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LETTER TO THE EDITOR

Magnetisation of quark gas in intense magnetic field

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Abstract. The magnetisation of a non-interacting quark gas in an intense magnetic field has been calculated assuming that the quarks obey parastatistics of order three. It is observed that magnetisation would attain larger values if quarks could obey parastatistics of higher order.

Recently questions have been asked concerning the state of matter which arises when the density increases beyond 10^{15} g cm^{-3}. Various possibilities have been suggested in answer to this, for example, with an increase in pressure, the residual electrons may be absorbed by neutrons, resulting in the formation of hyperon stars, or there may be neutron solidification. It is also suggested that strong interaction effects may generate a pion field with the possibility of pion condensation. In addition one can imagine the following interesting situation: namely that when the neutrons come very close to each other and nearly overlap, the constituent quarks fail to 'recognise' to which neutron they belong and as a result a quark soup may be generated. It then seems more appropriate to consider the system as a quark gas and, as we believe the quarks are pointlike, a state of quarks with arbitrarily high density can occur. Itoh (1970), assuming parastatistics of order three for quarks, has recently discussed the stability of a superstar of large mass with quarkion core. It is now generally accepted that the interaction between quarks is realised through the exchange of octet of massless vector gluons satisfying SU(3) colour group. An interesting consequence of this Yang–Mills theory is that quark–gluon interaction satisfies asymptotic freedom, which implies that at very short distances the quark–gluon interaction is vanishingly small, that is the quarks are almost free at short distances inside a hadron. Collins and Perry (1975) assumed that, in the super dense state of the matter, the quarks are free and form a strong degenerate system at absolute $T = 0$. With this hypothesis, they concluded that a central density much above 10^{15} g cm^{-3} can contain a neutron star in the form of a quarkion state. Some interesting thermodynamic questions have been raised (Baym and Chin 1976, Chapline and Naunberg 1976a, b, Freedman and Mclerran 1977 and Baluni 1977) as to whether a phase transition can take place from the neutron matter to quark matter phase.

A super dense system can presumably occur during gravitational collapse when the magnetic field strength increases and it is now known that a magnetic field strength as high as 50^{13} G is observed on the surface of a neutron star. Thus collective properties such as spontaneous magnetisation etc also become important. In this note we would like to discuss the thermodynamic properties of a magnetised quark gas assuming that the quarks in the super dense state are free in the presence of an external magnetic field.

To derive the magnetic properties of the system we first derive the magnetic moment, M, of the system assuming the quarks to be a relativistic parafermi gas obeying parastatistics of order three.

For the quark chemical potential $\mu < 1$ and $kT \ll mc^2$, m being the quark mass we get for M

$$\begin{aligned} M = (mc^2/\pi^2)(H_c\lambda_c^3)^{-1}(\pi/2)^{1/2}\phi^{5/2}\Big\{ & \tfrac{1}{2}(g_{3/2}(z) - (l')^{-1/2}g_{3/2}(z^{l'})) \\ & + (3\phi/16)(g_{5/2}(z) - (l'^3)^{-1/2}g_{5/2}(z^{l'})) \\ & + \sum_{n=1}^{\infty} \sqrt{a_n}[(g_{3/2}(z') - (l')^{-1/2}g_{3/2}(z'^{l'})) \\ & + (3\phi/8a_n)(g_{5/2}(z') - (l'^3)^{-1/2}g_{5/2}(z'^{l'}))] \\ & - (H/H_c)\phi^{-2}\sum_{n=1}^{\infty}(n/\sqrt{a_n})[(g_{1/2}(z') - (l')^{1/2}g_{1/2}(z'^{l'})) \\ & - (\phi/8a_n)(g_{3/2}(z') - (l'^3)^{-1/2}g_{3/2}(z'^{l'}))]\Big\} \end{aligned} \quad (1)$$

where

$$H_c = m^2c^3/e\hbar, \qquad \lambda_c = \hbar/mc \qquad \text{and} \qquad \phi = kT/mc^2,$$

k being the Boltzmann Constant

$$a_n = [1 + 2(H/H_c)n]^{1/2}, \qquad \mu = \tilde{\mu}/mc^2,$$

$\tilde{\mu}$ is the chemical potential and $l' = (l+1)$; where l is the order of parastatistics.

$$z = \exp[(\mu - 1)/\phi] \qquad \text{and} \qquad z' = \exp[(\mu - a_n)/\phi]$$

are fugacity parameters.

$$g_{5/2}(z) = \sum_{\gamma=1}^{\infty}(z^\gamma/\gamma^{5/2}), \qquad g_{3/2}(z) = \sum_{\gamma=1}^{\infty}(z^\gamma\gamma^{3/2}) \qquad \text{and} \qquad g_{1/2}(z) = \sum_{\gamma=1}^{\infty}(z^\gamma/\gamma^{1/2})$$

are well known series.

For $\mu \gg 1$ we find the following expression for M,

$$\begin{aligned} M = \frac{1}{2\pi^2}\left(\frac{mc^2}{H_c\lambda_c^3}\right)(l'-1)\Big[\!\Big[& \tfrac{1}{2}\mu(\mu^2-1)^{1/2} - \tfrac{1}{2}\ln[\mu + (\mu^2-1)^{1/2}] + \frac{\phi^2\mu\pi^2}{3l'(\mu^2-1)^{1/2}} \\ & + \sum_{n=1}^{\infty}\left\{\mu(\mu^2-a_n^2)^{1/2} - a_n^2\ln\left(\frac{\mu + (\mu^2-a_n^2)^{1/2}}{a_n}\right) + \frac{2\mu\pi^2\phi^2}{3l'(\mu^2-a_n^2)^{1/2}}\right\} \\ & - \frac{2H}{H_c}\sum_{n=1}^{\infty} n\left\{\ln\left(\frac{\mu + (\mu^2-a_n^2)^{1/2}}{a_n}\right) - \frac{\pi^2\mu\phi^2}{3l'(\mu^2-a_n^2)^{3/2}} + \dots\right\}\Big]\!\Big]. \end{aligned} \quad (2)$$

The equations (1) and (2) above represent the magnetisation density of the para-Fermi gas at low temperature and for chemical potential less or greater than quark mass. To see the effects of the magnetisation we study the behaviour of M with number density at $T = 0$ for a given value of external field strength $H = H_c$. One finds the undulatory behaviour of M with the variation of the number density, namely the existence of maxima and minima in M similar to that one finds in the Fermi–Dirac case (Canuto and Chiu 1968a, b, c). Another interesting question arises whether in a dense para-Fermi system permanent magnetisation can take place. It appears from equation (2) that magnetisation can attain larger value if quarks could obey parastatistics of higher order. If magnetisation is comparable to H, the external field, then there is a likelihood that the value of magnetisation for a quark gas is always greater than that of a Fermi gas and the former becomes roughly twice that of the latter at higher value of μ. The variation of magnetisation with ϕ is significant at low μ but at high value of μ it is only within five percent. The detail calculations of the thermodynamic properties will be presented elsewhere.

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