Interpretation of the “Excess” of Antiparticles within the Standard Cosmic Ray Paradigm with a Slight Modification

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The anomalously high fluxes of positrons and antiprotons found in cosmic rays (CR) can be satisfactorily explained by introducing two new elements to the current paradigm of Galactic CRs. First, we propose that the antiparticles are effectively produced in interactions of primary CRs with the surrounding gas not only in the interstellar medium (ISM) but also inside the accelerators. Secondly, we postulate the existence of two source populations injecting CRs into the ISM with different, (1) soft ($F \propto E^{-2.4}$) and (2) hard ($F \propto E^{-1.9}$), energy distributions. With an additional assumption that CRs in the 2nd population of accelerators accumulate “grammage” of the order of 1 g/cm$^2$ before being injected into ISM, we can explain the energy distributions and absolute fluxes of both positrons and antiprotons, as well as the fluxes of secondary nuclei of the Li,Be,B group. The superposition of contributions of two source populations also explains the reported hardening of the spectra of CR protons and nuclei around 200 GeV/amu. The 2nd source population accelerating CRs with a rate at the level below 10 per cent of the power of the 1st source population, may consist of PeVatrons responsible for the highest energy particles in galactic CRs up to the “knee” around 10$^{15}$ eV.

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Cosmic Rays (CRs) consist of primary and secondary components, the latter being a natural result of interactions of the primary (directly accelerated) protons and nuclei with the surrounding gas. According to the current concept of the origin of Galactic CRs, these interactions take place predominantly in the interstellar medium (ISM). This simple assumption based on the measured content of the secondary nuclei in CRs allows several important conclusions regarding the energy-dependent propagation of CRs in the interstellar magnetic fields and their confinement time in the Galaxy. Although in this scenario the positrons and antiprotons appear as unavoidable counterparts of the secondary nuclei, the measurements by the Pamela satellite [1] and, more comprehensively, by the Alpha Magnetic Spectrometer (AMS-02) [2] revealed unexpectedly hard energy spectra and enhanced (well above the expectations) fluxes of positrons and antiprotons. The reports on the “excess” of antiparticles have been enthusiastically received and interpreted by many researchers as a “smoking gun” related to the decay or annihilation products of Dark Matter (see, e.g., [3]). Such a strong claim in the context of one of the most fundamental objectives of the modern physics and astrophysics requires a careful judgment through the “Occam’s razor” principle, i.e., exploration of other, more conventional interpretations of the antiparticle “excess” in CRs [4]. While for positrons a possible solution to the problem could be the assumption of non-negligible direct contribution from specific “electron-positron” sources, e.g., pulsars, the interpretation of data on antiprotons is more problematic. Except for the Dark Matter channel, the only realistic possibility is the antiproton production through interactions of directly accelerated CRs with the ambient gas. The observed almost energy-independent $e^+/\bar{p}$ ratio seems to be an appealing indication for an intrinsic link between the positrons and antiprotons through the CR related channels (see the recent review of ref.[3]).

Generally, the spectra of high-energy positrons and antiprotons produced in nuclear reactions mimic the spectrum of primary protons and nuclei. Later, because of the energy-dependent diffusion, the spectra of positrons and antiprotons become substantially steeper compared to the primary (acceleration) spectrum of CRs. Thus, one can immediately conclude that the secondary positrons and antiprotons detected with hard spectra have not been produced in the ISM. In this regard, the models proposing production of secondary positrons and antiprotons in a nearby supernova remnant (SNR) [6, 7] seem more attractive. The model of a single local SNR as a source of CR positrons and antiprotons has a limitation; the SNR cannot be located much further than 100 pc and cannot
be much older than $10^5$ yr. Otherwise, the density of CRs would be reduced to a negligible level unless one assumes an unrealistically slow propagation of CRs in the local neighbourhood. The very idea of a nearby local SNR as the main contributor to the secondary positrons was proposed while ago [8] in the same context of interpretation of the first (tentative) claim of the anomalously high $e^+/(e^-+e^+)$ ratio in CRs [3]. The key condition for the realisation of this model is the effective interaction of directly accelerated protons and nuclei with the ambient gas inside the accelerators [8]. CRs can accumulate significant "grammage" also in the vicinity of SNRs due to the slow propagation caused by self-generation of plasma waves by escaping particles [10]. The assumption on the SNR origin of the source of CR positrons and antiprotons is not a principal condition. The major point of this and, in fact, of any other model, is the hard spectra of positrons and antiprotons injected into the ISM. This implies that the initial (acceleration) CR spectrum should also be hard, close to $E^{-2}$ or even harder. The spectral modification due to the propagation in the ISM makes this distribution steeper, but still harder than $E^{-2.5}$. Otherwise, it would contradict the reported energy dependence of the CR secondary-to-primary ratio. On the other hand, the measured spectrum of CR protons at low energies is very steep, $dN/dE \propto E^{-2.85}$ [12]. Combined with the measured CR secondary-to-primary ratio [15], one may conclude that the initial spectrum of protons injected into the ISM at energies less than 100 GeV, should be close to $E^{-2.35}$. This implies that, in addition to the (1st) source population, one should invoke the 2nd population, which would demand less power than the 1st (steep) component but still dominate at higher energies because of the harder spectrum. Below we show that this assumption not only can satisfactorily explain the the reported hardening of the spectrum of primary CR protons and nuclei above 200 GeV/nuc, but also, with an additional assumption of a non-negligible ($\approx 1$ g/cm$^2$) "grammage" accumulated inside the 2nd population sources can explain the fluxes of the secondary products of cosmic rays - positrons, antiprotons, and light nuclei of the (Li,Be,B) group - over the entire energy range of the reported data.

Under the standard assumption that all secondaries are produced by primary CRs injected into the ISM with a power-law spectrum $Q(E) \sim E^{-\gamma}$, the steady-state distribution of particles in the ISM is $N(E) \sim Q(E) \tau(E)$. Here $\tau(E)$ is the confinement time of CRs in the Galaxy; it decreases with energy and typically is presented in the form $\tau(E) \propto E^{-\delta}$. Thus, we have $N(E) \propto E^{-(\gamma+\delta)}$. By ignoring the slight dependence of the inelastic cross-sections on energy above 10 GeV, we assume, as a zeroth order approximation, that the production spectra of secondaries mimic the steady-state spectrum of primaries in the ISM. Due to the energy-dependent propagation, which we assume is the same as

![FIG. 1. The contributions of the ISM- and S-components of CRs to the fluxes of positron, antiprotons and secondary boron nuclei (three upper panels). The antiproton/proton, positron/proton and boron/carbon ratios are shown in the three bottom panels. The data for the positron and antiproton fluxes and the antiproton/proton ratio are from ref. [11, 12]. The points for the positron/proton ratio are derived from the data of ref. [11, 13]. The boron fluxes are from ref. [14] and the B/C ratio points are from ref. [15].](image-url)
for primaries, the steady-state spectrum of secondaries becomes \(N_{\text{sec}}(E) \propto Q(E) \tau^2(E) \propto E^{-(\gamma+2\delta)}\). Thus, the secondary-to-primary ratio monotonically decreases with energy, \(R(E) \propto E^{-\delta}\). This is true for all secondary nuclei and antiprotons, as well as for low energy (sub-TeV) positrons which do not suffer energy losses. Because of the radiative (synchrotron and inverse Compton) cooling, the spectra of secondary electrons and positrons at very high energies become steeper.

The secondary-to-primary ratio can be expressed as (see e.g. ref.\[18\]),

\[
R(E) = \frac{X_{\text{ISM}}(E) S(E)/N_p(E)}{1 + \sigma_1 X_{\text{ISM}}(E)/m_p},
\]

where

\[
S(E) = \int_{E}^{\infty} \frac{d\sigma_{p \rightarrow s}(E, E')}{dE'} N_p(E') dE'.
\]

Here \(E\) is the energy per nucleus, \(N_p(E)\) is the primary particle spectrum formed in the ISM, \(X_{\text{ISM}}\) is the propagation length in g/cm\(^2\) ("grammage"), \(\sigma_{p \rightarrow s}\) is the differential production cross section of the given secondary particle, \(\sigma_1\) is the total destruction cross-section of secondaries. For the spallation reactions, the energy per nucleus before and after the reaction remains the same (see, e.g. ref.\[19\]). Thus Eq.(1) can be reduced to

\[
R(E) = \frac{X_{\text{ISM}}(E) \sigma_{p \rightarrow s}}{1 + \sigma_1 X_{\text{ISM}}(E)/m_p}.
\]

In this paper, we use the production and annihilation cross sections of antiprotons from ref.\[20\]; the cross-sections of nuclear reaction are taken from ref.\[19\]. For the nuclei destruction total cross sections, we use the parametrization from ref.\[21\]. For the B/C ratio, we use the measurements of AMS-02 \[15\].

The "grammage" accumulated in the ISM is proportional to the confinement time,

\[
X_{\text{ISM}}(E) = c \ n_{\text{ism}} \ m_p \ \tau(E),
\]

where \(c\) is the speed of light, and \(m_p\) is the proton mass. We present \(X_{\text{ISM}}(E)\) in the form

\[
X_{\text{ISM}}(E) = X_0 \left(\frac{E}{10 \text{ GeV}}\right)^{-\delta}.
\]

Note that \(X_{\text{ISM}}\) depends on rigidity, \(R, R = AE\), where \(A\) and \(Z\) are the atomic and mass number, respectively. For protons and antiprotons, \(R=E\), while for nuclei it differs by a factor of \(\approx 2\). Below we limit our consideration by energies exceeding 30 GeV so that we can neglect the solar modulation effects.

To account for the flat \(e^+/p\) and \(\bar{p}/p\) ratios, an additional component of secondary antiparticles should be invoked:

\[
R(E) = R_1(E) + R_2(E),
\]

where \(R_1(E)\) is the ratio for secondaries produced in the ISM ("ISM-component"); see Eq.(1). The ratio \(R_2(E)\) corresponds to the second component represented by secondary particles produced inside the CR accelerators ("S-

FIG. 2. The contributions of the ISM- and S-component to the fluxes of protons (top panel) and the He, C and O nuclei (middle panel). The calculated \(\gamma\)-ray emissivities contributed by the ISM- and S-components of protons are shown in the bottom panel. The proton data are from the AMS-02 \[13\] and CREAM \[16\] collaborations. The He, C and O data points are taken from AMS-02 \[13\]. The proton fluxes corresponding to the S-component are calculated for three values of the exponential cutoff energy: \(E_0 = \infty\), 0.3 PeV, 1 PeV.
component”):

\[ R_2(E) = \frac{X_s(E)}{m_p} S'(E)/N_p(E) \left(1 + \sigma_s X_{e\text{em}}(E)/m_p \right), \tag{7} \]

where

\[ S'(E) = \int_E d\sigma_{p-s}(E, E') Q_s(E')dE'\tau(E). \tag{8} \]

Here \( Q_s(E) \) is the primary injection spectrum from the source with a power law index \( \gamma_s \). \( X_s \) is the "grammage" accumulated inside the source; we represent it in the form of Eq.(5) but with a different power-law index, \( \delta_s \).

The key point of the proposed model is the existence of the 2nd population of antiparticles produced inside the CR accelerators and then injected into ISM with hard energy spectra. The calculations show that the power-law index of the injection spectra of secondaries into the ISM from the sources of this population should be close to 1.9. The formation of energy distributions of the secondary particles inside the source depends on the specifics of the processes of acceleration, escape and interactions of accelerated particles. Assuming that the accelerated particles, before their energy-dependent escape, i.e. \( \delta_s \), are quasi-continuously injected into dense regions inside the source with a power-law spectrum \( Q_s(E) \propto E^{-\gamma_s} \), the secondary particles are produced, the spectrum of primaries established in these regions keeps to be a power-law but with the index \( \gamma_s + \delta_s \).

The production spectra of secondary nuclei and antiparticles have the same power-law index. Generally, at different epochs of the source evolution, the spectra of secondaries injected into the ISM may differ from their production spectra. Nevertheless, the injection spectrum of secondaries integrated over the lifetime of the accelerator is close to the production spectrum, i.e. a power law index \( \gamma_s + \delta_s \).

The time-integrated injection spectra of primary (accelerated) particles into the ISM repeat the acceleration spectra. At low energies, the contribution of this hard-spectrum component should be sub-dominant, otherwise it would contradict the observations. We normalize the contribution of the 2nd population of CRs to the total CR flux as \( \kappa(E) = Q_s(E)\gamma_{\text{ISM}}(E)/N_p(E) = \kappa_0 \left( \frac{E}{100 \text{ GeV}} \right)^{2.8-\gamma_{-\delta}} \), and fix \( \kappa_0 \) at the level of 0.15 of the total CR flux at 100 GeV which will transfer into 7 percent of the total CR energy if we integrate the spectrum above 10 GeV. Then, we derive the best-fit values for the remaining principal parameters: \( \delta = 0.51, X_0 = 7.5 \text{ g/cm}^2, X_s = 1.5(\text{E/10 GeV})^{-\delta_s} \text{ g/cm}^2 \). The fitted results of calculated \( \dot{p}/p \) and \( e^+/p \) ratios, as well as the absolute fluxes of antiprotons and positrons are shown in Figure[1]. Note that the values of \( X_0 \) and \( \delta \) are close but not identical to the values of these parameters derived using only the B/C ratio (see, e.g., ref.[22]). The spectra of parent CR protons from two sources populations are shown in Fig[2]. The absolute normalisation is chosen from the requirement that the sum of two components should match the detected flux of protons above 30 GeV.

The postulation of the additional hard CR component supplied by the 2nd population of particle accelerators has another important implication. It offers a natural explanation of the firmly established effect of spectral hardening of the flux of CR protons above 200 GeV [1, 13, 16, 27]. The superposition of two power-law components of CR protons with the best fitted (for the secondary positrons and antiprotons) parameters perfectly matches also the spectral points of CR protons. In particular, Fig[2] demonstrates that the sum of these two components reproduces the observed smooth transition between 100 GeV and 1 TeV. Similar behavior with a spectral hardening around 200 GeV/amu has also been found for the CR nuclei [17]. However, the measurements revealed that the spectra of nuclei are noticeably harder than the proton spectrum. Using the same normalisation parameter \( \kappa_0 = 0.30 \) but harder injection spectra for nuclei, namely 2.25 (instead of 2.35 for protons) for the 1st population and 1.8 (instead of 1.9 for protons) for the 2nd population of CRs, one can reproduce the observed fluxes of He, C and O; see Fig[2]. Most likely, the difference in the injection spectra of protons and nuclei is caused by the details of the acceleration process (see, e.g., ref.[28]).

A distinct signature of this interpretation is the hard spectrum of protons extending with the power-law index \( \approx 2.4 \) into the \( \geq 10 \text{ TeV} \) region where the second component strongly dominates. One can see from Fig[2] that the extrapolation of the spectrum to multi-TeV energies reasonably agrees, within the accuracy of 10 percent or so, with the CR proton measurements reported by the CREAM collaboration [16]. Although the statistical uncertainties of these measurements above 100 TeV are large, it is quite clear that one should assume a cutoff
in the proton spectrum around or below 1 PeV to avoid the excess of the proton flux. It is seen from Fig.2 where we show three spectra of the second component of CR protons: power-law without a cutoff and with an exponential cutoff, $E^{-2.4}\exp(-E/E_0)$ at $E_0 = 0.3$ PeV and 1 PeV. The current data give a preference to the cutoff at 300 GeV, but for a firm conclusion more precise measurements in this energy band are needed. In any case, within the framework of the two-component CR flux, the 2nd source population should contain PeVatrons responsible for fluxes above 0.1 PeV.

These objects can be observed in multi-TeV $\gamma$-rays. Due to the hard $\gamma$-ray spectra extending beyond 10 TeV, they could be feasible targets for observations with the next generation $\gamma$-ray detectors such as CTA [29] and LHAASO [30]. The chances of detection of these sources depend on several factors including the power and duration of active phases of particle acceleration in these objects, the number of currently operating accelerators, etc. A more definite conclusion can be drawn for the diffuse TeV $\gamma$-ray emission linked to this component. The $\gamma$-ray emissivities initiated by the 1st and 2nd populations of CR sources are shown in Fig.2. One can see that above 10 TeV the 2nd component exceeds, by order of magnitude, the $\gamma$-ray flux related to the 1st component. The fluxes of accompanying multi-TeV neutrinos are also significantly enhanced compared to the 1st component, increasing the chances dramatically to be detected by the km-cube scale water or ice neutrino detectors.