†Research was supported by a joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1]V. L. Telegdi, Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester (Interscience Publishers, Inc., New York, 1960), p. 713.

[2]J. Bernstein, T. D. Lee, C. N. Yang, and H. Primakoff, Phys. Rev. 111, 313 (1958).

[3]V. L. Telegdi, Phys. Rev. Letters 3, 59 (1959).

[4]The time dependence of the electron rates can, of course, be characterized over a span of several mean lives by K as defined in (1) if, and only if, K is a slowly varying function of time. This is the case when $R \lesssim \overline{\Lambda}$, an assumption that appeared plausible[3] when these measurements were performed.

[5]R. A. Swanson, Rev. Sci. Instr. 31, 149 (1960).

[6]R. A. Lundy (to be published).

[7]R. Winston and V. L. Telegdi, preceding Letter [Phys. Rev. Letters 7,104 (1961)].

SEARCH FOR HIGH-ENERGY COSMIC GAMMA RAYS*

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This note describes an attempt to detect gamma rays of cosmic origin in the energy region appropriate to π^0 decay. Since π^0 mesons are produced in nucleon-antinucleon annihilation, the existence or nonexistence of a gamma-ray flux from certain portions of the sky bears upon questions such as possible collisions between galaxies and antigalaxies[1] and cosmological models which postulate matter and antimatter creation.[2] New upper limits are set on the creation rate and on the density of interstellar antinucleons.

The existence of high-energy gamma rays in the primary cosmic radiation was first investigated by Schein, Jesse, and Wollan using G-M tubes,[3] by Hulsizer and Rossi using ionization chambers,[4] and by Critchfield, Ney, and Oleksa using cloud chambers.[5] These experiments set an upper limit for the flux of the electron-photon component above about 1 Bev at about 1% of the primary cosmic-ray flux. G-M telescopes were used by Perlow and Kissinger,[6] and more recently by Danielson.[7] All of these experiments suffered the disadvantages of either a high proportion of locally-produced background or an energy sensitivity which did not extend significantly into the 70-Mev region, and none had a directional survey of the sky as its purpose.

A cross section of the balloon-borne detector that was used in the present experiment is shown in Fig. 1. Incoming gamma rays, collimated by

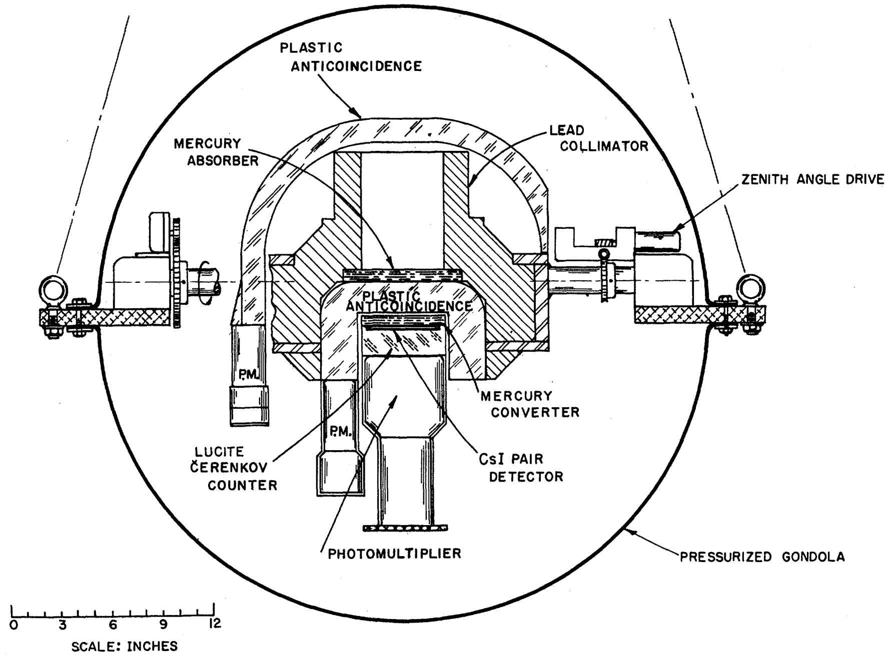

FIG. 1. Cross section of the apparatus. The geometrical figure for this telescope was 1.7 cm^2 sr.

the lead shield, produced electron pairs in either of two removable mercury radiators. The upper radiator, when inserted in flight, was used to measure the attenuation of the beam in order to identify the measured flux as photons. The lower radiator produced the pairs that were detected by the scintillator-Čerenkov combination at the bottom. A pulse corresponding to the traversal of two minimum-ionizing particles in the cesium iodide crystal was required in coincidence with a pulse from the Lucite Čerenkov counter. The pair detector was surrounded by an anticoincidence scintillator inside the lead shield. This anticoincidence requirement excluded incident charged particles as well as electron pairs or showers projected upwards from the detector. In addition, a large anticoincidence scintillator outside the lead shield was used to reduce the background produced by cosmic-ray interactions in that shield. The apparatus was rotated in flight to various zenith angles in order to pour the mercury in and out, to measure the zenith-angle dependence of the gamma-ray intensity and to measure the gamma-ray albedo.

The detection efficiency of the instrument was estimated as a function of gamma-ray energy from the known pair-production cross sections, electron multiple-scattering expressions, etc. This curve was combined with the experimentally determined energy spectrum of pair-producing gamma rays near the top of the atmosphere as measured in the emulsion experiments of Carlson, Hooper, and King,[8] and of Svensson.[9] The result was an effective efficiency of about 0.17. This efficiency differed by less than 10% with the substitution of the gamma-ray spectrum from low-energy proton-antiproton annihilation. The adequacy of the efficiency estimate was confirmed and the angular response of the instrument was measured in a π^0 decay gamma-ray beam at the MIT synchrotron.

The detector was balloon-borne at 55° geomagnetic latitude on July 1, 1960, for about one day of which 12 hours were spent at 8.5 g cm^{-2} atmospheric depth. Evidence that gamma rays were detected is as follows: The counting rate as a function of atmospheric depth, shown in Fig. 2, followed a transition curve having a maximum near 180 g cm^{-2}, entirely similar to that of the electron-photon component. The ratio of the counting rate with the upper mercury absorber inserted to the rate with this absorber removed was 0.40 ± 0.07, while the expected ratio for pure gamma-ray detection was 0.35. The gamma-ray albedo flux was measured and found to be in agreement with the results of the emulsion experiment of Svensson, having a value of about half that of the vertically downward gamma-ray flux at 14 g cm^{-2}.

The gamma-ray intensity versus atmospheric depth in the region 0 to 40 g cm^{-2} is shown in the inset of Fig. 2. The four measurements with the smallest indicated errors were taken at four zenith angles while the balloon floated at 8.5 g cm^{-2}. Since the corresponding atmospheric depths are small compared with any of the characteristic interaction lengths involved, a linear extrapolation to 0 g cm^{-2} is justified. The extrapolated intensity, determined by a least-squares fit, is $(1 \pm 3) \times 10^{-3}$ cm^{-2} sec^{-1} sr^{-1} and the corresponding upper limit to the gamma-ray intensity inci-

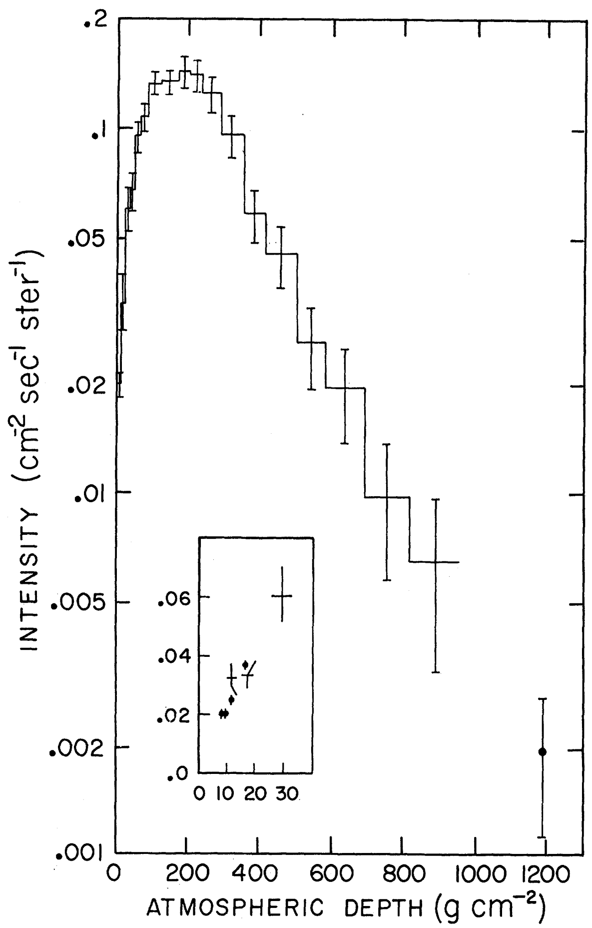

FIG. 2. Gamma-ray intensity versus atmospheric depth. (The axis of the detector was clamped at 30-degree zenith angle throughout the ascent, hence the 15% correction to depth.) The insert shows a linear plot of the intensity for small atmospheric depths; the units are the same for both graphs.

dent upon the top of the atmosphere, for a 95% statistical confidence limit, is 7×10^{-3} cm^{-2} sec^{-1} sr^{-1}. This value must be regarded as an average over the directions scanned, i.e., as a limit to the essentially isotropic intensity from the northern celestial hemisphere.

From a sidereal arrival direction analysis, the incident flux from the direction of Cygnus-A, having subtracted off the secondary flux, was found to be $(-2\pm7)\times10^{-4}$ cm^{-2} sec^{-1}, with the corresponding upper limit of 1.2×10^{-3} cm^{-2} sec^{-1} for a 95% statistical confidence limit. A previous upper limit, based upon the detection of one gamma ray, was set at 5×10^{-3} cm^{-2} sec^{-1} by Braccesi, Ceccarelli, and Salandin,[10] using emulsions. This corresponds to an upper limit of 1.5×10^{-2} cm^{-2} sec^{-1} for a 95% statistical confidence limit. Estimates of the flux from Cygnus-A, based on a galaxy-antigalaxy collision model, range from Morrison's value of about 1 cm^{-2} sec^{-1} to Savedoff's value,[11] which is yet three orders of magnitude below the upper limit set by this experiment.

Proton-antiproton annihilation taking place anywhere in the cone defined by the aperture of the instrument could also contribute to a gamma-ray intensity. The lifetime of an antiproton against annihilation with interstellar protons can be taken as $\tau=[nv(\sigma_0 c/v)]^{-1}$, where n is the proton number density, v is the relative velocity, and $\sigma=\sigma_0(c/v)$ is the annihilation cross section, in which σ_0 is about 10^{-25} cm^2. This lifetime is much greater than the time scale of the universe (1.4×10^{10} years) for proton densities appropriate to intergalactic space ($n\ll10^{-4}$ cm^{-3}), and is much less than the time scale of the universe for proton densities appropriate to the galaxy ($n\gg10^{-2}$ cm^{-3}). Within wide limits of proton densities, the annihilation frequency would therefore be constant within the galactic volume, so that the resulting annihilation gamma-ray flux depends only upon the geometrical shape of the galactic portion subtended by the aperture of the detector. The annihilation frequency, S, and the gamma-ray intensity, J, are related by $S=4\pi J(mRf)^{-1}$, where $m\geq3$ is the average number of gamma rays per annihilation, R is the distance to the surface of the galactic disk in the direction scanned, and f is a geometrical factor which takes into account the shape of the galaxy within the cone scanned. For the direction perpendicular to the galactic plane, $R=5\times10^{20}$ cm and $f=1$; for the direction of the galactic anticenter, $R=2\times10^{22}$ cm and $f=0.15$.

During the time that the balloon was near maximum altitude the aperture of the instrument scanned the galactic anticenter at certain known times, but, due to a partial loss of azimuth information, it was not possible to separate all of the data from the direction perpendicular to the galactic plane. However, an upper limit for each intensity can be established: The greater intensity would come from the galactic anticenter, so that a conservatively set upper limit results if the value for the isotropic intensity is treated as a value for the direction perpendicular to the galactic plane. With $J\leq7\times10^{-3}$ cm^{-2} sec^{-1} sr^{-1}, this gives $S\leq6\times10^{-23}$ cm^{-3} sec^{-1} as the upper limit to the annihilation frequency for the portion of the galaxy in the direction of the North Galactic Pole. This limit is independent of knowledge of the shape of the galaxy other than the perpendicular distance to the surface. An upper limit to the gamma-ray intensity from the direction of the galactic anticenter, for a 95% statistical confidence limit, was calculated to be 1.8×10^{-2} cm^{-2} sec^{-1} sr^{-1}. This value of J gives $S\leq2.5\times10^{-23}$ cm^{-3} sec^{-1} as the upper limit to the annihilation frequency for the galactic anticenter.

The product of the annihilation frequency, S, and the antiproton lifetime, τ, is the corresponding upper limit to the antiproton number density, $\bar{n}$. The result, which is a function of the proton number density, can be expressed as $\bar{n}=S(\sigma_0 cn)^{-1}\leq(8\times10^{-9})/n$ cm^{-3}. This upper limit to the interstellar antiproton density is a factor of ten below previous limits that assume $n\approx1$ cm^{-3}.[2]

The upper limit for the annihilation frequency of antiprotons can also be taken to be an upper limit for the creation rate of antiprotons. As long as the antiproton lifetime within the galaxy is short compared with the age of the galaxy, which seems certain for any proton density in excess of 10^{-2} cm^{-3}, an equilibrium between annihilation and any postulated long time-scale production mechanism should be established. The proton production rate has been required by steady-state cosmology to be about 3×10^{-22} cm^{-3} sec^{-1},[2] which is a factor of ten above the upper limit of 2.5×10^{-23} cm^{-3} sec^{-1} for antiproton annihilation (or production) reported here. The value of this required production rate in steady-state theory, however, depends upon the experimental determination of, e.g., the average universal mass density, which at present is uncertain and may be as much as a factor of 10^3 below the value of 10^{-28} to 10^{-29} g cm^{-3} assumed earlier by cosmologists.[12]

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[1]P. Morrison, Nuovo cimento 7, 858 (1958).

[2]F. Hoyle and G. R. Burbidge, Nuovo cimento 4, 558 (1956).

[3]M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. 59, 615 (1941).

[4]R. I. Hulsizer and B. Rossi, Phys. Rev. 73, 1402 (1948).

[5]C. L. Critchfield, E. P. Ney, and S. Oleksa, Phys. Rev. 85, 461 (1952).

[6]G. J. Perlow and C. W. Kissinger, Phys. Rev. 81, 552 (1951).

[7]R. E. Danielson, J. Geophys. Research 65, 2055 (1960).

[8]A. G. Carlson, J. E. Hooper, and D. T. King, Phil. Mag. 41, 701 (1950).

[9]G. Svensson, Arkiv Fysik 13, 347 (1958).

[10]A. Braccesi, M. Ceccarelli, and G. Salandin, Nuovo cimento 17, 691 (1960).

[11]M. P. Savedoff, Nuovo cimento 13, 12 (1959).

[12]A. Sandage, Astrophys. J. 113, 355 (1961).

SELF-CONSISTENT CALCULATION OF THE MASS AND WIDTH OF THE $J=1$, $T=1$, $\pi\pi$ RESONANCE

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The existence of a $J=1$, $T=1$ resonance in $\pi\pi$ scattering now seems to be very probable, though there are still rather large uncertainties in its position and width.[1] From a theoretical point of view, one may believe this resonance to be due to the existence of an unstable vector meson,[2] called ρ, or one may say the resonance is dynamical.[3] If the ρ meson has an infinite bare mass, there is essentially no difference in the results of these two points of view.[4,5] The principal distinction between the two philosophies comes from the fact that if the ρ meson is really a new particle, its mass and coupling constant must be thought of as new independent parameters which can be chosen to be anything, while if the ρ is a dynamical resonance, the mass and coupling constant are determined by other parameters already in the theory.

Within the "dynamical" philosophy, attempts have been made to calculate the mass and coupling constant of the ρ meson.[3,6] These have not been entirely successful; furthermore, the most complete and careful attempt to do this,[3] based on the Mandelstam representation, involves the solution of a very complicated set of coupled integral equations on a computing machine, and is therefore not very transparent. One qualitative feature which has been emphasized by Chew and Mandelstam,[3] however, is that the existence of the resonance seems to follow from the operation of a "bootstrap mechanism," in which the strong force between two pions in a P state, which is needed to produce the resonance, is provided by the exchange of a pair of resonating pions.

In this way, the basic underlying source of the pion-pion interaction (which could, for example, be the $\lambda\phi^4$ interaction or a force produced by the exchange of a strongly interacting S-wave pion pair) does not seem to play a large quantitative role in the final results, but merely provides the spark which sets the bootstrap off. One would, therefore, expect to be able to obtain the ρ meson's properties as the result of a self-consistent calculation with no parameters.

It is our purpose here to apply the bootstrap mechanism in a very simple-minded and trivial calculation, which yields quantitative values for the ρ mass and coupling constant. The approximation is the following: a ρ meson, of mass m_ρ and coupled to the pion with a coupling constant $\gamma_{\rho\pi\pi}$, is exchanged between two pions as shown in Fig. 1.

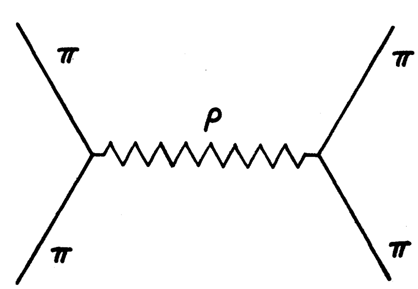

FIG. 1. The one ρ-meson exchange diagram.