Inner crusts of hot magnetars in strong quantizing magnetic fields

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Introduction

In the Universe ultrahigh magnetic fields are dominant in the interiors of white dwarfs and neutron stars. A class of neutron stars, known as Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) hold the record of the strongest magnetic fields. Their surface magnetic field strength can be as high as $10^{14} - 10^{15}$ G while the core field strength may reach up to $\sim 10^{18}$ G. Properties of dense matter in such extreme magnetic fields is less studied and is of great academic interest. In the present work, we study the effects of high magnetic fields and finite temperatures on the inner crusts of hot magnetars.

Formalism

The magnetic field is called quantizing because the relativistic electrons in the inner crust becomes Landau quantized at such field strengths. This changes the density of states of the electrons, hence the thermodynamic and transport properties of the inner crust. The ground state properties of inner crust in strong magnetic fields at zero temperature has been extensively carried out in [1]. Here, the effect of finite temperature is also included alongside the magnetic field.

The inner crust consists of nuclei immersed in a sea of electron and neutron gases. The matter is charge neutral and in β-equilibrium. The nuclei and neutron gas are also in mechanical equilibrium with each other. We employ the Wigner-Seitz (WS) cell approximation and calculate the equilibrium properties of the nuclei using the subtraction procedure of Bonche, Levit and Vautherin [2]. For the nuclear energy density we adopt the Skyrme energy density functional with the parameters of SkM* interaction [3].

We take the magnetic field direction to be along the positive z-axis. If the strength of the field is greater than a critical magnetic field $B_c = m_e^2/e = 4.414 \times 10^{13}$ G, (in natural units), the transverse motion of the electrons becomes relativistic. We define a dimensionless magnetic field $B_* = B/B_c$ and take $B_* = 10^4$ for our calculations. For lower values of B_* several Landau levels are populated and the magnetic field effects are barely noticeable. In addition we also take inner crust temperature values of $T = 0 - 4$ MeV. We discuss the results in the next section.

Results and Discussion

The free energy per nucleon in the WS cell is given by

$$F/A_{cell} = e_N + e_{lat} + e_{el} - Ts \qquad (1)$$

where e_N is the nuclear energy per nucleon including proton Coulomb energy, e_{lat} is the lattice energy per nucleon comprising of electron-proton and electron-electron Coulomb energies, e_{el} is the electron kinetic energy per nucleon and s is the entropy per nucleon including that of electrons. By minimizing the free energy we have computed the nuclei present in the inner crust at different temperature and magnetic field.

Fig. 1 shows the plot of total number of nucleons A (neutrons and protons) inside the nucleus as a function of the average baryon

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density ($< \rho >$) in the absence (dotted lines) and presence (solid lines) of magnetic field at temperatures $0-4$ MeV. The numbers of nucleons in the nucleus (liquid) phase are obtained from the subtraction of gas phase densities from those of gas+liquid phases. Neutron number and hence A increases first at low average densities, reaches a maximum and then falls off at higher densities. This is true for all temperatures. At higher temperatures we see that less number of nucleons are there in the nucleus phase at a fixed density due to increased neutron drip.

In the presence of a strong magnetic field ($B_* = 10^4$), the qualitative nature of the curves remain almost the same. The only difference is that in this case at a fixed average density and temperature the total nucleon number in the nucleus is larger compared to the field free case. The reason is that in strong quantizing magnetic fields the nuclear binding energy and proton fraction increase due to the decrease of electron chemical potential. As a result, in this case, nucleons in the gas phase decrease. The nuclear (liquid) phase is more stable in strong magnetic field.

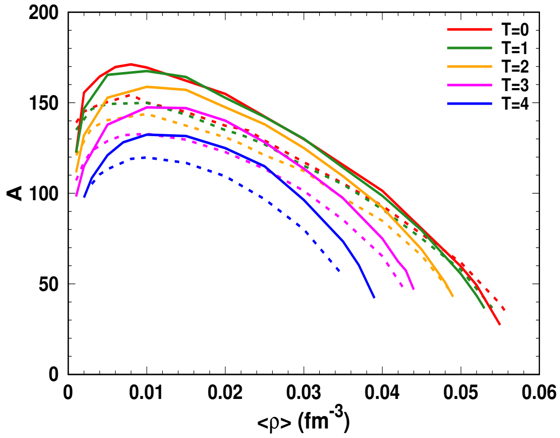

FIG. 1: Plot of total number of nucleons A (neutrons and protons) in the nucleus as a function of average baryon density $< \rho >$ for $T = 0-4$ MeV. Dotted lines are for $B_* = 0$ and solid lines are for $B_* = 10^4$.

The transition densities at which the inhomogeneous nuclear cluster phase melts into homogeneous nuclear matter phase can also be noted from Fig. 1. It is found that the transition densities decrease with increase in temperature for both $B_* = 0$ and 10^4. It is also observed that up to $T = 2$ MeV the transition densities are practically the same for both the non-magnetic and magnetic cases. However, at higher temperature the transition densities are little larger at $B_* = 10^4$ as compared to the field free case, the difference being increasing with temperature.

In summary, we find that strong quantizing magnetic field reduces the Coulomb energy of WS cell and thereby inducing more nuclear binding and tries to retain the nuclear cluster phase as opposed to high temperature which tries to destabilize the clusters [4]. Our results can be useful for r-process nucleosynthesis of heavy elements resulting from binary magnetized neutron star mergers which we plan to study in future.

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