ISSN 1330–0016
CODEN FIZBE7

THE INFLUENCE OF REACCELERATION ON THE ANTIPROTON ABUNDANCE IN THE INTERSTELLAR MEDIUM AND ITS ATTENUATION IN THE ATMOSPHERE

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Received 4 January 1999; revised manuscript received 12 October 1999
Accepted 20 December 1999

An estimation has been made of the influence of reaccelaration on the abundance of secondary $\bar{\mathrm{p}}$ flux in the interstellar medium, initiated by primary cosmic ray proton collisions in the confined p+He gases in the medium. The calculated $\bar{\mathrm{p}}$ spectrum and $\bar{\mathrm{p}}$/p flux ratio have been compared with the calculated results of Simon and Heinbach and also with the experimental data of Golden et al. and Hof et al. The present derivation is based on the production of antiprotons in the atmosphere by primary protons at several small depths. The results are also presented as ratios relative to the secondary $\bar{\mathrm{p}}$ flux at depth of 1 gm/cm^2 of atmosphere. Another investigation has been made of the energy spectrum of atmospheric antiprotons from primary elemental spectra obtained from the direct measurements using the active and passive detectors borne by balloons and satellites, fitted using a standard propagation diffusion equation and the Z factors from accelerator interaction cross-sections.

PACS numbers: 13.85.Tp, 98.70.Sa UDC 539.126

Keywords: secondary $\bar{\mathrm{p}}$ flux in the interstellar medium, influence of reaccelaration, production of antiprotons in the atmosphere, energy spectrum of atmospheric antiprotons

1. Introduction

The discovery of antiprotons in cosmic radiation has raised important questions concerning their origin since the observed $\bar{\mathrm{p}}$-flux shows an excess above the predictions. Untill now, due to the limitation of accelerator experiments in the search for the high-energy A-A collisions and also for the lack of proper cascade distribution formulation, the precise estimation of the secondary cosmic ray $\bar{\mathrm{p}}$ spectra in the atmosphere is difficult. Generally, it is expected that the acceleration of cosmic rays starts before the propagation in the interstellar medium (ISM). The most abundant protons interact with the medium producing new particles which mostly decay shortly after the production. Antiprotons survive unless they undergo annihilation with the normal matter.

Simon et al. [1] have calculated the interstellar $\bar{\mathrm{p}}$ density production spectra resulting from the different interactions between cosmic ray particles p, He, CNO and target particles as the interstellar gas measured by the IMAX instrument, using the Monte Carlo DTUNUC model. Pfeifer et al. [2] have calculated the $\bar{\mathrm{p}}$ flux below an atmospheric layer of 5 gm/cm^2, taking as inputs for the p and He spectra the data from the LEAP experiment [3], and for heavy nuclei from Wiebel [4]. Stephens [5] has estimated $\bar{\mathrm{p}}$ spectra in the atmosphere at small depths by taking into account the Fermi momentum of target nucleons. Pfeifer et al. [6] have presented a calculation on atmospheric antiproton spectra taking $\sigma_{\bar{\mathrm{p}}}^{\mathrm{tot}}$ from Flaminio et al. [7] and from Hagen [8], and using the total primary spectrum from Ryan et al. [9]. Simon and Heinbach [10] have pointed out that there should be no sharp deviation between acceleration and propagation of primary nuclei. They have shown that the interstellar $\bar{\mathrm{p}}$ spectra expected from the diffusive reacceleration model differ slightly from the calculated spectra in the standard leaky-box model. More recently, Orito et al. [11] have measured antiproton flux in the spectral range 0.18 GeV to 3.56 GeV during the period of solar minimum by the BESS experiment. Their results are found in accord with the expected results from the propagation calculations based on diffusion and leaky-box model.

In the present work, we have investigated the effect of reacceleration on the $\bar{\mathrm{p}}$ flux in interstellar medium and the results are compared with the similar calculated results of Simon and Heinbach [10] and also with the experimental data of Golden et al. [12] and Hof et al. [13]. We have estimated $\bar{\mathrm{p}}$ spectra and $\bar{\mathrm{p}}$/p ratio obtained from measured primary elemental fluxes at GeV energies based on the results of balloon borne measurements of JACEE [14], MSU [15] and the satellite borne SOKOL [16] and CRN [17] experiments. These results curves are shown along with the calculated results of Pfeifer et al. [2]. We have calculated the $\bar{\mathrm{p}}$ spectra at different low atmospheric depths and compared them with the theoretical prediction of Stephens [5].

2. *Nuclear physics*

Antiprotons are produced by high-energy collisions of protons with the interstellar gas through the inclusive reaction $\mathrm{p} + \mathrm{p} \to \bar{\mathrm{p}} + \mathrm{X}$, where X stands for other hadrons which emerge with $\bar{\mathrm{p}}$ from the interactions. The p – nuclei collisions are treated as p – p interactions since the de Broglie wavelengh of protons capable to produce antiprotons is short. The equilibrium $\bar{\mathrm{p}}$ spectrum at a particular energy in the mixed ISM composed of 93% H and 7% He can be evaluated from the conventional expression after Gaisser and Schaefer [18] as

$$J_{\bar{p}}(E_{\bar{p}}) = \frac{2\lambda_e^M}{(\lambda_p + \lambda_e^M)\sigma_{\rm pp}} \epsilon^M \int\limits_0^\infty \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\bar{p}}} N_p(E_p)\mathrm{d}E_p \,, \tag{1}$$

where N_p represents the flux of incident protons.

The differential primary cosmic ray elemental spectra for the i-th species usually follow the power law

$$N_i(E)\mathrm{d}E = K_i E^{-\gamma_i}\,\mathrm{d}E \,, \tag{2}$$

where K_i and γ_i are the elemantal spectral amplitudes and indices of i-th species, respectively. Using the conventional superposition model, one can convert the total primary fluxes of nuclei to nucleon fluxes by the relation

$$N_{p+n}(E)\mathrm{d}E = \sum_{i=H}^{i=Fe} A_i K_i E^{-\gamma_i}\,\mathrm{d}E \,. \tag{3}$$

The escape path length λ_e^M and nuclear enhancement factor ϵ^M in mixed media containing 93% H and 7% He are given by

$$\lambda_e^M = 1.30\, v\tau_e^M \rho_H^M \,, \tag{4}$$

and

$$\epsilon^M = \frac{1}{1.3}\left(\epsilon^H + \frac{0.07}{0.93}\epsilon^{He}\right) . \tag{5}$$

The numerical values of the parameters ϵ^H and $\epsilon^{\rm He}$ have been calculated using the method cited in Ref. [18] and found to be 1.20 and 4.28, respectively. So, for the total nucleon factor in ISM, one obtains

$$\epsilon^M = \frac{1}{1.3}\left(\epsilon^H + 0.075\epsilon^{He}\right) = 1.17 \,. \tag{6}$$

By adopting $\rho_H^M = 0.28$ atoms/cm and $\tau_e^M/\tau_e = 1.03$, one obtains the following escape time allowing the cosmic protons to propagate through a mixed ISM [19]:

$$\tau_e = 1.27189 \times 10^7 \left(\frac{e}{1\,\mathrm{GeV}}\right)^{-0.438} \mathrm{s} \,. \tag{7}$$

The mass of the average target atom is taken as

$$m_p = 2.24 \times 10^{-24}\ \mathrm{g} \,. \tag{8}$$

In the calculation, the hit nucleon is assumed to be responsible for one-half of the yield in a pp collision, which reveals the concept of half of the yield from the target and half of the yield from the projectile. The total inelastic cros-section $\sigma_{\rm pp}$ for pp collision has been estimated from the difference of $\sigma_{\rm pp}^{\rm tot}$ and $\sigma_{\rm pp}^{\rm el}$, where the fit to the accelerator data as a function of momentum p is given by [20]

$$\sigma_{\rm pp} = A + Bp^t + C\ln^2 p + D\ln p\,, \tag{9}$$

where A, B, C, D and t are constants.

The term $\mathrm{d}\sigma(E_{\bar{p}}, E_p)/\mathrm{d}E_{\bar{p}}$ denotes the differential cross-section. The usual p_T-integrated cross-sections follow the form

$$x\frac{\mathrm{d}\sigma}{\mathrm{d}x} = M(1-x)^n\,. \tag{10}$$

The Z factors can be estimated for inclusive reactions a + b → c + X by using the term

$$Z_{ac} = \int\limits_0^1 x^{\gamma-1} f_{ac}(x)\mathrm{d}x\,, \tag{11}$$

where the scaling function is defined as

$$f_{ac}(x) = \frac{\pi}{\sigma_{\rm in}}\int\limits_0^\infty E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\,\mathrm{d}p_T^2 = M(1-x)^n\,, \tag{12}$$

where M and n are the usual parameters.

The change of the $\bar{\rm p}$ intensity due to diffusive reacceleration R_{reacc} term is given by [21]

$$R_{\rm reacc} = \left[\frac{\mathrm{d}}{\mathrm{d}E}\left\langle\frac{\delta E_{\bar{p}}}{\delta x}\right\rangle_{\rm reacc}^{\rm gain}\right] J_{\bar{p}} \quad (\mathrm{m}^2\,\mathrm{s\ sr\ GeV})^{-1}\,, \tag{13}$$

where the average energy gain is described by,

$$\left\langle\frac{\delta E_{\bar{p}}}{\delta x}\right\rangle_{\rm reacc}^{\rm gain} = 0.6\ E_{\rm tot}(\mathrm{MeV})\ R^{-1/3}(\mathrm{MV})\ \left[\frac{\mathrm{MeV}}{\mathrm{g/cm}^2}\right]\,, \tag{14}$$

where R is the rigidity. The exponent (-1/3) and the factor 0.6 result from the fitting to the cosmic-ray nuclear data.

Ignoring ionization losses, the atmospheric $\bar{\rm p}$ intensity below a slab of thickness t gm/cm^2 can be estimated by solving the conventional differential equation [10] of the form

$$\frac{\mathrm{d}J_p}{\mathrm{d}t} = -\frac{N_{\bar{p}}(t, E_{\bar{p}})}{\lambda_{\bar{p}}^{\rm int}(E_{\bar{p}})} + \frac{1}{<m>}\int\limits_{E_{\rm th}^p(E_{\bar{p}}(t))}^\infty \frac{\mathrm{d}\sigma(E_{\bar{p}})}{\mathrm{d}E_{\bar{p}}}\,N_p(t, E_p)\,\mathrm{d}E_p\,. \tag{15}$$

The solution is,

$$J_{\bar{p}}(t, E_{\bar{p}}) = \frac{K}{< m >} \lambda_{\bar{p}}^{\rm int} (1 - {\rm e}^{-t/\lambda_{\bar{p}}^{\rm int}}) \int\limits_{E_{\rm th}^{p}(E_{\bar{p}}(t))}^{\infty} \frac{{\rm d}\sigma(E_{\bar{p}}, E_p)}{{\rm d}E_{\bar{p}}} N_p(E_p)\, {\rm d}E_p \,. \qquad (16)$$

Since antiprotons can only be produced in p̄p pairs (to conserve the baryon number), a lowest threshold energy of the incoming proton, $E_{\rm p}$, is required to produce an antiproton. At this threshold, $E_{\rm p}^{\rm th} = 6 m_{\rm p} c^2$, the produced p̄p pair is at rest in the centre of mass system (CMS), leading to an energy of about 1 GeV in the laboratory system (LS). With energies $E_{\rm p}$ above the threshold, the produced p̄ can emerge backward or forward from the interaction point, leading to antiprotons of either a lower or a higher energy than 1 GeV in the LS. Here

$$\lambda_{\bar{p}}^{\rm int} = \frac{< m >}{\sigma_{\bar{p}p}^{\rm tot}(E_{\bar{p}})} \quad ({\rm g\,cm^{-2}}) \qquad (17)$$

denotes the mean interaction length in the atmosphere for antiprotons, $< m >$ is the average mass number of air (14.5 amu) and $\sigma_{\bar{\rm p}{\rm p}}^{\rm tot}$ is the total cross-section taken from Ref. [20]. The factor in front of the integral accounts for the fact that not only protons produce the antiprotons, but also the cosmic ray nuclei with $Z \geq 2$. This contribution by weighing the total interaction cross-sections of the different particles with their abundace has been found to be 25%. Since not only p̄ emerge from a pp interaction, but also n̄ at the same rate which finally decay into p̄, the factor K is taken to be 2.5 [10].

3. Results and discussion

The total primary proton spectrum adopted from Ref. [22] is given by

$$N_p(E) = 1.32\, E^{-2.65}\, {\rm d}E \,. \qquad (18)$$

The interstellar p̄ spectrum without reacceleration follows the power law [22]

$$J_{\bar{p}} = 7.7\, E_{\bar{p}}^{-3.07} \quad ({\rm m^2\ s\ sr\ GeV})^{-1} \,. \qquad (19)$$

The p̄ intensity with reacceleration is given by

$$J_{\bar{p},\,{\rm reacc}} = J_{\bar{p}} - R_{\rm reacc} \,. \qquad (20)$$

Our results for the p̄ intensity and p̄/p flux ratio without and with reacceleration, estimated from Eqs. (1) and (20), are displayed in Table 1.

The interstellar antiproton spectra $J_{\bar{\rm p}}$ from a pure steady-state leaky-box (SSLB) model and from the condition of diffusive reacceleration are shown in

TABLE 1. Derived interstellar antiproton spectra with and without reacceleration.

$E_{\bar{p}}$ (GeV)	6	10	20	50	100
$^*J_{\bar{p}}$	5.50×10^{-2}	6.55×10^{-3}	7.80×10^{-4}	4.68×10^{-5}	5.58×10^{-6}
$^*R_{\rm reacc}$	1.31×10^{-2}	1.32×10^{-3}	1.31×10^{-4}	6.03×10^{-6}	5.86×10^{-7}
$^*J_{\bar{p}}/\text{reacc} = J_{\bar{p}} - R_{\rm reacc}$	4.19×10^{-2}	5.23×10^{-3}	6.49×10^{-4}	4.08×10^{-5}	4.99×10^{-6}
$\bar{p}/p/\text{reacc}$	2.26×10^{-4}	1.77×10^{-4}	1.38×10^{-4}	1.00×10^{-4}	7.50×10^{-5}

*In units of (m^2 s sr GeV)$^{-1}$.

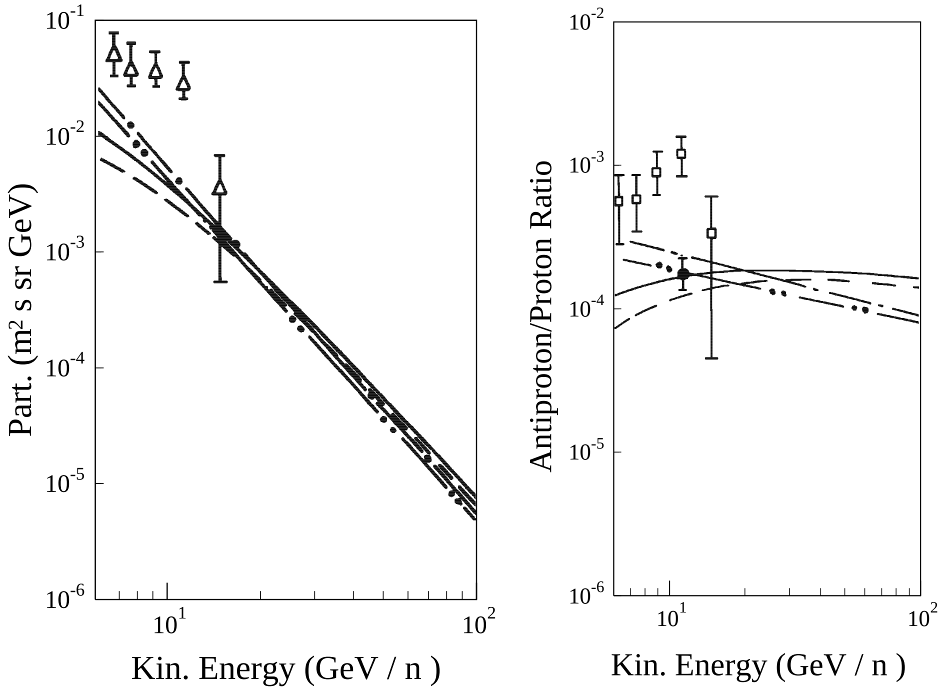
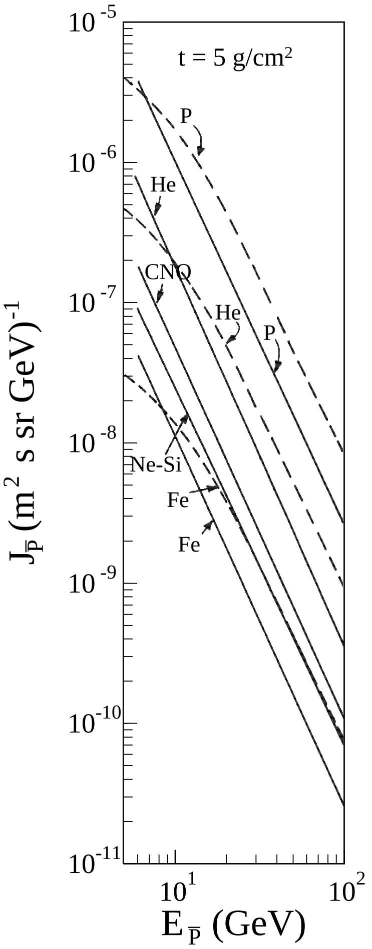


Fig. 1. Derived spectra of antiprotons in ISM under different assumptions: Full and broken curves represent derived results of Simon and Heinbach [10] expected from the SSLB model without and modified with reacceleration, respectively. Dash-dot and dash-dot-dot curves are the p̄ spectra expected from the SSLB model without and modified with reacceleration. Experimental data: △ – Golden et al. [12].

Fig. 2 (right). The p̄/p flux ratio expected from the SSLB model without and modified with reaccelerations: Full and broken curves represent the calculated spectra of Simon and Heinbach [10] from the SSLB model without and modified with reacceleration, respectively. Dash-dot and dash-dot-dot curves are the present results expected from SSLB without and modified with reaccelerations, respectively. Experimental data: □ – Golden et al. [12], • – Hof et al. [13].

Fig. 1 and the corresponding $\bar{\mathrm{p}}/\mathrm{p}$ flux ratio in Fig. 2. It is clear from the figures that above 5 GeV, the $\bar{\mathrm{p}}$ intensity and the $\bar{\mathrm{p}}/\mathrm{p}$ flux ratio are lower under the conditions of diffusive reacceleration when compared to the standard SSLB model. Our calculated $\bar{\mathrm{p}}$ spectra and $\bar{\mathrm{p}}/\mathrm{p}$ ratio with and without reacceleration are fairly well comparable with the results of Simon and Heinbach [10] and the experimental data of Golden et al. [12] and Hof et al. [13].



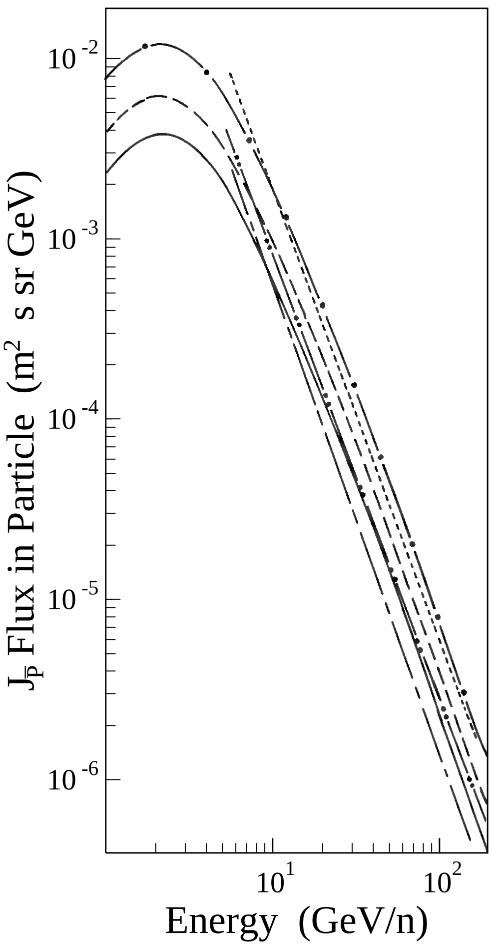


Fig. 3. $\bar{\mathrm{p}}$ *flux at atmospheric layer 5* gm/cm^2 *obtained from elemental components* P, He, CNO Ne - Si, Fe. *Solid curves – this work, broken curve – Pfeifer et al. [2].*

Fig. 4. (right). Atmospheric spectra of $\bar{\mathrm{p}}$ *flux at different depths. Chain curve – present work, full curve – Stephens [5] for 3* gm/cm^2*; Dash-dot-dot – present work, broken curve – Stephens [5] for 5* gm/cm^2*; Dashed curve – present work, dash-dot curve – Stephens [5] for 10* gm/cm^2.

The power-law fits to the directly measured primary elemental fluxes of p, He, CNO, Ne-Si and Fe at 10 – 1000 GeV energies obtained from Ref. [22] exhibit different spectral indices. Using those amplitudes and spectral indices for elemental components, and taking different parametric values from Ref. [22] with $K = 2.5$, the $\bar{\mathrm{p}}$ intensity at 5 gm/cm^2 have been estimated from Eq. (16). These five curves showing the generation of $\bar{\mathrm{p}}$ from p, He, CNO, Ne-Si and Fe (JACEE [14], MSU [15], SOKOL [16], CRN [17] and others [22]) are displayed along with three calculated energy spectra of $\bar{\mathrm{p}}$ fluxes generated from p, He and Fe (LEAP experiments, Refs. [3] and [4], surveyed by Pfeifer et al. [2]). The different curves illustrate how the different primary components contribute to the production of secondary antiprotons. The amplitudes and indices of these curves are shown in Table 2.

TABLE 2. Amplitudes and indices of $\bar{\mathrm{p}}$ *intensity generated from elemental components* p, He, CNO, Ne–Si *and* Fe, *in units of* $(\mathrm{m}^2\ \mathrm{s\ sr\ GeV})^{-1}$.

	$(J_{\bar{p}})_p$	$(J_{\bar{p}})_{\mathrm{He}}$	$(J_{\bar{p}})_{\mathrm{CNO}}$	$(J_{\bar{p}})_{\mathrm{Ne-Si}}$	$(J_{\bar{p}})_{\mathrm{Fe}}$
Amplitudes	0.428	0.063	0.022	0.055	0.0097
Indices	2.65	2.62	2.67	2.63	2. 59

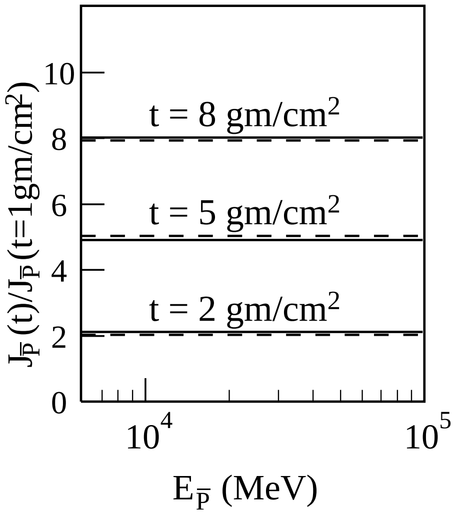


Fig. 5. Calculated $\bar{\mathrm{p}}$ *flux at 2, 5, 8* gm/cm^2 *relative to 1* gm/cm^2 *of atmosphere. Solid curves – present work, broken curves – Pfeifer et al. [2].*

The primary protons provide the largest contribution of 79% to the flux of atmospheric antiprotons and that is true at all $\bar{\mathrm{p}}$ energies, and helium contributes 14% $\bar{\mathrm{p}}$ which is approximately twice that of their primary abundance at the top of the atmosphere. The contribution from all heavier nuclei, such as CNO, Ne – Si and Fe, are about 3.7%, 2.2% and 1%, respectively. The derived curves displayed in Fig. 3 are somewhat lower than those obtained from Pfeifer et al. [2]. Considering the total primary proton spectrum (N_p), the $\bar{\mathrm{p}}$ spectra at different depths of 3, 5 and 10 gm/cm^2 in the atmosphere, shown in Fig. 4, are lower than the derived spectrum of Stephens [5]. The ratios of $\bar{\mathrm{p}}$ intensity at depths of 2, 5 and 8 gm/cm^2 relative to those at 1 gm/cm^2 are shown in Fig. 5. These curves are in good agreement with the results of Pfeifer et al. [2].

4. Conclusion

An estimate has been made of the effect of reacceleration on the abundance of secondary $\bar{\mathrm{p}}$ flux in ISM initiated by collisions in the confined p + He gases. The estimated $\bar{\mathrm{p}}$ spectrum, when corrected for the reacceleration, has been found to follow the power law of the form $(J_{\bar{\mathrm{p}}})_{\mathrm{reacc}} = 9.315\, E^{-3.15}$ (m^2 s sr GeV)$^{-1}$, which is in good agreement with the calculated results of Simon and Heinbach beyond 6 GeV. The decrease of $\bar{\mathrm{p}}$ flux due to the reacceleration is about 1.5%. The estimated $\bar{\mathrm{p}}$/p ratio has been found to decrease slightly with energy following the power law $(\bar{\mathrm{p}}/\mathrm{p})_{reacc} = 4.38 \times 10^{-4}\, E^{-3.08}$.

The energy spectra of $\bar{\mathrm{p}}$ at atmospheric depths of 3, 5, 10 gm/cm^2 of atmosphere have been estimated and lie appreciably below the calculated spectra of Stephens [5], which reveals that antiprotons are strongly attenuated with depth. Another conclusion that can be drawn from this study is that most of antiprotons in the atmosphere arise from proton interactions, rather than helium or other nuclei.

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UTJECAJ REAKCELERACIJE NA BROJNOST ANTIPROTONA U SVEMIRU I NJIHOVO SLABLJENJE U ATMOSFERI

Načinili smo ocjenu utjecaja reakceleracije na brojnost sekundarnih $\bar{p}$ u meduzvjezdanom prostoru, koji nastaju sudarima prvotnih protona u ograničenom prostoru mješavine protona i He. Izračunali smo spektar $\bar{p}$ i omjere $\bar{p}$ /p te ih usporedili s ishodima računa Simona i Heinbacha i s ishodima mjerenja Goldena i sur. i Hofa i sur. Sadašnji se račun zasniva na tvorbi antiprotona u atmosferi prvotnim protonima u nizu slojeva male debljine. Ishodi računa takoder se prikazuju kao omjeri prema toku $\bar{p}$ u dubini atmosfere od 1 gm/cm^2. Daljnje istraživanje koje smo načinili su energijski spektri atmosferskih antiprotona od prvotnih elementalnih snopova, koje su mjerili aktivnim i pasivnim detektorima nošenim balonima ili satelitima, a prilagodili smo ih primjenom standardne difuzijske jednadžbe i Z faktora odredenih mjerenjima udarnih presjeka pomoću akceleratora.