Secondary Antiprotons in Galactic Cosmic Radiation*

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Calculations are presented of the production of secondary antiprotons due to inelastic collisions of high-energy primary cosmic rays with interstellar gas nuclei. Cosmic-ray diffusion theory is assumed to apply in the steady-state approximation, with a constant average beam intensity taken over space. The cosmic-ray energy spectrum, production thresholds, cosmic-ray and target abundances and densities, and production and annihilation cross sections are examined and utilized. The results give a very approximate energy spectrum for the antiproton flux. Astrophysical ramifications of this collision source of antiprotons are discussed in light of the dominance of leakage over annihilation as a mechanism of antiproton loss.

1. INTRODUCTION

ANTIMATTER on an astrophysical scale has been a rich subject for speculation. Recently, Alfvén[1] has restimulated interest by postulating an electromagnetic process which can separate matter and antimatter, invoking symmetry arguments and suggesting the annihilation of matter and antimatter as an energy source for objects, such as quasars, which appear to emit large amounts of energy difficult to account for by other usual means.

Previous work was speculative, theoretical, or observational. Burbidge and Hoyle[2] placed an upper limit to the amount of antimatter (positrons and antiprotons) of 10^{-7} cm^{-3} in our Galaxy by requiring that the energy density due to annihilation in the interstellar medium be less than that due to magnetic fields, turbulent kinetic energy and cosmic radiation. The source of antimatter was taken as spontaneous steady-state creation at a rate of $q<\sim 3\times 10^{-22}$ cm^{-3} sec^{-1}, since the lifetime of positrons is found to be short ($\sim 10^{14}$ sec) compared to the Galaxy age ($\sim 3\times 10^{17}$ sec). It was proposed that these processes are responsible for electrons whose synchroton emission gives rise to radio waves in galactic and extragalactic systems.

An argument based on detailed balancing by Frank-Kamenetskii[3] relates nucleon-antinucleon pair production and subsequent stabilization by gravitational fields to ejecta and remnants of supernovae. During expansion, annihilation occurs leading to radiation of visible light; the supernova remnant is converted to normal matter by capture of matter and annihilation by antimatter.

Other theories assume steady-state creation in pairs due to symmetry arguments. Annihilation of matter and antimatter has often been suggested as an energy source in those astrophysical objects for which nucleosynthesis or gravitation may be inadequate.

Fradkin[4] invoked antiprotons, prior to their discovery, to aid in explaining the east-west asymmetry in intensity of the cosmic rays. Charged particles of different sign are bent in opposite directions by the Earth's magnetic field; this provides a means of placing a measured limit of up to 13–23% (depending on spectral index) on the fraction of negative particles in the cosmic-ray beam. The fraction of antiprotons in the primary beam was estimated by assuming equilibrium between the production and loss rates. Production was taken as due to high-energy proton- and antiproton-proton collisions. Losses were taken as due to the antiproton annihilations and inelastic collisions. Cross sections for the above processes were approximated by the Fermi[5] statistical theory of high-energy nuclear reactions, in which a compound nucleus or fireball is formed and subsequently radiates or evaporates mesons, nucleons and antinucleons.

The results of Ginzburg *et al.*[6] indicate 0.1% (modified recently to 0.05%), and 0.04% for the relative concentration of antiprotons in cosmic radiation having energy greater than 1.7 and 9.3 BeV, respectively. Hayakawa[7] obtains about 10^{-4} for the ratio of antiprotons to protons in galactic cosmic rays, presumably by similar methods.

The observations can be separated into proposals, possible identifications, and actual measurements. Vlasov[8] suggests an optical search for antimatter in the universe based on the emission lines of excited states of positronium and protonium. In the past, events seen in

* A brief account of this work was presented at the 1966 Spring meeting of the American Physical Society [S. Rosen and S. N. Milford, Bull. Am. Phys. Soc. 11, 399 (1966)].

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emulsions[9] have been attributed to cosmic-ray produced $\bar{p}$. However, none of these has been unquestionably certified as a genuine antiproton event.

The nonoccurrence of an antiparticle track among many in emulsions exposed to cosmic radiation sets limits on their relative concentration in the primary radiation. A group using balloon-borne emulsion[10] obtained no antiparticles in more than 1000 singly charged events, yielding $<0.1\%$ for the fraction $\bar{p}/p$. Emulsions carried aloft by a satellite[11] yield the same upper limit of 0.1% for the ratio of antinuclei to nuclei having $Z>2$. It is emphasized that no antiparticles to our knowledge have been detected with certainty.

The high-energy galactic-cosmic-ray flux limit by Kraushaar and Clark[12] allowed Milford and Rosen[13] to place upper limits on $\bar{p}/p$ of 0.1 to 20 depending on line of sight direction. The basis of this limit is the decay into γ rays of neutral π mesons produced by antiproton annihilations or by inelastic interactions with protons.

The calculations presented in this paper deal with the production of antiprotons due to inelastic collisions of high-energy primary cosmic rays incident on interstellar gas nuclei. In Sec. 2 the assumptions necessary to perform the calculation are discussed, and the equations developed from diffusion theory. Then the data required is examined and applied to these equations in Sec. 3. The results on cosmic-ray antiprotons are presented in Sec. 4, and some ramifications explored in Sec. 5.

2. DIFFUSION THEORY AND INELASTIC COLLISIONS OF COSMIC RAYS WITH INTERSTELLAR GAS NUCLEI

If a uniform steady-state source exists in a finite volume, with efficient mixing inside and leakage out of this volume, the general transfer equation reduces to[14,15]

$$n=qT_{\mathrm{eff}}\,, \tag{2.1a}$$

$$T_{\mathrm{eff}}^{-1}=T_{\mathrm{col}}^{-1}+T_{\mathrm{esc}}^{-1}\,, \tag{2.1b}$$

where n is the number of particles cm^{-3} in equilibrium due to a distributed uniform source q of particles $\mathrm{cm}^{-3}\,\mathrm{sec}^{-1}$; $T_{\mathrm{col}}=L_{\mathrm{col}}/c$ and $T_{\mathrm{esc}}=L_{\mathrm{esc}}/c$ are, respectively, the mean times for magnetic scattering collisions and for escape.

The source function q_{it} for production of a particle by an inelastic collision process, due to the cosmic-ray beam incident on interstellar gas nuclei acting as a target, is

$$q_{it}=\int_{E_{it}}^{\infty} n_t(r)\sigma_{it}(E)j_i(E)dE\,, \tag{2.2a}$$

$$\bar{q}\sim n_t(r)\bar{\sigma}\bar{J}(r,E_{it})\sim n_t\bar{\sigma}\bar{J}\,, \tag{2.2b}$$

where $n_t(r)$ is the tth component of the number concentration of target interstellar gas nuclei cm^{-3} in the Galaxy, such as hydrogen, helium, etc.; $j_i(E)$ is the differential energy spectrum or number of the ith component of the incident cosmic-ray beam such as hydrogen, helium, etc., $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{BeV}^{-1}$; the quantity $\sigma_{it}(E)$ is the energy-dependent cross section in cm^2 for the particle producing process in question, e.g., antiproton production; E_{it} is the laboratory kinetic-energy threshold in BeV for such a process;

$$J_i(E_{it})=\int_{E_{it}}^{\infty} j_i(E)dE$$

is the integral energy spectrum in $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$.

The quantities n_t, j_i, J_i, and thus q are space- and/or time-dependent. However, consideration of these quantities shows that local and present values are not known well enough and theories are not refined enough to extrapolate beyond observations. Constant values are chosen, therefore, to represent appropriate averages over time, position, and, in the case of Eq. (2.2b), over energy.

The above formulas are recast into a form more suitable for calculations. Since the cosmic-ray number density n is related to the flux J by

$$n=J/c\,, \tag{2.3}$$

then from above it follows that

$$\bar{q}_{it}(r,E)=nT_{\mathrm{eff}}^{-1}=\bar{J}L_{\mathrm{eff}}^{-1}. \tag{2.4}$$

The mean free paths L and times T for collision, loss by annihilation, or escape are given by

$$L(r,E)=n_t^{-1}(r)\sigma^{-1}(E)=cT(r,E)\,, \tag{2.5}$$

where L, σ, and T refer to the applicable process. Units of L can be either light years, cm, or g cm^{-2}, by adjusting Eq. (2.5) accordingly. For production, inelastic collision, or annihilation, clearly the values of σ for the appropriate process apply. However, for escape the author defines a non-nuclear equivalent escape cross section to describe particle departure from the disc or halo as follows:

$$\sigma_{\mathrm{esc}}(r,E)=m_pL_{\mathrm{esc}}^{-1}(r,E)\,. \tag{2.6}$$

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In Eq. (2.6), m_p is the proton rest mass in grams and L_{esc} is the total path length for escape in g cm^{-2}. Equation (2.6) transforms an astrophysical quantity, the total matter believed to be traversed by cosmic rays from their sources, L_{esc}, into an effective escape cross section for protons leaving the Galaxy. The comparison is convenient since other properties are given as nuclear cross sections and $\sigma_{esc} J$ is then the number of protons sec^{-1} leaving the Galaxy. Also from Eqs. (2.1), (2.4), and (2.6)

$$\sigma_{eff}=\sigma_{coll}+\sigma_{esc}. \tag{2.7}$$

Values for L_{esc} are found from the nuclide composition (especially Li, Be, B) observed in the galactic beam, assuming universal abundance at the source, and subsequent fragmentation *en route* causing enrichment of the light nuclides. Typical estimates put the matter traversal at about 3 g cm^{-2} for the "high-energy" part of the beam.[7] In the region of lower energies, recent work[16] appears to indicate that the matter traversed by the cosmic radiation is perhaps about 6 g cm^{-2}. By Eq. (2.6), $\sigma_{esc}\sim 533$ mb or 267 mb, respectively. Cross sections for various processes are tabulated in Sec. 4.

Another useful property of this cross-section formulation is that production and loss of particles in equilibrium can be expressed free of galactic geometry factors and target concentrations:

$$\begin{aligned}\bar\sigma_{prod}\bar J_p(E_{it})&=\bar\sigma_{loss}\bar J_a(E_a)\\ &=(\bar\sigma_{esc}+\bar\sigma_{ann})\bar J_a(E_a),\end{aligned} \tag{2.8}$$

where $\bar J_p\ (E_{it})$ is the average integrated cosmic-ray intensity which produces a particle of type a with spectrum $\bar J_a(E_a)$. Dividing by $\bar J_p(E_p)$ and rearranging gives

$$\frac{\bar J_a(E_a)}{\bar J_p(E_p)}=\frac{\bar\sigma_{prod}}{\bar\sigma_{esc}+\bar\sigma_{ann}}\frac{\bar J_p(E_{it})}{\bar J_p(E_p)} \tag{2.9}$$

for the fraction of particles of kind a in the cosmic-ray beam in equilibrium.

The equations developed up to this point are applicable to general particle production. In what follows, the results are particularized to proton-antiproton pair production, hence in Eq. (2.9) a represents antiprotons. Whenever an antiproton ($\bar p$) appears, it must be accompanied by a nucleon in order to be consistent with conservation of baryons. Nuclear reactions responsible for this process can be summarized as follows:

$$_zX^i+{}_{z'}Y^t\rightarrow({}_zX^i+{}_zY^t)^*+p+\bar p, \tag{2.10a}$$

where the incident nucleon number $i=1, 2, 3\cdots A$ and the target nucleon number $t=1, 2, 3\cdots A'$. This includes all important possibilities for a single pair production if it is understood that, for example, $_1X^1=p$, $_2Y^4=\text{He}$, $_0X^0=\gamma$, $_{-1}Y^1=\bar p$, etc. A large subset of (2.10a) results from $i=t=A=A'=1$, or

$$p+p\rightarrow p+p+p+\bar p. \tag{2.10b}$$

The total contribution is found by applying Eq. (2.2a) separately to each of the reactions indicated in Eq. (2.10a) by taking into account the threshold energy and summing:

$$q_{tot}=\sum_{i=1}^{A}\sum_{t=1}^{A'}q_{it}=\sum_{i,t}^{A,A'}n_tS_{it}, \tag{2.11a}$$

$$S_{it}=\sigma_{it}J(E_{it}). \tag{2.11b}$$

The threshold energy E_{it} is that incident laboratory kinetic energy for which the products of the reaction illustrated by Eq. (2.10a) are at rest in the center-of-mass system[17]:

$$E_{it}=-(2m_t)^{-1}\left[\left(\sum_{r=1}^{2}m_r\right)^2-\left(\sum_{p=1}^{4}m_p\right)^2\right], \tag{2.12a}$$

$$E_{it}=\frac{2(A+A')+2}{A'}(0.934)\text{ BeV}, \tag{2.12b}$$

where r indexes the initial particles or reactants of mass m_r, p indexes the final particle or products of mass m_p, the sum is over those particles indicated by subscripts, and 0.934 BeV is the proton rest-mass energy.

3. ENERGY THRESHOLDS AND SPECTRA; NUCLEAR REACTIONS, ABUNDANCES, AND CROSS SECTIONS

The purpose of this section is to collect and appraise the available numerical estimates of physical parameters and data needed to apply the equations developed in Sec. 2 to the calculation of the antiproton concentration in cosmic rays. Laboratory experiments supply the information on the energy thresholds, nuclear reactions, and the cross sections for production and annihilation of antiprotons; cosmic-ray observations provide information on the energy spectrum and nuclear abundances of cosmic rays; observations from optical and radio astronomy provide information on the interstellar gas densities and abundances.

A. Thresholds

The energy thresholds in BeV for Eq. (2.10a) to proceed, found in Eq. (2.12b) from purely kinematic considerations, are shown in Table I.

Note from this table that only $2m_p=1.9$ BeV is required if the target has an infinite nucleon mass since in this case the center-of-mass velocity is zero in the lab system. If the incident particle is infinitely massive and there is one target nucleon, then an infinite energy is required to create a nucleon pair. An intermediate case of some importance is cosmic-ray hydrogen striking

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TABLE I. Laboratory kinetic-energy threshold E_{it} (BeV) of incident nuclide i on target nuclide t for p-$\bar{p}$ pair production, Eqs. (2.10a) and (2.12b).

$t \backslash i$	1	2	3	4	···	A
1	5.6	7.5	9.3	11.2	···	$(2A+4)(0.934)$
2	3.7	4.8	5.6	6.5		
3	3.1	3.7	4.1	4.9		
4	2.7	3.3	3.7	4.2		
⋮	⋮					
A'	$(0.934)(2+4/A')$					$\frac{[2(A+A')+2]}{A'}(0.934)$

interstellar helium, and cosmic-ray helium striking interstellar hydrogen or helium. This is of interest since after hydrogen, helium has the second largest abundance in the primary beam, probably in the interstellar gas, and possibly in the intergalactic medium. Table I indicates that $E_{14}=2.7$ BeV, $E_{41}=11.2$ BeV, and $E_{44}=4.2$ BeV.

Photonuclear nucleon pair creation processes[18] (photoproduction) could contribute to the antiproton intensity. The photon rest mass is zero and hence $E_{0A'}=(2+2/A')m_p$, which is 3.7 BeV for a target proton, and 1.9 BeV for a very heavy target.

It is shown in the Appendix that these and other possible interactions are negligible within the accuracy of these calculations.

In calculating entries for Table I, it has been assumed that the entire nucleus participates as a single particle. The entries are therefore upper bounds to the threshold obtained by kinematics; as observed for protons on copper[19] the Fermi motion in the target nuclide will tend to reduce the threshold below 5.6 BeV. This effect is small in the expression $n_t\sigma J$, because the abundance of the very heavy target nuclides is very low ($\sim 10^{-2}n_p$), offsetting the small increase in cosmic-ray intensity at lower energies.

B. Cosmic-Ray Composition and Energy Spectrum

The relative abundances of the heavy primaries in the primary galactic beam and the energy spectrum of the particles in the beam are considered here. Then the abundance of nuclei heavier than hydrogen in the interstellar medium is discussed.

Relative cosmic-ray abundances have been measured by Waddington[20]. Table II is constructed from Waddington and displays the absolute intensities of various nuclei in the cosmic-ray beam above 4.5 BV.

It is seen that the helium constitutes the second largest population of nuclides in the beam and comprises about 15±1% of the proton intensity. Variations in the ratio $J_4(E)/J_1(E)$ as a function of energy are important but as yet uncertain.

The energy spectrum of the cosmic-ray primaries[14,15] is customarily expressed by the relation

$$J_i(E)=\int_E^\infty j_i(E)dE=k_iE^{-\gamma_i}, \qquad (3.1)$$

where $j_i=k_i\gamma_iE^{-(\gamma_i+1)}$ is the differential energy spectrum or number of the ith kind of particle cm^{-2} sec^{-1} BeV^{-1}, $J_i(E)$ is the integral energy spectrum or number of the ith type of particle cm^{-2} sec^{-1} BeV$^{+\gamma_1}$ having energy greater than E BeV, γ_i is the exponent in the power-law spectrum, and $k_1\sim 2.5$ particles cm^{-2} sec^{-1} for $E>\sim 10$ BeV.

Table III exhibits accepted values[21–23] of γ_i over the entire energy regime observed, for primary protons ($i=1$).

Unfortunately, the helium intensity is not known over a wide energy range. The ratio of hydrogen to helium intensities is 7.0±0.2 at BeV energies[20] and probably increases at elevated energies due to the enhancement of the galactic beam and suppression of the solar radiation.

Based both on the helium abundance and the energy threshold of 11.2 BeV (Table I), the helium-proton contribution is less than about $(1/7)\times(5.6/11.2)^{1.5}$ $\sim 3\times 10^{-2}$ times the proton-proton contribution to the antiproton source, Eq. (2.2b). The proton-helium contribution requires knowledge of the target helium concentration in the interstellar gas.

The energy spectrum and intensity of high-energy cosmic photons is incompletely known from observation. However, taking into account the main sources of γ rays (neutral pion decay, bremsstrahlung, and inverse Compton effect) both in the Galaxy and the Metagalaxy, Ginzburg and Syrovatskii[14] estimate that above about 1 BeV the photon intensity is less than about three to four orders of magnitude below the cosmic-ray intensity.

C. Interstellar Gas Abundance and Density

Allen[24] points out that the relative abundance of atoms in interstellar gas is probably very similar to stellar abundances. The so-called universal or cosmic (*not* cosmic ray) abundances are derived from terrestrial, solar, meteoritic, and stellar values. It is not an unreasonable assumption to use the universal ratio of

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TABLE II. The integral cosmic-ray intensity J_i(4.5 BV) versus nucleon number i of cosmic-ray nuclide.

Cosmic-ray nuclide i	H 1	He 4	Li 7	Be 9	B 11	C 12	N 14	O 16	F 19	$Z>10$ $A>23$
J_i $(\text{m}^2 \text{ sec sr})^{-1}$	610±30	88±2	0.27	0.12	1.12	1.82	0.87	1.25	0.18	1.7

helium to hydrogen atoms to represent the interstellar gas ratio.

Radio observations have confirmed the existence of interstellar H and OH and yielded number densities from the intensities of spectral lines.

Seuss and Urey[25] find about 8% and Cameron[26] finds about 15% for the helium to hydrogen number ratio, primarily in meteorites. Spectroscopic evidence from stars yields about 13% according to Aller.[27] The value 15% could not seriously overestimate the presence of helium in the target medium. Therefore, the proton-helium contribution, Eq. (2.2), is roughly $4\times(15\times10^{-2})=0.6$ times the proton-proton contribution to the antiproton production. This assumes the cross section per nucleon is the same for hydrogen and helium; hence the factor of 4.

It would be helpful to know the number density of hydrogen nuclei in the Galaxy as a function of position and time. Estimates exist only for the proton densities in differing regions of the Galaxy based on radio observations. Average disc-proton density is usually taken[24] as ~1 proton cm^{-3}, an average in the Galaxy halo is about 10^{-2} proton cm^{-3}, and the average intergalactic proton density is approximately 10^{-5} protons cm^{-3}. These average values are used in the next section.

D. Antiproton Production Cross Sections

Although antiprotons were first produced on earth at the Berkeley accelerator by bombarding copper with 6.2-BeV protons,[28] there has been a scarcity of pertinent $\bar{p}$ production cross-section data.

Accelerator experiments often use nonhydrogen targets, such as beryllium, carbon, aluminum, and copper. The cross sections for Eqs. (2.10a)and (2.10b) would therefore have to be deduced and extracted from data on proton reactions with heavy targets. Typical of these experiments is that a total integrated cross section per unit solid angle, and per unit recoil energy or momentum interval is given at a few selected points, which do not adequately cover the energy or momentum range needed for this calculation. In one experiment of the Berkeley Bevatron group,[29] for example, an attempt to study reaction (2.10b) was made, but the results were inconclusive because of problems associated with the internal beam and the subtraction methods. Apparently (2.10b) has not yet been studied in detail.

To further illustrate the uncertainties, consider that experimental evidence[30] suggested that free nucleon targets were several times more effective in generating antiprotons than bound nucleons. Later work[29,31] cast serious doubt on this conclusion, giving inconclusive results, even though the Pauli exclusion principle implies larger yields from neutron targets than from proton targets in (2.10b).

Theoretical work on antiproton production cross sections has not been lacking, although as Hagedorn[32] points out it is safer for this purpose to use experimental data even though it may not be overly plentiful. The initial theoretical work on these cross sections[33] employed a phase-space volume calculation and was limited to the energy region near threshold, 5.6 BeV, for Eq. (2.10b). Feldman[34] showed that antiprotons might be generated at a lower threshold, 4.1 BeV, if a two-step process were responsible: In the first stage, π mesons are produced by proton-nucleon collisions; in the second, these pions strike the target nucleons and yield antiprotons. However, there is no experimental evidence for this two-step process.[29]

A review by Barashenkov[35] surveys the total, elastic, and inelastic interaction cross sections at high energies for nucleon, antinucleon, and meson reactions. A comprehensive study of the available data is given by

TABLE III. The exponent $\gamma_i(E)$ in the power-law spectrum versus energy E for primary protons $(i=1)$.

$\log_{10}E$ (eV)	9	10	11	12	13	14	15	16	17	18	19	20
γ_1		(1.62±0.05), Ref. 23					(2.1±0.1), Ref. 21				(2.0,1.6), Ref. 22	

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[34] G. Feldman, Phys. Rev. **95**, 1699 (1954).
[35] V. S. Barashenkov, Usp. Fiz. Nauk **72**, 53 (1960) [English transl.: Soviet Phys.—Usp. **3**, 689 (1961)].

TABLE IV. The antinucleon production cross section $\sigma_{\bar{N}}$ *versus* kinetic energy E_p of incident proton for p-p collisions.

E_p (BeV)	6	10	20	30	10^3	10^4	10^5
$\sigma_{\bar{N}}$(mb)[a]	10^{-3}–10^{-4}	10^{-2}–10^{-3}	10^{-1}–10^{-2}	1–10^{-1}	<35	<70	<150
$\bar{\sigma}_{\bar{N}}$(mb)[b]	$<\sim5$	$<\sim5$	$<\sim5$	$<\sim5$	···	···	···
$\bar{\sigma}_{\bar{N}}$(mb)[c]	~0.3	~0.3	~0.3	~0.3	···	···	···

[a] Reference 36. [b] Upper limit from Eq. (3.2). [c] Very approximate estimate, G. Cocconi (private discussion).

Barashenkov and Patera.[36] These authors use direct data spanning accelerator energies, and indirect estimates beyond this range, to obtain approximate values for the relative yields of antinucleons and their production cross sections. Although it is mentioned that no cross-section measurements exist on antinucleon production from nucleon-*nucleon* collisions, it is still possible to make satisfactory estimates from nucleon-*nucleus* collisions if the antinucleon absorption or secondary production in the nucleus is neglected.[36] At very high incident proton energies, $E_p \gg 10$ BeV, the number or average multiplicity $\bar{m}$ of mesons, nucleons, and antinucleons produced can be described by the relation $\bar{m} \approx 3E_p^{1/4}$. The relation comes from the Fermi statistical model of high-energy collisions and is empirically verified.[36] Experimental ratios among the products[36] give the following upper estimate of the average antinucleon multiplicity: $\bar{m}_a < 0.1\bar{m} - 1$; this coupled with the guess that at these elevated energies the antinucleon production cross section must be less than the total inelastic cross section (about 35 mb) gives a few very coarse limits.[36] Table IV shows these estimates of the antinucleon production cross sections for both energy ranges.

A firm upper limit to the $\bar{p}$ production cross section up to 30 BeV is obtained from the following considerations:

(a) The inelastic p-p cross section from 6–9 BeV is roughly 22 mb[35] and is here taken to be the same up to 30 BeV.[37]

(b) From unpublished work at Dubna,[38] the fraction W_n of inelastic events having n-prong charged products over the energy range 6–30 BeV is approximately $W_4 \sim 0.5$–0.3, $W_6 \sim 0.1$–0.3, and $W_8 \sim 0.0$–0.1 for $n=4$, 6, and 8, respectively. Odd-n events are neglected.

(c) Many of the channels for which $n=4$, 6, 8 are rich in pions as implied by the relation $\bar{m}_a < 0.1\bar{m} - 1$ for energies in excess of 10 BeV. Relative $\bar{p}$ yields are: $\bar{p}/\pi^- \sim 10^{-2} - 10^{-3}$, in the forward direction for p-p collisions at 23 GeV/c[39] and $\bar{p}/\pi^- \sim 3\times10^{-3} - 10^{-2}$ for 25 BeV p on Al.[40]

(d) The thresholds for single, double, and triple $\bar{p}$ production in the $n=4$-, 6-, and 8-prong channels are $E_4 \sim 6$ BeV, $E_6 \sim 16$ BeV, and $E_8 \sim 30$ BeV [Eq. (2.12)]. The intensity of the cosmic-ray beam decreases sufficiently with energy in this range to neglect multiple antiproton production.

(e) The flux of cosmic rays having energies greater than 16 BeV is about $(6/16)^{1.6} \sim 0.22$ times the flux above 6 BeV [Eq. (3.1)].

From (a) and (b) the average cross section for the $n=6$ channel over 30–16 BeV is $\bar{\sigma}(6) = \frac{1}{2}[22(0.3) - 0] = 3.5$ mb; and by (c) the $\bar{p}$-producing events in this channel probably constitute $<\sim10^{-1}$ of all $n=6$ events. The upper limit to $\bar{p}$ production for $n=6$ is $\bar{\sigma}(6,\bar{p}) <\sim 10^{-1}(3.5) = 0.35$ mb. For $n=4$, $\bar{\sigma}(4) \sim \frac{1}{2}[22(\frac{1}{2})(0.5\text{–}0.3) - 0] = 4.5$ mb averaged over 16–6 BeV, by (a) and (b) above. This includes non-$\bar{p}$ events and is used here as an upper limit, $\bar{\sigma}(4,\bar{p}) <\sim 4.5$ mb. Combining these estimates with (e) gives $\bar{\sigma} = J^{-1}[4.5J + 0.35(0.22J)] \sim < 5$ mb averaged over 6–30 BeV. The uncertainties in W_n are about 10–20% and in σ(inelastic) could be up to 50% at 30 BeV. Therefore,

$$\bar{\sigma}_{\text{prod}} \sim < 5 \text{ mb}, \quad 6\text{–}30 \text{ BeV}. \tag{3.2}$$

For comparison, see Table IV.

Regarding the process of $\bar{p}$ photoproduction, the cross section given is not integrated over all solid angles and energy.[18] This makes it difficult to compare with

TABLE V. p-$\bar{p}$ total and annihilation cross sections, $\sigma_{\text{tot}}(\bar{p}p)$ and $\sigma_{\text{ann}}(\bar{p}p)$, versus cosmic-ray antiproton energy and momentum, $E_{\bar{p}}$ and $P_{\bar{p}}$.

$P_{\bar{p}}$ (BeV/c)	0.44	1.07	1.61	1.9	2	3	6	14	21
$E_{\bar{p}}$ (BeV)	0.1	0.5	0.93	1.2	1.27	2.21	5.1	13.2	20.1
σ_{tot} (mb)	180[a]	120[a]	96±3[b]	95[a]	102±3[c]	80±7[c]	62[c]	51[c]	47[c]
σ_{ann} (mb)	110[a]	70[a]	50±8[b]	58[a]	···	···	···	···	···

[a] Reference 29. [b] Reference 42. [c] Reference 43.

[36] V. S. Barashenkov and J. Patera, Fortsch. Physik 11, 469 (1963).
[37] A. M. Wetherell, Rev. Mod. Phys. 33, 382 (1961).
[38] V. S. Barashenkov, V. M. Maltsev, and I. Patera, Joint Institute for Nuclear Research, Laboratory of Theoretical Physics Report No. P-1577, Dubna, USSR, 1964 (unpublished).
[39] D. Dekkers, J. A. Geibel, R. Mermod, G. Weber, T. R. Willetts, K. Winter, B. Jordan, M. Vivargent, N. M. King, and E. J. N. Wilson, Phys. Rev. 137, B962 (1965).
[40] V. Cocconi, T. Fazzini, G. Fidecaro, M. Legros, N. H. Lipman, and A. W. Merrison, Phys. Rev. Letters 5, 19 (1960).

TABLE VI. Summary of cosmic-ray proton and antiproton fluxes J_p, $J_{\bar{p}}$, and production, annihilation, inelastic collision, and escape cross sections versus cosmic-ray proton and antiproton energies, E_p and $E_{\bar{p}}$.

Column / Row	A E_p (BeV)	B[a] $J_p(E_p)$ ($cm^{-2}sec^{-1}$)	C[b] σ_{prod} (mb)	D[c] σ_{ann} (mb)	E[d] σ_{esc} (mb)	F[e] σ_{inel} (mb)	G[f] σ_{loss} (mb)	H[g] $\bar{p}/p$	I[h] $J_{\bar{p}}(E_{\bar{p}})$ ($cm^{-2}sec^{-1}$)	J[i] $\bar{E}_{\bar{p}} \approx 0.1 E_p^{3/4}$ (BeV)	K[j] $J_{\bar{p}}/J_p$
1	6	0.265	3×10^{-4}	89	267	110	356	10^{-6}	3×10^{-7}	0.4	10^{-7}
2	10	0.121	3×10^{-3}	55	267	67	322	10^{-5}	10^{-6}	0.6	10^{-6}
3	20	0.043	0.03	50	533	63	583	5×10^{-5}	2×10^{-6}	0.9	10^{-6}
4	30	0.023	0.3	51	533	55–60	584	5×10^{-4}	10^{-5}	1.3	10^{-5}
5	10^3	1.2×10^{-4}	35	···	$(\frac{1}{2}-1)\times10^3$?	···	10^3?	3×10^{-3}	10^{-7}	30	2×10^{-6}
6	10^4	4×10^{-6}	70	···	10^3?	25 ± 18	10^3?	6×10^{-3}	10^{-9}	10^2	2×10^{-7}
7	10^5	1.2×10^{-7}	152	20?	10^3?	···	10^3?	1.2×10^{-3}	10^{-9}	4×10^2	10^{-6}
8	uncer-tainties	5–10%	rows 1–4: $\frac{1}{2}$–1 oom[k] rows 5–7: 1–2 oom[k]	10%	50%	10%		$\frac{1}{2}$–1 oom[k]	1 oom[k]	$\frac{1}{2}$ oom[k]	1–2 oom[k]

[a] Reference 15.
[b] Reference 36.
[c] References 42, 43, and 29.
[d] Equation (2.6).
[e] Reference 35.
[f] Column $d+e$, Eq. (2.7).
[g] Column c/Column g, Eq. (2.8).
[h] Equation (2.8).
[i] Reference 36.
[j] Equation (2.9).
[k] Order of magnitude.

the above cross-section estimates and to apply to the present calculation.

E. Antiproton Annihilation Cross Section

This section is concluded by considering antiproton annihilation and inelastic cross sections due to p-p collisions. A theorem due to Pomeranchuk[41] predicts equality for the total or interaction cross sections at very high energies for the $\bar{p}$-p and p-p reactions, if the total cross sections at high energy are energy-independent.

The $\bar{p}$-p total and annihilation cross-section data are summarized in Table V.[29,42,43] The annihilation cross section includes channels in which no baryons appear, and excludes, for example, $\bar{p}p$, $\bar{p}p\pi^0$, $\bar{n}n$, etc. Below threshold for pion production, inelastic and annihilation cross sections are taken to be identical.[29]

The total p-p cross section falls slowly to 40 mb above 10 BeV remaining roughly constant; comparison with Table V shows that the condition for validity of the Pomeranchuk theorem, energy independence of total cross sections, appears to be not fulfilled below 20 BeV. The $\bar{p}$-p annihilation cross section is about $\frac{1}{2}$ to $\frac{2}{3}$ of the total cross section as seen in Table V, for energies less than 2 BeV. Amaldi[44] has given a functional fit to the low-energy cross-section data.

The $\bar{p}$ annihilation cross sections in Table V are smaller than the cross sections in Sec. 2 for galaxy escape which is thus the more likely $\bar{p}$ removal process.

4. RESULTS

The results of the preceding sections are assembled here. The various cross sections in Secs. 2 and 3 are used here to determine the intensities of the cosmic-ray collision-produced antiprotons as well as the various collision mean free times in different galactic regions. The source functions in different regions are computed and the implications presented and discussed.

A. Cosmic-Ray Antiprotons

Table VI is a summary of the cosmic-ray proton flux $J_p(E_p)$, antiproton flux $J_{\bar{p}}(E_{\bar{p}})$, and production, annihilation, inelastic collision, and escape cross sections as a function of cosmic-ray proton energy E_p and antiproton energy $E_{\bar{p}}$ or $\bar{E}_{\bar{p}}$, constructed from Tables IV, V, and Eqs. (2.5)–(2.9) and (3.1). The average antiproton energies $\bar{E}_{\bar{p}}$ in column J are based on a rough semiempirical relationship to the incident proton energies $\bar{E}_{\bar{p}} \sim 0.1(E_p)^{3/4}$ adapted from Barashenkov and Patera.[36] This shows that there should be a spread in $\bar{p}$ energies for a given incident p energy. Column H gives the ratio of integrated fluxes $\bar{p}/p = J_{\bar{p}}(E_{\bar{p}})/J_p(E_p)$ from Eq. (2.8) for protons of greater than the energy shown in column A and antiprotons of much less energy; this ratio decreases with energy due to the very probable increase in $\bar{p}$ yield at higher energy, column (c). To find the ratio $\bar{p}/p$ for energies greater than that in column J one divides the entry in column I by that proton flux in column B having the same energy in both columns A and J. This ratio, column K, is extremely rough because of the uncertainty of $\bar{E}_{\bar{p}}$, the very doubtful values for σ_{prod} at high energy (rows 5–7), and the solar modulation of the low-energy proton spectrum (rows 1–4). Column I contains the expected cosmic ray $\bar{p}$ flux at energies indicated in column J. The $\bar{p}$ flux decreases with increasing energy, since the p-flux energy spectrum [Eq. (3.1)] decreases much more rapidly than the generous estimates for the $\bar{p}$ production cross section (column C) increase with energy. Uncertainties for the entries in Table VI are indicated in row 8, where available; otherwise, order-of-magnitude (oom) estimates are made.

Geometrical features and particle densities, together

[41] I. Pomeranchuk, Zh. Eksperim. i Teor. Fiz. 34, 725 (1958) [English transl.: Soviet Phys—JETP 7, 499 (1958)].
[42] N. Xuong and G. R. Lynch, Phys. Rev. 128, 1849 (1962).
[43] S. J. Lindenbaum, W. A. Love, J. A. Niederer, S. Ozaki, J.L. J. Russell, and L. C. L. Yuan, Phys. Rev. Letters 7, 185 (1961).
[44] U. Amaldi, T. Fazzini, G. Fidecaro, C. Ghesquiere, M. Legros, H. Stiener, Nuovo Cimento 34, 825 (1964).

TABLE VII. Mean free times in years for various collision processes at different locations, where n_p is the concentration of protons at each location.

	a	b	c	d	e
	n_p[a]	Production[b]	Annihilation[c]	Escape[d]	Mag. scat'g.[e]
Galaxy	10^{-2} cm^{-3}	$10^{14,12,9}$	$(1-3)\times10^{9}$	3×10^{8}	10^{2}
Core	10	$10^{11,9,6}$	$(1-3)\times10^{6}$	3×10^{5}	?
Disc	1	$10^{12,10,7}$	$(1-3)\times10^{7}$	3×10^{6}	1–10
Halo	10^{-2}	$10^{14,12,9}$	$(1-3)\times10^{9}$	3×10^{8}	10^{2}
Metagalaxy	10^{-5}	$10^{17,15,12}$	$(1-3)\times10^{12}$	···	10^{5}

a Reference 24.
b The three values are for 6–10, 30, and 10^4 BeV.
c The two values are for $E_p=0.7$ and 2 BeV.
d Equation (2.5).
e Reference 45.

with the appropriate cross sections, determine the mean free paths L and mean free times T for the various processes of interest. These are shown in Table VII,[45] constructed with Eq. (2.5). An estimate of the mean time between magnetic-scattering events is included for comparison purposes. Scattering from magnetic inhomogeneities or gas clouds is assumed to be elastic and causes changes in the direction of the charged particle orbit. In Table VII note that in each neighborhood, entries in column d are one-half to one order of magnitude smaller than those in column c. That is, the probability of antiproton escape is greater than the probability of antiproton annihilation in the core, disc, and halo, even at lower antiproton energies. Hence, Eq. (2.1b) simplifies approximately to $T_{\text{eff}}\sim T_{\text{esc}}$ in all three regions, although this is not necessary in the calculations that follow. To establish a firm upper limit to the ratio $\bar{p}/p=J_{\bar{p}}/J_p$ recall the approximate upper limit to the n-prong product production cross section averaged over 6 to 30 BeV from Eq. (3.2), $\sigma<\sim5$ mb. Letting $E_p=0$ in (2.9) and using the low-energy effective cross section from Table VI yields[13]

$$J_{\bar{p}}(0)/J_p(0)<\sim3\times10^{-3}. \tag{4.1}$$

Although this is an approximate upper limit, the very basis upon which it is deduced, Eq. (3.2), indicates that it must be quite conservative as discussed before, due to the fact that meson production is more likely than antinucleon production in nucleon-nucleon collisions. Even though it is a firm upper limit based on experiment, surely Eq. (4.1) must be one or more orders of magnitude larger than the true value. The conjecture is borne out by Tables IV and VI and by the rough estimate of 0.3 mb for antinucleon production.

In order to improve the $\bar{p}$ calculations, improved measurements of antiproton production cross sections are required as a function of incident proton energy for various targets, and in addition, as a function of the resulting antiproton momentum distributions. These measurements could reduce the uncertainties in the calculations of the intensity of cosmic-ray antiprotons from cosmic-ray collisions with interstellar matter.

45 H. Laster, Phys. Rev. **135**, B1274 (1964).

According to Peters,[46] all sea level nucleons with energy greater than about 3 BeV are extraterrestrial, since incident nucleons carry away from a nucleon-nucleon collision a large fraction of their energy. If the Pomeranchuk condition holds above about 10 BeV, $\bar{p}$-p and p-p collisions should have almost the same interaction cross sections; at very high energies, if the unknown annihilation cross sections are found to be much smaller than the interaction cross section, then the ratio of extraterrestrial antiprotons to extraterrestrial protons would be preserved through the air shower development down to sea level.[46] For example, each $\bar{p}$ and p incident on the top of the atmosphere with 10^3 BeV might have about 50 BeV after propagating to sea level, each having produced air shower $\bar{p}$'s which annihilate before reaching sea level due to their low energies. Based partly on these ideas, Brooke and Wolfendale[47] were able to place an experimental upper limit of 5% to the $\bar{p}$ fraction of extraterrestrial cosmic rays having energies about 10^3 BeV. Table VI indicates about 10^{-6} for the $\bar{p}$ fraction at this energy. In the future, an improved experiment may actually detect a very high energy extraterrestrial cosmic-ray antiproton.

B. Galactic and Metagalactic Antimatter

One can investigate the general nature of the antiproton generation in the Galaxy by obtaining the volume production rates from Eqs. (2.1) and (2.2). With reactions such as those in Eq. (2.10a), it is convenient for calculations to separate the target concentration variable n_t from the reaction rate S_{it} as done in Eqs. (2.11).

Drawing upon Table I for the energy thresholds, Tables IV and VI for the cross sections for $i=t=1$, and estimating very roughly that for all energies

$$\sigma(i=1,t)=t\sigma(i=1,t=1),$$
$$\sigma(i,t=1)=i\sigma(i=1,t=1), \tag{4.2}$$

values for S_{it} are obtained in Table VIII.

An upper limit for the p-p reaction rate due to Eq. (2.2) is $S'<\sim1.3\times10^{-27}$ sec^{-1} from 6 to 30 BeV, about three or more orders of magnitude larger than the entries in Table VIII.

Combining various hydrogen densities or total numbers of nuclei in different regions with the upper limit S' yields the volume or total production rates, respectively. This is shown in Table IX.

The final column represents upper limits; approximate values are at least three orders of magnitude smaller. In filling out this table, the assumption was made that the cosmic-ray beam has the same uniform intensity throughout the Galaxy and Metagalaxy as that in the solar neighborhood, as discussed in Sec. 2.

46 B. Peters, in *Proceedings of the 1963 Cosmic Ray Conference, Jaipur, India* (Commercial Printing Press, Ltd., Bombay, India, 1963), Vol. 3, p. 411.
47 G. Brooke and A. W. Wolfendale, Nature **202**, 480 (1964).

TABLE VIII. Values of the reaction rate S_{it} (sec^{-1}) for $\bar{p}$ production versus energy.[a]

E (BeV)	3	4.5	6	10	12	20	30	10^3
S_{11}	0	0	7×10^{-32}	3×10^{-31}	...	10^{-31}	7×10^{-30}	4×10^{-30}
S_{14}	8×10^{-31}	...	4×10^{-32}	2×10^{-31}	...	5×10^{-32}	4×10^{-30}	...
S_{41}	...	...	...	...	1.6×10^{-31}	...	...	...
S_{44}	...	7×10^{-32}	...	...	...	...	...	...

[a] Many entries for S_{it} in Table VIII are neglected because q_{it} is small. These cases are discussed in the Appendix.

TABLE IX. The volume and total antiproton production rates, $q=nS'$ and $Q=qV$, in different regions of space. In each region the volume V, number of gas protons N, and number density n, are shown. The upper limit for the p-p reaction rate is $S'<\sim1.3\times10^{-27}$ sec^{-1}.

Region	V (cm^3)	N (No. gas p)	q ($\bar{p}$ cm^{-3} sec^{-1})	Q ($\bar{p}$ sec^{-1})	$\bar{p}$ in 10^{10} yr	
Core	4×10^{62}	4×10^{63}	1.3×10^{-26}	5×10^{36}	$<10^{-3}$	$M_\odot$
Disc	4×10^{64}	4×10^{64}	1.3×10^{-27}	5×10^{37}	$<10^{-2}$	$M_\odot$
Halo	2×10^{68}	2×10^{66}	1.3×10^{-29}	3×10^{39}	<1	$M_\odot$
Galaxy	2×10^{68}	2×10^{66}	1.3×10^{-29}	3×10^{39}	<1	$M_\odot$
Observable universe	10^{84}	10^{79}	1.3×10^{-32}	1.3×10^{52}	$<10^{12}$	$M_\odot$

Almost certainly this is not correct; at the core for example, where violent events are believed to have occurred, the beam could be stronger; Metagalactic fluxes are unknown and observations do not yet rule out an intensity equal to or three to four orders of magnitude smaller than the galactic flux.[14]

It is of some interest to estimate the rate at which our Galaxy, which is fairly typical, injects antiparticles into the intergalactic space. The leakage rate sec^{-1} at the surface of a uniform spherical source is about $4LcT_{esc}Rq$, where L is the magnetic-scattering mean free path and R is the radius. Substituting reasonable values gives $8\times10^{38}\bar{p}$ sec^{-1}, which is smaller than the Galaxy-wide production rate, 3×10^{39} $\bar{p}$ sec^{-1}.

Approximately 10^9 observable galaxies contribute $\sim10^9\times10^{39}$ or 10^{48} $\bar{p}$ sec^{-1} to the visible universe which is four orders of magnitude smaller than the contribution from intergalactic cosmic rays assumed to have an intensity equal to that of galactic cosmic rays. In a time equal to the Hubble age of the universe, 10^{10} yr, about $10^8M_\odot$ antiprotons leave all galaxies. The same amount is produced in intergalactic space if the intergalactic cosmic-ray intensity is about 10^{-4} times the galactic intensity. Since a normal galaxy has a mass of about $10^{11}M_\odot$, a galaxy composed of collision-produced antiprotons could not be assembled in less than 10^{10} yr, apart from the difficulty of concentrating it into one region of space. Any antiprotons produced in the "primordial fireball" or at other primeval times would appear to be capable of surviving in intergalactic space to the present since annihilation there takes about 10^{12} yr (Table VII).

At present, there are no measurements of the true $\bar{p}$ flux and hence no comparison of its relative magnitude can be made with calculated $\bar{p}$ fluxes. However, subtraction of calculated $\bar{p}$ fluxes from future measured $\bar{p}$ fluxes would present an opportunity to place limits on the speculative, cosmological, and primeval $\bar{p}$ sources discussed at the beginning of this paper. This implies that expected $\bar{p}$ measurements of the flux would exceed the predicted $\bar{p}$ flux, but the opposite situation might obtain. Such an eventuality could suggest modification of the noncollision $\bar{p}$ source mechanisms or intensities.

5. CONCLUSIONS

From the discussion of other work on antimatter and antiprotons, certain aspects of the calculations done here emerge. The Fradkin[4] calculations of cosmic-ray antiprotons have been improved, extended and refined on the basis of diffusion theory (Sec. 2) and recent data (Sec. 3). The results (Sec. 4) are not inconsistent with available measurements. A nonspeculative galactic and intergalactic source of antiprotons is obtained here, hitherto not discussed in the literature in detail. Detection of antiprotons from this source would be more direct perhaps and possibly simpler than from other sources.

Specific conclusions indicated below are based on several of the following assumptions:

(a) Local primary cosmic radiation is representative of the uniform cosmic-ray intensity throughout the Galaxy. Diffusion-theory treatment (Sec. 2) is applicable.

(b) The upper limit to the $\bar{p}$-production cross section is about 5 mb from 6–30 BeV [Eq. (3.2)].

(c) Realistic estimates for the $\bar{p}$-production cross sections are about 10^{-4}–10^{-1} mb from 6–30 BeV (Table IV).

(d) The matter encountered by cosmic rays from their sources properly describes both p and $\bar{p}$ escape from the Galaxy.

(e) The average gas densities are approximately $1p$ cm^{-3} in the disc, 10^{-2} p cm^{-3} in the halo, and 10^{-5} p cm^{-3} in the Metagalaxy (Table VII).

The conclusions are:

(1) Excluding assumption (c), the upper limit to the ratio of low-energy secondary cosmic-ray antiprotons to low-energy primary cosmic-ray protons is about 3×10^{-3}. The upper limit to the antiproton flux is

$$J_{\bar{p}}(\sim0-1.3 \text{ BeV})<\sim2\times10^{-4} \text{ cm}^{-2} \text{ sec}^{-1}.$$

(2) Excluding assumption (b), the actual ratio $\bar{p}/p$ is probably two to four orders of magnitude smaller than the upper limit, depending on energy. The approximate antiproton fluxes are as follows:

$E_{\bar{p}}$ (BeV)	~0	~0.6	~0.9	~1.3
$J_{\bar{p}}(E_{\bar{p}})$ ($\text{cm}^{-2}\text{ sec}^{-1}$)	$\sim3\times10^{-7}$	$\sim10^{-6}$	$\sim2\times10^{-6}$	$\sim10^{-5}$

(3) Annihilation of $\bar{p}$ is a less important loss mechanism than leakage out of the Galaxy, which amounts to less than about $1M_\odot$ in 10^{10} yr.

(4) Assuming that the metagalactic flux

$$J_{mg}\sim(10^{-3}-10^{-4})J_g,$$

the amount of collision-produced $\bar{p}$ which leave all galaxies, and which are formed from intergalactic cosmic ray interactions with intergalactic gas, is about 10^8–10^9 $M_\odot$ in about 10^{10} yr.

(5) The mean annihilation time for intergalactic antiprotons is $\sim10^{12}$ yr; hence, primeval antiprotons could survive to the present epoch.

Potential improved measurements, coupled with the improved calculations of cosmic-ray antiprotons, could revise models of or place limits to speculative antiproton sources. Searching for measured upper limits or unambiguous detection of cosmic-ray antiprotons by high-energy counters placed in a satellite, space probe, balloon, or terrestrial laboratory should receive encouragement. Such cosmic-ray detectors perhaps will eventually register a true antiproton event in or above the atmosphere. Cosmic-ray antiprotons appear to be sufficiently provocative and important for further calculations and experiments to continue.

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APPENDIX

The reasons for ignoring small corrections due to interactions mentioned in the text are given in this appendix. These interactions are: cosmic-ray collisions with cosmic rays; antiproton production by $\bar{p}$-p, p-$\bar{p}$, and $\bar{p}$-$\bar{p}$ reactions; nucleon photoproduction by cosmic γ rays; reactions involving deuterons and tritons.

Within the accuracy of these calculations, one can neglect the interactions of the primary cosmic-ray beam with itself. The volume reaction rate of cosmic rays with cosmic rays is $R_{cc}=n_{cr}\sigma J_{cr}=cn_{cr}^2\sigma$. For cosmic rays with interstellar gas the rate is $R_{cg}=cn_{cr}\ n_{is}\sigma$. Therefore, $R_{cc}\ll R_{cg}$ since $n_{is}\sim10^{10}n_{cr}$.

For the remaining cases, consider Table X which displays possible contributions to q_{it} in Eqs. (2.11). In Table X, the cases (a) are discarded by virtue of both the negligible $\bar{p}$ content in the cosmic rays (Table VI), and the very small upper limit to $\bar{p}$ in interstellar gas.[2]

TABLE X. Matrix of q_{it} for i and $t=-1, 0, 1, 2, 3$.

Target	Incident i / t	$\bar{p}$ -1	γ 0	p 1	d 2	t 3
$\bar{p}$	-1	*a*	*b*	*a*	*a*	*a*
γ	0	*a*	*b*	*d*	*c*	*c*
p	1	*a*	*b*	...	*d*	*d*
d	2	*a*	*b*	*d*	*d*	*d*
t	3	*a*	*b*	*d*	*d*	*d*

The cosmic γ-ray intensity is at least three or four orders of magnitude below the cosmic proton fluxes,[12,14] which justifies neglecting cases (b). In the recent experiments by the DESY group on photoproduction of antiprotons, integrated cross sections for the process are not yet available,[18] but it is doubtful that such data would change this conclusion.

The photoproduction cross section would have to be three to four orders of magnitude larger than the nuclear production cross section, and this is unlikely. Cases (c) represent inverse nuclear Compton effects about which little appears known experimentally. The number of deuterons (d) and tritons (t) observed in the cosmic radiation is very small[48]; to the author's knowledge none have been determined in interstellar gas. Therefore, cases (d) in Table X are neglected.

[48] C. F. Powell, P. H. Fowler, and D. H. Perkins, *The Study of Elementary Particles by the Photographic Method* (Pergamon Press, Ltd., London, 1959).