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INELASTIC NUCLEON-NUCLEON INTERACTIONS

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The interactions between two nucleons in which either only one nucleon is "excited" or none of the nucleons are excited (process proceeds via the $\pi\pi$ interaction) are considered in the one-meson approximation. The magnitudes and asymptotic behavior of the cross sections for such processes are estimated. It is found that the asymmetry in the angular distribution of the secondary protons in pn interactions at 9 GeV can be due to processes of the type considered above.

ONE of the basic results of the experimental investigation [1] of pn interactions at 9 GeV is the observation of an asymmetry in the angular distribution of the secondary protons in the center of mass system of the nucleons. The asymmetry is manifest in the preferred emission of the secondary protons in a direction opposite to that of the primary protons.[1)]

Isospin analysis shows that among the processes of one-meson pn interactions responsible for the asymmetry [1] only processes in which either one or both nucleons remain unexcited (diagrams a and b of Fig. 1) can occur. As has been shown by Tamm [3] and Gramenitskiĭ et al, [4] interactions accompanied by the excitation of both nucleons should lead to a strong asymmetry of opposite sign.

The cross section for process a was estimated by Dremin and Chernavskiĭ, [5] but owing to the strong limitations in the integration over the angles and the virtualness of the intermediate meson, to which the cross section of process a is very sensitive, a very small value was obtained, and in subsequent work the contribution of process a to the NN cross section was no longer taken into account.

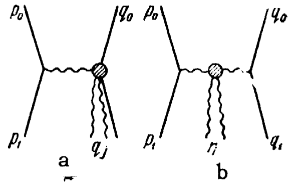

FIG. 1

In connection with the interpretation of this asymmetry, we estimated the cross section for processes a and b in the pole approximation, where we took the operator γ_5 as the vertex operator corresponding to the "unexited" nucleon. As regards the matrix elements corresponding to other nodes of the diagrams, we used the method suggested by Dremin and Chernavskiĭ, [5] and for convenience we retain the same notation used by them.

1. Case a. The expression for the probability of the process can be represented in the form [2)]

[1)]It should be mentioned that Vishky et al,[2] who also studied pn interactions at 9 GeV, found that the sign of the c.m.s. asymmetry for the emitted protons is opposite to that observed in [1]. The reason for the difference between the results of [1] and [2] are not sufficiently clear.

[2)]We use the system of units in which $\hbar = c = M = 1$ (M is the nucleon mass). The results are expressed in terms of c.m.s. values of the variables.

$$dw_{NN}^{(a)} = (2\pi)^4 \sum_{n,n'} \left| \frac{M_1(p_0, p_1) M_2(q_0, q_1)}{\Delta^2 + \mu^2} - \frac{M_1(p_0, q_1) M_2(q_0, p_1)}{\Delta'^2 + \mu^2} \right|^2$$
$$\times \delta\left(p_0 + q_0 - \sum_n p_i - \sum_{n'} q_j\right) \prod_i \frac{d^3 p_i}{(2\pi)^3} \prod_j \frac{d^3 q_j}{(2\pi)^3}, \qquad (1)$$

where M_1 and M_2 are the matrix elements corresponding to the first and second nodes of the diagram, $\Delta = p_0 - p_1$, $\Delta' = p_0 - q_1$, $\Delta^2 = \mathbf{\Delta}^2 - \Delta_0^2$.

Owing to the strong anisotropy of the nucleon angular distribution and the restriction introduced below on the virtualness, the contribution of the interference term is very small, and the probability of the interaction can be rewritten in the form

$$dw_{NN}^{(a)} = 2(2\pi)^4 \tau_\alpha^2 G^2 \sum_{n'} \frac{|M_{\pi N}|^2 \Delta^2}{4\varepsilon_0 \varepsilon_1 (\Delta^2 + \mu^2)^2}$$
$$\times \delta\left(p_0 + q_0 - p_1 - \sum q_j\right) \frac{d^3 p_1}{(2\pi)^3} \prod_j^{n'} \frac{d^3 q_j}{(2\pi)^3}, \qquad (2)$$

where τ_α is the nucleon isospin matrix and G = 13.5 is the pion-nucleon coupling constant.

Since we were not able to calculate the value of the matrix element $M_{\pi N}$, we followed the method suggested by Dremin and Chernavskiĭ [5] and used data on the total cross section for interactions between pions and nucleons. [6] For this, we represented the probability for the interaction between a real pion (with 4-momentum k) and a nucleon (with 4-momentum q_0) in the form

$$w_{\pi N}(k) = \sum_n (2\pi)^4 \int \frac{|M_{\pi N}|^2}{2\omega} \delta\left(q_0 + k - \sum_i q_i\right) \prod_i^n \frac{d^3 q_i}{(2\pi)^3},$$
$$\omega = \sqrt{\mathbf{k}^2 + \mu^2} \qquad (3)$$

and took into account the relation $w_{\pi N} = J_{\pi N} \sigma(\omega)$ ($J_{\pi N}$ is the relative pion and nucleon flux). Going over from the differential probability for the process to its cross section, we obtain

$$\sigma_{NN}^{(a)}(\varepsilon_0) = \frac{\tau_\alpha^2 G^2}{(2\pi)^3 j_{NN} \varepsilon_0} \int \frac{d^4 \Delta \, \Delta^2 \omega \sigma_{\pi N}(\omega) j_{\pi N}}{\varepsilon_1 (\Delta^2 + \mu^2)^2}. \qquad (4)$$

Going over in (4) to the nucleon variables and expressing them in terms of the mass variable m of the πN system, we obtain the final expression for the cross section

$$\sigma_{NN}^{(a)}(\varepsilon_0) = \frac{\tau_\alpha^2 G^2}{8(2\pi)^2}$$
$$\times \int \frac{m \sqrt{(m^2 + 1 - \mu^2)^2 - 4m^2}\, p(m) \Delta^2(m) \sigma_{\pi N}(m)\, dm\, d(\cos\vartheta)}{\varepsilon_0^2 \sqrt{\varepsilon_0^2 - 1}\, (\Delta^2(m) + \mu^2)^2},$$
$$\Delta^2(m) = -2 + (4\varepsilon_0 + 1 - m^2)/2$$
$$+ \mu^2 - 2\sqrt{\varepsilon_0^2 - 1}\, p(m) \cos\vartheta,$$
$$p(m) = \{[(4\varepsilon_0^2 + 1 - m^2)/4\varepsilon_0]^2 - 1\}^{1/2}. \qquad (5)$$

It is readily shown that the limits of integration in (5) should be the following:

$$[\varepsilon_0 \sqrt{p^2(m) + 1} - \Delta_{max}^2/2]/\sqrt{\varepsilon_0^2 - 1}\, p(m) \leqslant \cos\vartheta \leqslant 1,$$
$$1 + \mu \leqslant m \leqslant (4\varepsilon_0^2 + 1 - 4\varepsilon_0 \sqrt{p_{min}^2 + 1})^{1/2};$$
$$p_{min} = \tfrac{1}{2}\sqrt{\varepsilon_0^2 - 1}\, (\Delta_{max}^2 + 2)$$
$$- \tfrac{1}{2}\varepsilon_0 |\Delta|_{max} \sqrt{\Delta_{max}^2 + 4}. \qquad (6)$$

The value of the maximum "virtualness" of the intermediate pion Δ_{max}^2 is determined from the following considerations. In meson theory the nucleon is considered to be localized in a region characterized by its Compton wavelength $\lambda\!\!\!^{-} = 1$. Since the peripheral meson is localized in a larger region, then, according to the uncertainty relation, $|\boldsymbol{\Delta}| \leq 1$. Hence $\Delta_{max}^2 \leq 1 - \Delta_0^2$. In the nucleon rest system, $|\Delta_0| = \Delta^2/2$. This gives for the virtualness $\Delta_{max}^2 = 0.83 = (6.1\mu)^2$. The restriction on the virtualness introduced in this way corresponds to the energy cutoff used in relativistic meson theory.

The other value used in the calculations $\Delta_{max}^2 = 0.67 = (5.5\mu)^2$ corresponds to the energy cutoff $\omega = 6\mu$ used in the Chew and Low model. [7]

2. Case b. We write the expression for the probability of the NN interaction in the form

$$dw_{NN}^{(b)} = \frac{(2\pi)^4}{4} \sum_n \left| \frac{M_1(p_0, p_1) M_2(q_0, q_1)}{(\Delta_1^2 + \mu^2)(\Delta_2^2 + \mu^2)} - \frac{M_1(p_0, q_1) M_2(q_0, p_1)}{(\Delta_2'^2 + \mu^2)(\Delta_2'^2 + \mu^2)} \right|^2$$
$$\times |M_{\pi\pi}|^2 \delta\left(p_0 + q_0 - p_1 - q_1 - \sum_i r_i\right) \frac{d^3 p_1}{(2\pi)^3} \frac{d^3 q_1}{(2\pi)^3} \prod_i^n \frac{d^3 r_i}{(2\pi)^3}, \qquad (7)$$

where $\Delta_1 = p_0 - p_1$, $\Delta_2 = q_0 - q_1$, $\Delta_1' = p_0 - q_1$, $\Delta_2' = q_0 - p_1$, and $M_{\pi\pi}$ is the matrix element for the $\pi\pi$ interaction. An estimate shows that the contribution of the interference term is again small, which permits us to rewrite (7) in the following form:

$$dw_{NN}^{(b)} = (2\pi)^4 \frac{\tau_\alpha^2 \tau_\beta^2 G^4}{32} \sum_n \frac{\Delta_1^2 \Delta_2^2 |M_{\pi\pi}|^2}{\varepsilon_0^2 \varepsilon_1 \varepsilon_2 (\Delta_1^2 + \mu^2)^2 (\Delta_2^2 + \mu^2)^2}$$
$$\times \delta\left(p_0 + q_0 - p_1 - q_1 - \sum_i r_i\right) \frac{d^3 p_1}{(2\pi)^3} \frac{d^3 q_1}{(2\pi)^3} \prod_i^n \frac{d^3 r_i}{(2\pi)^3}. \qquad (8)$$

Using the relation

$$w_{\pi\pi} = (2\pi)^4 \sum_n \int \frac{|M_{\pi\pi}|^2}{4\omega_1 \omega_2} \delta\left(k_1 + k_2 - \sum_i r_i\right) \prod_i^n \frac{d^3 r_i}{(2\pi)^3},$$
$$(\omega_j = \sqrt{\mathbf{k}_j + \mu^2},\ j = 1, 2), \qquad (9)$$

we obtain

$$\sigma_{NN}^{(b)}(\varepsilon_0) = \frac{\tau_\alpha^2 \tau_\beta^2 G^4}{8(2\pi)^6} \int \frac{d^4 \Delta_1 d^4 \Delta_2 \Delta_1^2 \Delta_2^2 \omega_1 \omega_2 j_{\pi\pi}(\omega_1, \omega_2) \sigma_{\pi\pi}(\omega_1, \omega_2)}{j_{NN} \varepsilon_0^2 \varepsilon_1 \varepsilon_2 (\Delta_1^2 + \mu^2)^2 (\Delta_2^2 + \mu^2)^2}. \qquad (10)$$

Inserting in (10) the expressions for the fluxes, going over to the nucleon variables, and expressing the momentum of one of the nucleons in terms of the mass m of the excited $\pi\pi$ system (under the assumption that the latter is at rest in the c.m.s.), we obtain the final expression for the cross section of the process:

$$\sigma_{NN}^{(b)}(\varepsilon_0) = \frac{\tau_\alpha^2\tau_\beta^2 G^4}{64(2\pi)^4}\int \frac{p_1^2\Delta_1^2(p_1, \cos\vartheta_1)}{\varepsilon_0\sqrt{p_1^2+1}\,[\Delta_1^2(p_1,\cos\vartheta_1)+\mu^2]^2}\,\frac{m\Delta_2^2(m,\cos\vartheta_2)\sqrt{(2\varepsilon_0-m)^2/4-1}\,\sqrt{m^2-4\mu^2}\,\sigma_{\pi\pi}(m)\,dp_1 d(\cos\vartheta_1)\,dm\,d(\cos\vartheta_2)}{\sqrt{\varepsilon_0^2-1}\,[\Delta_2^2(m,\cos\vartheta_2)+\mu^2]^2}. \quad (11)$$

A more detailed expression for $\sigma_{NN}(\epsilon_0)$ is too cumbersome to give here.

3. The results of calculations of the cross sections for the inelastic nucleon-nucleon interactions from formulas (5) and (11) for various values of the primary particle energies in the l.s. are shown in Table I. We now discuss the obtained results.

Table I. Nucleon-nucleon interaction cross sections (in mb) for various values of E_{lab}

Type of reaction	Δ^2_{max}	E_{lab}, GeV				
		9	18	200	800	5000
a	0.83	37	38	38	38	38
	0.67	32	30	30	30	30
b	0.83	8.5	10.5	13	13	13
	0.67	7.3	7.8	8.1	8.1	8.1

A. Case of high and ultra-high energies ($E_{lab} \geq 200$ GeV). As shown by the calculations, the resonance effects of πN and $\pi\pi$ scattering do not affect the results. Therefore, in the calculations we used the values 30 and 65 mb for the cross sections $\sigma_{\pi N}$ and $\sigma_{\pi\pi}$, which we took to be constant. It is seen from Table I that the cross sections of both processes, under the condition of constant $\sigma_{\pi N}$ and $\sigma_{\pi\pi}$ and for a constant value of Δ^2_{max}, turn out to be asymptotically independent of the energy. If we did not introduce any restrictions on Δ^2 apart from those required by the conservation laws, then, under the previous simple conditions, the asymptotic behavior of the cross section is

$$\sigma_{NN}^{(a)}(\varepsilon_0) \sim \ln\varepsilon_0, \qquad \sigma_{NN}^{(b)} \sim \ln^2\varepsilon_0. \quad (12)$$

As regards the values of the calculated cross sections and the relative contribution of process b, it is readily shown that they are in satisfactory agreement with the results of studies [8] of nucleon-nucleon interactions at $E_{lab} \approx 200$ GeV and are not in contradiction with other data. We note that if the "two-center" jets are interpreted as NN interactions going through the $\pi\pi$ interaction, [9,10] then their expected contribution, as seen from Table I, should be about 30%.

B. The results obtained at $E_{lab} = 9$ BeV refer to interactions between protons and neutrons.

In the case of process b, the $\pi\pi$ interaction can proceed in states with total isospin T equal to 0, 1, and 2. If all three isospin states are considered equally probable, then

$$\sigma_{\pi\pi}(m,\ T) = \tfrac{5}{27}\sigma_{\pi\pi}(m,\ 0) + \tfrac{12}{27}\sigma_{\pi\pi}(m,\ 1) + \tfrac{10}{27}\sigma_{\pi\pi}(m,\ 2). \quad (13)$$

An estimate of the contribution of the resonance in the $\pi\pi$ interaction for T = 1 yielded the value 0.6 mb. At present there are no data on the value of the $\pi\pi$ total cross section at large values of m. Therefore the mean value of the $\pi\pi$ total cross section was set equal to the geometric cross section (65 mb).

In the case of process a, which includes process b, the values of $\sigma_{\pi N}(m, T)$ were taken from experiment. [6] Considering the states of the πN system with isospin $T = 1/2$ and $T = 3/2$ to be equally probable, we have

$$\sigma_{\pi N}(m,\ T) = \tfrac{5}{9}\sigma_{\pi N}\left(m, \tfrac{1}{2}\right) + \tfrac{4}{9}\sigma_{\pi N}\left(m, \tfrac{3}{2}\right). \quad (14)$$

The basis for the assumption on the equal probability of both isospin states of the πN system is illustrated in Fig. 2, from which it is seen that the influence of the resonance in the πN interaction for $T = 3/2$ is not large.

Finally, we estimated the expected c.m.s. asymmetry of the angular distribution of the secondary protons for pn interactions with three prongs. As a measure of the asymmetry, we took, as usual, the quantity η defined as follows:

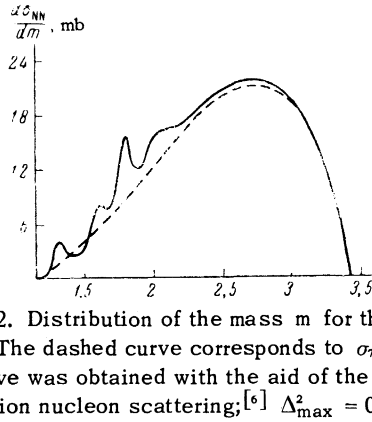

FIG. 2. Distribution of the mass m for the excited πN system. The dashed curve corresponds to $\sigma_{\pi N} = 30$ mb. The solid curve was obtained with the aid of the experimental data on pion nucleon scattering; [6] $\Delta^2_{max} = 0.67$.

$$\eta = [(Np)_f - (Np)_b] / [(Np)_f + (Np)_b], \quad (15)$$

where $(Np)_f$ and $(Np)_b$ are the numbers of protons emitted forward and backward in the c.m.s.

The calculation was carried out in accordance with the scheme suggested by Tamm.[3] We assumed that 1) the excited πN system decays into a nucleon and pion; 2) the nucleon from the decay of the πN system is emitted in the c.m.s. preferentially in the same direction as that in which the πN system is moving; 3) all isospin channels of the decay are equally probable. In the case of three-particle reactions, we took into account the contribution of diffraction scattering of the pion on the nucleon.

The results of the calculations are shown in Table II. It is seen from the table that the expected proton asymmetry is in satisfactory agreement with the data of [1].

Table II. Asymmetry η of the proton angular distribution in three-prong pn interactions at E_{lab} = 9 GeV

Type of reaction	Total no. of secondary particles in reaction	Proton asymmetry in three-prong cases
a	3	0
	4	−0.20
	5	−0.30
	6	−0.28
b	4	−0.35
	6	−0.47
experiment	for all reactions	−0.32±0.11

C. In connection with the foregoing results, it is necessary to make some general remarks.

First, it turns out that the one-meson NN interaction accompanied by the "excitation" of only one of the nucleons apparently makes a large, if not decisive, contribution to the cross section of the inelastic NN interactions. If we take into account interactions of this type only, we can satisfactorily explain many characteristics of NN interactions at high and ultra-high energies. On the other hand, theoretical investigations (see, e.g., [4,5]) indicate that the one-meson interaction accompanied by the excitation of both nucleons plays an important role. Hence, in order to explain the same set of experimental facts, the present theory suggests two possibilities. Within the framework of the theory, there are no obvious reasons to consider the two possibilities as alternatives and it is impossible to carry out programs of investigation in which all possible processes of the one-meson interaction would be considered from the same viewpoint. However, the final answer to the question on the relative contribution of different processes with the present state of the theory can be given only by experiment. In this connection, it is extremely desirable, along with a further increase in the accuracy of the measurements, to obtain reliable data on the nature of the secondary particles, the angular correlations, and other detailed information.

In conclusion, we take this opportunity to express our deep gratitude to Professor Zh. S. Takibaev for his constant interest in this work and for valuable comments, to V. A. Botvin, Ya. I. Granovskiĭ, and V. I. Rus'kin for helpful discussions on questions of experiment and theory, and to A. N. Akhmedshina for much help in the calculations.

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