Bose-Einstein condensation in dense nuclear matter and strong magnetic fields

Prantick Dey[(a)], Abhijit Bhattacharyya[(b)] and Debades Bandyopadhyay[(c)]
[(a)] *Physics Department, Raja Peary Mohan College, Uttarpara, Hooghly 712258, India*
[(b)] *Physics Department, Scottish Church College, 1 & 3 Urquhart Square, Calcutta 700006, India*
[(c)] *Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Calcutta 700 064, India*

Abstract

Bose-Einstein condensation of antikaons in cold and dense beta-equilibrated matter under the influence of strong magnetic fields is studied within a relativistic mean field model. For magnetic fields $> 5 \times 10^{18}$G, the phase spaces of charged particles are modified resulting in compositional changes in the system. The threshold density of K^- condensation is shifted to higher density compared with the field free case. In the presence of strong fields, the equation of state becomes stiffer than that of the zero field case.

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Recently, it has been inferred that some soft gamma ray repeaters (SGRs) and perhaps certain anomalous X-ray pulsars (AXPs) could be neutron stars having large magnetic fields $\sim 10^{14} - 10^{16}$ G [1]. Those objects are called "magnetars" [2]. Earlier large magnetic fields $\sim 10^{13}$G were estimated to be associated with the surfaces of some radio pulsars [3]. The origin of such ultra strong magnetic fields is still an unsolved problem. An attractive idea about the origin is that the small magnetic field of a progenitor star is amplified due to the magnetic flux conservation during the gravitational collapse of the star [3]. Recently, Thomson and Duncan argued that a convective dynamo mechanism might result in large fields $\sim 10^{15}$G [4]. On the other hand, it is presumed from the scalar virial theorem [5] based on Newtonian gravity that the limiting interior field in neutron stars could be as large as $\sim 10^{18}$G [6]. From the general relativistic calculation of axis-symmetric neutron stars in magnetic fields, it follows that neutron stars could sustain magnetic fields $\sim 10^{18}$G [7,8]. Because of highly conducting core, such large interior fields may be frozen and could not be directly accessible to observation. Its effects may be manifested in various observables such as the mass-radius relationship, neutrino emissivity etc. Motivated by the existence of large fields in the core of neutron stars, its influence on the gross properties of neutron stars was studied by various groups [6,9,10,11]. The calculations in the relativistic mean field (RMF) approach showed that the equation of state (EoS) was modified due to the Landau quantization and also by the interaction of magnetic moments of baryons with the field [11]. The intense magnetic field was found to change the composition of beta equilibrated matter relevant to neutron stars drastically [9,10,11]. The neutrino emissivity in neutron stars was reported to be enhanced in strong magnetic fields [12].

Besides strong interior fields, many exotic forms of matter may exist in the dense core of neutron stars. One such possibility is the appearance of the Bose-Einstein condensate of strange particles. Nelson and Kaplan first pointed out that antikaons may undergo the Bose-Einstein condensation (BEC) in dense matter at zero temperature because of the attractive s-wave antikaon-nucleon interaction [13]. Later, this idea was applied to neutron stars by various authors [14,15,16]. Bose-Einstein condensation in a magnetic field is an old and interesting problem in other branches of physics also namely condensed matter physics and statistical physics. It was shown by Schafroth [17] that a non-relativistic Bose gas could not condense in an external magnetic field. There are some calculations on the condensation of relativistic charged Bose gas in magnetic fields in the literature [18,19]. Elmfors and collaborators [18] noted that the relativistic Bose gas might condense for spatial dimension $d \geq 5$. They showed that the number density of bosons in the ground state diverges for $d < 5$ in the presence of a magnetic field. On the other hand, it was argued [19] that the condensation of bosons in a magnetic field could occur in three dimension if the chemical potential of bosons was taken as a function of density, temperature and magnetic field [19]. In this case, the BEC would be a diffuse one because there is no definite critical temperature. It was also shown in the latter calculation [19] that the number density of bosons in the ground state was finite. Recently, Suh and Mathews [10] have studied pion condensation in a beta equilibrated non-interacting n-p-e-μ system in magnetic fields.

In this paper, we investigate the influence of strong magnetic fields on the Bose-Einstein condensation of antikaons in cold and dense matter relevant to neutron stars. This may have profound implications on the gross properties of neutron stars. This method of studying the BEC in strong magnetic fields and dense matter is rather general; therefore it should be of correspondingly broad interest.

We consider strong magnetic field effects on antikaon condensation in the beta equilibrated neutron star matter composed of neutrons, protons, electrons, muons and K^- mesons within the framework of a relativistic field theoretical model [20]. As the constituents in neutron stars are highly degenerate, the chemical potentials of baryons are larger than the temperature of the system. Therefore, the gross properties of neutron stars are calculated at zero temperature. The total Lagrangian density may be written as the sum of baryonic, kaonic and leptonic parts i.e. $\mathcal{L} = \mathcal{L}_B + \mathcal{L}_K + \mathcal{L}_l$. In a uniform magnetic field, the baryonic Lagrangian density [21] is given by

$$\begin{aligned}\mathcal{L}_B = &\sum_{B=n,p} \bar{\psi}_B \left(i\gamma_\mu D^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu\omega^\mu - g_{\rho B}\gamma_\mu \boldsymbol{t}_B \cdot \boldsymbol{\rho}^\mu - \kappa_B \sigma_{\mu\nu} F^{\mu\nu}\right)\psi_B \\ &+ \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2\right) - U(\sigma) \\ &- \sum_{k=\omega,\rho}\left[\frac{1}{4}\left(\partial_\mu V_\nu^k - \partial_\nu V_\mu^k\right)^2 - \frac{1}{2} m_k^2 (V_\mu^k)^2\right] + \frac{1}{4} g_4 \left(\omega_\mu \omega^\mu\right)^2 - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \ . \qquad (1)\end{aligned}$$

Here ψ_B denotes the Dirac spinor for baryon B with vacuum mass m_B and isospin operator $\boldsymbol{t}_B$. The scalar self-interaction term [22] is, $U(\sigma) = g_2\sigma^3/3 + g_3\sigma^4/4$. Following Ref. [11], the interaction of anomalous magnetic moments of baryons with magnetic fields is given by the last term under the summation in Eq.(1). Here, $F^{\mu\nu}$ is the electromagnetic field tensor, $\sigma_{\mu\nu} = [\gamma_\mu, \gamma_\nu]/2$ and κ_B is the experimentally measured value of magnetic moment for baryon B. The covariant derivative for a charged particle is $D^\mu = \partial^\mu + iqA^\mu$ with the choice of gauge corresponding to the constant magnetic field (B_m) along z-axis is $A_0 = 0$, $\mathbf{A} \equiv (0, xB_m, 0)$. The form of 4-component spinor solutions for baryons is given by Ref. [11]. The (anti)kaon-nucleon interaction is treated in the same footing as that of the nucleon-nucleon interaction [15]. Therefore, the kaonic Lagrangian density in a magnetic field is given as,

$$\mathcal{L}_K = D_\mu^* K^* D^\mu K - m_K^{*2} K^* K \ , \qquad (2)$$

where the covariant derivative $D_\mu = \partial_\mu + iqA_\mu + ig_{\omega K}\omega_\mu + ig_{\rho K}\boldsymbol{t}_K \cdot \boldsymbol{\rho}_\mu$. There is no interaction term involving magnetic moments in the kaonic Lagrangian density because (anti)kaons having zero spin angular momentum do not possess magnetic moments. The effective mass of (anti)kaons in this minimal coupling scheme is given by $m_K^* = m_K - g_{\sigma K}\sigma$. The solution for negatively charged kaons in a magnetic field is $K \propto (qB_m/\pi)^{1/4}\,(1/\sqrt{2^n n!})\mathrm{e}^{-i\omega_{K^-}t + ip_y y + ip_z z}\mathrm{e}^{-qB_m\eta^2/2} H_n(\sqrt{qB_m}\eta)$, where $\eta = x + p_y/qB_m$, "H" denotes the Hermite polynomial with n the Landau principal quantum number. The Lagrangian density for neutrons is obtained by putting $q = 0$ in the covariant derivatives of Eq. (1). In the mean field approximation [20], the meson field equations in the presence of antikaon condensate and magnetic field are

$$m_\sigma^2 \sigma = -\frac{\partial U}{\partial \sigma} + \sum_B g_{\sigma B} n_B^S + g_{\sigma K} \frac{m_K^*}{\sqrt{m_K^{*2} + qB_m}} n_{K^-} \ , \qquad (3)$$

$$m_\omega^2 \omega_0 + g_4 \omega_0^3 = \sum_B g_{\omega B} n_B - g_{\omega K} n_{K^-} \ , \qquad (4)$$

$$m_\rho^2 \rho_{03} = \sum_B g_{\rho B} I_{3B} n_B + g_{\rho K} I_{3K^-} n_{K^-} \ . \qquad (5)$$

where n_B and n_B^s are baryon and scalar density for baryon B respectively; $I_{3B} = +1/2$ for protons, $-1/2$ for neutrons and $I_{3K^-} = -1/2$ for K^- mesons. The expressions of the scalar and baryon density corresponding to protons are given by [11]

$$n_p^s = \frac{|q_p|B_m}{2\pi^2} \sum_\nu \sum_s m_p^* \frac{\overline{m_p}}{\overline{m_p} - s\kappa_p B_m} \ln\left(\left|\frac{E_f^p + k_{f,\nu,s}^p}{\overline{m_p}}\right|\right) , \tag{6}$$

and

$$n_p = \frac{|q_p|B_m}{2\pi^2} \sum_\nu \sum_s k_{f,\nu,s}^p , \tag{7}$$

where the energy spectrum for protons is given by

$$E_{p,\nu,s} = \sqrt{k_z^2 + \left(\sqrt{m_p^{*\,2} + 2\nu q_p B_m} + s\kappa_p B_m\right)^2} + g_{\omega_p}\omega_0 + \frac{1}{2} g_{\rho_p}\rho_{03} , \tag{8}$$

$$\overline{m_p} = \sqrt{m_p^{*\,2} + 2\nu q_p B_m} + s\kappa_p B_m , \tag{9}$$

and

$$k_{f,\nu,s}^p = \sqrt{E_f^{p\,2} - \left(\sqrt{m_p^{*\,2} + 2\nu q_p B_m} + s\kappa_p B_m\right)^2} . \tag{10}$$

Similarly for neutrons, those expressions are given by [11]

$$n_n^s = \frac{m_n^*}{4\pi^2} \sum_s k_{f,s} E_f^n - \overline{m}^2 \ln\left(\left|\frac{E_f^n + k_{f,s}}{\overline{m}}\right|\right) , \tag{11}$$

and

$$n_n = \frac{1}{2\pi^2} \sum_s \frac{1}{3} k_{f,s}^3 + \frac{1}{2} s\kappa_n B_m \left[\overline{m} k_{f,s} + E_f^{n\,2}\left(\arcsin\frac{\overline{m}}{E_f^n} - \frac{\pi}{2}\right)\right] , \tag{12}$$

where

$$E_{n,s} = \sqrt{k_z^2 + \left(\sqrt{m_n^{*\,2} + k_x^2 + k_y^2} + s\kappa_n B_m\right)^2} + g_{\omega_n}\omega_0 - \frac{1}{2} g_{\rho_n}\rho_{03} , \tag{13}$$

$$\overline{m} = m_n^* + s\kappa_n B_m , \tag{14}$$

and

$$k_{f,s} = \sqrt{E_f^{n\,2} - \overline{m}^2} . \tag{15}$$

Solving the equation of motion for antikaons, the in-medium energy of K^- meson in a magnetic field is obtained as $\omega_{K^-} = \sqrt{p_z^2 + m_K^{*2} + qB_m(2n+1)} - g_{\omega K}\omega_0 - g_{\rho K}\rho_{03}/2$. The condition for the condensation of K^- meson in a magnetic field is $p_z = 0$ and $n = 0$. The number density of K^- meson in a magnetic field and in the ground state is obtained from the relation $J_\mu^K = i(K^* \partial\mathcal{L}/\partial^\mu K^* - \partial\mathcal{L}/\partial^\mu K \ K)$ and it is given by, $n_{K^-} = -J_0^{K^-} = 2(\omega_{K^-} + g_{\omega K}\omega_0 + g_{\rho K}\rho_{03}/2)K^* K$. The total energy density is given by

$$\begin{aligned}\varepsilon = &\frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{3}{4}g_4\omega_0^4 + \frac{1}{2}m_\rho^2\rho_{03}^2 \\ &+ \sum_{B=n,p}\varepsilon_B + \sum_l \varepsilon_l + \varepsilon_{\bar{K}} \ ,\end{aligned} \tag{16}$$

where ε_B and ε_l correspond to the kinetic energy densities of baryons and leptons respectively. The kinetic energy densities of protons and neutrons in a magnetic field are given by [11]

$$\varepsilon_p = \frac{|q_p|B_m}{4\pi^2}\sum_\nu\sum_s E_f^p k_{f,\nu,s}^p + \overline{m_p}^2 \ln\left(\left|\frac{E_f^p + k_{f,\nu,s}^p}{\overline{m_p}}\right|\right) , \tag{17}$$

and

$$\begin{aligned}\varepsilon_n = &\frac{1}{4\pi^2}\sum_s \frac{1}{2}E_f^{n\ 3} k_{f,s} + \frac{2}{3}s\kappa_n B_m E_f^{n\ 3}\left(\arcsin\frac{\overline{m}}{E_f^n} - \frac{\pi}{2}\right) \\ &+ \left(\frac{1}{3}s\kappa_n B_m - \frac{1}{4}\overline{m}\right)\left[\overline{m}k_{f,s}E_f^n + \overline{m}^3 \ln\left(\left|\frac{E_f^n + k_{f,s}}{\overline{m}}\right|\right)\right] .\end{aligned} \tag{18}$$

Similarly, the expression for the kinetic energy density of electrons has the same form as that of protons but electrons are noninteracting and anomalous magnetic moment of electrons is not considered here [11]. The energy density for antikaons in the condensate state is $\varepsilon_{\bar{K}} = \sqrt{m_K^{*2} + qB_m}\ n_{K^-}$. The other terms in Eq. (16) represent interaction energy densities. The pressure of the system follows from the relation $P = \mu_n n_b - \varepsilon$, where μ_n and n_b are the neutron chemical potential and total baryon density, respectively. In the core of neutron stars, strangeness changing processes such as $n \rightleftharpoons p + K^-$ and $e^- \rightleftharpoons K^- + \nu_e$ occur. The chemical equilibrium yields $\mu_n - \mu_p = \mu_{K^-} = \mu_e$, where μ_p and μ_{K^-} are respectively the chemical potentials of protons and K^- mesons. Employing Eq. (3) in conjunction with the chemical equilibrium conditions and charge neutrality $n_p - n_{K^-} - n_e - n_\mu = 0$, we obtain the effective masses self-consistently.

In the effective field theoretical approach adopted here, two different sets of coupling constants for nucleons and kaons with σ, ω and ρ meson are required. The nucleon-meson coupling constants are obtained by fitting experimental data for binding energies and charge radii for heavy nuclei [21]. This set of parameters is known as TM1 set. The values of coupling constants are $g_{\sigma N} = 10.0289$, $g_{\omega N} = 12.6139$, $g_{\rho N} = 4.6322$, $g_2 = -7.2325 fm^{-1}$, $g_3 = 0.6183$ and $g_4 = 71.3075$. The incompressibility of matter at normal nuclear matter density ($n_0 = 0.145 fm^{-3}$) is 281 MeV for the TM1 model. According to the simple quark model and isospin counting rule, the kaon-vector meson coupling constants are $g_{\omega K} = \frac{1}{3}g_{\omega N}$ and $g_{\rho K} = g_{\rho N}$. On the other hand, the scalar coupling constant is obtained from the real part of the antikaon optical potential at normal nuclear matter density i.e. $U_{\bar{K}}(n_0) = -g_{\sigma K}\sigma - g_{\omega K}\omega_0$ [16]. In this calculation, we have taken $U_{\bar{K}}(n_0) = -160$ MeV and the scalar coupling is $g_{\sigma K} = 2.0098$.

The TM1 model was adopted earlier for the description of heavy nuclei and the equation of state for neutron stars [21]. Besides the non-linear σ meson terms, the model also includes non-linear ω meson term. It was shown [21] that the TM1 model reproduced scalar and vector potentials close to those of the relativistic Brueckner Hartree Fock calculation using the realistic nucleon-nucleon interaction [23]. Recently, the TM1 model was used for the investigation of antikaon condensation in neutron star matter [16] for zero field. For TM1 parameter set, it was found that the phase transition was of second order [15,16]. In the TM1 model, the maximum masses and central densities of neutron stars without and with antikaon condensation where $U_{K^-} = -160$ MeV are respectively, $2.179(1.857)M_\odot$ and $5.97(6.37)n_0$.

In Figure 1, number densities of various particles are plotted with baryon density. The particle densities for $B_m = 0$ are shown by the solid lines, whereas those corresponding to $B_m = 1.5 \times 10^5 B_c^e$ are denoted by the dashed lines. The critical field for electrons (B_c^e) is that value where cyclotron quantum is equal to or above the rest energy of an electron and its value is $B_c^e = 4.414 \times 10^{13}$G. Here we note that the formation of K^- condensation is delayed to higher density than the field free case. The threshold densities of K^- condensation corresponding to $B_m = 0$ and $B_m = 1.5 \times 10^5 B_c^e$ are $2.67n_0$ and $3.85n_0$ respectively. The delayed appearance of K^- condensation may be attributed to the stiffer EoS because of the effects of magnetic moments. In the presence of the field, the enhancement of electron and muon fraction are pronounced whereas the proton fraction is smaller than the zero field value beyond $2.7n_0$. With the appearance of K^- condensate, it would try to diminish electron and muon density. On the other hand, the phase spaces of electrons and muons are so strongly modified in a quantizing field that their fractions are significantly increased. The net result is the reduction in the density of K^- condensate than that of the field free case. The proton density increases after the onset of K^- condensation. The neutron fraction also increases because of the interaction of anomalous magnetic moment of neutrons with the field. This may have important effects on the equation of state.

In the presence of magnetic fields $> 5 \times 10^{18}$G, the nucleon effective mass is enhanced in the high density regime than that of the field free case. This may be attributed to the effects of magnetic moments as it was also noted in Ref. [11]. The (anti)kaon effective mass in magnetic fields does not change appreciably from the zero field case.

The onset of K^- condensation is given by the equality of K^- chemical potential (μ_{K^-}) with electron chemical potential (μ_e). In the presence of magnetic field, we find the hadronic phase smoothly connects to the antikaon condensate phase resulting in a second order phase transition as it is evident from equation of state (pressure versus energy density curve) in Figure 2. For TM1 parameter set, we note that the phase transition is of second order with and without magnetic field.

In Figure 2, matter pressure (P) versus matter energy density (ϵ) is displayed for $B_m = 0$ (curve I), $B_m = 4 \times 10^4 B_c^e$ (curve II) and $B_m = 1.5 \times 10^5 B_c^e$ (curve III). For $B_m = 4 \times 10^4 B_c^e$, we note that the curve becomes slightly stiffer with the onset of K^- condensation. This stiffening may be attributed to the large enhancement in electron and muon fraction in the field. However, this effect is reduced in the high density regime where electron and muon fraction become small. As the field is further increased to $B_m = 1.5 \times 10^5 B_c^e$, not only electrons and muons are strongly Landau quantized, but also protons are populated in the zeroth Landau level. It was shown [9,11] that Landau quantization of charged particles was responsible for the softening in the equation of state. On the other hand, the effects of baryon magnetic moments for $B_m = 1.5 \times 10^5 B_c^e$ overwhelm the effects of Landau quantization. Consequently, the curve corresponding to $B_m = 1.5 \times 10^5 B_c^e$ stiffens further. It is found here that the effects of magnetic moments are important for $B_m > 10^5 B_c^e$. Besides the effects of Landau quantization and magnetic moments, the contribution of electromagnetic field to the matter energy density and pressure is to be taken into account. The magnetic energy density and pressure, $\varepsilon_f = P_f = B_m^2/(8\pi) = 4.814 \times 10^{-8}(B_m/B_c^e)^2 MeV fm^{-3}$, become significant in the core of the star for $B_m \geq 10^5 B_c^e$.

In this calculation, we have considered interior magnetic field $> 5 \times 10^{18}$G. However, it was found in a recent calculation [24] that the maximum value of the magnetic field within a star may not exceed 3×10^{18}G for a particular choice of a constant current function but independent of an EoS. In this case, the ratio of the maximum field to the average field is not large because of small spatial gradient. The authors [24] argued that the value of maximum field at any point may well exceed the average value as mentioned above for a different field geometry. In that event the effects of strong magnetic field $> 5 \times 10^{18}$G on the threshold of antikaon condensation, particle composition and EoS might be important.

To summarise, in this paper, we have focused on the formation of the antikaon condensation in dense nuclear matter in the presence of magnetic fields. We have considered the interaction of magnetic moments of baryons with the field and the magnetic energy density and pressure in this work. In the presence of strong magnetic fields $> 5 \times 10^{18}$G, we find a considerable change in the phase spaces of charged particles. The threshold density of K^- condensation is delayed to higher density in the presence of such a strong field and the EoS becomes stiffer. For $B_m > 10^{18}$G, the effects of magnetic moments are important and it adds to further stiffening of the equation of state. Also, the electromagnetic field contribution to the energy density and pressure becomes important in the core for $B_m > 10^{18}$G. The stiffening of the EoS in the presence of magnetic fields might have significant impact on the gross properties of neutron stars such as the mass-radius relationship, cooling etc. It is worth mentioning here that (anti)kaons do not interact with magnetic fields in the same way as fermions do because their spin angular momentum is zero.

In this calculation, we do not include the role of hyperons, pion condensation and nucleon-nucleon correlation on the antikaon condensation. Negatively charged hyperons, in particular Σ^- hyperon, could delay the onset of K^- condensation [14]. However, it was estimated that Σ^--nucleon interaction is highly repulsive in normal nuclear matter [25]. Recently, it has been also shown that threshold densities of most hyperons including Σ^- are substantially increased in strong magnetic field $B_m > 5 \times 10^{18}$G both due to Landau quantisation and magnetic moment interactions [24]. In this situation, Σ^- hyperons might have no impact on K^- condensation. Pion condensation could occur in neutron stars because of the attractive p-wave pion-nucleon interaction [26]. The condensation of π^- may modify the electron chemical potential which, in turn, would delay K^- condensation. In this paper, we have employed the RMF model which does not include nucleon-nucleon correlations. It was shown in non relativistic models [27] that nucleon-nucleon correlations shifted the threshold density of K^- condensation to higher density. We believe that the qualitative features of strong magnetic fields presented here would survive even in other models which include hyperons, pion condensation and nucleon-nucleon correlations. It would be interesting to look into the neutrino emissivity from an antikaon condensed matter and the structure of compact stars having antikaon condensate in the presence of a strong magnetic field.

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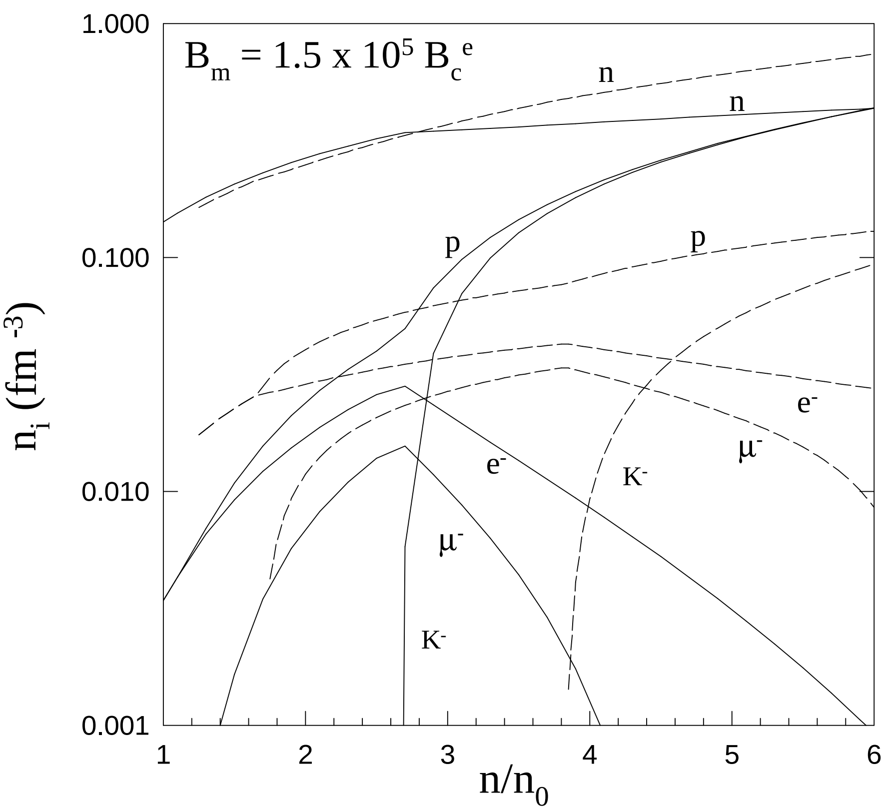

Fig.1 : The particle abundances are plotted with normalised baryon density for $B_m = 0$ and $B_m = 1.5 \times 10^5 B_c^e$. Solid lines indicate particle abundances for field free case whereas dashed lines denote those with the magnetic field. The critical electron field (B_c^e) is 4.414×10^{13}G.

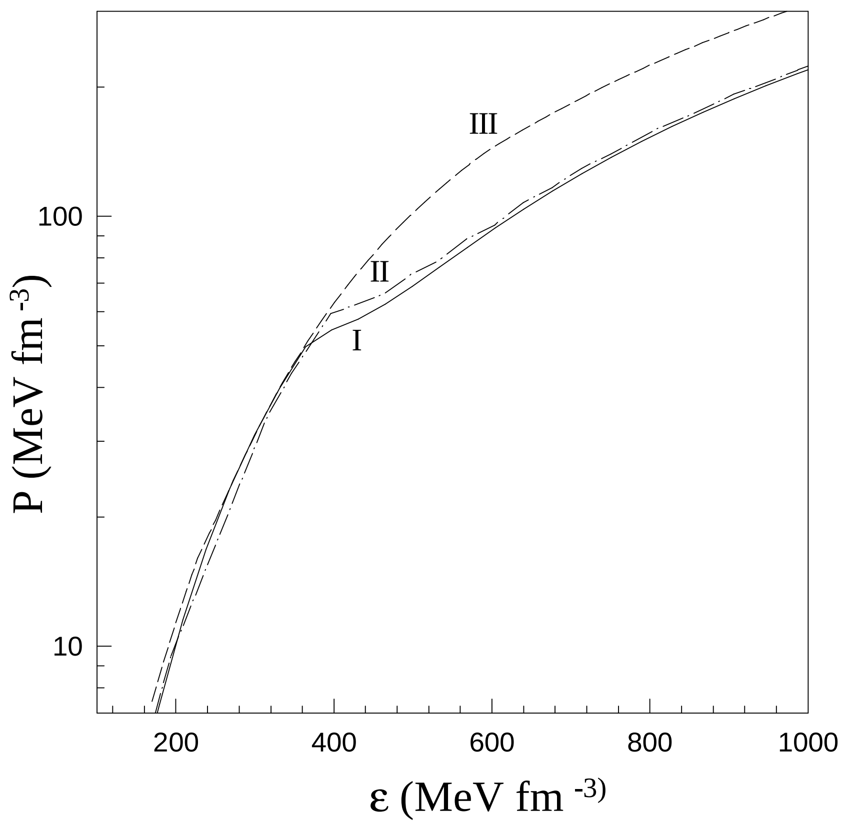

Fig.2 : The matter pressure (P) is shown as a function of matter energy density (ε) for different values of B_m. The field free case is shown by curve I (solid line) and curve II (dash-dotted line) and curve III (dashed line) represent calculations for $B_m = 4 \times 10^4 B_c^e$ and $B_m = 1.5 \times 10^5 B_c^e$, respectively. The critical electron field (B_c^e) is 4.414×10^{13}G.