Vacuum discharge as a possible source of gamma-ray bursts

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We propose that spontaneous particle–anti-particle pair creations from the discharged vacuum caused by the strong interactions in dense matter are major sources of $\gamma$-ray bursts. Two neutron star collisions or black hole-neutron star mergers at cosmological distance could produce a compact object with its density exceeding the critical density for pair creations. The emitted anti-particles annihilate with corresponding particles at the ambient medium. This releases a large amount of energy. We discuss the spontaneous $p\bar{p}$ pair creations within two neutron star collision and estimate the exploded energy from $p\bar{p}$ annihilation processes. The total energy could be around $10^{51} - 10^{53}$ erg depending on the impact parameter of colliding neutron stars. This value fits well into the range of the initial energy of the most energetic $\gamma$-ray bursts.

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Gamma-ray bursts (GRBs) were discovered accidentally in the late 1960s by the Vela satellites. The discovery was announced in 1973 [1]. Since then, they have been one of the greatest mysteries in high-energy astrophysics for almost 30 years. The situation has improved dramatically in 1997, when the BeppoSAX satellite discovered X-ray afterglow [2], which enabled accurate position determination and the discovery of optical [3] and radio [4] afterglows and host galaxies. The distance scale to GRBs was finally unambiguously determined: their sources are at cosmological distances [5]. In spite of all these recent progress, we still do not know what produces GRBs! The nature of the underlying physical mechanism that powers these sources remains unclear. The optical identification and measurement of redshifts for GRBs allow us to determine their distances and the amount of energy that would be radiated in an isotropic explosion. In recent three observations (GRB971214 [6], 980703 [7] and 990123 [8]), the total isotropic energy radiated was estimated to be in excess of $10^{53}$ erg. For GRB990123, the inferred isotropic energy release is up to $3.4 \times 10^{54}$ erg, or $1.9 M_\odot$ (where $M_\odot$ is the solar mass), which is larger than the rest mass of most neutron stars. It has been suggested that the explosion of GRB990123 is not isotropic, which reduces the energy released in $\gamma$-rays alone to be $6 \times 10^{52}$ erg [8] due to finite beaming angle. However, if one adopts the picture of the fireball internal shock model [9] that random internal collisions among shells produce the highly variable $\gamma$-ray burst emissions, the required initial energy will be raised by a factor of about 100 since it is argued that only 1% of the energy of the initial explosion can be converted into the observed radiation [10]. Therefore, it appears that the total exploded energy for the most energetic bursts is close to or possibly greater than $10^{54}$ erg. It seems to be difficult to imagine a source that could provide so much energy. The first and foremost open question concerning GRBs is what are the inner engines that power GRBs [9]?

On the other hand, the GRB spectrum is nonthermal. In most cases there is a strong power law high-energy tail extending to a few GeV. A particular high-energy tail up to 18 GeV has been reported in GRB940217 [11]. This nonthermal spectrum provides an important clue to the nature of GRBs.

Various GRB models have been suggested in the literature, see e.g. Refs. [9,12,15–19].
Among them, the neutron star merger seems to be the most promising candidate. Three-dimensional hydrodynamical simulations of the coalescence of binary neutron stars (NS-NS) \[13-15,20\], direct collision of two neutron stars \[21-23\] as well as black hole-neutron star (BH-NS) merger \[24\] have been performed by some authors. The largest energy deposition of $\sim 10^{51}$ erg by $\nu\bar{\nu}$ annihilation was obtained in the black hole-neutron star merger (for NS-NS collision, the total energy is around $10^{50}$ erg \[23\]). This may account for certain low-energy GRBs on the one hand, but it is, on the other hand, still far away from the energetic ones mentioned above. However, it should be pointed out that in those macroscopic simulations (and almost all GRB fireball models) the effects of strong interactions, e.g., the modification of hadron properties in dense matter, many body effects, vacuum correlations et al., have been largely neglected except that a nuclear equation of state is applied.

In this Letter we propose an alternative scenario for the source of the most energetic $\gamma$-ray bursts. It is well known that the density is fairly high at the center of neutron stars. The central density can be several times nuclear saturation density \[25\]. Furthermore, superdense matter could be formed at NS-NS/BH-NS mergers and direct NS-NS collisions. Three-dimensional hydrodynamical simulations showed that when two neutron stars collide with a free-fall velocity, the maximum density of the compressed core can be $1.4$ (off-center collision, the impact parameter $b = R$, i.e., one neutron star radius) to $1.9$ (head-on collision) times the central density of a single neutron star \[23\]. At such high density, not only the properties of baryons will be modified drastically according to the investigation of relativistic mean-field theory (RMF) and relativistic Hartree approach (RHA) \[26\], but also the vacuum, i.e., the lower Dirac sea, might be distorted substantially \[27\] since the meson fields, which describe the strong interactions between baryons, are very large. At certain densities, when the threshold energy of the “negative-energy sea”-nucleons (i.e., the nucleons in the Dirac sea) is larger than the nucleon free mass, the nucleon–anti-nucleon pairs can be created spontaneously from the vacuum \[28,29\]. A schematic picture for this phenomena is depicted in Fig. 1. The situation is quite similar to the electron-positron pair creations in QED with strong electromagnetic fields \[30\].
The produced anti-nucleons will then annihilate with the nucleons at the ambient medium through the $NN \rightarrow \gamma\gamma$ reaction. This yields a large amount of energy and photons. This process may happen in addition to the $\nu\bar{\nu}$ annihilation process. The sequential process, $\gamma\gamma \leftrightarrow e^+e^-$, inevitably leads to the creation of a fireball. The dynamical expansion of the fireball will radiate the observed $\gamma$-rays through the nonthermal processes in shocks [9].

In the following, we shall estimate whether enough energy is available within this scenario to satisfy the requirement of a source of energetic GRBs.

We start from the Lagrangian density for nucleons interacting through the exchange of mesons

$$
\mathcal{L} = \bar{\psi} (i\gamma_\mu \partial^\mu - M_N) \psi + \frac{1}{2} \partial_\mu \sigma \partial^{\mu} \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{4} \omega_\mu \omega^{\mu
u}
+ \frac{1}{2} m_\omega^2 \omega^{\mu} \omega^{\mu} - \frac{1}{4} R_{\mu\nu} R^{\mu\nu} + \frac{1}{2} m_\rho^2 R \cdot R
+ g_\sigma \bar{\psi} \gamma_\mu \psi \sigma - g_\omega \bar{\psi} \gamma_\mu \psi \omega^{\mu} - \frac{1}{2} g_\rho \bar{\psi} \gamma_\mu \tau \cdot \psi R^\mu,
$$

(1)

where the usual notation is used as given in the literature [20]. Based on this Lagrangian, we have developed a relativistic Hartree approach including vacuum contributions which describe the properties of nucleons and anti-nucleons in nuclear matter and finite nuclei quite successfully [29]. The parameters of the model are fitted to the ground state properties of spherical nuclei. The RHA0 set of parameters gives $g_\sigma^2 (M_N/m_\sigma)^2 = 229.67$, $g_\omega^2 (M_N/m_\omega)^2 = 146.31$, $g_\rho^2 (M_N/m_\rho)^2 = 151.90$. It leads to the nuclear matter saturation density $\rho_0 = 0.1513$ $fm^{-3}$ (0.1484 – 0.1854 $fm^{-3}$) with a binding energy $E_{bind} = -17.39$ MeV ($-16 \pm 1$ MeV) and a bulk symmetry energy $a_{sym} = 40.4$ MeV (33.2 MeV). The corresponding empirical values are given in parentheses. The model can be further applied to the neutron-proton-electron ($n$-$p$-$e$) system under the beta equilibrium and the charge neutrality conditions which is in particular important for the neutron star. The positive energy of the nucleons in the Fermi sea $E_+$ and the negative energy of the nucleons in the Dirac sea $E_-$ can be written as

$$
E_+ = \left\{ \left( k^2 + (M_N - g_\sigma \sigma)^2 \right)^{1/2} + g_\omega \omega_0 + \frac{1}{2} g_\rho \tau_0 R_{0,0} \right\},
$$

(2)

$$
E_- = - \left\{ \left( k^2 + (M_N - g_\sigma \sigma)^2 \right)^{1/2} - g_\omega \omega_0 + \frac{1}{2} g_\rho \tau_0 R_{0,0} \right\}.
$$

(3)
Here $\sigma$, $\omega_0$ and $R_{0,0}$ are the mean values of the scalar field, the time-like component of the vector field, and the time-like isospin 3-component of the vector-isovector field in neutron star matter, respectively. They are obtained by solving the non-linear equations of the meson fields including vacuum contributions under the constraints of charge neutrality and general equilibrium. The energy of anti-nucleons $\bar{E}_+\bar{E}_-$ is just the negative of $E_-$, i.e., $\bar{E}_+ = -E_-\ [29]$. By setting $k = 0$ in Eqs. (2) and (3), one gets the energies of nucleons and anti-nucleons at zero momentum. The critical density $\rho_C$ for nucleon-anti-nucleon pair creation is reached when $E_- = M_N$. The results are given in Fig. 2 where the single-particle energies of the positive-energy nucleon and the negative-energy nucleon are plotted as a function of density. Due to the effects of the $\rho$-meson field, $\rho_C = 6.1 \rho_0$ for $\bar{p}\bar{p}$ pair creation and 7.5 $\rho_0$ for $n\bar{n}$ pair creation. At the same time, we have calculated the equation of state (EOS) of neutron star matter. The structures and properties of neutron stars can be obtained by applying the equation of state to solve the Oppenheimer-Volkoff equation [31]. The maximum mass of stars turns out to be $M_{\text{max}} = 2.44 \, M_\odot$, and the corresponding radius $R = 12.75 \, \text{km}$ and the central density $\rho_{\text{cen}} = 5.0 \, \rho_0$. The $\rho_{\text{cen}}$ is smaller than the critical density $\rho_C$. That means that the spontaneous $N\bar{N}$ pair creation does not happen for a single neutron star within the model employed.

We consider the following case of neutron star collision: Two identical neutron stars with $\rho_{\text{cen}} = 4.5 \, \rho_0$ (with the current EOS, it is related to $M = 2.43 \, M_\odot$ and $R = 13.0 \, \text{km}$) collide with each other with a free-fall velocity. The impact parameter $b$ stays between 0 and $R$, which determines the factor of density enhancement. We assume that a compact object of average density 7.2 $\rho_0$ is created in the reaction zone. The radius of the compact object is assumed to be $r = 1 \, \text{km}$ (case A) or $r = 3 \, \text{km}$ (case B) depending on the values of $b$. Since for a single neutron star with $\rho_{\text{cen}} = 4.5 \, \rho_0$ the density at $r = 1 \, \text{km}$ is 4.46 $\rho_0$ and at $r = 3 \, \text{km}$ is 4.18 $\rho_0$, in case A the density is enhanced during neutron star collision by a factor around 1.6 while in case B around 1.7. In both cases the $p\bar{p}$ pair creation will happen while the contributions of the $n\bar{n}$ pair creation is negligible (it contributes at higher density but does not affect our discussions). We define a Dirac momentum $k_D$ which describes the negative-energy nucleons occupying the eigenstates of the Dirac sea.
from the uppermost level (the lowest-energy antiparticle level) to the negative continuum (see, Fig. 1), i.e., \( E_- = -M_N \) in Eq. (3). At the critical density for \( p\bar{p} \) pair creation \( \rho^{p\bar{p}}_C = 6.1 \rho_0 \), the Dirac momentum \( k_D^C = 11.28 \text{ fm}^{-1} \); and at \( \rho = 7.2 \rho_0 \), \( k_D = 12.45 \text{ fm}^{-1} \). We further define a momentum \( p_{\text{max}} \) at \( E_- = M_N \), which turns out to be

\[
p_{\text{max}} = \sqrt{\left( g_\omega \omega_0 - \frac{1}{2} g_\rho \tau_0 R_{0,0} + g_\sigma \sigma - 2M_N \right) \left( g_\omega \omega_0 - \frac{1}{2} g_\rho \tau_0 R_{0,0} - g_\sigma \sigma \right)}. \tag{4}
\]

Based on the semi-classical phase-space assumption we then estimate the number of the \( p\bar{p} \) pairs whose energies are larger than the nucleon free mass at \( \rho = 7.2 \rho_0 \) as

\[
N_{\text{pair}} = \frac{4}{3} \pi r^3 \times \frac{p_{\text{max}}^3}{3\pi^2} = 2.147r^3 \times 10^{54}. \tag{5}
\]

Before expansion, this compact object remains high density. Let us check whether most of the \( p\bar{p} \) pairs can be created spontaneously. The rates for the \( N\bar{N} \) pair production per unit surface area and unit time, \( dN_{\text{pair}}/dSdt \), has been calculated in Ref. [28] for compressed matter. In the case of \( \rho = 7 \rho_0 \) and tunnel distance \( d = 1 \text{ fm} \), the rate turns out to be \( 2.68 \times 10^{-2} \text{ fm}^{-3} \). For case B with \( r = 3 \text{ km} \), the time needed to emit the available \( p\bar{p} \) pairs is \( t = 1.9 \times 10^{19} \text{ fm} = 6.3 \times 10^{-5} \text{ s} \), which is smaller than the typical dynamical scale of NS-NS collision \( \tau \sim 10^{-3} \text{ s} \). Thus, we have enough time to produce proton–anti-proton pairs spontaneously. The produced protons stay in the atmosphere due to gravitational force. However, at that time holes (anti-protons) are still in bound states due to potentials they feel (a small fraction may be transported into the negative continuum). The above process may happen before the compact object expands (we are discussing a microscopic procedure in a macroscopic phenomenon). Then the compact object expands and the potentials in the Dirac sea fall down. Those anti-particles (holes) in bound states are pushed into the lower continuum and thus escape. They annihilate with the protons in the atmosphere or in the surrounding objects and release a large sum of energy. If one assumes that 80% of the produced anti-protons annihilate with protons in the surrounding medium and the released energy is 2 GeV at each event (at the moment it’s not very clear how many anti-protons in the Dirac-sea can escape through the lower continuum. This is a problem, which should be investigated more closely.), the
total exploded energy $E_{tot}$ turns out to be $5.5 \times 10^{51}$ erg and $1.5 \times 10^{53}$ erg for cases A and B, respectively. As mentioned before, the efficiency to transfer the initial energy to the observed radiation is only 1% \cite{10}. It seems to be necessary to adopt the picture of beaming explosion for the most energetic $\gamma$-ray bursts.

Some discussion is now appropriate. Neutron star collisions have repeatedly been suggested in the literature as possible sources of $\gamma$-ray bursts \cite{32,33}, powered either by $\nu\bar{\nu}$ annihilation or by highly relativistic shocks. In Ref. \cite{23} Ruffert and Janka claimed that a $\gamma$-ray burst powered by neutrino emission from colliding neutron stars is ruled out. Here we propose a new scenario caused by the strong interactions in dense matter. A large number of anti-particles may be created from the vacuum when the density is higher than the critical density for spontaneous particle–anti-particle pair creation. Such high density can be reached during the NS-NS collisions, BH-NS mergers, or even NS-NS mergers when the merged binary neutron stars have large maximum densities. Some of the produced anti-particles can be ejected from the reaction zone due to violent dynamics. They may be the novel source of low-energy cosmic-ray anti-particles which is currently an exciting topic in modern astrophysics \cite{34}. Most of them will annihilate with the corresponding particles at the ambient medium, and thus release a large amount of energy. As a first step we have discussed the $p\bar{p}$ pair creation in two neutron star collision scenarios because its critical density is lower than that of other baryons. Our calculations show that the exploded energy satisfies the requirement for the initial energy of the energetic GRBs observed up to now. The variation of the released energies of different GRBs can be attributed to the different impact parameters of colliding neutron stars. Those anti-protons, although produced spontaneously, annihilate during the dynamical procedure with random probability in collisions with protons. Furthermore, the anti-protons annihilating later might be accelerated by the photons produced by the nearby $p\bar{p}$ pair annihilations taking place earlier. This leads to the high-energy anti-protons and, consequently, the high-energy photons. Some of them may escape from the fireball before being distorted by the medium. Those escaping high-energy photons may constitute the observed high-energy tail of $\gamma$-ray bursts. This has to be pursued further theoretically.
In summary, we have proposed a new scenario of vacuum discharge due to strong interactions in dense matter as a possible source of $\gamma$-ray bursts. Based on the meson field theoretical model we have estimated the exploded energy $E_{\text{tot}} \sim 10^{51} - 10^{53}$ erg within two neutron star collisions, which fits well into the range of the initial energy necessary for most energetic $\gamma$-ray bursts. For a more quantitative study, one needs to introduce hyperon degrees of freedom \cite{25} and even quark degree of freedom \cite{35,36} if one assumes that the center of neutron star is in quark phase. Here we have mainly discussed NS-NS collisions. In fact, the proposed scenario may happen more frequently for BH-NS mergers since the production rate for BH-NS binaries is $\sim 10^{-4}$ per yr per galaxy \cite{37} which is much larger than the rate of direct NS-NS collisions (for an estimation of collision rate in dense cluster of neutron stars, see Ref. \cite{32}). In this case one might obtain a even higher explosion energy reaching the value of $10^{54}$ erg. A relativistic dynamical model like relativistic fluid dynamics incorporating meson fields is highly desirable to simulate NS-NS collisions, NS-NS/BH-NS mergers. At the end, we would like to mention that a similar process may happen in nucleus-nucleus collisions as discussed in the introduction of Ref. \cite{29} where a dynamical production of anti-matter clusters due to the variation of the time-dependent meson fields has been suggested. We propose to study the photon and anti-proton spectra in ultra-relativistic heavy-ion collisions which may provide us with information of structure of discharged vacuum. Works on these aspects are presently underway.

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FIG. 1. Schematic view of $N\bar{N}$ pair creation from the Dirac sea due to strong fields in dense matter.
FIG. 2. The single-particle energies of the positive-energy nucleon and the negative-energy nucleon in neutron star matter.