron beams. If we compare the current accuracies (0.5%) with those at the 1965 level (~5%), the progress is still more striking. This progress is explained by the natural development of the technology and experimental technique, but primarily by the fact that physicists have learned to work with neutron beams.

C. Total *np* cross sections

Figure 3 shows the total *np* cross sections obtained in the ITEP-MGU experiment,[2] in comparison with the total *pp* cross sections obtained in the Serpukhov accelerator (IHEP, 1971).[20] As can be seen from the figure, the neutron and proton cross sections are very close. The neutron cross sections indicate some energy dependence in the range 25–55 GeV. In the same figure we have shown the total *pp* cross sections recently measured by Carroll *et al.* at Batavia.[21] From this comparison we conclude that the total cross section of neutrons on protons and of protons on protons agree within experimental error in the energy range of the Serpukhov accelerator (20–60 GeV).

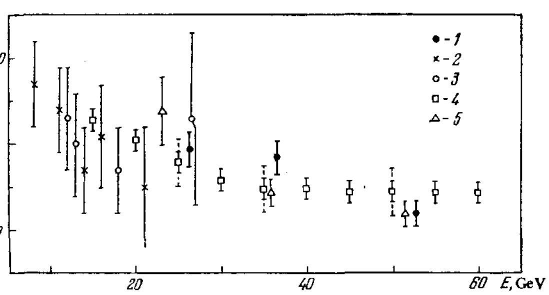

FIG. 3. Total *np* and *pp* cross sections in the Serpukhov energy range. *np* data: 1—Babaev *et al.* (1974), 2—Engler *et al.* (1970), 3—Jones *et al.* (1971); *pp* data: 4—Gorin *et al.* (1971), 5—Carroll *et al* (1975).

Figure 4 shows the total *np* cross sections measured by Longo *et al.*[7] at Batavia in the energy range 30-280 GeV. These data show a rise in the total cross section by about 1.5 mb in the energy region 50–280 GeV. Unfortunately, the increasing error in the cross sections at lower energies, which overlap the Serpukhov range, make the agreement of these results with the ITEP-MGU data not very informative. As far as comparison of the *np* data of Longo *et al.* with the proton-proton total cross sections in the energy region above 50 GeV is concerned, the situation here is not clear, since the data are inconsistent. In the same figure we have shown the total *pp* cross sections according to the measurements of Carroll *et al.*,[21] which disagree sharply with Longo's data. On the basis of this discrepancy it would, however, be pre-

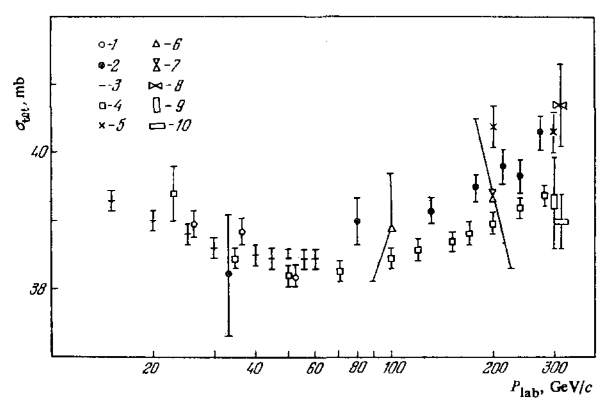

FIG. 4. Total *np* and *pp* cross sections in the energy range 15–300 GeV. *np* data: 1—Babaev *et al.*, Serpukhov (1974), 2—Longo *et al.*, Batavia (1974); *pp* data: 3—Gorin *et al.* (1971), 4—Carroll *et al.* (1975), 5—Gustafson *et al.* (1974), 6—Bromberg *et al.*[24] (1973), 7—Charlton *et al.*[23] (1972), 8—Firestone *et al.*[25] (1974), 9—Amendolia *et al.*[27] (1973), 10—Amaldi *et al.*[26] (1973).

TABLE II.

E_{lab}, GeV	50	100	150	200
σ_{pp}, mb σ_{np}, mb	38.14±0.07 38.50±0.20	38.39±0.06 38.46±0.20	38.62±0.06 38.62±0.20	38.90±0.06 38.90±0.20

mature to conclude that the total *np* cross sections exceed by almost 1 mb the total *pp* cross sections in the energy range 100–200 GeV, since, on the other hand, the total *np* cross sections appear to be less than or equal to the *pp* cross sections measured by Gustafson *et al.*[22] (the same group as Longo) in the same apparatus in which the neutron cross-section measurements were made. The Gustafson–Longo proton cross sections at 200 GeV are almost 1.5 mb above the corresponding value measured by Carroll *et al.*

Apparently there are significant systematic uncertainties in some of these experiments, and therefore the question of the relation of the total *np* and *pp* cross sections at energies above 50 GeV in direct measurements must be considered open.

The fact that in both experiments[7,21] the total cross sections were measured in deuterium permits some indirect evaluations to be made of these two experiments. As is well known, the Glauber theory[1)] relates the cross sections in deuterium with the elementary expression

$$\sigma_{pp} + \sigma_{np} - \sigma_{p(n)d} = \Delta \qquad (1.1)$$

with inclusion of inelastic screening

$$\Delta = \Delta_{el} + \Delta_{inel} = \Delta_{el}\left(1 + \frac{\Delta_{inel}}{\Delta_{el}}\right). \qquad (1.2)$$

As shown by Kaĭdalov and Kondratyuk[28] the ratio $\Delta_{inel}/\Delta_{el}$ can be obtained from analysis of inclusive spectra, and it turns out to be 0.38, 0.5, and 0.2 for pions, kaons, and nucleons, respectively.[2)] The elastic part of the screening is related by the Glauber–Wilkin relation[13]

$$\Delta_{el}(n,\ p) = \frac{\langle r^{-2}\rangle}{4\pi}\,\sigma_{pp}\sigma_{np}\,(1+\rho_n\rho_p) \qquad (1.3)$$

to the parameter $\langle r^{-2}\rangle$ characterizing the size of the deuteron. The quantity ρ is the ratio of the real part and the imaginary part of the scattering amplitude. The quantity Δ can be determined theoretically. Using theoretically calculated screening effects it is possible to obtain total *np* cross sections from the measured values of the total *pd* and *pp* cross sections in Carroll's experiment. The results are given in Table II.[29] As can be seen from the table, the total cross sections of neutrons on protons turn out to agree with the proton-proton cross sections over the entire energy range.

From the same experiment it has turned out to be possible, on the other hand, to check the validity of the Kaĭdalov–Kondratyuk model on the pion data. The point is that in the experiment of Carroll *et al.* the total cross sections for interaction of various particles including pions with protons and deuterons were measured. Thus, from the experiment it was possible to obtain

$$\Delta_{exp}(\pi,\ p) = \sigma_{\pi^+p} + \sigma_{\pi^-p} - \sigma_{\pi^\pm d}$$

and to compare it with the theoretical value

$$\Delta_T(\pi,\ p) = \Delta_{el} + \Delta_{inel} \approx \Delta_{el}(1+0.38) \approx 1.38\,\frac{\langle r^{-2}\rangle}{4\pi}\,\sigma_{\pi^+p}\sigma_{\pi^-p}\,(1-\rho_\pi^2). \qquad (1.4)$$

These values agreed within the experimental and theoretical uncertainties:

$$\Delta_{exp} - \Delta_T = 0.11 \pm 0.15\ \text{mb}.$$

It should be noted that the authors themselves[21] obtained the parameter $\langle r^{-2}\rangle$ from pion data without inclusion of inelastic screening, i.e., from Eq. (1.3) instead of Eq. (1.2). The use of different values of $\langle r^{-2}\rangle$ in Refs. 20 and 21 to extract *np* cross sections from *pp* and *pd* measurements aroused an unjustified discussion[30] regarding the "difference" of the *np* cross sections in the two experiments, although the measured values (*pp* and *pd* cross sections) were rather close (see Fig. 4 and Fig. 6 below). In general a certain lack of coordination existing in the literature[20,21,31] in use of the parameter $\langle r^{-2}\rangle$ eventually reduces to whether or not inelastic screening is taken into account in the Glauber correction. Today, however, this question is no longer debatable, since there is an experimental solution. Effects due to inelastic screening will be discussed later, in the discussion of neutron-nuclear data on total cross sections.

Let us turn now to the experiment of Longo *et al.*[7] If we use the Kaĭdalov–Kondratyuk model[28] exactly in the same way for calculation of the screening correction, it is possible to obtain total *pp* cross sections from the experimental data of Longo *et al.* on *np* and *nd* cross sections. Here it turns out that the *pp* data extracted from the experiment of Longo *et al.* differ by more than 1 mb from the neutron cross sections of the same experiment and are about 0.5 mb below the total *pp* cross sections according to the measurements of Carroll *et al.* To reconcile the data of the experiments of Longo *et al.*[7] and Gustafson and Longo[22] on the cross sections, a very large value of the Glauber corrections is needed. Thus, indirect considerations based on Glauber theory argue in favor of equality of the total *np* and *pp* cross sections also for the interval 50–300 GeV.

Additional arguments can be obtained from another direction. The optical theorem relates the difference of the total *np* and *pp* cross sections to the process of elastic charge exchange at $t=0$,

$$\frac{d\sigma^{ex}}{dt}(n,\ p)\,|_{t=0} \geqslant \frac{1}{16\pi}\,(\sigma_{pp}^{tot} - \sigma_{np}^{tot})^2.$$

If we now substitute into the right-hand side of this relation the data of Carroll *et al.*[21] and Longo *et al.*[7] on total *pp* and *np* cross sections, we should expect dramatic changes in the cross section for elastic *np* charge ex-

[1)]We will discuss Glauber theory in more detail in treatment of the interaction of neutrons with nuclei.

[2)]The ratios are given for an energy ~200 GeV. In the general case the ratios increase slowly with energy.

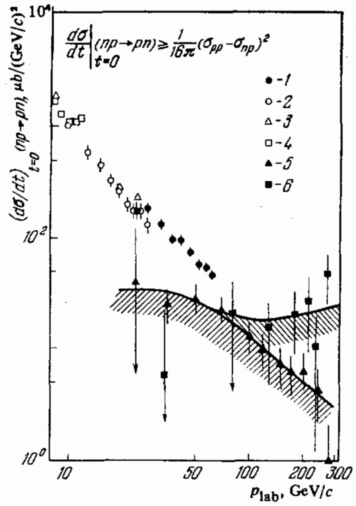

FIG. 5. Differential cross sections for np charge exchange from direct measurements, and lower limits obtained from total cross sections. $(d\sigma/dt)|_{t=0} \times (np\to pn)$: 1—Babaev *et al.* (1975), 2—Kreisler *et al.* (1975), 3—Engler *et al.* (1971), 4—Miller *et al.* (1971); $(1/16\pi) \times (\sigma_{pp}-\sigma_{np})^2$: 5—Carroll *et al.* (1974) (pp, $pd-pp$), 6—Longo *et al.* (1974) (np), Carroll *et al.* (1975) (pp).

change in the energy range 100–300 GeV: The drop in the cross section should slow down considerably to the point where it becomes constant or even begins to rise. As can be seen from Fig. 5, which is taken from the report by Schrempp and Schrempp,[30] the behavior of the np charge-exchange reaction in the Serpukhov energy range[5] (the charge-exchange reaction will be discussed in detail in Chapter 3 below) gives no indication of the major changes which would be expected from the different $\sigma^{tot}_{pp}-\sigma^{tot}_{np}$ as measured by Carroll *et al.*[21] and Longo *et al.*[7] Preliminary data (not yet published) on charge exchange, obtained at Batavia, are inconsistent with such a difference in the total cross sections.

D. The ρ-A_2 degeneracy

In the Regge representation the main contribution to the forward nucleon-nucleon scattering amplitude is from the five trajectories $\mathcal{P}$, $\mathcal{P}'$, ω, ρ and A_2. At high energies the Pomeranchuk pole dominates. However, a discussion of the energy behavior of nucleon-nucleon scattering and the investigation of Pomeron exchange is beyond the scope of the present article. Here we shall dwell only on the relation between the np and pp scattering amplitudes.

The contributions of the trajectories $\mathcal{P}$, $\mathcal{P}'$, and ω have the same sign, while those of ρ and A_2 change sign in the transition from the pp to the np interaction. Thus in Regge theory in correspondence with the optical theorem the difference in the total cross sections is expressed in terms of the ρ and A_2 amplitudes:

$$\frac{1}{2}(\sigma^{tot}_{pp}-\sigma^{tot}_{np}) = \mathrm{Im}\,[\varphi_\rho(0)-\varphi_{A_2}(0)] = \frac{4\pi}{S}\,[\gamma_\rho(0)\,s^{\alpha_\rho(0)}-\gamma_{A_2}(0)\,s^{\alpha_{A_2}(0)}], \quad (1.5)$$

where $\gamma(0)$ and $\alpha(0)$ are the residues and trajectories at $t=0$ for the ρ and A_2 amplitudes. Since $\alpha_\rho(0)$ and $\alpha_{A_2}(0)$ are less than unity, it can be seen from Eq. (1.5) that with increasing energy the difference in the total pp and np cross sections should asymptotically approach zero.

Recently in the Serpukhov accelerator the charge-exchange reaction $\pi^-p\to\eta^0n$ has been studied.[32] The dominant singularity in this reaction is the A_2 trajectory. It was found from these data that the parameters of the ρ and A_2 trajectories became much closer:

$$\alpha_\rho(0)=0.56\pm0.02\ ^{33},\qquad \alpha_{A_2}(0)=0.45\pm0.03\ ^{32}$$

(the previous value obtained at lower energies is $\alpha_{A_2}(0)=0.37$).[34] With equality of the trajectories, the $pp-np$ total-cross-section difference is determined by the difference of the ρ and A_2 residues. As we have already discussed, in the Serpukhov energy range the np and pp total cross sections coincide. From the pp measurements at IHEP[20] the pp measurements at FNAL,[21] and the np measurements by the ITEP-MGU group,[2] the experimental difference in the total np and pp cross sections averaged over the energy range 25–60 GeV is

$$\sigma^{tot}_{np}-\sigma^{tot}_{pp}=0.05\pm0.11\ \text{mb}.$$

Hence it follows (see Eq. (1.5)) that the difference in the residues of the ρ and A_2 amplitudes is small.

Equality of the trajectories and residues of the ρ and A_2 amplitudes is referred to as the $\rho-A_2$ degeneracy. Exchange degeneracy, which appears in a number of experimental facts, has no explanation in Regge theory—it is a consequence of duality.

As is well known, there is some ambiguity in the description of particle interactions. At low energies many processes are satisfactorily described by the sum of the contributions of s-channel resonances to the amplitude. On the other hand, at high energies the theory of complex angular momenta represents the amplitude in terms of t-channel poles and branch cuts. Duality postulates a direct connection between the s-channel resonance description and t-channel exchanges, making the two approaches equivalent,

$$\mathrm{Im}\sum \mathrm{Res}_s = \mathrm{Im}\sum \mathrm{Regge}_t. \quad (1.6)$$

Nucleon-nucleon scattering belongs to the so-called exotic reactions in which there are no resonances in the s channel. In this case

$$\mathrm{Im}\sum \mathrm{Regge}_t = 0.$$

This means that the imaginary parts of the poles associated with different signature factors mutually cancel. A necessary and sufficient condition for such cancellation is equality of the residues and coincidence of the trajectories, i.e., exchange degeneracy. For the nucleon–nucleon interaction this is the $\rho-A_2$ degeneracy.

E. Neutron-nuclear total cross sections. Inelastic screening

We now turn to nuclear data, in which the experimental situation is better defined. We start first with the cross section in deuterium. In Fig. 6 we have shown the measurements of total cross sections for interaction with deuterons of both neutrons and protons. The pd data from IHEP,[20] and the nd data from ITEP-MGU,[2] the pd data from FNAL,[21] and the nd data from Michigan and FNAL[8] agree with each other exceptionally well over the entire energy range studied, 10–300 GeV.

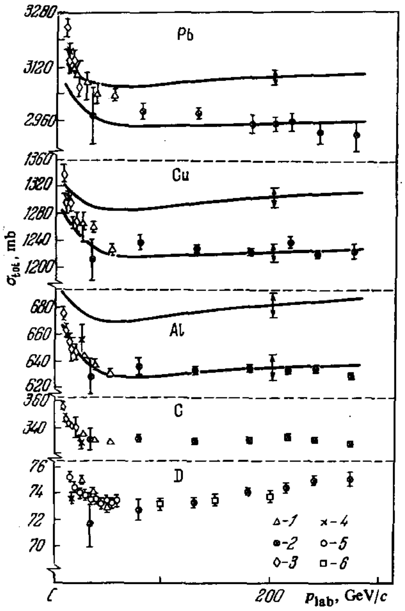

FIG. 6. Total cross sections for interaction of nucleons with nuclei. Curves—results of theoretical calculations: upper curves—according to Glauber theory,[23,35] lower curves—model of Karmanov and Kondratyuk[38] with inclusion of inelastic screening, *nA*: 1—Babaev *et al.* (1974), 2—Jones *et al.* (1974), 3—Engler *et al.* (1970); *pA*: 4—T. P. McCorriston *et al.* (1972), 5—Gorin *et al.* (1971), 6—Carroll *et al.* (1975).

Now that we have data available on the total *nd*, *pd*, *np*, and *pp* cross sections, we can check Glauber theory in the simplest nucleus—the deuteron. It is well known that calculation of the cross sections for interactions of particles with nuclei in the Glauber approximation consists of taking into account so-called shadow effects. In the classical theory the elastic rescattering of particles by a nucleon of the nucleus are discussed. In this case the correction is usually called elastic screening. In the case of deuterium

$$\Delta_{el} = \frac{\sigma_{pp}\sigma_{np}}{8\pi^2}(1+\rho_p\rho_n)\int F(q^2)\,e^{-bq^2}\,dq, \qquad (1.7)$$

where q is the momentum transfer to the deuteron, $F(q^2)$ is the deuteron form factor, and b is the slope of the diffraction peak for elastic scattering of nucleons.

Pumplin and Ross[37] and Gribov[38] took into account rescattering effects in which the intermediate state the nucleon is in an excited state. This correction is called inelastic screening. Kaĭdalov and Kondratyuk[28] give the following expression for it:

$$\Delta_{inel} = 2\int F(t)\,\frac{d^2\sigma}{dM^2\,dt}\,dM^2\,dt; \qquad (1.8)$$

here $d^2\sigma/dM^2dt$ is the diffraction part[3)] of the cross section for the inclusive process $N+N\to N+X$ with a state of X having a mass M.

The important difference between elastic and inelastic screening effects lies in the fact that in the first case the energy dependence of the effect is determined mainly by the behavior of the elementary total cross sections σ_{pp} and σ_{np} and does not change greatly if the cross section is constant, while Δ_{inel} is a quantity which increases with energy.

A check of the Glauber theory can be made for the Serpukhov energy range, where there are consistent data on *pp*, *pd* (IHEP[20] and FNAL[21]), and *np* (ITEP-MGU[2]) total cross sections. For the quantity

$$\Delta = \sigma_{np} + \sigma_{pp} - \sigma_{p(n)d},$$

averaged over the energy range 30–50 GeV, we have

$$\Delta_{exp} = 3.3 \pm 0.2\ \text{mb}.$$

Several theoretical studies are known in which values of Δ_T have been calculated.[28,39] The calculations differ in the details of taking into account the contribution of inelastic screening and predict for the indicated energy region $\Delta_T = 3.4 \pm 0.2$. Here the inelastic-screening contribution is 0.5 mb.[28] Thus, the experimental value Δ_{exp} agrees with the theoretical predictions taking into account the contribution of inelastic rescatterings.

Unfortunately, in the energy region above 50 GeV, as we have discussed above, the data of the three experiments: Longo *et al.*[7] (*np*), Carroll *et al.*[21] (*pp*), and Gustafson *et al.*[22] (*pp*), are inconsistent, and it has been necessary for us to use, on the other hand, the Glauber theory to evaluate the situation in experiments on the difference of the *np* and *pp* cross sections. However, fundamental conclusions regarding the Glauber theory have been possible to obtain from experimental data on the total cross sections for interaction of neutrons with heavier nuclei which we will discuss later.

In Fig. 7 we have shown total neutron-nuclear cross sections obtained in the ITEP-MGU experiment[2] (energy 53 GeV) in comparison with the theoretical cross sections of Galaktionov *et al.*[40] The calculations were carried out on the basis of formulas[35] utilizing the pa-

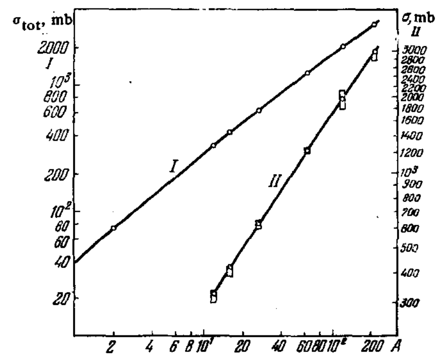

FIG. 7. Neutron-nuclear total cross sections as a function of atomic number A according to the ITEP-MGU data.[2] The data are shown on two scales. The curves are drawn by hand through the experimental points, whose size corresponds to the error. In curve II we have shown by the rectangles the uncertainty in the theoretical calculations of the cross sections.

[3)]That is, the part due to vacuum exchange. Reactions of this type are called diffraction dissociation. One of the reactions of this class, the diffraction dissociation of neutrons into the system (π^-p), will be discussed individually in Chap. 4.

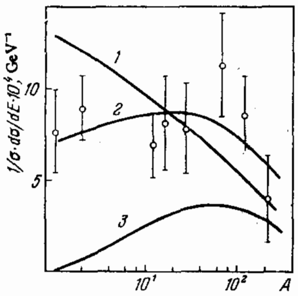

FIG. 8. Relative energy dependence of total cross sections as a function of atomic number. From the data of the ITEP-MGU experiment.[2] The curves are theoretical calculations: 1—Glauber theory,[13,35] 2—Karmanov-Kondratyuk model[36] with inclusion of inelastic screening, 3—the same as 2 but without inclusion of the energy dependence of the elementary nucleon-nucleon total cross sections.

rameters of the Woods–Saxon distribution of nuclear matter[41] and with inclusion of a correction for inelastic screening.[36] In Fig. 7 the data are represented in an unusual way: A curve drawn by hand connects the experimental points, whose size corresponds to the scale of the experimental errors, and the limits (rectangles) indicate the uncertainties in the theoretically calculated cross sections.

The large errors in the parameters of the nuclear density distribution do not permit sufficient accuracy to be obtained in the theoretical calculations to bring out details in comparison with the experimental data directly in the absolute cross sections. However, if we consider the *change* of the cross section with energy ($(1/\sigma)d\sigma/eE$), the accuracy of the theoretical calculations in this case is improved significantly, since our poor knowledge of the energy-independent parameters has little effect on the result obtained in Ref. 40. The energy dependence of the total neutron-nuclear cross sections turns out to be sensitive to the mechanism of interaction of the particles with nuclear matter, and comparison of the experimental data with the theory permits us to learn the details of this interaction. In fact, the total cross sections for interaction of neutrons with nuclei will have an energy dependence even in the case when there is no such dependence for the elementary total cross sections for interaction of nucleons. This behavior of the nuclear cross sections is the manifestation of purely nuclear effects, i.e., it is due to the difference in interaction of nucleons with nucleons and the interaction of nucleons with nuclear matter. This difference is due to the fact that the behavior of the nuclear total cross sections is affected by the variation with energy of the slope b of the diffraction peak, the variation of the ratio ρ of the real and imaginary parts of the scattering amplitude, and the increase with energy of the inelastic screening Δ_{inel}. The last two factors lead to a decrease in the neutron-nuclear cross sections with energy in the case where the elementary cross sections σ_{np} and σ_{pp} no longer change with energy. In Fig. 8 we have shown the energy dependence of the n-nucleus total cross sections measured experimentally in the ITEP-MGU experiment[2] in the energy range 25–60 GeV. The positive value of the derivatives on the plot means that in this interval the total cross sections decrease with energy. As can be seen from Fig. 8, the theoretical curve 2 with inclusion of inelastic screening[36] agrees remarkably well with the experimental points. The value obtained in this way (the only parameter of the theory) of the energy dependence of the elementary nucleon-nucleon cross section:

$$\left(\frac{1}{\sigma}\frac{d\sigma}{dE}\right)^T_{NN} = 7.2\cdot 10^{-4}\ \text{GeV}^{-1}$$

can be compared with values measured directly in experiment:

$$\left(\frac{1}{\sigma}\frac{d\sigma}{dE}\right)_{np} = (7.7 \pm 2.3)\cdot 10^{-4}\ \text{GeV}^{-1}\text{[2]},$$
$$\left(\frac{1}{\sigma}\frac{d\sigma}{dE}\right)_{pp} = (5.2 \pm 1.2)\cdot 10^{-4}\ \text{GeV}^{-1}\text{[21]}.$$

A similar calculation according to the Glauber theory[35,40] (curve 1, with nuclear effects turned off: $\Delta_{inel} = 0$, ρ, and b constant) leads to too large a parameter for the energy dependence of the elementary cross section:

$$\left(\frac{1}{\sigma}\frac{d\sigma}{dE}\right)^{\text{Glauber}}_{NN} = 13\cdot 10^{-4}\ \text{GeV}^{-1}$$

Thus, the experimental data are satisfactorily described by the theory and indicate the presence of nuclear effects in the energy dependence of the total neutron-nuclear cross sections. This unstimulated behavior, i.e., not due in any way to the energy dependence of the elementary np and pp total cross sections, of the nuclear cross sections was observed for the first time in the ITEP-MGU experiment.[2] This was possible as the result of a substantial increase in the accuracy of the measurements and the fact that the measurements were carried out in an energy range close to the minimum in the energy dependence of the elementary total cross sections.

As we have already seen, the total pp and np cross sections have a minimum in the region 50–100 GeV and then begin to rise with energy. The question arises, what will be the pattern of the energy dependence in this energy region for neutron-nuclear total cross sections? From the point of view of classical Glauber theory (elastic screening) the energy behavior of the nuclear cross sections will be similar to that which exists for the elementary cross sections, but to a considerable degree smoothed. It is natural to call this behavior stimulated. However, the situation changes if we consider inelastic screening. As is well known, the increase of the total cross section with energy corresponds to a logarithmic law, and on the other hand in the Karmanov–Kondratyuk model[36] Δ_{inel} also increases logarithmically with energy. The inelastic-screening effect compensates the rise of the elementary cross sections, and in principle we can have a situation in which the nuclear cross sections a) will continue their rise but more slowly, b) will reach a constant value, or c) even begin to fall with energy. The compensation effect depends on atomic number.

In Fig. 6 we have shown data on the total cross sections for interaction of neutrons with nuclei, obtained at Batavia[8] in the energy range 30–280 GeV. These data have high accuracy (unfortunately, decreasing at lower energies) and agree excellently with the ITEP-MGU data.[2]

The total *nd* cross sections show a slow rise for energies greater than 100 GeV but, beginning with carbon, the experimental cross sections become practically constant, and in the case of lead and uranium (not shown in Fig. 6) a decrease with energy is even possible. In a certain sense in nuclei we have a different asymptotic behavior in the energy dependence of the total cross sections than in the total cross sections of the elementary particles. Gribov predicts[42] that at superhigh energies the total cross sections in nucleons and nuclei are equal. It is possible that we are already at the beginning of the approach of the cross sections. From this point of view the ideas first expressed by Pumplin and Ross[37] and Gribov[38] and the inelastic-screening models based on them, which were developed by Kaĭdalov, Kondratyuk, Karmanov, Anisovich, and others[28,38,39] and which have received experimental confirmation in the work of the ITEP-MGU group[2] and at Batavia,[8] have a deep physical significance. Of course, experimental verification of the asymptotic behavior of nuclear total cross sections is not a simple problem, but it is a possible one; for this purpose it is necessary to build colliding beams of nuclei.

2. ELASTIC SCATTERING OF NEUTRONS BY PROTONS

A. Measure of *np* scattering in a neutron beam. Experimental data at energies up to 24 GeV

Use of neutron beams to study elastic neutron–proton scattering imposes certain additional requirements on the experimental apparatus. First, in addition to the scattering angle or momentum transfer, it is necessary to measure the energy at which the scattering occurred, since the momentum of the incident neutron is unknown. Second, it is necessary to know the flux of neutrons of a given energy, i.e., the spectrum of the neutrons in the beam, in order to normalize the obtained cross sections in absolute value. In order to understand the basic scheme of measurements, let us consider several simplified kinematic formulas.

$$|t| \approx p_\perp^2 \approx p_{lab}^2 \theta_n^2 \qquad (2.1)$$

where p_{lab} is the incident-neutron momentum and θ_n is the scattered-neutron angle. On the other hand, the transverse momentum can be determined from the recoil-proton scattering angle:

$$p_\perp \approx 2M_p \operatorname{ctg} \psi_p, \qquad (2.3)$$

where M_p is the proton mass and ψ_p is the recoil-proton angle. As can be seen from Eq. (2.3), $p_\perp$ does not depend on p_{lab}. Thus, if we measure the scattering angles of the neutron and recoil proton θ_n and ψ_p, it is possible by equating (2.2) to (2.3) to obtain the momentum of the incident neutron:

$$p_{lab} \approx \frac{2M_p \operatorname{ctg} \psi_p}{\sin \theta_n} \qquad (2.4)$$

and from Eq. (2.3) to obtain $|t|$:

$$|t| \approx 4M_p^2 \operatorname{ctg}^2 \psi_p. \qquad (2.5)$$

In addition, $p_\perp$ can be measured on the basis of the tangential component of the time of flight τ of the recoil proton. Separation of an elastic reaction can be accomplished from the condition of coplanarity: The directions of the scattered neutron and recoil proton in the plane perpendicular to the beam direction should be collinear.

The selected elastic events form a two-dimensional array of numbers, each element of which is the product of the elastic-scattering cross section by the flux of neutrons of a given energy:

$$\Delta N(E, t) = \frac{d\sigma_{el}}{dt}(E, t)\, W(E)\, \Delta E\, \Delta t. \qquad (2.6)$$

To obtain the absolute cross section $d\sigma_{el}/dt$ it is necessary either to determine the shape of the spectrum and the total flux of neutrons in the beam from additional measurements, or to carry out a procedure of extrapolation (for a fixed energy) of Eq. (2.6) as $t \to 0$. Using the optical theorem, which relates $d\sigma/dt(E, 0)$ to $\sigma^{tot}(E)$, we can obtain an absolute normalization of the cross sections and at the same time also the spectrum of neutrons in the beam $W(E)$.

All measurements of elastic *np* scattering in neutron beams have been carried out approximately by this method. The first measurements at energies above 10 GeV were made by the Schopper group (see Ref. 43) at CERN in 1969 and by Longo *et al.* (see Ref. 44) in 1970–1971. The measurements were carried out with the optical-spark-chamber technique and were in the diffraction-scattering region. In 1973 Engler *et al.*[45] used wire spark chambers for the first time for detection of the neutrons, which enabled them to increase the statistics substantially. In addition, in this work the investigations were extended to a much wider range of momentum transfer. A total of $\sim 2 \times 10^5$ elastic events were recorded in the interval of $|t|$ from 0.06 to 3 $(\text{GeV}/c)^2$ for the energy interval 10–24 GeV. Absolute normalization of the cross sections was accomplished by normalization to the total cross sections with use of the optical theorem. The data obtained in this work are shown in Fig. 9.

In Fig. 10 we have shown a comparison of *np* elastic scattering at 19 GeV/*c* with the data of Allaby *et al.*[46] on *pp* scattering at 19.2 GeV/*c*. As can be seen from the figure, the *np* data agree within the experimental error with those for *pp* scattering not only in the region of small momentum transfer, which was noted also in earlier studies,[43,44] but also over the entire measured region up to $|t| = 2.8$ $(\text{GeV}/c)^2$. Here the *np* data accurately repeat the irregularity and change of slope of the t dependence of the cross section in the region $|t| = 1.2$ $(\text{GeV}/c)^2$. This irregularity in elastic *pp* scattering was first observed and studied by Allaby *et al.*[47]

B. Study of *np* scattering in the Serpukhov accelerator[4]

The investigation of *np* elastic scattering in the accelerator at Serpukhov[4] is part of a larger series of

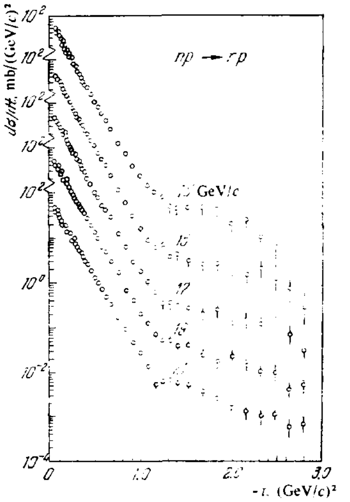

FIG. 9. Differential cross section for elastic np scattering according to Engler *et al.*[45]

studies of the interaction of neutrons with protons carried out in the joint ITEP-Karlsruhe-CERN experiment.[3–6]

The measurements were made in a neutron beam with a broad momentum spectrum. The kinematic parameters t and p_{lab} were determined by measurement of tne angles of the forward-scattered neutron and the recoil proton. In addition the recoil-proton momentum was determined by measurement of the time of flight in a 2-m flight path. A diagram of the apparatus is shown in Fig. 11.

Absolute normalization of the cross sections was accomplished by determining the neutron flux by means of beam monitors and use of the shape of the momentum distribution of the neutrons in the beam. The neutron momentum spectrum (Fig. 12) was measured in a special experiment by means of a calorimeter, which we have already discussed.[3] In the same experiment the monitor telescopes were calibrated to the absolute neutron flux determined by means of the calorimeter. The accuracy of absolute normalization of the cross sections in this procedure was ± 35%. Independent verification of the absolute normalization of the cross sections was made by extrapolation of the cross sections to the optical point with use of data[2,20] on the total cross sections and the ratio of the real and imaginary parts of the scattering amplitude.[48,49] The two methods of normalization agreed within 20%. The experimental data on the cross section for elastic np scattering as a function of t in the energy interval from 10 to 70 GeV are shown in

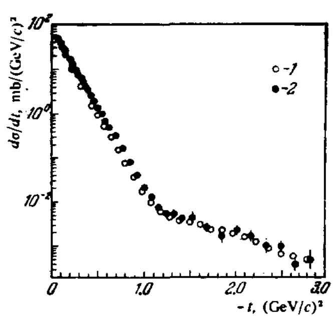

FIG. 10. Comparison of elastic np and pp scattering at 19 GeV. pp: 1—Allaby *et al.* (1968); np: 2—Engler *et al.* (1973).

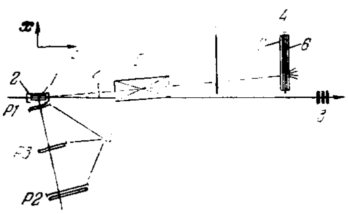

FIG. 11. Diagram of CERN-ITEP apparatus for elastic-scattering measurement[4]: 1—hydrogen target, 2—anticoincidence counters, 3—monitor, 4—hybrid chambers, 5—clearing magnet, 6—neutron counter, 7—iron converter; P1, P2, P3—proton counters.

Fig. 13. The behavior of the scattering is very similar to that which occurred at lower energies. As before, in the region $|t| \sim 1$ GeV a change in the t dependence is observed. If we describe the diffraction region ($|t| > 0.13$ (GeV/c)^2) by the expression Ae^{bt}, then for the slope b we obtain the data shown in Fig. 14. The slope of the diffraction peak in np scattering increases slowly with energy (roughly as ln$s$) in the region investigated. The np and pp data agree in the overlapping regions. The dependence of b on energy becomes flatter if we judge on the basis of the pp data obtained at colliding-beam energies.[50]

Let us summarize the last two sections. The equality of the total np and pp cross sections and the closeness of elastic scattering in the diffraction region, from the optical point of view, means that the distribution of nuclear matter in neutrons and protons in the peripheral regions is practically identical.

3. BACKWARD ELASTIC SCATTERING OF NEUTRONS BY PROTONS (*np* CHARGE EXCHANGE)

A. Methods of measurement

In most of the experimental studies of the backward scattering of neutrons by protons (elastic np charge exchange) at high energies, two methods have been used.

1) *Double-charge-exchange method.* The neutron arises as the result of elastic charge exchange of protons in the internal target of the accelerator. In the external hydrogen target the neutron in turn is elastically

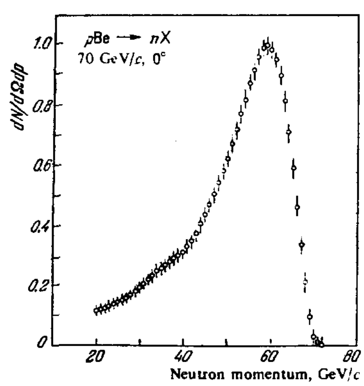

FIG. 12. Momentum spectrum of neutrons produced by 70-GeV protons in a beryllium target at 0°.

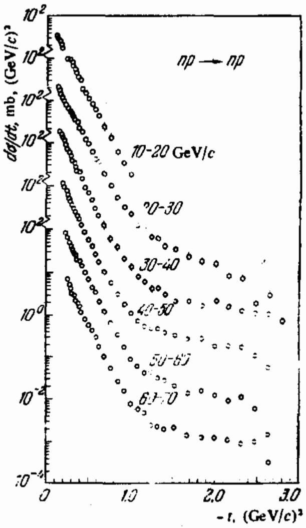

FIG 13. Differential cross section for elastic np scattering from the CERN-ITEP experiment.[4]

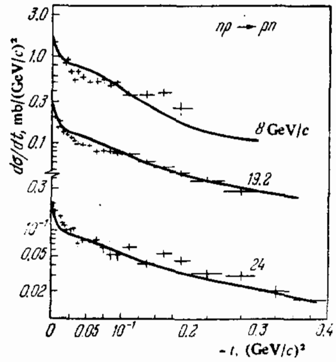

FIG. 15. Differential cross sections for np charge exchange according to Engler *et al.*[56] Curves—theoretical calculation according to an interference model of a reggeized pion with branch cuts.[57]

charge-exchanged into a proton. The proton is analyzed in momentum, and its scattering angle is measured. The condition that double elastic charge exchange has occurred is the equality of the energy of the secondary proton and the energy of the proton in the accelerator ring.

An advantage of this method is that the distributions in the momentum transfer can be measured down to very small values of $|t|$ (determined by the angular resolution of the proton spectrometer). However, at high energies very good momentum resolution is required of the proton spectrometer for reliable separation of elastic events. In this method there are also difficulties associated with absolute normalization of the cross sections.

2) *Complete-kinematics method.* In this method a beam of neutrons is used in a wide range of momentum. To reproduce the complete kinematics of the elastic reaction, measurements are made of the angle and momentum of the proton, and also the energy of the recoil neutron from time of flight, and in addition the neutron angles were measured. Inelastic events can be separated from elastic events, since the kinematics of each event turns out to be overdetermined.

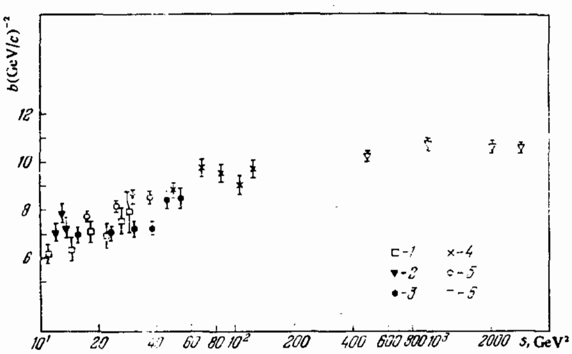

FIG. 14. Diffraction peak slope parameter for np and pp scattering. The values are given for $|t| \geqslant 0.13$ (GeV/c)^2. np: 1—Engler *et al.* (1969); 2—Perl *et al.* (1970), 3—Gibbard *et al.* (1971), 4—Böhmer *et al.* (1975). pp: 5—Harting *et al.*[51] (1965), 6—Barbiellini *et al.* (1972).

The advantages of this method include high reliability in separation of elastic events from background, which is important in particular in studies at high energies, and the possibility of obtaining good statistics as the result of utilizing the complete spectrum of the beam neutrons. A deficiency of the method is the need for reliable determination of the neutron-detector efficiency over a wide range of neutron energy. This quantity is very important, since it enters directly into the dependence of the charge-exchange cross section on momentum transfer, which is being investigated. To obtain absolute cross sections in this method, knowledge of the shape of the beam neutron spectrum and measurement of the absolute neutron flux are required.

B. *np* charge exchange at energies up to 30 GeV

The first measurements of backward elastic np scattering at energies above 2 GeV were made in 1962 by Palevsky *et al.*[52] by the double-charge-exchange method. In the distribution in t in the region $t\sim 0$ a very sharp peak was obtained with width at half-height equal to $p_\perp \approx 150$ MeV/c.

In 1965 this same group[53] found that the distribution in momentum transfer in this reaction can be described by two exponentials with slopes of 50 and 4 (GeV/c)$^{-2}$. A similar result was obtained by Manning *et al.*[54] in 1966 at an energy 8 GeV. Miller *et al.*[55] in 1971 studied charge exchange in the energy range 3–12 GeV. The energy dependence of the cross section at $t=0$ turned out to be

$$\left(\frac{d\sigma}{dt}\right)^{\text{ex}}_{t=0} \approx p^{-2.1}.$$

In Fig. 15 we have shown the data obtained by Engler *et al.*[56] in 1971 at energies of 8, 19, and 24 GeV by the double-charge-exchange method.

The last measurements in this region were carried out by Davis *et al.*[57] in 1972 in the energy interval 8–29 GeV. This work was performed with the complete-kinematics method. The cross sections obtained were fitted by the expression

$$\frac{d\sigma}{dt} = A\,(e^{-b|t|} + ce^{-d|t|}). \qquad (3.1)$$

It was found that the slope of the peaks of the exponentials, b and d, and also the parameter c, do not depend on the energy (Fig. 16). It followed from this that,

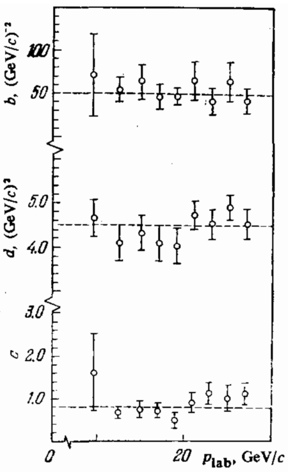

FIG. 16. Parameters of the two-exponential description of the charge–exchange differential cross section: $d\sigma/dt = A(e^{-b|t|} + ce^{-d|t|})$ in the energy range 8–29 GeV according to the data of Davis *et al.*[57]

first, there is no change in the slopes (narrowing or broadening) of the diffraction peaks in either of the exponentials and, second, the ratio between the exponentials does not change with energy. Thus, the cross section can be represented in the form

$$\frac{d\sigma}{dt} = f(p_{\rm lab})\,[e^{-(51\pm 8)|t|} + (0.8\pm 0.1)\,e^{-(4.5\pm 0.15)|t|}].$$

In regard to the energy dependence, the experimental data are satisfactorily described by the power function

$$\frac{d\sigma}{dt} = F(t)\,p_{\rm lab}^{-n}$$

with an exponent $n = 1.95 \pm 0.10$ according to the data of Refs. 55 and 57.

C. Pion exchange in *np* charge-exchange reactions

Thus, in *np* charge-exchange reactions a long-range interaction is observed which is expressed in the existence of a very sharp peak. The slope of the peak is of the order $1/m_\pi^2$, where m_π is the pion mass. It is natural to associate this peak and the smooth and simple kinematic law of change of the cross section with energy, $p_{\rm lab}^{-2}$, with pion exchange. Chew[58] showed as early as 1958 that the *np* scattering amplitude has a pole in the unphysical region at $t = m_\pi^2$ which should lead to a sharp t dependence near zero. However, as the result of the pseudo-scalar nature of the pion, a single pion exchange by itself gives, instead of a peak, a zero of the cross section at $t = 0$. In order for a peak to appear, pion exchange must be accompanied by some background which is a weak function of t. Then this peak can be the result of destructive interference between pion exchange and the associated background. The nature of the background was not clear from the theoretical point of view, and in most of the early models it was treated phenomenologically.[59,60] The simplest model is that of exchange of an elementary pion with an energy-independent form factor and a background practically equal to the pion coupling constant $g^2/4\pi$,[61] i.e., the value obtained from so-called "poor people's absorption".[62] In this model[63]

$$\left(\frac{d\sigma}{dt}\right)^{\rm ex}_{np} \approx \frac{2\pi}{s(s-4M_p^2)}\,(|\varphi_2^{(\pi)}|^2 + |\varphi_4^{(\pi)}|^2),$$
$$\varphi_2^{(\pi)} = \frac{g^2}{4\pi}\left(\frac{t}{t-m_\pi^2} - 1\right)e^{at}, \qquad (3.2)$$
$$\varphi_4^{(\pi)} = \frac{g^2}{4\pi}\,\frac{t}{t-m_\pi^2}\,e^{at},$$

where $g^2/4\pi = 15$, $a \approx 5.5$ (GeV/c)$^{-2}$. This simple model describes all of the principal experimentally observed characteristics of *np* charge exchange:

1) It gives the correct order of magnitude of the cross section.

2) It describes the sharp forward peak.

3) It gives a dependence $\approx p_{\rm lab}^{-2}$ of the cross section on energy, and there are therefore serious bases to consider that the interfering pion exchange is dominant in the mechanism determining the behavior of *np* charge exchange at intermediate energies.

The features of the model do not greatly depend on whether we consider the exchange of an elementary particle (as discussed above) or of a reggeized pole[64] (this is understandable, since $\alpha_\pi(0) \approx 0$), or the case when the "background" in the reggeized theory consists of branch cuts generated by a pole.[65–68] 4) All of this is valid as long as we are discussing only pion exchange. However, the quantum numbers of the *np* charge-exchange reaction also permit ρ and A_2 exchange. In the reggerized theory the cross section for charge exchange is

$$\left(\frac{d\sigma}{dt}\right)^{\rm ex}_{np} \approx \frac{2\pi}{s(s-4M_p^2)} \sum_{i=\pi,\,\rho,\,A_2} |\varphi^{(i)}|^2,$$
$$\varphi^{(i)} = F_i(t)\,s^{\alpha_i(t)}, \qquad (3.3)$$

where $\alpha_i(0) \approx 0$, 0.5, and 0.5 for π, ρ, and A_2, respectively. It can be seen from this that the energy dependence of the charge-exchange cross section for $t = 0$ will be $p_{\rm lab}^{-2}$ if pion exchange dominates, and $p_{\rm lab}^{-1}$ in the case of ρ and A_2 exchange. The question arises: Why is the influence of the ρ and A_2 poles not observed in the experimental data on *np* charge exchange, which has been investigated up to an energy of 27 GeV?

The contribution of the ρ and A_2 poles can be evaluated if we make use of factorization. The role pole is dominant in the reaction πN charge exchange. The vertex ($\rho\pi\pi$) can be extracted from analysis of $\pi\pi$ scattering. The contribution of the A_2 can be taken equal to the ρ from the condition of $\rho - A_2$ degeneracy (see above). According to the estimate of Diu and Leader[63] the numerical values of the residues of the amplitudes $\varphi^{(\rho, A_2)}$ turn out to be small in comparison with the pion-exchange constant. Thus, it becomes understandable why reggeized behavior does not manifest itself at least up to energies $\leqslant 30$ GeV. However, with increasing energy the reggeized terms should play a more and more important role; the point 30 GeV may turn out to be a break point in the behavior of the *np* charge-exchange reaction.

A curious situation has developed. It has been found

4)In contrast to the phenomenological models, in the theory of complex angular momenta this "background" has a clear physical meaning and arises from the internal logic of the theory as a π-Pomeron branch uct generated by the pion. The branch cut does not have definite parity and does not go to zero at $t = 0$; in contrast to a pole, it has a smooth t dependence, i.e., all those qualities which should be possessed by the "background" for reproduction of the correct interference pattern.

experimentally that the amplitudes φ of the np charge-exchange reaction do not depend on energy. This is true over the entire energy range studied from 1 to 27 GeV.

The reggeized theory explains this behavior by the dominant effect of pion exchange. However, the theory *predicts* that with increasing energy the nature of the behavior of charge exchange will change (the role of the ρ and A_2 poles will increase), namely:

1) The energy dependence of the cross section will begin to decrease (a gradual transition from a p_{lab}^{-2} dependence to a dependence p_{lab}^{-1}).

2) An energy dependence will appear in the t distribution: The drop of the cross section with energy at small t will be greater (dying out of the forward peak).

This prediction has not stimulated direct experimental data, and it must be considered as *theoretical*.

It may, however, turn out that the nature of the behavior of np charge exchange is preserved at all energies. There will exist the one-pion model discussed above, in which the role of ρ and A_2 exchange is completely excluded. There are no theoretical reasons why this should be so, and therefore the prediction of this model should be considered as a "naive pragmatic extrapolation" (Ref. 63). It was approximately in this way that Diu and Leader[63] formulated the situation, which developed before the results of np charge-exchange studies at energies above 30 GeV became known.

D. *np* charge exchange in the energy range 22-65 GeV (The ITEP-Karlsruhe-CERN experiment[5])

The experiment was carried out in the neutron beam of the Serpukhov accelerator. The apparatus consisted of a two-arm spectrometer (Fig. 17). The charge-exchange reaction was studied by the method of complete kinematics. The angle and momentum of the forward-scattered proton were determined in the magnetic spectrometer. The neutron was detected in the scintillation counters of the neutron detector. The azimuthal angle of the scattered neutron was determined by observing which of the neutron counters operated. The neutron energy was measured by the time-of-flight method. The experiment utilized hybrid spark chambers having better resolving time than ordinary spark chambers (~125 nsec). This permitted use of a neutron flux in the beam of $\sim 2\times 10^7$ neutrons per accelerator cycle. A total of

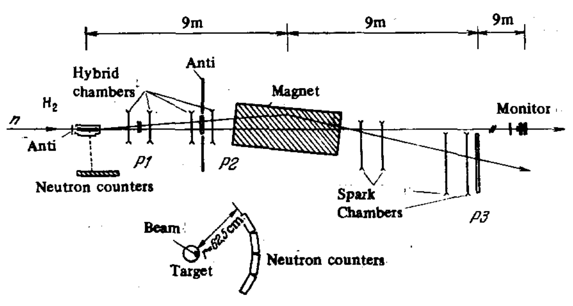

FIG. 17. Diagram of the ITEP-Karlsruhe-CERN apparatus for study of np charge exchange.[5]

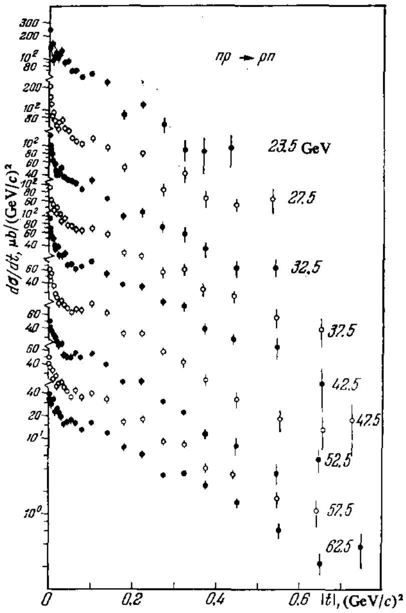

FIG. 18. Differential cross section for np charge exchange in the Serpukhov energy range.[5]

about 50 000 elastic np charge-exchange events were recorded in the experiment.

The differential cross sections for np charge exchange are given in Fig. 18 for nine intervals of primary-neutron momentum.

As can be seen from the data presented, a sharp peak is observed in all momentum intervals up to 65 GeV. In the region $|t| \sim 0.1$ (GeV/c)^2 there is an indication of a "shoulder" in the curve. For $|t| > 0.2$ (GeV/c)^2 the cross section can be represented as an exponential function of t with a slope of about 7 (GeV/c)$^{-2}$. Since pion exchange is dominant in the charge-exchange cross section at small values of t, we obtained the cross section at the point $t=0$ by an extrapolation formula in which the dependence due to pion exchange was separated in explicit form (see Eq. 3.2):

$$\frac{d\sigma}{dt}=\frac{1}{s(s-4M_p^2)}\,\frac{1}{(t-m_\pi^2)^2}\,Ae^{at}. \qquad (3.4)$$

The region $|t| < 0.02$ (GeV/c)^2 was used for the extrapolation. The values of $(d\sigma/dt)_{t=0}$ obtained in this way are shown in Fig. 19. In the Serpukhov energy range a weakening of the energy dependence is observed:

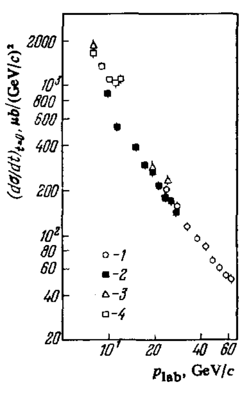

FIG. 19. Cross section for np charge exchange at $t=0$ as a function of momentum. 1—Babaev *et al.* (1975), 2—Davis *et al.* (1972), 3—Engler *et al.* (1971), 4—Miller *et al.* (1971).

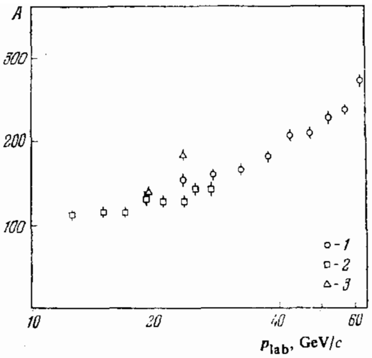

FIG. 20. The coefficient A as a function of momentum in parametrization of the differential cross section for np charge exchange in the form

$$\frac{d\sigma}{dt}=\frac{A}{s(s-4M_p^2)}\frac{1}{(t-m_\pi^2)^2}Ae^{at}.$$

1—Babaev *et al.* (1975), 2—Davis *et al.* (1972), 3—Engler *et al.* (1971).

$$\left(\frac{d\sigma}{dt}\right)_{t=0}\approx p_{\rm lab}^{-(1.5\div1.6)}.$$

This can be seen especially distinctly in Fig. 20, where we have plotted the dependence on energy of the parameter A in the extrapolation formula (3.4). In the case of one-pion exchange (3.2), which is characterized by a dependence $p_{\rm lab}^{-2}$, the parameter A should be a constant independent of energy. Such behavior of the parameter A is consistent with the experimental data with energy less than 25 GeV. However, at higher energies an undoubted rise is observable in the parameter A, which signifies a change in the energy dependence determined by one-pion exchange.

Analysis of the data by means of the two-exponential description (3.1) showed that a change in the t dependence with energy is observed: A gradual relative decrease of the forward peak occurs.

The change in the energy dependence of the cross section as a function of t can be seen more in detail in Fig. 21, where we have shown the effective trajectory $\alpha_{\rm eff}$ determined from the relation

$$\frac{d\sigma}{dt}\sim s^{2\alpha_{\rm eff}(t)-2}F(t)=s^{-n(t)}F(t).$$

The value of $\alpha_{\rm eff}(t)$ is related by an obvious expression to the exponent of the power dependence of the cross section on energy:

$$\alpha_{\rm eff}(t)=\frac{2-n(t)}{2}.$$

The principal changes (in comparison with data at lower energies, < 30 GeV) are observed in the region $|t|>0.06$ (GeV/c)^2, where $\alpha_{\rm eff}$ takes on values 0.3–0.4, which is already close to the value expected for the ρ and A_2 trajectories. At the same time in the region $|t|<0.02$ (GeV/c)^2 the values of $\alpha_{\rm eff}$ are smaller. Here we can see a "dip" with a width the same as in the peak in the differential cross section. This indicates, on the one hand, continued dominance of pion exchange in this region of momentum transfers ($\alpha_{\rm eff}$ has here its smallest value, close to zero) and, on the other hand, a dying out of the forward peak in the cross section (in this region is the largest exponent of the energy dependence of the cross section). It can be seen that there is an irregularity in the intermediate region (0.02< $|t|$ < 0.06 (GeV/c)^2, which can be seen also in the angular distributions (Fig. 18).

Thus, in the experimental study of the np charge-exchange reaction in the Serpukhov energy range, changes are observed in the mode of behavior of the charge-exchange cross section. Changes of this type were predicted long ago in the Regge models[63,68,69] and this was associated, as we have already discussed above, with the increasing role of ρ and A_2 exchange at high energies. The experimentally observed tendency agrees with these predictions.

4. DIFFRACTION DISSOCIATION OF NEUTRONS BY PROTONS

A. Methods of study of nucleon dissociation

The dissociation of nucleons into a πN system, like other inelastic reactions with many particles in the final state, has been studied mainly in bubble chambers. Only recently has nucleon dissociation begun to be studied in experiments with electronic methods.[6,9,70] An electronic experiment has an important advantage—the possibility of obtaining large statistics. However, use of electronic methods to study reactions with many particles in the final state encounters serious difficulties, and these difficulties increase catastrophically with increasing number of particles in the final state. For description of a $2\to2$ reaction two kinematic parameters are necessary and sufficient: s and t. For a $2\to3$ transition such as dissociation of nucleons into a (πN) system, it is already necessary to have five parameters. In general: $3N-4$ parameters for a $2\to N$ reaction.

Thus, the first difficulty consists of identifying the reaction. Experimental apparatus intended for investigation of a $2\to3$ reaction must permit measurement of a number of variables sufficient to determine all five kinematic parameters.

The second difficulty lies in obtaining the cross section. This requires knowledge of the efficiency with which the apparatus detects multiparticle states. The number of independent kinematic variables determines the dimensionality of the phase space. Thus, for a $2\to3$

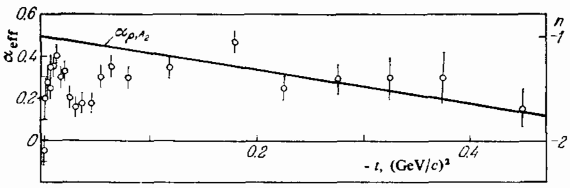

FIG. 21. Effective trajectory of np charge exchange in the energy interval 20–65 GeV according to the data of the ITEP-Karlsruhe-CERN experiment.[5] For comparison we have shown the averaged ρ and A_2 trajectory: $\alpha_{\rho,A_2}=0.5+0.8t$. The right-hand scale shows the exponent of the power dependence of the np-charge-exchange cross section on s; n and $\alpha_{\rm eff}$ are related by the expression $n=2-2\alpha_{\rm eff}$.

reaction the efficiency matrix must be five-dimensional. The number of cells in the matrix is determined by the size of a cell, and the size is chosen so that the cell length along the axis of a given kinematic variable will be greater than (or of the order of) the corresponding experimental error. The differential efficiency in the cells is determined by a simulating Monte Carlo program. The accuracy in measurement of the parameters, the informativeness of the experiment, and the statistics required turn out to be closely related: The number of cells must be less than the statistics, and the linear size of a cell must exceed the corresponding measurement error. In the ITEP-Karlsruhe-CERN experiment,[6] which contains ~15 000 neutron-dissociation-reaction events, the five-dimensional efficiency matrix consisted of 6048 cells: $\Delta E\times\Delta t\times\Delta M^*\times\Delta\cos\theta^*\times\Delta\varphi = 3\times 7\times 12\times 6\times 4$.

Finally, the third problem is representation of the results obtained. The most informative method is to give directly measured experimental differential cross sections: $d^5\sigma/dx_1dx_2dx_3dx_4dx_5$, where x_i $(i=1,\ldots,5)$ are independent kinematic parameters.[5)] However, the number of points turns out to be very large, and in this form the data are practically inaccessible for direct examination. The traditional representation of the data in the from of one-dimensional plots or two-dimensional distributions is possible only in integro-differential form: $d\sigma/dx_i$ and $d\sigma/dx_idx_k$ for x_i fixed—one-dimensional curves; $d^2\sigma/dx_idx_k$ and $d^3\sigma/dx_idx_kdx_L$ for x_i fixed—two-dimensional curves. The principal difficulty here is in integration over variables which are not fixed. The geometrical dimensions of the apparatus and the event-selection procedure itself define some limited region of phase space. This region is not the same in different experiments. Reduction of the data to the total volume (extrapolation of the data on integration into unmeasured regions) is in the general case an incorrect procedure. Therefore data in integro-differential form have primarily illustrative value, and to obtain quantitative data it is necessary to use the differential cross section as much as possible.

Let us turn now to a brief description of experiments on nucleon dissociation performed by electronic methods.

In the ITEP-Karlsruhe-CERN experiment[6] diffraction dissociation of neutrons on protons into a (π^-p) system was studied in the Serpukhov accelerator energy range (35–65 GeV). Measurements were made in the same apparatus (with insignificant changes) in which the np charge-exchange reaction discussed above was studied. The quantities measured were the momentum and angle of the proton and the angle of the π^- of the (π^-p) system, and the azimuthal angle, energy, and time of flight of the recoil proton. Measurement of these quantities was sufficient for kinematic determination of the reaction

$$n + p \to (\pi^-p) + p.$$

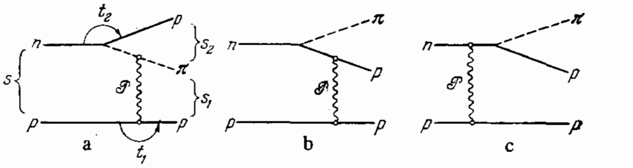

FIG. 22. Diagrams of the Deck mechanism describing dissociation of neutrons into the system (π^-p): a) with pion exchange, b and c) with baryon exchange.

In the FNAL experiment[9] the same reaction was studied in the neutron beam of the Batavia accelerator in the energy range 50–300 GeV. The proton and π^- from the $(p\pi^-)$ system were analyzed in a magnetic spectrometer, and in addition the azimuthal angle of the recoil proton was measured in a scintillation hodoscope surrounding the high-pressure gaseous hydrogen target. The reaction $n+p\to(\pi^-p)+p$ was identified from the condition of coplanarity of the recoil proton and the (π^-p) system. The results obtained in this experiment[9] are preliminary.

Finally, in the CERN experiment[70] electronic methods were used to study proton dissociation: $p+p\to(n\pi^+)+p$ in colliding beams at an energy of the colliding protons 45 GeV. Preliminary results were presented at the London conference on high-energy physics in 1974.

Before turning to discussion of the data obtained in these studies, let us dwell briefly on the results of investigations at low and intermediate energies.

B. Nucleon dissociation at energies up to 30 GeV. Pion exchange in the Deck mechanism[31]

The studies were carried out with bubble chambers.[71] The main features of diffraction dissociation observed at intermediate energies (< 30 GeV) are the following:

1) The πN system is formed preferentially with low values of invariant mass.

2) The energy dependence of the reaction is weak.

3) The t dependence has a diffraction nature ($\approx e^{bt}$) with a slope B which is a function of the mass of the πN system (the higher the mass value, the smaller the slope).

4) The distribution in $\cos\theta_{GJ}$ in the Gottfried–Jackson system has a peak in the region $\cos\theta_{GJ}=1$.

All of these features find explanation in the Deck mechanism,[72] which is illustrated by diagram a) in Fig. 22. The matrix element corresponding to this diagram is

$$|M_a| = \gamma_1(t_1)\,\gamma_2(t_2)\, s_1^{\alpha_{\mathcal{P}}(t_1)} s_2^{\alpha_\pi(t_2)}; \tag{4.1}$$

here $\gamma_1(t_1)$ and $\gamma_2(t_2)$ are functions of the momentum transfer; $\alpha_{\mathcal{P}}\approx 1+0.3t_1$ and $\alpha_\pi\approx -0.02+t_2$ are the Pomeron and pion trajectories. The peripheral nature of the function $\gamma_1(t_1)$ is determined by the diffraction behavior of the vertex $P-\mathcal{P}-P'$, and that of $\gamma_2(t_2)$ by the pion prop-

[5)]As parameters we can choose, for example, p_N, t, M^*, $\cos\theta^*$, and φ^*, where p_N is the primary-nucleon momentum, t is the squared 4-momentum transfer to the recoil nucleon, M^* is the invariant mass of the πN system, and θ^* and φ^* are the helical angles od decay of the πN system in its center-of-mass system.[6] Sometimes instead of the angles θ^* and φ^* the standard Gottfried–Jackson angles are chosen.

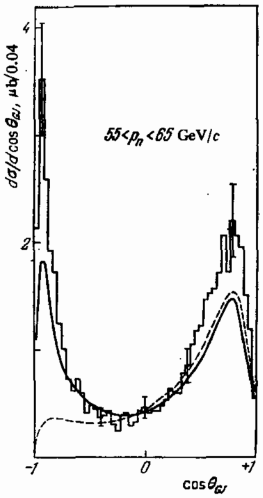

FIG. 23. Distribution in polar angle in the Gottfried–Jackson coordinate system. From the data of the ITEP-Karlsruhe–CERN experiment.[6] The solid curve represents the Deck model with pion and baryon exchange (Ponomarev[74]), and the dashed curve is the Deck model with only pion exchange (OPER[73]).

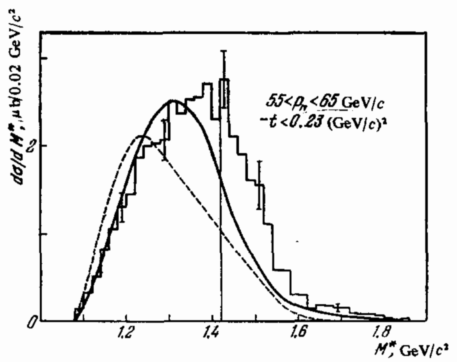

FIG. 25. Distribution in mass of the π^-p system for $|t|<0.23$ (GeV/c)^2. According to the data of the ITEP-Karlsruhe-CERN experiment.[6] The solid curve is the Deck model with pion and baryon exchange,[74] and the dashed curve is with only pion exchange (OPER[73]). The theory is applicable only in the small-mass region ($M^*\lesssim 1.4$ GeV/c^2).

agator: $(t_2-m_\pi^2)^{-1}$. Thus, the t dependence of the process can be represented as

$$|M_a|^2\approx \exp(at_1+bt_2). \tag{4.2}$$

The multiperipheral nature of the matrix element (4.2) leads to strong kinematic restrictions on s_1 and s_2:

$$\frac{s_1s_2}{s}\approx \text{const.} \tag{4.3}$$

Since the Pomeron trajectory is significantly above the pion trajectory, preference will be given to processes for which $s_1\sim s$ and $s_2\ll s$. This leads to small mass values of the πp system and a Pomeron-exchange energy dependence of the dissociation reaction. For the same reasons there is an increased density of population of the regions near $\cos\theta_{GJ}=1$ and the azimuthal angle $\varphi_{GJ}=0$. For the helical angles this corresponds to the regions $\cos\theta^*=0$ and $\varphi^*=\pi$.

C. Angular and other characteristics of decay of the excited system in nucleon dissociation at high energies. Baryon exchange in the Deck mechanism

At low and intermediate energies (< 30 GeV) in the angular distributions of a dissociation reaction a peak is observed in the scattering forward in the Gottfried–Jackson angles ($\cos\theta_{GJ}>0$). In the transition to high energies substantial changes appear in the angular distributions. There were observed for the first time in the ITEP-Karlsruhe-CERN experiment[6] in the reaction $n+p\to(\pi^-p)+p$ at 60 GeV. These data are shown in Fig. 23. In addition to a clearly expressed forward peak ($\cos\theta_{GJ}>0$), which is well described by the Deck mechanism with reggeized one-pion exchange (OPER),[73] the experimental data also show a backward peak ($\cos\theta_{GJ}<0$) which is not predicted by this model. The backward peak in the distribution in $\cos\theta_{GJ}$, as was noted in Ref. 70, may originate from decays of the s-channel resonances ($N^*_{1520}N^*_{1688}$), produced in reactions with Pomeron exchange. The influence of the resonances can be suppressed to a significant degree if we select events with invariant mass smaller than the mass of the resonances and with small t. (The t distribution of a reaction with formation of s-channel resonances is broader than the diffraction peak of the dissociation reaction.) In Fig. 24 we have shown the angular distribution for events with $M^*<1.42$ GeV/c^2 and $-t<0.23$ (GeV/c)^2. It can be seen that the backward peak remains significant and cannot be due to production of s-channel resonances.

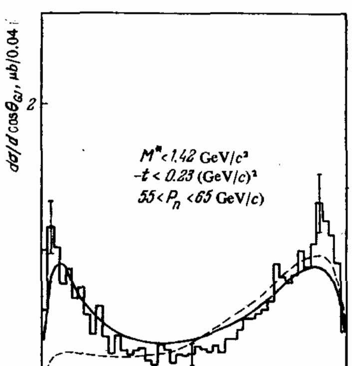

FIG. 24. The same as Fig. 23 but with limitations on the mass of the π^-p system $M^*<1.42$ GeV/c^2 and $-t<0.23$ (GeV/c)^2.

In Fig. 25 we have shown the distribution in invariant mass of the π^-p system. The OPER model predicts too soft a mass spectrum and cannot pretend to describe the experimental distribution. Just as the one-pion-exchange model in the Deck system leads to appearance of a forward peak, the backward peak can be obtained by means of a similar mechanism if one-pion exchange in the Deck model is replaced by baryon exchange. This model, which includes all diagrams of Fig. 22 and takes into account their interference, was developed by Ponomarev.[74] As can be seen from Figs. 24 and 25, this model satisfactorily describes both the angular distribution with the backward peak, and the hardening of the mass spectrum.

The separation of the pion and baryon exchange mechanisms is particulary evident in the two-dimensional distribution in the angular variables, for example $\cos\theta^*$ and φ^*. From comparison of the experimental spectrum (Fig. 26a) and the theoretical calculations (Figs. 26b and c) we can identify the regions where the one-pion and baryon exchanges are respectively dominant. For these regions, separated in the two variables $\cos\theta^*$ and φ^*, we can plot the distributions in a third variable—the mass—and make a comparison with theory individually for pion and baryon exchange (Fig. 27).

The theoretical curves[74] of the Ponomarev model, which include baryon exchanges, satisfactorily describe the *shape* of the various experimental distributions, but in absolute value the cross sections in the theory are about twice the experimental values (the theoretical curves in all of Figs. 23–27 have a common normalization to the experimental data in Fig. 24). The theoretical model discussed[74] does not take into account rescattering effects. It has been shown[75] that the destructive interference arising when rescattering is taken into account can substantially reduce the theoretical cross sections. An independent indication of the existence of rescattering effects is the observed structure in the t distribution near $-t \approx 0.2\ (\mathrm{GeV}/c)^2$ (Fig. 28).

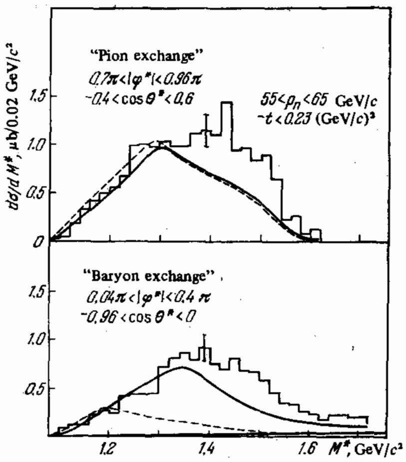

FIG. 27. Mass spectra of the $(\pi^- p)$ system, corresponding to the separated regions (see Fig. 26) in $\cos\theta^*$ and φ^*: a) where pion exchange is dominant, b) where baryon exchange is dominant. Curves—theoretical models. The Deck model, taking into account pion and baryon exchange,[74] is shown by the solid curve. The dashed curve shows the OPER model[73] with only pion exchange.

D. The t dependence of nucleon dissociation. Mass-slope correlation

The angular distribution for all diffraction-dissociation reactions has a clearly expressed peripheral nature. In Fig. 28 we have shown the differential cross sections

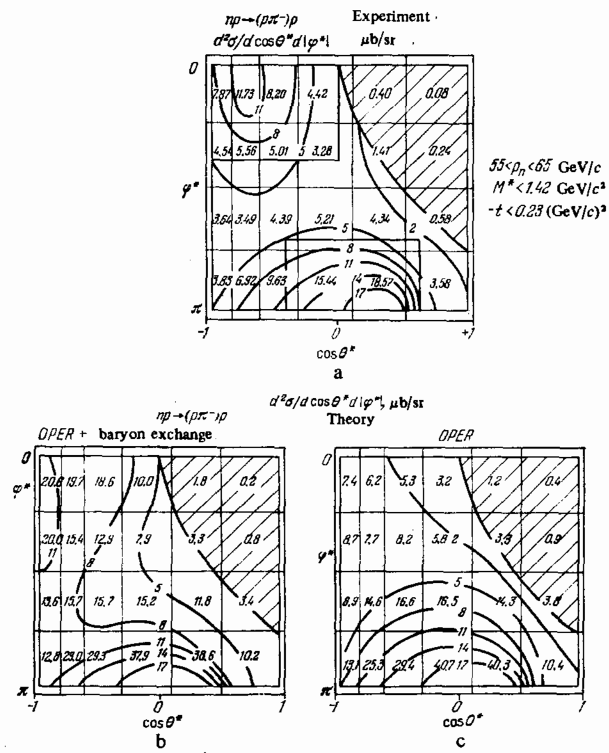

FIG. 26. Distribution in $\cos\theta^*$, φ^*. a) Experimental cross sections $d^2\sigma/d\cos\theta^* d|\varphi^*|$ in μb/sr for $55<p_n<65$ GeV/c, $M^*<1.42$ GeV/c^2 and $0.05<|t|<0.23\ (\mathrm{GeV}/c)^2$ (the curves, drawn by hand, are isobars; the data presented are from the ITEP-Karlsruhe–CERN experiment[6]; the region where the detection efficiency for events in the apparatus is small has been shaded); b and c) theoretical cross sections $d^2\sigma/d\cos\theta^* d|\varphi^*|$ μb/sr for pion and baryon exchange[74] and for only pion exchange[73] respectively for the same restrictions on the kinematic variables as in Fig. a).

for the reaction $np\to(\pi^- p)p$ for various mass intervals of the $\pi^- p$ system. The data were obtained in the FNAL experiment.[9] A break is observed in the t dependence of the cross section in the region $|t|\approx 0.2\ (\mathrm{GeV}/c)^2$ for small masses, which disappears in the transition to larger masses. Note the following interesting phenomenon: The slope of the differential cross section depends on the mass of the excited system produced. In Fig. 29 we have given the dependence of B, the slope of the diffraction peak, as a function of the mass, as obtained in a number of experiments[6,9,70,71] in the energy range 19–1000 GeV. For small mass values the slope is about a factor of two larger than the slope of the diffraction peak of elastic nucleon–nucleon scattering. For masses about 0.5 GeV/c^2 above the threshold for production of the $(\pi^- p)$ system, the slope falls to the level of about half of the elastic slope. This pattern occurs for all energies in the range 19–1000 GeV. The mass-slope correlation is shown in Fig. 30 individually for the for-

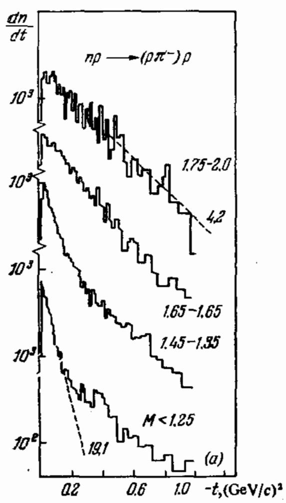

FIG. 28. The t distribution of neutron dissociation for various mass intervals of the $\pi^- p$ system. Data of the FNAL experiment.[9]

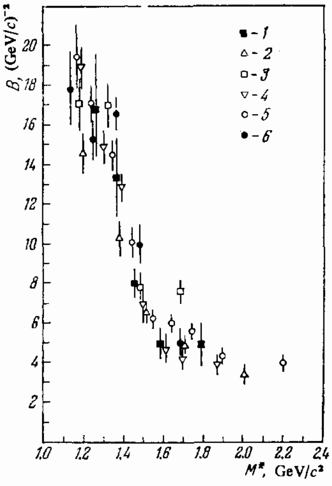

FIG. 29. The mass-slope correlation in diffraction dissociation of nucleons. 1–3 are bubble-chamber data: 1—19 GeV; 2—24 GeV; 3—28 GeV; 4—FNAL, np, 50–300 GeV; 5—colliding beams, CERN, $\bar{p}p$, 1000 GeV; 6—ITEP-Karlsruhe-CERN, np, 60 GeV.

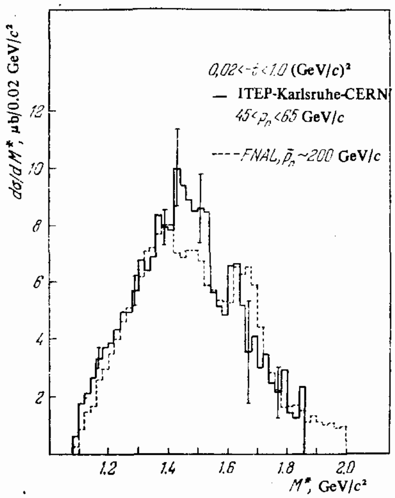

FIG. 31. Mass spectra of the π^-p system in neutron dissociation at energies 45–65 GeV (ITEP-Karlsruhe-CERN[6]—solid line) and 200 GeV (FNAL[9]—dashed line).

ward peak ($\cos\theta_{GJ} > 0$) and the backward peak ($\cos\theta_{GJ} < 0$) according to the ITEP-Karlsruhe-CERN data.[6] In the small-mass region the slope of the backward peak is almost twice the slope for the forward peak, but with increase of the mass the slopes for the different regions in $\cos\theta_{GJ}$ approach each other.

The slope-mass correlation may be understandable, at least qualitatively, as a kinematic effect in the Deck mechansim.[74] The multiperipheral nature of the dissociation leads to expression (4.2) for the square of the matrix element. In the general case the kinematic variables t_1 and t_2 are independent, and the differential cross section $d\sigma/dt_1$ of interest to us (integrated over all the kinematic variables except t_1) should have a slope ($\sim b$) characteristic of processes with Pomeron exchange, i.e., roughly equal to the slope of elastic scattering.

However, near the threshold for formation of the (π^-p) system: $M^* \sim M_p + m_\pi$ the variables t_1 and t_2 turn out to be related by the conservation laws,

$$t_2 \approx t_1 \pm 2q\sqrt{|t_1|}, \tag{4.4}$$

where q is the modulus of the 3-momentum in the center-of-mass system of M^*. The signs (+) or (−) in Eq. (4.4) correspond to values $\cos\theta_{GJ} = +1$ or -1 (i.e., they are different for the forward and backward peaks in the distribution in $\cos\theta_{GJ}$).

Thus, in the small-mass region, the slope of the peak for events corresponding to backward scattering ($\cos\theta_{GJ}$ < 0) will be greater than for forward-scattering events ($\cos\theta_{GJ} > 0$) ($B_{back} \approx a + b + (2qb/\sqrt{|t_1|})$, $B_{forw} \approx a + b - (2qb/\sqrt{|t_1|})$. If we make no distinction between forward and backward scattering events, i.e., if we integrate over $\cos\theta_{GJ}$, then $\bar{B} \sim (a+b)$. For large masses the correlation (4.4) is destroyed. This should lead to a decrease of the slope B to the elastic-scattering level. However, formation of s-channel resonances may further decrease this slope, since the angular distribution of a reaction involving resonance production is significantly broader than the diffraction-dissociation peak. In fact, in Figs. 29 and 30 the steep falloff of the slopes in the mass region $\sim 1.4-1.5$ GeV/c^2 corresponds to the threshold for production of the resonances N^*_{1520} and N^*_{1688}, which are visible in the mass distribution of the dissociation reaction (Fig. 31).

E. Energy dependence of nucleon dissociation

In Fig. 31 we have shown the mass distribution of the (π^-p) system in dissociation of neutrons on protons, obtained in experiments with the Serpukhov[6] and Batavia[9] accelerators. These distributions are given in absolute cross sections and practically coincide, in spite of a large difference in the energies at which the reactions were studied. In Fig. 32 we have shown the energy de-

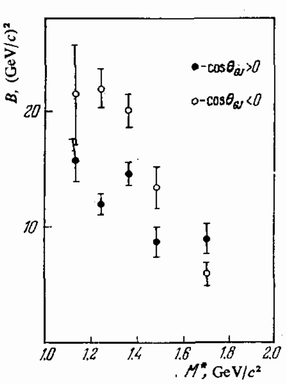

FIG. 30. The slope-mass correlation individually for forward scattering ($\cos\theta_{GJ} > 0$) and backward scattering ($\cos\theta_{GJ} < 0$) in the Gottfried-Jackson system. From the data of the ITEP-Karlsruhe–CERN experiment.[6]

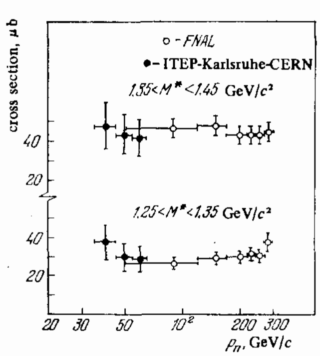

FIG. 32. Energy dependence of the cross section for dissociation of neutrons for two mass intervals, integrated over the interval $|t| = 0.02-1.0$ (GeV/c)^2. Data of the ITEP-Karlsruhe-CERN[6] and FNAL[9] experiments.

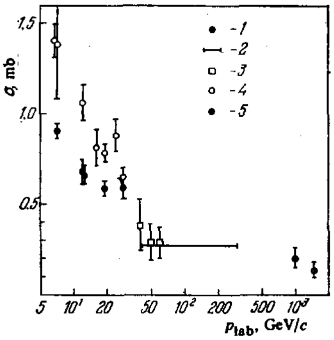

FIG. 33. Total cross sections for diffraction dissociation of nucleons. $np \to (p\pi^-)$: 1—bubble chamber, 2—FNAL, 3—ITEP-Karlsruhe-CERN; $pp \to (n\pi^+)p$: 4—bubble chambers, 5—colliding beams.

pendences of the neutron-dissociation cross sections for different mass intervals of the π^-p system. The data of the ITEP-Karlsruhe-CERN[6] and FNAL[9] experiments are in good agreement, and the cross sections are practically independent of energy.

Finally, the total cross sections for nucleon dissociation in the interval from 8 to 1500 GeV are shown in Fig. 33. It can be seen from the data presented that the weak falloff of the cross section for nucleon dissociation on protons with increasing energy, observed at low and intermediate energies, is further slowed and practically reaches a constant value at high energies. The cross sections for dissociation of protons and neutrons, which are different at intermediate energies, gradually approach each other with increasing energy and apparently are comparable at high energies (if we compare the Serpukhov[6] and Batavia[9] data with the colliding-beam pp data).[70] 6) This behavior is reasonable from the theoretical point of view. In view of isotopic invariance, the diagrams of the Deck mechanism are identical for dissociation of protons and neutrons. Since Pomeron exchange occurs in the Deck mechanism, this mechanism is dominant at high energies, which leads to equality of these reactions. At low and intermediate energies the reactions $pp \to (\pi^+n)+p$ and $np \to (\pi^-p)+p$ also receive contributions from other diagrams (exchange of states with isospin unity) which are different for the two reactions, but all of them die out with increasing energy.

In concluding this section let us formulate our conclusions.

1) Detailed studies, based on good statistics, of the diffraction dissociation of neutrons on protons, obtained by electronic methods in the two experiments of ITEP-Karlsruhe-CERN[6] and FNAL,[9] have enabled us to establish that at energies above 30 GeV there are a number of previously unobserved features, such as the backward peak in the distribution in $\cos\theta_{GJ}$ in the Gottfried–Jackson system, the shift of the peak in the mass spectrum to larger mass values, the flattening out of the cross section to a constant value at high energies, and other effects.

6)In all of the reactions we discuss the dissociation of the incident particle (in the laboratory system), and therefore in Fig. 33 we have given the pp cross sections from Ref. 70 divided by 2.

2) The entire group of observed effects can be explained in the Deck mechanism if, in addition to one-pion exchange, we take into account baryon exchanges and interference.[74]

CONCLUSION

Let us summarize the new things that have been learned about the interaction of nucleons as the result of recent studies of neutron interactions.

1. The total cross sections of neutrons on protons have a minimum in the vicinity of ~70 GeV and then begin to rise with energy (FNAL),[7] a behavior similar to that of the total pp cross sections.

2. The total cross sections for np and pp interactions agree with high accuracy (np:ITEP-MGU[2]; pp:IHEP,[20] FNAL[21]) (in the energy range of the Serpukhov accelerator). From the point of view of the Regge approach, this means that the difference in the residues of the ρ and A_2 amplitudes is small, since the ρ and A_2 trajectories are close to each other.[32,33] The equality of the trajectories and the residues means that the singularities are degenerate. Exchange degeneracy is a consequence of duality.

3. Measurements of neutron-nuclear total cross sections[2,8] have shown the validity of the Glauber approach to description of nucleon-nuclear interactions; it has been observed for the first time that, in addition to taking into account elastic screening in classical Glauber theory,[13] it is necessary to consider also inelastic rescattering effects.[35,36,28,37,41] The small correction for inelastic screening, however, plays an important role, since it is one of the main reasons that the asymptotic behavior of nucleon-nuclear cross sections and the elementary nucleon–nucleon cross sections are qualitatively different.

4. Studies of np elastic scattering[4] have shown that with increasing energy the diffraction peak narrows. As for the pp data, the change in the slope corresponds approximately to a logarithmic law. The narrowing of the diffraction peak of nucleon–nucleon scattering is one of the fundamental predictions of Regge theory.

5. The closeness of elastic np and pp scattering over a wide range of momentum transfer, and also the equality of the total cross sections, mean that the interaction of nucleons in the different isotopic states is practically the same, both in the peripheral regions and in the deeper regions.

6. In the experimental investigation of the np charge-exchange reaction in the Serpukhov energy range, changes have been observed in the type of behavior of the charge-exchange cross section.[5] A change of this type was predicted long ago in the Regge models,[69,66,63] and is due to the increasing role of ρ and A_2 exchanges at high energies. The experimentally observed tendency agrees with these predictions.

7. Studies of the diffraction dissociation of neutrons

on protons, carried out in the ITEP-Karlsruhe-CERN[6] and FNAL[9] experiments, permit us to establish that at energies above 30 GeV there are a number of previously unobserved phenomena: the backward peak in the distribution in $\cos\theta_{GJ}$ in the Gottfried–Jackson system, the shift of the peak in the mass spectrum to higher masses, the approach of the cross section to a constant value at high energies. All of these effects can be explained by the Deck mechanism,[72] if baryon exchanges are taken into account in addition to one-pion exchange.[74]

What questions regarding nucleon–nucleon interactions would we like to find answers for in the near future?

1) First of all it is necessary to clarify the situation with the total cross sections for interaction of protons with protons and of neutrons with protons for energies above 50 GeV.

2) It is very important to study the structure of nucleons at small distances. For this purpose it is necessary to study the interaction of nucleons with very large transverse momentum transfers (scattering by 90° in the c.m.s.). Such experiments with neutrons at high energies have not yet been performed.

3) On the other hand, it is an open question as to the interaction of nucleons in the remote peripheral region, the region of super-small momentum transfers. The Coulomb interaction hinders the performance of such studies with charged particles. However, neutral hadrons permit such studies. The neutron is a marvelous tool with which we can study the interactions of nucleons with each other in the momentum-transfer interval 10^{-2}–10^{-5} $(\text{GeV}/c)^2$.[76] Up to the present time this possibility has not been realized.

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[1] I. Ya. Pomeranchuk, Zh. Eksp. Teor. Fiz. 30, 423 (1956) [Sov. Phys. JETP 3, 306 (1956)]. L. B. Okun' and I. Ya. Pomeranchuk, Zh. Eksp. Teor. Fiz. 30, 424 (1956) [Sov. Phys. JETP 3, 307 (1956)].
[2] A. I. Babaev *et al.*, Yad. Fiz. 20, 71 (1974) [Sov. J. Nucl. Phys. 20, 37 (1975)].
[3] V. Böhmer *et al.*, Nucl. Instr. and Meth. 122, 313 (1974).
[4] V. Böhmer *et al.*, Nucl. Phys. B91, 266 (1975).
[5] A. Babaev *et al.*, Nucl. Phys. B110, 189 (1976).
[6] A. Babaev *et al.*, Diffraction Dissociation of Neutrons into $(p\pi^-)$ on Protons in the Momentum Range 35 to 65 GeV/c. Preprint CERN, Geneva, 23 June 1976.
[7] M. J. Longo *et al.*, Phys. Rev. Lett. 33, 725 (1974).
[8] L. W. Jones *et al.*, Phys. Rev. Lett. 33, 1140 (1974).
[9] J. Biel *et al.*, Phys. Rev. Lett. 36, 504 (1976), J. Biel *et al.*, Investigation of the Reaction $n+p\to(p\pi^-)+p$ at Fermilab Energies, Contribution to the EPS International Conference on High Energy Physics, Palermo, 1975.
[10] V. N. Gribov, Zh. Eksp. Teor. Fiz. 41, 667 (1961) [Sov. Phys. JETP 14, 478 (1962)]. G. F. Chew and S. C. Frautchi, Phys. Rev. Lett. 7, 394 (1961); 126, 1202 (1962). S. C. Frautchi, M. Gell-Mann, and F. Zachariasen, Phys. Rev. 126, 2204 (1962).
[11] I. Ya. Pomeranchuk, Zh. Eksp. Teor. Fiz. 34, 725 (1958) [Sov. Phys. JETP 7, 499 (1958)].
[12] V. A. Lyubimov, in: Problemy yadernoĭ fiziki i fiziki êlementarnykh chastits (Problems of Nuclear and Elementary-Particle Physics), Moscow, Nauka, 1975, p. 81.
[13] R. J. Glauber, Phys. Rev. 100, 242 (1955).
[14] V. N. Gribov and A. A. Migdal, in: Proc. of the Fourteenth Intern. Conference on High Energy Physics, Geneva, 1968, p. 943.
[15] N. L. Grigorov *et al.*, Zh. Eksp. Teor. Fiz. 34, 506 (1958) [Sov. Phys. JETP 7, 348 (1958)].
[16] M. N. Kreisler *et al.*, Phys. Rev. Lett. 20, 468 (1968).
[17] J. Engler *et al.*, Phys. Lett. B31, 669 (1970); J. Engler *et al.*, Phys. Lett. B32, 716 (1970).
[18] Yu. V. Galaktionov, Doctoral Dissertation, Institute of Theoretical and Experimental Physics, 1976.
[19] L. W. Jones *et al.*, Phys. Lett. B36, 509 (1971).
[20] Yu. P. Gorin, *et al.*, Yad. Fiz. 14, 998 (1971) [Sov. J. Nucl. Phys. 14, 560 (1972)].
[21] A. S. Carroll *et al.*, Phys. Rev. Lett. 33, 928 (1974); A. S. Carroll *et al.*, Total Cross Sections on $\pi^\pm$, $K^\pm$, p, and $\bar{p}$ on Protons and Deuterons between 23 and 280 GeV/c. Preprint Fermilab–Pub–75/51-EXP. 7100.104.
[22] H. G. Gustafson *et al.*, Phys. Rev. Lett. 32, 441 (1974).
[23] G. Charlton *et al.*, Phys. Rev. Lett. 29, 515 (1972).
[24] C. Bromberg *et al.*, Phys. Rev. Lett. 31, 1563 (1973).
[25] A. Firestone *et al.*, Phys. Rev. D10, 2080 (1974).
[26] U. Amaldi *et al.*, Phys. Lett. B44, 112 (1973).
[27] S. R. Amendolia *et al.*, Phys. Lett. B44, 119 (1973).
[28] A. B. Kaidalov and L. A. Kondratyuk, Nucl. Phys. B56, 90 (1973).
[29] V. A. Lyubimov, in: Elementarnye chastitsy. Tret'ya shkola fizikov ITÉF (Elementary Particles. Third ITEP School for Physicists), No. 2, Moscow, Atomizdat, 1975, p. 18.
[30] F. Schrempp and B. Schrempp, Rapporteur talk at Palermo Conf., Ref. TH 2054-CERN (1975).
[31] A. Bouquet *et al.*, Possible Incompatability between the *NN* and $\bar{N}N$ Total Cross Sections and the Regge Pole Model, Preprint PAR-LPTHE 74/11 (1974).
[32] W. D. Apel *et al.*, A Study of the Reaction π^-p in η^0n at Momenta up to 40 GeV/c. Preprint IHEP 74-117, Serpukhov, 1974.
[33] V. N. Bolotov *et al.*, Yad. Fiz. 18, 1046 (1973) [Sov. J. Nucl. Phys. 18, 538 (1974)].
[34] O. Guisan *et al.*, Phys. Lett. 18, 200 (1965).
[35] V. Franco, Phys. Rev. Lett. 24, 1452 (1970).
[36] V. A. Karmanov and L. A. Kondratyuk, Pis'ma Zh. Eksp. Teor. Fiz. 18, 451 (1973) [JETP Lett. 18, 266 (1973)].
[37] J. Pumplin and M. Ross, Phys. Rev. Lett. 21, 1788 (1968).
[38] V. N. Gribov, Zh. Eksp. Teor. Fiz. 56, 892 (1969) [Sov. Phys. JETP 29, 483 (1969)].
[39] V. V. Anisovich *et al.*, Phys. Lett. B42, 224 (1972).
[40] Yu. V. Galaktionov, A. V. Lyubimov, and T. N. Tsvetkova, Pis'ma Zh. Eksp. Teor. Fiz. 20, 210 (1974) [JETP Lett. 20, 91 (1974)].
[41] L. R. Elton, Nuclear Sizes, Oxford, 1961.
[42] V. N. Grivov, in: Élementarnye chastitsy. Pervaya shkola fizikov ITÉF (Elementary Particles, First ITEP School of Physicists), No. 1, Moscow, Atomizdat, 1973, p. 65.
[43] J. Engler *et al.*, Phys. Lett. B29, 321 (1969).
[44] M. L. Perl *et al.*, Phys. Rev. D1, 1856 (1970). B. G. Gibbard *et al.*, Nucl. Phys. B30, 77 (1971).
[45] J. Engler *et al.*, Nucl. Phys. B62, 160 (1973).
[46] J. V. Allaby *et al.*, Phys. Lett. B28, 67 (1968).
[47] J. V. Allaby *et al.*, Phys. Lett. B34, 431 (1971).
[48] G. G. Beznogikh *et al.*, Phys. Lett. B30, 274 (1969).

[49]L. M. Dutton *et al.*, Nucl. Phys. **B9**, 594 (1969).
[50]G. Barbiellini *et al.*, Phys. Lett. **B39**, 663 (1972).
[51]D. Harting *et al.*, Nuovo Cimento 38, 60 (1965).
[52]H. Palevsky *et al.*, Phys. Rev. Lett. **9**, 509 (1962).
[53]J. L. Friedes *et al.*, Phys. Rev. Lett. 15, 38 (1965).
[54]G. Manning *et al.*, Nuovo Cimento **A41**, 167 (1966).
[55]E. L. Miller *et al.*, Phys. Rev. Lett. 26, 984 (1971).
[56]J. Engler *et al.*, Phys. Lett. **B34**, 528 (1971).
[57]M. B. Davis *et al.*, Phys. Rev. Lett. 29, 139 (1972).
[58]G. F. Chew, Phys. Rev. 112, 1380 (1958).
[59]A. Ashmore *et al.*, Nucl. Phys. **36**, 258 (1962).
[60]R. J. N. Phillips, Phys. Lett. 4, 19 (1963).
[61]G. Bizard and B. Diu, Nuovo Cimento A25, 467 (1975).
[62]P. K. Williams, Phys. Rev. 181, 1963 (1969).
[63]B. Diu and E. Leader, Neutron-Proton Charge Exchange at High Energy—a Crucial Reaction. Preprint PAR-LPTHE 75/1 (1975).
[64]J. Engler *et al.*, Nuovo Cimento A9, 311 (1972).
[65]K. Huang and I. J. Muzinich, Phys. Rev. 164, 1726 (1967).
[66]A. B. Kaĭdalov and B. M Karnakov, Yad. Fiz. 7, 1147 (1968) [Sov. J. Nucl. Phys. 7, 685 (1968)].
[67]G. L. Kane *et al.*, Phys. Rev. Lett. 25, 1519 (1970).
[68]K. G. Boreskov *et al.*, Yad. Fiz. 21, 825 (1975) [Sov. J. Nucl. Phys. 21, 425 (1975)].
[69]K. A. Ter-Martirosyan, Vzaimodeĭstvie pri vysokikh énergiyakh (teoriya kompleksnykh momentov i éksperiment). (Interaction at High Energies (Theory of Complex Angular Momenta, and Experiment)). Preprint, ITEP, No. 417, Moscow, 1966.
[70]E. Nagy *et al.*, The *pp* Diffraction Dissociation into $(n\pi^+)+p$ at $\gamma_\delta=45$ GeV. Contribution to the Seventeenth Intern. Conf. on High Energy Physics, London, 1974. C. Broll, La Reaction $pp\to p(n\pi^+)$ a Haute Energie, Thesis, Orsay, 1976.
[71]E. Dahl-Jensen *et al.*, (Scandinavian Bubble-Chamber Collaboration), Nucl. Phys. B87, 426 (1975); also references cited there.
[72]R. T. Deck, Phys. Rev. Lett. **13**, 169 (1964).
[73]K. G. Boreskov *et al.*, Yad. Fiz. 15, 361 (1972) [Sov. J. Nucl. Phys. 15, 203 (1972)]. K. G. Boreskov *et al.*, Yad. Fiz. 15, 557 (1972) [Sov. J. Nucl. Phys. 15, 309 (1972)].
[74]See the preprint cited in Ref. 6, p. 57.
[75]E. L. Berger and P. Pirilä, Phys. Lett. B59, 361 (1975). V. A. Tsarev, Phys. Rev. D11, 1864 (1975).
[76]Institute of Theoretical and Experimental Physics, Moscow, and Institute for Experimental Nuclear Physics, Karlsruhe, Letter of Intent. Neutron Elastic Scattering at Very Small Angles, CERN/SPSC/74-47/169 (1975).

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