Nucleon Pair Production in the Upper Atmosphere

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The production of antiprotons due to collisions of primary cosmic rays with atmospheric nuclei is considered. On the basis of approximate experimental information on nuclear cross sections, an approximate value for the flux of antiprotons from this source is obtained. This flux is found to be about 5–50 times the flux of secondary antiprotons generated by cosmic-ray collisions with interstellar gas nuclei.

In the near future, high-energy particle detectors will be flown at the top of the atmosphere. By also placing a superconducting magnet aloft, one could discriminate charge at high energy, and thus possibly distinguish between protons and antiprotons in the incident high-energy cosmic-ray beam. The predicted antiproton flux from cosmic-ray collisions with interstellar gas nuclei is at most three orders of magnitude below the proton flux, but very likely much smaller.[1] Measurements of antiproton fluxes, therefore, would require long observation times to detect those antiprotons from the interstellar collision source.

Situated in the atmosphere, a detector would also receive antiprotons generated in collisions of the primary beam with atmospheric nuclei. It is the purpose here to consider the antiproton flux from this source in anticipation of their measurement. Comparison between these two sources, interstellar and atmospheric collisions, may then be undertaken.

The cosmic-ray flux at an atmospheric depth x (in g cm^{-2}) is given as[2]

$$J_p(x)=J_0\exp(-x/\Lambda)\,, \tag{1}$$

where $\Lambda=120$ g cm^{-2} is the absorption length for nucleons in the atmosphere. The antiproton flux $J_{\bar{p}}$ at a depth t (g cm^{-2}) due to production in dx and annihilation in $t-x$ is

$$J_{\bar{p}}(t)=\int_0^t J_p(x)\exp[-(t-x)/L_{\mathrm{ann}}]dx/L_{\mathrm{prod}}\,, \tag{2}$$

where L_{ann} and L_{prod} are the annihilation and production mean free paths, to be defined in terms of their respective nuclear cross sections. Integrating Eq. (2), making use of Eq. (1), yields

$$J_{\bar{p}}(t)=J_0(l_{\mathrm{eff}}/L_{\mathrm{prod}})[\exp(-t/L_{\mathrm{ann}})-\exp(-t/\Lambda)]\,, \tag{3}$$

where $l_{\mathrm{eff}}\equiv(1/\Lambda-1/L_{\mathrm{ann}})^{-1}$ and $t_{\mathrm{max}}=l_{\mathrm{eff}}\ln(L_{\mathrm{ann}}/\Lambda)$. If instead of taking the incident beam collimated (as above), one uses an isotropic beam incident on the atmosphere, then the distances x, dx, and $t-x$ in Eq. (2) must be divided by $\mu=\cos\theta$, where θ is the zenith angle. Then the integration of Eq. (2) over the solid angle $d\Omega=-2\pi d\mu$ gives

$$J_{\bar{p}}=J_0(l_{\mathrm{eff}}/L_{\mathrm{prod}})[E_2(t/L_{\mathrm{ann}})-E_2(t/\Lambda)]\,, \tag{4}$$

where

$$E_2(a)=\int_1^\infty e^{-ay}dy/y^2$$

is an exponential integral.[3] This function, like Eq. (2), has a maximum t; however, it is smeared out because of the longer optical depth encountered by part of the beam. A proposed detector will probably be positioned at a depth $t=10$–20 g cm^{-2}, far from our estimated $t_{\mathrm{max}}\sim 26$ g cm^{-2}. Any masking of interstellar antiprotons by atmospheric antiprotons will be most evident near t_{max}.

In cosmic-ray transport, matter traversal is important; atmospheric depth t as well as various interaction path lengths L_{ann}, L_{prod}, and Λ are quoted in units of g cm^{-2}. To convert from nuclear cross section σ to mean free path against a given nuclear process, we use

$$L=m_{\mathrm{H}}/\sigma A\,, \tag{5}$$

where $A=14.4$ is the atomic weight of a mean atmospheric nuclide and m_{H} is the hydrogen atomic mass.

The cross sections for antiproton production from nucleon-*nucleus* collisions have been estimated for accelerator energies ($\leqslant\sim 30$ BeV), and guessed at for much higher energies.[4] The accelerator data are ob-

Table I. Cross sections and mean free paths for antiproton production and annihilation in air nuclei. (Values in parentheses are extrapolations.)

T (BeV)	σ_{prod} (mb)[a]	L_{prod} (g cm^{-2})[b]	$\bar{E}_{\bar{p}}$ (BeV)[c]	σ_{ann} (mb)[d]	L_{ann} (g cm^{-2})[b]
6	$\sim 10^{-3}-10^{-4}$	$2\times(10^{7-8})$	~ 0	(120)	1
10	$\sim 10^{-2}-10^{-3}$	$2\times 10^{6-7}$	~ 0.3–0.6	~ 90–55	1.3–2.2
20	$\sim 10^{-1}-10^{-2}$	$2\times 10^{5-6}$	~ 0.9	50	2.4
30	$\sim 10-1$	$2\times 10^{3-4}$	~ 1.3	30	(4)
10^2	$\sim(10-1)$	$(2\times 10^{3-4})$	~ 3.2	(20)	(6)
10^3	$\sim(10^2-10)$	$(2\times 10^{2-3})$	~ 30	(20)	(6)

[a] Reference 4. [b] Equation (5). [c] See text. [d] Reference 1.

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TABLE II. Collimated and isotropic incident fluxes versus atmospheric depth t (g/cm²) for $\Lambda=120$ g/cm², $L_{ann}=6$ g/cm², from Eqs. (3) and (4).

(a)	(b)	(c)	(d)
$L_{prod}J_{\bar{p}}/l_{eff}J_0$		Column (b)/Column (a)	t
Collimated [Eq. (3)]	Isotropic [Eq. (4)]		(g/cm²)
0.368	0.562	1.53	3
0.731	0.693	0.95	10
0.772	0.640	0.83	30
0.434	0.189	0.44	100

tained from collisions of protons with Al and Be and are shown, together with mean free paths L_{prod} from Eq. (5) versus incident proton lab energy T, in Table I.

Also shown are approximate average laboratory antiproton energies $\bar{E}_{\bar{p}}$ estimated as follows: the average multiplicity of particles produced in high-energy nucleon-nucleon collisions is given by $\bar{n}\sim 3T^{1/4}$ for $T\gg 10$ BeV.[4] The inelasticity K (the fraction of initial energy transferred in these collisions) is quite constant up to very high energies, e.g., for $T=10$–10^6 BeV, $K\sim 0.3$–0.5.[5] Hence the average energy in the lab system available to the products is $\bar{E}=KT$. If we assume that all the products share equally in the energy in excess of threshold (5.6 BeV), then the average laboratory kinetic energy of each product is very roughly $\bar{E}_{\bar{p}}\sim\bar{E}/\bar{n}=KT/3T^{1/4}=(0.1\text{–}0.2)T^{3/4}$. The angular distribution of all products is neglected.

Antiprotons with energies above about 50 BeV may have been produced by incident protons of energy $T>[(5\text{–}10)\bar{E}_{\bar{p}}]^{4/3}\sim 340$–$850$ BeV. Consultation of Table I indicates that the production cross sections at and above this energy, as well as the annihilation cross section at the probable detector threshold energy of ~ 50 BeV,[6] are inadequately known. A very approximate extrapolation produced the values in parentheses. Applying these values to Eq. (3) yields $l_{eff}\sim 8.6$ g cm^{-2} and $t_{max}\sim 8.6\ln(6/120)\sim 26$ g cm^{-2}. Assuming that the quoted extrapolated values of σ_{ann} are reasonable, then annihilation is important and $l_{eff}\sim L_{ann}$.

Cosmic-ray balloons are usually placed near the top of the atmosphere at a depth $t\sim 10$–20 g cm^{-2}. The effect of a collimated incident beam versus an isotropic incident beam is shown in Table II, where Eqs. (3) and (4) are compared for different depths $t\sim 3$–100 g cm^{-2}. The maximum collimated flux occurs as predicted near $t\sim 30$ g cm^{-2}, and the maximum isotropic flux is found at somewhat smaller t. In either case, choice of $l_{eff}=8.6$ g cm^{-2}, $L_{prod}=2\times 10^{2-3}$ g cm^{-2} from Table I, and $J_0=J_p(T>\sim 10^3\text{ BeV})\sim 1.2\times 10^{-4}$ cm^{-2} sec^{-1} yields $J_{\bar{p}}(E_{\bar{p}}>\sim 50\text{ BeV})\sim 5\times 10^{-6,-7}$ cm^{-2} sec^{-1} for the atmospheric collision $\bar{p}$ flux at a depth of ~ 10 g cm^{-2}.

For comparison, the secondary antiproton flux at about 30 BeV incident on the atmosphere, arising from primary collisions with interstellar matter, is of the order of 10^{-7} cm^{-2} sec^{-1};[7] we would therefore expect this to be obscured by the contribution from collisions with atmospheric nuclei, considered above. Because the interstellar collision source of antiprotons is very small, its contribution to atmospheric antiproton production is negligible. The problem of distinguishing the source of a detected antiproton is not insurmountable. Aside from the result here that the atmospheric collision flux is about 5–50 times larger than the interstellar collision flux, there is another large difference: The interstellar collision-produced antiprotons, like the primary cosmic-rays, are isotropic, whereas the atmospheric produced antiprotons should increase in those directions having large optical depths (or large zenith angle θ) such as the earth's horizon.

Peters has pointed out[8] that at energies high enough for p-p and $\bar{p}$-p collisions to have roughly the same interaction cross sections, the ratio of extraterrestrial antiprotons to protons should be preserved throughout the air-shower development down to sea level. However, the low-energy ratio of antiprotons to protons would not survive passage through the atmosphere because of the annihilation of antiprotons *en route*.

When measurements are made of the antiproton production cross section at high energies, the antiproton flux predictions can be improved. On the other hand, the detection of antiprotons near the top of the atmosphere can provide a means of estimating such cross sections by the inversion of calculations similar to those presented here. The extension of the high-energy cross-section measurements with cosmic rays will be useful, since to obtain such data we might otherwise have to await the next generation of high-energy accelerators.

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