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The duality of matter and anti-matter: from gravitation to neutron star

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Abstract
Rare in our universe, antimatter may provide tremendous energy supply through matter-antimatter annihilation. Although continuous efforts have been made on the search of new antiparticles, the mechanism on the generation and transformation of anti-matter remains fully understood yet. Here we propose a dual matter-antimatter model based on quantum coherence of the two states interchanged under mass conjugation, which allows a consistent transition between matter/antimatter and massless radiation in a general nonadiabatic framework. The model not only offers a new perspective for the symmetric universe picture, but also suggests a mechanism of neutron star evolution regarding to the balance between gravitational energy and mass energy. The mechanism predicts a phase transition from the neutron/antineutron mixture to the zero-mass neutral pair, i.e. graviton, which may elucidate the power source of relativistic jet ejection or massive explosion related to unusual astronomical objects such as supernovae, quasar, and active galactic nuclei. The duality of matter and antimatter therefore may provide new physical insights into the understandings of our universe.

Keywords: mass conjugation, antimatter, neutron star, quantum transition, nonadiabatic, gravitation, negative mass

(Some figures may appear in colour only in the online journal)

1. Introduction

Antiparticle is rare in our universe and particle-antiparticle annihilation can transform mass energy fully into radiation, resulting in a much higher efficiency than solar energy powered by nuclear reactions in Sun. Antiparticles may be produced in cosmic radiations and also by high energy nuclear collisions experiments on Earth [1–6]. However, the fundamental mechanisms regarding to the origins and transformations of antimatter are largely unknown. In analogy with particle mixtures under the charge conjugation suggested by Gell-Mann and Pais [7], in this work we propose a dual matter-antimatter model based on mass conjugation instead of charge conjugation, in which particles are coherent mixtures of matter and antimatter. In a general mnonadiabatic framework, the model predicts a transition between matter antimatter mixture and massless neutral pair (MLNP), analogous to the electron-positron creation and annihilation, which implies that MLNP plays a role as the neutral intermediate boson in the gravitational interactions, i.e. graviton, just like photon in the electromagnetic interactions.

In this work, antimatter is referred to the particles (antiparticles) with negative mass. The concept of negative mass is not new, [8–15] and could be responsible for a variety of ubiquitous characteristics, [8, 10, 15] including the antigravity. Particularly interested is its potential role in a symmetric universe model, [12, 16–21] which may offer an alternative simple resolution for a variety of serious cosmological problems such as dark energy. However, it is not always straightforward to incorporate the concept of the negative mass with the existing fundamental principles, e.g. the Newton's law, and the Einstein's equivalence principle. Here our model in this work provides a new alternative perspective for the negative mass, and for the symmetric universe picture, which suggests that

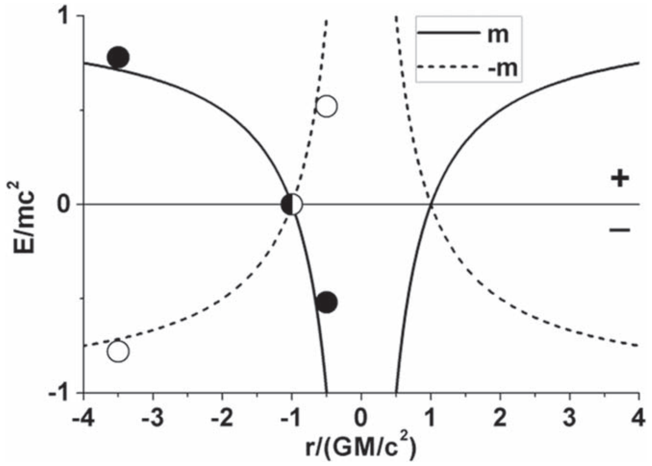

Figure 1. The dual matter antimatter model in the energy representation. The solid and dashed lines denote the total energy of matter (filled circles) and antimatter (open circles) in the single world representation, respectively. The two are degenerated at the critical distance $|r_c| = GM/c^2$, which is represented by a half-black-half-white circle. The particle (and its antiparticle) in the symmetrical universe that combines the positive world ($E > 0$) and the negative world ($E < 0$) is the mixture of matter and antimatter.

antimatter could exist inside massive stars rather than just stay apart from matter. Therefore the model may help understand why our world appears with a matter-antimatter asymmetry, how neutron star may evolve, and the potential power source of relativistic jet ejection or massive explosion related to pulsar, supernovae, quasar, and active galactic nuclei [22–26].

2. The dual matter antimatter model

The antimatter of a particle of mass m is here referred to its conjugated particle with only the sign of mass reversed, i.e. from m to –m, under the mass conjugation. Just like electric force describing the Coulomb interaction between charged particles through their charges, the universal law of gravitation governs the interaction between physical particles (or bodies) through their masses. So we suggest that the mass conjugation would be more appropriate for discussions related to gravitational interactions and the matter-antimatter duality, although the particle-antiparticle pair may be connected through the conjugation of other general physical properties, such as charge.

Consider a neutral particle of mass m in a gravitational potential of mass point M in the rest frame, the total energy of the particle is $E = -GMm/|r| + mc^2$, with G, c the gravitational constant, speed of light, and r the distance between the particle and the mass point. The attractive gravitational force indicates that at some critical distance $r_c = GM/c^2$, the amount of gravitational energy and mass energy (rest energy) will be equal in magnitude and the total energy vanishes. For the antiparticle of mass –m in the same model, opposite results can be obtained for gravitational energy, mass energy and the total energy, as shown in figure 1. And two energy curves come across at the critical distance r_c, which may be taken as the radius of black hole in the sense of that within the radius the particle does not have enough energy ($E < 0$) to directly trigger any response of apparatus (therefore to be seen) in the positive (energy) world ($E > 0$).

Therefore we propose a symmetrical model of the Universe, which is a unification of positive world and negative world. The two worlds are connected through mass conjugation and the positivity and negativity is determined by the sign of total energy. In this symmetrical mass conjugation representation (SMCR), the apparent particle (or antiparticle) in the symmetrical world is a coherent mixture of matter (the physical body in the single world picture) and antimatter. The connection between particle/antiparticle and matter/antimatter can be well described in a nonadiabatic frame work, i.e.

$$\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = U\begin{pmatrix} |\Psi\rangle \\ |\bar{\Psi}\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} |\Psi\rangle \\ |\bar{\Psi}\rangle \end{pmatrix}, \tag{1}$$

Here θ is the transformation angle. $|\Psi\rangle^+$ (and $|\Psi\rangle^-$) are the wavefunctions of the particle (antiparticle) corresponding to the positive (negative) energy state. $|\Psi\rangle$, and $|\bar{\Psi}\rangle$ are the wavefunctions of matter and antimatter, which are the mass eigen-states of the mass operator $\mathbb{M}$, i.e.

$$\mathbb{M}|\Psi\rangle = m|\Psi\rangle, \tag{2a}$$

$$\mathbb{M}|\bar{\Psi}\rangle = -m|\bar{\Psi}\rangle. \tag{2b}$$

Here m is the mass of matter.

Following Gell-Mann and Pais [7], we denote the transformation of mass conjugation and world parity (see the appendix) by operators $\mathcal{M}$ and $\mathscr{P}_W$, then we have

$$\mathcal{M}|\Psi\rangle = |\bar{\Psi}\rangle, \mathcal{M}|\bar{\Psi}\rangle = |\Psi\rangle; \tag{3a}$$

$$\mathscr{P}_W|\Psi\rangle = -|\Psi\rangle, \mathscr{P}_W|\bar{\Psi}\rangle = -|\bar{\Psi}\rangle. \tag{3b}$$

When $\theta = 0$, the particle/antiparticle representation coincides with the matter/antimatter representation, i.e.

$$\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = \begin{pmatrix} |\Psi\rangle \\ |\bar{\Psi}\rangle \end{pmatrix}. \tag{4a}$$

The two components of the total wavefunstion are uncoupled, and neither of them is the eigenstate of the mass conjugation operator. Here we note that

$$\mathcal{M}\mathscr{P}_W\,|\Psi\rangle^+ = -|\Psi\rangle^-, \tag{5a}$$

$$\mathcal{M}\mathscr{P}_W\,|\Psi\rangle^- = -|\Psi\rangle^+. \tag{5b}$$

This corresponds to the large $|r|$ region in figure 1. On the other hand when $\theta = \frac{\pi}{2}$, we have

$$\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = \begin{pmatrix} -|\bar{\Psi}\rangle \\ |\Psi\rangle \end{pmatrix}, \tag{6}$$

which represents the uncoupled two-state case with matter/antimatter eigenstates switched corresponding to the small $|r|$ region in figure 1. The wave function undergoes the following transformation under the $\mathcal{M}\mathscr{P}_W$ conjugation,

$$\mathcal{M}\mathscr{P}_W\,|\Psi\rangle^+ = |\Psi\rangle^-, \tag{7a}$$

$$\mathcal{M}\mathscr{P}_W\,|\Psi\rangle^- = |\Psi\rangle^+. \tag{7b}$$

Another special case is that $\theta = \frac{\pi}{4}$, the particle (and antiparticle) contains equal contributions from matter and antimatter, i.e.

$$\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(|\Psi\rangle - |\bar{\Psi}\rangle) \\ \frac{1}{\sqrt{2}}(|\Psi\rangle + |\bar{\Psi}\rangle) \end{pmatrix}. \tag{8}$$

This corresponds to the degenerated states at the critical distance $|r| = r_c$ in figure 1, which are also the eigenstates of the mass conjugation operator $\mathcal{M}$. Interestingly in this case, the particle (antiparticle) transforms into itself under the combination of the operations of $\mathcal{M}\mathscr{P}_W$, i.e.

$$\mathcal{M}\mathscr{P}_W\,|\Psi\rangle^+ = +|\Psi\rangle^+, \tag{9a}$$

$$\mathcal{M}\mathscr{P}_W\,|\Psi\rangle^- = -|\Psi\rangle^-. \tag{9b}$$

In particular note that

$$\langle\Psi^+|\,\mathbb{M}|\Psi^+\rangle = \langle\Psi^+|\,\mathrm{m}|\Psi^-\rangle = 0, \tag{10a}$$

$$\langle\Psi^-|\,\mathbb{M}|\Psi^-\rangle = \langle\Psi^-|\,\mathrm{m}|\Psi^+\rangle = 0, \tag{10b}$$

Both the particle and the antiparticle have a zero mass. As shown in figure 1, the particle (antiparticle) in the positive (negative) world behaves like matter (antimatter) outside the critical radius r_c but transforms into antimatter (matter) inside r_c. In between these two regions exists a transition region where particle and antiparticle become massless.

It is also interesting to examine the transition in the energy representation. In the nonadiabatic framework, the time dependent Schrödinger equation for the mass eigenstates is

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} |\Psi\rangle \\ |\bar{\Psi}\rangle \end{pmatrix} = H\begin{pmatrix} |\Psi\rangle \\ |\bar{\Psi}\rangle \end{pmatrix} = \begin{pmatrix} E & 0 \\ 0 & -E \end{pmatrix}\begin{pmatrix} |\Psi\rangle \\ |\bar{\Psi}\rangle \end{pmatrix}. \tag{11}$$

The equation for the particle/antiparticle can be obtained from equation (11) under the unitary transformation U, i.e.

$$\begin{aligned} i\hbar\frac{\partial}{\partial t}U\begin{pmatrix} |\Psi\rangle \\ |\bar{\Psi}\rangle \end{pmatrix} &= UHU^TU\begin{pmatrix} |\Psi\rangle \\ |\bar{\Psi}\rangle \end{pmatrix} \\ &= U\begin{pmatrix} E & 0 \\ 0 & -E \end{pmatrix}U^TU\begin{pmatrix} |\Psi\rangle \\ |\bar{\Psi}\rangle \end{pmatrix}, \end{aligned} \tag{12a}$$

which is

$$\begin{aligned} i\hbar\frac{\partial}{\partial t}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} &= \tilde{H}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} \\ &= \begin{pmatrix} E\cos2\theta & E\sin2\theta \\ E\sin2\theta & -E\cos2\theta \end{pmatrix}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix}. \end{aligned} \tag{12b}$$

When $\theta = 0$,

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = \tilde{H}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = \begin{pmatrix} E & 0 \\ 0 & -E \end{pmatrix}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix}, \tag{13a}$$

when $\theta = \frac{\pi}{2}$,

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = \tilde{H}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = \begin{pmatrix} -E & 0 \\ 0 & E \end{pmatrix}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix}, \tag{13b}$$

And for $\theta = \frac{\pi}{4}$,

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = \tilde{H}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix} = \begin{pmatrix} 0 & E \\ E & 0 \end{pmatrix}\begin{pmatrix} |\Psi\rangle^+ \\ |\Psi\rangle^- \end{pmatrix}. \tag{13c}$$

Note that equations (13a) and (13b) are the first order (in time) Schrödinger equation, whereas equation (13c) is the second order Wave function, i.e.

$$\frac{\partial^2}{\partial t^2}\,|\Psi\rangle^\pm = -\left(\frac{E}{\hbar}\right)^2|\Psi\rangle^\pm = -\omega^2\,|\Psi\rangle^\pm. \tag{14}$$

It is clear that when the value of θ varies from 0 to $\frac{\pi}{2}$, the particle undergoes a transition from the matter state through a zero mass radiation state, then to the antimatter state. Note that the nonadiabatic transition characterized by the unitary transformation is not necessarily limited to the case shown in figure 1.

3. Phase transition in neutral star

It is extremely hard to detect the antimatter dominated negative world directly since antimatter only exists at extreme conditions. Neutron star would be a good cosmic lab to study the matter-antimatter duality. So let us now consider a simple model in the SMCR to understand the evolution of neutron stars. We associate the particles $|\Psi\rangle/|\bar{\Psi}\rangle$ with the mixture of neutron and antineutron, and $|\Psi\rangle^+/|\Psi\rangle^-$ to be the massless neutral pair (MLNP).

When the mass of a star exceeds the Chandrasekhar limit, i.e. $\sim$1.4 $M_\odot$, the pressure of degenerated neutrons will counterbalance gravity to prevent the collapse of the star. If we model the neutron star as a homogeneous sphere of neutron gas, the gravitational energy of a neutron of mass m is given by

$$V = \begin{cases} -\dfrac{GMm}{r} & (r \geqslant R) \\ -\dfrac{GMm}{R}\left(1.5 - 0.5\dfrac{r^2}{R^2}\right) & (r < R) \end{cases}, \tag{15}$$

with M, R the mass and the radius of the neutron star. The lowest potential energy is -1.5 GMm/R at $r = 0$. If we denote the ratio of the magnitude of the lowest gravitational energy to mass energy, $\alpha = 1.5\frac{GM}{Rc^2}$, a special limit of the mass of neutron stars may be obtained at a critical value of $\alpha = 1$, which corresponds to the zero total energy of the particle.

Figure 2 illustrates the SMCR model of neutron star at an equilibrium or steady state in this critical regime. The plotted are the total energy of a neutral particle in the system. For $\alpha = 1$, the energy of neutron and conjugated antineutron are degenerated only at $r = 0$ (figure 2(a)). A small increase of α will result in the overlap of the energy curves of matter and antimatter within the critical radius, and the neutron-antineutron

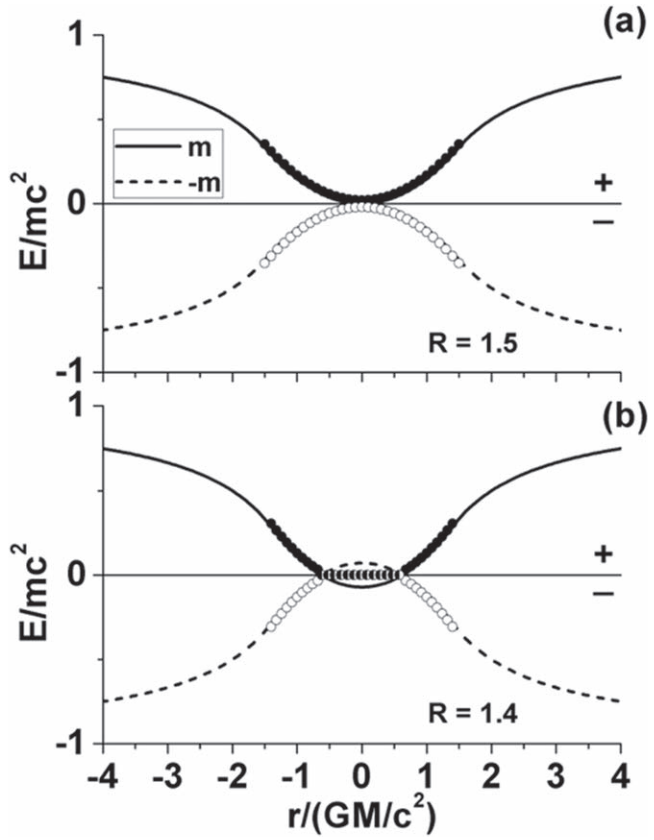

Figure 2. The dual matter-antimatter model for neutron stars. Filled and open circles represent for the neutron and antineutron components of the particle in the homogeneous gas occupied in the positive and negative worlds, respectively. (a) Equilibrium state with the radius R = 1.5. (b) nonequlibrium state with a heavier mass and shorter radius R = 1.4. The MLNP in the innermost regime are represented by half-black-half-white circles. One may associate MLNP with zero mass neutrinos, but this conjecture requires further justifications.

mixture and MLNP are degenerated when two energy curves cross each other so that a phase transition may occur and neutral particle could transform into MLNP through the neutron anti-neutron annihilation (figure 2(b)). If no phase transition took place, there would be a strong repulsion between the inner antimatter regime and the outside matter regime at the critical distance and the energy of the particle would increase dramatically. The phase transition also reduces the effective mass of neutron star since the mass of MLNP is zero, therefore the energy curve would avoid across the boundary of the two worlds and the neutron star relaxes to its equilibrium state as shown in figure 2(a). The critical value of α therefore may set a mass limit of neutron star. If we take the mass density of neutron star to be $2^{*}10^{17}\mathrm{kg/m}^3$, the equilibrium mass is given by $M_{eq} \approx \frac{4}{3}\pi\rho c^3\left(\frac{\alpha}{2\pi G\rho}\right)^{3/2} \sim 15M_{\odot}$.

The MLNP carries the radiation energy transformed from the mass energy of the neutron/antineutron mixture. The inner core generates a radiation pressure of $\frac{\rho c^2}{3}$, which is 2.5 times higher than the gravitational pressure of neutron star

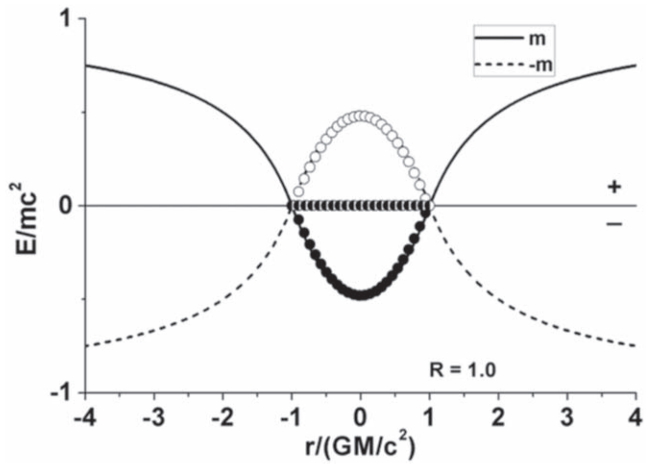

Figure 3. The same as figure 2(a) but for another critical value of $\alpha = 1.5$.

at the critical value of $\alpha = 1$. This may cause an explosion from inside of neutron star, which could be responsible for the relativistic jet emission [23–26]. When ejecting out from the inside, the high energy MLNP may transform back into neutron antineutron pair, undergo superfluity transition to enhance neutrino emission [27–29] or interact with neural particles to produce (anti)proton, and (anti)electron. The matter-antimatter annihilation and the matter-radiation interaction may result in enormous photon emission span over full spectrum including Gamma ray, x ray, visible light, etc Therefore we suggest that the relativistic jet, Gamma ray burst from point sources may be related to the matter-antimatter annihilation and MLNP explosion. The pulsing emission may be due to the equilibrium fluctuation of the mass and energy of neutron star as shown in figures 2(a) and (b), here the neutron star just works as a matter-antimatter engine. Note that our model does not have to invoke black hole or magnetic field, therefore provides a potentially alternative mechanism.

For neutron star with a mass even heavier than M_{eq}, there exists another critical value of $\alpha = 1.5$, i.e. the gravitational energy matches the mass energy and $R = GM/c^2$ as shown in figure 3. The star in the positive world is now completely made of antimatter if there were no phase transition! However if the phase transition takes place fast enough, the primitive neutron star could evolve into a critical neutron star which ends up with a complete explosion. Note that even though the critical radius indicates the neutron star may become a black hole, it is however unstable due to quantum coherence between matter and antimatter. According to our model, black hole may not form simply due to the gravitational collapse of neutron star. The critical mass forming a critical neutron star is about 27 $M_{\odot}$ if the density $\rho = 2 \times 10^{17}\,\mathrm{kg\,m^{-3}}$ is assumed. The total energy released is on the order of 10^{48} J, which is enough to power supernovae explosions. In addition our model suggests that it is not surprise if no leftover survives after the explosion of the whole neutron star, which may explain the observation on supernovae 1987A [22].

4. Discussion and conclusion

There are many sophisticated theoretical models available [30, 31], which provide valuable information to understand high density matter in neutral stars. We note that these models predict the maximum mass of neutral star about an order of magnitude smaller than what our model does. However the predictions by most existing approaches rely on input parameters with unclear physical meanings, and some of them have already been excluded by recent discovery of neutral stars with a mass around 2 $M_\odot$ [32, 33]. The advantage of our simple model is that it provides a clear physical mechanism free of parameters to explain the evolution of neutral star and related pulsing emissions. Therefore we hope it offer an alternative way of thinking about the high density matter in neutral stars.

In analogy to photon involved in electron-positron creation or annihilation related to electromagnetic interactions, the MLNP in our model behaves like zero-mass neutral intermediate boson. Since only the gravitational interactions get involved here, we conjecture that the MLNP is indeed the graviton. The MLNP explosion may generate gravitational wave, which might be detected by LIGO [34]. Further investigations are under the way.

Just as the symmetry of charge conjugation results in charge conservation, the duality of matter and antimatter guarantees the conservation of mass conjugation quantum number. Therefore the mass symmetry of the Universe is restored if mass conjugation, rather than charge conjugation, is applied. Instead, the latter is responsible for the charge neutrality of the Universe. The reason why our observed universe shows a matter-antimatter asymmetry may be that we seem to only look at the positive (or negative) world.

In summary, the balance of gravitational energy and mass energy suggests a dual matter-antimatter model. In a general nonadiabatic representation of the model, matter and antimatter may transform into massless radiation, in analogy to electron-positron annihilation. The proposed model may explain the symmetrical universe, and predict a phase transition under high density from neutron/antineutron mixture to massless neutral pair, therefore offer a potential mechanism to the neutron star evolution and relativistic jet ejection or supernovae explosion.

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Notes

The authors declare no competing financial interests.

Appendix

Negative mass

There are three types of mass involved related to the gravitation, [8, 10, 18] i.e. the active gravitational mass m_a, the passive gravitational mass m_p, and the inertia mass m_i. In a simple two-body model for gravitational interactions, one object is assigned to be the active one (normally the massive one, e.g. Earth) with the active mass m_a which generates the gravitational field. The other object is the passive object (normally the tiny one, e.g. apple) with the passive mass m_p, which moves in the gravitational field or subject to the gravitational force, and the proportionality of the external force (including gravitational force) and the acceleration of the object gives its inertia mass m_i, according to the Newton's second law. In the conventional framework of physical laws, all three types of mass are non-negative. And the universal law of gravitation indicates that the active mass and the passive mass are at the same footing, i.e. they are interchangeable while keeping the gravitational force the same. Therefore we do not consider the situation in which an object has two different gravitational mass [8, 17]. Also the gravitational mass (either active or passive one) is normally assumed to be the same as its corresponding inertia mass (both active and passive objects have their own inertia mass), according to the Einstein's equivalence principle.

When negative mass is allowed, the picture of gravitation becomes complicated. Several possibilities of combinations of the positive-negative mass have been investigated [8]. If the gravitational mass and the inertia mass are the same and both can be negative, we would see that like objects (having the same sign in mass) attract each other while unlike objects (having different signs in mass) repel each other according to the universal law of gravitation. In this case, two negative objects move apart from each other although the gravitational force is attractive, so negative objects would not collapse without other interactions involved. For the two objects with one positive and the other negative mass, both have the same acceleration in the same direction.

If on the other hand, the inertia mass is different from the gravitational mass, there are two possibilities. First the inertia mass can be negative while the gravitational mass is always positive. This results in conventional attractive gravitational force but negative acceleration for the object with negative mass. Second the inertia mass is always positive and the gravitational mass can be negative. This corresponds to the model we consider in this work, i.e. like objects attract to each other and also move toward to each other, and unlike objects repel to each other and move apart from each other.

It worth noting that our model respects the equivalence principle too considering the fact of that the latter states that the gravitational acceleration is equivalent to the acceleration due to other interactions. Most importantly, our dual matter antimatter model is a nonadiabatic coherent model, in which matter and antimatter are coupled with each other. And the phase transition predicted by the model suggests that antimatter could exist inside massive stars rather than just stay apart from each

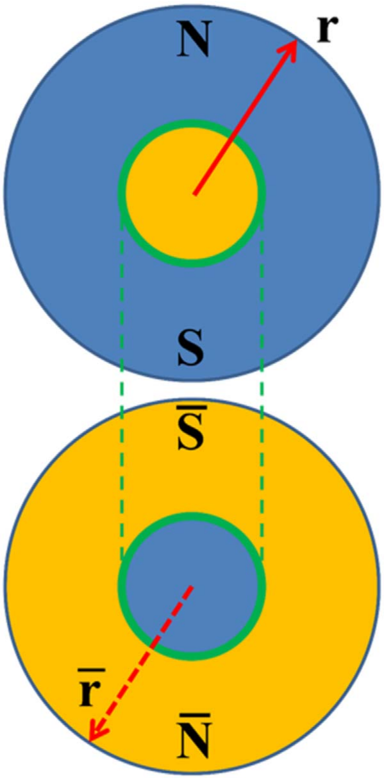

Figure A1. The cartoon for the dual world model of matter and antimatter. The upper sphere represent for the positive world, which is coupled with the lower sphere for the negative world. The matter regime is in blue while antimatter is in orange, and the massless mixture is in green. Under the world parity transformation, both the vector and poles turn upside down.

other [17]. Therefore our model seems consistent with the observations on that no diffusive gamma rays background [12] but gamma ray burst from points sources exist.

Mass conjugation

The proposed mass conjugation formalism suggests the duality of matter and antimatter, which are interchangeable upon the sign change of mass. To illustrate the dual matter antimatter picture, a symmetrical world is depicted in the energy representation in figure 1 for a model system consisting of a neutral testing particle $m > 0$ (and its mass conjugation image $-m < 0$) with a mass point $M > 0$ in the rest frame, without loss of generality. In fact, for the case of $M < 0$, the same figure 1 would be obtained by applying the mass conjugation, i.e. $M \rightarrow \bar{M} = -M$, and $m \rightarrow \bar{m} = -m$, except that the negative (energy) and positive (energy) world are switched.

It would be helpful to understand the dual world of matter and antimatter in high dimensional space, as seen in Figure A1. Two spheres represent for positive world and negative world, respectively, and both are connected with each other at the crossing shells (the contacted surface is stretched as a cylinder), which defines the boundary of the matter and antimatter regimes. The parity in the normal positive world is related to the transformation of space inversion, i.e. $\mathrm{r}(r, \theta, \varphi) \rightarrow \mathrm{r}(r, \pi - \theta, \pi + \varphi)$. By contrast, in the dual world, we consider the world parity $\mathscr{P}_W$ related to the transformation between the positive space and the negative space, i.e. $\mathrm{r} \rightarrow \bar{\mathrm{r}}$. Also the poles of the sphere turns upside down between the two worlds. Therefore, the spin will flip when the interchange between the positive and negative worlds takes place and the magnetic moment of antimatter will be equal to that of matter but with the opposite sign.

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