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Explaining GRB in the light of energy deposition rate for $\nu + \overline{\nu} \rightarrow e^+ + e^-$ in a compact star

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Gamma Ray Burst (GRB) and its possible connection with neutrino production in compact stars is a field of high current interest. It has been suggested in the literature that the phase transition inside a compact star may serve as the engine for the observed GRB. The central density of these stars can be as high as 10 times that of normal nuclear matter. Due to beta equilibration, a large number of neutrinos and antineutrinos may be produced inside the compact stars. These neutrinos and antineutrinos could annihilate and give rise to electron-positron pairs through the reaction $\nu\bar{\nu} \rightarrow e^+e^-$. These e^+e^- pairs may further give rise to gamma rays which could be a possible explanation of the observed GRBs. Hence it is very important to study the energy deposition in the $\nu\bar{\nu}$ annihilation process.
In this work we calculate the said energy deposition rate for a rotating compact star. This is for the first time that such an energy deposition rate has been calculated for the rotating star. We have also incorporated the General Relativistic effects in calculating the energy deposition rates. The structure of the star is described by the metric

$$ds^2 = -e^{\gamma+\rho}dt^2 + e^{2\alpha}(dr^2 + r^2 d\theta^2) + e^{\gamma-\rho}r^2 sin^2\theta(d\phi - \omega dt)^2$$

Einstein's equations are solved using the non-linear version of the Walecka model with TM1 parameter set. Due to high rotational velocity the star takes the shape of an oblate spheroid. Although the star becomes oblate spheroid the photosphere still remains spherical. We find that the general relativistic (GR) effect increases the energy deposition rate by 30 times. The rotational effect creates an asymmetry in the star which creates a difference in the increment along polar and equatorial directions. Away from the photosphere, the energy deposition rate starts to fall. Beyond the surface of the star the deposition rate falls off steeply. The total energy deposition rate for this scattering process is of the order of $10^{52} ergs/s$, which is quite a large fraction of the total neutrino energy liberated from a compact star. This large amount of energy in electron-positron pairs can account for the magnitude of gamma ray bursts.

PHASE TRANSITION IN HYBRID STARS: MAXWELL AND GIBBS CONSTRUCTION

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It is believed that the nuclear matter can undergoes a phase transitions to quark matter at the core of a heavy neutron stars, known as hybrid stars. There are two schemes for theoretical constructions of these phase transitions, namely Maxwell construction and Gibb's construction [1]. We present a detail study of phase transition using both these constructions for various EOSs, describing nuclear matter and quark matter. In the present work we have employed potential model like APR [2], some mean field models having only the nucleonic degrees of freedom [1] and quadratic form of parametric EOS [3] for the nuclear matter and MIT-Bag [4] and effective bag model [5] for quark matter EOS. Maxwell construction is characterized by sudden discontinuity in the density profile at the phase boundaries. Our studies shows that there are certain combinations of EOS which provides smooth phase transition in Maxwell construction. It is further observed that, in the Gibbs construction, these pairs of EOSs provides rather sudden change in the density profile. We have also studied relative dominance of nuclear matter and quark matter in the density profile of the mixed phase in Gibb's construction. We observe that these EOSs correspond to low value of critical density for phase transition and also provides heavy mass hybrid star. This result is particularly important in light of claims of observation of pulsar with mass $\sim 2M_{\odot}$. We have also identified, in which combinations of EOS, mixed phase (under Gibb's construction) is dominated by quark matter and in which it is dominated by nuclear matter. Our study suggests high value of coupling constant ($\alpha_s \sim 0.7$) and low value of bag constant ($B^{1/4} \sim 145$ MeV) provides low critical density, high limiting mass for hybrid star, and wider range ($\sim 1 - 2M_{\odot}$) of stable hybrid stars masses.

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Bulk viscosity and r-modes of neutron stars

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We discuss the effects of exotic matter such as, hyperon and K^- condensed matter on bulk viscosity in neutron stars. The bulk viscosity coefficient due to non-leptonic processes involving hyperons and K^- mesons are investigated here. Further, we show how the bulk viscosity coefficient is modified by superfluidity. Finally, we demonstrate how the exotic bulk viscosity coefficients influence r-modes of neutron stars which might be sources of detectable gravitational waves.

Baryon density and pressure of Neutron star within Relativastic Hartree Fock Scheme

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The interior side of the neutron star has high temperature and strong magnetic field. The baryon density and pressure under this physical situation are effective tools to guess the interior structure of this neutron star which practically exists within the assembly of high density baryonic matter. The Density and pressure under the the influence of strong magnetic field as well as without the effect of magnetic field have been investigated within the frameworki of Relativastic Hartree fock Model and Physical datas have been compared with the experimental astrophysical values.

HYPERON-QUARK MIXED PHASE IN COMPACT STARS

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In cold neutron star matter a phase transition has been expected from hadron phase, including hyperons, to quark phase. The hyperon mixture causes large softening of the equation of state (EOS) of matter and brings about too small maximum mass of neutron stars (NS), which contradicts the observation [1]. On the other hand, considering a phase transition to quark matter with harder EOS at high density, the theoretical NS maximum mass may increase to a reasonable value [2]. If this is the case, the appearance of a mixed phase

during the first-order phase transition should may have large influences on the EOS and consequently on this scenario.

We investigate the property of the hadron-quark mixed phase [3] using the Brueckner-Hartree-Fock model for hadron (hyperon) phase and the MIT bag model for quark phase. To satisfy the Gibbs conditions, charge density as well as baryon number density becomes non-uniform in the mixed phase, accompanying phase separation. Then, taking into account the density distribution and the Coulomb interaction in a self-consistent way, we will clarify the roles of the surface tension and the charge screening effect. We will show that the screened Coulomb interaction tends to make the geometrical structure of the mixed phase less stable, and the resultant EOS becomes similar to the one given by the Maxwell construction.

Using the Bag-model parameters, we demonstrate that hyperons are suppressed in the mixed phase, because hadron phase is positively charged. This is a novel mechanism of hyperon suppression in compact stars.

Finally we will discuss some consequences of our EOS on the structure and the maximum mass of NS.

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Spherical sound waves in dense hadronic matter

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Over the last 50 years hydrodynamics has been applied to cold nuclear physics, to low and high energy nuclear reactions and to phenonema taking place in dense stars. Recently hydrodynamical models became more sophysticated and received more support from experimental data. One of the recent improvements in the theory of strongly interacting fluids was the study of supersonic flow in the form of wakes and Mach cones. These effects may qualitatively explain the shape of the away-side jets observed by the PHENIX collaboration. Mach cones are formed when sound waves propagate in hadronic matter.

We study the propagation of sound waves in dense and hot hadronic matter. More specifically we study the propagation of perturbations in the baryon density. These perturbations may generate ordinary waves and also Korteweg - de Vries (KdV) solitons. Starting from the equations of relativistic hydrodynamics at finite temperature in spherical coordinates, we derive differential equations and find their numerical solutions. The equation of state is derived from relativistic mean field models of the Walecka type. We discuss the features of the solutions and the role played by the microscopic interactions in the shape and propagation of the sound waves. In particular we study the necessary conditions for the formation of KdV solitons. These objects are very interesting since they can transport energy and momentum much farther than ordinary sound waves in a hadronic medium. They may be very relevant for processes happening in stars. We discuss possible applications of our results to the phenomenology of RHIC and astrophysics.

Our first results on this subject were published in [1] and [2]. The present contribution contains new (yet unpublished) material, such as the formulation of the problem in spherical coordinates and the introduction of temperature.

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Conversion of nuclear to 2-flavour quark matter in rotating compact stars: A general relativistic perspective

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Strange Quark Matter (SQM), consisting of approximately equal numbers of up (u), down (d) and strange (s) quarks, is the putative *true* ground state of strong interaction. There have been concerted efforts at confirming the existence of Quark-Gluon Plasma (QGP) and SQM, though transiently, in ultra relativistic collisions. On the other hand, QGP and SQM could naturally occur in the cores of compact stars, where central densities of about an order of magnitude higher than the nuclear matter saturation density are expected. Thus, neutron stars with sufficiently high central densities ought to get converted to strange star. It has been argued that the conversion process may be a two step process. The first process involves the deconfinement of nuclear to two-flavour quark matter. The second process deals with the conversion of excess down quarks to strange quarks, which occurs via weak interaction, forming stable SQM.

The general relativistic (GR) and rotational effects on the conversion front for the conversion of nuclear to two-flavour quark matter are studied in rotating compact stars. We use nonlinear Walecka model for the nuclear matter EOS. The metric of the star is given by

$$ds^2 = -e^{\gamma+\rho}dt^2 + e^{2\alpha}(dr^2 + r^2 d\theta^2) + e^{\gamma-\rho}r^2 sin^2\theta(d\phi - \omega dt)^2$$

With the help of this metric, Einstein's equation of motion for an ideal gas is utilised to obtain the appropriate GR hydrodynamical equations, namely the continuity and Euler's equations. The equations are solved to obtain the velocity of the propagation front. The velocity shoots up near the center and saturates at larger radii. The propagating front breaks up into fragments which propagate with different velocities along different directions. The velocity is maximum at the pole and minimum at the equator. The time taken for this conversion to happen is of the order of few ms. This calculation indicates the inadequacy of non-relativistic (NR) or even Special Relativistic (SR) treatments for these cases.

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r-modes in quark matter

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r-modes are pulsations of the star associated with the Coriolis force, and they are unstable toward gravitational radiation. r-modes might play a significant role in spinning down of newly formed neutron or quark stars. Damping due to viscosity can impact the growth of these r-mode instabilities. We study the effect of viscosity on r-modes in color-flavor locked (CFL) quark star.

STRANGELETS and QCD: The Exotic Features of Hadronic Cascade Fluctuations in an Ionization Calorimeter

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Studies of the hadronic cascade fluctuations, performed in cosmic rays using the ionization calorimeter, are indicative of a new mechanism of hadron-nucleus interaction that may appear at high energies — the mechanism which creates massive (~ 10 GeV/c^2) stable ($\gtrsim 10^{-11}$ sec) particles with interaction length in a dense absorber substantially larger than that of nucleons.

Existence of such kind mechanism provides a reasonable explanation for the number of "exotic" phenomena, reported by different authors from different exoeriments, and is significant in that it points toward the type of effects to be expected from a change in the characteristics of interaction at high energies.

Magnetic susceptibility of quark matter

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The phase diagram of QCD has been elaborately studied in density-temperature plane. Here

we study the magnetic properties of QCD [1]. Since the discovery of magnetars the problem of the origin of strong magnetic field in compact stars has revisited. There are three ideas at hand about its origin. The fossil-field hypothesis and the dynamo mechanism in the crust are two of them. The third one is a microscopic origin based on hadron or quark dynamics. Once spins of nucleons or quarks are aligned, they can exhibit a large magnetic field with the strong interaction scale. Since nuclear matter calculations have given negative results about spontaneous spin polarization in nuclear matter, it would be interesting to study the possibility in quark matter. Here we evaluate the magnetic susceptibility by the use of the Fermi-liquid theory for QCD. Within the Fermi-Liquid theory, the magnetic susceptibility is given by

$$\chi_M = \left(g_D^F \mu_q/2\right)^2 \{N^{-1}(T) + \bar{f}^a\}^{-1},$$

where $N(T)$ is the effective density of states at the Fermi surface and $\bar{f}^a$ is the angle-average of the spin-dependent Fermi-liquid interaction. At $T = 0$, $N(0)$ can be expressed in terms of another Landau parameter f_1^s [2]. We take into account the static and dynamical screening effects for gluons; the former improves the infrared (IR) behavior of the gauge interaction for the longitudinal gluons to give a contribution of $g^2 \ln(1/g^2)$, while there is no static screening for the transverse gluons. We shall see that some IR divergences are still left due to the transverse gluons, but they never spoil the framework of the Fermi-liquid theory to give a finite result for the susceptibility [3].
Subsequently we evaluate the magnetic susceptibility at finite temperature by considering the temperature dependence of $N(T)$ and $\bar{f}^a$. The peculiar temperature dependence of the Landau parameters comes from the effect of the dynamical screening. We shall show χ_M using the self-energies of the longitudinal and transverse gluons,

$$\Pi_L(p_0, \mathbf{p}) = m_D^2 + i\frac{\pi m_D^2}{2v_F}\frac{p_0}{|\mathbf{p}|}\coth\frac{p_0}{2T}, \quad \Pi_T(p_0, \mathbf{p}) = -i\frac{\pi v_F m_D^2}{4}\frac{p_0}{|\mathbf{p}|}\coth\frac{p_0}{2T},$$

to see an anomalous term $\propto T^2 \ln T$ as a non-Fermi liquid effect, which corresponds to $T \ln T$ term appearing in specific heat [4].

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Is there quark matter in (low-mass) pulsars?

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There has been a tremendous activity in the area of pulsar physics in particular triggered by the recent pulsar radio scans and several new pulsar mass measurements ranging from very massive pulsars to pulsars with quite low masses. Based on symmetry properties of QCD several new phases have been predicted to be present at high densities. The phenomenon of colour superconductivity implies the existence of several first order phase transitions which could be right in the range of densities as encountered in the core of neutron stars. The equation of state will be substantially modified giving rise to new observable signals from neutron star measurements. I outline the mass-radius relation for compact stars with quark matter in both regimes, for the high-density high mass and the moderate density low-mass regions. I argue that the simultaneous measurement of the mass and the radius for low-mass pulsars could already constrain the onset of the QCD phase transition or signal that there is exotic matter in the core of compact stars. New astrophysical observations will be discussed with regard to the possible existence of quark matter in compact stars.

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Spin wave in the polarized quark matter

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Origin of the strong magnetic field in compact stars has been one of the important issues since the first discovery of pulsars. We have proposed a microscopic origin, based on an idea of ferromagnetism in quark matter [1], different from the fossil-field hypothesis or the dynamo mechanism.

Ferromagnetic phase should be clearly distinguished from other origins by spin wave excitation. Spin waves are expected to bring about the interesting effects in relation to compact star phenomena, especially its thermal evolution through reduction of magnetization, specific heat etc. We formulate and quantize the spin waves in quark matter within the coherent-state path integral, which is an extension of the *spiral approach* for electron gas [2].

Consider a matrix element of the evolution operator

$$\langle \Omega'', t'' \,|\, e^{-iT\hat{H}/\hbar} \,|\, \Omega', t' \rangle = \int \prod_{n=1}^{\infty} \prod_{k=1}^{N_k} \prod_{x} \frac{d\Omega_{k.n}(x)}{2\pi} \exp\left(i \sum_k \int_{t'}^{t''} dt \int d^3x \left[i\langle \Omega_k \,|\, \dot{\Omega}_k \rangle - H(\Omega) \right] \right),$$

where $|\Omega\rangle = |\Omega_1\rangle \otimes \cdots \otimes |\Omega_{N_k}\rangle$ is the spin coherent state [3]. Introducing the collective variables $\bar{\theta}, \bar{\phi}$, that describe spin wave, defined by

$$\cos\bar{\theta} \equiv \frac{1}{N_k}\sum_k \cos\theta_k, \bar{\phi} \equiv \frac{1}{N_k}\sum_k \phi_k,$$

and replacing $\theta_k(x) = \bar{\theta}(x) + \xi_k(x), \phi_k(x) = \bar{\phi}(x) + \eta_k(x)$, we find the effective action for the spin wave,

$$e^{iS_{\rm eff}(\bar{\Omega})} = \int \mathcal{D}\xi\mathcal{D}\eta\delta\left(\sum_k \xi_k\right)\delta\left(\sum_k \eta_k\right) e^{\left\{\frac{i}{\hbar}\sum_k \int_{t'}^{t''} dt \int d^3x\left[\frac{1}{2}(1-\cos(\bar{\theta}+\xi_k))(\dot{\bar{\phi}}+\dot{\eta}_k)-H(\bar{\theta},\bar{\phi},\xi_k,\eta_k)\right]\right\}}.$$

If we take a stationary approximation with respect to the fluctuation fields, one may recover the spiral approach [2]. Anyway the effective Hamiltonian should take the form, $H_{\rm eff}(\bar{\Omega}) = A/2(\nabla_r \mathbf{U})^2$, in terms of the unit vector $\mathbf{U}(\bar{\Omega})$ with the Bloch-wall coefficient A. Then dispersion relation for the spin field reads $\propto A\mathbf{q}^2$ for a wave vector $\mathbf{q}$. We can also see that the effective action has some topological features, which gives the second quantization for the spin fields to define *magnons*.

For further applications of magnons, we shall derive the relevant coupling vertex with quarks [4], which gives rise to a novel cooling mechanism or superconductivity.

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A comparative study of red shifts of compact stars

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It has been noticed in recent years that the study of diquarks is of basic importance for understanding high energy density physics. In fact, it is argued to play an important role in the study of compact stars, astrophysical phenomena and the origin of the universe. In the present work, an attempt is made to compute the red shifts of diquark stars within the frame work of phi-four theory. It is found that red shift for the diquark stars varies from 0.15 to 0.48 for effective interaction parameter 27.8. The result is then compared with the results obtained from other theoretical models and experimental observations.

COLOR SUPERCONDUCTING QUARK MATTER IN COMPACT STARS

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Recently, observations of compact stars have provided new data of high accuracy which put strong constraints on the high-density behaviour of the equation of state of strongly interacting matter otherwise not accessible in terrestrial laboratories [1]. Recent indications for high neutron star masses ($M \sim 2\ M_\odot$) and large radii ($R > 12$ km) could rule out soft equations of state and have provoked a debate whether the occurence of quark matter in compact stars can be excluded as well. We show that modern quantum field theoretical approaches to quark matter including color superconductivity and a vector meanfield allow a microscopic description of hybrid stars which fulfill the new, strong constraints [2,3,4]. For these objects color superconductivity turns out to be essential for a successful description of the cooling phenomenology in accordance with recently developed tests [5]. We discuss QCD phase diagrams for various conditions [6,7] thus providing a basis for a synopsis for quark matter searches in astrophysics and in future generations of nucleus-nucleus collision experiments such as low-energy RHIC and CBM @ FAIR.

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