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K.K.Gudima*, V.A.Karnaukhov

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Гудима К.К., Карнаухов В.А. E7-92-38

О проблеме связанных состояний пионов и нейтронов

Обсуждается возможность экспериментального обнаружения в ядро-ядерных соударениях пион-нейтронных кластеров, если таковые существуют. Проведен расчет выходов экзотических фрагментов типа $\pi^{-Z}n^{A}$ при взаимодействии ядер ^{12}C и ^{56}Fe с ^{208}Pb при энергиях от 0,3 до 3,7 ГэВ/A. Расчеты делались в рамках модели коалесценции, в которой использовались дифференциальные сечения рождения пионов и нейтронов, полученные в модели файерстрика. Рассчитаны дифференциальные поперечные сечения для образования $\pi^{-1}n^{2}$, $\pi^{-2}n^{2}$, $\pi^{-2}n^{4}$, $\pi^{-4}n^{6}$ и $\pi^{-12}n^{6}$. Показано, что для экспериментального поиска π-нейтронных кластеров наиболее перспективно использование пучков очень тяжелых ионов (типа ^{56}Fe) с энергией около 1 ГэВ/A.

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Gudima K.K., Karnaukhov V.A. E7-92-38

On the Problem of Bound States of Pions and Neutrons

The problem of existence of the bound states of negative pions and neutrons has been widely discussed for the last years. In this paper we consider possibilities of the experimental observation of pion-neutron clusters, if they do exist, in nucleus-nucleus collisions. We calculated the yields of exotic fragments $\pi^{-Z}n^{A}$ in the interactions of ^{12}C and ^{56}Fe with ^{208}Pb at the energies from 0.3 to 3.7 GeV per nucleon. For $^{40}Ar + ^{238}U$ and $^{139}La + ^{238}U$ collisions the calculations were performed at the energies of 1.8 GeV and 1.3 GeV per nucleon, respectively. These calculations were perfromed in the framework of the coalescence mechanism with the differential cross sections for pion and neutron production generated by firestreak model. The differential cross sections for production of $\pi^{-1}n^{-2}$, $\pi^{-2}n^{2}$, $\pi^{-2}n^{4}$, $\pi^{-4}n^{6}$, and $\pi^{-12}n^{6}$ were calculated. It is shown that the use of very heavy projectiles like ^{56}Fe and ^{139}La has a great advantage in the experimental search for the exotic clusters.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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1. INTRODUCTION

The problem of the possible existence of the clusters composed by a number of the negative pions and neutrons ($\pi^{-Z} n^A$) has already been discussed for many years. They are called pineuts or negative deltons. A short review of the theoretical and experimental studies on the topic was presented by van Dantzig et al.[1]. A system of neutrons alone cannot form a bound state. But the self-energy of the system can be changed significantly by adding negative pions because of strong attractive P_{33} π^--n interaction. The situation is similar to that with ordinary nuclei, when the strong optical potential of a proton in a piece of neutron matter causes a decrease in the self-energy of the system, which results in the bound state.

Only for the lightest delton πN^2 the problem of the bound state is investigated in detail both theoretically[2-5] and experimentally. Garcilazo[5] has found strong binding of the system, solving the relativistic Fadeev equations with the P_{33} π^--n force and some n-n potentials. This is the only paper with a positive conclusion.

One should expect that adding neutrons and pions to the system will increase the depth of the average π^--potential. Garcilazo[6] evaluated the self-energy of heavier pineuts $\pi^{-Z} n^A$ by solving the Klein-Gordon equation with the optical potential of the Kisslinger form, taking into account the self-energy of neutrons and the Coulomb repulsion between pions. He found that the system is bound if it includes a minimum of 12 pions and 5 neutrons at twice the ordinary nuclear density or approximately 20 π's and 20 neutrons at normal density. The restrictions of this approach are analyzed in Ref.[1].

A qualitative description of the $\pi^{-Z} n^A$ system in terms of Δ^--n interaction is given by van Dantzig[1]. As a starting point, the theoretical findings were used that Δ-Δ and Δ-n systems may be quasi-bound because of strong interaction (see for example, Ref.[7]). According to different estimations binding energies are in the range of 10-100 MeV, which is not enough to stabilize Δ^- against π^--n disintegration. For the systems containing more Δ^-'s and neutrons the binding energy is expectied to grow simply because of the increase in the number of interacting pairs. It was assumed that binding for Δ-nuclear clusters would scale up in the same way as for normal nuclei ($\Delta^- n : \Delta^- n^2 : \Delta^{-2} n^2 \sim d : {}^3H : {}^4He$). Taking 30 MeV as the binding energy for a $\Delta^- n$ system one should get about 400 MeV for $\Delta^{-2} n^2$ ($\pi^{-2} n^4$). So this exotic alpha-particle is expected to be stable as one needs approximately 300 MeV as binding to prevent the decay of Δ's. Without pretending to be quantitative these estimations are very exciting. It would be extremely interesting anyhow to test stability of a system, made up of two negative pions and four neutrons. It should be mentioned that isospin partners of pineuts, composed of positive pions and protons, might also occur as bound clusters with slightly smaller binding because of the additional Coulomb repulsion.

The points in favour of the hadronically stable deltons are closely related to those of pionic bound states in ordinary nuclei. Ericson and Myhrer[8] pointed out that the real part of the pion-nucleus potential is strong enough to allow negative pions to form the bound state. However, according to Friedman et al.[9], the imaginary part of the optical potential calls forth a very large widths for these states ($\Gamma \approx$ $\approx$ 2000–3000 MeV), so they cannot in fact be observed experimentally.

Another approach to the problem of pion binding in the nucleus is suggested by Goldanskii[10]. It is expected from the qualitative consideration that pion binding would manifest itself as an excited state of nucleus with isospin $T > A/2$ and excitation energy slightly below the pion rest mass. The lifetime of these states would be not less than 10^{-19} s because of isospin violation.

2. LIFETIME OF DELTONS

Deltons, if they do exist, are hadronically stable clusters: pions cannot be absorbed by nucleons because of the charge conservation law. The lifetime is determined by the weak decay of the bound pions. If the hadronic environment does not change the matrix element, the pion decay rate will be mainly conditioned by the available final state phase space, depending on the pion binding energy B_π. The mean lifetime of a cluster with Z pions, whose binding energies are small as compared to $(m_\pi - m_\mu)c^2 = 34$ MeV, will be equal to

$$\tau_{Z\pi} = \frac{\tau_\pi}{Z} \quad (34/(34 - B_\pi))^2, \qquad (1)$$

where $\tau_\pi = 2.6 \cdot 10^{-8}$ s is the lifetime of a free pion. For $B_\pi > 34$ MeV the muonic decay will be forbidden and the bound pion will decay through the electronic mode with the lifetime $\tau_{\pi \to e\nu} = 2 \cdot 10^{-4}$ s. However, it should not be excluded that pion decay properties may be significantly modified inside dense hadronic matter. The electronic mode of the free pion decay is strongly suppressed due to lepton helicity. This suppression may be eliminated completely (or partly) for a bound pion because the strong coupling to a medium may allow linear and angular momentum exchange. In this case electronic emission becomes the prominent decay mode for a bound pion with the lifetime about 10^{-9} s if the available phase space volume is not changed. This important question of the medium effect is waiting for careful theoretical consideration.

3. THE CALCULATIONS OF THE PINEUTS YIELD IN NUCLEUS-NUCLEUS COLLISIONS

At the present time several experimental papers devoted to the search for single charged deltons have been published[11-14]. No definite indications of the existence of exotic clusters were found. Studies were carried out with proton and pion beams. As an example we mention the paper by De Boer et al.[11]. The experiments were conducted at SIN with a proton beam of high intensity. The very low limits for the production cross sections obtained practically exclude the existence of $\pi^- n^2$ and $\pi^- n^3$ with the lifetime of the free pion or longer.

The most promising tools in the experimental search for heavier deltons are beams of relativistic heavy ions (later on we shall discuss the first paper on that topic)[1]. One can imagine two delton creation processes:

a) Multiple pion exchange with production of the anomalous projectile spectator, e.g.:

$$^4He + {}^AZ \to (\pi^{-2} n^4) + {}^A(Z+4).$$

b) Clusterization of the hadron gas in the fireball region of violent nucleus-nucleus collisions.

The latter process seems to be more promising because of high multiplicity of pions and nucleons in the central collisions. We have calculated the yields of pineuts, taking into account experimental advantages of the search for the negative charged heavy particles. The calculations were made in the framework of the coalescence model[15]. This model assumes that several hadrons can stick together and form a composite fragment, if they have approximately the same velocities. The probability of pineut creation process is expressed through the differential cross sections of the pion and neutron production. For the $\pi^{-Z} n^A$ cluster the following expression can be written for the probability (multiplicity):

$$W_{ZA}(\vec{p}) = \left(\frac{4}{3}\pi p_o^3\right)^{Z+A-1} (Z!A!)^{-1} \; [W_\pi(\vec{p}_\pi)]^Z \, [W_n(\vec{p}_n)]^A ,$$

where

$$W_{ZA}(\vec{p}) = \gamma_{ZA} \frac{1}{\sigma} \frac{d^3\sigma_{ZA}}{d^3 p_{ZA}},$$

$$W_\pi(\vec{p}_\pi) = \gamma_\pi \frac{1}{\sigma} \frac{d^3\sigma_\pi}{d^3 p_\pi}, \qquad (2)$$

$$W_n(\vec{p}_n) = \gamma_n \frac{1}{\sigma} \frac{d^3\sigma_n}{d^3 p_n}, \quad \gamma_i = \left(1 + \frac{p_i^2}{m_i^2}\right)^{1/2},$$

$$\vec{p}_{ZA} = Z\vec{p}_\pi + A\vec{p}_n, \quad p_\pi = \frac{m_\pi}{m_{ZA}} p_{ZA}, \quad p_n = \frac{m_n}{m_{ZA}} p_n.$$

The total inelastic cross section of the collision is denoted by σ. The only parameter of the model is coalescence radius p_o, which can be related to the Fermi momentum of cluster. A qualitative link between the coalescence radius and the structure of the fragment is established in Ref.[15]: $p_o^{-1} \sim (R^2 + R_f^2)^{1/2}$, where R and R_f are the radii of the source and of an emitted fragment (pineut), respectively. The lower pineut binding is, the larger R_f and the smaller p_o. This model demands that the differential cross sections for the pion and neutron production should be used. They were obtained by means of the firestreak model[16]:

$$\frac{d^3\sigma}{d^3 p_i} = \int \frac{d\sigma}{d\eta} f_i(\vec{p}_i^{\,*}, \eta)\, L_{\vec{p}_i^{\,*} \to \vec{p}_i}\, d\eta , \qquad (3)$$

where the geometrical factor $\frac{d\sigma}{d\eta}$, giving a cross section distribution over the streaks, is entirely determined by the density distribution of colliding nuclei. The decay of each streak η in its own coordinate system is described by the single-particle function $f_i(\vec{p}_i^{\,*}, \eta)$. The factor $L_{\vec{p}_i^{\,*} - \vec{p}_i}$ shifts the spectrum to the laboratory system. The firestreak model overestimates the cross sections for nucleon production at small angles and momenta less than 1.5 GeV/c. As for pions, it underestimates the cross sections for momenta less than 0.4 GeV/c and overestimates above this point[16b]. This should result in the overestimation of the pineut yield. But it may be compensated for by some change of the p_o value. The coalescence radius p_o is the crucial parameter in this approach owing to the strong dependence of W_{ZA} upon p_o (to the power $3(Z + A - 1)$). Taking into account the analysis of the yields of composite fragments in the framework of the coalescence model made in Ref.[17], we have chosen as a starting point the value $p_o = 200$ MeV/c.

The calculations were performed for the collisions $^{12}C + ^{208}Pb$ and $^{56}Fe + ^{208}Pb$ at the energies 0.3, 0.5, 1.0, 2.0, 3.7 GeV/nucleon. Figs.1 and 2 show the multiplicities of π^-, n and of pineuts $\pi^- n^2$, $\pi^{-2}n^2$, $\pi^{-2}n^4$, and $\pi^{-4}n^6$ (if they do exist) as a function of the beam energy. To estimate the yields of other clusters, one can use

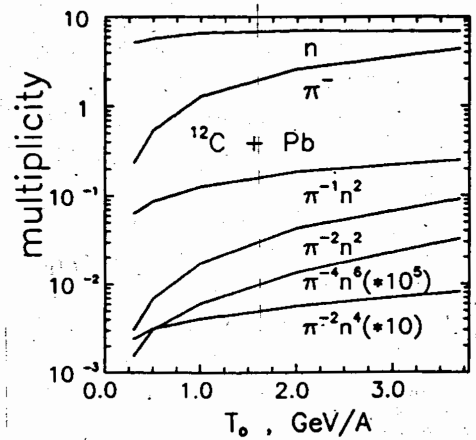

Fig.1. Multiplicity of pineuts produced in the lead target by ^{12}C with the energy in the range (0.3–3.7) GeV/A. Calculations were made in the framework of the coalescence model with $p_o = 200$ MeV/c. Multiplicities of pions and neutrons were obtained by the firestreak model.

Fig.3, presenting the dependence of the multiplicities upon the number of hadrons in a cluster. The yields are significantly larger for ^{56}Fe-beam. This is an evident consequence of higher multiplicities of pions and neutrons in comparison to the case of ^{12}C and ^{208}Pb collision.

Figures 4, 5 show the differential cross sections for the cluster production at the beam energy 1 GeV/A at laboratory angles $\theta = 10°$ and $30°$. The angular distributions are forward peaked.

Having in mind the dramatic sensitivity of the results to the coalescence radius, we also made calculations with $p_o = 100$ MeV/c. The multiplicities obtained are shown in Fig.6. The yields fall down drastically. So, for $\pi^{-2}n^4$ the multiplicity becomes more than 4 orders of magnitude lower.

In the optimistic variant of the calculations ($p_o = 200$ MeV/c) the cross sections for the ^{56}Fe projectile are so high that it is reasonable to search for pineuts with the hadron number up to 10.

Recently, when the first version of this work was completed[18], paper by de Boer et al. has been published[19].

It is devoted to the search for bound states of negative pions and neutrons in relativistic heavy-ion reactions. The 1.8 A GeV ^{40}Ar and 1.3 A GeV ^{139}La beams of Bevalac were used with ^{238}U as a target. The experimental setup includes a magnetic spectrometer with a relatively short flight path of 3.4 m

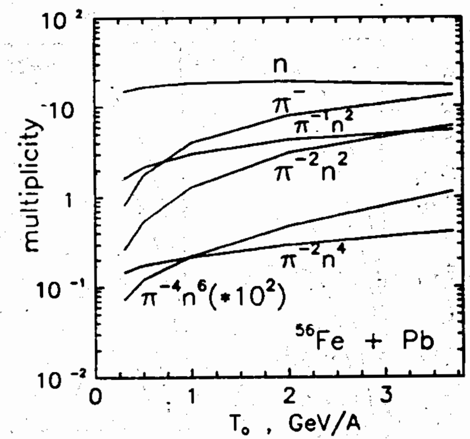

Fig.2. The same as in Fig.1, but for the ^{56}Fe-projectile.

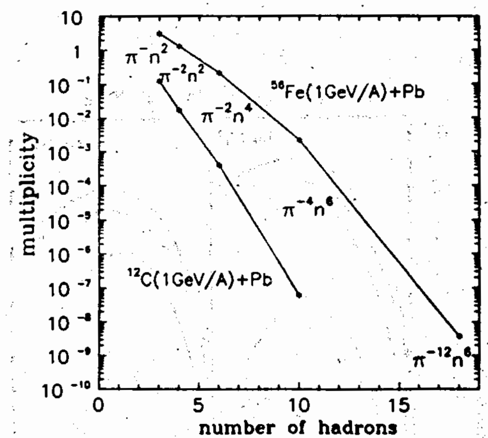

Fig.3. Multiplicities of exotic clusters as a function of the hadron number in the cluster for the collisions of ^{12}C and ^{56}Fe projectiles with the ^{208}Pb-target at 1 GeV/nucleon.

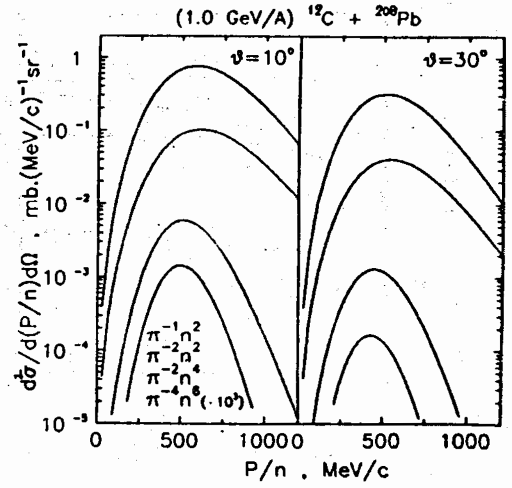

Fig.4. Differential cross sections for production of $\pi^{-}n^{2}$, $\pi^{-2}n^{2}$, $\pi^{-2}n^{4}$, $\pi^{-4}n^{6}$ in ^{12}C and ^{208}Pb collisions at 1 GeV/nucleon. Cross sections for $\pi^{-4}n^{6}$ are shown with the factor of 10^{3}. The same is valid for Figs.5 and 7, too.

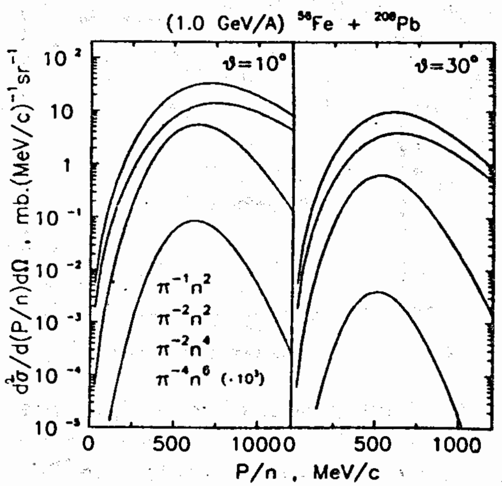

Fig.5. The same as in Fig.4, but for the ^{56}Fe projectile at 1 GeV/nucleon.

which is important in view of the short lifetime expected for pineuts. After analysis of the data five candidates for pineuts have been separated. But they were attributed to the background because it could not be excluded that these events emerged from some combination of the background sources. As an estimation of the upper limit for the $(\pi^{-2}n^{4})$-multiplicity the value of $2\cdot10^{-6}$ was obtained for Ar + U collisions. This value is $2.5\cdot10^{2}$ times smaller than the theoretical estimate by Kozlowski, who used the coalescence model with Δ^{-}'s and neutrons as the constituents of the pineuts /20/.

We applied our approach to estimate the yield of $\pi^{-2}n^{4}$ for Ar + U and La + U collisions. The results obtained for $p_0 =$ = 100 MeV/c are shown in Fig.7 and 8. Our value for the yield of $\pi^{-2}n^{4}$ in the Ar+U collisions is of the same order of magnitude as the upper limit for that in Ref. /19/. Therefore one should conclude that the data of Ref. /19/ do not exclude the existence of double charged pineuts even for half-lives of the order of the free pion one. Further searches at higher sensitivity are of interest.

And it is very desirable to develop new experimental approaches to search for pineuts with half-lives significantly shorter than 10 ns, taking into

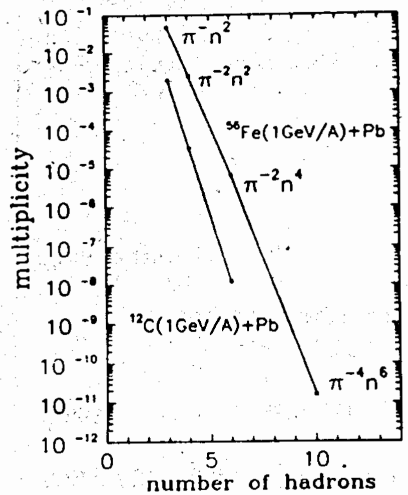

Fig.6. Pineut yields calculated with the coalescence radius of 100 MeV/c.

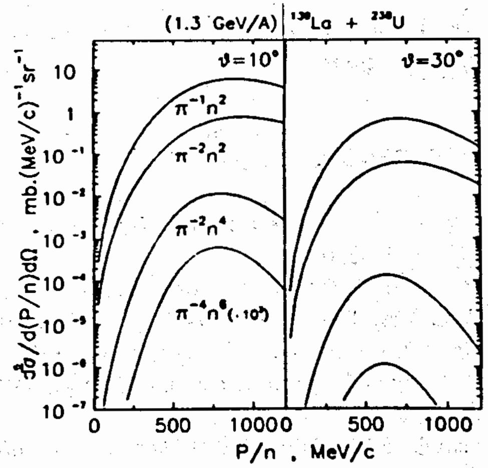

Fig.7. Differential cross sections for pineut production in ^{139}La + ^{238}U collisions at 1.3 GeV/nucleon.

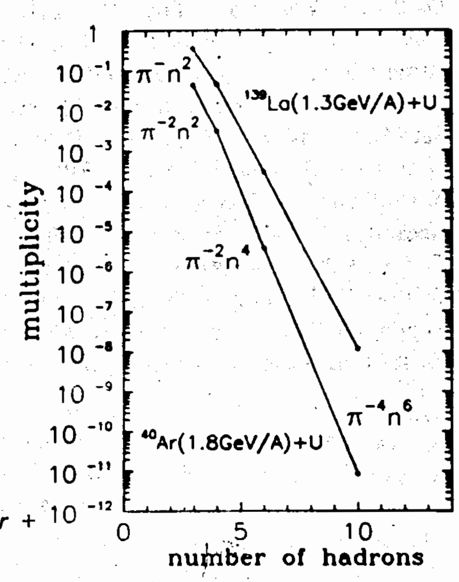

Fig.8. The same as in Fig.6, but for ^{40}Ar + ^{238}U and $^{139}La + ^{238}U$ collisions.

account the possible elimination of the helicity suppression of the electron mode of the decay of the bound pions.

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