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DERIVATION OF COSMIC RAY POSITRON SPECTRUM IN THE INTERSTELLAR SPACE

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Using the latest primary cosmic ray nucleon spectrum of Allkofer, Bhattacharyya and Capdevielle and the precise Fermilab Single Arm Spectrometer (SAS) data on $pp \to \pi^+ X$ inclusive reaction after Brenner et al. the energy spectrum of cosmic ray positron in the interstellar space has been estimated by adopting the leaky box model for cosmic ray propagation. The calculated result has been compared with the balloon flight positron flux data of Fanselow et al. and Buffington et al. The present estimate is higher when compared to the calculated results of Giler, Wdowczyk and Wolfendale and Tan and Ng.

1. Introduction

For the progress of astrophysical study the investigation of the origin of cosmic ray positron and its energy spectrum is necessary. Using the knowledge of all particle primary spectrum along with the information of fundamental particle production processes, the secondary positron spectrum may be calculated in the interstellar medium (ISM). The majority of interstellar positron above 100 MeV energy are usually produced from the decay of positively charged pions produced from the interactions of cosmic ray nuclei with the ISM via $\pi^+ \to \mu^+ \to e^+$ decay sequence.

Earlier Daniel and Stephens[1] and Ginzburg and Pituskin[2] have surveyed the astrophysical origin of positrons. Later some theoretical estimates have been reported by Badhwar et al.[3], Orth and Buffington[4], Giler, Wdowczyk and Wolfendale[5] and Tan and Ng[6]. They have used the primary spectrum of Ryan, Ormes and Balasubrahmanyan[7] along with the radial scaling data of Carey et al.[8] for the charged pion production spectrum estimation. The balloon flight data on positron flux after Fanselow et al.[9] and Buffington et al.[10] show a disagreement with the previously calculated results beyond 10 GeV energy.

In the present work we have adopted the all particle primary nucleon spectrum after Allkofer, Bhattacharyya and Capdevielle[11] (to be referred to as ABC spectrum) based on JACEE measurements[12] near the top of the atmosphere and Kiel DEIS muon spectrometer data[13] along with the recent precise Fermilab Single Arm Spectrometer data after Brenner et al.[14] for positive pion production at 100—175 GeV/c to derive the positron spectrum in the ISM. The derived result has been compared with the balloon borne spectrometer measured data of Fanselow et al.[9] and Buffington et al.[10]. The theoretical estimate of Giler, Wdowczyk and Wolfendale[5] and Tan and Ng[6] has been compared with our result.

2. *Nuclear physics and kinematics*

According to the scaling hypothesis of Feynman[15] the differential cross section for the production of a particle of a given type in high energy hadron collision tends to a limit given by

$$\lim_{s\to\infty} E\,(\mathrm{d}^3\sigma/\mathrm{d}^3p) = f\,(x, p_T) \qquad (1)$$

where s is the square of center of mass energy, E, p, p_T are energy, momentum and transverse momentum, respectively, of the produced positive pion in the center of mass system and $x = 2\,p_L/\sqrt{s}$ where p_L is the longitudinal component of p parallel to the momentum p_{inc} of the incident particle. At high energies and not too small positive value of x close to zero, x is also given by E/E_{inc}. In the present case $x = E/E_p$ where E_p is the incident proton energy. The single particle distribution for positive pions produced in p-p collision,

$$f_{p\pi^+}\,(E, E_p) = \frac{E}{\sigma_{in}}\frac{\mathrm{d}\sigma}{\mathrm{d}E}\bigg|_{p\to\pi^+} \qquad (2)$$

where E_p and E are the lab. energies of the primary proton and secondary pion, respectively, σ_{in} is the total inelastic pp collision cross section. Usually the steep decline of the primary flux is dominant with increasing energy and follows the form

$$\mathrm{d}N\,(E_p)/\mathrm{d}E_p = A\,E_p^{(-\gamma+1)} \qquad (3)$$

where A is the spectral amplitude and γ is the integral spectial index of the primary spectrum.

The positively charged pion spectrum can be calculated from the primary proton spectrum from leaky box model by following the conventional procedure after Ginzburg and Syrovatskii[16], Dooher[17] and Badhwar et al.[3] which follows

$$J_{\pi^+}(E) = \frac{m(E)\,A}{m_p} \int\limits_E^{\infty} \frac{d\sigma}{dE}(E, E_p)\, E_p^{-(\gamma+1)}\, dE_p. \tag{4}$$

The μe decay calculations after Ginzburg and Syrovatskii[16] show the probability of the production of an electron with an energy $y = E^*/m_e c^2$ in the $\mu^\pm \to e^\pm + \nu + \bar{\nu}$ decay of a rest $\mu^\pm$ obey the expression

$$W(y)\, dy = 12\, y\, y_m^{-4} \sqrt{y^2 - 1}\, \{(y_m - y) + \frac{2}{9}(4y - 3y_m)\} \tag{5}$$

where $y_m \cong m_\mu/2m \cong 105$ is the maximum energy of a decay electron and the experimental value of Michel's parameter ϱ is close to $\varrho = 3/4$.

In the decay of a meson with an energy $z = E_\mu/m_\mu c^2$ the energy of an electron $x = E/m_e c^2$ flying away in the rest system of a muon at an angle Θ^* with an energy y is

$$x = yz + \sqrt{y^2 - 1}\sqrt{z^2 - 1}\cos\Theta^*. \tag{6}$$

Isotropic distribution with respect to the angle Θ^* corresponds to an energy distribution

$$f(x, y, z)\, dx = dx/2\sqrt{z^2 - 1}\sqrt{y^2 - 1} \tag{7}$$

in the range

$$|x - yz| < \sqrt{y^2 - 1}\sqrt{z^2 - 1}. \tag{7'}$$

The positron energy spectrum can be calculated from the muon energy spectrum $J_{\mu^+}(E)$ by the following expression

$$J_{e^+}(x)\, dx = dx \int\int \frac{W(y)\, J_\mu(z)\, dy\, dz}{2\sqrt{z^2 - 1}\sqrt{y^2 - 1}}. \tag{8}$$

The above integration was carried over for $y < y_m$ and z.

In $\pi^+ \to \mu^+ \to e^+$ decay one can safely assume

$$E_\pi/m_\pi c^2 \simeq E_\mu/m_\mu c^2 = z$$

and

$$J_{\pi^+}(z)\, dz = J_{\mu^+}(z)\, dz \tag{9}$$

where m_μ and m_π are the masses of muons and pions.

The positron spectrum $J_{e^+}(E)$ can be calculated

$$J_{e^+}(E)\,\mathrm{d}E = (m_\mu/m_\pi)^\gamma \frac{2(\gamma+6)}{(\gamma+1)(\gamma+3)(\gamma+4)} J_{\pi^+}(E)\,\mathrm{d}E. \qquad (10)$$

3. *Results and discussions*

The latest all particle primary nucleon spectrum obtained from the fits to the balloon flight primary flux data[12)] and DEIS muon flux data[13)] yield the form after Allkofer, Bhattacharyya and Capdevielle[11)] which follows the form

$$N(E_p)\,\mathrm{d}E_p = A\,E_p^{-(\gamma+1)}\,\mathrm{d}E_p\,(\mathrm{cm}^2\ \mathrm{s\ sr\ GeV})^{-1} \qquad (11)$$

for $A = 2.026$ and $\gamma = 1.7$.

The Fermilab Single Arm Spectrometer data on $pp \to \pi^+X$ inclusive reactions at 100—175 GeV/c after Brenner et al.[13)] yield the p_T integrated invariant cross section viz.

$$x\frac{\mathrm{d}\sigma}{\mathrm{d}x} = E\frac{\mathrm{d}\sigma}{\mathrm{d}E} = \pi\int_0^\infty f(x, p_T)\,\mathrm{d}p_T^2 = B(1-x)^n. \qquad (12)$$

Fig. 1 shows the fit to the Single Arm Spectrometer data after Brenner et al.[13)] for $pp \to \pi^+X$ inclusive reaction data at 100 and 175 GeV/c which follows the relation (12) for $B = 24.7 \times 10^{-27}\,\mathrm{cm}^2$ and $n = 3.5$. The conventional form of the p_T integrated invariant cross section obtained from the relation (12) follows

$$\mathrm{d}\sigma/\mathrm{d}E = 24.7 \cdot 10^{-27}(1-x)^{3.5}\,\mathrm{cm}^2. \qquad (13)$$

Usually in the fragmentation region viz. for $x > 0.1$ the spectrum of particle produced in hadron-nucleus collisions coincides with the spectrum of particles generated in the hadron-nucleon collisions. Using the relations (4), (10)—(11), (13) and by adopting $m(E) = 4.7\ \mathrm{g}\cdot\mathrm{cm}^{-2}$ of interstellar hydrogen as the mean matter traversed by the secondary cosmic rays; $m_p = 1.673 \cdot 10^{-24}$ g as the mass of the proton; the secondary positron flux leaks from Galaxy in a stochastic manner has been estimated which follows the form from $J_{\pi^+}(E)$ viz.

$$J_{\pi^+}(E)\,\mathrm{d}E = \frac{m(E)\,A}{m_p} 24.7\,E^{-2.7}\,B(\gamma, 4.5)\,10^{-27}\,\mathrm{cm}^2\,\mathrm{d}E \qquad (14)$$

which yields

$$J_{e^+}(E)\,dE = 11.63\,E^{-2.7}\,dE\,(\mathrm{m}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV})^{-1}. \tag{15}$$

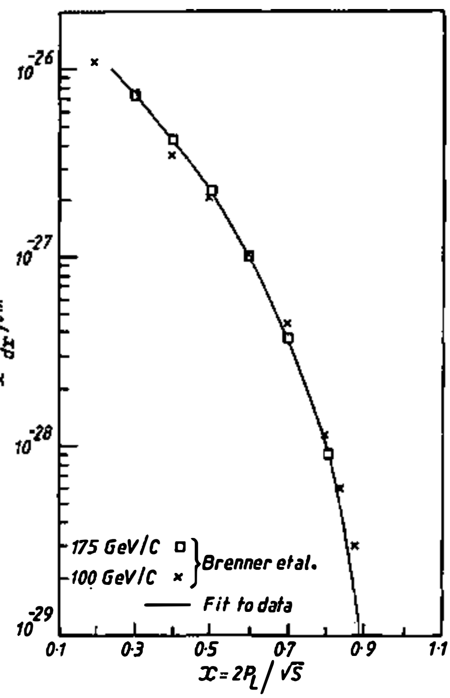

Fig. 1. The p_T integrated invariant cross section $x\,(d\sigma/dx)$ as a function of x for $pp \to \pi^+ X$ inclusive reactions. Experimental data: X — 100 GeV/c, □ — 175 GeV/c, Brenner et al.[14]. Full line represents the fit to the SAS data after relation (5).

This spectrum has been displayed in the Fig. 2 along with the upper atmospheric balloon borne spectrometer data after Fanselow et al.[9] and Buffington et al.[10]. The plot indicates an agreement of the presently derived result with the data of Buffington et al.[10] in the spectral range 10—10^2 GeV. The best estimate of Giler, Wdowczyk and Wolfendale[5] and the derived result of Tan and Ng[6] shows a steeper spectral shape viz. $\gamma > 1.75$ and it shows a large difference when compared to the measured data beyond 10 GeV energy.

4. Conclusion

Using the latest primary cosmic ray spectrum of Allkofer, Bhattacharyya and Capdevielle and precise SAS Fermilab data on positively charged pion production after Brenner et al. the positron spectrum in the interstellar medium has been estimated. The derived result is well in accord wit the balloon flight data of Buffington et al. in the spectral range 10—10^2 GeV.

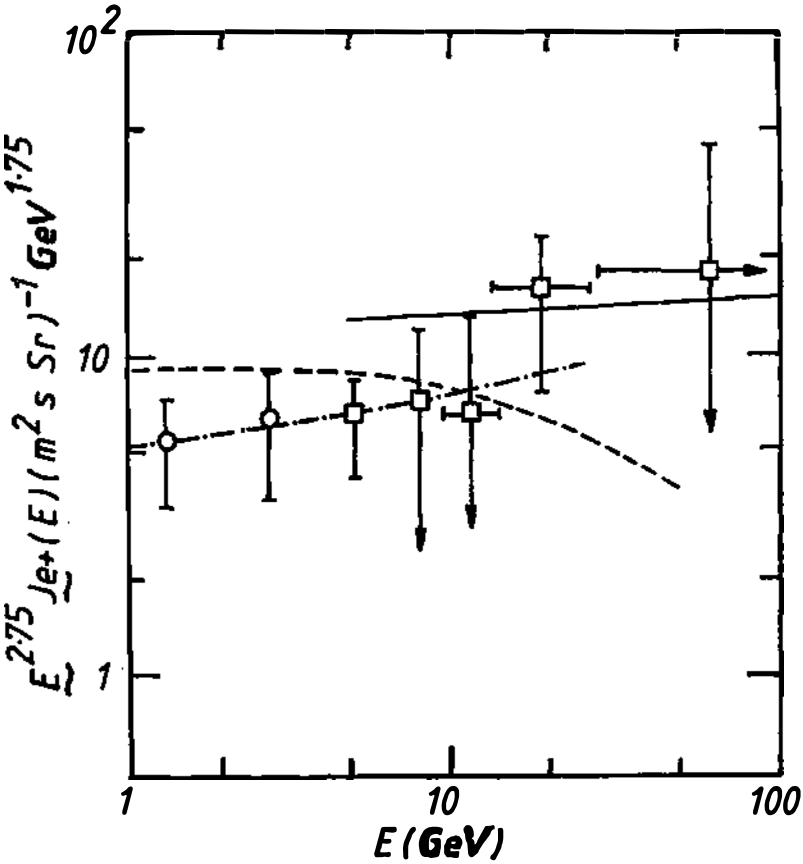

Fig. 2. The secondary interstellar positron flux $J_{e^+}(E)\,dE$ plotted as a function of positron energy E.

Experimental data: ○ Fanselow et al.[9], □ Buffington et al.[10].

Theoretical results: Full line represents the present calculated result, chain curve represents the result of Giler, Wdowczyk and Wolfendale[5], broken curve is the calculated result after Tan and Ng[6].

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IZVOD SPEKTRA POZITRONA KOZMIČKIH ZRAKA U MEĐUZVJEZDANOM PROSTORU

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Koristeći nedavne podatke od Allkofera, Bhattacharyya i Capdevielle i precizne podatke Fermilab Single Arm Spektrometra (SAS) za inkluzivnu reakciju $pp \to \pi^+ X$ prema Brenneru, energetski spektar pozitrona kozmičkih zraka je procijenjen u okviru »leaky box« modela za propagiranje kozmičkih zraka. Izračunati rezultati uspoređeni su s balonskim podacima Fanselowa i Buffingtona. Sadašnja procjena je veća u usporedbi s izračunatim vrijednostima Gilera, Wdowczyka, Wolfendalea te Tan i Nga.