Nuclear collision in strong magnetic field

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Abstract

Based on the Boltzmann-Uehling-Uhlenbeck transport model coupled with the Lorentz force equation, we studied nucleus-nucleus collision in strong magnetic field. We find that neutrons and protons can be separated from a nucleus by strong magnetic field and neutron-rich high density nuclear matter and low density proton collectivity matter can be formed during nucleus-nucleus collision. The electric field produced by proton collectivity can accelerate proton and charged meson up to very high energies. Besides the studies of isospin physics such as symmetry energy, these results may help us to understand the acceleration mechanisms of high energy charged particles in the cosmic rays.

Key words: Nuclear collision, strong magnetic field, isospin physics, acceleration mechanisms, origin of cosmic rays.
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The question of the origin of cosmic rays continues to be regarded as an unsolved problem even after almost one century years of research since the announcement of their discovery in 1912 [1]. The cosmic rays of extremely high-energy pose a serious challenge for conventional theories of origin of cosmic rays based on acceleration of charged particles in powerful astrophysical objects. The question of origin of these extremely high-energy cosmic rays is currently a subject of much intense debate and discussions [2]. On the origin of energetic cosmic-rays in the universe, except through decay of sufficiently massive particles originating from processes in the early universe, there are basically two kinds of acceleration mechanisms considered in connection with cosmic rays acceleration, i.e., direct acceleration of charged particles by an electric field and statistical acceleration in a magnetized plasma. In the direct acceleration mechanism, the electric field in question is generally due to a rotating magnetic neutron star (pulsar) or, a (rotating) accretion disk threaded by magnetic fields, etc. [1]. In this article, we show that nuclear collision in strong magnetic field can produce proton collectivity in space, protons or other charged particles thus can be accelerated directly by electric fields, which are produced by positive charges, not by changing magnetic fields.

The condition of strong magnetic field may exist in the universe, such as white dwarfs, neutron stars, and accretion disks around black holes, and the maximum value of magnetic fields in the universe may reach $10^{20} \sim 10^{42}$ G [3]. And with the rapid development of laser technology, obtaining strong magnetic field artificially in terrestrial laboratory also may be possible [4,5]. Although nuclear collisions exist extensively in the universe, up to now, nuclear reactions in the strong magnetic field were seldom reported. The separation of neutrons and protons from a nucleus while nucleus-nucleus collision in strong magnetic field may shed light on the acceleration mechanisms of high energy charged particles in the cosmic rays.

Nuclear matter studies can be carried out semiclassically following the so called nuclear pasta phases [6,7,8,9]. In this study we also use the semiclassical isospin-dependent Boltzmann-Uehling-Uhlenbeck (BUU) transport model [10,11], which is quite successful in describing dynamical evolution of nuclear collision. The BUU equation describes time evolution of the single particle phase space distribution function $f(r, p, t)$, it reads:

$$\frac{\partial f}{\partial t} + \upsilon \cdot \nabla_r f - \nabla U \cdot \nabla_p f = I_{collision}. \tag{1}$$

$f(r, p, t)$ can be viewed semi-classically as the probability of finding a particle at time t with momentum p at position r. The mean-field potential U depends on position and momentum of the particle and is computed self-consistently using the distribution functions $f(r, p, t)$. The collision item $I_{collision}$ on the right-hand side of Eq. (1) governs the modifications of $f(r, p, t)$ by elastic and inelastic two body collisions caused by short-range residual interactions [12]. The proton and neutron densities of colliding nuclei are given by Skyrme- Hartree-Fock with Skyrme M^* force parameters [13]. The isospin dependence is included in the dynamics through nucleon-nucleon collisions by using isospin-dependent cross sections and Pauli blocking factors [14]. The isospin and momentum-dependent mean field potential used is [15]

$$\begin{aligned} U(\rho, \delta, \mathbf{p}, \tau) &= A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} \\ &+B\left(\frac{\rho}{\rho_0}\right)^\sigma \left(1 - x\delta^2\right) - 8x\tau\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'} \\ &+ \sum_{t=\tau,\tau'} \frac{2C_{\tau,t}}{\rho_0}\int d^3\mathbf{p}'\frac{f_t(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p} - \mathbf{p}')^2/\Lambda^2}. \end{aligned} \tag{2}$$

In the above equation, $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry parameter, $\rho = \rho_n + \rho_p$ is the baryon density and ρ_n, ρ_p are the neutron and proton densities, respectively. $\tau = 1/2(-1/2)$ for neutron (proton) and $\tau \neq \tau'$, $\sigma = 4/3$, $f_\tau(\mathbf{r}, \mathbf{p})$ is the phase-space distribution function at coordinate $\mathbf{r}$ and momentum $\mathbf{p}$. The parameters $A_u(x), A_l(x), B, C_{\tau,\tau}$, $C_{\tau,\tau'}$ and Λ were set by reproducing the momentum-dependent potential $U(\rho, \delta, \mathbf{p}, \tau)$ predicted by the Gogny Hartree-Fock and/or the Brueckner-Hartree-Fock calculations [16,17], the saturation properties of symmetric nuclear matter and the symmetry energy of about 31.6 MeV at normal nuclear matter density $\rho_0 = 0.16$ fm^{-3}. The incompressibility of symmetric nuclear matter at normal density is set to be 211 MeV. The parameters $A_u(x)$ and $A_l(x)$ depend on the parameter x according to

$$A_u(x) = -95.98 - \frac{2B}{\sigma+1}x, A_l(x) = -120.57 + \frac{2B}{\sigma+1}x, \tag{3}$$

where $B = 106.35$ MeV. $\Lambda = p_F^0$ is the nucleon Fermi momentum in symmetric nuclear matter, $C_{\tau,\tau'} = -103.4$ MeV and $C_{\tau,\tau} = -11.7$ MeV. The $C_{\tau,\tau'}$ and $C_{\tau,\tau}$ items are the momentum-dependent interactions of a nucleon with unlike and like nucleons in the surrounding nuclear matter. The parameter x is introduced to mimic various density-dependent symmetry energies $E_{\text{sym}}(\rho)$ predicted by microscopic and phenomenological many-body approaches. Because we do not study nuclear symmetry energy here, in this article we just let the variable x be 1 [18]. The isoscalar part $(U_n + U_p)/2$ of the single nucleon potential was shown to be in good agreement with that of the variational many-body calculations and the results of the BHF approach including three-body forces. The isovector part $(U_n - U_p)/2\delta$ is consistent with the experimental Lane potential [14]. We use the isospin-dependent in-medium reduced nucleon-nucleon elastic scattering cross section from the scaling model according to nucleon effective mass. For in-medium nucleon-nucleon inelastic scattering cross section, we at present use the free nucleon-nucleon inelastic scattering cross section [19].

Updates of nucleonic momentum are generally owing to momentum and spatial location dependence of its mean-field potential U, decided by the gradient force ∇U in Eq. (1). Besides the gradient and Coulomb forces added on the charged particles, momentum of charged particle also changes owing to the Lorentz force. For the additional magnetic filed force of charged hadron, we use the Lorentz force equation

$$\overrightarrow{F} = q\overrightarrow{v} \times \overrightarrow{B}. \tag{4}$$

Where $\overrightarrow{v}$ is the velocity of charged particle and $\overrightarrow{B}$ is the additional magnetic field. In the practical calculations we add the Lorentz force to the Coulomb and mean-field gradient forces. Because the strength of magnetic field in this study is huge, we in the present simulations use the relativistic form of the Lorentz force equation and let the time step interval dt of updates of particle's phase space information be a very small value ($dt = 0.0025 fm/c$).

Studying nucleus-nucleus collision in strong magnetic field, we should firstly get a picture of how the collision evolves with or without magnetic field. Fig. 1 shows nuclear collision process with and without strong magnetic field. From upper panels we can see that, without magnetic field, protons and neutrons have almost the same mode of motions. Protons and neutrons go through the same compressions and inflations. These are normal knowledge of nuclear reaction. With strong magnetic field, however, the whole situation is changed. From the lower panels we can first see that, protons in the target and projectile refuse to collide and look like keeping still collectively owing to the Lorentz forces added on the protons. Whereas the neutrons in the target and projectile trend to collide, just like the case without magnetic field. The colliding neutrons form high density neutron matter transiently. The "still" protons of the target and projectile form low density proton matter. We dub neutron matter or proton matter asymmetric nuclear matter. If the strength of magnetic field is smaller than $\sim 10^{17}$ Tesla, the Lorentz force can not overcome the mean-field gradient force. The separation thus can not happen. With such strong magnetic field, the protons almost keep still in space, i.e., fixed in coordinate space by the magnetic field and can be kept macroscopically. The separation of neutrons and protons from a nucleus with strong magnetic field may shed light on the possible origin of cosmic rays. If the magnetic fields are not homogeneous, such as the wandering magnetic fields, the separation of neutrons and protons within a nucleus can be kept ultimately. And the separating neutrons and protons move respectively. In the universe, the collision between nuclei may be replaced by physical collisions between stars [20,21,22]. Collisions among light nuclei in stars or interstellar matter with magnetic field are similar to the ^{124}Sn+^{112}Sn collision here. In case the magnetic field decreases or disappears, the existing proton collectivity disperses promptly owing to the Coulomb actions.

To show the acceleration mechanisms of high energy charged particles in the cosmic rays by the electric field, we draw the sketch-map of Fig. 2. The left-hand side of Fig. 2 is the sketch-map of proton collectivity forms in magnetic field via large number of "nucleus-nucleus collision" (in fact it is not nucleus-nucleus collision, but mainly is neutron-neutron collisions and protons keep "still"). When two dense stars with strong magnetic field collide, as shown in Fig. 2, large number of proton collectivity can be formed. They are fixed in certain space by the strong magnetic field so that the coulomb potentials are stored. While without strong magnetic field, however, this configuration changes promptly. The right-hand side shows the case without strong magnetic field. Protons in the collectivity disperse in all directions with the actions of the Coulomb potential. The first escaped protons or the boundary protons will be greatly accelerated, so they possess large velocities. The inner protons will have small velocities. Some escaped protons can be accelerated again and again here and there. This may be a reason why the cosmic-ray composition (above 1.6 EeV) is proton-dominated [23,24,25]. The energy of proton accelerated can be roughly calculated via

$$U = \sum_{q_i=1}^{q_i=Q} \frac{1}{4\pi\varepsilon_0} \frac{q_i}{r_i} \sim 0.047 \frac{Q}{R}\ (GeV). \tag{5}$$

Here U is the Coulomb energy (in unit of GeV), Q (in unit of elementary charge) and R (in unit of fermi) are the accelerating charges and mean distance between accelerated proton and accelerating charges, respectively. If the value Q is large enough, the proton then can obtain a energy of several or even tens/hundreds of GeV. Assuming the accelerated proton mean R is 100 fm and proton density in collectivity (for proton collectivity, we suppose a semi-spherical shell distribution) is the same as that in ^{208}Pb, the proton then can obtain a maximal energy of about $0.03 \times R/fm \times GeV = 3GeV$. Practically, scale of proton collectivity formed in strong magnetic field may be much larger than 100 fm, the proton energy is thus also much larger than $3GeV$. Note here that proton may be accelerated many times as shown on the right-hand side of Fig. **??** owing to the winding magnetic field. Therefore the energetic cosmic-ray protons or other charged particles may be accelerated by electric field. As for other cosmic-ray nuclei, they can be accelerated directly by the electric field, having no colliding separation of neutrons and protons via nucleus-nucleus collision.

Because of the separation of neutrons and protons within a nucleus while nucleus-nucleus collision in strong magnetic field, the compressed nuclear matter must be neutron-rich matter. Fig. 3 shows neutron to proton ratio n/p of such high density nuclear matter formed during the collision with strong magnetic field. Here the n/p of high density nuclear matter formed can reach 4 (if the colliding nuclei are far apart, the n/p of compressed nuclear matter can be even more large), is much larger than obtained from general nuclear reaction in terrestrial laboratory, in which the n/p of transiently formed nuclear matter is about 1. If in the universe, somewhere there are strong magnetic fields as large as 10^{17} Tesla, one then can possibly in heaven use such asymmetric nuclear matter to study isospin physics (physics relevant to unequal numbers of neutrons and protons), such as nuclear matter symmetry energy (energy relevant to the changing of mean energy per nucleon owing to unequal numbers of protons and neutrons, is a main subject of isospin physics), which is crucial for understanding many interesting issues in both nuclear physics and astrophysics [26,27,28,29,30,31,32] and has been regarded as the most uncertain property of dense neutron-rich nuclear matter [33,34]. The advantage of using such asymmetric nuclear matter to study isospin physics is that such asymmetric nuclear matter formed in strong magnetic field via nuclear collision has huge asymmetry, effects of isospin are thus enlarged remarkably. Ever since a long time ago, the small asymmetry of compressed nuclear matter obtained in terrestrial laboratory has been one of the most troublesome factors (which is owing to small resolution of isospin effect caused by small asymmetry of nuclear matter produced through ordinary nuclear collision) to study isospin physics, especially for nuclear symmetry energy.

Pion production in nuclear reaction nowadays has attracted much attention in nuclear physics community [28,29,19]. One important reason is that pion production is connected with the high density behavior of nuclear symmetry energy [35]. Here we only study pion meson in original cosmic rays. Fig. 4 shows evolution of π^-/π^+ ratio with and without magnetic field, using ^{124}Sn+^{112}Sn collision at 400 MeV/nucleon as a example. At early stage of nucleus-nucleus collision in the magnetic field, as shown in Fig. **??**, we can see that neutron-neutron collisions can happen while protons nearly do not take part in the collisions. We thus see a very large π^-/π^+ ratio with magnetic field (π^-'s are mainly from neutron-neutron collisions, π^+'s are mainly from proton-proton collisions, neutron-proton collisions produce roughly equal numbers of π^- and π^+). In the universe, with strong magnetic field, such behavior can happen during nucleus-nucleus collision. Maybe some of π mesons, especially π^- mesons in the cosmic rays come from such nucleus-nucleus collision, and they are accelerated (the acceleration mechanisms may be that pions are attracted by proton collectivity and then their trajectories are bent by magnetic field) by the electric field produced by proton collectivity originating from nucleus-nucleus collision in strong magnetic field.

In conclusion, we do a study of nuclear collision with strong magnetic field. It is found that nuclear collision in strong magnetic field (roughly $\sim 10^{17}$ Tesla) causes the separation of neutrons and protons from a nucleus. The formed proton collectivity can produce electric field and accelerates proton or charged pion meson up to very high speeds. Nuclear collision in strong magnetic field can also produce asymmetric nuclear matter transiently. The formed asymmetric nuclear matter may be used to study isospin physics such as nuclear symmetry energy someday in both heaven and terrestrial laboratory.

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