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THE PRODUCTION OF COSMIC GAMMA RAYS IN COSMIC-RAY COLLISIONS - IV

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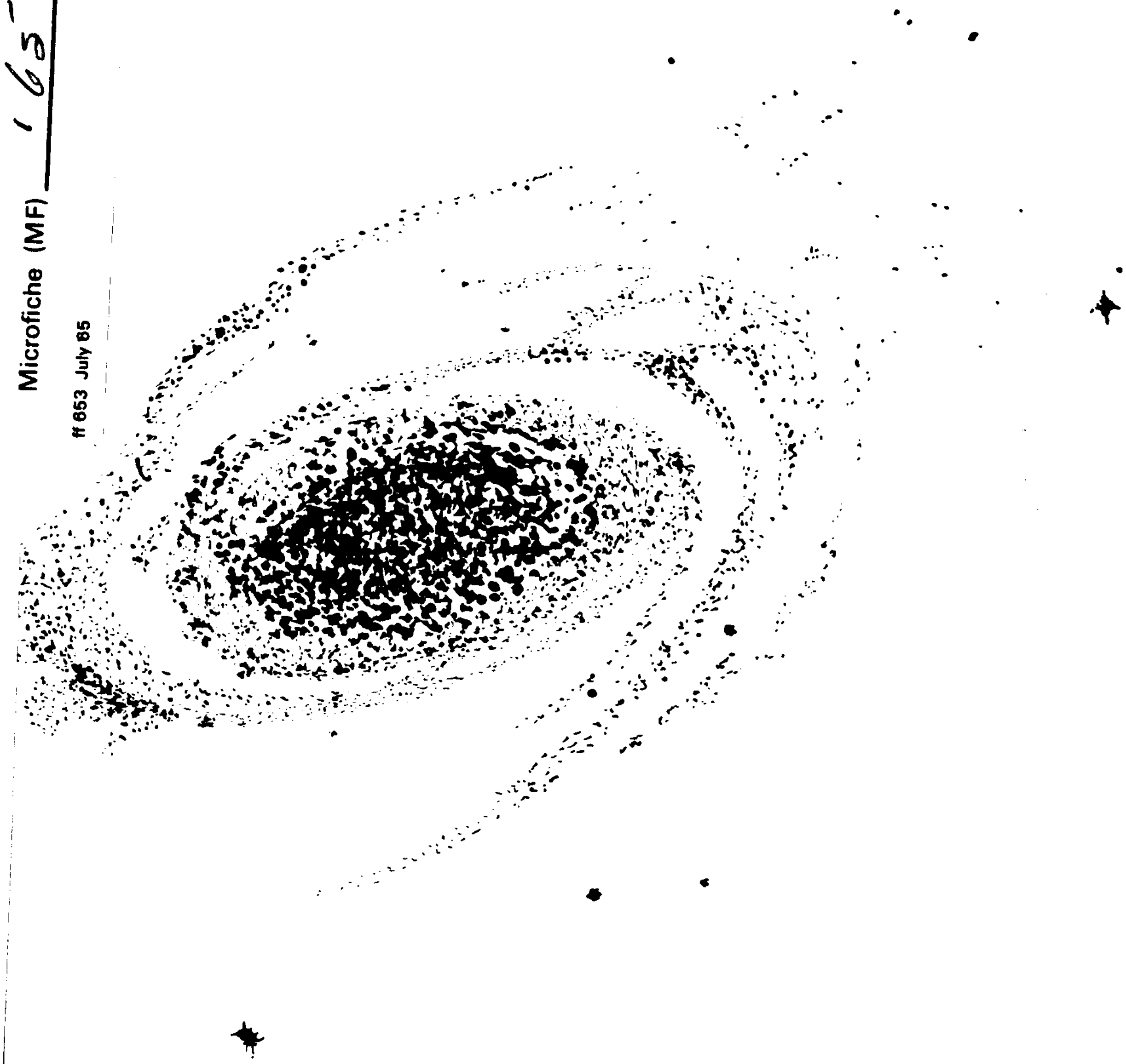

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THE PRODUCTION OF COSMIC GAMMA RAYS IN INTERSTELLAR AND INTERGALACTIC COSMIC-RAY COLLISIONS

IV: GAMMA-RAY PRODUCTION FROM COSMIC PROTON-ANTIPROTON INTERACTIONS

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ABSTRACT

Various cosmological situations are discussed in which the annihilation of antimatter will produce cosmic gamma rays. An upper limit is placed on the amount of cosmic matter-antimatter interaction consistent with recent cosmic gamma-ray observations. It is shown that the production of mesons other than pions have little effect on the annihilation gamma-ray spectrum. It is also shown that gamma rays arising from annihilations at rest have energies between 5 and 865 MeV. The gamma-ray spectrum from annihilations at rest is calculated and compared with the calculations of Frye and Smith.

A discussion is then presented of the various characteristics of proton-antiproton interactions in flight. Production of various mesons, hyperons, and isobars is discussed and cross sections are given. General implications of the data on the resultant gamma-ray spectra are stated.

RÉSUMÉ

Diverses situations cosmologiques sont envisagées, susceptibles de produire des rayons gamma cosmiques par annihilation d'anti-matière. En accord avec de récentes observations du rayonnement gamma cosmique, on place une limite supérieure à la quantité d'interaction possible entre matière et anti-matière dans le cosmos. On montre que la production de mésons autres que les pions n'a que peu d'effet sur le spectre du rayonnement gamma d'annihilation. On montre également que les rayons gamma, produits par annihilation de matière au repos ont des énergies comprises entre 5 et 865 MeV. Le spectre du rayonnement gamma d'annihilation au repos est calculé et comparé avec les calculs de Frye et Smith.

On présente ensuite une discussion des diverses caractéristiques des interactions en vol entre protons et anti-protons. On discute la production de divers mésons, hypérons et isobares et les sections efficaces correspondantes sont données. Les implications générales des données sur les spectres des rayonnements gamma résultants sont indiquées.

КОНСПЕКТ

Обсуждаются различные космологические обстоятельства при которых аннигиляция противо-материи будет производить космические гамма лучи. Накладывается верхний предел на количество взаимодействий между материей и противо-материей в согласовании с недавними наблюдениями космических гамма лучей. Указывается на то что производство мезонов иных чем пионов слабо влияет на аннигиляцию спектра гамма лучей.Указывается также что гамма лучи возникают из аннигиляций в спокойном состоянии имеют энергии между 5 и 865 MeV. Высчитан спектр гамма лучей из аннигиляций в спокойном состоянии и согласовался с исчислениями Фрей и Шмита.

Приводится дальше обсуждение различных характеристик взаимодействий между протонами и антипротонами в полете. Обсуждается производство различных мезонов, гиперонов и изобаров и приводятся поперечные сечения. Выведена причастность данных на проистекающий спектр гамма лучей.

THE PRODUCTION OF COSMIC GAMMA RAYS IN INTERSTELLAR AND INTERGALACTIC COSMIC-RAY COLLISIONS

IV: GAMMA-RAY PRODUCTION FROM COSMIC PROTON-ANTIPROTON INTERACTIONS

F. W. Stecker

1. INTRODUCTION

A topic of importance to both cosmology and particle physics is the existence or nonexistence of antimatter in the universe (Alfvén, 1965). It is therefore of interest to determine the extent to which gamma-ray astronomy may be useful in determining the existence of 1) cosmologically distributed antimatter and 2) antimatter sources in which matter-antimatter interactions take place.

For the purpose of discussion we define the terms "R. G." and "C. R." as follows. An R. G. (rest-gas) proton (or antiproton) is one possessing negligible kinetic energy with respect to the surrounding gas in an astronomical system. For example, nuclei of the interstellar gas clouds in the galaxy from which stars are formed may be considered R. G. nuclei. A C. R. (cosmic-ray) proton (or antiproton) would be one possessing relativistic energy. We may thus envision four situations for discussion in which matter and antimatter might interact:

A. R. G. matter + R. G. antimatter (R. G. -$\overline{\text{R. G.}}$)
B. R. G. matter + C. R. antimatter (R. G. -$\overline{\text{C. R.}}$)
C. C. R. matter + R. G. antimatter (C. R. -$\overline{\text{R. G.}}$)
D. C. R. matter + C. R. antimatter (C. R. -$\overline{\text{C. R.}}$)

Although astrophysics has revealed many surprising phenomena, we would be hard put to imagine a system in which the number of R. G. nuclei did not greatly outnumber the number of C. R. nuclei. Indeed, the evolution of such a system from a more balanced one would violate the second law of thermodynamics. Therefore, if we let the number of R. G. nuclei in a typical system be N and the number of C. R. nuclei in the system be of the order ϵN, with $\epsilon \ll 1$, then typical interaction rates would have the properties

$$\frac{R(\text{R. G. -}\overline{\text{C. R.}})}{R(\text{R. G. -}\overline{\text{R. G.}})} \sim \frac{R(\text{C. R. -}\overline{\text{R. G.}})}{R(\text{R. G. -}\overline{\text{R. G.}})} \sim \epsilon \quad , \tag{1}$$

$$\frac{R(\text{C. R. -}\overline{\text{C. R.}})}{R(\text{C. R. -}\overline{\text{R. G.}})} \sim \frac{R(\text{C. R. -}\overline{\text{C. R.}})}{R(\text{R. G. -}\overline{\text{C. R.}})} \sim \epsilon \quad , \tag{2}$$

and

$$\frac{R(\text{C. R. -}\overline{\text{C. R.}})}{R(\text{R. G. -}\overline{\text{R. G.}})} \sim \epsilon^2 \quad . \tag{3}$$

We will thus assume that the likelihood of C. R. -$\overline{\text{C. R.}}$ interactions is negligible compared to the likelihood of R. G. -$\overline{\text{C. R.}}$ or C. R. -$\overline{\text{R. G.}}$ interactions that will produce gamma rays of similar characteristics, and we may limit ourselves to the discussion of R. G.-$\overline{\text{R. G.}}$ and R. G. -$\overline{\text{C. R.}}$ (or C. R. -$\overline{\text{R. G.}}$) interactions.

2. THE GAMMA-RAY SOURCE SPECTRUM

The gamma-ray source spectrum from p-p interactions of the R. G. -$\overline{\text{C. R.}}$ type is given by

$$I_{\text{R. G.}-\overline{\text{C. R.}}}(E_\gamma) = \int dr\, n_p(\vec{r}) \int dE_{\bar{p}}\, I(E_{\bar{p}}, \vec{r}) \sum_s \int dE_s\, \sigma_s(E_s;E_{\bar{p}})$$
$$\times \sum_d \zeta_{\gamma d}\, R_{\gamma d}\, f_{ds}(E_\gamma;E_s) \quad . \tag{4}$$

For interactions of the C. R. -$\overline{\text{R. G.}}$ type, we use the corresponding expression

$$I_{\text{C.R.}-\overline{\text{R.G.}}}(E_\gamma) = \int dr\, n_{\bar{p}}(\vec{r}) \int dE_p I(E_p, \vec{r}) \sum_s \int dE_s\, \sigma_s(E_s;E_p)$$
$$\times \sum_d \zeta_{\gamma d}\, R_{\gamma d}\, f_{ds}(E_\gamma;E_s) \quad . \tag{5}$$

The notation for equations (4) and (5) is as follows: The quantity $n(\vec{r})$ is the number of target nucleons in the medium in cm^{-3} as a function of position; $I(E,\vec{r})$ is the differential cosmic-ray particle flux in $\text{cm}^{-2}\ \text{sec}^{-1}\ \text{sr}^{-1}\ \text{GeV}^{-1}$. The subscript p stands for proton, $\bar{p}$ for antiproton, s for secondary particle produced in the collision, and d for decay mode. The production function $\sigma_s(E_s;E_p)$ represents the cross section for production of secondary particles of type s and energy E_s in a collision of primary energy E_p, $\zeta_{\gamma d}$ represents the number of gamma rays produced in the decay mode d, $R_{\gamma d}$ is the branching ratio for the decay mode d (the probability that a secondary particle s will decay via mode d) and $f_{ds}(E_\gamma;E_s)$ is the normalized distribution function representing the probability that a secondary particle with energy E_s will decay to produce a gamma ray of energy E_γ.

The gamma-ray source spectrum from p-$\bar{p}$ interactions at or near rest is given by

$$I_{R.G.-\overline{R.G.}}(E_\gamma) = \int dr\; n_p(\vec{r})\, n_{\bar{p}}(\vec{r}) \int dv\; f(v)\; v \sum_s \int dE_s\; \sigma_s(E_s;v)$$

$$\times \sum_d \zeta_{\gamma d} R_{\gamma d} f_{ds}(E_\gamma;E_s) \quad , \tag{6}$$

where v is the relative velocity between the proton and antiproton, f(v) is a normalized distribution function expressing the distribution of relative velocities between the interacting nucleons of matter and antimatter.

The form of equation (6) suggests that the introduction of the term "emission measure" be defined in analogy with its use in astrophysics (Shklovsky, 1960).

We therefore define the emission measure B as

$$B = \int dr\; n_p(\vec{r})\; n_{\bar{p}}(\vec{r}) \quad . \tag{7}$$

Therefore, it follows from equation (6) that

$$I_{R.G.-\overline{R.G.}}(E_\gamma) \propto B \quad . \tag{8}$$

3. PROTON-ANTIPROTON ANNIHILATIONS AT REST

We now state more precisely what we mean by a "rest gas." We define a rest gas to be a gas of particles such that no particle in the gas has an energy greater than 286 MeV. This rather liberal definition of rest is sufficient to ensure that the only secondary particles produced in R. G. -$\overline{\text{R. G.}}$ interactions that yield gamma rays are secondary mesons produced by nucleon-antinucleon annihilation. Our restriction leaves out interactions of the type

$$p + \bar{p} \rightarrow p + \bar{p} + \pi^0 \quad , \tag{9}$$

since the threshold for reactions of this type is 286 MeV (see Part I*).

Since the threshold for nonannihilation inelastic p-$\bar{p}$ interactions which produce other particles is even greater, it follows that in the R. G. -$\overline{\text{R. G.}}$ case, only annihilations, i.e., reactions of the form

$$\begin{array}{l} p + \bar{p} \rightarrow \text{bosons} \\ \qquad\qquad \hookrightarrow \text{neutral pions} \\ \qquad\qquad\qquad\qquad \hookrightarrow \text{gamma rays} \end{array} \tag{10}$$

need be considered.

Table 1 lists the experimental cross sections for proton-antiproton annihilation as a function of incident antiproton kinetic energy. Also listed is β_{cms} and the product of the annihilation cross section (σ_A) and c. m. s. (center-of-momentum system) velocity (β_{cms}). It can be seen from Table 1 that the product of c. m. s. velocity and annihilation cross section is constant over a very large energy range. For nonrelativistic energies

$$\beta_{cms} \simeq \frac{1}{2} \beta \quad , \tag{11}$$

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*See Stecker, 1966 in reference list.

β being the relative velocity of the particles, so that we find experimentally

$$\sigma_A \simeq \frac{4.8 \times 10^{-26}\ \mathrm{cm}^2}{\beta} \simeq \frac{1.4 \times 10^{-15}\ \mathrm{cm}^3\ \mathrm{sec}^{-1}}{v}, \tag{12}$$

which agrees with the theoretical cross section

$$\sigma_A = \frac{\pi r_p^2}{\beta_{cms}}, \tag{13}$$

taking

$$r_p = 0.87 \times 10^{-13}\ \mathrm{cm} \tag{14}$$

as the proton (or antiproton) radius and using the model of Koba and Takeda (1958) in which the nucleon acts as a black absorbing sphere of radius r_p.

Table 1. Experimental cross sections for proton-antiproton annihilation as a function of incident antiproton kinetic energy

$T_{\bar{p}}$(MeV)	σ_A(mb)	$\beta_{\bar{p}}$(c.m.s.)	$\beta_{\bar{p}}\sigma_A$(mb)	Reference
25-40	192 ± 34	0.13	25	Loken and Derrick (1963)
45	175 ± 45	0.15	26	Cork, Dahl, Miller, Tenner, and Wang (1962)
40-55	155 ± 27	0.16	25	Loken and Derrick (1963)
55-80	118 ± 26	0.20	24	Loken and Derrick (1963)
90	101 ± 9	0.22	22	Cork <u>et al.</u> (1962)
145	99 ± 8	0.28	28	Cork <u>et al.</u> (1962)
245	66 ± 6	0.36	24	Cork <u>et al.</u> (1962)
7000	23.6 ± 3.4	~1	24	Ferbel, Firestone, Johnson, Sandweiss, and Taft (1965)

We have thus shown that for annihilation interactions involving kinetic energies less than 286 MeV, we may write

$$\sigma_{A,s}(E_s;v) = C_s\, f(E_s)\, v^{-1} \quad , \tag{15}$$

where C_s is a constant, and $f(E_s)$ is a normalized energy distribution function, so that from (6) and (15) we obtain

$$\begin{aligned} I_{R.G.-\overline{R.G.}}(E_\gamma) &= B\int dv\, f(v)\, v \sum_s \int dE_s\, \sigma_s(E_s;v) \sum_d \zeta_{\gamma d} R_{\gamma d} f_{ds}(E_\gamma;E_s) \\ &= B\int dv\, f(v)\, v\cdot v^{-1} \sum_s \int C_s\, dE_s f(E_s) \sum_d \zeta_{\gamma d} R_{\gamma d} f_{ds}(E_\gamma;E_s) \\ &= B\left[\sum_s C_s \int dE_s\, f(E_s) \sum_d \zeta_{\gamma d} R_{\gamma d} f_{ds}(E_\gamma;E_s)\right] \quad , \end{aligned} \tag{16}$$

where the reduction

$$\int dv\, f(v)\, v\cdot v^{-1} = \int dv\, f(v) = 1 \tag{17}$$

follows from the normalized definition of $f(v)$.

As a simplified numerical example of equation (16) let us roughly calculate the gamma-ray spectrum from secondary neutral pions produced by annihilation. Let us assume on the average three gamma rays are produced per annihilation from π^0 decay. From equation (12), we then find

$$C_{\pi^0} \simeq 4.2 \times 10^{-15}\ \mathrm{cm}^3\, \mathrm{sec}^{-1}\, \mathrm{sr}^{-1} \quad . \tag{18}$$

If metagalactic space were then made up of equal numbers of nucleons and antinucleons with a density of 10^{-5} cm^{-3} out to a radius of 10^{28} cm (typical) cosmological parameters), then we would obtain

$$B = 10^{18}\ \text{cm}^{-5}\ , \tag{19}$$

or an expected gamma-ray flux from p-$\overline{\text{p}}$ annihilation ($I_{\text{ann.}}$) on the order of

$$I_{\text{ann.}} = BC \simeq 4,000\ \text{photons}\ (\text{cm}^2\ \text{sec sr})^{-1}\ . \tag{20}$$

However, recent experiments place upper limits on the cosmic gamma-ray spectrum in the 100-MeV region at about 10^{-4} photons $\text{cm}^{-2}\ \text{sec}^{-1}\ \text{sr}^{-1}$, or about 7 orders of magnitude below this value, thus placing severe restrictions on cosmological speculations about the amount of antimatter interacting with matter in the universe.

Conversely, the experimental upper limit on $I(E_\gamma)$ places an upper limit of

$$B \le 2 \times 10^{10} \tag{21}$$

on the "emission measure" of matter-antimatter interaction in the universe.

Any matter-antimatter cosmology, such as the model of Alfvén (1965) and Alfvén and Klein (1963), must take into account the experimental upper limit on the gamma-ray flux.

4. SELECTION RULES

If we assume that the large majority of gamma rays from R. G. -$\overline{\text{R. G.}}$ interactions arise through π^0 decay, equation (16) reduces to

$$I_{\text{R. G.}-\overline{\text{R. G.}}}(E_\gamma) = BC_{\pi^0} \int_{E_\gamma + \frac{m_\pi^2}{4E_\gamma}}^{\infty} dE_\pi \frac{f_A(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} \quad . \tag{22}$$

The process

$$p + \overline{p} \rightarrow \pi^0 \tag{23}$$

is, of course, forbidden by conservation of momentum. The process

$$p + \overline{p} \rightarrow \pi^0 + \pi^0 \tag{24}$$

is also forbidden when it is noted that proton-antiproton annihilations at rest occur predominantly from the S states of the proton-antiproton system.

The selection rule that forbids reaction (24) follows from conservation of G conjugation parity.

The process of G conjugation is an extension of charge (C) conjugation, which holds for charged, as well as neutral particles. It is defined as

$$G = C\, e^{i\pi T_2} \quad , \tag{25}$$

where C is the charge-conjugation operator and T_2 is the second component of the isospin vector. From (25) we can show the commutation relation

$$[\vec{T}, G] = 0 \quad . \tag{26}$$

Thus, we may describe particle states as simultaneous eigenstates of both G and T.

We can show (Sakurai, 1964) that systems having baryon number 0 are in an eigenstate of G. The proton-antiproton system is just such a system. For this system

$$G = (-1)^{L+S+T} \quad , \tag{27}$$

where L, S, and T are the orbital, spin, and isospin quantum numbers of the state, respectively.

In a final state consisting of ζ_π pions, G is given by

$$G = (-1)^{\zeta_\pi} \quad . \tag{28}$$

The selection rules (28) and (29) indicate that for an S-state annihilation (L = 0), the final state consisting of two neutral pions is strictly forbidden (Lee and Yang, 1956).

Therefore, the extremum gamma-ray energies that we would expect from this decay would result from interaction of the type

$$p + \bar{p} \rightarrow \pi^+ + \pi^- + \pi^0 \quad , \tag{29}$$

resulting in pions with the given maximum energy

$$E_{\pi^0, \max} = M_p - \frac{1}{2} M_\pi \quad .$$

Thus, the annihilation gamma rays are limited to the energy region

$$\frac{1}{2}\left(E_{\pi^0,\max} - \sqrt{E^2_{\pi^0,\max} - m^2_\pi}\right) \leq E_\gamma \leq \frac{1}{2}\left(E_{\pi^0,\max} + \sqrt{E^2_{\pi^0,\max} - m^2_\pi}\right), \tag{30}$$

or 5 MeV $\leq E_\gamma \leq$ 865 MeV.

The process

$$p + \bar{p} \rightarrow \gamma + \gamma \tag{31}$$

may also occur, but this process, involving the electromagnetic emission (e. m.) of two photons, is of order

$$\sigma_{\text{e. m.}} = \alpha^2 \sigma_{\text{A, strong}} \simeq \frac{2.6 \times 10^{-30}\ \text{cm}^2}{\beta} \quad . \tag{32}$$

We can also examine the production and decay of various other mesons leading to gamma-ray production. (In annihilations at rest, we need not consider production and decay of baryon-antibaryon pairs having $M_B > M_p$, since their production is forbidden by conservation of energy.)

5. THE STATISTICAL MODEL OF MATSUDA

In considering the production of mesons other than pions, we refer to the simple statistical model of Matsuda (1966) and the data of the Columbia University group presented in the Matsuda reference.

The Matsuda model assumes that shortly after annihilation the total energy of the p-$\bar{p}$ system (equal to $2M_p$) is distributed in an interaction volume Ω and that the system reaches thermal equilibrium. Since in the annihilation the wave pockets of the two particles completely overlap in an S state, then for

$$\Omega \simeq \left(\frac{\hbar}{m_\pi} \right)^3 ,$$

$$\rho \simeq \frac{\langle \zeta \rangle_{expt}}{\Omega} ,$$

$$\sigma \simeq \left(\frac{\hbar}{m_\pi} \right)^2 , \tag{33}$$

we find that the mean free path of the meson produced, ℓ_{mfp}, is

$$\ell_{mfp} \simeq 10^{-1} \lambda_{st} \tag{34}$$

for an experimentally observed average number of mesons produced, where λ_{st} is the distance traveled by the meson during the strong interaction in time $t_{st} = \lambda_{st} c \simeq 10^{-23}$ sec. Thus, we find that there is enough time available for the created mesons to collide with each other and reach thermal equilibrium before they leave the interaction volume Ω. Matsuda then assumes that there exists a quantized energy level $\epsilon_\tau > 0$ for each type of meson ($\tau = \pi, \rho, \omega, \eta$, K, K^*, etc.) produced in the annihilation. The whole system reaches a thermal equilibrium given by the parameter $\Phi = 1/kT$ at temperature T, which is therefore the same for each nonstrange boson (type $\sigma = \pi, \rho, \omega, \eta$, etc.)

or strange meson pair (type $\nu = K\overline{K}$, $K^*\overline{K}^*$, etc.). We designate the statistical weights by

$$g_\tau = (2S_\tau + 1)(2T_\tau + 1) \quad , \tag{35}$$

T_τ being the isospin of particle τ. Since the created mesons are bosons, we therefore obtain

$$\langle \zeta_\tau \rangle = \frac{g_\tau}{e^{\Phi\epsilon_\tau} - 1} \quad . \tag{36}$$

Matsuda then introduces the chemical potential parameter ϵ_0 associated with the production of each particle and related to the observed average energy $\langle E_\tau \rangle$ of each particle through the relation

$$\epsilon_\tau = \langle E_\tau \rangle - \epsilon_0 \quad , \tag{37}$$

which must satisfy the condition

$$\epsilon_0 < \langle E_\tau \rangle \quad , \tag{38}$$

so that equation (36) for nonstrange mesons becomes

$$\langle \zeta_\sigma \rangle = \frac{g_\sigma}{e^{\Phi(\langle E_\sigma \rangle - \epsilon_0)} - 1} \quad . \tag{39}$$

For pairs of strange mesons, equation (36) becomes

$$\langle \zeta_\nu \rangle = \frac{g_\nu}{e^{\Phi(\langle E_\nu \rangle - 2\epsilon_0)} - 1} \quad , \tag{40}$$

since the formation of each meson involves energy ϵ_0.

The observed average energies of the various mesons produced in $p\bar{p}$ annihilations at rest are listed by Matsuda and given here in Table 2. It is then found that by specifying

$$\frac{1}{\Phi} = 150 \text{ MeV}$$

and

$$\epsilon_0 = 295 \text{ MeV} \quad , \tag{41}$$

excellent agreement with the experimental production rate is obtained as shown in Table 2. The total average number of produced particles calculated from equations (39) and (40) is

$$\langle \zeta_{tot} \rangle = \sum_\sigma \langle \zeta_\sigma \rangle + \sum_\nu 2 \langle \zeta_\nu \rangle = 4.37 \quad . \tag{42}$$

The value given by the experimental results is

$$\langle \zeta_{tot} \rangle_{expt} = 4.34 \quad , \tag{43}$$

also showing excellent agreement.

Both the experimental data and the simple statistical model of Matsuda indicate that in proton-antiproton annihilations at rest ρ-meson production is an order of magnitude less important than π-meson production and that production of other mesons is at least 2 orders of magnitude less frequent than π-meson production. Table 3 shows the decay schemes of these mesons that lead to final-state gamma rays and other relevant data. Table 4 shows some recent data on meson production indicating that about 20% of the gamma rays produced arise through nonpionic meson production. The largest non-pion contribution to the gamma-ray spectrum is due to the ρ-meson decay schemes

$$\begin{tikzcd} \rho^\pm \arrow[r] & \pi^\pm + \pi^0 \arrow[d, start anchor=south east] & \\ & & \gamma + \gamma \quad . \end{tikzcd} \tag{44}$$

The ρ meson is an isospin triplet (T = 1) constructed from two pions, each having T = 1. Evaluation of the Clebsch-Gordon coefficients for this construction yields

$$\begin{aligned} |\rho^+\rangle &= \frac{1}{\sqrt{2}}\Big(|\pi^+\rangle\,|\pi^0\rangle - |\pi^0\rangle\,|\pi^+\rangle\Big) \\ |\rho^0\rangle &= \frac{1}{\sqrt{2}}\Big(|\pi^+\rangle\,|\pi^-\rangle - |\pi^-\rangle\,|\pi^+\rangle\Big) \\ |\rho^-\rangle &= \frac{1}{\sqrt{2}}\Big(|\pi^0\rangle\,|\pi^-\rangle - |\pi^-\rangle\,|\pi^0\rangle\Big) \quad . \end{aligned} \tag{45}$$

Since the ρ^0 construction does not contain any $|\pi^0\rangle|\pi^0\rangle$ terms,

$$|\langle\pi^0\pi^0|\rho^0\rangle|^2 = 0 \quad , \tag{46}$$

and, therefore,

$$\rho^0 \not\to \pi^0 + \pi^0 \quad . \tag{47}$$

Table 2. Average energies and production rates for various particles produced in proton-antiproton annihilations at rest (from Matsuda, 1966)

τ Particle or pair	Average energy (MeV)	Calculated production rate	Experimental production rate
π	380	3.96	3.94 ± 0.33
ρ	850	2.3×10^{-1}	$(2.5 \pm 0.6) \times 10^{-1}$
ω	940	4.2×10^{-2}	$(4.5 \pm 0.7) \times 10^{-2}$
η	860	2.4×10^{-2}	$(1.4 \pm 0.5) \times 10^{-2}$
$K\overline{K}$	(K)660	3.1×10^{-2}	$(3.3 \pm 1.6) \times 10^{-2}$
$K\overline{K}^*$, $\overline{K}K^*$		20.6×10^{-3}	$(8.8 \pm 1.8) \times 10^{-3}$
$K^*\overline{K}^*$	(K^*)980	3.8×10^{-3}	$(3.9 \pm 0.7) \times 10^{-3}$

Table 3. Decay modes, branching ratios, and gamma-ray multiplicities for various particles produced in proton-antiproton annihilations

	Decay mode		Branching ratio (R)	$\zeta_\gamma R$
$\rho^{\pm}$	→	$\pi^{\pm} + \pi^0$	~1.00	2.0
ω	→	$\pi^+ + \pi^- + \pi^0$	0.89	1.78
	→	$\pi^0 + \gamma$	0.10	0.30
η	→	$\gamma + \gamma$	0.386	0.78
	→	$3\pi^0$ or $\pi^0 + 2\gamma$	0.308	1.5
	→	$\pi^+ + \pi^- + \pi^0$	0.250	0.5
	→	$\pi^+ + \pi^- + \gamma$	0.055	0.05
$K^{\pm}$	→	$\pi^{\pm} + \pi^0$†	0.215	0.43
K_0 { K_1^0	→	$\pi^0 + \pi^0$	0.155	0.62
K_2^0	→	$\pi^0 + \pi^0 + \pi^0$	0.133	0.80
K_2^0	→	$\pi^+ + \pi^- + \pi^0$	0.067	0.1
K^*	→	$K + \pi$	—	—

† Other gamma-ray-producing decay modes have negligible branching ratios.

Table 4. Production rates for various meson-producing channels in proton-antiproton annihilations at rest *

Channel	Rate(%)	ζ_γ	$\zeta_\gamma R$
$\rho^0\pi^0$	1.4 ± 0.2	2	2.8
$\rho^{\pm}\pi^{\mp}$	2.9 ± 0.4	2	5.8
† $\rho^0\pi^+\pi^-$	$5.8^{+0.3}_{-1.3}$	0	0
$\rho^0\rho^0$	0.4 ± 0.3	0	0
$\rho^0\pi^+\pi^-\pi^0$	7.3 ± 1.7	2	14.6
$\rho^{\pm}\pi^{\mp}\pi^+\pi^-$	6.4 ± 1.8	2	12.8
† $\omega^0\pi^+\pi^-$	3.8 ± 0.4	2	7.6
† $\eta^0\pi^+\pi^-$	1.2 ± 0.3	~2.6	3.1
$\omega^0\rho^0$	0.7 ± 0.3	2	—
$\eta^0\rho^0$	0.22 ± 0.17	~2.6	—

* From Baltay, Ferbel, Sandweiss, Taft, Culwick, Fowler, Gailloud, Kopp, Louttit, Morris, Sanford, Shutt, Stonehill, Stump, Thorndike, Webster, Willis, Bachman, Baumel, and Lea (1964).

† Includes cases where $\pi^+\pi^-$ were from ρ^0 decay.

Gamma rays from this process possess an average energy of 210 MeV, not much different from the 190-MeV average energy given to gamma rays from the directly produced pions that are an order of magnitude more frequent. Other mesons being even less frequently produced than the ρ mesons, we can conclude that mesons other than pions have a negligible effect on the total gamma-ray spectrum from proton-antiproton annihilation.

6. THE GAMMA-RAY SPECTRUM FROM PROTON-ANTIPROTON ANNIHILATIONS AT REST

Calculation of the gamma-ray spectrum from proton-antiproton annihilations at rest was therefore made, neglecting the contribution from decay of mesons other than neutral pions. The normalized gamma-ray spectrum was calculated numerically on the CDC 6400 computer from the relation

$$f_A(E_\gamma) = \int_{E_\gamma + \frac{m_\pi^2}{4E_\gamma}}^{\infty} \frac{f_A(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} \quad , \tag{48}$$

with the normalized distribution function $f_A(E_\pi)$ taken from the calculations of Maksimenko (1958), based on the statistical theory of multiple particle production.

The resulting spectrum, up to 750 MeV, is shown in Figure 1. Frye and Smith (1966) have recently calculated the gamma-ray spectrum from proton-antiproton annihilation up to 500 MeV, based on recent measurements by the Columbia University group on charged pions from $p\bar{p}$ annihilation. The excellent agreement between the results of Figure 1 and the calculations of Frye and Smith not only serves as a mutual check on the calculations, but also supports our previous conclusion that mesons other than pions have a negligible effect on the total gamma-ray spectrum from proton-antiproton annihilation at rest.

The absolute magnitude of the gamma-ray spectrum from proton-antiproton annihilation at rest is obtained from equation (22) as

$$I_A(E_\gamma) = B\, C_{\pi^0}\, f_A(E_\gamma) \quad . \tag{49}$$

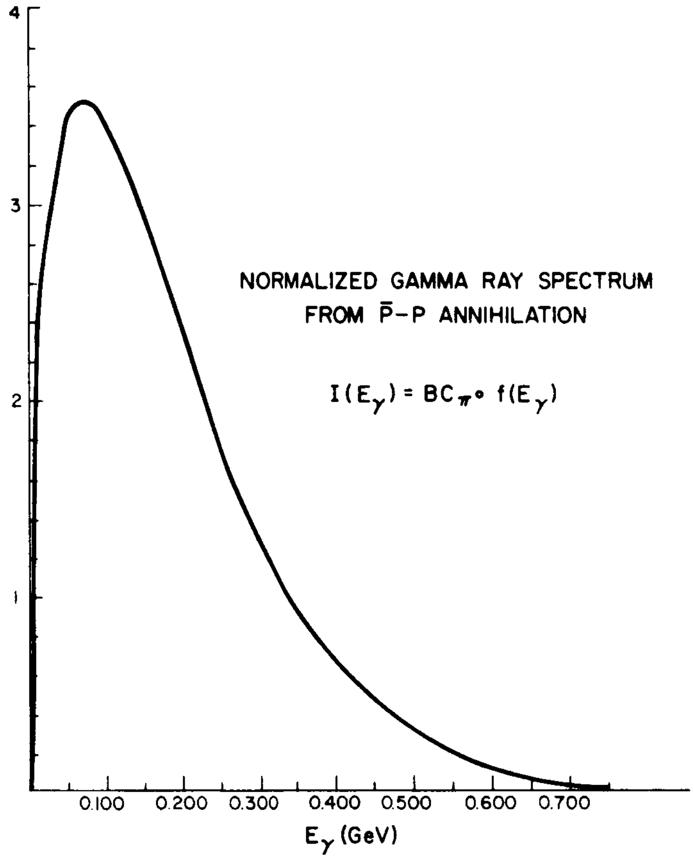

Figure 1. Normalized gamma-ray spectrum from proton-antiproton annihilation.

7. PROTON-ANTIPROTON ANNIHILATIONS IN FLIGHT

We now turn our attention to R. G. -$\overline{\text{C. R.}}$ interactions. Here, owing to limitations in the data, as well as kinematic and dynamical similarities that would make the gamma-ray spectra from such interactions difficult to distinguish from the gamma-ray spectra due to the much more prevalent R. G. -C. R. interactions, we will present only a qualitative treatment.

An excellent review article on high-energy interactions of antiprotons in hydrogen has been presented by Baltay et al. (1964). For high-energy $p\bar{p}$ interactions, annihilations of the type

$$p + \bar{p} \rightarrow p + \bar{p} + \text{bosons} \quad , \tag{50}$$

$$p + \bar{p} \rightarrow \begin{cases} N + \bar{N}^{*} + \text{bosons} \\ N^{*} + \bar{N} + \text{bosons} \\ N^{*} + \bar{N}^{*} + \text{bosons} \quad , \end{cases} \tag{51}$$

and

$$p + \bar{p} \rightarrow \begin{cases} Y + \bar{Y} \\ Y + \bar{Y}^{*} + \text{bosons} \\ Y^{*} + \bar{Y} + \text{bosons} \\ Y^{*} + \bar{Y}^{*} + \text{bosons} \end{cases} \tag{52}$$

may occur, as well as annihilations of the type previously considered.

Reactions of the type given by equation (51) seem to occur frequently and to be of a similar nature as pp interactions. For example (Ferbel, Sandweiss, Taft, Gailloud, Kalogeropoulos, Morris, and Lea, 1962; Ferbel et al., 1965), proton-antiproton interactions in the 3- to 4-GeV/c range lead to strong production of the $N^*_{3/2}(1.237)$ isobar, while at 7 GeV/c no single resonance seems to dominate. The angular distribution of the outgoing baryons is strongly peaked in the forward and backward directions in the collision c. m. s. All these facts hold true for the p-p interactions discussed in Parts II[*] and III.[**] In the energy range where production of the $N^*(1.237)$ isobar predominates, production of neutral pions occurs at roughly the same rate in both p-p and p-$\bar{p}$ interactions, as indicated in Table 5 (Baltay et al., 1964).

Table 5. Cross sections for inelastic single neutral-pion production in proton-antiproton interactions as a function of incident momentum

Reaction	Collision momentum (GeV/c)	Cross section (mb)
$\bar{p} + p \rightarrow \bar{p} + p + \pi^0$	3.25	2.3 ± 0.5
$p + p \rightarrow p + p + \pi^0$	3.67	2.9 ± 0.3

This fact, too, strongly highlights the similarity between p-p and nonannihilation $\bar{p}$-p interactions at similar energies. Thus, in the 3- to 4-GeV/c range, neutral (and charged) pion production is dominated by the channel

$$\begin{tikzcd}[row sep=small] & N^*_{3/2} + \bar{N} \arrow[dr] & \\ p + \bar{p} \arrow[ur] \arrow[dr] & & N + \bar{N} + \pi^0 \ . \\ & \bar{N}^*_{3/2} + N \arrow[ur] & \end{tikzcd} \tag{53}$$

It may therefore be assumed that the nonannihilation R. G. -$\overline{\text{C. R.}}$ (or C. R. -$\overline{\text{R. G.}}$) interactions will lead to gamma-ray spectra having the same characteristics as those from high-energy p-p interactions (see Parts II and III). Experiments also show that in p-$\bar{p}$ interactions between 1.6 and 7.0 GeV/c (Böckmann, Nellen, Paul, Wagini, Borecka, Diaz, Heeren, Liebermeister, Lohrmann, Raubold, Söding, and Wolff, 1966), nonannihilation

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[*] See Stecker, Tsuruta, and Fazio, 1967 in reference list.

[**] See Stecker, 1967 in reference list.

production of pions increases with respect to annihilation production, and that at 5.7 GeV/c, the cross sections for the two processes are comparable (and also comparable to the cross section for inelastic p-p interactions).

Böckmann et al. (1966) find these values for the cross sections at 5.7 GeV/c:

$$\begin{array}{lll} p + \bar{p} \rightarrow p + \bar{p} + \text{bosons (inelastic)} & 24.8 \pm 2.0 \text{ mb} & \\ & & (54) \\ p + \bar{p} \rightarrow \text{bosons (annihilation)} & 22.5 \pm 2.0 \text{ mb}. & \end{array}$$

The pion multiplicity in annihilation interactions rises slowly with energy, as shown in Table 6.

Table 6. Average pion multiplicity in annihilation interactions as a function of incident momentum

Momentum (GeV/c)	Multiplicity	Reference
0	~4.3	Matsuda (1966)
3.25	~6.0	Baltay et al. (1964)
5.7	~7.3	Böckmann et al. (1966)

The cross sections in Tables 7 and 8 are comparable in magnitude to those given in Part II for hyperon production in p-p interactions. As in p-p interactions, these cross sections are small relative to pion production cross sections, but increase with energy. The outgoing hyperons are observed to be emitted strongly in the forward and backward directions, as in the case of p-p interactions. Also, in interactions involving final-state Y- and π-production resonances (strange isobars) of the type

$$Y^* \rightarrow Y + \pi \qquad (55)$$

are commonly produced.

Table 7. Cross sections for hyperon-antihyperon production in proton-antiproton interactions

Final state	Cross section 3.25 GeV/c	(μb) 3.69 GeV/c
$\Lambda\bar{\Lambda}$	87 ± 13	94 ± 14
$\Lambda\bar{\Sigma}^0$, $\bar{\Lambda}\Sigma^0$	56 ± 11	76 ± 14
$\Sigma^+\bar{\Sigma}^-$ $\Sigma^-\Sigma^+$	38 ± 11	56 ± 14
$\Xi^-\Xi^+$	$4^{\dagger}$	$5^{\dagger}$
$\Lambda\bar{\Lambda} + n\pi^0$ $\Lambda\bar{\Sigma}^0 + n\pi^0$, $\bar{\Lambda}\Sigma^0 + n\pi^0$	102 ± 39	122 ± 43
$\Lambda\bar{\Lambda}\pi^+\pi^-$	15 ± 6	30 ± 9
$\Sigma^\pm\bar{\Lambda}\pi^\mp$, $\bar{\Sigma}^\pm\Lambda\pi^\mp$	51 ± 18	143 ± 45
$\Sigma^\pm\bar{\Sigma}^\mp\pi^0$	7 ± 5	28 ± 19
$KN(\bar{\Lambda}$ or $\bar{\Sigma})$, $K\bar{N}(\Lambda$ or $\Sigma)$	24 ± 10	41 ± 14
Total antihyperon production	438 ± 52	710 ± 78

† Based on one event at each energy.

Table 8. Cross sections for the reaction $p + \bar{p} \rightarrow \Lambda + \bar{\Lambda}$ as a function of incident momentum

Momentum (GeV/c)	Cross section (μb)	Reference
1.61	57 ± 18	Button *et al.* (1961)*
3.25	87 ± 13	Baltay *et al.* (1964)
3.69	94 ± 14	Baltay *et al.* (1964)

* Button, Eberhard, Kalbfleisch, Lannutti, Lynch, Maglić, Stevenson, and Xuong (1961).

Thus, we can summarize the findings for high-energy p-p interactions as follows.

A. There are two distinct types of pion-production processes that may be considered. They are

1. Annihilations.
2. Inelastic pion production without annihilation.

B. The ratio of occurrence of process 2 relative to process 1 increases with increasing energy between 1.6 and 7.0 GeV/c and is approximately 1 at 5.7 GeV/c.

C. Inelastic interactions (without annihilation) are very similar to p-p interactions and exhibit similar resonance production and forward-backward peaking.

D. Strange particles are produced in similar quantities in both inelastic p-p and $\bar{p}$-p interactions.

For these reasons, we may assume that

A. An "isobar-plus-fireball" model, similar to that used in Part III, may be applicable to high-energy $\bar{p}p$ interactions. In this case, annihilation interactions may be included as an added contribution to the fireball component.

B. At high energies ($E_\gamma > 5$ GeV) there is at present no reason to assume that the characteristics of the gamma-ray spectrum from p-$\bar{p}$ interactions will differ from those of the gamma-ray spectrum from p-p interactions.

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