

Kaon Condensation and Dynamical Nucleons in Neutron Stars

Norman K. Glendenning and Jürgen Schaffner-Bielich

*Nuclear Science Division and Institute for Nuclear & Particle Astrophysics, Lawrence Berkeley National Laboratory,
University of California, Berkeley, California 94720*

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We discuss the nature of the kaon condensation phase transition. We find several remarkable features which, if kaons condense in neutron stars, will surely affect superfluidity and transport properties. The mixed phase region occupying a large fraction of the star is permeated with microscopic drops located at lattice sites of one phase immersed in the background of the other phase. The electric charge in the drops is opposite to that of the background phase *and* nucleons have a mass approximately a factor of 2 different depending on whether they are in the drops or the background phase. [S0031-9007(98)07730-8]

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Kaon condensation as well as pion condensation has been the focus of a number of papers over the years [1–10]. The possible presence of a kaon condensate in neutron stars has received special attention recently [11–14]. However, two important facets of the problem have not been realized: The dynamical nature of the nucleons, as well as stability with respect to the electric charge at the interface between phases. Both facets and their structural consequences for the true nature of the kaon condensed phase are elucidated here.

The effect of the nuclear medium on the energy of a test kaon has been studied by a number of authors, and it is believed that the interactions reduce the K^- energy as a function of baryon density [15–17]. Kaonic data support the conclusion that there is a highly attractive kaon optical potential in dense nuclear matter [18]. If the kaon energy intersects the electron chemical potential at some density, kaons thereafter will be energetically more favorable than electrons as the neutralizing agent of positive charge [7]. The very interaction that reduces the kaon energy modifies the nucleons with which they interact. Therefore, the kaon condensed phase is not merely nuclear matter in which kaons are present—it is a fundamentally different phase in every way, including the masses of nucleons.

Moreover, first order kaon condensation requires careful attention to the manner in which phase equilibrium is found so as to ensure a stable configuration. The Maxwell construction is inadequate for this purpose in neutron star matter, which has two conserved charges: Baryon number and electric charge (which vanishes globally). The Maxwell construction, which has formerly been employed in treatments of both first order pion [2–6] and kaon condensation [11–14], can ensure the equality of only one chemical potential in the two phases in equilibrium [19,20]. Therefore, if the equality of the baryon chemical potential has been ensured there must be a potential difference in the electron chemical potential at the interface of the two phases.

Details in the matters discussed in this paper will, of course, depend on the particular nuclear model and the

kaon interaction with nucleons. But the physics will be similar for any physically correct implementation. So as to emphasize the impact of kaon condensation we neglect the possible suppression by hyperons [7,21–23]. For the nucleon sector, we choose the standard nuclear field theory of nucleons interacting through scalar, vector, and vector isovector mesons (σ , ω , and ρ), solved in the mean field approximation [24]. The kaon is then coupled to the vector meson fields using minimal coupling

$$\mathcal{L}_K = \mathcal{D}_\mu^* K^* \mathcal{D}^\mu K - m_K^{*2} K^* K, \quad (1)$$

where

$$\mathcal{D}_\mu = \partial_\mu + ig_{\omega K} V_\mu + ig_{\rho K} \vec{\tau}_K \vec{R}_\mu. \quad (2)$$

The kaon and scalar fields are coupled through

$$m_K^* = m_K - g_{\sigma K} \sigma. \quad (3)$$

We choose to couple the vector fields according to the simple quark and isospin counting rule

$$g_{\omega K} = \frac{1}{3} g_{\omega N} \quad \text{and} \quad g_{\rho K} = g_{\rho N}. \quad (4)$$

The scalar coupling constant $g_{\sigma K}$ is fixed to the optical potential of the K^- at normal nuclear density ρ_0 ,

$$U_K(\rho_0) = -g_{\sigma K} \sigma(\rho_0) - g_{\omega K} V_0(\rho_0). \quad (5)$$

Coupled channel calculations find an optical potential between -100 MeV [16] and -120 MeV [17]. We choose the latter value in the following. The five coupling constants in the nucleon sector are determined algebraically [24] to reproduce the saturation properties of symmetric nuclear matter; $E/A = -16.3$ MeV, $\rho_0 = 0.153$ fm $^{-3}$, $a_{\text{sym}} = 32.5$ MeV, $K = 240$ MeV, and $m^*/m = 0.78$.

The equation of motion for the kaon can be written as

$$[\mathcal{D}_\mu \mathcal{D}^\mu + m_K^{*2}] K = 0. \quad (6)$$

One gets then a dispersion relation for the K^- for s -wave condensation ($\vec{k} = 0$) of the form

$$\omega_K = m_K - g_{\sigma K} \sigma - g_{\omega K} V_0 - g_{\rho K} R_{0,0}. \quad (7)$$

It is possible to satisfy Gibbs conditions for phase equilibrium simultaneously with conservation laws for substances of more than one conserved charge *only* by applying the conservation law(s) in a *global* rather than a *local* sense [19,20]. Thus for neutron star matter, which has two conserved charges, the Gibbs conditions and conservation of electric charge read

$$p_N(\mu_B, \mu_e) = p_K(\mu_B, \mu_e), \quad (8)$$

$$q_{\text{total}} = (1 - \chi)q_N(\mu_B, \mu_e) + \chi q_K(\mu_B, \mu_e) = 0, \quad (9)$$

where q_N and q_K denote the charge densities including leptons in the normal and kaon condensed phase, μ_B the baryochemical potential, and μ_e the electrochemical potential. This pair of equations can be solved for μ_B and μ_e for any proportion of kaon phase χ in the interval (0,1). Therefore the chemical potentials are functions of proportion χ and therefore also all other properties of the two phases, including, very importantly, the common pressure. The total baryon density for the chosen χ and corresponding chemical potentials is given by

$$\rho_{\text{total}} = (1 - \chi)\rho_N(\mu_B, \mu_e) + \chi\rho_K(\mu_B, \mu_e), \quad (10)$$

where ρ denotes baryon density. The equation of state is shown in Fig. 1 and compared with that of a Maxwell construction and the corresponding sequence of neutron stars in Fig. 2 where the maximum mass can be read as $1.56M_\odot$. Since the pressure varies monotonically in a star, a mixed phase of the Maxwell type would be totally absent because the constant pressure is mapped onto a single radial point. Gravity squeezes out a constant pressure mixed phase. This has been so in all previous treatments of first order kaon condensation [12–14] as well as pion condensation [2–6].

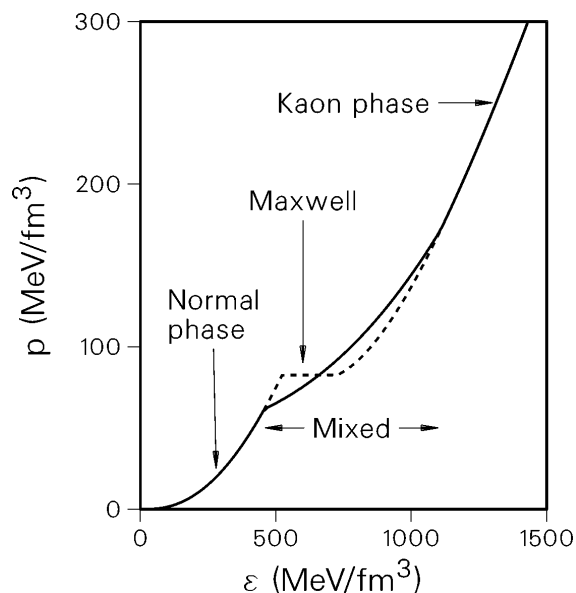


FIG. 1. The equation of state with the three phases indicated. Pressure increases monotonically for Gibbs equilibrium. The pressure range of the mixed phase exceeds that of the normal phase. The Maxwell construction is shown for comparison.

We can trace the density dependence of energy ω_K of a test kaon in the normal medium as depicted in Fig. 3. The kaon energy decreases with increasing density because of the attractive vector potential. At some density it may intersect the electron chemical potential. At the density for which the equality $\omega_K = \mu_e$ first holds, kaons of modified mass occupy a small volume fraction of the total medium with a number density of

$$n_K = 2(\omega_K + g_{\omega K}V_0 + g_{\omega K}R_{0,0})K^*K = 2m_K^*K^*K. \quad (11)$$

The energy of these medium modified kaons is less than that of a test kaon in the normal phase even when the two phases are in equilibrium, as seen in Fig. 3.

The kaon-nucleon interaction affects not only the kaon mass in the medium, but also the nucleon mass. Therefore, in the mixed phase of normal and condensed matter, the nucleon mass is different by a factor of more than 2, as seen in Fig. 4, depending on which region of the mixed phase the nucleon is in.

The imposition of charge conservation as a global constraint, as in (9), rather than as a local constraint, is not only necessary so that Gibbs equilibrium can be achieved—it is also necessary so as to find the lowest energy state [19,20]. In general, the lowest energy state in the mixed phase of a substance of more than one conserved charge is achieved by the exchange of conserved quantities between the phases in equilibrium, the exchange being driven by an internal force. In the case of neutron star matter, the internal force is the isospin driving force to which both the Fermi energies and the specific nuclear force (coupling of the rho meson to the isospin) contribute. The normal phase of neutron star matter is highly isospin asymmetric because of the constraint of charge neutrality imposed by

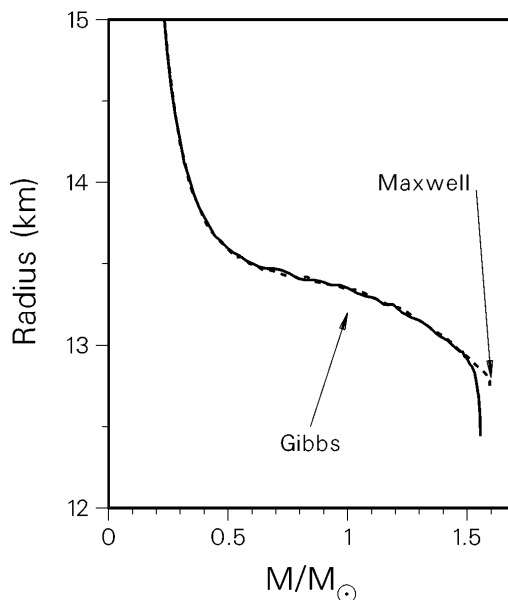


FIG. 2. Mass-radius relation of neutron stars corresponding to Fig. 1.

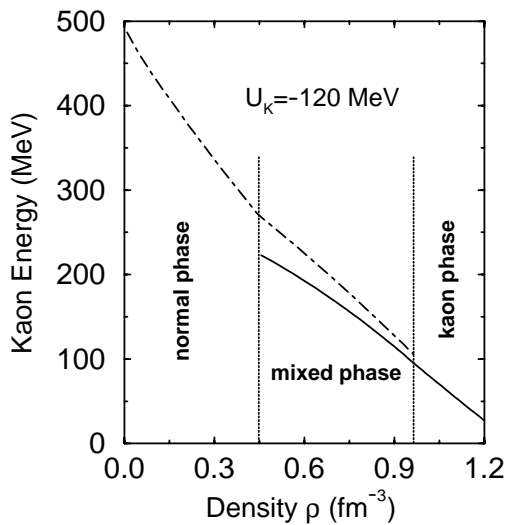


FIG. 3. Dashed line shows the medium modified energy of a test kaon. The energy of the real kaons begins in the condensed fraction of the mixed phase (solid line).

gravity. The isospin symmetry energy of nuclear matter drives a redistribution of charge between the normal and condensed phase as soon as some of the latter is formed. In this way the repulsive isospin energy can be reduced and the normal phase becomes more symmetric in neutrons and protons as the proportion of kaon phase increases.

For the above reason, the kaon phase is maximally negatively charged when its volume fraction is small and the charge density of this phase approaches zero as it becomes the dominant phase. Such behavior is easy to understand: under the constraint of charge neutrality, the total energy can be optimized by a configuration that places the dominant phase closest to its lowest energy, even at the expense of the rarer phase being far from its

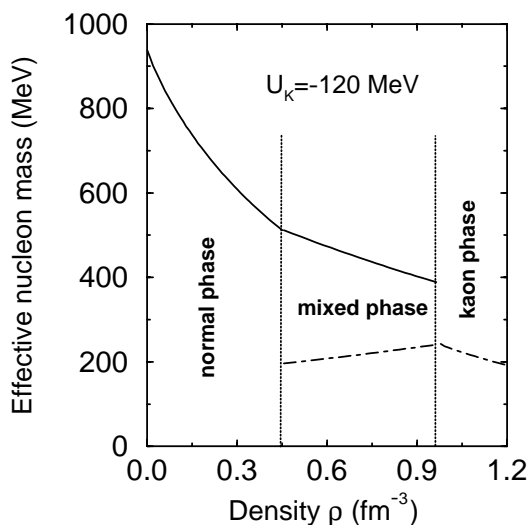


FIG. 4. The effective nucleon mass in the three phases. The nucleon masses differ by a factor of 2 or more in the regions of the mixed phase occupied by normal and kaon phases, respectively, being smaller in the latter.

optimum. The volume weighted charge densities sum to zero as required for a stellar medium which must be neutral on account of the disproportionate strength of the long-range forces—Coulomb and gravitational. The oppositely charged densities as a function of position in the star are shown in Fig. 5 and are seen to vary strongly as a function of position in the star as the kaon phase becomes more dominant at greater depth. Of course, the charge density vanishes identically in the pure homogeneous phases.

The mixed phase of normal and kaon condensed matter, having opposite electric charge, will form a Coulomb lattice of the rarer phase immersed in the dominant. The competition between Coulomb and surface interface energy will determine the size of the rare phase objects, their geometry and their spacing in the background of the dominant phase [19,20,25–27]. The idealized geometrical structures that appear in our model star are illustrated in Fig. 6, which shows the diameter (D) of objects at lattice sites and their spacing (S) as a function of position in the star. Sizes and spacings depend on the surface tension as $\sigma^{1/3}$ and is proportional to the difference in the energy densities of the phases in contact [26]. For the present choice of parameters the pure kaon phase does not appear and the geometrical phases terminate with slabs of normal hadronic matter embedded in the kaon condensed phase. If the optical potential (5) were stronger, the geometries would span the full range from kaon-condensed-phase drops immersed in normal matter to the inverse, and the pure kaon condensed phase would occupy the core of the star. Of course, further investigations are needed to disclose details of the geometrical structures, including, for example, a computation of the surface tension between phases.

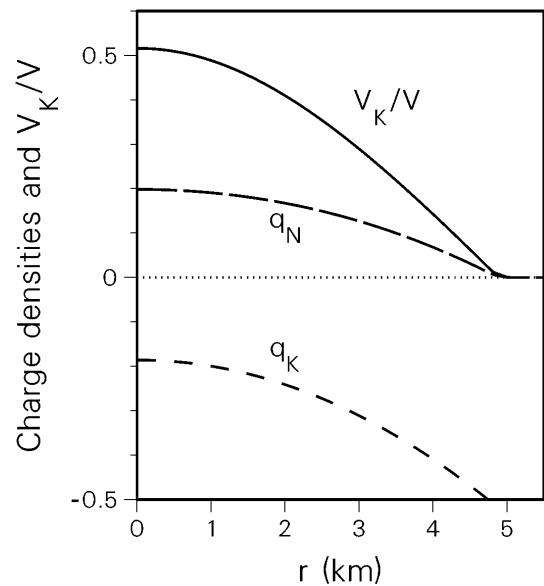


FIG. 5. Charge density on regions of normal and kaon condensed phase in the region of mixed phase in a neutron star at the mass limit. The volume weighted sum is zero. The fraction of the kaon phase is also shown.

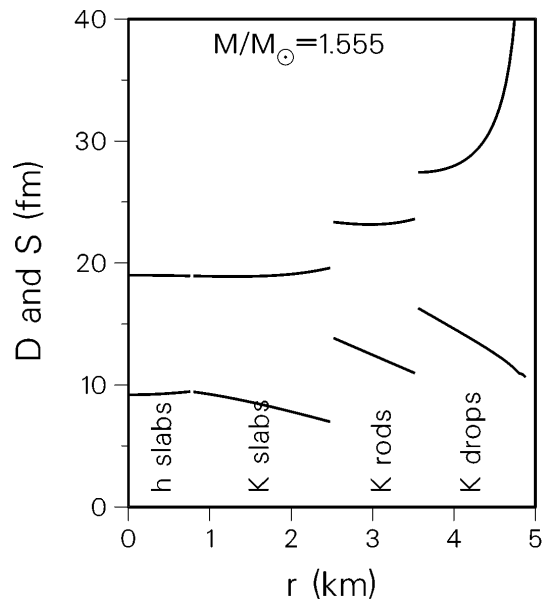


FIG. 6. The diameter (D) (lower curve) and spacing (S) of geometrical structures at lattice sites in the mixed phase are shown as a function of position in the star. Shapes of the rare phase object immersed in the dominant phase background are denoted by K drops for kaon condensed phase droplets, and h slabs for normal hadronic phase slabs, etc.

From the above results the following picture emerges. If kaons condense in neutron stars, there will exist a region where normal matter will coexist in phase equilibrium with the condensed phase. The properties of the mixed phase are particularly noteworthy. It will occupy a wide radial extent of the star because of the wide range of pressure that it exists under. It is dotted by electrically charged blobs of one phase immersed in the other phase of opposite charge, all arranged on a Coulomb lattice. The size of the objects at the lattice sites, their geometry and their spacing, will vary with depth in the star because of the pressure variation. More than this, the eigenmass of nucleons are different by a factor of 2 or more in the background phase than in the blobs occupying the lattice sites *and* also vary with depth in the star. All of these remarkable properties certainly give food for thought as to what the superfluid and transport properties might be for such an unusual configuration of matter, as well as for the cooling and glitch behavior of pulsars. The kaon condensation phase transition might be signaled in pulsar timing just as for the deconfined phase transition [28].

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