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THE NUCLEAR MATTER MODIFICATION AT INTERMEDIATE ENERGIES

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Рассматривается гипотеза о взаимодействии адронов с веществом ядер, где, как предполагается, наряду с нуклонами ядра в качестве мишени для налетающего адрона могут служить известные частицы, резонансы и, возможно, кварки. Проверка гипотезы была проведена на основе экспериментальных данных о CC-, dC-, CTa-, pC-взаимодействиях при 4,2 ГэВ/с/нуклон. Кроме того, анализ рождения $\Delta(1232)\,P_{33}$-, $N(1440)\,P_{11}$-изобар и ρ-мезонов в этих же взаимодействиях обнаруживает некоторое подавление их образования в рассматриваемых ядрах по сравнению с взаимодействиями на нуклонах, что, возможно, связано с образованием в ядре плотной «резонансной» материи.

A new hypothesis on hadron interactions with nuclear matter is discussed. It is supossed that the well-known particles and resonances as well as nucleons might serve as a target in the nucleus. The experimental data on CC, dC, CTa, pC interactions at 4.2 GeV/c/nucleon are used for the testing of the hypothesis. A certain suppression of production of the $\Delta(1232)\,P_{33}$, $(1440)\,P_{11}$ isobars and ρ mesons is observed in these interactions, compared to the nucleon–nucleon interactions. It may be caused by the formation of the so-called dense «resonance matter» in the nucleus. Special experiments with multiple rising statistics are required to examine the hypothesis.

INTRODUCTION

During 60–70s of the last century it was accepted that the difference between the free nucleon and the nucleon inside a nucleus is very small. Naturally, the nucleons are bound in the nucleus, but the binding energy is not great and it may affect only the value of the total interaction energy. A lot of models were developed to describe cascade mechanisms of hadron interactions in the nuclear matter.

A few years later, the anomalous number of hadrons with high momentum were registered in hadron–nucleus collisions at LHE and ITEPH, that contradicts the kinematics of the hadron–nucleon interactions. To explain the effect, A. M. Baldin [1] supposed that some nuclei interactions could be descended on a group of nucleons, but the nucleons do not lose their identity in the nuclear matter. Hence, the name «cumulative» appeared for the produced particles with «wrong» kinematics.

On the other hand, the well-known particles — mesons and resonances, realizing the interactions between nucleons, might attend virtually in the nuclei. And, finally, the particles deconfined in nuclei lead to [2] the presence of a small part of «free» quarks and gluons in the nuclei. The same quarks, as well as mesons and resonances may be examined as target objects inside the nucleus (Sec. 1).

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The problem, how the properties of hadrons in the nuclear matter change in comparison with their free state, attracts a great deal of attention. Yet it is known that the nucleon mass m_N^* in nuclear environment is not equal to m_N, although there is no consent about its exact value. Quite approximately it would be accepted that in the middle of the nuclei (where nuclear density is ρ_0) m_N^* $(\rho_0)/m_N \approx 0.8$. The remarkable consequence from this estimation is [3] that the quark condensate has dropped by $\sim$ 50 % in the middle of nuclei. Other particles also change their masses, and the difference between «free mass» and the «bound mass» increases with the particle mass.

The energy E ($E \geqslant m_N$, where m_N is a nucleon mass) coming in the nuclei can strongly modify the nuclear matter in some part of the nucleus, or in the whole one, changing the particle parameters. But the search for free particles and resonances, with modified parameters, has not been successful so far.

While the high-energy colliders try to probe the hot quark–gluon plasma at the low net baryon density, the matter, possibly the quark-matter, may be produced at rather high baryon density and moderate temperature on the fixed target at the Nuclotron. Reproduction of hadron distributions on the base of central Si + A collisions data at the AGS at freeze-out shows baryon densities exceeding the nuclear matter density five times for a typically extended time of about 5 fm/c [4, 5].

Intensive production or «dressing» of resonances in such conditions increase the matter density even more. Metag [6] on the base of calculations of S. A. Bass et al. [7] and S. Teis et al. [8] concluded that for 30 % of nucleon resonance population at 2 $A \cdot$GeV, the mean distance between separate constituents becomes $\sim$ 2 fm attaining the boundary in strong interactions. Thus the density of resonances is so high that they start interacting with each other, and then we can speak about these systems as of the resonance matter.

The resonances are produced intensively in elementary particle interactions at 2–4 GeV, whereas in nuclear–nuclear interactions the resonances are hardly found at the same energies. What is the reason? We shall try to give the answer in Sec. 2.

1. MODIFICATION OF THE «TARGET»

So, the first hypothesis for testing was the following one: inside one nucleus there are a lot of known objects ready to serve as a target for incident particles. So, the experimental data [10] on CC, dC, CTa, pC interactions at 4.2 GeV/c/nucleon were analyzed.

1.1. Method of Testing. The way of target investigation was prompted by a very handy target–mass analysis, proposed 40 years ago by N. G. Birger and Yu. A. Smorodin [9]. Following [9] we write the target–mass M_t as:

$$M_t = \Sigma_i (E_i - p_{\mathrm{IIi}}) - \epsilon_0. \tag{1}$$

Here, E_i, p_{IIi} are the energy and the longitudinal momentum of the particles produced in the interaction; $(i = 3, \ldots (n_{\mathrm{ch}} + 2))$, $(\epsilon_0 = E_1 - p_1)$, E_1, p_1 determine the initial energy and momentum.

In the case of the moving target, M_t distribution looks like a peak at

$$M_{\mathrm{eff}} + \langle T_{\mathrm{eff}} - U_{\mathrm{eff}} \rangle, \tag{2}$$

where $T_{\rm eff}$ and $U_{\rm eff}$ are the kinetic and potential energies of the interacting objects. The width is determined by the target Fermi-momenta inside the nucleus $p_{\rm eff\|}$, and $\langle p_{\rm eff\|}\rangle = 0$.

The invariant target mass square is

$$M_x^2 = (\Sigma P_i - P_1)^2. \tag{3}$$

Here P_1 and P_i, the four-momenta of the initial and produced particles, were also used for the testing.

1.2. Background Reduction

(i) Indeed, in the propane bubble chamber the distinction of protons from π^+ mesons was successful to the momentum of ~ 0.7 GeV/c only. At the higher momenta the identification was made by the statistic weight, w_p, [11]. To reduce the neutron contribution, the events with only one well-identified proton were taken into account.

(ii) Bad measured tracks, the lost particles, as well as the events containing unambiguously identified particles were taken into account with the help of the corresponding weights [11].

(iii) Obviously, the proposed consideration requires all particles to be registered thoroughly. To exclude the events, in which neutral particles were not registered, as well as to share out the effect, the test of transverse momentum compensation was applied. The request of the transverse momentum compensation means that a sum of transverse momentum components p_{xi} and p_{zi} does not exceed a small value, designated as the p_x and p_z limits simultaneously. Figure 1 shows transverse momenta of all charged particles produced in CC interactions at 4.2 GeV/c [10]. The events from the narrow stripes were taken for the further analysis.

(iv) *The missing-mass method.* The method was used for the separation of the events which were suitable to the definite process kinematics. The missing mass square was written as:

$$M_{\rm mis}^2 = (\Sigma P_i - (P_1 + P_2))^2, \tag{4}$$

or:

$$M_{\rm mis}^2 = ((E_1 + M_{\rm targ}) - \Sigma E_i)^2 - (\mathbf{p}_1 - \Sigma \mathbf{p}_i)^2, \tag{5}$$

where P_1, P_2 are the four-momenta of the initial particles; P_i is the four-momentum of the produced particles; also E_1, $\mathbf{p}_1$ and E_i, $\mathbf{p}_i$ are the energies and momenta of the initial and produced particles, respectively; $M_{\rm targ}$ is the mass of the object, on which the interaction took place. The width of the maximum at $M_{\rm mis}^2 = 0$ is determined by target Fermi-momenta, by the measured errors and, of course, by a natural width of resonance, if it occurs to be a target.

Separation of definite reactions (CC and Cp from C-C_3H_8 or pC and pp interactions from p-C_3H_8) was made by the weights, calculated in [11] on the base of the known inelastic cross section and some additional criteria. Figure 2 demonstrates the spectra of some separate channels. All necessary weights are used here and the nucleon mass is taken as $M_{\rm targ}$. Further, the missing mass spectra, received in different assumptions about $M_{\rm targ}$ value: $M_{\rm targ} = M_N$, M_ρ, M_π, and $\sim M_q$, were calculated. The events having the $M_{\rm mis}^2$ values inside the narrow region near zero of the appropriate distribution correspond to the process, which is searched for.

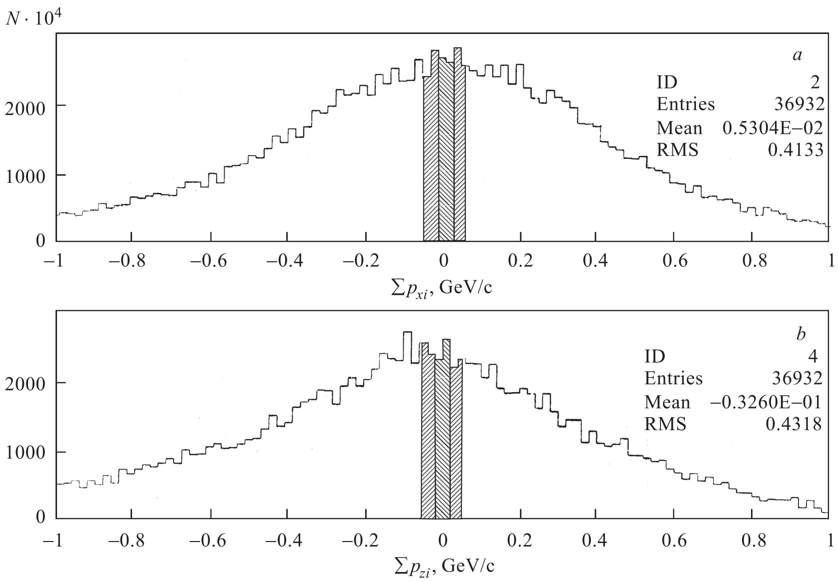

Fig. 1. Summary transverse-momentum components $\sum p_{xi}$ (*a*) and $\sum p_{zi}$ (*b*) for all measured CC interactions. The request of the transverse momentum compensation means that the $\sum p_{xi}$ and $\sum p_{zi}$ do not exceed any small value simultaneously — only the events from the narrow stripes of $\sum p_{xi}$ and $\sum p_{zi}$ are taken for the analysis

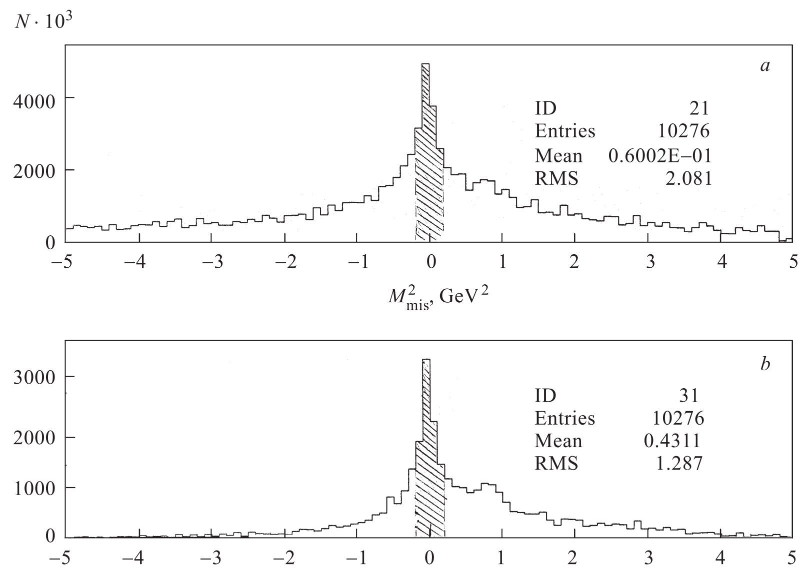

Fig. 2. Missing-mass spectrum $M^2_{\rm mis}$ for pC (*a*), pC and pp interactions (*b*) from p-Pr with weights w_t and w_p. The mass of the target is: $M_{\rm targ} = M_N$

1.3. «Targets» Inside the Target. The mass–targets M_t for different demands on transverse momentum balance are shown in Fig. 3, *a, b, c, d.* All criteria besides «missing mass»

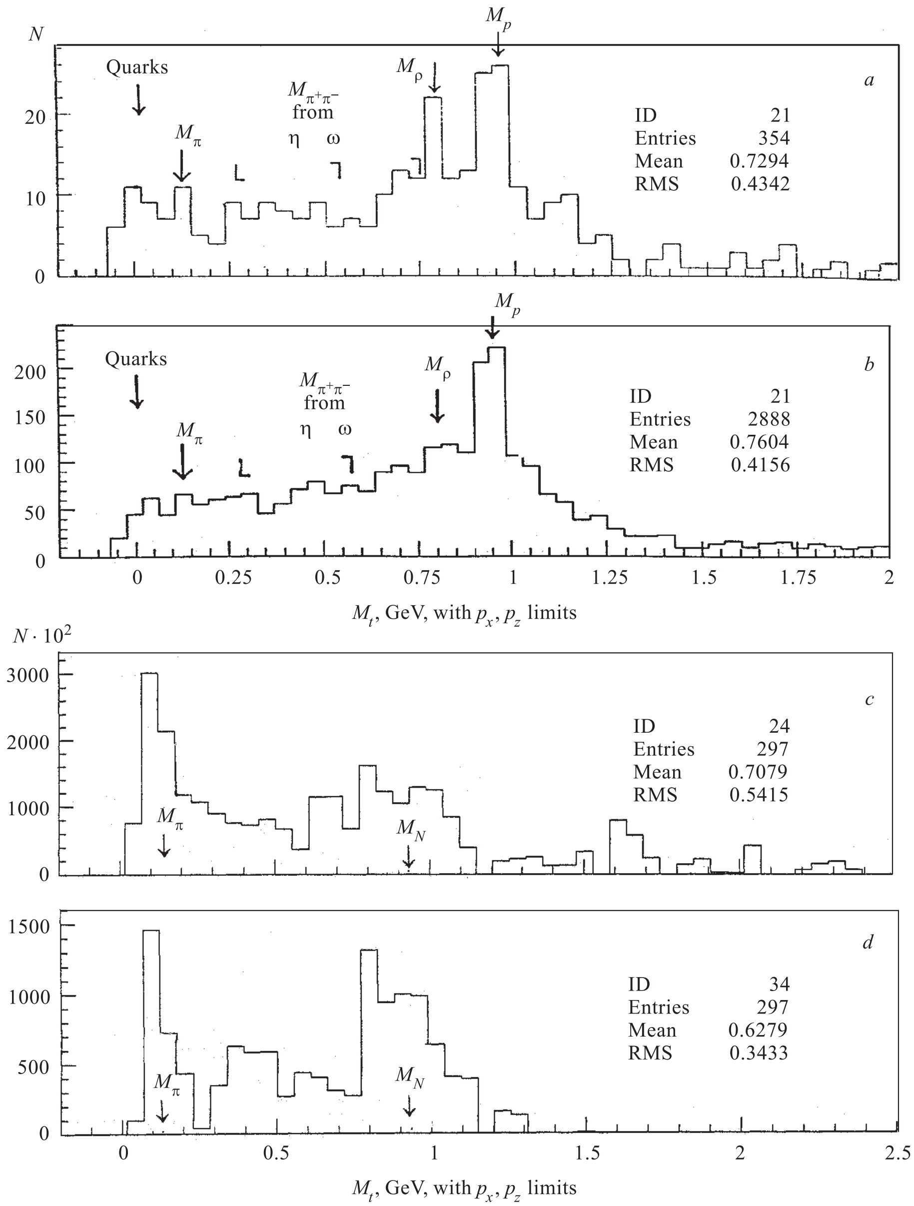

Fig. 3. Mass–target (M_t) distributions with transverse momentum balance: *a*) $\Delta \sum p_t = \mathrm{sqrt}\,((\sum p_{xi})^2 + (\sum p_{zi})^2) = \pm 70$ MeV/c; *b–d*) $\Delta \sum p_t = \mathrm{sqrt}\,((\sum p_{xi})^2 + (\sum p_{zi})^2) = \pm 140$ MeV/c. C-C_3H_8 interactions without weights (*a, b*); *p*C (*c*) and *pp* interactions (*d*) from *p*-C_3H_8 interactions with weights w_t, w_p, and w_e

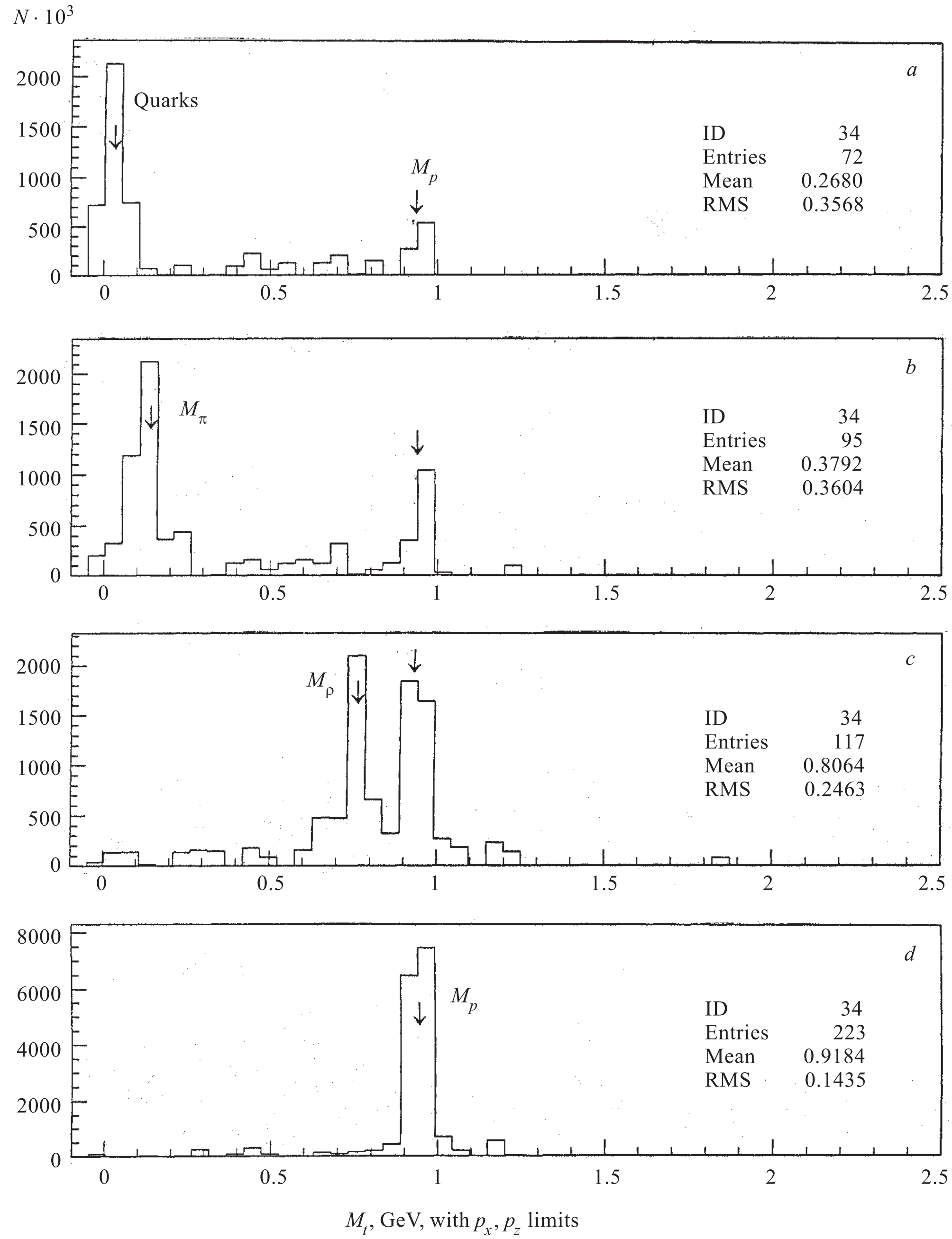

Fig. 4. Mass–target (M_t) distributions of the candidates for separate reactions of protons with quarks (*a*), π mesons (*b*), ρ mesons (*c*) and nucleons (*d*) for Cp interactions

were used here. As seen from the figure, the nucleon was used as a target approximately in 30 % of the events, a lot of them ($\sim 20\,\%$) have the mass–target less than a proton mass. For

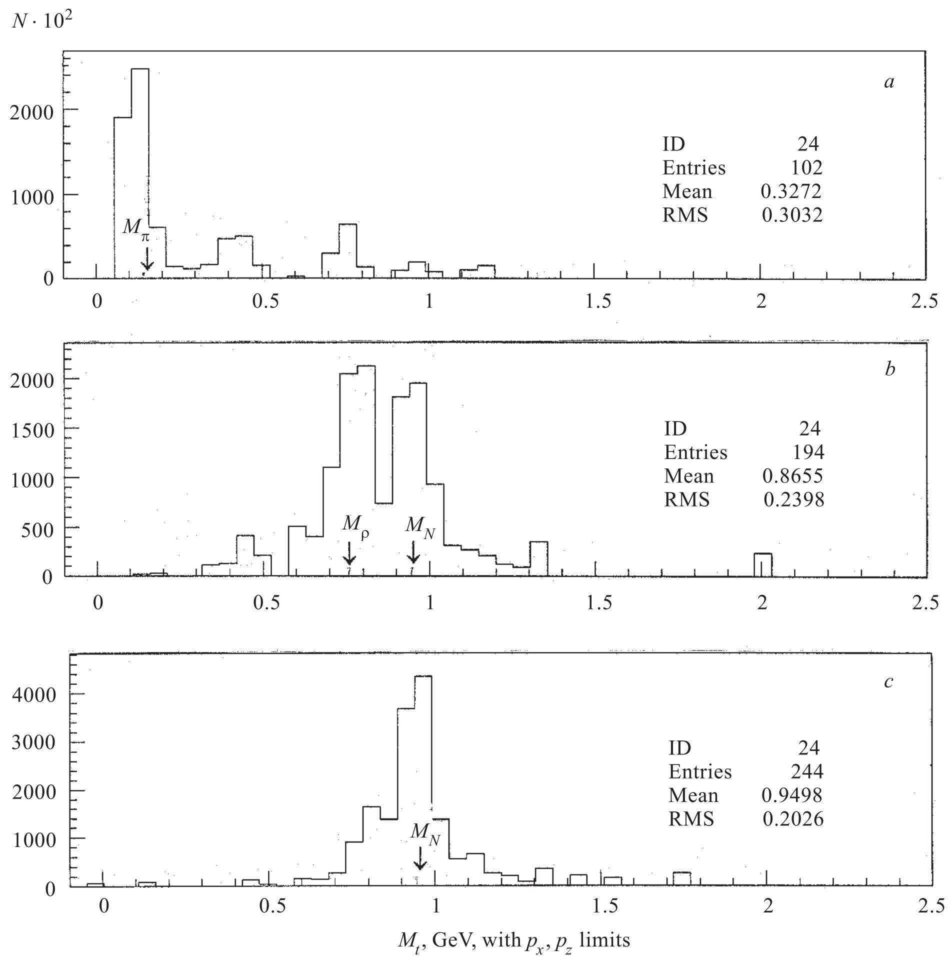

Fig. 5. Mass–target (M_t) distributions of the candidates for separate reactions of protons with π mesons (a), ρ mesons (b) and nucleons (c) for pC interactions

those last events the separate groups may be identified with the ones where quarks or π mesons, pairs $\pi^+\pi^-$, rest from ω, η mesons, or ρ mesons, are used as a target.

Further the missing-mass method (iv) was applied to Cp, pC, and pp interactions. The results are shown in Figs. 4, 5, 6. The groups of events where initial particles interacted with objects having the mass equal or less than the nucleon mass, are separated clearly.

M_x^2 distributions demonstrate the same effects, but they are not so descriptive as at the M_t spectra.

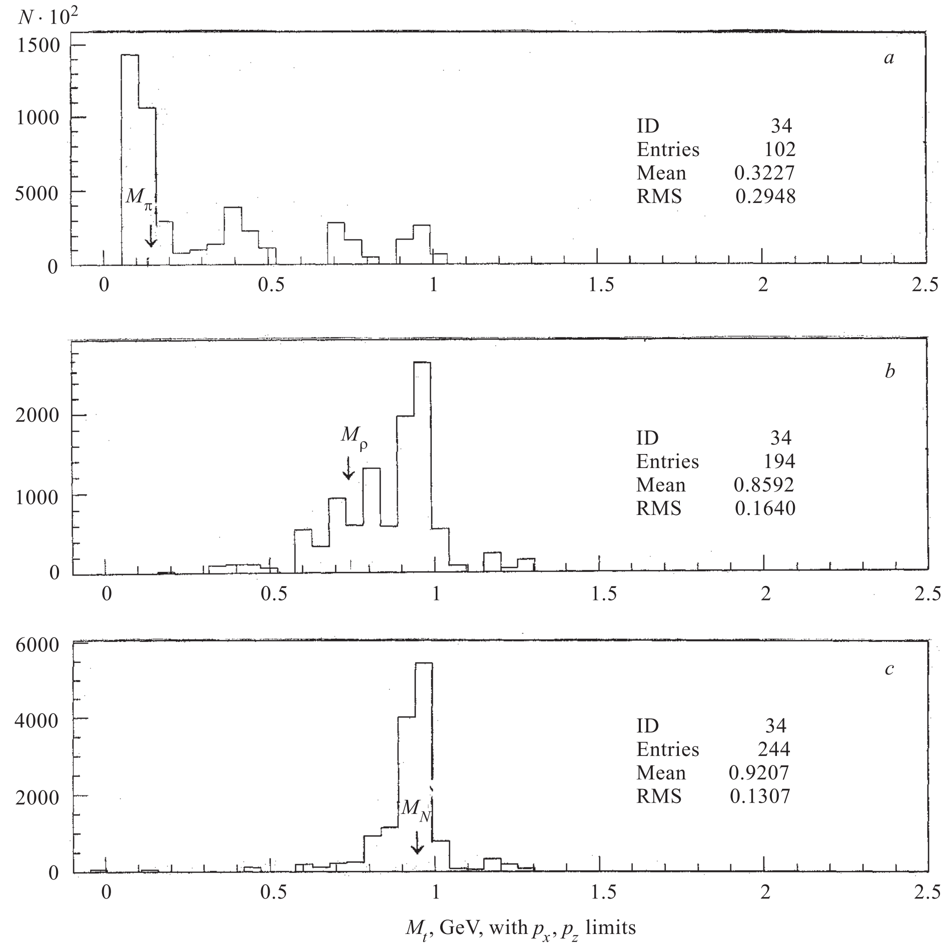

Fig. 6. The same as in Fig. 5 for *pp* interactions

2. RESONANCE MATTER — DOES IT EXIST?

The energy of interactions puts in action the resonances, already existing in the nucleus, or excites the new ones. If the region of the produced resonances occupies a small value, then, perhaps, in that region the dense resonance matter is produced.

2.1. Resonance Source Dimensions. The question is: what is the dimension of the resonance source $R_{\rm sp}$ in the nuclei determined in experiments?

Many of the particles produced can be the result of resonance decay. Thus, the measuring radii $R_{\rm sp}$ or $R_{\rm tr}$ include, besides dimensions of the original producing region, the decay range of intervening particle, the path of the particle to eventual secondary interactions, etc. Therefore the $R_{\rm sp}$ or $R_{\rm tr}$, obtained up to now are not exact values.

The interference effect between identical particles is used to measure the source dimensions. But the resonances prefer to decay into nonidentical particles.

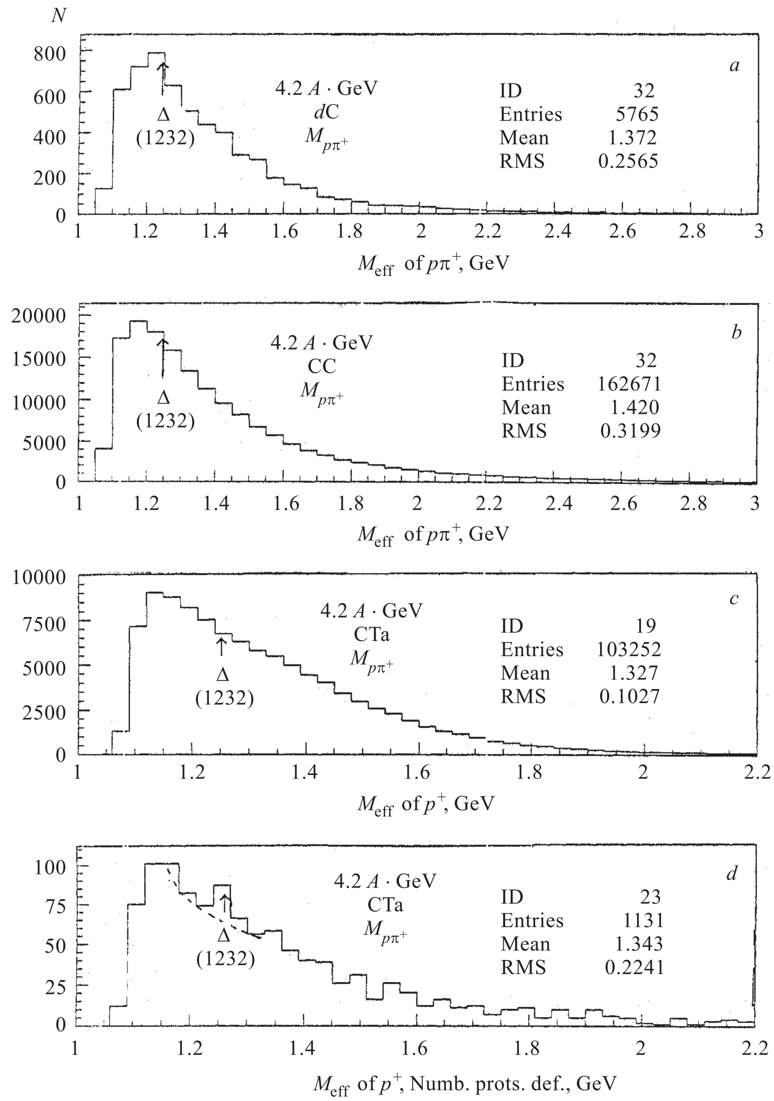

Fig. 7. Effective mass ($M_{p\pi+}$) distributions for nuclear–nuclear interactions at 4.2 GeV: *a*) for *d*C interactions; *b*) for CC interactions; *c*) for CTa interactions; *d*) for CTa events with multiplicities of charged particles $n_s < 6$

In the case, when one of the two identical particles comes directly from its source and the other one comes from the decay of intervening particle (or resonance), the correlation between these particles is determined by the intervening particle decay range L and by the dimension R of the production region.

Proposed by Podgoretsky and Lednitsky [12] and by Grassberger [12], the method of $R_{\rm sp}$ or $R_{\rm tr}$ determination with the use of decay range (L), was tested in [14] for Z-bosons production and decay into muons in CMS set-up. The results have shown that the interference effects, coming from Z bosons, could be clearly determined, if the source radius of produced Z bosons is small.

Similar research may be applicable to ϕ, η, ρ mesons and Δ resonances at the Nuclotron energies. New putting-up of the precise experiment is necessary. A long base ($\sim$ 50 m) would guarantee precise measurements of moments and angles of both identical particles.

2.2. Resonance Production in Nuclear–Nuclear Interactions at 4.2 $A\cdot$GeV. Middle numbers of positive and negative mesons produced in carbon–carbon interactions are nearly two and seven times correspondingly greater than the ones, produced in proton–proton interactions. Usually the increase of the charged particle multiplicity, particularly π mesons, happens due to the plenty of resonances. They are effectively produced, apparently in all types of interactions considered here. So, the observation of abundance of a small π-meson p_t momentum confirms this approval [15].

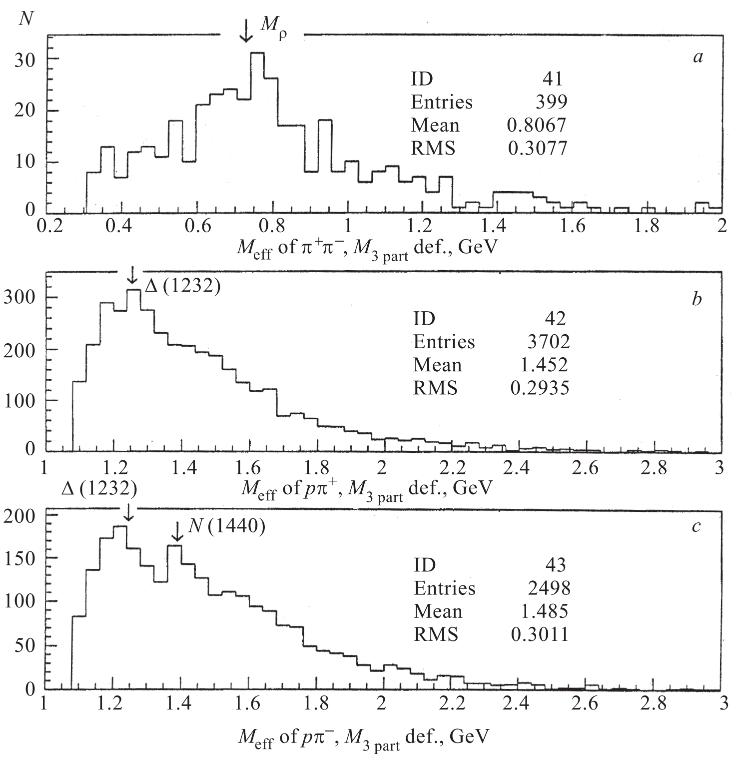

Fig. 8. Effective mass distributions for *pp* quasi-interactions shared out from C-C_3H_8 interactions on the base of M_t spectrum and of summary charge of all produced particles analysis. *a*) $M_{\pi^+\pi^-}$; *b*) $M_{p\pi^+}$; *c*) $M_{p\pi^-}$. The meaning of the $M_{\rm 3part^+}$ restriction consists in the following: all two-particle effective mass values coming from three-particle combinations «decays» having the effective mass less than minimal mass (the boundary for the «correspondent reaction») are rejected. The «correspondent reaction» is the reaction which produces the resonance being searched for

The spectra of effective-mass $\pi^+\pi^-$ mesons and $p\pi^+$ particles indicate the presence of the Δ^+ isobars and, maybe, of ρ mesons in dC interactions. They disappear, however, in CC and CTa interactions with high charge particle multiplicity entirely (Fig. 7). Here the combinatorial background prevented to observation of the resonances. To reduce the number of bad combinations, the analysis of many-particle effective-mass spectra was applied [16]. In this case, as is seen from Figs. 8, 9, the situation improves significantly.

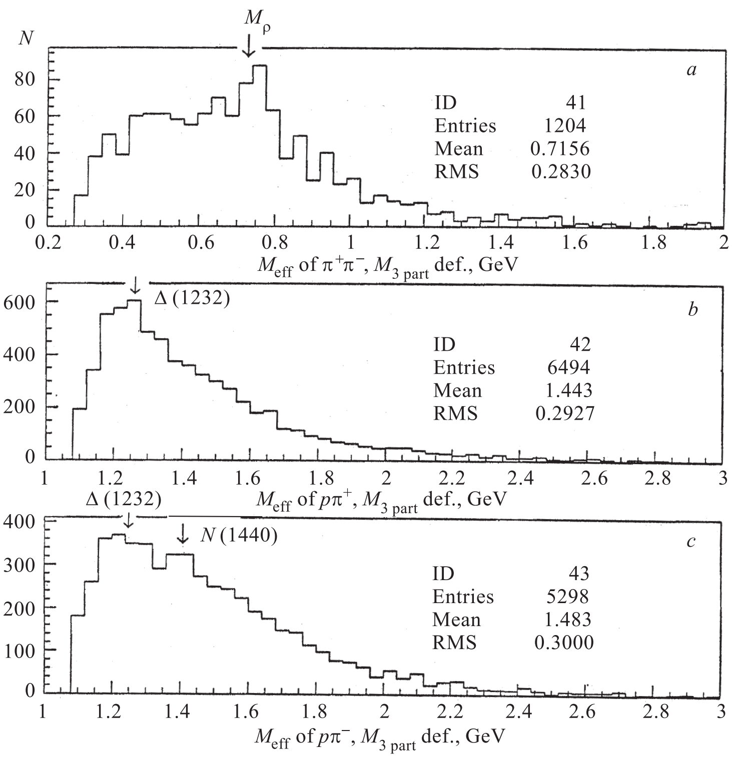

Fig. 9. Effective mass distributions for CC interactions at 4.2 $A \cdot$ GeV/n. See description of Fig. 8 for details

CONCLUSION

In consequence of some expounded speculations we can conclude that the hypothesis on the presence in the nucleus of the objects other than nucleons, which can serve as the target, has some confirmation. At 4.2 GeV/c/nucleon the results for CC interactions do not contradict the following evidence: initial nuclear collisions between particles, having a mass less than the nucleon one, may happen in a large part ($R \sim 20\,\%$) of all events. Many known resonances or particles and, possibly, quarks can be used as the target. Separate groups of such events are clearly seen.

The production of the so-called cumulative particles [1] can be explained by the interaction of the incident particle with heavy resonances. Heavy resonances have the great binding energy, and it may change its mass in rather wide boundaries.

The testing of the second hypothesis — resonance production suppressing in nuclear–nuclear interaction — has not obtained full confirmation.

But, the $\Delta(1232)\,P_{33}$ and $N(1440)\,P_{11}$ isobars and ρ mesons are produced in the CC and CTa interactions with the same intensity as in nucleon–nucleon interactions. Hence it follows that some suppression exists, particularly for more «central» events (with high $N_{\rm part}$).

The nature of this suppression is not clear so far. It is known that the secondary interactions may suppress resonances not more than by 20–30 %. It is necessary to perform a more detailed study of this problem. Probably, the resonance matter model with anomalously high cross sections of the interaction between constituents in superdense matter will help to perform it. However, obviously the development of such researches requires to enlarge statistics.

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