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Pair production by a strong wakefield excited by intense neutrino bursts in plasmas

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Abstract

We consider the production of electron–positron pairs due to accelerated electrons in a strong wakefield that is created by intense neutrino bursts in plasmas. By using a classical fluid description, we investigate the generation of electrostatic wakefields at the plasma wave-breaking limit, and estimate the number of pairs that is produced by a trident process. We find that the pair concentration produced is huge, and this result can be very important in studies of astrophysical plasmas and in intense laser-plasma interaction experiments which are aimed to understanding several astrophysical phenomena in laboratory.

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Nonthermal electron–positron (pair) plasmas are known to be abundant in many astrophysical environments from pulsars to quasars, as well as in our own galaxy and in supernovae remnants. Electron–positron pair production has been the subject of many studies in astrophysics [1–4], as well as in theoretical, computational and experimental physics [5–15]. In astrophysics, pair production has a central role in the "fireball model" for GRBs [1] and the decay of photons into pairs is usually assumed as the mechanism responsible for populating a pulsar magnetosphere [3]. Laboratory astrophysics studies involving super strong short laser pulses also encounter pair plasmas.

There are several mechanisms by which electron–positron pairs can be produced. One of the most popular mechanisms is the Schwinger pair production model [16], where pairs are spontaneously produced in a constant electric field if the strength of the latter in vacuum exceeds the Schwinger critical value $E_{\mathrm{QED}} = 1.3 \times 10^{16}$ V/cm. Another possibility of the

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electron–positron pair production is by means of intense laser pulses, where in the focal region of a laser pulse (near the intensity 10^{29} W/cm^2, corresponding to the critical electric field), electron–positron pairs can just "appear" from vacuum [6]. However, the cross-section for this process at optical frequencies (or below) is so small at any laser intensity, so that this effect is insignificant [17]. Recently, Nitta et al. [18] considered pair production by photons in nonuniform strong fields. Furthermore, production of pairs is also possible in the Coulomb field of a nucleus via virtual photons ("tridents"), which is a dominant energy loss mechanism at high energies. In a trident process, high-energy electrons, whose kinetic energy exceeds the pair-production threshold $2m_0c^2$, can produce electron–positron pairs by scattering in the Coulomb potential of a nucleus. Several authors [21,22] presented a preliminary discussion of the pair production by relativistic electrons accelerated by intense lasers, while Berezhiani et al. discussed pair production due to scattering of relativistic electrons, which are produced by strong wakefields [23] driven by ultra-intense short laser pulses, in Coulomb potential of stationary ions in plasmas.

It is believed that neutrinos can be one of the natural sources of electron–positron plasmas. Dominant processes of neutrino production and neutrino-induced electron–positron pair production can be responsible for the generation of ultra-relativistic electron–positron plasma jets, which produce the gamma-ray bursts (fireball model) [19]. Besides, the effect of neutrino-induced pair production can be important on the explosion dynamics of a type II supernova [20]. In a recent Letter, we have shown that an intense neutrino burst can generate a strong wakefield during its interaction with either unmagnetized or magnetized plasmas [24,25]. In that case, a classical fluid description is used to investigate nonlinear interactions between an electron-type neutrino burst and a collisionless magnetized electron–ion plasma. It is found that the neutrinos can excite large amplitude wakefields, which can produce acceleration of charged particles to extremely high energies. These results, which are independent on the electron-type neutrino density but dependent on the neutrino energy variation during the interaction, can be applied to understand charged particle acceleration in supernovae and in extreme astrophysical environments containing gamma-ray bursts.

In this Letter, we present a study of the electron–positron pair production by electrons accelerated in a wakefield generated by the interaction between an intense electron-type neutrino beam and a collisionless cold unmagnetized electron–ion plasma. The electrons produce pairs by scattering in the Coulomb potential of immobile ions. Neutrinos are treated as quasi-classical particles by assuming that the neutrino de Broglie wavelength is much shorter than the typical scalelength of the perturbation in the effective neutrino weak interaction potential. Besides, neutrino–neutrino scattering contributions are found to have a small effect on neutrino flavour evolution [26]. We use a classical fluid description to analyse nonlinear interactions between neutrino bursts and an unmagnetized electron–ion plasma in order to investigate the generation of electrostatic wakefields at the wave-breaking limit, and determine the pair concentration produced by the scattering of accelerated electrons.

Following Refs. [24,25], the dynamics of an ensemble of the neutrinos can be described by

$$\frac{\partial N_\nu}{\partial t} + \nabla \cdot \vec{J}_\nu = 0, \tag{1a}$$

and

$$\frac{\partial \vec{p}_\nu}{\partial t} + (\vec{v}_\nu \cdot \nabla)\vec{p}_\nu = -\frac{1}{N_\nu}\nabla P_\nu + \sum_\sigma G_{\sigma\nu}\left(\vec{E}_\sigma + \frac{\vec{v}_\nu}{c} \times \vec{B}_\sigma\right), \tag{1b}$$

which couple the neutrino density N_ν and the neutrino momentum $\vec{p}_\nu$. The coupling between neutrinos and the plasma fluid is given by the "bare" weak-interaction charge $G_{\sigma\nu} = \sqrt{2}G_F[\delta_{\sigma e}\delta_{\nu\nu_e} + (I_\sigma - 2Q_\sigma \sin^2\theta_W)]$ [27], where $G_{\sigma\nu} = -G_{\bar{\sigma}\nu}$ and G_F ($\approx 9 \times 10^{-38}$ eV cm^3) is the Fermi weak-interaction coupling constant. Furthermore, σ denotes the plasma particles (e for electrons and i for ions), θ_W is the Weinberg mixing angle ($\sin^2\theta_W \approx 0.23$), I_σ is the weak isotopic spin of the particle of specie σ (equals $-1/2$ and $1/2$ for the electrons and ions (protons), respectively), and $Q_\sigma = q_\sigma/e$ is the particle normalized electric charge. It should be noted that the first term in $G_{\sigma\nu}$ is due to charged weak currents (and thus applies only to electrons and electron-type neutrinos), while the remaining terms are due to neutral weak currents (and thus apply to all species).

Here we consider a cold neutrino gas, so the neutrino kinetic pressure $P_\nu = N_\nu T_\nu$ in Eq. (1b) can be neglected. The second term in this equation is the weak force on a single neutrino due to the plasma, and $\vec{E}_\sigma = -\nabla N_\sigma - (1/c^2)\partial \vec{J}_\sigma/\partial t$ and $\vec{B}_\sigma = c^{-1}\nabla \times \vec{J}_\sigma$ are the effective electric and magnetic fields, respectively. $\vec{J}_\nu = \vec{v}_\nu N_\nu$ and $\vec{J}_\sigma = \vec{v}_\sigma N_\sigma$ are the neutrino and σ species currents, respectively, and the linear momentum of the neutrino is given by $\vec{p}_\nu = (\vec{v}_\nu/c^2)E_\nu$, with E_ν being the neutrino total energy. The term $\partial \vec{J}_\sigma/\partial t$ is the neutrino-plasma analog of the electromagnetic-plasma energy transfer, as described in Ref. [27].

The plasma particles are governed by the continuity and momentum equations

$$\frac{\partial N_\sigma}{\partial t} + \nabla \cdot \vec{J}_\sigma = 0, \tag{2a}$$

and

$$\frac{\partial \vec{P}_\sigma}{\partial t} + (\vec{v}_\sigma \cdot \nabla)\vec{P}_\sigma = q_\sigma \vec{E} + \sum_\nu G_{\sigma\nu}\left(\vec{E}_\nu + \frac{\vec{v}_\sigma}{c} \times \vec{B}_\nu\right), \tag{2b}$$

where $\vec{P}_\sigma = \gamma_\sigma m_\sigma \vec{v}_\sigma$ and $\gamma_\sigma = 1/\sqrt{1 - v_\sigma^2/c^2}$ are the momentum of the particle species σ (electrons and ions) and the relativistic Lorentz factor. The right-hand side in Eq. (2b) is the total force acting on the plasma due to all types of the neutrinos, $\vec{E}_\nu = -\nabla N_\nu - c^{-2}\partial \vec{J}_\nu/\partial t$ and $\vec{B}_\nu = c^{-1}\nabla \times \vec{J}_\nu$ are the "weak-electromagnetic" fields, and N_σ is the number density of the species σ. Since we are looking for wakefield generation on timescales that are either comparable to or shorter than the electron plasma period, collisions between electrons and ions are neglected.

To simplify our model, we consider a cold electron-type neutrino beam along the x-direction with the velocity v_ν ($v_\nu \approx c$) during its nonlinear interaction with a collisionless cold unmagnetized electron–ion plasma. Anti-neutrinos are not considered, and the ion dynamics is neglected. We can assume that the electron-type neutrino flux only transfers a very small part of its energy (E_ν) to the plasma and keeps its density (N_ν) nearly constant, since it is well known that the interaction of electron neutrinos with a plasma do not change their local energy and density significantly (for instance, in type II supernova explosions only 1% of the neutrino energy is supposed to be transferred to the plasma which surrounds the core of star [28]). We are looking for the generation of longitudinal (electrostatic) waves, so our equations should be supplemented by Ampère's law

$$\vec{J}_e = (1/4\pi e)\partial \vec{E}/\partial t. \tag{3}$$

According to Ref. [24], for a collisionless cold unmagnetized electron–ion plasma the set of final equations reduces to

$$\frac{d^2\Psi}{d\chi^2} = -1 + \frac{\Gamma_e\sqrt{1+P_e^2}}{P_e - \beta_\phi\sqrt{1+P_e^2}} - S_\nu, \tag{4}$$

and

$$\frac{dP_e}{d\chi} = \frac{\sqrt{1+P_e^2}}{P_e - \beta_\phi\sqrt{1+P_e^2}}\frac{d\Psi}{d\chi}, \tag{5}$$

where the new independent variable $\chi = (\omega_p/v_\phi)(x - v_\phi t)$ has been introduced and $\omega_p = (4\pi e^2 N_0/m_e)^{1/2}$ and v_ϕ are the electron plasma frequency and the plasma wave phase speed, respectively. Here, $P_e = p_e/m_e c$ is the normalized electron momentum (along the x-direction) and $\beta_\phi = v_\phi/c$ is the normalized phase speed. $\Psi = e\Phi/m_e c^2$ is the normalized plasma potential, with Φ and $E = -d\Psi/d\chi$ is the electric potential associated with the wakefield and the normalized electric field, respectively. The constant $\Gamma_e = (P_0 - \beta_\phi\sqrt{1+P_0^2})/\sqrt{1+P_0^2}$ depends on the initial value of the electron momentum, P_0, and $S_\nu = (E_0(1-\beta_\phi)/\sqrt{2}G_F N_0)\Delta E_\nu/E_0$ represents the neutrino driven term, with $\Delta E_\nu/E_0 = \Delta\omega_\nu/\omega_\nu$ being the amount of the neutrino energy transferred to the plasma (E_0 is the neutrino initial energy) where $\Delta\omega_\nu$ is the spectral width of the neutrino spectrum. Assuming that $\Delta E_\nu/E_0 = \Delta\omega_\nu/\omega_\nu \ll 1$, we can consider the neutrino flux as an external action into the plasma in such a way that the amount of the neutrino energy deposited in the plasma can be taken as a constant input in Eq. (4).

Eqs. (4) and (5) form a set of nonlinear equations for studying the generation of large amplitude plasma waves during the collective neutrino-plasma interactions. We notice that Eq. (4) is a generalized Poisson equation written in a moving frame, where the total charge density includes the neutrino effective charge density represented by the term S_ν. Thus, the normalized electron plasma density in a moving frame is given by

$$\frac{N_e}{N_0} = \frac{\Gamma_e\sqrt{1+P_e^2}}{P_e - \beta_\phi\sqrt{1+P_e^2}}. \tag{6}$$

We note that Eqs. (4) and (5) depend on the sign of the linear momentum of the plasma, i.e., the plasma can be moving either in the positive or negative χ-direction.

Assuming that each electron accelerated in the wakefield and scattered on the ions produces a pair (i.e., reach the pair production threshold), the electron–positron pair concentration n_p produced via the Bhabha trident process can be determined from the fraction of scattered electrons, i.e.,

$$\frac{dn_p}{dt} = \sigma_T N_i N_e v_e, \tag{7}$$

where N_e and N_i are the electron and ion concentrations, respectively, v_e is the electron speed, and σ_T is the total cross-section for the trident pair production process [29]. According to Ref. [22], the cross-section σ_T can be written as

$$\sigma_T \cong 9.6\times 10^{-4}(Zr_0/137)^2(\gamma_e-3)^{3.6}, \tag{8}$$

where $r_0 = 2.8\times 10^{-13}$ cm is the classical electron radius, Z is the ion nuclear charge, and γ_e is the Lorentz factor for the electrons accelerated in the wakefield. Eq. (8) is a good approximation at $\gamma_e \leqslant 10$, but for larger values we shall use the expression [29]

$$\sigma_T = (28/27\pi)(Zr_0/137)^2(\ln\gamma_e)^3. \tag{9}$$

In order to determine pair concentrations, Eq. (7) can be rewritten in the moving frame in the following form

$$\frac{dn_p}{d\chi} = \frac{v_\phi}{\omega_p}\left(1-\frac{1}{\gamma_e^2}\right)^{1/2}\left(1-\frac{1}{\gamma_\phi^2}\right)^{-1/2} N_0 N_e \sigma_T, \tag{10}$$

where we used the definition of γ_e. Here, $\gamma_\phi = 1/\sqrt{1-v_\phi^2/c^2}$, N_e is given by Eq. (6) and $N_i = N_0$, since the ions are at rest.

Eqs. (4) and (5) coupled with Eq. (10) are solved numerically for the case where $S_\nu = 100$, $\gamma_\phi \approx 224$ and $N_0 = 10^{30}$ cm^{-3} (typical supernova plasma density at the neutrino sphere). This value of S_ν corresponds to $\Delta E_\nu/E_0 \approx 1.28\times 10^{-7}$, which means that the neutrino beam deposits only 10^{-7} of its initial energy E_0 in the plasma. This is a very small value, but it is in accordance with supernova observations [28].

Fig. 1 shows the normalized electric field $E = -d\Psi/d\chi$. It reaches a maximum value at $E \approx 13$,

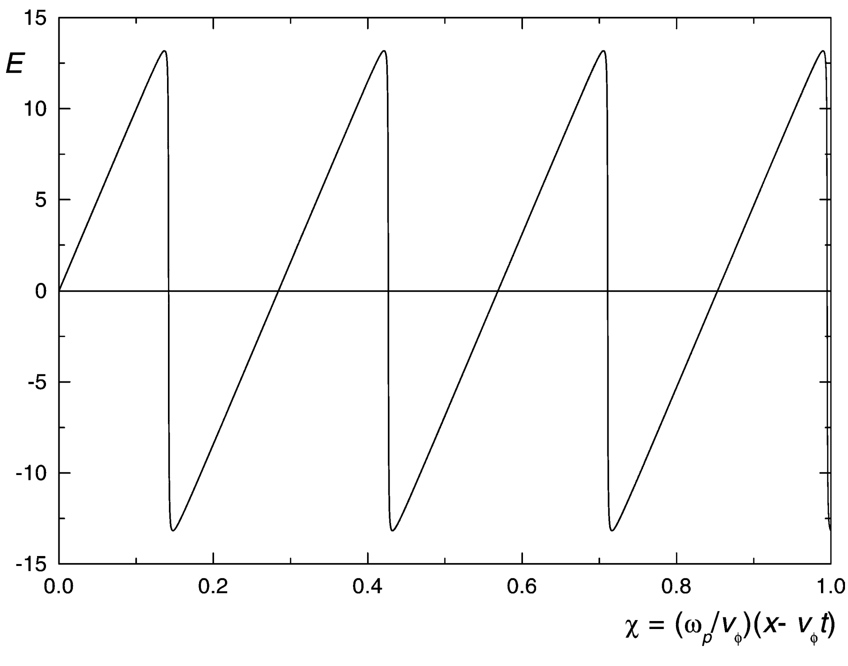

Fig. 1. The normalized electric field E versus the normalized distance χ for the neutrino driven term $S_\nu = 100$.

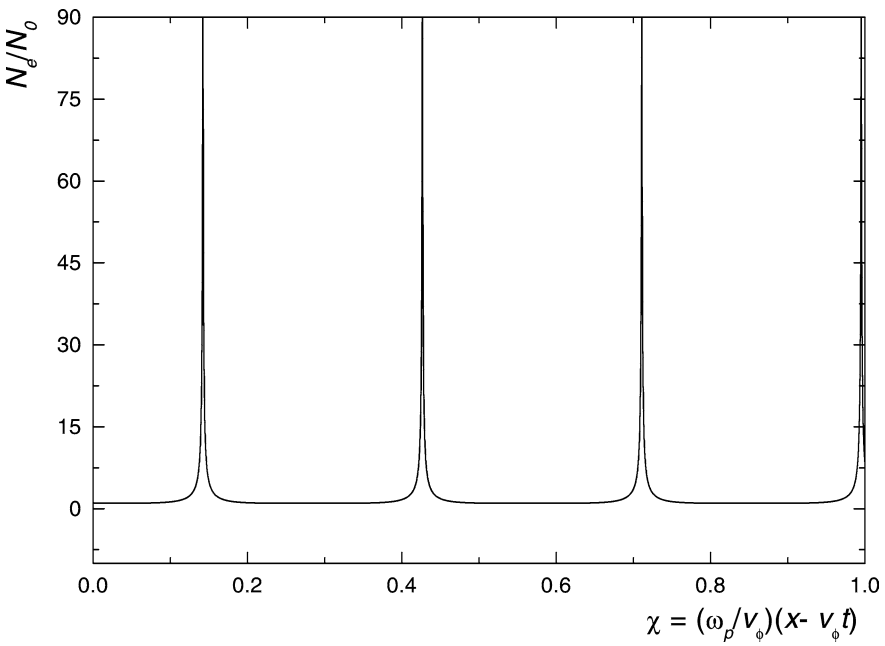

Fig. 2. The normalized electron plasma density n_e/n_0 (in units of 10^3) versus the normalized distance χ for the neutrino driven term $S_\nu = 100$.

which corresponds to a real electric field $E \approx 1.25 \times 10^{16}$ V/cm. This electric field intensity associated with the excited wakefield is close to the critical quantum value E_{QED}, when the spontaneous production of electron–positron pairs from vacuum starts. We do not determine this pair concentration here. As S_ν increases, the electric field of the excited plasma wave slowly grows and soon it reaches the relativistic wave-breaking field, $E_{\mathrm{WB}} \approx 1.36[(\gamma_\phi - 1)N_0]^{1/2} \approx 2.03 \times 10^{16}$ V/cm [30]. The nonlinearity of the strong wakefield causes the steepening of the wave and formation of localized maximum in the electron density, the "spikes" [31], as we can see from Fig. 2. This is a characteristic of the wave-breaking regime, where electrons are accelerated to speeds close to v_ϕ ($\gamma_e \to \gamma_\phi$) [32]. According to Eq. (2a), which is given in a moving frame by Eq. (6), the electron density is given by $N_e = N_0 v_\phi/(v_\phi - v_e)$ for $v_{e_0} = 0$. Since the electron velocity v_e can vary from $-v_\phi$ to v_ϕ, the electron density varies from the minimal value $N_0/2$ to infinity (integrable). In our case the minimum electron velocity is $v_e = 0$, since the electrons do not reach negative velocities, and then our minimum electron density is $N_e = N_0$, as we can see in Fig. 2.

Fig. 3 shows the electron–positron pair concentration n_p produced in the wakefield by the trident process. As in Ref. [23], the "jumps" in the electron–positron pair concentration are explained by a rapid increase in the electron density (Fig. 2) and the energy (γ_e) at the points where the electric field is steeper and the potential Ψ is minimum in the wakefield. At these points it is "easier" for the electrons to reach the pair production threshold and to be scattered on the plasma ions. As we can see, the pair concentration produced is huge, and can be greater if neutrinos deposit more energy into the plasma. This result can be important in studies of gamma-ray bursts.

In conclusion, we have presented a mechanism for creating electron–positron pairs via trident process, where the primary electrons are accelerated in the wakefield generated by an intense neutrino beam. It has been demonstrated that the wakefield can accelerate electrons to relativistic speeds, reaching the wave-breaking limit where $\gamma_e \to \gamma_\phi$. The fast electrons can be scattered off in the Coulomb potential of stationary positive ions, thereby producing electron–positron pairs. As the electric field increases, it reaches the critical Schwinger field E_{QED}, when electron–positron pairs can be produced from vacuum. The results obtained here are valid in any astrophysical scenarios [33], and can be important to understand the origin of high-energy gamma rays [34] in association with

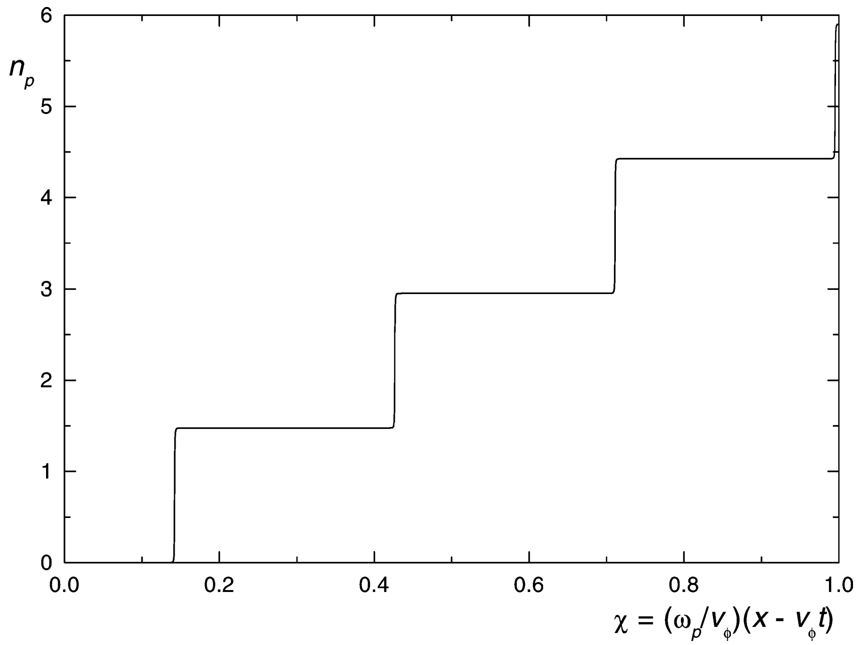

Fig. 3. The electron–positron pair concentration n_p (in unities of 10^{24} cm^{-3}) versus the normalized distance χ for the neutrino driven term $S_\nu = 100$.

TeV neutrons [35], as well production of pairs in supernovae and hypernovae.

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