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FIELDS, PARTICLES, AND NUCLEI

Production of Positrons by Cosmic Rays

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It is shown that electromagnetic interactions of cosmic ray protons provide a noticeable contribution to positrons production. This is due to a combination of low energy threshold of electron–positron pair creation compared to the thresholds of pion creation in strong interactions and rapid decrease of the cosmic rays energy spectrum. Moreover, the electromagnetically produced positrons are very soft, therefore their annihilation with background electrons directly produces the observed 511 keV gamma-line.

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1. INTRODUCTION

Observations of the Galactic gamma rays revealed the strong structure of their energy spectrum with a strong peak at 511 keV and a slow decrease at higher energies (see the recent review [1]). The peak position is directly related with production of soft positrons and their subsequent annihilation with atomic electrons of the background gas. Total positrons annihilation rate in the Galaxy, estimated from the measured intensity of the electron–positron annihilation line at 511 keV is about 5×10^{43} ann/s. Specifically about 2×10^{43} annihilations correspond to the Galactic bulge and 3×10^{43} annihilation corresponds to the Galactic disk. Origin of these positrons is not known and is widely debated at the moment.

One of the possible source of positrons is decay of radioactive isotopes ^{26}Al and ^{44}Ti during supernovae explosions. Galactic positrons production rates due to decay of these nuclei are 3×10^{42} and 2×10^{42} e^+/s, respectively, and therefore they are an order of magnitude lower than production rate required to reproduce the observed intensity of 511 keV line. For other sources, such as decay of ^{56}Ni or pair production in pulsar magnetospheres and compact binary systems there are only theoretical speculations [1].

Cosmic rays interactions with the environment can provide another source of positrons. Since protons are the main component of cosmic rays we limit our study here to proton–proton interactions. The novel point of our research is that positrons can be effectively produced not only due to strong interaction through production and decay of charged pions, but also due to interaction of the electromagnetic field of colliding protons. We introduced this hypothesis in our earlier works [2, 3]. Below we provide general estimations.

Positron production by strong interactions of cosmic rays can be restricted due to generation of the accompanying gamma-radiation from neutral pion decays. According to [4], its upper limit can be estimated as $(1–2)\times10^{42}$ e^+/s. This estimate is reliable because it is based on the directly observed intensity of gamma-ray emission. Therefore, cosmic rays contribution to the production of the Galactic positrons even in the Galactic disk does not exceed 10% of the required rate.

The major difference between ultraperipheral and strong interactions is characteristic energy, when the interactions become effective. Since masses of electron and positron are much lower than the mass of pion, electromagnetic pair productions start at much lower energies of colliding protons as compared to positrons production through decay of π^+-mesons. Thus, interplay of the power-law spectrum of cosmic ray protons and sharp energy dependance of cross sections of corresponding processes is crucial for their relative contribution to the production of positrons.

Also it is worth noting that "ultraperipheral" positrons are much softer than "strong" ones. Thus the former annihilate into the observed 511 keV line, while the latter need to be cooled to nonrelativistic energies first. As result, "strong" positrons form a continuum emission at high energies (see, e.g., [5]). Therefore, unlike "ultraperipheral" positrons, only a small fraction of "strong" positrons can contribute to the 511 keV line.

2. POSITRONS PRODUCTION THRESHOLDS IN ULTRAPERIPHERAL AND STRONG INTERACTIONS

To produce new particles in proton–proton collisions it is necessary to provide enough energy. The necessary condition can be naturally stated in the center of mass system as equality of the total energy of colliding particles $\sqrt{s_{\mathrm{th}}}$ and the total mass of all final state particles

$$\sqrt{s_{\mathrm{th}}} = \Sigma_i m_i. \quad (1)$$

For astrophysical applications however it is more convenient to use the laboratory system of the target particles instead. Lorentz invariance of s leads to the following expression for the energy of the projectile proton in this system

$$E_{\mathrm{lab}} = \frac{s_{\mathrm{th}}}{2m_p} - m_p = m_p\gamma = E_k + m_p = \sqrt{p_{\mathrm{lab}}^2 + m_p^2}, \quad (2)$$

where m_p is the mass of the proton, $\gamma = 1/\sqrt{1-\beta^2}$ and β are Lorentz factor and velocity of the projectile proton in the laboratory system, while E_k and p_{lab} are its kinetic energy and momentum, respectively.

Using these expressions and the masses of secondary particles, one can estimate the threshold energies for positron production in ultraperipheral and strong proton–proton interactions.

• $pp \to ppe^+e^-$

This process starts at very low nonrelativistic energies and momenta of about $E_k = 2.05$ MeV and $p_{\mathrm{lab}} =$ 60 MeV, respectively. Correspondingly, $\beta = 0.066$, $\gamma = 1.0022$.

• $pp \to pn\pi^+$

The energy threshold for this process is significantly higher since mass of the pion is much higher—$E_k = 290$ MeV and $p_{\mathrm{lab}} = 780$ MeV. Correspondingly, $\beta = 0.64$ and $\gamma = 1.30$; i.e., the process starts at subrelativistic energies.

3. POSITRONS IN ULTRAPERIPHERAL AND STRONG INTERACTIONS OF COSMIC RAYS

To estimate the contribution of cosmic rays into the positrons production it is necessary to calculate the product of corresponding processes inclusive cross section and cosmic rays spectrum.

Here we use a conservative upper limit on the cosmic rays spectrum by taking it in momentum power-law form in the following way:

$$dn/dp_{\mathrm{lab}} \propto p_{\mathrm{lab}}^{-2.7}. \quad (3)$$

Obviously this approximation is only valid in a limited energy range. However, as we show below, due to strong energy dependence of the cross sections, the main contribution comes from protons with energies higher than 100 MeV, where the approximation (3) is valid within the order of magnitude.

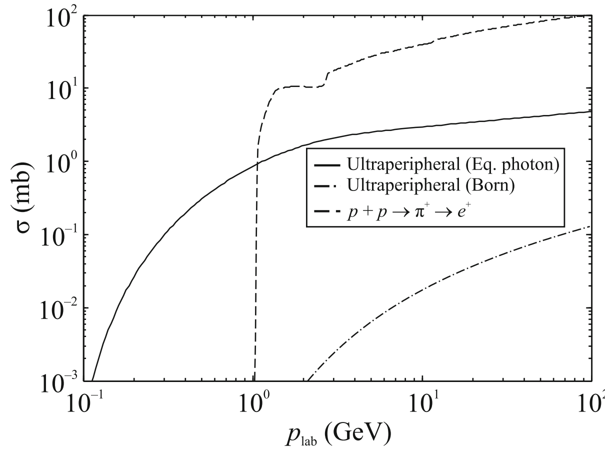

Fig. 1. Solid line corresponds to the electron–positron pair production cross section calculated by us [3] using the equivalent photon approximation. Dashed line corresponds to total inclusive cross section of inelastic production of π^+-mesons in strong interactions, widely used for cosmic rays applications [6, 7]. The difference in threshold momenta is clearly visible. Dash-dotted line corresponds to the pair production obtained in the Born approximation [8].

Inclusive cross section of positrons production from decay of π^+ are available from experimental data (see Fig. 1). Unfortunately there is no experimental data on the ultraperipheral processes for relevant energy range. Therefore we use theoretical estimations, which are available only for asymptotically high energies of protons. Extrapolations of the existing analytical expressions to low energies are controversial and they show significant deviations between the results obtained in the Born approximation (lower bound limits) and by using the equivalent photon approximation (upper bound limits) (see [3]). Products of cross sections and cosmic ray spectrum are shown in Fig. 2. As one can see, that ultraperipheral process produces positrons at much lower energies of projectile protons compared to strong interactions.

Distance between the peaks of the curves is almost 1 GeV, and therefore positrons produced in the ultraperipheral collisions have significantly lower energy. Peak of positrons production for the curve on the right is located at protons momenta of about 1.1 GeV. Its position is determined by Δ(1232) resonance. The threshold of positrons production due to strong interactions is slightly above our earlier estimation of 780 MeV. The inelastic cross section sharply increases after $p_{\mathrm{lab}} = 1.07$ GeV, which is consistent with resonance width being equal to 60 MeV. This behavior can also be observed in Fig. 1.

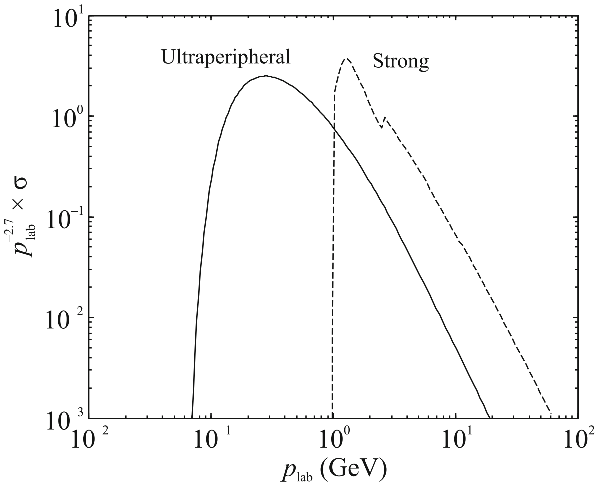

Fig. 2. Contributions to the positrons production by ultraperipheral (on the left) and strong (on the right) collisions of the protons with momentum p_{lab} with background protons.

Relative contributions of the ultraperipheral and strong interactions of protons can be estimated from the areas below the corresponding curves, and their ratio is about

$$R \approx 0.38. \quad (4)$$

Therefore if the estimations based on the equivalent photon approximation are valid, the ultraperipheral collisions can provide a major contribution of positrons production by cosmic rays. If we take into account collisions of heavier ions the contribution of the ultraperipheral process increases by almost 20% (since the cross section is proportional to the square of their charges), given we estimate the increase as $\Sigma_i \rho_i (Z_i^2 - 1)$, where ρ_i is the abundance of nuclei with charge Z_i in cosmic rays.

It is especially important to point out the difference between positrons spectra from these two sources. This difference leads to the difference in corresponding gamma-ray spectra of the positrons annihilating with background electrons. Particularly, only soft positrons can provide a noticeable contribution to observed (but unexplained) gamma-ray bump at 511 keV. As one can see from Fig. 2, maximum of ultraperipheral pair production corresponds to protons with momenta of about 300 MeV, therefore to the velocities of about $\beta \approx 0.3$. Pair components move with about the same velocity. If a positron annihilates with a background electron, their total energy is converted into gamma rays. Masses on annihilating particles and the positron initial momentum p_p provide longitudinal p_l and transversal p_t momenta of gamma rays, which are according to conservation law $p_l = p_p/2$ and $p_t = \sqrt{s_{ep}}/2$, respectively, where $s_{ep} = p_p^2 + 4m_e^2$. Therefore, the energies of produced gamma rays are

$$\omega_\gamma = 0.5\sqrt{s_{ep} + p_p^2} = m_e\sqrt{1 + \frac{\beta^2}{2}} \approx 1.02 m_e. \quad (5)$$

These gamma rays provide a major contribution to the observed line. Additional energy losses of the positron prior to its collision with background electron reduce its velocity β and shift energies of produced gamma rays closer to 511 keV.

In our earlier work [3] we provided a detailed comparison of the ultraperipheral cross sections calculated in the Born approximation and by using the equivalent photon approximation. Their extrapolations in subrelativistic energies are controversial, therefore only lower and upper bounds are available. Figure 1 illustrates this issue. In the case of the Born approximation (i.e., when we take the lower bound estimates), ratio R becomes negligible, and therefore the ultraperipheral cannot contribute to the positrons production.

4. CONCLUSIONS

We compared two processes of positrons production due to interaction of cosmic rays with background plasma: namely the production due to strong interactions through decay of charged pions, and production of electron–positron pairs due to electromagnetic interactions. Our estimations based on the equivalent photon approximation showed that electromagnetic production rate of the e^+e^- pairs due to cosmic rays interaction with medium can be comparable to that in strong interactions. The main difference is that electromagnetic interactions produce positrons with low energy, not exceeding several MeV, while positrons born in strong interactions have energies higher than 100 MeV. Therefore, the electromagnetic interactions of cosmic rays with plasma can provide a contribution to the electron–positron annihilation line which is comparable to or even exceeds the contribution of cosmic rays through the strong interactions.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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