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QUASINUCLEON INTERACTIONS OF 24 BeV/c PROTONS WITH PHOTOEMULSION NUCLEI IN A STRONG MAGNETIC FIELD

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We have used photoemulsion in a 180-kG pulsed magnetic field to study quasinucleon interactions of 24-BeV/c protons. In addition to complete information on all charged secondary particles (emission angle, momentum, and type of particle), we determined the total energy of neutral mesons. Various criteria were used to separate the events into peripheral and non-peripheral interactions. The distributions of multiplicity, inelasticity coefficients, and the angular distributions of the particles have been determined for both types of interactions, and large fluctuations have been observed in the distribution of energy between charged and neutral mesons. We have also established that there is a noticeable difference between the energy spectra of π^+ and π^- mesons. The results obtained indicate a high probability for excitation of various nucleon isobars.

1. APPARATUS AND EXPERIMENTAL TECHNIQUE

THE study undertaken by us of the general characteristics of the nuclear interaction of protons with photoemulsion nuclei was based on use of the technique recently developed at CERN[1] for use of emulsion in a strong pulsed magnetic field (180 kG).1) Use of the strong magnetic field in irradiation of emulsion stacks in accelerators considerably broadened the possibilities of the emulsion method since, in addition to angle and ionization measurements, it permitted determination of the sign of the charge of the particles and much more accurate measurement of the momentum of fast particles (up to the primary momentum). As a result we have achieved a definite advantage even over the hydrogen bubble chamber, in which direct identification of positively charged particles with momentum above 2 BeV/c is already impossible.

At our disposal were ten circular emulsion layers of Ilford type G-5, 600 μ thick and 6 cm in diameter, irradiated in the CERN 24-BeV/c proton beam with an intensity of about 10^4 cm^{-2}. The experimental data analyzed below (200 quasinucleon stars) were obtained by along-the-track scanning.

1)A similar method has been used by the Warsaw group[2] who studied the interactions of protons of the same energy with Ag and Br nuclei.

The emission angles and ionization were measured for all secondary particles; the sign of charge and momentum were measured for particles with a track length ≥ 1 mm in one layer. The main source of error in determining the sign of charge and momentum from the curvature in the magnetic field is Coulomb scattering; the distortion of the photoemulsion layer was taken into account by measuring the lengths of the horizontal projections of tracks of an auxiliary beam perpendicular to the plane of the emulsion. The mean-square relative error in measurement of the momentum due to Coulomb scattering was $0.4/\sqrt{t}$, where 2t is the total length of measured track in mm.

By extension of the measured tracks into neighboring emulsion layers and corresponding measurements of the ionizing ability of the particles we were able to identify the particles in 80–85% of the cases for a momentum measurement accuracy on the average of about 20% (for inelastic interactions with a number of charged particles $n \leq 4$). The momentum measurement accuracies achieved allowed us, under favorable conditions, to determine the effective masses of rather light isobars ($M_{eff} \leq 1.7$ BeV/c^2) with an average error of about 5%. The technique used provides for most events complete information on all secondary charged particles and does not require introduction of any geometrical corrections.

2. SELECTION OF INTERACTIONS WITH QUASIFREE NUCLEONS

As in our previous work[3] on 8.7-BeV protons, we selected the interesting interactions with quasifree nucleons mainly from the criterion of a small number of small particles, specifically $N_h \leq 3$, $N_g \leq 1$ (N_g is the number of "gray" tracks, which correspond to protons with energy above 30 MeV, and N_h is the combined number of "gray" and "black" tracks). As in the earlier work we used as a criterion of the correctness of the selection the determination of the target mass M_t, with the difference that in the present work we could take into account directly the contribution to the mass M_t by essentially all the charged particles in each interaction. The most significant events in this respect are those where a recoil proton is directly observed and consequently no correction for neutrons is needed. If we estimate the experimentally measured π^0-meson contribution as half of the $\pi^{\pm}$-meson contribution, then the target mass distributions obtained can be represented by Fig. 1. It can be seen that for a measured number of secondary charged particles n = 4–6 (Fig. 1a), about 90% of the events correspond to a mass $M_t \leq M_N \times 1.5$, with the median and average values of M_t in the vicinity of $M_t = M_N$ (with an accuracy of 10% or better).2) As will be seen subsequently, the comparatively broad distribution of the mass M_t around the average value can be explained by the fact that the relative contribution of π^0 mesons fluctuates very strongly from event to event.

Proceeding now to analysis of the distribution of M_t for events with high multiplicity ($n \geq 7$) in Fig. 1b and comparing it with Fig. 1a, we can see that now already about half of the events cannot be assigned to nucleon-nucleon interactions, although this half amounts to only about 10% of the total number of stars with any n. An arbitrary upper limit to M_t values, separating the nucleon-nucleon events, can be obtained from the requirement that the contribution of charged particles alone ($M_{t\ ch}$), including actually observed (or even "averaged") recoil nucleons, not exceed the mass of a single nucleon M_N.

Comparison of the interactions selected in this way with the corresponding data of Dodd et al.[4] obtained with a hydrogen bubble chamber showed good agreement of the distributions both in multiplicity and in the momenta of the negatively charged particles.

2)For $n \leq 3$ the admixture of events with large values of M_t turns out to be very small.

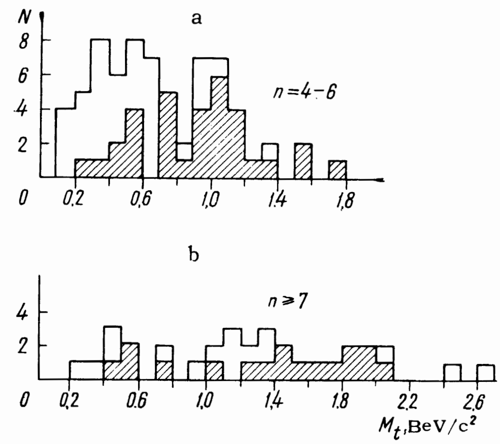

FIG. 1. Distributions of events with different numbers of charged particles ($n = n_s + n_g$, n_s is the number of relativistic particles) as a function of target mass M_t. Events with observed (and measured) recoil protons have been shaded.

3. MOMENTUM SPECTRA OF PROTONS, COEFFICIENT OF INELASTICITY, SEPARATION OF INTERACTIONS INTO PERIPHERAL AND CENTRAL

Figure 2a shows the dependence on multiplicity of four quantities: the average momenta of the proton, of the π^+ and π^- mesons emitted forward in the c.m.s., and finally the average energy of all neutral mesons; the latter is obtained by subtracting from the primary energy the energies of the proton emitted forward3) and of all $\pi^{\pm}$ mesons (nucleons emitted backward were taken into account by using the average value of their energy). It is evident that with increasing multiplicity the inelasticity of the interaction increases to roughly 70%, after which it remains practically at one level. At the same time, the average energies of individual π^+ and π^- mesons emitted forward in the c.m.s. remain almost constant, amounting to about 15% of the primary energy.

Figure 2b considers the distributions of the inelasticity coefficient (here we have in mind the fraction of energy given up to all the mesons). It is clear that events with small (n = 2–4) and large ($n \geq 5$) multiplicity overlap in inelasticity coefficient only to a relatively small degree: in the first case an inelasticity of $K > 0.6$ occurs with a probability of 10–15% and in the second case, on the other hand, a value of $K < 0.6$ has a probability of 20–25%.

Figures 3a–c show the distribution of the squared 4-momentum lost by the nucleons, Δ^2, for

3)For events with charge exchange it was assumed that the average momentum of the neutron is equal to the average momentum of the proton for a given n.

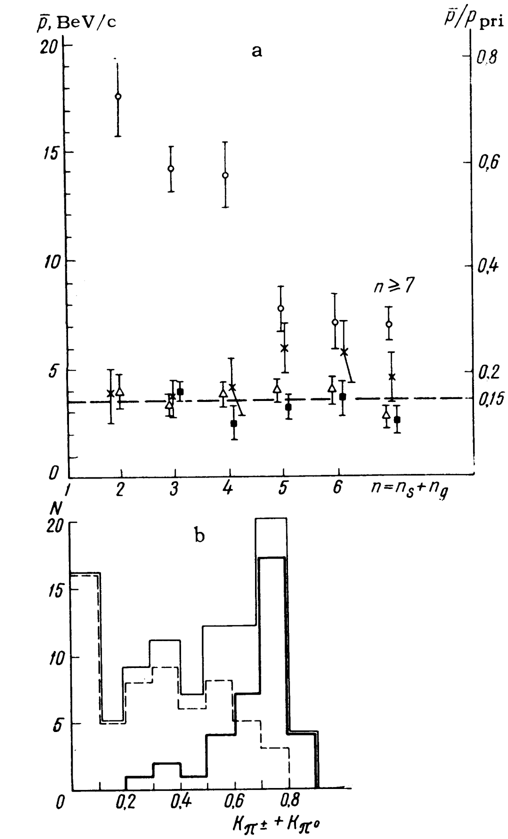

FIG. 2. Characteristics of events as a function of production multiplicity: a—average momentum of a single fast proton p (○), π^+ mesons (Δ), and μ^- mesons (■), and also the average energy of all neutral particles (lab.) $\Sigma p_{\pi^0}(+p_{K^0})$ (×); b—distributions of inelasticity coefficient: broken line—n = 2–4, heavy solid line—n $\geq$ 5, thin solid line— n $\geq$ 2.

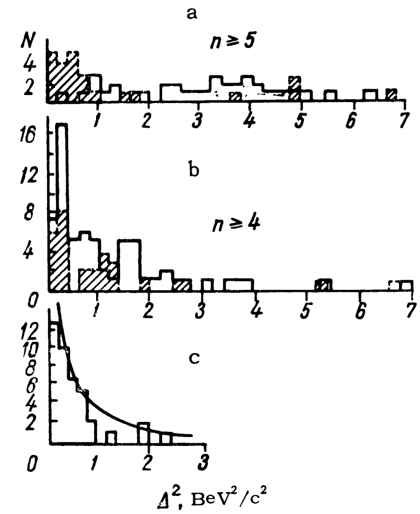

FIG. 3. Distributions in 4-momenta for different multiplicities (the shaded regions represent protons emitted backward): a, b—values of Δ^2 determined without allowance for isobar formation; c—momentum transferred to the isobar such that $\Sigma p_i \geq 12$ BeV/c, or to a single proton; theoretical curve—one-pion exchange according to Chew and Low.[5]

events of different multiplicity, the data for a nucleon target being shown separately. For interpretation of the data of Fig. 3, we can arbitrarily establish the criterion $\Delta^2 < 1$ (BeV/c)^2 for separation of peripheral interactions, since 90% of the events described by the one-pion-exchange model (see Fig. 3c) fall within this limit. It is evident that for $n \geq 5$ the momentum lost by the proton is as a rule large: $\Delta^2 > 1$ (BeV/c)^2 in roughly 85% of the events, if we neglect the effect of the intermediate process of formation and decay of isobars. For events of low multiplicity, n = 2–4, even if we assume the absence of isobars the value of Δ^2 turns out to be noticeably smaller ($\Delta^2 < 1$ (BeV/c)^2 in 60% of the events). If we calculate the value of Δ^2 transferred as a single unit to possible isobars with mass $M_{eff} \leq 1.55$ BeV/c^2 for two-particle decays and $M_{eff} \leq 1.8$ BeV/c^2 for three-particle decays, or consider events in which the proton is not accompanied by other charged particles emitted in the same hemisphere (Fig. 3c), we obtain a still steeper falloff in the Δ^2 distribution, and it agrees to a rough approximation with the prediction of the simple one-pion-exchange model according to Chew and Low.[5] One is particularly struck by the fact that events with $M_{eff}(p\pi^+\pi^-) < 1.8$ BeV/c^2 and $\Delta^2 \leq 0.2$ (BeV/c)^2 all belong to the type 0 + 0 + 3p and apparently can be interpreted as diffraction production of pions. In general some asymmetry can be noted in the Δ^2 distribution for an incident proton and a nucleon target; however, when we consider the particles falling in the momentum interval 1.5–2.5 BeV/c and when we average over all values of n, this asymmetry is considerably flattened out.

Another possibility for separation of the interactions into different classes (independent of the multiplicity) is associated with the experimentally observed strong relation between the momentum and angular characteristics of the protons.

Figure 4 shows the momentum distributions of protons in the c.m.s. for two angular intervals: 1) $\theta^* = 20-160°$; 2) $\theta^* \leq 20°$, $\theta^* \geq 160°$. The same figure shows the corresponding data obtained by us previously in photoemulsions without a magnetic field for 19.6-BeV/c primary protons. The curve calculated from the statistical theory[6] satisfactorily describes just the distribution which refers to the first interval, over the greater part of which (40–140°) the angular distribution has a roughly isotropic nature. The large values of longitudinal momentum characteristic of the second angle interval are due to the fact that a comparatively small variation of Δ^2 occurs in the interaction of the incident nucleons with the target. This is con-

Table I. Distributions in number of charged pions

Type of event	Number of events	Number of protons	$n_{\pi^\pm}$ 0	1	2	3	4	5	6,7	8–10	$\bar{n}_{\pi^\pm}$
Peripheral	20	2	7	4	2	5	2	—	—	—	1.5±0.3
	34	1	3	5	17	7	1	—	1	—	2.0±0.3
Nonperipheral	22	2	—	1	5	6	4	1	4	1	3.9±0.4
	14	1	2	1	3	1	3	1	1	2	3.6±0.5

Table II. Distributions in elasticity coefficient K_{lab}

Type of event	Number of events	K_{lab} 0.1–0.3	0.3–0.5	0.5–0.7	0.7–1.0	$(K_{lab})_{1/2}$
Peripheral (experiment)	53	13 (25%)	17 (30—35%)	17 (30—35%)	6 (—10%)	0.45±0.07
Nonperipheral (experiment)	36	1 (<10%)	6 (15—20%)	9 (25—30%)	20 (50—60%)	0.72±0.08
One-pion-exchange* (theory)		35%	35%	20%	(3—5) %	0.35

*Private communication from P. A. Usik.

firmed by comparison of experimental histograms 2 and 2a in Fig. 4 with the curve calculated by Usik[4)] on the basis of the one-pion-exchange model with an additional assumption regarding the nucleon form factor.

A rather definite judgment of the type of interaction can be made on the basis of the characteristics of the two nucleons, but the possibilities for such an analysis are very limited. Thus, of 26 events in which the two protons are observed, in seven cases $\Delta^2 \geq 1$ BeV^2/c^2 for both particles, which corresponds to a fraction of nonperipheral interactions of ~25%. The number of events with a small value of Δ^2 ($\Delta^2 < 1$ BeV^2/c^2), even if for only one of the protons, gives another, somewhat reduced estimate for the fraction of peripheral collisions, amounting to ~60% (we must take into account that large values of Δ^2 can also be obtained in a small percentage of events with noncentral interactions).

The distributions of the peripheral and nonperipheral interactions in multiplicity and inelasticity, which are given in Tables I and II, turn out to be rather broad; they show that division of the events into two classes only on the basis of the $\pi^\pm$ mesons produced or only on the basis of the inelasticity coefficient (in the laboratory system) is rather crude.

4. MOMENTUM AND ANGULAR DISTRIBUTIONS OF $\pi^\pm$ MESONS

The momentum distributions of the pions also depend on their emission angle, although to a lesser degree than the proton distributions. If we consider only the angle interval 60–120° (c.m.s.), the momentum spectrum (see Fig. 5a) is in good agreement with the Planck equilibrium spectrum for a temperature kT = μc^2, at which the average meson energy is 2.5 μc^2. We will arbitrarily assign the isotropic part of the total π-meson angular distribution to the process of "pionization" (i.e., production of π mesons in addition to isobars). From a comparison of the momentum distributions of π^+ mesons, π^- mesons, and πp particles, it is evident that a large part of the πp particles must be associated with π^+ mesons, but even in this case the ratio N_{π^+}: N_{π^-} is only insignificantly greater than unity.

A calculation shows that the total energy release associated with the "pionization" process is on the average 0.24 ± 0.03 in the c.m.s. or 0.18 ± 0.02 in the lab.

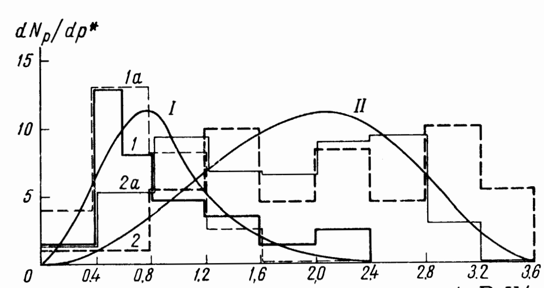

FIG. 4. Momentum spectra of protons (in the c.m.s.) for different angular intervals: 1, 1a–$\theta^* = 20–160°$; 2, 2a–$\theta^* \leq 20°$ (1, 2–data obtained in photoemulsions with a magnetic field for p_0 = 24 BeV/c; 1a, 2a–data obtained without a magnetic field for a primary momentum p_0 = 19.6 BeV/c). Solid curves–theoretical: I–statistical theory,[6] II–one-pion-exchange theory (communicated by P. A. Usik).

4)P. A. Usik, private communication.

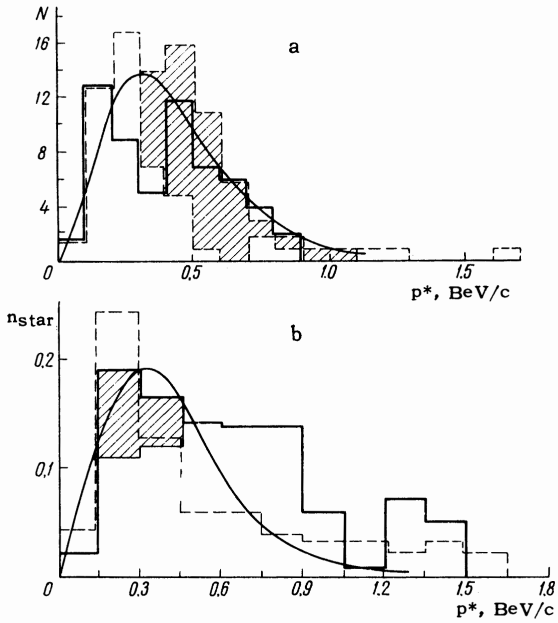

FIG. 5. Momentum spectra of π^+ and π^- mesons in different angular intervals: a–$60° \leq \theta^* \leq 120°$, solid line–$\pi^-$ ($N = 66$), broken line–π^+ ($N = 51$), shaded region–πp particles ($N = 40$); b–$\theta^* < 30°$, $\theta^* > 150°$, solid line–π^+ mesons, $\langle p^* \rangle_{\pi^+} = 0.63 \pm 0.03$ BeV/c; broken line–π^- mesons, $\langle p^* \rangle_{\pi^-} = 0.53 \pm 0.05$ BeV/c; shaded region–πp particles. The curve in both cases is a Planck function $cp^{*2}/\exp(\epsilon^*/kT - 1)$ for $kT = \mu c^2$; n_{star} is the number of particles in a single star.

Figure 5b shows the momentum spectra of π^+ and π^- mesons at small ($\theta^* < 30°$) and large ($\theta^* > 150°$) angles. It is evident that for momenta $p^* > 0.6$ BeV/c a noticeable excess is observed over the spectrum characteristic of "pionization," this excess occurring mainly for π^+ mesons. On the average the number of "excess" particles per interaction is small ($n_{\pi^+} = 0.35$, $n_{\pi^-} = 0.15$); however, the contribution of these particles to the total energy of charged mesons reaches roughly 50%.

The angular distributions of π mesons in the lab. system are shown in Fig. 6. Theoretical curve 1[7] corresponds to an isotropic angular distribution (in the system with $\gamma^* = 3.5$) with a Planck spectrum at a temperature μc^2. It is evident that this curve agrees satisfactorily with the experimental pion distributions both in stars of high multiplicity ($n \geq 7$) and in central interactions with any n, selected on the basis of the proton properties. In processes with measured multiplicity ($n = 4$–6) the anisotropic part is noticeably separated at angles $\leq 4°$ (i.e., $\leq 20°$ c.m.s.). Finally, for asymmetric three-prong stars, which can be interpreted as the result of peripheral, and in some cases coherent, production and three-particle decay of a nucleon isobar emitted forward, the angular distribution corresponds to the same thermal spectrum, but referred to a system moving with a Lorentz factor $\gamma \approx 11$ (curve 2 in Fig. 6).

The distributions in transverse momentum for protons and $\pi^{\pm}$ mesons for peripheral and central interactions are shown in Fig. 7. We can see that: 1) the transverse momenta of the protons are on

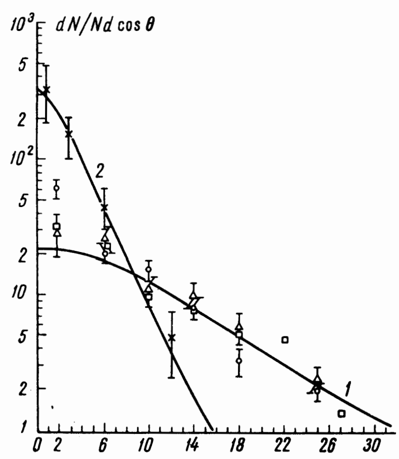

FIG. 6. Angular distributions of mesons (lab.) for different types of events: Δ–$n \geq 7$, □–central interactions, ○–$n = 4$–6, ×–$n = 3$ ($M_{eff} = 1.5$–1.7).

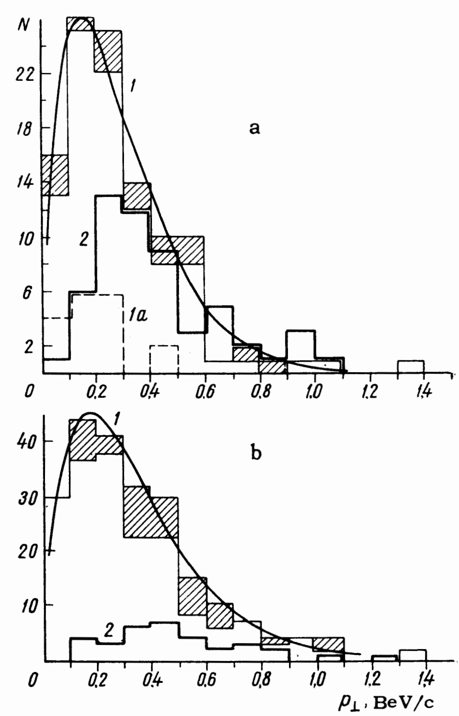

FIG. 7. Distribution of transverse momenta of π mesons (1) and protons (2): a–for peripheral interactions ($\theta^{p*} \leq 20°$, $\geq 160°$; $p^{p*} > 1$ BeV/c), average values–1–0.30 ± 0.02, 1a–0.20 ± 0.03, 2–0.42 ± 0.03 BeV/c; b–for central interactions ($\theta^{p*} = 20$–$160°$), average values–1–0.35 ± 0.03, 2–0.49 ± 0.05 BeV/c. 1a–distribution of π^+ mesons for $M_{eff}(p\pi^+) \leq 1.3$ BeV/c^2; curve—$p_\perp \exp(-2p_\perp/\langle p_\perp \rangle)$.

the average roughly 40% greater than those of the pions (this is evidently because [8] the proton carries away a larger part of the transverse momentum of the "parent" isobar), and 2) the transverse momenta of particles in peripheral and central interactions differ only slightly on the average; however, processes (mainly peripheral) apparently associated with formation of a very light isobar are characterized by already noticeably smaller transverse momenta of the π^+ mesons.

5. FLUCTUATIONS IN THE DISTRIBUTION OF ENERGY BETWEEN CHARGED AND NEUTRAL MESONS

In those cases (about 60% of the events) when the primary proton retains its charge after the interaction, we can determine the total energy released as neutral and charged mesons. Figure 8 shows distributions in the corresponding partial inelasticity coefficients K_{π^0} and $K_{\pi^\pm}$ (in the lab. system) for the two types of interactions.

It can be seen from Fig. 8a that in peripheral interactions with a total inelasticity coefficient $\geq 50\%$ there is a sharply unequal division of energy, specifically: in group I, $\bar{K}_{\pi^0} = 0.65$, $\bar{K}_{\pi^\pm} = 0.05$; in group II, $\bar{K}_{\pi^0} = 0.15$, $\bar{K}_{\pi^\pm} \approx 0.50$. A more detailed analysis of the interactions of group II shows that a considerable fraction (at least 50%) can in theory be associated with the production and three-particle decay of isobars with an effective mass $M_{\text{eff}}(p\pi^+\pi^-) = 1.5-1.7\ \text{BeV}/c^2$. We can therefore assume that the neutral decay modes of the same singly charged isobars $N_{1/2}^{*+}$ are responsible also for the large values of K_{π^0} in group I.

Analysis of the data of Fig. 8b shows that for processes of the nonperipheral type there is a practically symmetric division of energy between charged and neutral mesons, with comparatively large fluctuations (although not as large as in the preceding case). Thus, both in peripheral and nonperipheral interactions (not accompanied by charge exchange of the primary proton) the ratios of the "partial" inelasticity coefficients $\alpha = K_{\pi^\pm}/K_{\pi^0}$ are on the average close to unity for a dispersion of the quantity $\ln \alpha$, $D(\ln \alpha) = 2$, which in both cases corresponds to a "characteristic" difference of $K_{\pi^\pm}$ and K_{π^0} of roughly a factor of four. In the case of charge exchange, the situation changes sharply in the direction of dominance of energy release in the charged mesons. This means: 1) that in the final averaging over all interactions the quantity $\bar{\alpha}$ cannot greatly differ from the value expected on the basis of isotopic

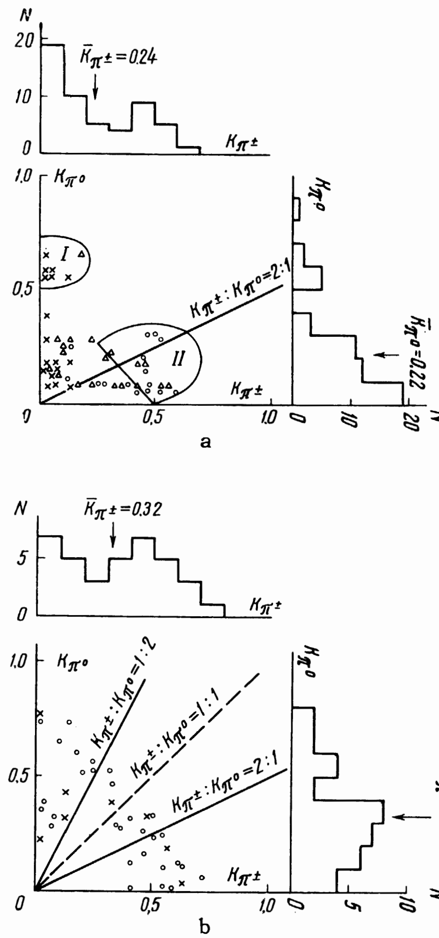

FIG. 8. Distribution in partial inelasticity coefficients for peripheral (a) and nonperipheral (b) interactions in the absence of charge exchange of the fast nucleon: o–$n_{\pi^\pm} = 3$, 4, 2p; Δ–$n_{\pi^\pm} = 2$, 2p; ×–$n_{\pi^\pm} = 0$, 1, 2p.

invariance, $\bar{\alpha} = 2$, and 2) that in the case of charge exchange the proton transfers its charge mainly to the energetically released mesons, whose origin we can associate, for example, with the decay of an isobar $N_{1/2}^{*+} \rightarrow n + \pi^+$.

As can be seen from the foregoing, the existence of rather complete information on the nature and kinematical characteristics of all (or almost all) charged secondary particles produced in quasinucleon interactions in photoemulsion, with a pulsed magnetic field, has permitted establishment of a number of nontrivial features of these processes. The most important of these, in our view, are:

a) Large fluctuations in the values of the three- and four-momenta lost by each of the interacting nucleons.

b) An appreciable positive excess of energetically released charged π mesons.

c) Large fluctuations in the distribution of energy between charged and neutral π mesons, apparently associated with the small number (1–2) of energetically released mesons.

Feature a), which is characterized also by a substantial correlation between the value of Δ^2 for nucleons, on the one hand, and the multiplicity and angular distribution of the mesons, on the other hand, can be interpreted from the point of view of differences in the degree of peripherality of the interactions and the possibility of approximate separation of the interactions into two extreme cases—one-meson exchange, and central interactions. Features b) and c) compel us to assume the existence of a substantial probability (tens of per cent) for excitation of nucleons to isobar states with masses which as a rule do not exceed 1.8 BeV/c^2.

For a final solution of this problem, investigations are necessary of the correlations between the kinematic characteristics of the nucleons and mesons. We propose to make this problem the subject of future work.

CONCLUSIONS

1. Use of photoemulsions in a pulsed magnetic field yields in most cases complete information on the momenta and emission angles of the secondary charged particles produced in nuclear interactions with energies of 20–25 BeV. This allows a study of a number of average characteristics and the corresponding fluctuations about the average, which are important for understanding the mechanism of the phenomenon and for verification of the corresponding theoretical concepts.

2. We have established comparatively simple criteria both for selection of interactions of primary particles with quasifree nucleons of complex nuclei in photoemulsion, and for the approximate separation of these interactions into two classes—peripheral and nonperipheral interactions.

3. It has been shown that the main part of the events which satisfy the criteria of a peripheral interaction are characterized by comparatively low multiplicity (on the average 1.5–2 charged mesons), appreciably anisotropic angular distributions of protons and (to a smaller degree) mesons, and large fluctuations in the transfer of energy to charged or neutral mesons.

4. We have established that the properties of the central interactions agree in the first approximation with the statistical theory, and that they are distinguished crudely by an isotropic angular distribution of protons and pions, and an equilibrium thermal spectrum of mesons of both signs corresponding to a temperature $kT = \mu c^2$.

5. The ratio of the energy release in charged ($K_{\pi^\pm}$) and neutral (K_{π^0}) mesons depends strongly on whether there is a change in the charge of the primary nucleon, which on the average is about unity in the absence of charge exchange, the spread around the average being characterized by a factor of four (in both directions).

6. A substantial charge asymmetry occurs in the energetically released π mesons. Together with the large fluctuations in the ratio of the energy release in charged and neutral mesons, this phenomenon serves as an indication of an important role of the process of nucleon isobar formation.

7. We have observed the existence of processes with a sharply asymmetric angular distribution, which essentially do not show up at all at primary energies of ~ 10 BeV and, possibly, are associated with the mechanism of coherent generation of particles in the complex nuclei of the emulsion.

In conclusion the authors express their deep gratitude to E. Dahl-Jensen (CERN) and E. Skrzypczak (Warsaw University) for their cooperation in obtaining the emulsions irradiated in the magnetic field, to the technician group for their remarkably conscientious performance of the time-consuming emulsion measurements, and to V. M. Maksimenko, Yu. A. Smorodin, E. L. Feĭnberg, D. S. Chernavskiĭ, and I. M. Dremin for discussion of the results.

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Translated by C. S. Robinson
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