possible smallest length. The problem is rather to understand the simple optical model within the framework of dispersion theory.

We appreciate the generous help of F. von Hippel with the numerical calculations.

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[3]R. Oehme, Phys. Rev. 130, 424 (1963).

[4]We note that the dispersion theoretic model for nonshrinking diffraction scattering by Y. Nambu and M. Sugawara [Phys. Rev. Letters 10, 304 (1963)] implies $\alpha(t)\equiv 1$. It therefore appears that this model is excluded by the theorem of reference 2.

[5]R. Oehme (unpublished); a complete discussion of these extensions of the theorem of reference 2, and its applicability in the case of the continued unitarity condition for reactions like $\pi\bar{\pi}\to N\bar{N}$, will be given in the lecture notes by R. Oehme, Scottish Universities' Summer School in Physics, 1963 (in preparation), and in those by P. G. O. Freund, Summer Institute of Physics, University of Colorado, 1963 (in preparation).

[6]V. N. Gribov, Nucl. Phys. 22, 249 (1961).

[7]A counter example is given by $F(s,t)\sim id(s)t+C(s)t^{\gamma(s)}$ with $\mathrm{Re}\gamma(s)<1$ for real $s\leqslant 0$ and $\mathrm{Re}\gamma(s)>1$ for real $s\geqslant 4m_\pi^2$. Such an asymptotic form is excluded by reference 2, but not by Gribov's argument.

[8]P. G. O. Freund and R. Oehme, Phys. Rev. Letters 10, 199,315(E) (1963).

[9]R. Oehme, Nuovo Cimento 25, 183 (1962).

[10]These fixed branch points should not be confused with possible moving branch points in the λ plane. Concerning the problem of branch-point trajectories, see reference 3 and R. Oehme (to be published).

[11]Fixed branch points can also be obtained in perturbation theory if one sums ladder graphs with couplings which give rise to more singular "potentials." See J. D. Bjorken and T. T. Wu, Phys. Rev. (to be published); R. Sawyer (private communication).

[12]See reference 9, Sect. 3; in potential scattering the branch points are at $\lambda=-\frac{1}{2}\pm i(|g|)^{1/2}$. On the line $\mathrm{Re}\lambda=-\frac{1}{2}$ the centrifugal potential is real, and we have "collapse" for $\lambda=-\frac{1}{2}+i\lambda_i$ with $\lambda_i^2>|g|$. In field theory the position of these branch points may well be changed[11] such that they are on the line $\mathrm{Re}\lambda=1$, which is, of course, an upper limit.

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RECOIL PHOTONS FROM SCATTERING OF STARLIGHT BY RELATIVISTIC ELECTRONS*

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The processes which have been proposed[1] for the cosmic production of high-energy photons, recently detected above the atmosphere,[2,3] depend on the presence of particles and fields whose densities are themselves poorly known or unknown. One additional process, however, does not share this particular uncertainty. Collisions between the electrons which are known to produce the nonthermal radio emission (in particular, the galactic halo emission) and the photons of starlight have long been recognized as contributors to electron energy degradation, but the observable radiation they must produce has not been considered. Yet such observations are of astrophysical interest, for unlike synchrotron radiation, which depends strongly on B, this inverse Compton process depends only on the rather smoothly distributed starlight density and on the electron density, and must occur wherever fast electrons are found in space.

We can calculate roughly the photon flux due, say, to electrons in the halo, and compare it with observations. We use units convenient for astrophysical purposes: magnetic fields in microgauss, energies in MeV or eV, frequencies in Mc/sec, volume densities in cm^{-3}, and distances in light years.

Some results pertinent to the halo synchrotron emission must first be presented. It is well known[4] that the power radiated per electron is

$$P_s(\gamma, B_\perp) = 9.9\times10^{-22}\gamma^2 B_\perp{}^2 \text{ MeV sec}^{-1}\ \mu\text{G}^{-2}, \quad (1)$$

where $\gamma \equiv E/(m_0c^2)$ and $B_\perp \equiv B\sin\theta$, with θ the angle between $\vec{v}$ and $\vec{B}$. The spectrum peaks at the characteristic frequency

$$\nu_s = 1.26\times10^{-6}\gamma^2 B_\perp \text{ Mc sec}^{-1}\ \mu\text{G}^{-1}. \quad (2)$$

Consider a volume element $d\tau$ much smaller than the galaxy but large enough for the direction of $\vec{B}$ to be randomly distributed and for its magnitude and direction to be uncorrelated. Make the highly plausible assumption that $\vec{B}$ is strong enough to provide strong guidance for the electrons of importance; then the helical paths imply that the electron $\vec{v}$ distribution depends at most upon γ and θ, and the emission from $d\tau$ must be isotropic. Let $P(\nu, \gamma, B_\perp)d\nu$ be the power emitted by an electron into $d\nu$. To simplify the problem we collapse the emission spectrum into a δ function at its peak frequency:

$$P(\nu, \gamma, B_\perp) \approx P_s(\gamma, B_\perp)\delta(\nu - \nu_s). \quad (3)$$

Let $\tilde{n}(\gamma, \theta)d\gamma d\Omega$ be the density of electrons in $d\gamma d\Omega$. Then integration shows that the spectral power emitted, $P_\nu \equiv dP/(d\nu d\tau d\omega)$, expressed in MeV $(\text{Mc/sec})^{-3/2}$ cm^{-3} sr^{-1} $\mu\text{G}^{-1/2}$ is

$$P_\nu = 2.8\times10^{-14}\nu^{1/2}B^{1/2}\int d\Omega\tilde{n}(\gamma_s, \theta)\sin^{1/2}\theta. \quad (4)$$

$\gamma_s \equiv \gamma_s(\nu)$ is given by (2).

The angular distribution will, in general, depend upon energy, but if we assume independence and a power-law spectrum, i.e., $\tilde{n}(\gamma, \theta) = \gamma^{-m}n^*(\theta)$, then (4) reduces to

$$P_\nu = 2.8\times10^{-14}(1.12\times10^{-3})^m \times n_0 B_e^{\frac{1}{2}(m+1)}\nu^{\frac{1}{2}(1-m)}, \quad (5)$$

where $\gamma^{-m}\int n^*(\theta)d\Omega \equiv n_0\gamma^{-m} = n(\gamma)$, $n(\gamma)d\gamma$ being the number of electrons/cm^3 in energy range $m_0c^2d\gamma$, and the effective field B_e is

$$B_e^{\frac{1}{2}(m+1)} \equiv B^{\frac{1}{2}(m+1)}\frac{\int d\Omega n^*(\theta)\sin^{\frac{1}{2}(m+1)}\theta}{\int d\Omega n^*(\theta)}. \quad (6)$$

We simplify: Assume the velocities isotropic. Then (6) becomes $B_e^{\frac{1}{2}(m+1)} = KB^{\frac{1}{2}(m+1)}$, where K is a factor involving gamma functions which is ≈ 1 for reasonable values of m and may be neglected.

The specific intensity received from an emitting region of dimension R along the line of sight is $I_{\nu s} = RP_{\nu s}$, and the one-way flux across a detector, assuming $I_{\nu s}$ equal in all directions, will be $\mathfrak{F} = \pi RP_{\nu s}$ or

$$\mathfrak{F} = 8.3\times10^4(1.12\times10^{-3})^m \times Rn_0B_e^{\frac{1}{2}(m+1)}\nu^{\frac{1}{2}(1-m)} \quad (7)$$

in MeV $\text{sec}^{-1}\,\text{cm}^{-2}\,(\text{Mc/sec-}\mu\text{G})^{-\frac{1}{2}(1+m)}$. It can be shown that the error in this due to (3) is less than a factor of 2 for m's in the range 1-3.

Turning to the scattering of starlight, we find that a method for calculating the gamma-ray power scattered by a fast electron has been set forth by Feenberg and Primakoff[5] and by Donahue.[6] After suitable approximations the scattering can be integrated over angles to yield the total scattered power per electron:

$$P_c(\gamma, \rho) \cong 2.7\times10^{-20}\rho\gamma^2 \text{ MeV sec}^{-1}, \quad (8)$$

where ρ is the starlight density in eV cm^{-3}, isotropy being assumed in the frame of the fixed stars. This calculation is valid only for $30 \lesssim \gamma \lesssim 10^4$; the lower limit is set by the fact that for small γ the photons striking the electron in its rest frame are no longer essentially confined to a small forward cone; and the upper, by the failure of several approximations in the integration, notably the departure of the Klein-Nishina cross section from the Thomson limit. Equation (8) is the analog to (1); Feenberg and Primakoff derive the analog to (2), which is

$$\nu_c \cong 3.6\gamma^2kT/h = 7.5\times10^4\gamma^2T \text{ Mc sec}^{-1} \text{ deg}^{-1}. \quad (9)$$

T is the effective blackbody temperature of the starlight distribution, ~6000°K.

It is now clear that if we approximate the recoil photon spectrum by a δ function as in (3) and assume isotropy of electrons averaged over a region $d\tau$, the argument goes as before and we can take over the flux result (7). The gamma-ray flux obtained is

$$\mathfrak{F} = 5.8\times10^{11}(1.76\times10^{-5})^m \times Rn_0\rho T^{\frac{1}{2}(m-3)}E^{\frac{1}{2}(1-m)} \quad (10)$$

in MeV sec^{-1} cm^{-2} MeV^{-1}, for ρ, T, and E in the units already given.

Present measurements of hard photon fluxes

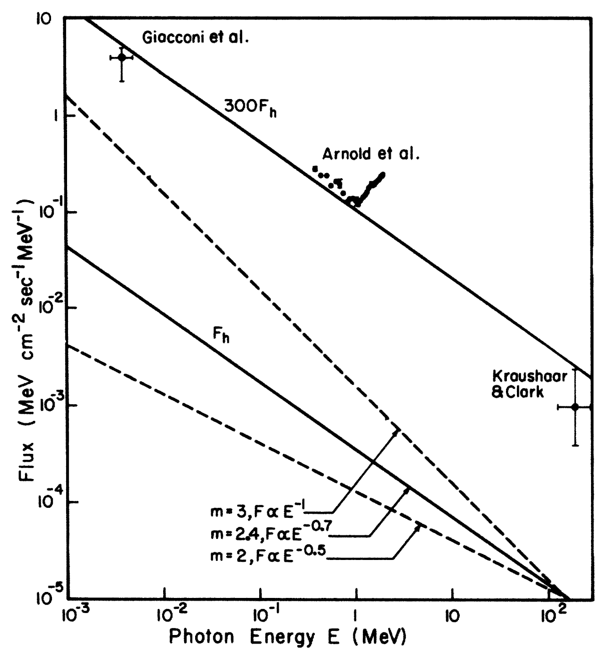

FIG. 1. Data on hard photon fluxes in space, compared with theoretical recoil spectra. The lines are explained in the text. In reducing the data[2] we have indicated probable errors. The points from Arnold et al. follow directly from their measured spectrum; the last 14 merge into a line of slope +1 (corresponding to nearly equal numbers of counts in all the higher channels) and are perhaps of instrumental origin. Some support for this interpretation is provided by earlier data.[3] We ignore these points in further work. Giacconi et al. reported x-ray counts integrated over 2-8 Å; in assigning the point we have assumed $\bar{\lambda} \sim 3$ Å and effective bandwidth ~ 4 Å. Point-source contributions are omitted. Kraushaar and Clark observed γ rays above 50 MeV, with mean energy ~ 200 MeV; the effective bandwidth is apparently ~ 400 MeV.

from space (Fig. 1) sample the range from a few keV up to some hundreds of MeV. These recoil photons correspond to the emitting electron energies and associated radio frequencies shown in Table I. We note that (8) and hence (10) are valid throughout this range of γ's. Recoil photons are, of course, not the only source of such radiation in space. Nuclear gamma rays, synchrotron emission, mesonic decays, and ordinary collisional bremsstrahlung are competing sources. These are negligible in regions of sufficiently low gas density and magnetic field. The recoil photons are perhaps the only indication of the possible presence of electrons in tenuous regions. With such regions in mind, we shall first estimate the recoil photon spec-

Table I. Energies of recoil photons, energies of electrons producing them, and frequencies of radio emission from the same electrons for two assumed values of B_e.

Photon energy	Electron energy $\gamma \equiv E/m_0c^2$	Radio frequency with $B=10^3$ μG	Radio frequency with $B=1$ μG
5 keV	50	3 Mc/sec	3 kc/sec
500 keV	500	300 Mc/sec	300 kc/sec
100 MeV	7×10^3	6×10^4 Mc/sec	60 Mc/sec

trum expected near earth from the halo of our galaxy, where electrons are known to exist, to determine whether this alone is sufficient to account for the observations. Throughout this work we neglect cosmic absorption of the photons, which is easily shown to be small throughout the range of energies considered.

Using (7) and (10) it is possible to infer a gamma-ray spectrum from knowledge of the halo radio spectrum. Several investigations[7] indicate $m = 2.4 \pm 0.6$, and to normalize we use the observed radio brightness temperature (near the galactic poles) $T_b \approx 500°$K at 100 Mc/sec, with the relation $2k\nu^2 T_b = c^2 I_\nu$. Ten or 20% of this radiation is probably extragalactic, and we have neglected anisotropy effects, but these errors are not serious. Setting $B_e \approx 1$ μG (somewhat less than values measured in the disk) and $\rho_h \approx 0.2$ eV cm^{-3} (about one third the local density), we obtain for the halo flux the line marked F_h in Fig. 1. This estimate varies inversely as $B_e^{1.7}$. The slope is -0.7, and for comparison we show lines calculated in the same way for $m = 2$ (slope -0.5) and $m = 3$ (slope -1). Also shown is the line corresponding to F_h arbitrarily multiplied by 300. The fit of this line to data over a wide range suggests that, rather than looking for other processes to account for these photons, we might try tentatively to explain the factor 300 in terms of additional electrons in space, in regions of low magnetic field.

In Table II various simple models of electron distribution in space are considered and the corresponding photon fluxes are calculated. The universe is treated as Euclidean with a cutoff at 10^{10} light years. For volumetric purposes we have taken the distance between galaxies as $10^{6.3}$ light years and that between clusters as $10^{7.3}$.

Case (d) corresponds to Sciama's model,[8] in which electrons are confined to whole clusters,

Table II. Parameters assumed for various hypothetical electron distributions, and photon fluxes obtained.

Location of electrons	Radius of contributing region (lt yr)	Starlight density in source object (relative to ρ_h)	Electron density in source object (relative to n_h)	Volumetric dilution	Calculated photon flux
(a) Halo of our galaxy	$10^{4.5}$	1	1	(1)	F_h
(b) Halos of all external galaxies	10^{10}	0.3	0.5	2×10^{-6}	$\sim0.1F_h$
(c) Local cluster of galaxies	$10^{6.3}$	0.2	0.1	(1)	$\sim1F_h$
(d) All external clusters	10^{10}	0.2	0.1	10^{-3}	$\sim6F_h$
(e) All space	10^{10}	0.1	1	(1)	$\sim3\times10^4F_h$

and clearly this model cannot supply the observed photon flux unless B_e in the halo is taken much smaller than the 1 μG assumed, e.g., by invoking close collimation of the electrons along field lines. On the other hand, the extreme model (e), in which all space is filled with relativistic electrons (and presumably protons) to the same density as our halo, produces too many photons and seems definitely excluded even if present data turn out to be upper limits only. Note that this conclusion is independent of assumptions as to the gas density and effective field in extragalactic space. One might still have high extra-galactic densities and pressures (as postulated in the "hot universe" model[9]) due to protons and electrons of nonrelativistic energies, but the view that cosmic rays themselves are primarily an extragalactic phenomenon appears to conflict with these experiments.

Model (e) may, however, be adapted to give the desired factor of ~300 by assuming an electron density only one percent of the halo density, yet extended over most of space. The last column of Table I strongly suggests this approach. Slow dissipation of the great stores of electrons in strong radio galaxies can lead in a rough estimate to such an electron distribution. Should this suggestion be confirmed by later measurements, the over-all importance of these radio galaxies as cosmic-ray sources would be strongly indicated.

Recoil photons reach earth from discrete radio sources also, and, in principle, would provide, together with the radio data, a means to measure effective magnetic fields in such objects. We calculate, however, that the expected recoil photon flux from such a source as the Crab Nebula would be at most $\sim10^{-7}$ of the flux actually observed from the whole sky. Sensitive narrow-angle detectors would be needed to observe such point sources above the background. Probably other processes in the object would dominate the recoil contribution.

It is a pleasure to acknowledge valuable conversations with J. R. Arnold, D. W. Sciama, K. Greisen, and our visitor at Cornell, S. Ozaki (Osaka City University).

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frequencies $\lesssim 30$ Mc/sec. Observations, however, become more difficult at low frequencies, and in any case this spectral change may reflect a change in emission or absorption rates and not in the actual electron density spectrum. For the present we therefore choose to extrapolate from the well-known spectrum at frequencies $\gtrsim 100$ Mc/sec.

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EVIDENCE FOR A TWO-PION DECAY MODE OF THE ω MESON

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A two-pion decay mode of the ω meson is inferred from the effective-mass distribution of the two pions produced in the reaction

$$\pi^- + p \rightarrow n + \pi^- + \pi^+ \tag{1}$$

at an incident pion momentum of 1.7 BeV/c. 2137 events of Reaction (1) show, above background, approximately 900 events in the ρ-resonance band. When the events of the reaction are analyzed as a function of momentum transfer to the nucleon, it is found that a statistically significant number of events fall in a narrow band peaked at a mass close to the mass of the ω meson. Thus both ρ and ω intermediate states for Reaction (1) are implied:

$$\pi^- + p \rightarrow n + \rho^0 \hookrightarrow \pi^- + \pi^+, \tag{2}$$

$$\pi^- + p \rightarrow n + \omega \hookrightarrow \pi^- + \pi^+. \tag{3}$$

The accepted properties of the resonances, obtained from the decays $\rho \rightarrow 2\pi$ and $\omega \rightarrow 3\pi$, are summarized in Table I. The ω resonance has the same spin and parity as the ρ, but different isotopic spin; its mass is about 4% greater and its width much less than the mass and width of the ρ.

The ω can decay into two pions only through electromagnetic interaction. Glashow[1] suggested that, because of the small ω-ρ mass difference, electromagnetic interference between the two states may greatly enhance the G-forbidden decay $\omega \rightarrow 2\pi$. Calculations by Bernstein and Feinberg[2] showed that this forbidden decay might be observed in $\pi^+\pi^-$ effective-mass distributions as a spike near the ω mass superimposed on the broad ρ peak. Some indications of this structure have appeared in several experiments.[3]

Table I. Properties of ρ and ω mesons.

Particle	Mass (MeV)	Γ (MeV)	I	J	P	G
ρ	~750	~120	1	1	-	+
ω	~780	$\leq$ 20	0	1	-	-

To study this effect further, the BNL 20-inch hydrogen bubble chamber was exposed to negative pions from the AGS separated beam; the nominal beam momentum was 1.7 BeV/c and the spread approximately ± 0.5%. 60 000 pictures were taken with 20-25 tracks per picture. Bubble density was kept low so that the chamber's excellent ionization discrimination could be employed to separate positive pions from protons.

Events were selected in a small fiducial volume corresponding to about one fourth of the total chamber. The volume was placed well upstream to insure long secondary tracks for accurate momentum measurements. All two-prong stars within the fiducial volume were measured and kinematically fitted with the exception of those in which, at the scanning stage, the positive secondary was identified unambiguously as a proton by its ionization. 5535 events were measured; in addition to the 2137 identified as Reaction (1), 1196 were from the reaction

$$\pi^- + p \rightarrow \pi^- + \pi^+ + n + (1 \text{ or more } \pi^0). \tag{4}$$

The remainder consisted of events with secondary protons not eliminated in the scanning.

A Chew-Low plot of all events from Reaction (1) is shown in Fig. 1. The large concentration of events at low four-momentum transfer (Δ) and in the region of the ρ mass [0.56 (BeV/c)^2] is obvious. Figure 2(a) shows the $\pi^+\pi^-$ effective-mass distribution. The broad band, 650-850 MeV, typical of the ρ, is apparent, but the distribution is asymmetric about 750 MeV, with 393 events between 750 and 800 MeV and 298 events between