

UNSTABLE MATTER AND THE 1-10 MeV GAMMA-RAY BACKGROUND

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ABSTRACT

The spectrum of photons produced by an unstable particle which decayed while the universe was young is calculated. This spectrum is compared to that of the 1-10 MeV shoulder, a feature of the high-energy, extragalactic gamma-ray background, whose origin has not yet been determined. The calculated spectrum contains two parameters which are adjusted to obtain a maximal fit to the observed spectrum; the fit thus obtained is accurate to the 99% confidence level. The implications for the mass, lifetime, initial abundance, and branching ratio of the unstable particle are discussed.

Subject headings: cosmic background radiation — dark matter — elementary particles — gamma rays: general

I. INTRODUCTION

The 1-10 MeV shoulder is a non-power-law feature of the high-energy, extragalactic gamma-ray background. This feature is clearly displayed by Schönfelder, Graser, and Daugherty (1977) and Pinkau (1978). The 1-10 MeV shoulder appears to be superposed on an underlying power-law spectrum which extends from energies less than 100 keV to energies greater than 100 MeV. The mechanism responsible for producing the photons which comprise the shoulder has not yet been determined, although several possibilities have been considered. Stecker (1971) suggests that this feature results from photons produced by neutral pion decay. Stecker, Morgan, and Bredekamp (1971) propose that the photons comprising this feature result from matter-antimatter annihilation. Heffernan and Liboff (1984) discuss positronium annihilation from accreting objects as a possible source for these photons. Olive and Silk (1985) suggest that this feature may result from the decay of a long lived SUSY particle, such as the gravitino. They point out that for gravitino masses $\sim 1-10$ GeV and a decay redshift of $\sim 10^3$ the flux of photons from the decay which would be observed at ~ 1 MeV is close to that detected. Stecker (1986) claims that the spectral shape of the photons would not match that observed, and Olive and Silk (1986) point out that, for some parameter values, the spectrum of photons from the decay roughly parallels that observed.

Here, we consider the general spectrum of photons resulting from the decay of an unstable particle. A detailed comparison of this spectrum with the observed spectrum is carried out. It is assumed that the initial energy of the decay photon is constant; hence, the spectrum results from the fact that photons produced at different times experience different cosmological redshifts. An excellent fit may be obtained by adjusting the two parameters characterizing the decay spectrum, and since these parameters are related to the particle properties, the fit constrains the particle properties.

The spectrum of photons produced by a particle decay is calculated in § II. In § III this spectrum is compared to that observed. The implications for the mass, lifetime, initial abundance, and branching ratio of the unstable particle are discussed in § IV. A summary is given in § V.

II. CALCULATED SPECTRUM

Photons are produced by the decay of an unstable particle at a redshift z with an energy E_γ . The energy of the photon, E_γ , is assumed to be constant (as will be the case when the unstable particle decays into two particles). At a redshift of zero, photons from the decay have an energy $E_0 = E_\gamma(1+z)^{-1}$, where z is the redshift at which the photon was produced. The unstable particle, m , may decay into two photons, a photon and another particle or there may be a branching ratio, b , so that the unstable particle decays into a photon and another particle a small fraction, b , of the time and two particles (not photons) the rest of the time. Hence, b , used in equation (1), may take on values less than one, one, or two. The rate at which photons are produced dn_γ/dt is given by

$$\frac{dn_\gamma}{dt} = -b \frac{dn_m}{dt}, \quad (1)$$

where dn_m/dt is the rate at which the unstable particles of mass m decay;

$$\frac{dn_m}{dt} = -\frac{n_m}{\tau} = -\frac{n_{0m}(1+z)^3 e^{-t/\tau}}{\tau}, \quad (2)$$

where n_m is the number density of the unstable particles, n_{0m} is the initial number density (set at a time $\ll \tau$) of m scaled to the current epoch, t is the age of the universe at redshift z , and τ is the lifetime of m . The observed spectrum $dn_{0\gamma}/dE_0$ may be obtained using the chain rule:

$$\frac{dn_{0\gamma}}{dE_0} = \frac{dn_\gamma}{dt} \frac{dt}{dz} \frac{dz}{dE_0}, \quad (3)$$

where $n_{0\gamma}$ is the number density of photons at a redshift of zero. We use the relations $dn_\gamma = (1+z)^3 dn_{0\gamma}$, $dn_\gamma/dt = bn_{0m}\tau^{-1}(1+z)^3 e^{-t/\tau}$, $t = t_0(1+z)^{-3/2}$, and $\tau = t_0(1+z_d)^{-3/2}$ (for a matter-dominated, Einstein-de Sitter universe) and $E_0 = E_\gamma(1+z)^{-1}$, where z_d is the decay redshift, when the age of the universe is τ . Equation (3) implies that

$$\frac{dn_{0\gamma}}{dE_0} = \kappa_m E_0^{1/2} e^{-(\kappa_\gamma E_0)^{3/2}}, \quad (4)$$

where $\kappa_m = 1.5bn_{0m}\kappa_\gamma^{3/2}$ and $\kappa_\gamma^{-1} = E_\gamma(1+z_d)^{-1}$ is the energy a decay photon produced at z_d has at a redshift of zero. We note that, if the universe is radiation-dominated during the decay epoch a similar result is obtained

$$\frac{dn_{0\gamma}}{dE_0} = \kappa_\gamma E_0 e^{-(\kappa_\gamma E_0)^2}, \quad (5)$$

where $\kappa_\gamma = 2bn_{0m}\kappa_\gamma^2$. If, prior to the decay, the unstable particle has more than about one-half of the critical mass-energy density of the universe, the universe will enter a second radiation dominated epoch at a time $t \approx \tau$. In this case one should use the appropriate parameter values listed below.

III. COMPARISON WITH OBSERVED SPECTRUM

The observed intensities (with 1σ errors) at energies of 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, and 10.0 MeV are given by Trombka *et al.* (1977). The underlying power law is given by Schönfelder, Graser, and Daugherty (1977) and is $I_{pL} = 1.1 \times 10^{-2} [E(\text{MeV})]^{-2.3}$ photons $\text{MeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. For comparison with the observations we multiply the calculated spectrum (given by eq. [4]) by $c/4\pi$, so that this spectrum is in units of photons $\text{MeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{ster}^{-1}$. At any given energy E_0 , the intensity of decay photons is $I_{\text{decay}\gamma} =$

$(\kappa_m c/4\pi)E_0^{1/2}e^{-(\kappa_\gamma E_0)^{3/2}}$ in a matter-dominated universe. The expected total intensity at an energy E_0 is the sum of that due to the decay photons and the underlying power law: $I_{\text{total}}(E_0) = I_{\text{decay}\gamma}(E_0) + I_{pL}(E_0)$. This is calculated at energies E_0 of 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, and 10.0 MeV. The parameters κ_m and κ_γ are adjusted until the calculated spectrum gives a minimum χ^2 when compared with the observed spectrum. Figure 1 displays the calculated spectrum (*solid line*) along with the observed data points. A minimum χ^2 is obtained for $\kappa_\gamma^{-1} \approx 2.5$ MeV and $\kappa_m(c/4\pi) \approx 0.0035$ photons $\text{MeV}^{-3/2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. The fit is accurate to the 99% confidence level. A similar result is obtained if the universe is radiation dominated during the epoch of the particle decay. In this case the fit yields a minimum χ^2 for $\kappa_\gamma^{-1} \approx 2.9$ MeV and $\kappa_\gamma(c/4\pi) = 0.0017$ photons $\text{MeV}^{-2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. The fit is accurate to the 94% confidence level. The calculated curve and the observed data points are displayed in Figure 2.

IV. IMPLICATIONS FOR THE PARTICLE PROPERTIES

The implications of these results are similar whether the universe is matter or radiation dominated during the decay epoch. The decay epoch must be subsequent to recombination ($z_{\text{rec}} \approx 10^3$) or the decay photons would be absorbed, the rele-

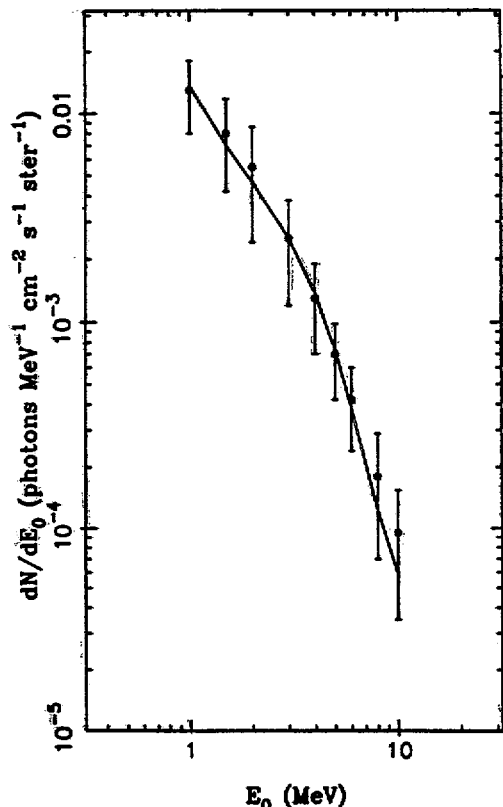


FIG. 1

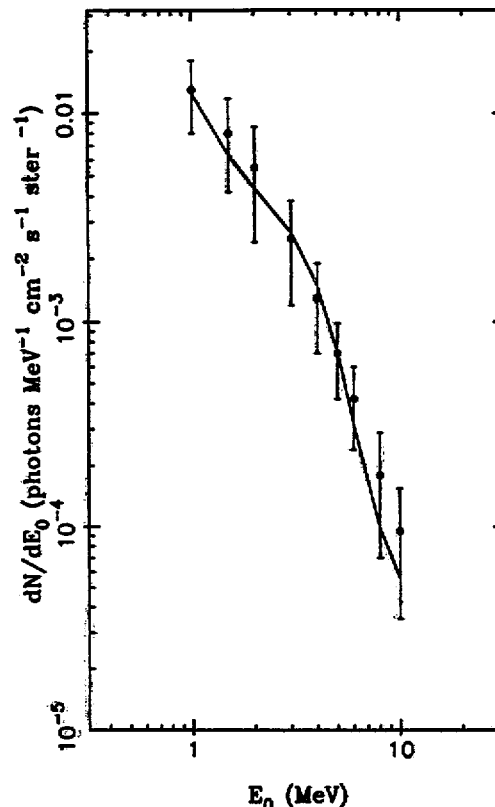


FIG. 2

FIG. 1.—Comparison of the calculated and observed spectrum of the 1–10 MeV shoulder. The solid line shows the sum of the calculated spectrum and the underlying power law for a matter-dominated, Einstein–de Sitter universe with $\kappa_\gamma^{-1} \approx 2.5$ MeV and $\kappa_m c/4\pi \approx 0.0035$ photons $\text{MeV}^{-3/2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. The observed intensities are denoted by points with 1σ error bars. The fit is accurate to the 99% confidence level.

FIG. 2.—Comparison of the calculated and observed spectrum of the 1–10 MeV shoulder assuming the universe is radiation-dominated during the decay epoch. The solid line shows the sum of the calculated spectrum and the underlying power law for a radiation-dominated, Einstein–de Sitter universe with $\kappa_\gamma^{-1} \approx 2.9$ MeV and $\kappa_\gamma c/4\pi \approx 0.0017$ photons $\text{MeV}^{-2} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. The observed intensities are denoted by points with 1σ error bars. The fit is accurate to the 94% confidence level.

vant cross section being that for pair production (Olive and Silk 1985; Babul, Paczyński, and Spergel 1987). Unless the universe enters a second radiation-dominated phase at redshifts less than z_{rec} (as it will if the unstable particles have an initial mass-energy density greater than about one-half of the critical density of the universe), the universe must have been matter-dominated during the decay epoch. We first discuss implications assuming the universe is matter-dominated during the decay epoch, and comment later on constraints if the universe is radiation dominated during the decay epoch.

A fit to the observed spectrum, assuming the universe to be matter-dominated during the decay epoch gave $\kappa_\gamma^{-1} \approx 2.5$ MeV, where $\kappa_\gamma^{-1} = E_\gamma(1+z_d)^{-1}$ is the energy a decay photon produced at a redshift z_d has at a redshift of zero. Since the photons which extend up to 10 MeV must have been produced at redshifts greater than or equal to zero, we know that $(1+z_d) \geq 4$. Also $z_d \lesssim z_{\text{rec}} \approx 10^3$. The decay photon has an energy E_γ when it is produced, $E_\gamma = \kappa_\gamma^{-1}(1+z_d)$. Hence, $10 \text{ MeV} \lesssim E_\gamma \lesssim 2.5 \text{ GeV}$. If the unstable particle has a mass $m = 2E_\gamma$, then the particle mass m lies in the range $20 \text{ MeV} \lesssim m \lesssim 5 \text{ GeV}$.

In a matter-dominated, Einstein-de Sitter universe $\tau = t_0(1+z_d)^{-3/2}$. For $(1+z_d)$ ranging from 5 to 10^3 , the lifetime of the particle ranges from $3 \times 10^5 \text{ yr} \lesssim \tau \lesssim 9 \times 10^9 \text{ yr}$ for $t_0 \approx 10^{10} \text{ yr}$, where t_0 is the age of the universe at the current epoch.

A relationship between the lifetime of the unstable particle and the photon energy E_γ may be obtained from the relations $E_\gamma = \kappa_\gamma^{-1}(1+z_d)$ and $\tau = t_0(1+z_d)^{-3/2}$. These imply that

$$\left(\frac{E_\gamma}{2.5 \text{ MeV}}\right) = \left(\frac{t_0}{\tau}\right)^{2/3}, \quad (6)$$

since $\kappa_\gamma^{-1} \approx 2.5$ MeV, where t_0 is the current age of the universe, τ is the lifetime of the unstable particle, and E_γ is the energy of the decay photon when it is produced. If $E_\gamma = m/2$, the mass of the unstable particle, m , is given by

$$\left(\frac{m}{5 \text{ MeV}}\right) = \left(\frac{t_0}{\tau}\right)^{2/3}. \quad (7)$$

The value of $\kappa_m c/4\pi$ of $0.0035 \text{ photons MeV}^{-3/2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ implies that

$$bn_{0m} \approx 3.8 \times 10^{-12} \text{ cm}^{-3}. \quad (8)$$

In addition

$$mn_{0m} = \rho_{0c} \Omega_i(m), \quad (9)$$

where n_{0m} is the initial number density (set at a time $\ll \tau$) of m scaled to the current epoch, ρ_{0c} is the critical density of the universe at the current epoch, and $\Omega_i(m)$ is the ratio of the average mass density of the particles m to the critical density set at $t \ll \tau$. Equations (8) and (9) imply that

$$\Omega_i(m) \approx \frac{3.6}{bh^2} \left(\frac{m}{\text{MeV}}\right) \times 10^{-10}. \quad (10a)$$

If $m = 2E_\gamma$, equations (7) and (10a) imply that

$$\Omega_i(m) \approx \frac{1.8}{bh^2} \left(\frac{t_0}{\tau}\right)^{2/3} \times 10^{-9}, \quad (10b)$$

or

$$\Omega_i(m) \approx \frac{1.8}{bh^2} (1+z_d) \times 10^{-9}. \quad (10c)$$

For $h \approx 0.5$, b equal to one or two, and $4 \lesssim (1+z_d) \lesssim 10^3$, $\Omega_i(m)$ ranges from $(1-4) \times 10^{-8}$ to $(3-7) \times 10^{-6}$. For $\Omega_i(m) \approx 1.0$ equation (10c) may be solved for the branching ratio, b , given the allowable values of z_d . For $h \approx 0.5$, $\Omega_i(m) \approx 1.0$ and $4 \lesssim (1+z_d) \lesssim 10^3$, $b \approx (3 \times 10^{-8})-(7 \times 10^{-6})$. If a specific particle physics model is chosen, the average mass-energy density in the unstable particle species relative to the critical density of the universe, $\Omega_i(m)$, may be related to the annihilation cross section of the particle (see, for example, Steigman 1979). Substituting this into equations (10), one may obtain a relationship between the branching ratio, the annihilation cross section, and the lifetime of the particle.

Similar conclusions are drawn if the universe is radiation-dominated from a redshift z_1 to a redshift z_2 . In this case, a fit to the observed spectrum yields $\kappa_\gamma^{-1} \approx 2.9$ MeV. Hence $(1+z_1) \geq 2.9(1+z_d)$ and $(1+z_2) \lesssim 0.29(1+z_d)$, so that photons with $1 \text{ MeV} \lesssim E_0 \lesssim 10 \text{ MeV}$ were emitted while the universe was radiation-dominated.

V. SUMMARY

Photons produced by a particle decay when the universe was young ($z_d \geq 3$) have a spectral shape remarkably similar to that of the 1-10 MeV shoulder, an unexplained feature of the extragalactic gamma-ray background. If the decay occurs in a matter-dominated, Einstein-de Sitter universe, the decay photon is produced with an energy $E_\gamma \approx 2.5(1+z_d)$ MeV, where z_d is the redshift at which the age of the universe is τ , τ being the lifetime of the unstable particle. The relationship between τ and z_d is $\tau = t_0(1+z_d)^{-3/2}$, where t_0 is the current age of the universe, $t_0 \approx 10^{10} \text{ yr}$. Therefore, the relationship between the lifetime of the unstable particle and the energy of the decay photon is $E_\gamma \approx 2.5(t_0/\tau)^{2/3}$ MeV. Simple arguments indicate that $4 \lesssim (1+z_d) \lesssim 10^3$ which implies that $3 \times 10^5 \text{ yr} \lesssim \tau \lesssim 9 \times 10^9 \text{ yr}$ and $10 \text{ MeV} \lesssim E_\gamma \lesssim 2.5 \text{ GeV}$. If $m = 2E_\gamma$, the mass of the unstable particle lies within the range $20 \text{ MeV} \lesssim m \lesssim 5 \text{ GeV}$. If one or two photons are produced per particle decay, the initial abundance of the unstable particles relative to the critical density of the universe is $\sim (1-4) \times 10^{-8}$ to $(3-7) \times 10^{-6}$ for $h \approx 0.5$ and $4 \lesssim (1+z_d) \lesssim 10^3$. If the initial abundance of the unstable particles is close to the critical density of the universe, the branching ratio is $\sim 3 \times 10^{-8}$ to 7×10^{-6} for $h \approx 0.5$ and $4 \lesssim (1+z_d) \lesssim 10^3$.

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