The impact of standard neutrino processes into positron and antiproton fluxes

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Abstract. The possibility of the contribution from standard neutrino processes to the total secondary positron and antiproton fluxes detected by contemporary experiments is analyzed in details. The results show that the considered impact is negligible that confirms once more a necessity of application a new physics beyond the standard conceptions. The designed technique could be implied to the further studies that is extremely interesting in the light of the results of the recent experiments in high energy cosmic ray physics such as PAMELA and AMS-02.

1. Introduction

The observed steep rise in the positron to electron ratio at high energies observed by antimatter experiment PAMELA [1], the excess of positron+electron flux detected by Fermi-LAT [2], H.E.S.S. [3] and ATIC [4] which were confirmed later by more precise measurements of AMS-02 [5, 6] opened a new region of physics attracted thousands researchers. The surprisingly hard antiproton spectrum first hinted by PAMELA [7] and later announced by AMS-02 [8] also raised new questions. Further improvement in statistics and minimization of positron contamination via protons is suspected in the near future. The most promising explanations can be naturally divided into two different kinds of astrophysical and dark matter origin.

Nowadays the existence of dark matter is hard to be refuted in the context of modern astronomical observations. The rotation curves of spiral galaxies should be affected by the presence of some mysterious matter. The key problem of high energy physics and cosmology is to establish as much as possible characteristics of dark matter and to correlate the data with existing models. It seems to be paradoxically but now we wait for the improvement in our knowledge of dark matter from indirect rather than from direct observations because the latest have not been successful yet.

One of the most likely way to establish the basic properties of dark matter particles is to analyze neutrinos been produced from dark matter. Neutrino deservedly attracts attention of scientists because in contradistinction to other particles the trajectory of neutrinos and energy loss are weakly affected during propagation. This gives the way to distinguish between astrophysical and particle origin and also to follow the distribution properties of initial dark matter in order to disentangle between decaying and annihilating dark matter [9]. The flux and

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the spectrum of neutrinos could give comprehensive information on the decay channel [10]. First attempts to evaluate the neutrino fluxes from antiprotons was made about thirty years ago [11].

The signal from dark matter may be extremely weak in comparison with background processes, so to distinguish that processes and to estimate contribution from them to the observed cosmic antiparticle fluxes seem to be an important task. In order to distinguish the contribution of dark matter scenarios to the observable effects one has to be sure that other possibilities are eliminated [12]. That is, the less exotic scenarios with more prosaic explanations can be discarded (methodics of Occam’s razor). One of the most discussed scenarios is a possible supernova explosion — the remnant should have appropriate energetics and energy spectrum to explain the problem [13, 14, 15]. Pulsars and pulsar wind nebulae in principle are powerful sources of charged particles within our Galaxy, and two single sources could be enough to explain experimental observations [16, 17, 18].

Eventually neutrino is a unique particle that rules the processes of supernova explosions, gives a chance of indirect confirmation of dark matter models and the way to confirm the possible explanations of positron and antiproton puzzles. In this case it is not surprising to pay additional attention to neutrino processes while solving the problems raised by contemporary experiments.

In the present article we look at the stated problems at different angle in attempt to analyze the contribution of the standard neutrino processes to the observed by PAMELA positron and antiproton fluxes. For the first evaluation we should neglect the impact of the process of propagation (scattering of random magnetic fields, stellar wind, interstellar radiation field, solar modulation and so on). More strictly recorded estimates including for example the details of propagation should not drastically change the total conclusion of the paper.

To evaluate the order of the contribution of standard neutrino processes to the background of the most discussed effects on positron and antiproton fluxes we analyze two typical neutrino processes that are \( \bar{\nu}_e + e \rightarrow \bar{p} + n \) and \( \bar{\nu}_e + p \rightarrow e^+ + n \). The reason of choosing such processes is an attractive possibility to perform the entire evaluation semi-analytically.

2. A general approach for calculation of the secondary antiparticle flux

Let us evaluate the role of neutrino processes in the total positron and antiproton fluxes measured in an experiment. For simplicity, we neglect the effects of propagation through the Galaxy and assume that all positrons and antiprotons, produced in the selected volume, reach the detector. The total flux of any type of cosmic ray particles is defined by the formula

\[
\Phi = \frac{dN}{dE \, dt \, ds \, d\Omega}.
\]

where \( dN \) is the number of particles detected per the energy interval \( dE \), per the time interval \( dt \), per the detector area interval \( ds \), and arrived from the solid angle interval \( d\Omega \). On the other hand, a number of particles produced in the reaction \( 1 + 2 \rightarrow 3 + X \) in the volume \( dV \) per the time interval \( dt \) is expressed via the total cross-section \( \sigma \) of the reaction: \( dN_3 = \sigma v n_1 n_2 dV \, dt \), where \( v \) is the so-called relative velocity, and \( n_1,2 \) are the particle densities. If one needs to have a distribution of the produced particles over the energies and the solid angles, the differential cross-section \( d\sigma/(dE \, d\Omega) \) should be taken instead of the total cross-section. The particle densities \( n_{1,2} \) should be expressed via the particle fluxes. Finally, the total antiproton and positron fluxes caused by the reactions \( \bar{\nu}_e + e^- \rightarrow \bar{p} + n \) and \( \bar{\nu}_e + p \rightarrow e^+ + n \) correspondingly take the form:

\[
\Phi_{\bar{p}} = \int dr \, dE_\bar{p} \, d\Omega_{\bar{p}} \, \frac{1}{v_{\bar{p}}} \, \Phi_{\bar{\nu}_e} (E_{\bar{\nu}_e}) \, E_{\bar{\nu}_e} \, \sigma (\bar{\nu}_e + e^- \rightarrow \bar{p} + n) / E_{\bar{\nu}_e} \, E_{\bar{p}} \, dE_{\bar{p}} \, d\Omega_{\bar{p}} \, c,
\]

\[
\Phi_{e^+} = \int dr \, dE_{\nu} \, d\Omega_{\nu} \, \frac{1}{v_{\nu}} \, \Phi_{\nu} (E_{\nu}) \, n_p \, (P_{\nu} P_p) \, \sigma (\bar{\nu}_e + p \rightarrow e^+ + n) / E_{\nu} \, dE_{\nu} \, d\Omega_{\nu} \, c,
\]
Thus the threshold neutrino energy is  
\[
E_{\nu}^{\text{thr}} = \frac{(m_p - m_e)^2 - m_n^2}{2m_p} \approx 1.8 \text{ MeV},
\]

where \( c \) is the speed of light and the integration over \( r \) involves the detectable part of the Galaxy. If one takes for estimation the initial protons to be in rest and the proton concentration \( n_p \) to be a constant, the integral (3) can be simplified as follows:

\[
\Phi_{e^+} = R_G n_p \int dE_\nu d\Omega_\nu \Phi_\nu(E_\nu) \frac{d\sigma}{dE_\nu d\Omega_\nu},
\]

where \( R_G \) is a characteristic linear size of the Galaxy. Note that the discussed approach can be used for other processes or astrophysical sources of elementary particles. The derived equation could be compared with the equation of the spectrum from dark matter decay [19].

3. Antiproton flux estimation

The antineutrino-electron process \( \bar{\nu}_e + e^- \rightarrow \bar{p} + n \) resulting in antiproton and neutron, is a cross process to the standard neutron beta-decay. To calculate the differential cross-section, we start with the matrix element in the following form:

\[
\mathcal{M} = \frac{G_F V_{ud}}{\sqrt{2}} [\bar{v}_\nu \gamma_{\mu} (g_V + g_A \gamma_5) \nu_\mu] \times [\bar{v}_\nu \gamma^\mu (1 - \gamma_5) u_e],
\]

where \( g_V \) and \( g_A \) are the vector and axial-vector constants, \( |V_{ud}| \approx 0.974 \) and \( G_F \) is the Fermi constant. After some standard evaluations we get the averaged amplitude squared in the form:

\[
|\mathcal{M}|^2 = 32 G_F^2 |V_{ud}|^2 \left[ (1 + \alpha)^2 (P_n P_e) (P_p P_e) + (1 - \alpha)^2 (P_p P_n) (P_e P_n) + (1 - \alpha^2) m_n m_p (P_e P_n) \right],
\]

where \( \alpha = |g_A/g_V| \approx 1.27 \). Note that for the case of antineutrino-proton interaction, the equation would be almost the same excepting the sign of the last term.

An estimation of the total antiproton flux from the neutrino processes is based on equation (2), where we use the cross-section of the process and the following values of the electron antineutrino flux: \( \Phi_\nu \simeq 2.9 \times 10^{-6} E_\nu^{-2.58} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \), that is one sixth of the diffuse astrophysical neutrino spectrum derived in [21] (see also [22] for previous estimations). We also used a value \( \Phi_\nu \simeq 3 \times 10^{-2} E_\nu^{-3.2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \), which is the rough approximation of the linear part of the electron curve presented in [20]. Despite of the fact that the accurate expressions for the neutrino and electron fluxes depend on the the actual range of measured energies, these values afford to make a zero-order estimation and evaluate an effect size.

Further integration could be significantly simplified by introducing new variables: i) the vector of the initial momentum: \( \mathbf{Q} = \mathbf{p}_\nu + \mathbf{p}_e = \mathbf{p}_\bar{p} + \mathbf{p}_n \); ii) the polar angle \( \theta_1 \) between the vectors \( \mathbf{p}_\bar{p} \) and \( \mathbf{Q} \); iii) the polar angle \( \theta_2 \) between the vectors \( \mathbf{Q} \) and \( \mathbf{p}_e \); iv) the azimuthal angle between the planes formed by the vectors \( \mathbf{p}_\bar{p}, \mathbf{Q} \) and \( \mathbf{Q}, \mathbf{p}_e \). The integration over the azimuthal angle can be easily performed analytically.

The numeric value for the total antiproton flux is \( \Phi_{\bar{p}} \sim 10^{-30} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) for \( E_\nu = 10^2 \text{ GeV} \).

4. Positron flux estimation

In order to estimate the total positron flux we can suppose that an initial proton is in rest.

The limitation on the initial antineutrino energy from the kinematics of the process takes the form:

\[
E_{\nu}^{\text{min}} = \frac{\Delta^2 + 2m_p E_e}{2(p_e + m_p - E_e)}, \quad \Delta = m_n - m_p.
\]

Thus the threshold neutrino energy is

\[
E_{\nu}^{\text{thr}} = \frac{(m_p - m_e)^2 - m_n^2}{2m_p} \approx 1.8 \text{ MeV}.
\]
Figure 1. Positron flux from $\bar{\nu}_e + p \to e^+ + n$ as the function of the positron kinetic energy.

The total positron flux from the antineutrino-proton interaction has the form:

$$\Phi_{e^+} = \frac{R_G n_p}{\pi m_p} \int_{E_{\nu}^{min}}^{\infty} \frac{dE_\nu}{E_\nu^2} \Phi_\nu(E_\nu) |\mathcal{M}(x_0)|^2.$$  (9)

where the averaged amplitude squared $|\mathcal{M}(x)|^2$ is the function of energies and of an angle $x \equiv \cos(p_e, p_\nu)$, $x_0$ denotes the solution of the equation $f(x_0) = 0$ where $f$ is the argument of the delta function of energies:

$$|\mathcal{M}(x)|^2 = \frac{1}{2} g^2 V_{ud}^2 m_p \left\{ x \left[ (1 + \alpha)^2 E_\nu p_\nu E_e - (1 - \alpha)^2 E_\nu^2 p_\nu + (1 - \alpha^2) m_n E_\nu p_e \right] + + (1 + \alpha)^2 (E_\nu m_p - E_\nu E_e) E_e + (1 - \alpha)^2 (E_\nu^2 E_e + E_\nu E_e m_p - E_\nu m_e^2) - (1 - \alpha^2) m_n E_\nu E_e \right\}.  \quad(10)$$

For large neutrino energies the contribution from the nonlocality of the weak interaction could become significant. It could be taken into account by multiplying the aforementioned expression by the factor of $(1 - q^2/m_\nu^2)^{-2}$, where $q$ is the 4-momentum transferred. The numeric values for the total positron flux is $\Phi_{e^+} \sim 10^{-18}$ GeV$^{-1}$ cm$^{-2}$ s sr$^{-1}$ for $E_{e^+} = 10^2$ GeV and $n_p = 1$ cm$^{-3}$ (see figure 1). The value was obtained under the assumption that $n_p$ is almost isotropic. Eventually taking into account the complicated macro structure of cosmic objects this should be much higher (for example that structure could be the nebulas or the objects of the Edgeworth—Kuiper belt (see e.g. [23]).

One can pay attention to the rise of the flux in the limit of low energies, but unfortunately it would be mistaken to spread our assumptions to this region of energies. Applying formally the discussed method for evaluating the flux for the case of low-energy neutrinos ($E_\nu < 1$ GeV) and supposing a neutron to be in rest one can state that the flux should be proportional to the total cross-section of the process:

$$\Phi_{e^+} = R_G n_p \Phi(E_e + \Delta) \sigma(E_e + \Delta),$$ \quad (11)

where

$$\sigma = \frac{g^2 |V_{ud}|^2 (1 + 3\alpha^2)}{\pi} \left[ E_\nu^2 \left( 1 - \Delta \right) \sqrt{1 - \frac{2\Delta}{E_\nu} + \frac{\Delta^2 - m_e^2}{E_\nu^2}} \right] \theta(E_\nu - \Delta).$$ \quad (12)
However this would be erroneous in the region of high neutrino energies where we should take the integral more precisely.

5. Conclusion
The positron and antiproton fluxes from the standard neutrino processes $\bar{\nu}_e + e \rightarrow \bar{p} + n$ and $\bar{\nu}_e + p \rightarrow e^+ + n$ have been estimated. There are several more common processes involving neutrino and antiproton, mainly the inclusive processes $\bar{\nu}_e + p \rightarrow \bar{p} + X$. One can expect a significantly greater flux of antiprotons from that processes but the small value of the weak interaction constant should nullify this benefit.

The specific values calculated in an assumption of the uniform distribution of protons are negligible. Despite this fact one may expect much greater values taking into account a complicated structure of the protons’ distribution. Taking into account for example a concentration of protons in nearby objects like the Edgeworth—Kuiper belt should significantly enhance the resulted values.

The analysis of the specific process of the positron and antiproton production was conducted almost entirely by analytical calculations, so one can use this technique for an analysis of other mechanisms of antiproton production with other fluxes of initial particles and with the other dynamics of the interaction, which is defined by the cross-section of a particular process, such as the annihilation of dark matter particles.

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