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Production of π Mesons and Gamma Radiation in the Galaxy by Cosmic Rays

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A detailed analysis is presented of the most probable sources in our galaxy of gamma radiation with energy greater than 0.2 MeV. Predictions are made of the resulting fluxes and their angular distribution in the vicinity of the earth. The results of these calculation and their implications for future gamma-ray experiments and detectors are discussed.

THE purpose of this paper is to present a detailed analysis of the most probable sources of gamma radiation in our galaxy and to predict more accurately the resulting fluxes and their angular distribution in the vicinity of the earth. Gamma-ray photons with energy greater than 0.2 MeV are considered.

I. GAMMA-RAY PRODUCTION MECHANISMS

Several authors[1–5] have discussed possible sources of primary gamma rays and have given order-of-magnitude estimates of the flux.

The most probable sources of gamma rays of energy greater than 0.2 MeV are

(1) decay of neutral π mesons produced in high-energy nuclear interactions and produced in antiparticle annihilations; (2) electron-positron annihilations; (3) electron bremsstrahlung by collision; (4) synchrotron radiation (magnetic bremsstrahlung); (5) de-excitation of nuclei; (6) Compton scattering.

Broad line emission occurs in electron-positron annihilation and in nuclear de-excitation; the remaining interactions result in a continuous emission spectra.

Estimates of the incident gamma-ray flux resulting from each of these interactions indicates that for photons of energy greater than 50 MeV the primary method of production in the galaxy is by the decay of neutral π mesons:

$$\pi^0 \rightarrow \gamma + \gamma\,,$$

which occurs with a mean lifetime of $\sim 10^{-16}$ sec. Both neutral and charged mesons are produced as a result of high-energy interactions of cosmic-ray protons, alpha particles, and other nuclei with the gas in the galaxy.

In the lower energy region of the gamma-ray spectrum the primary source of photons appears to be electron-positron annihilation:

$$e^+ + e^- \rightarrow \gamma + \gamma\,.$$

This reaction, occurring at rest, results in two photons each with 0.51-MeV energy. The positrons are derived from the decay of positive π mesons. A positive π meson decays with a short mean lifetime ($\sim 10^{-8}$ sec) into a μ meson and a neutrino:

$$\pi^+ \rightarrow \mu^+ + \nu\,.$$

The μ meson then decays with a mean lifetime of $\sim 10^{-6}$ sec into a positron, a neutrino, and an antineutrino:

$$\mu^+ \rightarrow e^+ + \nu + \bar{\nu}\,.$$

Positrons produced in the galaxy in this manner lose practically all of their energy by radiation and ionization, and then annihilate with electrons associated with the galactic gas.

The mean time for a positron to lose its initial energy by radiation and ionization $\sim 10^9$ yr, and the mean time for annihilation of a positron at rest is $\sim 10^6$ yr. Therefore, the 0.51-MeV gamma radiation measured now is dependent on the cosmic ray flux $\sim 10^9$ yr ago, if we assume no other sources of positrons with comparable intensity. The measurement of this flux is, therefore, a test for the long time-dependence of the intensity of cosmic radiation (see Appendix).

The generation of π mesons is the keystone to gamma-ray production in the galaxy. To compute a photon flux, we must therefore consider in detail (a) the nature of the galactic cosmic radiation, (b) the density and composition of the gas in the galactic disk and halo, and (c) the probability of π-meson production in nuclear interactions.

II. GAMMA-RAY INTENSITIES

The gamma-ray flux per unit area per unit time due to the ith-type meson at the earth is given by

$$G^i = \sum_k \int_{\text{source in cone of view}} r^{-2} n_k(\mathbf{r})\, q_k{}^i(\mathbf{r}) d\mathbf{r} \quad \text{photons cm}^{-2}\,\text{sec}^{-1}, \quad (1)$$

* National Science Foundation Predoctoral Fellow.
[1] P. Morrison, Nuovo Cimento **7**, 858 (1958).
[2] V. L. Ginzburg, in *Progress in Elementary Particle and Cosmic Ray Physics*, edited by J. G. Wilson and S. A. Wouthuysen (Interscience Publishers, Inc., New York, 1958), Vol. IV, p. 339.
[3] S. N. Milford and S. P. Shen, Nuovo Cimento **23**, 77 (1962).
[4] S. Hayakawa, K. Ito, and Y. Terashima, Suppl. Prog. Theoret. Phys. (Kyoto) **6**, 28 (1958).
[5] W. L. Kraushaar and G. W. Clark, Phys. Rev. Letters **8**, 106 (1962).

where $\mathbf{r}$ is the radial vector from the earth to the source, $n_k(\mathbf{r})$ is the density of the kth component of the galactic gas at the source, $q_k(\mathbf{r})$ is the rate of production of gamma rays per nucleus at the source, and

$$q_k{}^i(\mathbf{r})=\sum_j q_{jk}{}^i(\mathbf{r})=\sum_j \int_{T_0}^{\infty} I_j(T,\mathbf{r})\sigma_{jk}{}^i(T)m_{jk}{}^{\gamma i}(T)dT \quad \text{photons sec}^{-1}\text{ sr}^{-1}, \quad (2)$$

where $I_j(T,\mathbf{r})dT$ is the intensity of the jth component of the cosmic radiation between kinetic energies T and $T+dT$, $\sigma_{jk}{}^i,(T)$ is the cross section for production of the ith-type meson in the reaction of j- and k-type particles, and $m_{jk}{}^{\gamma i}(T)$ is the average multiplicity of gamma-ray photons produced per interaction.

III. THE GALACTIC COSMIC-RAY SPECTRUM

Our only information on the cosmic-ray energy spectrum is that energy spectrum we observe in the vicinity of the earth. We assume that the local spectrum and intensity are the same throughout the entire galactic disk and halo. The reason for this assumption is the observed isotropy and the continuous spectrum at the earth of cosmic radiation. It is important to realize that this does not imply that the cosmic-ray flux is generated uniformly throughout the galaxy. Within a time much shorter than the lifetime of a cosmic-ray particle ($\sim 4\times 10^8$ yr) all particles are dispersed uniformly throughout the galaxy.[2] One method responsible for this dispersal is the nonuniformity of the galactic magnetic field. Observations of the primary gamma-ray flux yield information about the distribution of cosmic rays. If the predicted fluxes differ from the observations, the assumed galactic spectrum can be modified.

The integral spectrum of primary protons is usually represented by the form[2]

$$I_p(E>E_0)=[K_p/(\gamma-1)]E_0{}^{-\gamma+1}. \quad (3)$$

where I_p is the intensity of protons with total energy E greater than E_0, and K_p and γ are constants within a defined energy range. The differential energy spectrum $I_p(E)$ can be obtained from Eq. (3), assuming K_p and γ are constants and $\gamma-1>1$:

$$I_p(E>E_0)=\int_{E_0}^{\infty} I_p(E)dE, \quad (4)$$

$$I_p(E)=K_pE^{-\gamma}. \quad (5)$$

The following approximate differential spectra, gives as functions of the kinetic energy T in BeV, are adopted[2,6,7]:

$$I_p(T)=\frac{0.380}{(1+T)^2}\text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}\text{ BeV}^{-1} \quad 0.3<T<1\text{ BeV}; \quad (6)$$

$$I_p(T)=\frac{0.437}{(1+T)^{2.2}}\text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}\text{ BeV}^{-1} \quad 1<T<10\text{ BeV}; \quad (7)$$

$$I_p(T)=\frac{0.894}{(1+T)^{2.5}}\text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}\text{ BeV}^{-1} \quad 10<T<100\text{ BeV}. \quad (8)$$

The coefficients are adjusted to satisfy continuity at the limits of the energy region. The following integral fluxes result from these spectra:

$$I_p(T>1\text{ BeV})=0.15\text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1},$$
$$I_p(T>10\text{ BeV})=0.016\text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}.$$

Alpha particles are the only other constituent of cosmic radiation that can contribute significantly to π-meson production. We take the primary alpha-particle spectrum expressed as a function of total energy per nucleon to be identical to the proton spectrum,[2,5,7] and the alpha particle intensity to be 0.15 that of the proton intensity.[8] Therefore,

$$I_\alpha(T)dT=0.15I_p(T)dT, \quad (9)$$

where T is the kinetic energy per nucleon.

IV. DENSITY DISTRIBUTION AND COMPOSITION OF GAS IN THE GALAXY

The primary component of gas in the galaxy is hydrogen, which exists in three forms: neutral (HI), ionized (HII), and molecular (H_2). The distribution of hydrogen can be divided into two regions: the flat galactic disk where the concentration is the greatest and the spherical galactic halo.

Consider first the density of hydrogen in the galactic disk. Estimates[9] of the amount of molecular hydrogen in the galaxy are quite small, $\sim$0.8%. Continuous radio emission at decimeter wavelengths throughout the galaxy and optical observations in our surroundings[10] indicate that there is a small amount of HII, $\sim$10% of HI. In general, HII has the same distribution as HI. An exception to this, however, is the apparently large content ($\sim$5 to 10 protons/cm^3) of HII within 150 parsec (pc) of the galactic center,[11] as indicated by the absorption of the long wavelength continuous radio radiation in the direction of the galactic center.

The density distribution of neutral hydrogen is obtained from radio observations of the 21-cm spectral line.[11] The thickness of the neutral-hydrogen disk is almost uniform; only in the region within 3 kiloparsec

[6] C. J. Waddington, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Academic Press Inc., New York, 1960), Vol. 8, p. 1.

[7] S. F. Singer, in *Progress in Elementary Particle and Cosmic Ray Physics*, edited by J. G. Wilson and S. A. Wouthyusen (Interscience Publishers, Inc., New York, 1958), Vol. IV, p. 205.

[8] E. P. Ney, Astrophys. J., Suppl. No. 44 4, 373 (1960); C. W. Allen, *Astrophysical Quantities* (Athlone Press, London, 1955), p. 31.

[9] F. D. Kahn, *Gas Dynamics of Cosmic Clouds, I.A.U. Symposium No. 2, 1953* (Interscience Publishers, Inc., New York, 1955), p. 60.

[10] E. R. Hill, Bull. Astron. Inst. Neth. **15**, 6 (1958–59).

[11] J. H. Oort, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1959), Vol. 53, p. 100.

(kpc) from the center is the thickness markedly smaller. There is no corresponding bulge in the center of the galaxy as seen in the star configurations. The smoothed out over-all density is 0.7 hydrogen atom/cm^3, but within 3 kpc from the center the average density is 0.4. Between 11 and 12 kpc from the galactic center the average density begins to drop sharply. We define the thickness of the disk, $2h_0$, such that

$$2h_0n_0=\int_{-\infty}^{+\infty} n(h)dh\,, \tag{10}$$

where n_0 is the density in the galactic plane and $n(h)$ is the density at a distance h from the plane. We then have[11]

$$2h_0=320 \text{ parsec}. \tag{11}$$

Table I lists the average densities of hydrogen n_p in

TABLE I. Average proton density in the galactic disk.

r' (kpc)	n_p protons/cm^3
$0<r'<0.15$	8
$0.15<r'<3$	0.45
$3<r'<8$	0.85
$8<r'<12$	0.45
$12<r'<15$	0.15
$r'>15$	0

the galactic disk as a function of the distance r' from the galactic center. These densities are averaged over the corresponding distance interval over galactic longitude. The nearby variations in density due to the location of the solar system at the edge of a spiral arm were obtained by extrapolation from density contours given by Kerr.[12]

Unfortunately, our knowledge of the galactic halo is rather meager. From radio observations at meter wavelengths we can set the radius of the halo equal to 13.5 kpc.[13,14] The density is assumed to be uniform; unfortunately, however, even a crude estimate of the density of HI in the halo cannot be obtained. By comparison of our galaxy with the galaxies M31 and M81, an upper limit of 10^{-2} protons/cm^3 can be placed on the halo density.[15] In our calculations we assume two density values: $n_p=10^{-2}$ and $n_p=10^{-3}$ proton/cm^3.

The density of helium in the galaxy is taken everywhere to be 10% of the hydrogen density.[8] We neglect the effects of the other components in the galactic gas, since their relative contribution to π-meson production is negligible.

[12] F. J. Kerr, Monthly Notices, Roy. Astron. Soc. **123**, 340 (1961).
[13] J. E. Baldwin, Monthly Notices, Roy. Astron. Soc. **115**, 690 (1955).
[14] C. A. Shain, *Paris Symposium on Radio Astronomy*, edited by R. N. Bracewell (Stanford University Press, Stanford, California, 1959), p. 328.
[15] M. Roberts (private communication).

V. PRODUCTION OF π MESONS IN PROTON-PROTON COLLISIONS

The principal method of production of π mesons in the galaxy is by the interaction of a cosmic-ray proton with neutral or ionized hydrogen. The important reactions are

$$p+p\rightarrow p+p+a(\pi^++\pi^-)+b\pi^0\,, \tag{12}$$

$$p+p\rightarrow p+n+\pi^++c(\pi^++\pi^-)+d\pi^0\,, \tag{13}$$

$$p+p\rightarrow n+n+2\pi^++f(\pi^++\pi^-)+g\pi^0\,, \tag{14}$$

$$p+p\rightarrow D+\pi^++l(\pi^++\pi^-)+t\pi^0\,, \tag{15}$$

where p indicates a proton, n a neutron, D a deuteron, and a, b, c, d, f, g, l, t positive integers. The threshold kinetic energy of the incident proton for the above reactions is 290 MeV. In the energy region from 290 MeV to 1 BeV only single π-meson production is important:

$$p+p\rightarrow p+n+\pi^+\,, \tag{16}$$

$$p+p\rightarrow p+p+\pi^0\,, \tag{17}$$

$$p+p\rightarrow D+\pi^+\,. \tag{18}$$

Reaction (16) dominates in this energy region. When the kinetic energy of the incident proton exceeds 1 BeV, multiple pion production becomes important. The minimum kinetic energy $T_{\min}$, of the incident proton needed to produce n mesons is given by

$$T_{\min}=\frac{n^2M_\pi^2c^4}{2Mc^2}+2nM_\pi c^2\,, \tag{19}$$

$$\approx n(280+10n)\text{ MeV}\,, \tag{20}$$

where $M_\pi c^2$ and Mc^2 are the rest energy in MeV of the π meson and proton, respectively. For proton energies greater than 1.5 BeV, the cross section for pion production is constant, and approximately equal to 27 mb. For energies greater than 100 BeV the cross sections for production of positive, neutral, and negative pions are equal.

Table II contains the pion production cross sections and the multiplicities for gamma rays resulting from positive and neutral pions and the multiplicity for negative pions as a function of the kinetic of the incident proton, for proton-proton reactions. For each positive or neutral pion produced the gamma-ray multiplicity is 2.

Above 3 BeV the experimental data on partial cross sections are incomplete. However, the following experimental information is available, from which the partial cross sections and multiplicities per inelastic event can be determined.

(1) The average charge multiplicity $\bar{m}_c$. $\bar{m}_c$ is the average number of charged pions produced per inelastic interaction. Table II gives the values of $\bar{m}_c$ for proton kinetic energies T from 2 to 300 BeV. Above a proton energy of 6 BeV the energy dependence of the multi-

TABLE II. Cross sections for pion production in p-p collisions.

T (BeV)	$\sigma_{pp}{}^0$ (mb)	$m_{pp}{}^{\gamma 0}$	Ref.	$\sigma_{pp}{}^+$ (mb)	$m_{pp}{}^{\gamma +}$	Ref.	$\sigma_{pp}{}^-$ (mb)	m_{π^-}	Ref.
0.29	0	0		0	0				
0.34	0.01±0.003	2	a, b	0.46±0.16	2	b			
0.43	0.45±0.15	2	b	5.9 ±0.37	2	b			
0.50	0.60±0.10	2	c	6.8	2				
0.56	1.2 ±0.3	2	d	7.6 ±1.2	2	d			
0.66	3.4 ±0.4	2	d	13.3 ±1.4	2	d			
0.80	4.7	2		22.9 ±3	2	i			
0.925	6 ±2	2	e	27.6 ±3.4	2	e	0	0	f, g
2.0	9.1 ±0.6	2	f, g	23.9 ±1.1	2	f, g	3.14±0.21	1	f, g
2.9	12.6	2	h	24.6 ±1.0	2	h	4.6 ±0.2	1	h

[a] J. W. Mather and E. A. Martinelli, Phys. Rev. **92**, 780 (1953).
[b] See Ref. 29.
[c] Iu. D. Prokoshkin, in *CERN Symposium Proceedings* (CERN, Geneva, 1956), Vol. 2, p. 385.
[d] M. G. Meshcheriakov, V. P. Znelov, B. S. Neganov, I. K. Vzorov, and A. F. Shabudin, in *CERN Symposium Proceedings* (CERN, Geneva, 1956), Vol. 2, p. 347.
[e] I. S. Hughes, P. V. March, H. Muirhead, and W. O. Lock, in *CERN Symposium Proceedings* (CERN, Geneva, 1956), Vol. 2, p. 344.
[f] W. J. Fickinger, E. Pickup, D. K. Robinson, and E. O. Salant, Phys. Rev. **125**, 2082 (1962).
[g] E. Pickup, D. K. Robinson, and E. O. Salant, Phys. Rev. **125**, 2091 (1962).
[h] See Ref. 20.
[i] See Ref. 32.

plicity $\bar{m}_c$ is in agreement with that computed from Fermi's statistical model,[16] which gives

$$\bar{m}_c \sim (T+Mc^2)^{0.25}. \tag{21}$$

Cosmic-ray data also support this formula for energies greater than 10 BeV.[17–19]

(2) For proton kinetic energies greater than 10 BeV the ratio of the average number of neutral to charged mesons produced is constant[18] and is given by

$$\bar{m}_{\pi^0}/\bar{m}_c = 0.5. \tag{22}$$

Since the charge multiplicity at 6 BeV differs only slightly from the multiplicity at 10 BeV, we extend the above ratio to 6 BeV.

(3) For the energy interval from 3 to 100 BeV we assume the following empirical relationship between the average positive and negative pion multiplicity and the average charged pion multiplicity:

$$\bar{m}_{\pi^+} \approx \tfrac{1}{2}(\bar{m}_c+1), \tag{23}$$

$$\bar{m}_{\pi^-} \approx \tfrac{1}{2}(\bar{m}_c-1). \tag{24}$$

These relationships agree with the experimental π^+- to π^--meson ratio of 5 at 2.9 BeV[20] and 2 at 9 BeV.[21]

(4) For proton energies greater than 1.5 BeV the total cross section for pion production remains constant and is approximately equal to 27 mb.[22–26]

For incident proton energies greater than 3 BeV, Table IV contains the total cross section for pion production in proton-proton interactions, the multiplicities per inelastic interaction for gamma rays resulting from positive and neutral pions, and the multiplicity per

TABLE III. The average charged pion multiplicity in proton-proton inelastic collisions.

T (BeV)	$\bar{m}_c$	Ref.
2	0.98±0.05	a
4.15	2.02±0.4	b
6.15	2.65±0.4	c
10	3±0.1	b
300	8±1	b

[a] E. Pickup, D. K. Robinson, and E. O. Salant, Phys. Rev. **125**, 2091 (1962).
[b] See Ref. 17.
[c] See Ref. 18.

TABLE IV. Cross sections for pion production in p-p collisions ($T>3$ BeV).

T (BeV)	$\sigma_{pp}{}^t$ (mb)	$m_{pp}{}^{\gamma 0}$	$m_{pp}{}^{\gamma +}$	m_{π^-}
6.2	27	2.7	3.7	0.8
10	27	3.0	4.0	1.0
50	27	4.4	5.4	1.7
100	27	5.3	6.3	2.1

[16] E. Fermi, Progr. Theoret. Phys. (Kyoto) **5**, 570 (1950).
[17] N. A. Dobrotin and S. A. Slavatinsky, in *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester*, edited by E. C. G. Sudarshan, J. H. Tinlot, and A. C. Melissinos (Interscience Publishers, Inc., New York, 1960), p. 819.
[18] K. Sitte, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1961), Vol. 46, pp. 189–192.
[19] G. N. Fowler and A. W. Wolfendale, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1961), Vol. 46, p. 300.
[20] A. C. Melissinos, T. Yamanouchi, G. G. Fazio, S. J. Lindenbaum, and L. C. L. Yuan, Phys. Rev. **128**, 2373 (1962).
[21] N. P. Bogachev, S. A. Bunyatov, Yu. P. Merekov, V. M. Sidorov, and V. A. Yarba, Zh. Eksperim. i Teor. Fiz. **38**, 1346 (1960) [translation: Soviet Phys.—JETP **11**, 968 (1960)].
[22] F. F. Chen, C. P. Leavitt, and A. M. Shapiro, Phys. Rev. **103**, 211 (1956).
[23] B. Cork, W. A. Wenzel, and C. W. Causey, Jr., Phys. Rev. **107**, 859 (1957).
[24] R. W. Wright, G. Saphir, W. M. Powell, G. Maenchen, and W. B. Fowler, Phys. Rev. **100**, 1802 (1955).
[25] N. P. Bogachev, S. A. Buniatov, Iu. P. Merekov, and V. M. Sidorov, Dokl. Akad. Nauk. SSSR **4**, 617 (1958) [translation: Soviet Phys.—Doklady **3**, 785 (1958)].
[26] A. E. Brenner and R. W. Williams, Phys. Rev. **106**, 1020 (1957).

TABLE V. Cross sections for pion production in p-α collisions.

BeV/ nucleon	s	$\sigma_{p\alpha}{}^0$ (mb)	$m_{p\alpha}{}^{\gamma 0}$	Ref.	$\sigma_{p\alpha}{}^+$ (mb)	$m_{p\alpha}{}^{\gamma +}$	Ref.	$\sigma_{p\alpha}{}^-$ (mb)	$m_{\pi}{}^-$	Ref.
0.17		0	0		0	0		0		
0.38	0.88	1.4	2	a	2.8	2	c, d	0		
0.45	0.74	2.4	2	a	4.8	2	c, d	0		
0.50	0.60	2.8	2	a	5.6	2	a, d	0		
0.56	0.60	6.0	2	a	10.6	2	c, d	1.4	1	c, d
0.61	0.60	8.0	2	a	14.3	2	c, d	1.7	1	c, d
0.66	0.60	14.0	2	a	24.0	2	c, d	4	1	c, d
0.97	0.50	20	2	b	33.0	2		7	1	b

[a] See Ref. 27.
[b] A. P. Batson, B. B. Culwick, J. G. Hill, and L. Riddiford, Proc. Roy. Soc. (London) **A251**, 281 (1959).
[c] See Ref. 28.
[d] See Ref. 29.

inelastic interaction for negative pions. To complete Table IV in the energy region from 3 to 6 BeV, extrapolation of the data was performed.

It is important to note in Table II the large suppression of π^0- and π^--meson production relative to π^+ production in the proton energy region below 2 BeV. This effect has been neglected in previous estimates of the primary gamma-ray intensity and position density in the galaxy.

VI. PRODUCTION OF π MESONS IN PROTON-ALPHA PARTICLE COLLISIONS

Although the ratio of alpha particles α to protons p in the primary cosmic radiation ($\sim 15\%$) and in the galactic gas ($\sim 10\%$) is small,[8] in the kinetic energy region below 1 BeV per nucleon the cross section for π^0-meson production by $p-\alpha$ collisions may be important relative to $p-p$ collisions. The threshold for $p-\alpha$ pion production ($\sim$172 MeV) is also lower than the $p-p$ threshold.

Unfortunately, there exist no experiments on the cross sections for pion production in $p-\alpha$ interactions, so we must calculate these cross sections from other data. A review article by Proshkin[27] on π^0-meson production in proton-nucleon collisions below 660 MeV provides the principal data.

Within experimental errors the ratio of (p,Li^6) to (p,D) production of π^0 mesons is the same as the ratio of the atomic numbers of Li^6 and D, viz. 3. Since $He^4(\alpha)$ has an atomic number intermediate to that of D and Li^6, and D, α, and Li^6 all have isotopic spin zero, a reasonable approximation is that the ratio of (p,α) to (p,D) cross sections for π^0-meson production is two.

To determine the charged π-meson production in $p-\alpha$ interactions we use the following relationships based on isotopic spin invariance[28,29]:

$$\sigma_{pN}{}^+ + \sigma_{pN}{}^- = 2\sigma_{pN}{}^0, \tag{25}$$

where $\sigma_{pN}{}^i$ is the cross section for proton-nucleon production of the ith-type meson; N is a nucleus of zero isotopic spin. For energies less than 1 BeV,

$$\sigma_{pn}{}^+ = \sigma_{pn}{}^-. \tag{26}$$

We also assume

$$\sigma_{p\alpha}{}^i = s[2\sigma_{pp}{}^i + 2\sigma_{pn}{}^i], \tag{27}$$

where s is a constant less than one, to account for shadowing effects and other channels of interaction. Combining Eqs. (25), (26), and (27), and the result that $\sigma_{pp}{}^-$ below 1 BeV is zero (Table II), we have

$$\sigma_{p\alpha}{}^+ = \sigma_{p\alpha}{}^0 + s\sigma_{pp}{}^+, \tag{28}$$

$$\sigma_{p\alpha}{}^- = \sigma_{p\alpha}{}^0 - s\sigma_{pp}{}^+, \tag{29}$$

$$\sigma_{p\alpha}{}^t = 3\sigma_{p\alpha}{}^0 = 2s[\sigma_{pp}{}^t + \sigma_{pn}{}^t], \tag{30}$$

where σ^t is the total cross section for pion production.

From these formulas the cross section for π^0-meson production from 660 MeV to 1 BeV and the cross sections for charged meson production to 1 BeV were determined. The cross section $\sigma_{p\alpha}{}^-$, obtained by subtraction of two large quantities with large errors, is only a very approximate value. These cross sections appear in Table V.

For energies greater than 1 BeV, no direct experimental information exists for meson production in (p,α) reactions. Therefore, Eq. (30) is used to calculate the cross section. In the energy region 1 to 10 BeV, $\sigma_{pp}{}^t - \sigma_{pn}{}^t$ varies from 6 mb to approximately zero.[30] Therefore, in the energy region greater than 1 BeV we assume that

$$\sigma_{pp}{}^t \approx \sigma_{pn}{}^t, \tag{31}$$

$$s = 0.5, \tag{32}$$

and, therefore,

$$\sigma_{p\alpha}{}^t \approx 2\sigma_{pp}{}^t. \tag{33}$$

Above an energy of 1 BeV per nucleon, $p-\alpha$ and $\alpha-p$ meson production in the galaxy is about 50% of the meson production due to $p-p$ collisions.

[27] Iu. D. Prokoshkin and A. A. Tiapkin, Zh. Eksperim. i Teor. Fiz. **33**, 313 (1958) [translation: Soviet Phys.—JETP **6**, 245 (1958)].

[28] A. G. Meshiovskii, Ia. Ia. Shalamov, and V. A. Shebanov, Zh. Eksperim. i Teor. Fiz. **33**, 602 (1958) [translation: Soviet Phys.—JETP **6**, 463 (1958)].

[29] A. H. Rosenfeld, Phys. Rev. **96**, 146 (1954).

[30] A. N. Diddens, H. Lillenthun, G. Manning, A. E. Taylor, T. G. Walker, and A. M. Wetherell, Phys. Rev. Letters **9**, 32 (1962).

We neglect the contribution of meson production due to $\alpha-\alpha$ collisions.

VII. EVALUATION OF THE GAMMA-RAY INTENSITIES

We now evaluate Eq. (1). Since the cosmic-ray intensity $I_j(T,\mathbf{r})$ was assumed uniform throughout the galaxy and $n_\alpha(\mathbf{r})=0.1n_p(\mathbf{r})$, we have

$$G^i=\sum_k q_k{}^i \int_{\text{source in cone of view}} r^{-2}n_k(\mathbf{r})d\mathbf{r} \quad \text{photons cm}^{-2}\text{ sec}^{-1}, \tag{34}$$

$$=\sum_k q_k{}^i S_k,$$

$$=(q_p{}^i+0.1q_\alpha{}^i)S_p,$$

where

$$S_k=\int_{\text{cone of view}} r^{-2}n_k(\mathbf{r})d\mathbf{r}.$$

The calculation of G^i therefore consists of the calculation of two separate integrals:

(1) Evaluation of q_k is

$$q_k{}^i=\sum_j q_{jk}{}^i=\sum_j \int_{T_0}^{\infty} I_j(T)\sigma_{jk}{}^i(T)m_{jk}{}^i(T)dT. \tag{35}$$

We can calculate the value of this integral numerically:

$$\int g(\epsilon)d\epsilon=\sum_k \langle g(\epsilon)\rangle_{\text{av}}\Delta\epsilon_k, \tag{36}$$

where $\langle g(\epsilon_k)\rangle_{\text{av}}$ is the average value of g in the interval between ϵ_k and ϵ_{k+1}, and $\Delta\epsilon_k=\epsilon_{k+1}-\epsilon_k$. For T greater than 10 BeV, the integral can be computed exactly.

Using the values found in Tables II–V, we obtain the following results:

$$q_{pp}{}^0=6.3\times10^{-27}\text{ photons sec}^{-1}\text{ sr}^{-1}, \tag{37}$$

$$q_{pp}{}^+=12.7\times10^{-27}\text{ photons sec}^{-1}\text{ sr}^{-1}, \tag{38}$$

$$q_{\alpha p}{}^0+0.1q_{p\alpha}{}^0=3.4\times10^{-27}\text{ photons sec}^{-1}\text{ sr}^{-1}, \tag{39}$$

$$q_{\alpha p}{}^++0.1q_{p\alpha}{}^+=6.0\times10^{-27}\text{ photons sec}^{-1}\text{ sr}^{-1}. \tag{40}$$

For gamma-ray production by π^0 mesons,

$$q_p{}^0+0.1q_\alpha{}^0=(q_{pp}{}^0+q_{\alpha p}{}^0)+0.1q_{p\alpha}{}^0=9.7\times10^{-27}\text{ photons sec}^{-1}\text{ sr}^{-1}. \tag{41}$$

For annihilation gamma rays produced via π^+ meson decay,

$$q_p{}^++0.1q_\alpha{}^+=(q_{pp}{}^++q_{\alpha p}{}^+)+0.1q_{p\alpha}{}^+=18.7\times10^{-27}\text{ photons sec}^{-1}\text{ sr}^{-1}. \tag{42}$$

(2) Evaluation of the integral is

$$S_p=\int_{\text{cone of view}} r^{-2}n_p(\mathbf{r})d\mathbf{r}\text{ cm}^{-2}\text{ sr}. \tag{43}$$

With the axis of the detector parallel to the galactic plane, we have

$$S_{p\parallel}=S_{p\parallel}{}^h+S_{p\parallel}{}^d, \tag{44}$$

where $S_{p\parallel}{}^h$ and $S_{p\parallel}{}^d$ are the contributions from the halo and disk, respectively; and

$$S_{p\parallel}{}^h=2\pi(1-\cos\theta)n_{ph}R_h, \tag{45}$$

where R_h is the distance along the detector axis from the detector to the point of penetration of the halo sphere, θ is the half-angle of the acceptance cone of the detector, and n_{ph} is the proton density in the halo.

The contribution from the disk is divided into sections and summed, on the assumption that θ is greater than the angle subtended by the disk,

$$S_{p\parallel}{}^{d_1}=2\pi(1-\cos\theta)n_{p1}r_1,\quad 0<r_1<h/\sin\theta; \tag{46}$$

$$S_{p\parallel}{}^{d_2}=2n_{p2}h\tan\theta\left\{\ln\left[\frac{1+[1+(r_1/r_2)^2]^{1/2}}{r_1/r_2}\right]-[1-(r_1/r_2)^2]^{1/2}+\frac{\sin^{-1}(r_1/r_2)}{(r_1/r_2)}-\frac{\pi}{2}\ln\left[\frac{1-[1-(r_1/r_2)^2]^{1/2}}{r_1/r_2}\right]\right\},$$
$$r_2<r<r_1,\quad \theta\leq30°; \tag{47}$$

$$S_{p\parallel}{}^{d_2}=4\theta hn_{p2}\left\{\frac{r_2}{h}\cot^{-1}\left(\frac{r_2}{h}\right)+\frac{1}{2}\ln\left[1+\left(\frac{r_2}{h}\right)^2\right]-\frac{r_1}{h}\cot^{-1}\left(\frac{r_1}{h}\right)-\frac{1}{2}\ln\left[1+\left(\frac{r_1}{h}\right)^2\right]\right\},$$
$$r_2<r<r_1,\quad \theta\geq30°; \tag{48}$$

$$S_{p\parallel}{}^{d_3}=4\theta h\sum_i n_{pi}\ln\left(\frac{r_{i+1}}{r_i}\right),\quad r_{i+1}>r>r_i,\quad r_i\gg h. \tag{49}$$

Perpendicular to the galactic plane we have

$$S_{p\perp}=S_{p\perp}{}^h+S_{p\perp}{}^d, \tag{50}$$

$$S_{p\perp}{}^h=2\pi(1-\cos\theta)n_{ph}R_n, \tag{51}$$

where $R_h=(r_h{}^2-R_0{}^2)^{1/2}$; r_h is the radius of the halo; and R_0 is the distance from the earth to the galactic center.

$$S_{p\perp}{}^d=2\pi(1-\cos\theta)n_{p1}h. \tag{52}$$

We assume that the sun lies in the galactic plane; in actuality, however, the sun is a height of 13.5 ± 1.9 pc north of the galactic plane.[31] The result of this is that the net difference in $S_{p1}{}^{d}$ calculated for northerly and southerly directions is $\sim 17\%$.

Tables VI and VII show the results of the evaluation of the integral S_p for proton densities of 10^{-2} cm^{-3} and 10^{-3} cm^{-3} in the halo.

TABLE VI. Value of integral (S_p) for $n_{\text{halo}}=10^{-2}$ protons cm^{-3}.

Cone half-angle	Galactic center	S_p (cm^{-2} sr) galactic anticenter	Normal to galactic plane
5°	6.0×10^{20}	3.0×10^{20}	0.18×10^{20}
10°	14.6×10^{20}	7.9×10^{20}	0.73×10^{10}
15°	24.0×10^{20}	12.8×10^{20}	$1.6\ \times10^{20}$
20°	34.8×10^{20}	18.6×10^{20}	$2.9\ \times10^{20}$
30°	59.5×10^{20}	31.8×10^{20}	$6.5\ \times10^{20}$

TABLE VII. Value of integral (S_p) for $n_{\text{halo}}=10^{-3}$ protons cm^{-3}.

Cone half-angle	Galactic center	S_p (cm^{-2} sr) galactic anticenter	Normal to galactic plane
5°	5.9×10^{20}	3.0×10^{20}	0.11×10^{20}
10°	14.0×10^{20}	7.8×10^{20}	0.45×10^{20}
15°	22.7×10^{20}	12.5×10^{20}	$1.0\ \times10^{20}$
20°	32.5×10^{20}	18.0×10^{20}	$1.8\ \times10^{20}$
30°	54.4×10^{20}	30.5×10^{20}	$4.0\ \times10^{20}$

VIII. RESULTS

The gamma-ray intensity incident on the earth due to cosmic-ray interactions in the galaxy is given in Tables VIII and IX; $G(\pi^0)$ is the high-energy gamma-ray flux due to the decay of π^0 mesons, and consists primarily of photons with energy greater than 50 MeV; $G(e^+)$ is the flux at 0.51 MeV gamma-ray energy due to positron annihilation.

The following important results should be noted:

(1) The predicted high-energy gamma-ray flux from the direction of the galactic center is $\sim10^{-4}$ photons cm^{-2} sec^{-1} sr^{-1}. The gamma-ray flux at 0.5 MeV is about twice the intensity of the high-energy flux.

(2) The gamma-ray flux essentially measures the product of the cosmic-ray intensity and the galactic gas density. If a knowledge of the gas density is assumed, the cosmic-ray intensity and distribution in the galaxy can be determined. Similarly, if the cosmic-ray intensity is assumed to be uniform throughout the galaxy and to have an intensity equal to that in the vicinity of the earth, the gamma-ray flux can be used to determine the galactic gas density.

(3) The ratio of the intensity of the high-energy gamma-ray flux to the 0.51-MeV gamma-ray flux is a measure of the cosmic-ray intensity 10^9 yr ago, if the primary source of gamma rays is assumed to have been cosmic-ray interactions.

(4) The directional asymmetry in the gamma-ray flux is greatest between the galactic center and perpendicular to the galactic plane. The value of the ratio of the fluxes in these directions is a function of the angle of the sensitive cone of the detector (Tables VIII and IX). A smaller cone angle shows the greater asymmetry, but provides less sensitivity. Future gamma-ray detectors should have large sensitive areas and the ability to determine arrival directions to within a few degrees.

TABLE VIII. Gamma-ray intensity for $n_{\text{halo}}=10^{-2}$ protons cm^{-3}.

Detector cone half-angle	Solid angle (sr)	G (10^{-5} photons cm^{-2} sec^{-1}) Galactic center (A) $G(\pi^0)$	Galactic center (A) $G(e^+)$	Galactic anticenter (B) $G(\pi^0)$	Galactic anticenter (B) $G(e^+)$	Normal to galactic plane (C) $G(\pi^0)$	Normal to galactic plane (C) $G(e^+)$	$(A)/(C)$
5°	0.024	0.58	1.1	0.29	0.56	0.017	0.033	30
10°	0.095	1.4	2.7	0.77	1.5	0.071	0.14	20
15°	0.21	2.3	4.4	1.2	2.3	0.16	0.31	14
20°	0.38	3.4	6.6	1.8	3.5	0.28	0.54	12
30°	0.84	5.8	11	3.1	6.0	0.63	1.2	9

TABLE IX. Gamma-ray intensity for $n_{\text{halo}}=10^{-3}$ protons cm^{-3}.

Detector cone half-angle	Solid angle (sr)	G (10^{-5} photons cm^{-2} sec^{-1}) Galactic center (A) $G(\pi^0)$	Galactic center (A) $G(e^+)$	Galactic anticenter (B) $G(\pi^0)$	Galactic anticenter (B) $G(e^+)$	Normal to galactic plane (C) $G(\pi^0)$	Normal to galactic plane (C) $G(e^+)$	$(A)/(C)$
5°	0.024	0.57	1.1	0.29	0.56	0.011	0.041	52
10°	0.095	1.4	2.7	0.76	1.5	0.044	0.085	32
15°	0.21	2.2	4.2	1.2	2.3	0.10	0.19	22
20°	0.38	3.2	6.2	1.7	3.3	0.17	0.33	19
30°	0.84	5.3	10	3.0	5.8	0.39	0.75	14

[31] R. J. Trumpler and H. F. Weaver, *Statistical Astronomy* (University of California Press, Berkeley, California, 1953), p. 425.

(5) The ratio of the gamma-ray flux from the direction of the galactic center to the flux from the anticenter is about 2 and is independent of the sensitive angle of the detector ($\theta \geq 5°$).

In this paper only our galaxy was considered as the source of gamma radiation. It is entirely possible that gamma-ray sources outside our galaxy exist that contribute a comparable, if not larger, background flux.[32]

APPENDIX: POSITRON ANNIHILATION RATE

Most of the positrons produced by cosmic-ray collisions with the galactic gas are the result of proton-proton interactions, where the incoming proton has kinetic energy in the 1 to 10 BeV interval. The resulting mean total energy is 250 MeV for positrons emitted forward in the center-of-mass system, and 75 MeV for positrons emitted in the backward direction. Equal numbers of positrons are emitted in each hemisphere in the center-of-mass system. Positrons in this energy interval are assumed to be distributed by diffusion uniformly throughout the galactic disk and halo. The primary methods of energy loss by these positrons are[2]

(1) magnetic bremsstrahlung,

$$dE/dt = -4\times10^{-15}E^2B_\perp{}^2 = -bE^2 \text{ eV/sec}; \quad \text{(A1)}$$

(2) ionization of atomic hydrogen,

$$dE/dt = -7.62\times10^{-9}n[20.1+3\ln(E/mc^2)] \approx -a \text{ eV/sec}; \quad \text{(A2)}$$

where E is the total energy of the positron; $B_\perp$ is the component of the magnetic field (G) perpendicular to the direction of motion; n is the atomic hydrogen density (cm^{-3}); mc^2 is the rest energy of the positron (0.511 MeV), and a and b are constants.

The total rate of energy loss is

$$dE/dt = -a - bE^2 \text{ eV/sec}, \quad \text{(A3)}$$

where

$$a = 4\times10^{-9},$$
$$b = 4\times10^{-26},$$
$$B_\perp{}^2 = 10^{-11} \text{ (G)}^2,$$
$$n = 10^{-2} \text{ cm}^{-3},$$

since the positron is primarily in the galactic halo region. Solving the above equation for t, we have[2]

$$t = \frac{\tan^{-1}[(b/a)^{1/2}E_0] - \tan^{-1}[(b/a)^{1/2}E]}{(ab)^{1/2}}, \quad \text{(A4)}$$

where $E = E_0$ at $t = 0$.

The positron annihilation cross section[33] has its maximum at $E \approx mc^2$ and is given by

$$\sigma = \pi r_0{}^2 = 0.25\times10^{-24} \text{ cm}^2, \quad \text{(A5)}$$

where r_0 is the electron radius. For $E \gg mc^2$, the annihilation cross section is small and is given by

$$\sigma = \pi r_0{}^2(mc^2/E)(\ln 2E/mc^2 - 1). \quad \text{(A6)}$$

Therefore, positrons lose almost all their energy by magnetic bremsstrahlung (synchroton radiation) and ionization and then annihilate with electrons. The annihilation time for a positron with $E \approx 0.5$ MeV is given by

$$t_a = 1/n_e \pi r_0{}^2 c, \quad \text{(A7)}$$

where n_e is the electron density. Most positrons annihilate in the galactic disk where $n_e \approx 1 \text{ cm}^{-3}$.

For $E_0 = 250$ MeV and $E = 0.5$ MeV, the time for the positron to lose its energy by synchrotron radiation and ionization is given by Eq. (A4):

$$t = 1.7\times10^9 \text{ yr};$$

and for $E_0 = 75$ MeV and $E = 0.5$ MeV,

$$t = 0.6\times10^9 \text{ yr}.$$

The annihilation time is

$$t_a = 4\times10^6 \text{ yr}.$$

The 0.5-MeV gamma-ray flux at the present time was thus the result of cosmic-ray interactions 10^9 yr ago.

Since the high-energy galactic gamma-ray flux ($E_\gamma > 50$ MeV) is a measure of the present galactic cosmic-ray intensity, the ratio of the high-energy to the 0.5-MeV gamma-ray flux is a measure of the cosmic-ray intensity 10^9 yr ago.

These calculations are based on the assumption that the primary source of gamma radiation is cosmic-ray interactions in our galaxy.

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[32] J. E. Felton and P. Morrison, Phys. Rev. Letters **10**, 453 (1963).

[33] W. Heitler, *The Quantum Theory of Radiation* (Clarendon Press, Oxford, England, 1936), p. 207.