CENTRAL INSTITUTE OF PHYSICS
CENTRE OF ASTRONOMY AND SPACE SCIENCES
Bucharest, P.O.Box MG-6, ROMANIA

[*] *University of Bucharest, Department of Nuclear Physics, Bucharest, P.O.Box MG-6, Romania*

[**] *Institute of Physics and Nuclear Engineering, Bucharest, P.O.Box MG-6, Romania*

[***] *Centre of Astronomy and Space Sciences, Bucharest, P.O. Box MG-6, Romania*

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Multi-Quark Effects in High Energy Nucleon-Nucleon and Nucleus-Nucleus Collisions

C. Beşliu[*], I. Caraciuc[*], F. Cotorobai[**], A. Jipa[*], A. Olariu[*], D. Pantea[**], L. Popa[**], V. Popa[***], R. Topor-Pop[*], V. Topor-Pop[***]

ABSTRACT. Recent data obtained in two experiments performed in the framework of the Bucharest-Dubna collaboration are presented i.e.: the observation of narrow dibaryonic resonances in neutron-proton interactions in 1m HBC at different momenta of incident neutrons in the range 1-5 GeV/c, and the cumulative production of negative pions in nucleus-nucleus interactions in SKM-200 streamer chamber at 4.5 GeV/c. The interpretation of these results in terms of multi-quark states is discussed.

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INTRODUCTION

Multiquark systems, i.e. colour singlet $q^n\bar{q}^m$ combinations with $n+m > 3$ are new objects predicted in different quark models which incorporate the QCD properties of short distance asymptotic freedom and long distance confinement. Their experimental manifestation can be observed for example in hadronic spectroscopy as multiquark resonances (eg.g. $q^4\bar{q}$ - mezobaryons, q^6 - dibaryons, etc.), or in relativistic nuclear physics in such phenomena as the cumulative effect. A study of multiquark systems can be made in scattering experiments in hadron and nuclear physics at a small GeV allowing to test these QCD - based models for hadrons and perhaps to obtain new information on the dynamics at quark level.

The search for dibaryonic resonances has aroused lately a considerable interest. This was generated mainly by the results obtained at Argonne in experiments with polarised protons (see for a review Yokosawa (1980)). Indications for dibaryonic resonances result from two different types of experiments:

i) experiments using electronic methods to investigate the excitation function of certain observables related to nucleon-nucleon scattering: σ_{tot}, $\Delta\sigma_T$, $\Delta\sigma_L$ and different spin parameters. Additional information was obtained from the investigation of the $\pi d \rightarrow \pi d$, $pp \rightarrow \pi d$, $\gamma d \rightarrow pn$ and $\pi d \rightarrow \pi pn$ processes. Interpreting these data by phase analysis has led to conclude on the existence of dibaryon resonances. The possible candidates fro dibaryon resonances have generally large widths (around 150 MeV/c^2). The resonance-like behaviour observed in the Argand plot of some N-N partial wave amplitudes is not exempt from ambiguity. According to some authors such as Kloet and others (1983), a loop in the Argand plot can be generated by the NΔ box diagram without existence of any dibaryon resonance. A review of the current state of such experiments has been provided by Makarov (1984) and Locher and coworkers (1985).

ii) experiments concerned with peak hunting in the effective mass of the two nucleon systems. In these experiments, where electronic technique (see Tatischeff (1985a)), or bubble chambers (Siemiarczuk and others (1983, 1984)) are employed, there are nuclear collisions that provide the data. In these experiments, narrow peaks ($\Gamma < 20$ MeV/c^2) are reported, but their interpretation is complicated by the possible occurrence of nuclear effects (for example see Dolidze (1986)). In a recent paper of Tatischeff

(1985b), a review of the latest results concerning the observation of narrow dibaryons is given. Our experiment used the 1 m HBC to study exclusive channels in neutron-proton reactions. The main advantage of such an experiment is that it dwells in the direct observation of dibaryon resonances as narrow peaks of the pp effective mass distribution in a clean nucleon-nucleon reaction rather in a nuclear one.

In the field of relativistic nucleus-nucleus collisions (mainly the central ones) a cumulative production of particles (Baldin 1980, 1985) which consist in the production of secondary particles with kinematical characteristics outside the limits allowed by the 4-momentum conservation for nucleon-nucleon interactions can be found among the consequences of multiquark clusterisation effects. The explanation of such production processes is based on the assumption that actual targets are not simple collections of nucleons, but multiquark clusters generated by the nuclear impact. The use of large and trigerable streamer chambers in experiments looking for such phenomena is very suitable.

EVIDENCE FOR NARROW DIBARYONS IN NEUTRON-PROTON INTERACTIONS

The 1 m HBC from JINR Dubna was irradiated with quasi-monochromatic ($\Delta p/p \lesssim 3\%$) neutron beams of the incident momentum in the range of 1-5 GeV/c: 1,25, 1.43, 1.73, 2.23, 3.10, 3.83, 4.35 and 5.10 GeV/c. We report here results obtained at 1.25, 2.23 and 5.1 GeV/c in the search for narrow dibaryons.

The neutron beams were obtained by the stripping on an internal Al target of the deuterons accelerated at the JINR Dubna synchrophasotron. The realisation of the neutron beam and the conditions of the bubble chamber irradiation are described elsewere (Gasparyan and others (1977)). The quasi-monochromaticity and the very good collimation of the neutron beam allowed us to use, instead of the measured momentum of the incident neutron (which is not seen in the bubble chamber), the average value of the beam momentum determined by Gasparian and coworkers (1977) and hence work in the same conditions for the kinematical fit as in the charged beam case.

The separation of reaction channels and the determination of their cross-sections is described in Besliu and others (1986). At 1.25 GeV/c the reaction $np \rightarrow pp\pi^-$ ($\sigma = 0.89 \pm 0.15$ mb) was studied. At this energy, in three prong interactions, just one more channel opens: $np \to pp\pi^-\pi^0$, but its cross section is negligible because the incident energy is very close to the threshold of this channel. This ensures a high purity of the experimental sample of the $np \to pp\pi^-$ events. In Fig. 1.a, the effective mass distribution of the two final protons was plotted. As it can be noticed, this distribution exhibits a narrow peak around 1.935 GeV/c^2.

Assuming that this peak is due to a resonance, the effective mass distribution was fitted to a theoretical function including two terms: a Breit-Wigner function describing the resonance and a smooth function describing the background. For this we chose a three-parameter function

$$\Gamma(M) = (M-M_1)^{\alpha}(M_2-M)^{\beta} e^{a(M-M_1)}$$

M being the current value of the two-proton effective mass, M_1 and M_2 - the limits of the mass range employed for fitting ($M_1 = 1.877$, $M_2 = 2.050$ GeV/c^2). To determine the unknown parameters, the maximum - likelihood method was employed and the following values of the Breit-Wigner function parameters were obtained: $m_0 = 1.936 \pm 0.002$ GeV/c^2 and $\Gamma_0 = 0.007 \pm 0.005$ GeV/c^2. From the weight of the Breit-Wigner function in the fit and the total cross section of the $np \to pp\pi^-$ reaction, the value of the cross-section for the resonance was determined: $\sigma = 46.7 \pm 22.8$ ub. Among the results of the fit, we notice the very low value ($\Gamma_0 = 7 \pm 5$ MeV/c^2) of the Breit-Wigner function width. The effect of the experimental resolution on the observed width was estimated by constructing the resolution function for the effective mass of the two protons for events having $1.930 \leq M \leq 1.940$ GeV/c^2. Using the width of the resolution function $\Gamma_{res} = 6$ MeV/c^2, a rough estimate of the upper bound of the natural width of the observed peak $\Gamma_{nat} \leq 6$ MeV/c^2 is obtained.

A natural explanation of the observed peak relies on a dibaryon resonance produced by a one-baryon exchange mechanism, corresponding to diagram in Fig. 2. To prove this, the effective mass distribution of the two-proton system was plotted using kinematical cutting criteria to select the one-baryon exchange. The following criterion was used:

$$t_{n-\pi^-} \geq -0.45 \ (\mathrm{GeV/c})^2$$

where $t_{n-\pi^-}$ is the 4-momentum transfer between the incident neutron and the final π^- meson. In the new effective mass distribution (Fig. 1b), a narrow peak can be observed, positioned at the same value as in the previous fit ($m_0 = 1.936$ GeV/c^2). Again in this case, the distribution has been fitted using a Breit-Wigner function and a background curve derived by phase space calculations as exposed by Beşliu and others (1983). If we take into account the effects of resolution, the results are also in agreement with $\Gamma_{nat} \leq 6$ MeV/c^2 for the natural width of the resonance. The value of the cross-section $\sigma = 38.6 \pm 11.0$ μb is consistent, within the limits of errors, with the value obtained from the full distribution in Fig. 1a.

We can conclude that in the *reaction* $np \to pp\pi^-$ at 1.25 GeV/c a narrow dibaryonic resonance was observed, whose production mechanism is dominated by baryon exchange.

In a recent paper of Beşliu and others (1985a), we reported the observation of a new narrow peak in the pp invariant mass distributions for other two values of the incident neutron momenta: 2.23 and 5.1 GeV/c. In Fig. 3, the peak seen in the $np \to pp\pi^-$ at 2.23 GeV/c reaction is indicated. The fit with Breit-Wigner and the background function which included a 85% contribution from the OPER model and a 15% from the diffractive production of the $N_{1/2}^*$ (1.470) resonance have given $M = 1.965 \pm 0.002$ GeV/c^2 for the mass, $\Gamma = 9.0 \pm 2.0$ MeV/c^2 for the experimental width and $\sigma = 48.0 \pm$ $\pm$ 14.0 μb for the cross-section. The probability for the peak to be a statistical effect was $P = 2.0\ 10^{-3}$. This narrow peak, with the same mass and width, is seen in Fig. 4 in the pp invariant mass distribution from another reaction: $np \to pp\pi^+\pi^-\pi^-\pi^0$ at 5,1 GeV/c. Its parameters estimated from the fit are $M = 1.965 \pm$ $\pm\ 0.003$ GeV/c^2, $\Gamma = 11.0 \pm 4.0$ MeV/c^2 and the production cross-section is $\sigma = 8.1 \pm 1.8$ μb.

We estimated the probability for a statistical fluctuation at 1.965 GeV/c^2 in this distribution, $P = 1.2\ 10^{-4}$ and also simultaneously in both distributions in Fig. 3 and 4, $P = 2.5\ 10^{-7}$. Other experiments (Tatischeff, 1987 and references therein) give also evidence for these dibaryon resonances. Non-observation of peaks at the above energy values in the total pp and np cross sections could be explained by the narrowness of these resonances. The values which were estimated fro the widths are affected by experimental resolution and the natural widths can be of the order of or somewhat below 1 MeV/c.

The study of the pp invariant mass spectrum from the $np \rightarrow pp\pi^+\pi^-\pi^-$ channel at 5.1 GeV/c has shown three enhancements (four standard deviations over the Monte-Carlo background) corresponding to 1.971 ± 0.007, 2.051 ± 0.005 and 2.138 ± 0.012 GeV/c^2 with widths around 10 MeV/c^2. We have also obtained a clear peak in the np invariant mass spectrum (over five standard deviations) from the $np \rightarrow np\pi^+\pi^+\pi^-\pi^-$ reaction, at the same incident momentum, which corresponds to a mass of $M = 2.124 \pm 0.002$ GeV/c^2 and a fitted width $\Gamma_{exp} = 3.4 \pm 2.7$ MeV/c^2, being in good agreement with the dibaryon candidate reported by Tatisceff and others, 1986. Our spectrum is presented in Fig. 5. Other maxima with lower statistical significance can be seen, at values of the invariant mass compatible to the values claimed by Tatischeff in the same paper (Tatischeff and others, 1986).

A common way to understand the existence of these narrow dibaryons the mass below the pion production threshold value $(2M_N + m_\pi)$ is to consider them as six-quark states confined in a bag. However, the present calculations in the frame of spherical approximation of the MIT bag models cannot reproduce the value of masses and widths. Additional hypotheses must be made. In a previous paper (Besliu and coworkers, 1985a), we discussed the interpretation of Baldin and Kaidalov of narrow dibaryons as isospin $I = 2$ resonances. Their mass being under pion production threshold, they are stable against strong decay. The mechanism of production and their possible electromagnetic decays are plotted in the diagrams of Fig. 6. The experimental signature of this process would be the observation of γ-quanta with energy $E_\gamma \leq 40$ MeV and work is in progress to search for them. A recent experiment (Tatischeff, 1987) seems to be in disagreement with the $I = 2$ assignment.

Another possible explanation is to consider the small width as a manifestation of the strong centrifugal barrier effect. In this scheme, the bags are deformed and the spherical approximation is no longer valid. To test this hypothesis, the spin determination of dibaryons is essential.

Structures of the $NN\pi$ Invariant Mass Spectra

The effective mass spectra for various $NN\pi$ combinations for five prong events at 5.1 GeV/c have shown different maxima. The position of such maxima for different combinations and channels seems to indicate the possibility of resonance states with isospin I = 2. Such maxima have already been reported, in $nn\pi^+$ mass spectra from dp reactions (Siemiarczuk, 1964).

The fitted values of masses and of the experimental widths for the quoted maxima are listed in the table.

Reaction	Combination	Mass (GeV/c^2)	Γ_{exp} (MeV/c^2)	No. of std.dev.
$np \to pp\pi^+\pi^-\pi^-\pi^0$	$pp\pi^+$	2.195 ± 0.009	37 ± 39	5.7
		2.316 ± 0.012	80 ± 15	4.6
		2.395 ± 0.007	32 ± 16	3.3
		2.447 ± 0.004	8 ± 2	3.2
	$pp\pi^0$	2.234 ± 0.008	90 ± 17	4.9
		2.348 ± 0.004	53 ± 16	4.4
		2.428 ± 0.005	41 ± 16	3.7
		2.521 ± 0.008	101 ± 14	5.6
$np \to p\pi^+\pi^+\pi^-\pi^-n$	$pn\pi^+$	2.179 ± 0.001	6 ± 1	4.5
		2.389 ± 0.001	1 ± 5	4.2
		2.513 ± 0.017	1 ± 1	2.2
	$pn\pi^-$	2.310 ± 0.003	23 ± 24	3.9
		2.476 ± 0.061	11 ± 4	3.1
		2.539 ± 0.018	1 ± 1	3.1
		2.620 ± 0.008	1 ± 1	2.2

The statistical significance of the peaks observed in the invariant mass spectrum for the $pn\pi^-$ combination is smaller than in the other cases because of the higher contribution of the non-resonant background (two different combinations are possible for each event. In Fig. 7, we present the invariant mass spectrum for the $pp\pi^0$ combination. The background curve was constructed using a Monte-Carlo method.

CUMULATIVE PRODUCTION OF NEGATIVE PIONS IN NUCLEUS-NUCLEUS COLLISIONS

The cumulative production of particles denotes the production of secondaries from nuclear reactions which is forbidden as taking place outside the physical phase-space of the nucleon-nucleon collisions. Quantitatively, the effect is measured by means of the Bjorken variable.

$$X = \frac{E-p_L}{m_p} \text{ (Lab. Syst.)}$$

where E and p_L denote the energy and the longitudinal momentum of the emitted particle respectively and m_p is the proton mass. In the case of cumulative production of particles, variable X is greater than unity and it denotes the effective minimal number of nucleons of the fragmenting nucleus involved in the reaction. Among the hypotheses related to the cumulative effect, the presence of nuclear multiquark systems is advanced by some authors (see Baldin, 1980; 1985; Huber, 1987).

The Cumulative Production of Negative Pions in O+Pb and O+Ne Collisions at 4.5 AGeV/c

The data that will be presented in the following were obtained in the 2 m streamer chamber - SKM 200 - at JINR Dubna. The experimental set-up and other experimental results concerning the pion production have been presented elsewhere (see e.g. Beşliu and coworkers, 1985b, 1987). Distributions of the X variable for O+Pb (305 events) and O+Ne (175 events) central collisions (the impact parameter b = 0.3 fm) are presented in Fig. 8. In order to determine the physical limit of the variable X above which cumulative pion production occurs, the same distribution was studied for the np five-prongs events with the incident neutron momenta around 4.5 GeV/c, selected from the 4.35 and 5.1 GeV/c np experimental data discussed in the previous section. The value of X in this latter case is found to be limited to 0.6, a value that should be considered as the maximum limit for the Bjorken variable for pionic production in our experiment (N-N collisions).

The tails of the distributions represented in Fig. 8 are extending up to X = 4, which is consistent with the hypothesis of the formation of clusters of 12 quarks in nuclear matter (as suggested in (Kondratyuk and Shmatikov, 1985; Huber, 1987) but few pions are considerably above that value. In the symmetric reaction O+Ne, the production of cumulative pions is more frequent (14 per cent of all pions have X > 0.6) than in the case of the asymmetric process O+PB (only 2 per cent of pions are cumulative ones).

It should be noticed that the previously reported value of the radius of the pionic source, 3.68 fm (Beşliu and others, 1985b) seems to be in agreement with the formation of multiquark clusters in the nuclei. The study of double plots, X versus different kinematical variables, indicates that the production of highly cumulative pions occurs at high transverse momenta ($p_T >$ [illegible].5 GeV/c in the case of the O+Pb reaction) and in the forward hemisphere, with respect to the laboratory frame.

CONCLUSIONS

Data from two different experiments support the idea of the formation of multiquark clusters, both in nucleon-nucleon and in nucleus-nucleus collisions. The observation of narrow dibaryons in neutron-proton collisions excludes all nuclear effects that could affect other experimental dibaryon searches. The cumulative effect indicates that the presence of multiquark systems in nuclear matter is possible, at least in conditions far from stability.

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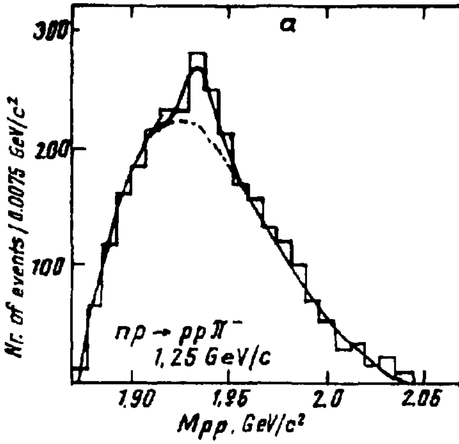


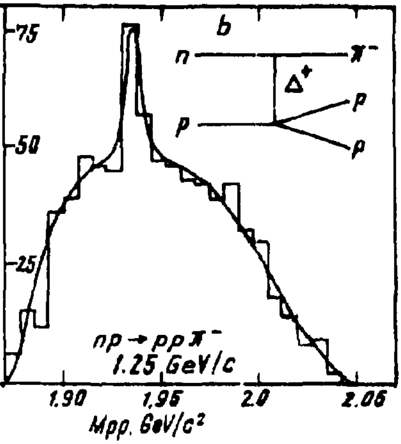


Fig. 1a.

pp effective mass distribution in np pp reaction at P_n= 1.25 GeV/c

Fig. 1b.

The same distribution as in Fig.1a with t_{n-} $-0.45\ (GeV/c)^2$

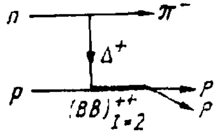


Fig. 2

One-baryon exchange diagram for the production of dibaryonic resonances

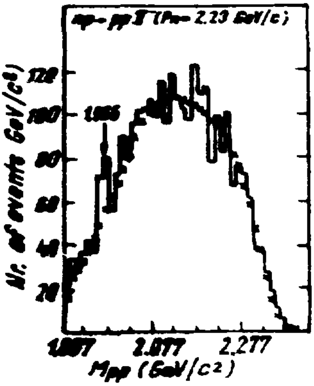


Fig. 3.

pp effective mass spectrum in np→ ppπ^- reaction at p_n=2.23 GeV.

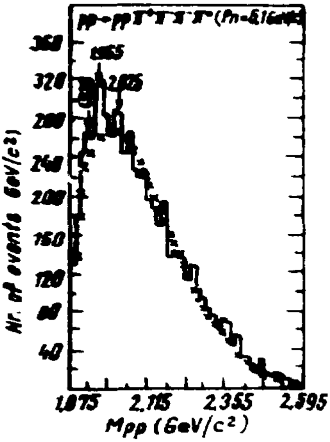


Fig. 4.

pp effective mass spectrum in np→ pp$\pi^+\pi^-\pi^-\pi^0$ reaction at P_n= 5.1 GeV/c

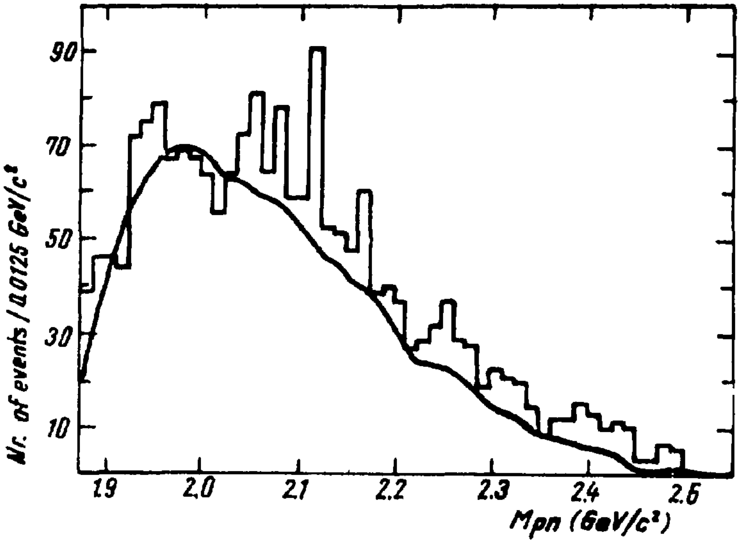


Fig. 5
np effective mass distribution in $np \rightarrow p\pi^+\pi^-\pi^-n$ reaction at $p_n = 5.1$ GeV/c

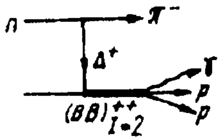


Fig.6
Diagram for the production and electromagnetic decay of the dibaryonic states under the pion production thereshold

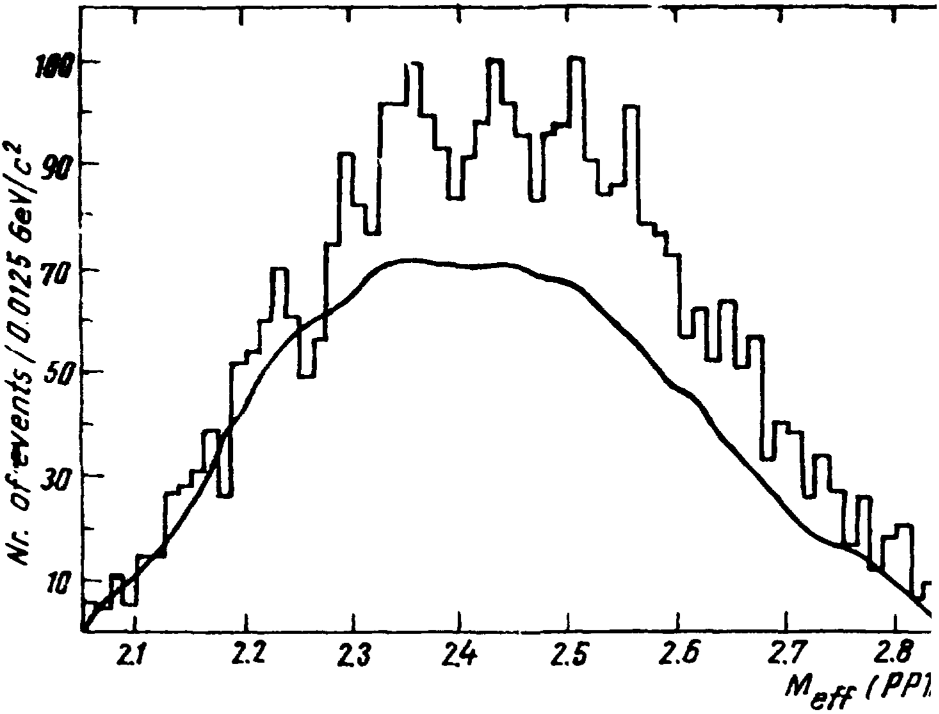
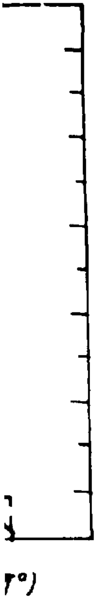


Fig.7

Distribution of the $(pp\pi^0)$ invariant mass in the $np \to pp\pi^+\pi^-\pi^-\pi^0$ reaction at $p_n = 5.1$ GeV/c



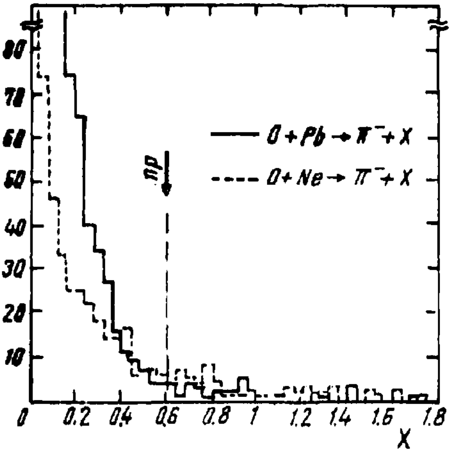


Fig. [illegible]

Distribution of the cumulative number of the negative pions resulting from the O+Pb and O+Ne reaction at p_n = 4.5 AGeV/c