DIFFRACTION PRODUCTION OF PARTICLES BY 20–23 GeV PROTONS

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Submitted February 28, 1968

Zh. Eksp. Teor. Fiz. 55, 170–178 (July, 1968)

The angular and momentum distributions of secondary particles in reactions of the type p + nucleus → p + π^+ + π^- + nucleus (in the absence of nuclear excitation) were measured in photographic emulsions exposed to a pulsed magnetic field (180 kOe). The distribution of longitudinal momenta transferred to the nucleus is obtained for 30 events interpreted as processes of coherent generation of particles on the emulsion nuclei. The range of the given process in the photographic emulsion is estimated to be 47 m (± 20%).

IN an earlier paper[1] we presented preliminary data on diffraction generation of particles by protons with momentum 21–24 GeV/c on photoemulsion nuclei irradiated in a pulsed magnetic field of 180 kOe in the CERN accelerator. We analyzed interactions of the type p + nucleus → p + π^+ + π^- + nucleus, not accompanied by visible excitation of the nucleus.

Retaining the previously employed procedure for measuring the kinematic characteristics of the interactions, we used some new possibilities of separating the coherent and diffraction events, and performed a more complete analysis of their properties. These properties are of interest, in particular, for a comparison with the theoretical results[2,3] obtained by starting from the notion of exchange of a vacuum pole between the incoming nucleon and the nucleus.

Two principal characteristics distinguishing the inelastic diffraction nucleon-nucleus interactions from incoherent nucleon-nucleon interactions are connected, first, with the fact that the former have a "single-jet" form with asymmetrical (forward) angular distribution of the secondary particles in the nucleon-nucleon system, and, second, with the absence of slow particles due to the excitation of the target nucleus or to the knockout of nucleons from it.

As seen from a comparison of Figs. 1a and b, for interactions containing a proton and π^+ and π^- mesons in the final state, both features appear simultaneously, namely, 3-prong stars $p\pi^+\pi^-$ without black traces (N_V = 0) and without visible traces of a slow electron or recoil nucleus[1)], which we shall henceforth call stars of type I (unlike 3-prongs stars of type II, N_V = 1–3 or N_V = 0 in the presence of an electron or recoil nucleus), are characterized by a sharply pronounced directivity of the emission of the $\pi^\pm$ pions forward in the c.m.s.

As will be shown later, only about 1/3 of all the stars of type I (the shaded part of the distribution in Fig. 1a) are unrelated to the diffraction-generation processes, and this causes the angular symmetry of the $\pi^\pm$-meson emission in these stars. Figure 1b shows that an approximate symmetry of the angular distributions is ob-

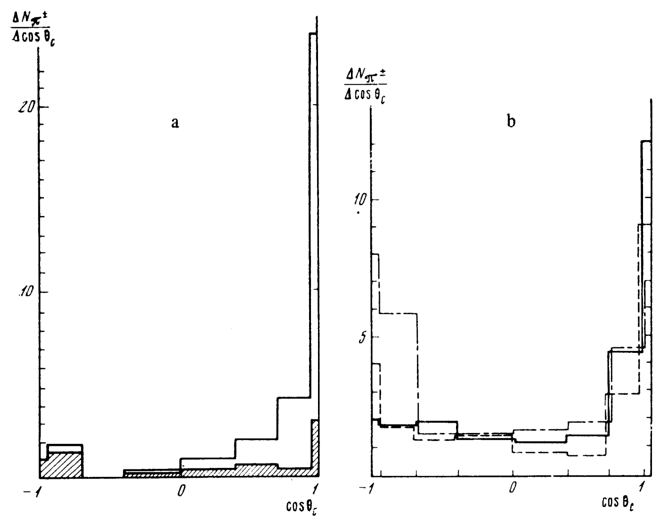


FIG. 1. Angular distributions of $\pi^\pm$ mesons in the c.m.s.: a – for stars of type I (58 events) with $q_{\|} < 150$ MeV/c having $p\pi^+\pi^-$ in the final state; the cases with $q_{\|} < 150$ MeV/c are shaded; b – heavy solid line – for stars of type II (42 events), dashed line – for stars of type $pn\pi^+$ or $2n\pi^+\pi^-$ (52 events), dash-dot – for stars of type $2p\pi^+\pi^-$ (57 events).

tained for both pp interactions (2- and 4-prong stars) and pn interactions (3-prong stars) with the quasi-free nucleons of the nucleus. In the analysis of the angular distribution of three fast particles in the laboratory system (Fig. 2), predominance of narrowly collimated "jets" in stars of type I is observed. A similar picture was indeed the basis for the separation of the diffraction events in the work of Boos et al.[4] However, the unfavorable ratio of the separated effect to the background (20 and 26 events) in[4] leads to a large error when the cross sections of the investigated process are estimated from distributions such as in Fig. 2.

In Figs. 3a, b, and c and in Fig. 4 we see one more feature of stars of type I; namely, as a rule, they have no fast neutral mesons (whose energy is determined as the difference between the initial energy and the total energy of the secondary charged particles), more accurately, the energy of the neutral particles lies within the limits of the measurement error of the energy of the charged particles, which as a rule amounts to 10–15%. At the same time, for stars of type II both the average

1)The track of the recoil nucleus (range ≥ 1 μ) can be observed only for light emulsion nuclei provided the transverse momentum transferred to the nucleus is ≳ 0.4 GeV/c. In the considered experimental material, not more than three events with $p\pi^+\pi^-$ in the final state (in the presence of a visible recoil track) could be attributed to diffraction.

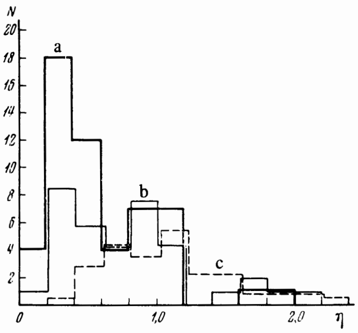


FIG. 2

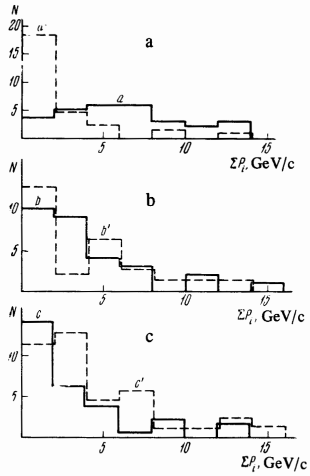


FIG. 3

FIG. 2. Distribution of events with respect to $\eta = \sin\theta_{\pi^+} + \sin\theta_{\pi^-} + 6.7\sin\theta_p$ for stars of type I (55 events, a), stars of type II (42 events, b), and stars of type $2p\pi^+\pi^-$ (56 events, c), all normalized to the number of events with $\eta > 0.6$.

FIG. 3. Distribution of events with respect to $\Sigma P_{\pi^\pm}$ (a, b, c) and $\Sigma P_{\pi^0} + K^0$ (a′, b′, c′) for stars of type I (a), II (b), and $2p\pi^+\pi^-$ (c).

energy and the general character of the energy distribution of the neutral particles are practically the same as for the charged mesons, so that one might assume that the average number of π^0 mesons emitted in this case also equals 2. We note incidentally that the total angular distribution of the $\pi^\pm$ mesons produced upon excitation of any isobar in pn collisions should be symmetrical, since a mirror symmetry of the protons and neutrons in isotopic space corresponds to a similar symmetry of the π^+ and π^- mesons. This circumstance, together with the possibility of obtaining complete information on all the secondary particles, makes events with p, π^+, and π^- particles in the final state most attractive for the study of the process of diffraction generation of particles and for the separation of this process from ordinary inelastic interaction.

An important characteristic of the diffraction process is the longitudinal momentum $q_{\parallel}$ transferred to the nucleus, which by virtue of the conservation laws is connected in the following manner with the transverse

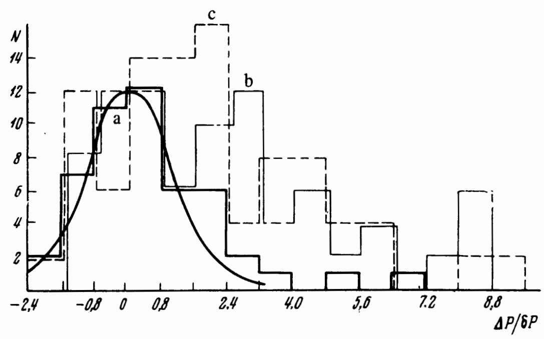


FIG. 4. Distribution of particles with respect to $\Delta P/\delta P$, where $\Delta P = P_0 - \Sigma P_{i.\,ch}$, δP – error in measurement of $\Sigma P_{i.ch}$, for stars of type of I (50 events), Gaussian distribution (a), for stars of type II (42 events, b), and for stars of type $2p\pi^+\pi^-$ (48 events, c), normalized to number of events with $\Delta P/\delta P < 0$.

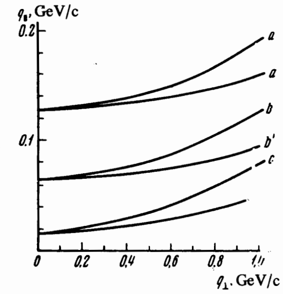


FIG. 5. Plot of $q_{\parallel}$ ($q_{\perp}$) from relation (1): a, b, c – $M_A = 14$, a′, b′, c′ – $M_A = 94$; a, a′ – $M^* = 2.5$ GeV/c^2; b, b′ – $M^* = 1.9$ GeV/c^2, c, c′ – $M^* = 1.3$ GeV/c^2.

momentum $q_{\perp}$ transferred to the nucleus and the effective mass M_{eff} of the system, obtained as a result of excitation of the incoming nucleon N:

$$q_{\parallel} = \frac{M_A + P_0}{2M_A P_0} q_{\perp}^2 + \frac{M_{eff}^2 - M_N^2}{2P_0}, \qquad (1)$$

where M_A—mass of target nucleus, P_0, M_N—initial momentum and mass of the nucleon (we put c = 1 throughout).

The connection between $q_{\perp}$ and $q_{\parallel}$ for an average light emulsion nucleus (A = 14) and an average heavy nucleus (A = 94) is shown in Fig. 5, from which we see that when $q_{\perp} < 0.5$ GeV/c the value of $q_{\parallel}$ is determined practically completely by the mass $M_{eff}(p\pi^+\pi^-) = M^*$, and depends little on either the mass of the target nucleus M_A or on the transverse momentum $q_{\perp}$. Once it is verified (on the basis of Fig. 4) that for stars of type I the probability of appearance of π^0 mesons is small, we can determine with sufficient degree of reliability the mass M*, starting from the kinematic characteristics of the charged particles only, and this allows us to increase greatly the accuracy with which $q_{\parallel}$ is determined, by using the relation (1) instead of a direct measurements of the missing longitudinal momentum of the secondary particles.

Figure 6 shows the distributions with respect to the excited masses (M*) for stars of types I and II, and also of the combinations $p\pi^+\pi^-$ from stars of type $2p\pi^+\pi^-$. As expected even from the difference in the kinematics of the particle scattering, in the former case the distribution is greatly enriched by small masses ($M^* \le 2.3$ GeV/c^2), and a relatively large contribution in the region of the smallest excitations ($M^* \le 1.7$ GeV/c^2) is made by interactions with a large initial energy ($P_0 = 24$ GeV/c). In spite of the small statistics on which the latter conclusion is based, we consider it to be sufficiently natural, since the investigated energy region is near the threshold of the diffraction process for heavy emulsion nuclei.

Figure 7 shows the distribution with respect to $q_{\parallel}$

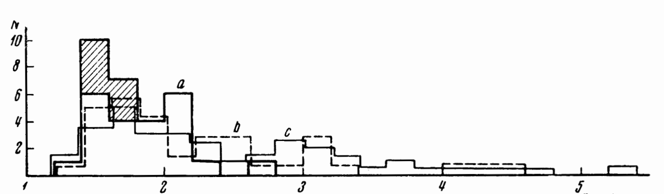


FIG. 6. Distribution with respect to M* ($P\pi^+\pi^-$): a – for stars of type I with $q_{\parallel} < 150$ MeV/c, the cases with $P_0 = 24$ GeV/c one shaded (altogether 30 events); b – for stars of type II (42 events); c – for stars of type $2p\pi^+\pi^-$ (62 events).

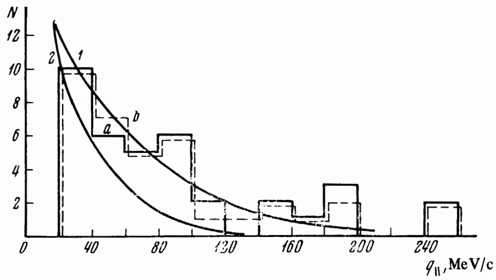


FIG. 7. Distribution with respect to $q_{||}$ for events of type I, having $p\pi^+\pi^-$ in the final state: a – assuming that $M_A = 14$; b – that $M_A = 94$; curves 1 – $\sim \exp[-14^{-1/3} q_{||}/\mu c]$, 2 – $\exp[-94^{-1/3} q_{||}/\mu c]$.

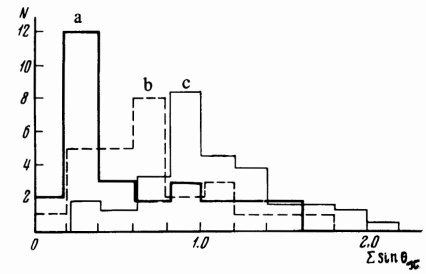


FIG. 8. Distribution with respect to $\Sigma \sin\theta_\pi$: a – for stars of type I with final state $2\pi^+\pi^-$ (28 events), b – for stars of type II (27 events), c – for stars of type $p2\pi^+\pi^-$ (44 events).

obtained by us for those 38 stars of type I ($p\pi^+\pi^-$) for which the missing longitudinal momentum of the secondary particles ΔP does not exceed twice the error of its measurements and at the same time (as seen from the histogram a of Fig. 4), the background from non-diffraction processes should be small (or else the deviations from the point $\Delta P = 0$) on both sides are practically equally probable, and their distribution is symmetrical). The two distributions on Fig. 7 (both experimental and theoretical) are constructed under two different assumptions concerning the mass of the target nucleus. We see that assuming a light nucleus ($M_A = 14$) the experimental distribution is in satisfactory agreement (in the presence of a small background) with an exponential in the form $\exp(-14^{-1/3} q_{||}/\mu c)$. It corresponds to the condition assumed usually for the diffraction process, $q_{||} < \mu c^{-1/3}$, but without a sharp "cutoff" in the longitudinal momentum transfer. The assumption that all the target nuclei have a large mass disagrees strongly even with such an exponentially "smooth" "cutoff" threshold. The heavy emulsion nuclei make apparently a small contribution to the observed phenomenon, owing to the relatively small initial energy of the incoming protons.

Returning again to Fig. 1a, we see that the events for which $q_{||} > 150$ MeV, together with the already discarded events for which $q_{||}$ exceeds twice the error of direct measurement of the missing longitudinal momentum, have an approximately symmetrical angular distribution of the π^+ mesons in the nucleon-nucleon c.m.s. To the contrary, 30 stars of type I with $q_{||} < 150$ MeV have an angular distribution with a sharp concentration of the pions near the direction of the primary particle: approximately 50% of these particles are emitted at an angle not larger than 30° in the c.m.s. We therefore assume that "cutoff" with respect to the longitudinal momenta at 150 MeV/c makes it possible to separate in first approximation the inelastic diffraction processes on nuclei from the background connected with the non-diffraction inelastic interactions with individual nucleons.

Starting from all the selection criteria considered above, we obtain the following estimate of the range of the diffraction process on emulsion nuclei with 3-particle production (p, π^+, π^-) in the final state: $\lambda = (47 \pm 9)$ m. For the total range of the diffraction generation of particles on nuclei (at the given initial momentum) this estimate may be too high by 3–5 times, since we certainly did not take into account diffraction excitation of the proton to the isobar state, with subsequent decay of the isobar into two or three particles, including neutral particles. These processes should appear as single-prong stars with emission of one proton or one π^+ meson in the final state. Experiment has shown that the angular distribution of the produced particles in these stars is sharply asymmetrical (in the overwhelming majority of cases both the protons and the pions are emitted forward in the c.m.s.), however, the separation of the diffraction processes is quite difficult. This is connected both with the admixture of elastic scatterings (if a proton is observed in the final state) and with the effect of asymmetrical decay of the isobars, occurring in pn interactions, since there is at least partial conservation of the projection of the isotopic spin when each of the interacting nucleons is excited.

The overestimate of the range is connected in addition with the possibility of four-particle decay of the produced isobars. This includes 3-prong stars with two charged mesons, for which the role of the background is much smaller. If we use the distribution of the observed events with respect to the angular quantity $\eta = \Sigma \sin\theta_i$, which is due only to the $\pi^\pm$ mesons, as a rough criterion for the separation of the diffraction process, then we can compare, as is done in Fig. 8, the distribution for stars with 3 pions of type I ($N_V = 0$) and the analogous distributions for the same stars of type II and all stars of type $p2\pi^+\pi^-$ (which appear already as the result of pp and not pn or p-nucleus interactions). Such a comparison shows that the possible contribution of the diffraction processes with final state $n2\pi^+\pi^-$ is approximately 20% of the corresponding contribution of stars of type I with final state $p\pi^+\pi^-$. It can be assumed, however, that the relative magnitude of the indicated contribution increases with increasing initial energy as a result of the stronger excitation of the incoming proton.

An even more serious factor in the increase of the initial energy may be the passage through the energy threshold of diffraction generation of isobars with mass up to 2.5 GeV/c^2 not only on light but also on heavy emulsion nuclei. We note in this connection that for particles with an average energy 200 GeV the range for the production of narrowly collimated 3-prong stars does not exceed 10 m in accordance with the data of[5].

By selecting the investigated events with respect to the magnitude of the longitudinal momentum transferred to the nucleus ($q_{||} < 150$ MeV/c), we can consider further other properties of these events, particularly those connected with the transverse momentum transfer to the nucleus.

Figure 9 shows the experimental distribution with

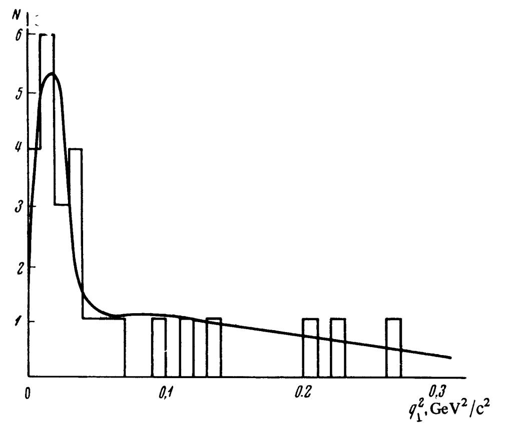


FIG. 9. Distribution with respect to $q_\perp^2 = t$ – 4-momentum transfer for diffraction events (histogram). Curve – experiment with distribution with respect to t for elastic scattering of protons by carbon[6], multiplied by $q_\perp^2$, from which the curve $\sim \exp(-10\ \ t)$, corresponding to nucleon-nucleon scattering, is subsequently subtracted, normalized to the number of events with $q_\perp^2 \leqslant 0.07$ GeV²/c². The figure shows four events with $q_\perp^2 > 0.3$ GeV²/c².

respect to $q_\perp^2$, from which we get an average value $\overline{q_\perp^2} = (0.12 \pm 0.03)\ (\text{GeV/c})^2$ (in 20 out of 30 events $q_\perp^2 < 0.07$). In accordance with results of calculations[3] using the model of Reggeon exchange between the incoming proton and the target nucleus, we can expect this distribution to differ only by a factor $q_\perp^2$ from the corresponding distribution for the process of elastic scattering. Therefore the same Fig. 9 shows the expected plot of the distribution for a carbon nucleus using the data of Belletini et al.[6] for elastic scattering of protons by carbon nuclei at a momentum 21.5 GeV/c. As seen from Fig. 9, the experimental distribution with respect to q^2 obtained by us does not contradict the expected distribution.

For comparison with the Reggeon-exchange model, it is of interest to investigate the distribution of the investigated events with respect to the parameter[2)] Z, which equals approximately the ratio of the transverse and longitudinal momenta transferred to the nucleus (see Fig. 10). In accordance with the predictions of the theory, the condition $Z \gg 1$ is satisfied for most events.

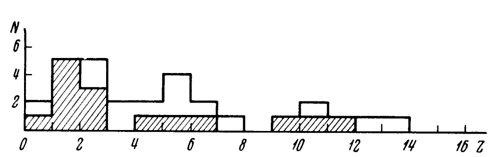
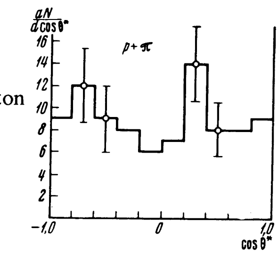


FIG. 10. Distribution with respect to the parameter Z. Shaded part of the histogram – $M^* > 1.7$ GeV/c², light – $M^* < 1.7$ GeV/c². The figure does not show one event with Z = 22.

In conclusion, we present the angular distribution of all the charged particles in the system of the excited mass $p\pi^+\pi^-$ (Fig. 11). We see that this distribution is practically isotropic.

2)In the theory of Reggeon poles, this parameter is the cosine of the scattering angle in the crossing channel (for details see[3]).

FIG. 11. Angular distribution of proton and $\pi^\pm$ mesons in the rest system M_{eff} $(p\pi^+\pi^-)$.



CONCLUSIONS

1. For inelastic interactions of protons with emulsion nuclei, accompanied by emission of a proton and a π^+ and π^- meson in the final state, the following criteria are proposed for the separation of the diffraction processes:

a) absence of visible excitation of the target nucleus,

b) vanishing (within the limits of errors) of the energy that can be attributed to the neutral particles,

c) the longitudinal momentum transferred to the target nucleus, determined from formula (1) must not exceed $q_{\parallel\max} = 150$ MeV/c.

2. For the events separated in this manner, the distribution with respect to the transverse momenta $q_\perp$ transferred to the nucleus, and also with respect to the parameter $Z = q_\perp/q_\parallel$, agrees with the predictions of the Reggeon-exchange model.

3. A direct estimate of the range for the investigated process is (with a statistical error of approximately 20%) $\lambda = 47$ m of emulsion. Taking into account the neutral modes of the decay of the produced isobars, this estimate may be strongly exaggerated.

In conclusion, the authors thank E. L. Feĭnberg and D. S. Chernavskiĭ for a fruitful discussion of the results, and also laboratory assistants E. A. Krupetskov, A. S. Kolyadin, M. V. Tyurin, and N. A. Sobolev for carefully performed measurements of the particle tracks.

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Translated by J. G. Adashko
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