Secondary Positrons in Galactic Cosmic Rays

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Abstract. We present a recent calculation of the secondary positron flux at Earth obtained in a self-consistent propagation model. We also derive the positron on total positron and electron fraction and compare our results with the Pamela data.

Keywords: antimatter; galactic cosmic rays; propagation models

I. INTRODUCTION

Recent cosmic ray measurements [1], [6] have created a lot of excitement in the Cosmic Ray community. Cosmic rays have been studied for many years and have given extremely satisfactory agreement between theory and observations for various species. However PAMELA [1] and then ATIC [6] have changed this bright situation by confirming a discrepancy between theoretical expectations and observations for high energy (≥ 10 GeV) electrons and positrons that had been previously suspected thanks to HEAT[4] experiment. After stressing the various uncertainties that affect the description of the life of a cosmic ray, from creation to detection, we will discuss how difficult it is to find a correct explanation for all experimental data at once.

Even though very accurate methods [14] have been developed, the estimation of the flux of positrons, electrons and anti-protons still suffers from many uncertainties.

II. POSITRON PRODUCTION

Secondary positrons are created by spallation of cosmic–ray nuclei (mainly protons and helium nuclei) on interstellar matter (mainly hydrogen and helium). We compute \( q_{e^+}(x, E_p) \), the number of positrons of energy \( E_p \) created per unit volume at position \( x \), per unit time and per GeV. The positron source term reads:

\[
q_{e^+}(x, E_p) = 4\pi \sum_{targ=H,He} \sum_{nuc=p,a} n_{targ}(x) \times \phi_{proj}(x, E_{proj}) \times E_{proj} \frac{d\sigma}{dE_e} (E_{proj} \rightarrow E_p)
\]

where \( \phi_{proj}(x, E_{proj}) \) denotes the cosmic ray nucleon flux at position \( x \), \( n_{targ}(x) \) the number density of target nuclei and \( d\sigma/dE_e \) the cross–section for the reactions creating positrons. At energies below about 3 GeV, the main channel for production of positrons goes through the excitation of a Delta resonance, which then decays into pions. The charged pions decay into muons, that subsequently decay into positrons. At larger energies direct production of charged pions proceeds through the process:

\[
p + H \rightarrow p + n + \pi^+
\]

and the decay of kaons yields muons (63.44 %) and pions (20.92 %), which then decay into positrons as final products of their decay chain. This second quantity can be computed from basic quantum electrodynamics whereas several parameterizations of the first quantity can be found in [16], [17], [11].

In Fig. 1 we plot the cross section for the positron production from the p-H scattering, as a function of positron energy. The incident proton energy is set equal to 2, 10 (left), 50 and 200 (right) GeV. The three different plots at fixed proton energy correspond to the cross section parameterizations by [11] (solid), [16] (dashed) and [17] (dotted). The differences between these plots vary with both incident proton and final positron energies. For protons of intermediate energy of 10 and 50 GeV, the flatter part of the cross section (at low energies) is only mildly changing with the various parameterizations. Only in the high energy range, the Kamae et al. parameterization undershoots and then overshoots the other two models while for slow protons (see the 2 GeV case), it gives more positrons. This is due to the inclusion in their model of the multiple baryonic resonances around 1600 MeV in addition to the standard \( \Delta(1232) \) state.

A. Energy losses

At the energy range we are interested in, energy losses concern only positrons. Some energy losses (e.g. Bremsstrahlung, ionisation of the Inter-Stellar Medium and adiabatic losses accompanying convection) are only relevant at energies lower than ~ 10 GeV where solar modulation dramatically affects the flux and make any comparison between data and prediction extremely dubious. But, the main energy losses, namely synchrotron radiation due to the steady part of the galactic magnetic field and inverse Compton scattering off of positrons on stellar, dust and CMB light, make positrons (and electrons) a very special species in the cosmic ray environment.
framework. Because we know this effect is important, positrons we detect at the Earth have to be created in the solar vicinity (around 80% of the background at 10 GeV comes from less than 1 kpc). Measurements of galactic magnetic field and Inter-Stellar Radiation Field exist but both are affected by complex systematic effects. Even though we limit ourselves to the local region where positrons are created, the uncertainty on the typical energy loss time scale is still of order $\sim 3$. This translates into very small variation of the shape of the expected flux but also in a change of the normalisation by a factor $\sim \sqrt{3}$. This uncertainty also drastically affects how far the sources of the positrons we detect on Earth are. If interested in interpreting the PAMELA result in term of a point-like source, one cannot change the normalization of the flux without affecting the number and distance of sources.

### B. Propagation

Charged particles do not travel easily in the galaxy: they scatter off on the inhomogeneities of the galactic magnetic field and are re-accelerated by them, they convect under the pression of the galactic wind, they loose energy, some of them decay and they interact with the Interstellar Medium through spallation processes. All these processes are summed up in the diffusion equation that has to be solved with the proper boundary conditions. Observations of other galaxies suggest that cosmic rays are diffusing in a cylindric slab, the height of which seems to vary from one galaxy to another. As soon as a cosmic ray reaches an edge of the diffusion zone, it is expected to leave the zone and to never return. All these processes are not very well constrained neither theoretically nor observationally. However the ratio of secondary over primary cosmic rays depends almost only on propagation. Using Boron/Carbon data, Maurin et al. [13] have constrained the values of the parameters of the propagation equation. However, even under these constraints, the compatible parameter space is still quite extended and sizing the underlying uncertainty requires to scan the complete parameter space. This is why one needs a fast method to compute cosmic ray fluxes, which is allowed by our method. Depending on the energy we are interested in, the parameter set that maximizes (or minimizes) the flux is not always the same. This is why it is not enough to look at the envelope of fig. 2 to estimate uncertainties due to propagation and analysing data really requires a full scan of the parameter space. For the discussion below, it is convenient to isolate three sets of parameters labeled MIN, MED and MAX and defined in Tab. I. For all the details we refer to Ref. [7].

### III. Results

Fig. 2 displays the calculated secondary positron flux modulated at solar minimum along with the most recent experimental data. We use here a Fisk potential $\phi = 600$ MV for solar modulation. The MIN, MED and MAX cases are featured by the red solid, long-dashed and short-dashed lines, respectively, while the yellow area denotes the uncertainty band on the propagated flux arising from the uncertainty in the astrophysical

![Fig. 1. Comparison between various parameterizations of the positron production cross-section at different incident proton energies.](image-url)
Fig. 2. Secondary positron flux as a function of the positron energy. The blue hatched band corresponds to the CR propagation uncertainty on the Inter-Stellar prediction whereas the yellow strip refers to Top Of the Atmosphere fluxes. Kamae\textsuperscript{14} parameterization of nuclear cross sections, the Shikaze\textsuperscript{19} injection proton and helium spectra and the MED set of propagation parameters. Data are taken from CAPRICE\textsuperscript{5}, HEAT\textsuperscript{4}, [2], [3] and MASS\textsuperscript{10}.

parameters. The nuclear cross section from Kamae et al. and the Shikaze proton and alpha injection spectra have been used\textsuperscript{15}. In the same figure, we also plot the interstellar flux. The upper long-dashed curve corresponds to the MED case whereas the slanted band encompasses the uncertainty in galactic propagation parameters. The solid line shows the IS flux from\textsuperscript{19}. Below $\sim 100 \text{ GeV}$, the yellow uncertainty band is delineated by the MIN and MAX models. From Fig. 2, we see that the variation in the propagation parameters induces an uncertainty in the positron flux which reaches about one order of magnitude over the whole energy range considered here. It is a factor of 6 at 1 GeV, and smoothly decreases down to a factor of 4 or less for energies larger than 100 GeV. The agreement with experimental data is quite good at all energies within the uncertainty band. The\textsuperscript{19} prediction of the IS secondary positron flux as parameterized by\textsuperscript{20} is featured by the black solid curve which hardly differs from our reference model (long-dashed curve and MED propagation) above a few GeV. Interestingly enough, the HEAT data points are in good statistical agreement with that MED model.

In Fig. 3, we show the positron fraction obtained for an electron spectrum having spectral index equal to 3.34 (for details we refer to\textsuperscript{7}). For the positrons we have used the Kamae nuclear cross sections and the Shikaze proton and helium injection spectra. A solar modulation with $\phi = 600 \text{ MV}$ has been applied to the positron flux, which corresponds to the level of solar activity during the data taking of AMS. In the same figure, we also report the positron fraction obtained with the positron flux of\textsuperscript{19}. We see that a sizeable excess is present in the high energy tail. The MED reference curve is marginally compatible with the HEAT data above 10–20 GeV, but when the theoretical uncertainties are considered a clear assessment of an excess is not statistically significant on the basis of the HEAT data alone. Instead, in the case of the PAMELA data, the MED reference flux is clearly incompatible with the experimental determinations for energies above 10 GeV. Even when theoretical uncertainties on the positron flux are taken into account, the presence of an excess is manifest for a hard electron spectrum. This excess can then be originated by additional astrophysical processes or by the exciting possibility of a signal from dark matter annihilation.

REFERENCES

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