

Resonance states below the pion-nucleon threshold and their consequences for nuclear systemsEvgeni E. Kolomeitsev¹ and Dmitri N. Voskresensky^{2,3}¹*ECT*, Villa Tambosi, I-38050 Villazzano (TN), INFN G. C. Trento, Italy*²*Moscow Engineering Physical Institute, Kashirskoe shosse 31, 115409 Moscow, Russia*³*GSI, Planck Street 1, D-64291 Darmstadt, Germany*

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Regular sequences of narrow peaks have been observed in the missing mass spectra in the reactions $pp \rightarrow p\pi^+X$ and $pd \rightarrow ppX_1$ below the pion-production threshold. They are interpreted in the literature as manifestations of supernarrow light dibaryons, nucleon resonances, or light pions forming resonance states with the nucleon in its ground state. We discuss how the existence of such exotic states would affect the properties of nuclear systems. We show that the neutron star structure is drastically changed in all three cases. We find that in the presence of dibaryons or nucleon resonances the maximal possible mass of a neutron star would be smaller than the observational limit. The presence of light pions does not contradict the observed neutron star masses. Light pions allow for the existence of extended nuclear objects of arbitrary size, bound by strong and electromagnetic forces.

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I. INTRODUCTION

The experimental search for exotic states in one-baryon and two-baryon spectra has a long history; see the review in [1]. Enthusiasm has been revived in the field after two recent experimental reports [2,3]. In Ref. [2] the reaction $pp \rightarrow p\pi^+X$ was investigated and three narrow peaks (width ~ 5 MeV) in the missing mass spectrum were seen at $M_X = 1004, 1044,$ and 1094 MeV with a high statistical significance. Reference [3] reported a study of the reaction $pd \rightarrow ppX_1$. Three peaks of the width of 5 MeV were clearly observed in the missing mass M_{pX_1} spectrum at $M_{pX_1} = 1904 \pm 2, 1926 \pm 2,$ and 1942 ± 2 MeV. In the missing mass M_{X_1} spectrum the peaks are located at $M_{X_1} = 966 \pm 2, 986 \pm 2,$ and 1003 MeV. The correspondence between peaks in Refs. [2,3] was discussed in [4].

The evident regularity of the peaks observed in [2,5] is in contrast with previous experimental data [1], which were limited by a lower resolution in energy and lower statistics. The compiled analyses of all available data of Refs. [5,6] indicates, however, that a similar pattern shows up in the old data too.

The true nature of these resonances is obscure so far and three interpretations are suggested in the literature: (i) The peaks can be assigned to supernarrow dibaryon resonances (D'), which have been predicted theoretically within the bag [7] and the chiral soliton [8] models. (ii) The peaks can be interpreted as new nucleon resonances (N'). (iii) They are bound states of one or two nucleons with several light pseudoscalar particles ($\tilde{\pi}$) having mass $m_{\tilde{\pi}} \approx 21 \pm 2.6$ MeV [9].

The above interpretations imply that the new particles should have an exotic internal quark structure, having only a small overlap with the usual nucleon and pion states. Otherwise they would be produced with a large probability and would manifest themselves in many nuclear reaction channels, where they are not seen, as we know. For the dibaryonic interpretation, the smallness of the production cross sections [3,10] and estimates in [10] suggest that the pion-

D' -deuteron coupling should be at least 10 times weaker than the standard πNN coupling. Nucleon resonances below the πN threshold should have tiny couplings to πN and γN states; otherwise, they would spoil the dispersion relations for πN and Compton scattering, which are fulfilled with good precision [11]. Smallness of the $\gamma NN'$ coupling requires also smallness of $\omega NN'$ and $\rho^0 NN'$ couplings. The coupling of "light pions" ($\tilde{\pi}$) to the usual pions and nucleons should also be strongly suppressed in order not to contradict the data on $\pi\pi$ and πN interactions; cf. discussions in Ref. [9].

Despite the fact that the exotic states do not show up on the typical time scale of strong interactions, according to their properties mentioned above, they could manifest themselves in long-living nuclear systems, such as atomic nuclei and neutron stars (NSs). They could also be produced with a detectable probability in particle-nucleus and nucleus-nucleus collisions as well as other rare probes (photons, dileptons, strange particles, etc.). The small probability of an elementary reaction is enhanced in the latter case due to a large number of interactions.

In the present paper we shall discuss the possible consequences of the very existence of these three suggested hypothetical states ($D', N', \tilde{\pi}$) for nuclear systems. In order to make our analysis more transparent, we consider the lightest state in the dibaryon spectrum, $m_{D'} = 1904$ MeV, and the two lightest states in the nucleon spectrum, $m_{N'_1} = 966$ MeV and $m_{N'_2} = 986$ MeV. For "light pions" we take $m_{\tilde{\pi}} = 22$ MeV.

We shall model the equation of state (EOS) of nuclear matter using the parametrization [12], which is a good fit to the optimal EOS of the Urbana-Argonne group [13] up to 4 times the nuclear saturation density, $\rho_0 = 0.16 \text{ fm}^{-3}$, and which smoothly incorporates the causality limit at higher densities. The energy density, counted from the nucleon mass, is

$$E_N(\rho_N) = \rho_N \mathcal{E}_N(n = \rho_N/\rho_0, x = \rho_p/\rho_N),$$

$$\mathcal{E}_N(n, x) = \mathcal{E}_0 n \frac{2.2-n}{1+0.2n} + S_0 n^{0.6} (1-2x)^2, \quad (1)$$

where $\rho_{p(n)}$ is the proton (neutron) density, $\rho_N = \rho_p + \rho_n$, $\mathcal{E}_0 = -15.8$ MeV, and $S_0 = 32$ MeV. Having the compressibility modulus $K \approx 200$ MeV, this EOS allows for NS masses up to $2.2M_\odot$, where $M_\odot = 2 \times 10^{33}$ g is the solar mass.

II. LIGHT DIBARYONS

Consider a mixture of nucleons and dibaryons with total baryon density ρ_B and dibaryon density $\rho_{D'}$. The energy density of such a system is given by

$$E = E_N(\rho_B - 2\rho_{D'}) + \delta m_{D'} \rho_{D'} + E_{D'N}^{\text{pot}} + E_{D'D'}^{\text{pot}}, \quad (2)$$

where $\delta m_{D'} = m_{D'} - 2m_N = 28$ MeV, and the quantities $E_{D'N}^{\text{pot}}$ and $E_{D'D'}^{\text{pot}}$ are potential-energy densities of dibaryon-nucleon and dibaryon-dibaryon interactions. Following [6] we assume here that dibaryons (having spin and isospin zero) obey Bose statistics, and therefore occupy only the single lowest-energy state. As they are compact systems, we may assume that they do not undergo a Mott transition in baryon matter at the densities we are interested in.

Consider first the case of a small dibaryon concentration. Expanding Eq. (2) in $\rho_{D'}$ for isospin-symmetrical matter and $\rho_{D'} \ll \rho_B$, we obtain

$$E \approx E_N(\rho_B) - (2\mu_N^{(0)} - \mu_{D'}^{(0)})\rho_{D'} + \kappa \rho_{D'}^2/2. \quad (3)$$

Here $\mu_{D'}^{(0)} = \delta m_{D'} + \delta \mu_{D'N}$ and

$$\mu_N^{(0)} = \left. \frac{\partial E_N}{\partial \rho_B} \right|_{\rho_B = \rho_N}, \quad \delta \mu_{D'N} = \left. \frac{\partial E_{D'N}^{\text{pot}}}{\partial \rho_{D'}} \right|_{\rho_{D'} = 0},$$

$$\kappa = 4 \left. \frac{\partial^2 E_N}{\partial \rho_B^2} \right|_{\rho_B = \rho_N} + \left. \frac{\partial^2 (E_{D'N}^{\text{pot}} + E_{D'D'}^{\text{pot}})}{\partial \rho_{D'}^2} \right|_{\rho_{D'} = 0}. \quad (4)$$

Minimizing Eq. (3) with respect to $\rho_{D'}$, we find that for $\kappa > 0$ a dibaryon admixture becomes energetically favorable, if $2\mu_N > \mu_{D'}$. Then the dibaryon density and the energy density gain are

$$\rho_{D'} \approx \frac{2\mu_N^{(0)} - \mu_{D'}^{(0)}}{\kappa}, \quad \Delta E_{D'} \approx -\frac{1}{2\kappa} (2\mu_N^{(0)} - \mu_{D'}^{(0)})^2. \quad (5)$$

To model the unknown dibaryon-nucleon interaction we assume that the $D'N$ potential is proportional to the NN potential and that $\delta \mu_{D'N} = \zeta(\mu_N^{(0)} - \epsilon_F)$. Here ϵ_F is the Fermi energy of the isospin symmetrical matter, $\epsilon_F = \epsilon_{F,p} = \epsilon_{F,n}$, with $\epsilon_{F,i} = (m_N^2 + p_{F,i}^2)^{1/2} - m_N$ and $p_{F,i} = (3\pi^2 \rho_i)^{1/3}$ for $i = n, p$. The exotic internal structure of light dibaryon states implies that the parameter ζ is small. Specifically, Refs. [3,10] put the constraint $0.1 \gtrsim \zeta \geq 0$. A naive quark counting would give, on the other hand, $\zeta = 2$ (such an assumption is

analogous to the one in Ref. [14]). A repulsive dibaryon self-interaction can be introduced with $E_{D'D'}^{\text{pot}} = \pi f_{D'D'} \rho_{D'}^2 / m_{D'}$, where $f_{D'D'} > 0$ is the $D'D'$ scattering length. It can be estimated using an assumption, which is justified in the bag model [7]—namely, that the hard core radius in the third power scales as the particle mass, $f_{D'D'} \sim r_N^{\text{cor}} (m_{D'}/m_N)^{1/3} \sim 0.4$ fm, with $r_N^{\text{cor}} \sim 0.3$ fm. The coefficient κ can be evaluated using the fact that at saturation density $\partial^2 E_N / \partial \rho_N^2 |_{\rho_N = \rho_0} = K / (9\rho_0)$ and assuming that $E_{D'N}^{\text{pot}}$ is exhausted by the term $\propto \rho_{D'} \rho_N$, thereby giving $\partial^2 E_{D'N}^{\text{pot}} / \partial \rho_{D'}^2 |_{\rho_{D'} = 0} = 0$. Then we have $\kappa \approx 610$ MeV fm⁻³.

Applying now the results (5) to atomic nuclei we find that for the favorite choice $\zeta = 0$ we have $\mu_{D'}^{(0)} > 0$ and dibaryons are absent in atomic nuclei, since nucleons are bound with $\mu_N^{(0)} < 0$. Thus, *the dibaryon interpretation of experiments [2,3,6] does not contradict the atomic nucleus experiments* if their interaction with nucleons is, indeed, sufficiently weak. Note that choosing $\zeta = 2$, according to a quark counting, we would have at saturation density $2\mu_N^{(0)} - \mu_{D'}^{(0)} \approx p_F^2 / m_N - \delta m_{D'} \approx 46$ MeV, corresponding to $\rho_{D'} \sim 0.5\rho_N$. This would evidently contradict the known properties of nuclei. The critical value of ζ at which dibaryons would just appear in nuclei is $\zeta_c = (\delta m_{D'} - 2\mu_N^{(0)}) / (\epsilon_F - \mu_N^{(0)})$, which gives $\zeta_c \approx 0.8$ for ⁵⁶Fe with $\mu_N^{(0)} \approx -8$ MeV.

We turn now to NSs, which could in principle contain an admixture of dibaryons. Consider a NS consisting of neutrons, protons, dibaryons, electrons, and muons. Following the assumptions above we model the nucleon-dibaryon potential energy as

$$E_{D'N}^{\text{pot}} = \frac{\zeta}{2} (V_n + V_p) \rho_{D'}, \quad V_i = \frac{\partial E_N}{\partial \rho_i} - \epsilon_{F,i}, \quad (6)$$

with $i = n, p$. The chemical potentials of nucleons and dibaryons are given by

$$\mu_i = \frac{\partial (E_N + E_{D'N}^{\text{pot}})}{\partial \rho_i}, \quad \mu_{D'} = \delta m_{D'} + \frac{\partial (E_{D'N}^{\text{pot}} + E_{D'D'}^{\text{pot}})}{\partial \rho_{D'}}.$$

The composition of the NS matter is controlled by conditions of charge neutrality and β equilibrium [15]. The latter means in particular that $\mu_{D'} = 2\mu_n$. Calculations (in line with the standard procedure [15]) show that the presence of dibaryons would completely change the NS composition. Dibaryons appear at very small densities. For homogeneous baryon matter it happens at $\rho_B \approx 0.2\rho_0$. With further increase of the baryon density they expel protons and strongly reduce the neutron concentration; e.g., at $\rho_B \approx 4.5\rho_0$ we have $\rho_n / \rho_B \approx \rho_{D'} / \rho_B \approx 0.33$ and $\rho_p / \rho_B \approx 10^{-4}$.

The total energy density E_{tot} is given by Eq. (2) plus the kinetic energy of the leptons. The latter contribution is very small since the number of leptons, being equal to the number of protons, is suppressed in the presence of dibaryons. The pressure is equal to $P = \sum_a \mu_a \rho_a - E_{\text{tot}}$, where the sum goes over all species present in the system.

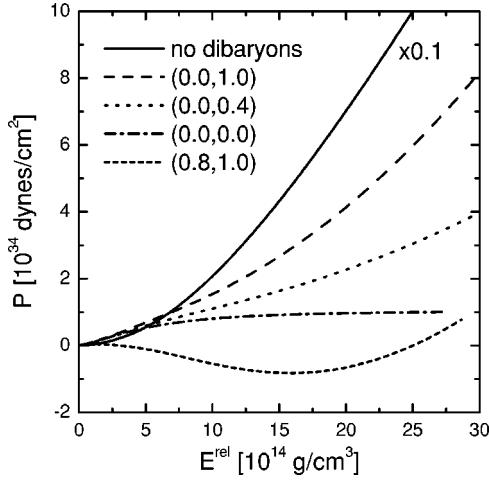


FIG. 1. Pressure of NS matter as a function of the energy density with and without dibaryons. The numbers in the brackets indicate parameter sets $(\zeta, f_{D'D'})$ in fm. The curve for the dibaryon-free case is scaled by a factor of 0.1.

In Fig. 1 we show the pressure versus full relativistic energy density $E^{\text{rel}} = m_N \rho_B + E$ of NS matter with and without dibaryons, calculated for various values of parameters ζ and $f_{D'D'}$. We observe that dibaryons make the EOS very soft. In the presence of dibaryons the pressure is typically smaller by an order of magnitude compared to the one without dibaryons. The stiffness of the EOS is increased with an increase of $f_{D'D'}$. However, even for the case $f_{D'D'} = 1$ fm, which corresponds to the stiffest EOS among those presented in Fig. 1, the maximum mass of the NSs, as we calculated, is significantly less than the observational lower limit $1.4M_\odot$. Moreover, an increase of $f_{D'D'}$ up to unrealistically large values $f_{D'D'} \sim 10$ fm would not lead to an increase of the NS maximum mass above $1.4M_\odot$. The EOS becomes softer if one assigns dibaryons to the isospin-1 states, assuming thereby the existence of charged dibaryons. The same happens for finite values of ζ . For $\zeta = 0.8$ and $f_{D'D'} = 1$ fm the pressure would be negative in some density interval, indicating that the system would undergo a collapse to a superdense state, which would be bound even in the absence of the gravity.

Thus, the analysis above allows us to conclude that *the existence of light dibaryons would be in severe contradiction with the information on NS masses.*

III. NUCLEON RESONANCES

We turn now to another possible interpretation of experiments [2,3] with the help of exotic nucleon resonances of isospin 1/2. Consider the two lightest resonances N'_1 and N'_2 with $\delta m_{N'_1} = m_{N'_1} - m_N = 28$ MeV and $\delta m_{N'_2} = m_{N'_2} - m_N = 48$ MeV. We denote neutral and positively charged particles as $n'_{1,2}$ and $p'_{1,2}$ by analogy with neutrons and protons. Our treatment of the N' resonances in NS matter is similar to that for hyperons; cf. [15]. However, the critical density for the appearance of N' is much smaller than the one of hyperons due to the smaller N' mass. In line with Refs. [2,5], we

assume that the quark structure of the N' resonances is quite different from the nucleons. Therefore, the Pauli principle is not operating between them and the nucleons.

The energy density of the system with baryon density ρ_B , composed of nucleons and $N'_{1,2}$ resonances with density $\rho_{N'_{1,2}} = \rho_{n'_{1,2}} + \rho_{p'_{1,2}}$, is

$$E = E_N(\rho_B - \rho_{N'_1} - \rho_{N'_2}) + \sum_{i'=p'_{1,2}, n'_{1,2}} E_{i'}^{\text{kin}} + E_{N'_1 N'}^{\text{pot}} + E_{N'_2 N'}^{\text{pot}}, \quad (7)$$

where $E_{p'(n')}^{\text{kin}}$ denotes the kinetic energy of the $p'(n')$ resonance counted from the nucleon mass. Similarly to Eq. (2), the quantity $E_{N'_1 N(N'_1 N')}$ stands for the $N'_1 N(N'_1 N')$ potential-energy density. Assuming $\rho_{N'_1} \ll \rho_B$ ($\rho_{N'_2} = 0$ for this case) we expand Eq. (7) in $\rho_{N'_1}$ and obtain, for the case of isospin-symmetrical matter,

$$E = E_N(\rho_B) - (\mu_{N'}^{(0)} - \mu_{N'_1}^{(0)})\rho_{N'_1} + \frac{3}{5} \frac{\rho_{N'_1}^{5/3}}{m_{N'_1}} \left(\frac{3}{2} \pi^2 \right)^{2/3},$$

$$\mu_{N'_1}^{(0)} = \delta m_{N'_1} + \partial E_{N'_1 N'}^{\text{pot}} / \partial \rho_{N'_1} |_{\rho_{N'_1} = \rho_{N'_2} = 0}, \quad (8)$$

where we retained $\rho_{N'_1}^{5/3}$ terms but dropped the higher-order terms, and $\mu_{N'}^{(0)}$ is defined as in Eq. (3). Minimization of the energy density with respect to the $\rho_{N'_1}$ yields for the case $\mu_{N'}^{(0)} > \mu_{N'_1}^{(0)}$ the following N' density and energy gain:

$$\rho_{N'_1} \approx 2 [m_{N'_1} (\mu_{N'}^{(0)} - \mu_{N'_1}^{(0)})]^{3/2} / (3 \pi^2),$$

$$\Delta E_{N'_1} \approx - \frac{4}{15 \pi^2} m_{N'_1}^{3/2} (\mu_{N'}^{(0)} - \mu_{N'_1}^{(0)})^{5/2}, \quad (9)$$

and is zero otherwise. As for dibaryons, we express the N'_1 chemical potential through the nucleon chemical potential, $\mu_{N'_1}^{(0)} = \delta m_{N'_1} + \zeta' (\mu_N^{(0)} - \epsilon_F)$, with the same constraint $0.1 \geq \zeta' \geq 0$. For $\zeta' = 0$ there are no N' resonances in atomic nuclei, since $\mu_{N'}^{(0)} = \delta m_{N'_1} > 0$ and $\mu_N^{(0)} < 0$. A quark counting suggests $\zeta' = 1$, and correspondingly, we would get $\mu_{N'}^{(0)} - \mu_{N'_1}^{(0)} \approx p_F^2 / (2 m_N) - \delta m_{N'_1} \approx 9$ MeV in atomic nuclei. This gives $\rho_{N'_1} \approx 0.04 \rho_0$ and $\Delta E_{N'_1} \approx 0.2$ MeV, which are rather small contributions. The critical value of ζ' , when N'_1 resonances could just appear in atomic nuclei, is $\zeta'_c \approx 0.9$. For $0.1 \leq \zeta' \leq \zeta'_c$, even if N' resonances are absent in atomic nuclei, they could be produced and detected in nuclear reactions. This is, however, not the case. Therefore, ζ' should be small, and for small ζ' *the existence of light nucleon resonances would not contradict known properties of atomic nuclei.*

Consider now NS matter in β equilibrium consisting of nucleons, N'_1 , N'_2 and leptons. We express the $N'_1 N$ and $N'_1 N'$ potential energies as

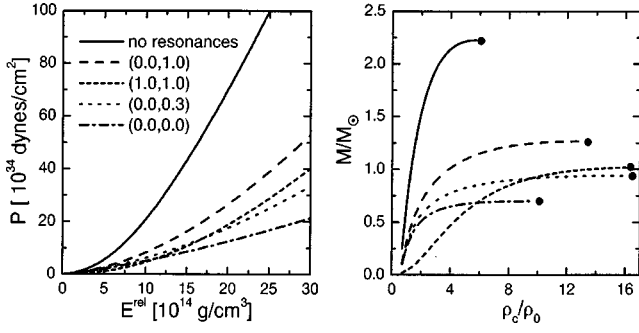


FIG. 2. Left panel: pressure as a function of the relativistic energy density of NS matter with and without $N'_{1,2}$ resonances. The curves are presented for different parameter sets (ζ' , $f_{N'N'}$ in fm). Right panel: the NS mass as a function of the central baryon density. The line styles are identical in both panels.

$$E_{N'N'}^{\text{pot}} = \zeta' [V_n(\rho_{n'_1} + \rho_{n'_2}) + V_p(\rho_{p'_1} + \rho_{p'_2})],$$

$$E_{N'N'}^{\text{pot}} = \frac{\pi f_{N'N'}}{m_{N'}} (\rho_{N'_1} + \rho_{N'_2})^2,$$

where the nucleon potentials $V_{n,p}$ are given in Eqs. (6), and we take $f_{N'N'} \sim r_N^{\text{cor}} \approx 0.3$ fm. The chemical potentials of nucleons and N' are then

$$\mu_i = \frac{\partial(E_N + E_{N'N'}^{\text{pot}})}{\partial \rho_i}, \quad \mu_{i'} = \epsilon_{F,i'} + \frac{\partial(E_{N'N'}^{\text{pot}} + E_{N'N'}^{\text{pot}})}{\partial \rho_{i'}},$$

where $i = n, p$, $i' = n'_{1,2}, p'_{1,2}$, and $\epsilon_{F,i'} = (m_{N'_{1,2}}^2 + p_{F,i'}^2)^{1/2} - m_N$ with $p_{F,i} = (3 \pi^2 \rho_{i'})^{1/3}$. The β equilibrium requires that $\mu_n = \mu_{n'_1} = \mu_{n'_2}$ and $\mu_p = \mu_{p'_1} = \mu_{p'_2}$.

The composition of NS matter would be significantly changed in presence of N' resonances. For $\zeta' = 0$ and $f_{N'N'} = 0.3$ fm the neutron and proton concentrations decrease continuously starting from $\rho_B \approx 0.2\rho_0$ (in the approximation of a homogeneous medium) with neutrons being first replaced by n'_1 and then after $1.2\rho_0$ by n'_2 . At $\rho_B \approx 4\rho_0$ the chemical potential $\mu_{p'}$ exceeds $m_{N'}$. At this point all protons are replaced by p'_1 resonances, whose population grows slowly, reaching 0.5% at $10\rho_0$. The p'_2 resonances do not appear. The pressure of NS matter with N' resonances is shown in Fig. 2 (left panel) as a function of the energy density E^{rel} . We see that N' resonances make the EOS softer, decreasing the pressure by factor of about 2–5 for $0 \leq \zeta' \leq 1$ and $0.3 \text{ fm} \leq f_{N'N'} \leq 1 \text{ fm}$. The softness of the EOS increases with the increase of ζ and decrease of $f_{N'N'}$. In the right panel of Fig. 2 we show the masses of NS cores as a function of central baryon densities, ρ_c . The solid circles indicate the maximum masses of NSs, M_{max} . Since astronomical observations put the limit $M_{\text{max}} \geq 1.4M_{\odot}$ [15], we can conclude from Fig. 2 that *the existence of N' resonances would contradict information on the NS masses for $\zeta' \geq 0$ and $f_{N'N'} \leq 1 \text{ fm}$. To reach the observational limit of $1.4M_{\odot}$ the $N'N'$ repulsion should be as large as with $f_{N'N'} \geq 2 \text{ fm}$. A further stiffening of the EOS of nuclear matter (1) would*

not help since then N' resonances would appear at even smaller densities, leading to the same consequences for NSs.

IV. LIGHT PIONS

We follow now the assumption of Ref. [9] that there exist light pions ($\tilde{\pi}$) whose strong coupling constant is essentially suppressed.

Our approach here is similar to that one used for pion condensate systems; cf. [16,17] and references therein. Negative light pions could be accumulated in nuclei due to the reaction $n \rightarrow p + \tilde{\pi}^-$, if $\mu_n - \mu_p \geq \mu_{\tilde{\pi}}$. Having a suppressed strong coupling constant, light negative pions satisfy the Klein-Gordon equation

$$\Delta \phi + [(\omega - V)^2 - m_{\tilde{\pi}}^2] \phi = 0, \quad (10)$$

where ϕ is the $\tilde{\pi}^-$ wave function and V is the Coulomb potential well. Multiplying Eq. (10) by ϕ^* and averaging over the volume we find the solution

$$\omega = \bar{V} + [m_{\tilde{\pi}}^2 + \bar{k}^2 + (\bar{V})^2 - \bar{V}^2]^{1/2}, \quad (11)$$

where $\bar{k}^2 = \int |\nabla \phi|^2 d\vec{r}$. The critical value of the pion energy ω at the $\tilde{\pi}^-$ condensation point is $\omega = \mu_n - \mu_p \approx 0$, for isospin-symmetrical nuclei. For the light pions the Compton wavelength is ~ 10 fm, which is larger than the radius (R) of the nucleus. Thus, \bar{k}^2 is the dominating term in Eq. (11).

Let us first model a nucleus as a spherical potential well of the constant depth $V = -V_0 \approx -Ze^2/R$ for $r < R \approx 1.2A^{1/3}$ fm and $V = 0$ for $r > R$, where e is the electron charge and A the atomic number. Then the pion spectrum follows from the equation $kR \cot(kR) = -\lambda R$, with $k = \sqrt{(\omega + V_0)^2 - m_{\tilde{\pi}}^2}$ and $\lambda = \sqrt{m_{\tilde{\pi}}^2 - \omega^2}$. In the limit $Rm_{\tilde{\pi}} \ll 1$ the spectrum of deeply bound states can be found from the condition $\cos(kR) = 0$ and in the opposite limit $Rm_{\tilde{\pi}} \gg 1$ from $\sin(kR) = 0$. In the most favored case for the $\tilde{\pi}^-$ condensation [$\cos(kR) = 0$] the critical condition reads $V_0 = [m_{\tilde{\pi}}^2 + \pi^2/(4R^2)]^{1/2}$. For atomic nuclei (with the atomic number $A \leq 200$) we then estimate $[m_{\tilde{\pi}}^2 + \pi^2/(4R^2)]^{1/2} > 50$ MeV, and the critical condition is not yet achieved. The solution of Eq. (11) with the realistic Coulomb potential does not change this conclusion. *Thus, there is no $\tilde{\pi}^-$ condensate in atomic nuclei, their size and the value of the Coulomb field being too small for that.*

In Refs. [17,18] it was argued that, if there exist light bosons of mass < 30 MeV, then there could exist exotic objects, “nuclei stars,” of an arbitrary size, with density $\rho \sim \rho_0$, and which are bound by strong and electromagnetic interactions. The light pion proposed in Ref. [9] could play such a role. To demonstrate this idea, let us consider the spherical nuclear ball of a constant density $\approx \rho_0$ and radius $1 \text{ km} \gg R \gg m_{\tilde{\pi}}^{-1}$, consisting of A nucleons. Then we may neglect both surface and gravitational effects. The total energy is given by

$$\mathcal{E} \approx \mathcal{E}_0 A + S_0(A - 2Z)^2/A + Zm_{\tilde{\pi}}. \quad (12)$$

Minimizing the energy with respect to Z at fixed A , we get $Z/A \approx 0.41$ and the corresponding binding energy $\mathcal{E}_N/A \approx -5.7$ MeV. Although this quantity is slightly larger than the binding energy per particle for the α particle (-7 MeV), the $\tilde{\pi}$ nucleus cannot decay into α particles and light pions or atomic nuclei and light pions. The total energy per particle of $\alpha + 2\tilde{\pi}$ is ≥ -7 MeV $+ m_{\tilde{\pi}}/2 = 3$ MeV. This is larger than the energy per particle of the initial bound state (≈ -5.7 MeV). (This, however, does not exclude the possibility of weak radioactive decays of $\tilde{\pi}$ nuclei.) At finite temperature (excitation energy) $T > T_{c1} \sim$ several MeV, the binding energy reaches zero and the condensate melts. The system, however, still exists as a whole, being in a metastable state, until the excess of energy is smaller than $Zm_{\tilde{\pi}}$. Such an excited object cools down via γ and ν radiation from weak $\tilde{\pi}$ decays. At $T > T_c \sim m_{\tilde{\pi}}$ the system decays, expanding into the vacuum.

Consider light pions in NS matter. Here we first assume that the N' resonance and D' dibaryon do not exist as elementary particles, and the experiments [2,3,5] are explained with the help of the usual nucleons and the light pions only. In the case of homogeneous baryon matter $\tilde{\pi}^-$ mesons could appear already at the density $\rho_B \approx 0.05\rho_0$, when the electron chemical potential reaches $m_{\tilde{\pi}}$. Then at higher densities, in the NS interior, $\mu_e = m_{\tilde{\pi}}$, and the positive proton charge is compensated by the negative charge of the $\tilde{\pi}^-$ meson condensate. First, this leads to the isospin equilibration of NS matter, e.g., at $\rho = 2\rho_0$ the ratio $\rho_p/\rho_B \approx 0.44$, increasing further with the baryon density. Second, with the $\tilde{\pi}^-$ condensate the EOS of NS matter becomes softer, as is illustrated in Fig. 3. The pressure is negative at $0.3\rho_0 < \rho_B < \rho_0$, indicating that the system is self-bound at $\rho_B = \rho_0$ (when $P = 0$) even in the absence of gravity. The softening of the EOS reduces the maximal mass of the NS but still keeps this value above the observational limit of $1.4M_\odot$. Thus the existence of light pions would not contradict the observed NS masses. If light pions coexist with N' resonances and/or D' baryons, the EOS would be softer than in the case without light pions. Such a situation would contradict observable neutron star masses.

In heavy-ion collisions, $\tilde{\pi}$ mesons would contribute to dilepton spectra and could be seen as a peak in the dilepton spectrum at ~ 20 MeV energy.

V. SUMMARY

Being motivated by recent experimental studies [2,3,6] and their interpretations, we have investigated how the exist-

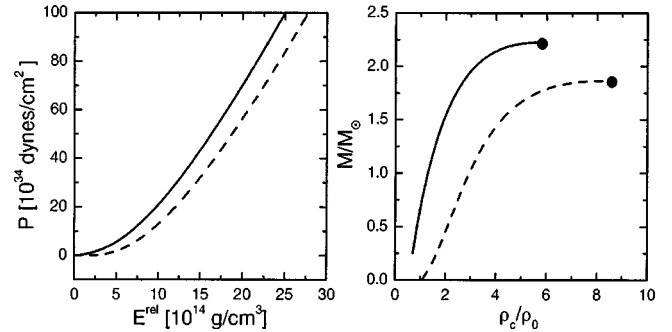


FIG. 3. Left panel: pressure of NS matter as a function of the relativistic energy density without (solid line) and with (dashed line) the presence of light pions $\tilde{\pi}$. Right panel: NS mass as a function of the central baryon density. The line styles are the same in both panels.

tence of exotic light dibaryons, nucleon resonances, and pions would manifest itself in nuclear systems. We have shown that dibaryons and N' resonances below the πN threshold would be absent in atomic nuclei if their interactions with nucleons are sufficiently small, as is demanded by their production rates. Also light pions cannot be accumulated in atomic nuclei.

In neutron star matter the new exotic states could manifest themselves in a remarkable way: they would drastically change the composition of a neutron star and make the equation of state much softer. The equation of state with dibaryons and nucleon resonances becomes so soft that it would not be able to support neutron stars with the observed masses. Thus the dibaryon and nucleon-resonance interpretations of the above-mentioned experiments should be questioned.

The existence of light pions would not lead to a contradiction with observed neutron star masses. The presence of light pions would allow the existence of abnormal nuclei ($A \geq 10^3$) and “nuclei stars” of arbitrary size, bound by strong and electromagnetic interactions.

Thus, the importance of the astrophysical consequences of the low-mass resonance states should strongly motivate further experimental investigations, as well as a search for new theoretical interpretations.

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