SRC and the fate of cold neutron stars

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Trieste May 2008

One of challenging problems of particle, nuclear and statistical physics is the theory of dense hadron matter.

I will discuss general properties of cold nucleon matter which are missed in the text books

Review and references in L.Frankfurt& M.Strikman & M.Sargsian in print

Understanding of the role of interactions gives key to old questions:

Stability or instability of neutron, hyperon stars at zero temperature

Luminocity of neutron stars at nonzero temperature

Eventual fate of neutron stars -QCD challenge.

Basic facts from low energy nuclear phenomenology.

Existence and stability of nuclei requires attraction in NN interaction and stronger NN repulsion at small distances.

Prediction of large high momentum nucleon component with universal, independent on atomic number properties.
F.S. 70th

Theory: distribution of nucleons within neutron star differ from Fermi step- $\geq 30\%$ tail of nucleons with momenta above Fermi surface.

In the low energy processes SRC can not be observed because of proximity of scales characterizing measuring process and SRC. 60 years of attempts.

In the hard high energy processes SRC can be investigated using universality and properties of SRC as the signature. The methods of hard processes were adjusted to search of SRC in F.S. 70th

Observed indirectly in 70 th (Dubna, ITEP, IHEP, FNAL) in the significant cross section of the processes:

$$a + T \to backward(proton, pion, kaon) + X$$

a=proton, pion, photon, electron, neutrino,light nuclei

T is nuclear target

New information from high energy nuclear physics

Last few years SRC were observed directly in the processes with predicted rate cf talk of E.Pisetzky:

$e+A \to e+X$ for $3>x>1$ TJNF

$p+A \to p+N+n+X$ BNL

$e+A \to e+N+N+X$ TJNF

Nucleon occupation number in nuclei is around 0.8 instead of 1

(p-n) correlations dominate over pp correlations

Theoretical conclusion: distribution of nucleons within gas of strongly interacting nucleons even at zero temperature is different from step function. Occupation number for a nucleon within Fermi surface <0.7 at nuclear density.

Introduction

Neutron stars are stellar objects with masses (1-2) solar masses and radii of the order 10 - 12 km, and temperatures well below one MeV. The matter becomes more neutron rich with an increase of the density, as a result of the increase of the electron Fermi energy which favours the electron capture by the protons, $e + p \rightarrow n + \nu$

At a density of the order of a half of the nuclear matter density, the matter dissolves into uniform liquid composed primary of neutrons, $\sim 5 - 10\%$ protons, and equal number of electrons.

Ideal gas approximation for a neutron star .

n, p, e noninteracting gases.

$$N_n \gg N_p = N_e$$

$$N_i = (1/3\pi^2)(k_F(i))^3$$

$$E_F(n) = E_F(p) + E_F(e)$$

$$k_F(p)/k_F(n) = (N_p/N_n)^{1/3} \ll 1$$

For an electron from a neutron decay for any positive neutron density :

$$k_F(e) \geq k_{max}(e)$$

Proton and electron states are filled at zero temperature so Pauli blocking forbids neutron decay.

Thus a neutron within a neutron star is stable within the ideal gas approximation

Pauli blocking disappears due to strong and Coulomb interactions between neutrons, protons and electrons leading to the collapse of neutron star into quark-gluon stage of the star.

Life-time of neutron star at zero temperature but nuclear density is $\sim 10^9$ years . Life time of hyperon, muon stars should be significantly lesser because of larger energies of electrons in the β decay. However assumption that strange matter may appear ground state of stable hadron matter (E.Witten et al) may complicate conclusions.

Neutrino cooling of a neutron star at nonzero temperature is parametrically enhanced as compared to the ideal gas approximation because of the SRC.

Content

Internucleon interactions

Coulomb p,e interactions

Collapse of neutron star at $T = 0$

Neutrino cooling at $T > 0$

Conclusions

Theoretical challenge is to build theory of 3 interacting liquids: neutron ,proton and electron liquids.

L.Landau theory of Fermi liquid needs drastic modifications to become effective tool for the description of 3 interacting liquids if the number of neutrons significantly exceeds the number of protons.

For certainty we shall attack this problem within the nonrelativistic framework for nucleons and relativistic one for electrons.

Internucleon interaction tends to equilibrate momenta of protons and neutrons -strong departure from the ideal gas approximation for the asymmetric matter . Distinctive effect is the strong distortion of the proton Fermi surface in momentum space , appearance of significant number of nucleons with momenta above Fermi surface. Application of baryon sum rules found significant probability of proton,neutron holes in the proton,neutron Fermi seas.

Thus Fermi blocking of neutron β decay related to proton sector disappears as the consequence of internucleon interactions.

Calculation of many properties of high momentum component of proton ,neutron momentum distributions like dependence on nucleon momentum is rather straightforward for any system :neutron star or nucleus. This is because high momentum component of w.f. of many body system is given by Fourier component of singular part of internucleon potential. Below are the formulae for high momentum tail of proton, neutron occupation numbers derived from singular behaviour of pair nucleon potential.

In the leading order over $1/k^2$ for $k \gg k_F$:

$$f_n(k) \approx \left(\frac{N_n}{V}\right)^2 \left(\frac{V_{nn}(k)}{k^2/m_N}\right)^2 + 2\left(\frac{N_p}{N_n}\right)\left(\frac{N_n}{V}\right)^2 \left(\frac{V_{pn}(k)}{k^2/m_N}\right)^2 ,$$

$$f_p(k) \approx 2\left(\frac{N_p}{N_n}\right)\left(\frac{N_n}{V}\right)^2 \left(\frac{V_{pn}(k)}{k^2/m_N}\right)^2 .$$

Here $V = (4\pi/3)R^3$

and R is radius of neutron star ;V is potential of NN interaction.

Recent calculation of nucleon occupation numbers within the frame of Schrodinger equation with realistic potentials of nucleon-nucleon interactions cf. T.Frick et al found that occupation numbers of protons with zero momenta are

$$\approx 70\%$$

for the asymmetric nuclear matter. Even larger depletion of occupation numbers is for protons with momenta near the Fermi surface.

Thus significant jump in the proton occupation numbers at $k = k_F(p)$ which is the basis of L.Landau-A.Migdal Fermi liquid theory for one type constituents is improbable for the asymmetric nuclear matter consisting of different constituents.

Numerical analysis (L.Frankfurt&.M.Strikman.1976,1981) shows that high momentum component of many body wave function at achievable nucleon momenta is dominated by Fourier transform of coordinate space wave function in the region where internucleon attraction dominates .Therefore. high momentum nucleon component arises due to classically allowed trajectories.

Coulomb interaction between protons with momenta above Fermi surface and electrons with momenta within Fermi surface produces electrons with momenta "k" above electron Fermi surface:

$$f_e(k_e \geq k_F(e), T=0) \approx (1/2) \int (d^3k_p/(2\pi))^3 f_p(k_p)\theta(k_p - k_F(p))(N_e/V)\cdot$$
$$\cdot H(k_p) \left(\frac{k_e + \frac{3}{4}k_F(e)}{\sqrt{k_e} \cdot \sqrt{\frac{3}{4}k_F(e)}} \right) \left(\frac{V_{Coulomb}(k)}{k_e - k_e^2/2m_N - \frac{3}{4}k_F(e)} \right)^2$$

$H(k_p)=1-f_p(k_p,T=0)$ accounts for the number of free holes needed to avoid Pauli blocking for the proton which interacted with the electron.

High momentum component is evaluated in the framework of Feynman diagrams-nonrelativistic Schrodinger equation is inapplicable in the important kinematics. We accounted for the probability of (p-n) short range nucleon correlation - $P_{p,n}$. k_p is the proton momentum within SRC. N_i/V is the density of the constituent "i" .

It follows from the sum rule accounting for the conservation of electron number that Coulomb (e-p) interaction between proton from SRC and electron from Fermi sea produces holes in the electron Fermi sea. Thus Pauli blocking of neutron decay is not absolute in the electron sector also because of Coulomb (e-p) attraction .

So neutron star with any mass is unstable to β decay .
Energy-momentum conservation in the neutron β decay when electron fills the hole, dominance of attraction in (p-n), (p-e) interactions lead to the collapse of neutron star.

Inverse β decay: $e+p \to n + \nu$ helps to keep p/n ratio approximately constant. It produces low energy neutrino which easily leave star -gravity did not influence much on such a neutrino.

Width of a neutron within neutron star at nuclear density and zero temperature:

$$\left(\frac{\Gamma_n(medium)}{\Gamma_n(free)}\right) \approx (1 - f_p(< k_p >, T = 0)) \left(\frac{\langle k_e \rangle}{k_F(e)}\right)^3 \int (V/N_n) f_e(k_e) d^3k_e/(2\pi)^3 \Theta(k_e \geq k_F(e))$$

Assuming the ideal gas approximation for electrons and neutrons which do not belong to SRC and :

$$N_p/N_n = 0.1 \qquad k_F(e) = 250 MeV$$

we evaluate life time of a neutron within the neutron star: 10^9 years . This is an estimate only, since N_p/N_n=0.1 is significantly larger than the ideal gas number.

β

Quark-gluon stage of a neutron star is also unstable to β decay of "d" quark because of larger number of "d" quarks and dominance of Coulomb interaction between u quarks and electrons. Combination of these effects allowed β decay of "d"quark. Quantitative calculation of life time of such stage of a star requires better understanding of QCD.

Energy of an electron in the decays of hyperon , muon is significantly larger than that for a neutron decay. But phase volume for electron holes with larger momenta is significantly larger. As a result life time of hyperon, muon stars , strange matter (if it is not lowest energy state of the matter) should be significantly less than life time of a neutron star- however analysis of the role of absorption of high energy neutrino is needed.

Enhancement of neutrino cooling of the neutron stars at finite temperatures.

Common wisdom: dominant process of neutrino cooling of neutron stars at finite temperature is URCA process:

$$n \rightarrow p + e^- + \bar{\nu}_e, \; p + e^- \rightarrow n + \nu_e$$

It is allowed by the energy-momentum conservation law if the proton concentration exceeds

$(11 - 15)\%$ (Lattimer et al)

Neutrino luminosity in the Fermi liquid approach:

$$\epsilon_{URCA} = c(kT)^6 \theta(k_F(e) + k_F(p) - k_F(n))$$

Account for the high momentum proton component leads to more rapid neutrino cooling-larger neutrino luminocity:

$$\epsilon_{URCA} = c(kT)^6 R$$

where enhancement factor R is

$$R \approx \frac{\int f_p(k_p, T=0)\theta(k_F(e) + k_(p) - k_F(n))d^3k_p/(2\pi)^3}{\int(1 - f_{p,bare}(k_p, T))\theta(k_F(e) + k_F(p) - k_F(n))d^3k_p/(2\pi)^3}.$$

Major enhancement is due to presence of proton holes in the proton Fermi sea. Approximate estimate gives for

$T \ll 1MeV$ $\qquad$ $R \approx 0.16(MeV/kT)^{3/2}$

$R = \infty$ $\qquad$ for $\qquad$ $N_p/N_n \ll 0.1$

Conclusions

It seems that neutron star has no ground state in QCD. The fate of any neutron star is to collapse into quark-gluon state and probably eventually into black hole. More heavy neutron star - more rapid transition to black hole.
Hyperon, muon..stars, (strange matter if not ground state of matter) should be more rapidly transformed into black holes.

Internucleon interactions lead to enhancement of neutrino cooling of neutron stars at non zero temperature as compared to Fermi liquid approximation.