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METAGALACTIC GAMMA RAYS FROM RELATIVISTIC ELECTRON BREMSSTRAHLUNG INTERACTIONS

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METAGALACTIC γ-RAYS FROM RELATIVISTIC ELECTRON BREMSSTRAHLUNG INTERACTIONS

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Abstract: We present here γ-ray spectra calculated for relativistic electron bremsstrahlung interactions. We conclude that such spectra cannot match the form of the observed spectrum above 1 MeV as has been previously suggested.

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I. INTRODUCTION

The cosmic X-ray spectrum from nonrelativistic electrons has been calculated by Silk and McCray (1969) taking account of energy losses of the lower energy electrons by coulomb interactions with intergalactic gas as well as by expansion of the universe in calculating the equilibrium spectrum of extragalactic electrons as a function of redshift, z. Their suggestion was that the X-ray background spectrum (below 1 MeV) and particularly the apparent change in spectral index at about 40 keV might be explained by assuming an electron bremsstrahlung origin for this background. The results of a subsequent calculation of the intensity of cosmic-ray electrons needed to produce these X-rays as a function of redshift were given by Stecker and Silk (1969). The bremsstrahlung explanation of the X-ray background has been criticized on the basis that an injection of such a large quantity of nonrelativistic electrons into intergalactic space as would be needed to account for the X-ray background would possibly heat the intergalactic medium to 10^9K and distort the initial electron spectrum so as to make the Silk and McCray model invalid (Cowsik and Pal, 1971). Setti and Rees (1970) have also pointed out the problem of injecting nonrelativistic electrons into intergalactic space without large distortion of the electron spectrum in the sources themselves.

The above-mentioned problems are less severe when one considers relativistic electrons and it has recently been suggested by Silk (1970) that bremsstrahlung of relativistic electrons might account for the γ-ray background spectrum about 1 MeV, particularly the apparent flattening in the spectrum as observed by Vette, et al. (1970). Several other mechanisms have been suggested by various authors in order to account for this flattening as due to cosmic-ray interactions at high redshifts (Stecker, 1969 a,b; 1971), matter - anti-matter annihilation (Stecker, et al., 1971a), galactic electron bremsstrahlung (Rees and Silk, 1970), extragalactic proton bremsstrahlung (Brown, 1970) and nuclear emission lines (Clayton and Silk, 1969). Vette et al. (1970) have indicated that nuclear emission lines cannot account for the intensity of the γ-ray flux in the 3-6 MeV energy range observed by them. Jones (1971) has pointed out that the calculation of Brown is in error with regard to the shape of the proton-bremsstrahlung spectrum and that the cross sections for this process are, in any case, much too low to explain the intensity of the observed 1-6 MeV flux. Stecker, et al. (1971 b) have presented arguments against a galactic electron bremsstrahlung origin for the 1-6 MeV vlux. We have here calculated the γ-ray spectrum which would be produced by the extragalactic relativistic-electron bremsstrahlung hypothesis of Silk (1970); and the results, which we present here, indicate that such spectra cannot match the form of the observed γ-ray spectrum above 1 MeV.

II. THE METAGALACTIC ELECTRON SPECTRUM

The kinetic equation describing the evolution of relativistic electrons as a function of redshift, z, where the electrons undergo energy loss predominantly by Compton interactions with the universal blackbody radiation and due to expansion effects, has been given by Rozental and Shukalov (1970) in the form

$$\frac{\partial I_e}{\partial \omega} + \frac{3 I_e}{\omega} + \chi^2 \frac{\partial}{\partial \chi} \left\{ \left[\frac{\chi}{\omega} + \frac{X}{\omega^4} \phi(\omega) \right] \frac{I_e}{\chi^2} \right\} = \frac{\phi(\omega)}{H_0} Q(\omega, \chi) \qquad (1)$$

where I_e is the electron intensity as a function of ω and χ, $\omega \equiv (1+z)^{-1}$

and $\chi \equiv E_e^{-1}$. The quantity

$$\mathfrak{X} = \frac{1}{E_c} \simeq \frac{1}{130\ \mathrm{MeV}} \qquad (2)$$

where E_c is the critical electron energy defined as the energy an electron would have whose energy loss rate by Compton interactions equals that caused by the expansion of the universe at a redshift $z = 0 (\omega = 1)$. Electrons of greater energy will suffer energy loss primarily due to Compton interaction with the universal blackbody radiation. The quantity H_o is the Hubble constant. The cosmological function

$$\phi(\omega) \equiv \left[\frac{\omega}{\Omega + \omega(1-\Omega)} \right]^{1/2} \qquad (3)$$

where $\Omega = (8\pi G/3H_o^2)\, n_b \simeq 10^5 n_b$, n_b being the present mean matter density of the universe in cm^{-3}. $Q(\omega,\chi)$ is the electron source function.

The characteristic equation for equation (1)

$$\frac{d\chi}{d\omega} = \frac{\chi}{\omega} + \frac{\mathfrak{X}\,\phi(\omega)}{\omega^4} \qquad (4)$$

has a solution given by

$$\chi = \omega \left[\xi + \mathfrak{X} \int_{\omega_o}^{\omega} d\omega' \, \frac{\phi(\omega')}{(\omega')^5} \right] \qquad (5)$$

where ξ is an arbitrary constant.

Along a characteristic given by $\chi = \chi(\omega,\xi)$ from equation (5), equation (1) reduces to the ordinary differential equation

$$\left(\frac{dI_e}{d\omega} \right)_{\xi} + \frac{2I_e}{\omega} - \frac{2\mathfrak{X}\,\phi(\omega)\, I_e}{\chi\,\omega^4} = \frac{\phi(\omega)}{H_o}\, Q(\omega, \chi(\xi,\omega)) , \qquad (6)$$

which has a general solution of the form

$$I_e(\omega,\chi) = \chi^2\omega^{-4}\left\{\psi\left(\frac{\chi}{\omega} - \overline{X}\int_{\omega_0}^{\omega} d\omega' \frac{\phi(\omega')}{(\omega')^5}\right)\right.$$

$$\left. + \frac{1}{H_0}\int_{\omega_0}^{\omega} d\omega_1 \frac{Q\left[\omega_1, \omega_1\left(\frac{\chi}{\omega} - \int_{\omega_1}^{\omega} d\omega' \frac{\phi(\omega')}{(\omega')^5}\right)\right]\phi(\omega_1)\,\omega_1^2}{\left(\frac{\chi}{\omega} - \int_{\omega_1}^{\omega} d\omega' \frac{\phi(\omega')}{(\omega')^5}\right)^2}\right\} \tag{7}$$

where χ is an arbitrary function determined by the boundary conditions. The solution (7) to equation (1), as given by Rozental and Shukalov, may be obtained from equation (6) by using the method of variation of parameters.

We will consider here the examples discussed by Silk (1970) for cosmological models where $\phi(\omega) = 1$ (low density models) and where the function $Q(\omega,\chi)$ is a power law in energy of the form $\sim \chi^{\Gamma}$ and either a delta function in ω (burst model) or of the evolutionary form $\sim \omega^{-\beta}$.

For the evolutionary case

$$Q_\beta(\omega,E) = KE^{-\Gamma}\omega^{\beta}\theta_+(\omega-\omega_i) \tag{8}$$

where θ_+ is the Heavyside function defined by

$$\theta_+(x) \equiv \begin{cases} 1, & x>0 \\ 0, & x\leq 0 \end{cases} \tag{9}$$

and ω_i corresponds to the maximum redshift for production of cosmic-ray electrons, Rozental and Shukalov give the reduction of equation (7) as

$$I_e(E_e,\omega) = \frac{K}{H_0}E_e^{-2}\omega^{-4}\int_{\omega_k}^{\omega} d\omega_1\,\omega_1^{-\beta+\Gamma+2}\left(\frac{1}{E_e\omega} - \overline{X}\int_{\omega_1}^{\omega} d\omega' \frac{\phi(\omega')}{(\omega')^5}\right)^{\Gamma-2}\phi(\omega_1)\,\theta_+(\omega_1-\omega_i) \tag{10}$$

where $\omega_K(E,\omega)$ is determined implicitly by the relation

$$\frac{1}{E\omega} - \chi \int_{\omega_K}^{\omega} d\omega' \frac{\phi(\omega')}{(\omega')^5} = 0 \tag{11}$$

if $\omega_K > \omega_i$, $\omega_K \equiv \omega_i$ otherwise.

For the burst model

$$Q_S(\omega, E) = K E^{-\Gamma} \delta(\omega - \omega_i) \tag{12}$$

and for this case, equation (7) reduces to

$$I_e(E,\omega) = \left(\frac{K \omega_i^{\Gamma}}{H_0}\right) E^{-2} \omega^{-4} \left(\frac{1}{\omega E} - \chi \int_{\omega_i}^{\omega} d\omega' \frac{\phi(\omega')}{(\omega')^5}\right) \tag{13}$$

II. THE METAGALACTIC BREMSSTRAHLUNG γ-RAY SPECTRUM

Let us define the function

$$f(E_\gamma, \omega) = \frac{\langle\sigma_b\rangle}{E_\gamma} \int_{E_\gamma}^{\infty} dE_e \, I_e(E_e, \omega) \tag{14}$$

where $\langle\sigma_b\rangle \simeq 3.4 \times 10^{-26}$ cm^2. Then the bremsstrahlung γ-ray spectrum from relativistic electrons interacting with intergalactic gas of density $n(\omega)$ is well approximated by the relation

$$I(E_{\gamma_0}) = \frac{c}{H_0} n_0 \int_{\omega_i}^{1} d\omega \frac{\phi(\omega)}{\omega} f\left(\frac{E_{\gamma_0}}{\omega}, \omega\right) \tag{15}$$

where $E_{\gamma 0}$ is the presently observed γ-ray spectrum (see, e.g., Ginzburg and Syrovatskii, 1964; McVittie, 1965).

IV. RESULTS OF THE NUMERICAL CALCULATION

Equations (10), (13) and (15) were numerically evaluated for the assumptions discussed by Silk (1970) of $\omega_i = 1/3.5$, $\phi(\omega) \simeq 1$ (low density model, zero cosmological constant) and $\Gamma = 1.5, 2.5$. The resultant electron and γ-ray spectra for the present epoch (ω=1) are shown in figures 1 through 4. The spectral index, Γ', of these ω=1 spectra as a function of energy are shown in figures 5 through 8.

In these figures, we have indicated the energy E_B which corresponds to the maximum energy that electrons can have at $\omega = 1$ when propagating from $\omega = 1/3.5$. This limiting electron energy is obtained analytically by setting $\omega = 1$ in equation (13) and is found to be ~3.5 MeV. For $\Gamma < 2$, a pileup of electrons occurs at energies close to but smaller than E_B.

The assymptotic limits on the spectral indeces Γ' for the electron and γ-ray spectra are shown in the figures as obtained from the numerical calculation. These assymptotic limits may also be obtained analytically. For the electron spectra this can be done by solving equation (1) with I_e expressed as a power series in χ where the coefficients are functions of ω. For large χ ($E_e \ll E_B$) the leading term is the χ^{Γ} term and the other terms consist of algebraically lower powers of χ. For small χ ($E_e \gg E_B$) the leading term is the $\chi^{\Gamma+1}$ term and the other terms consist of algebraically higher powers of χ. Thus

$$\Gamma' \rightarrow \begin{cases} \Gamma, & E_e \ll E_B \\ \Gamma+1, & E_e \gg E_B \end{cases} \tag{16}$$

Equation (16) does not apply for the burst model, $Q(\omega,\chi) = Q_\delta$ for $E_e > E_B$ where I_e is identically zero. In this case, the boundary conditions require that all coefficients in the expansion be zero.

The spectral index of the γ-ray spectra for $E_{\gamma o} << E_B$ and $E_{\gamma o} >> E_B$ may be determined by taking the limits $E_{\gamma o} \to 0$ and $E_{\gamma o} \to \infty$ in Equation (15) with $f(E_{\gamma o}/\omega, \omega)$ given by Equation (14). It is found that for both the evolutionary and burst models that

$$\Gamma' \to \begin{cases} \Gamma , & E_{\gamma o} << E_B \\ \Gamma + 1 , & E_{\gamma o} >> E_B \end{cases} \tag{17}$$

The value of the spectral index for the γ-ray spectra at ω=1 is determined by electron bremsstrahlung interactions at all $1/3.5 \leq \omega \leq 1$ and is weighted more heavily by production at the higher redshift (smaller ω) as can be seen from Equation (15). At the higher redshifts, γ-rays of energy $E_{\gamma o} >> E_B$ are produced and there is no cutoff in the resultant γ-ray spectrum corresponding to the cutoff in the ω=1 electron spectrum for the burst model.

The results of our calculations as presented here indicate that the "qualitative" schematic spectra given by Silk (1970) for relativistic electron bremsstrahlung are in error.

The form of the γ-ray spectra produced by metagalactic electron bremsstrahlung interactions cannot be brought into agreement with the observational data on the γ-ray background spectrum, both as discussed by Silk (1970) and updated by Stecker et al. (1971a).

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FIGURE CAPTIONS

Figure 1 - Calculated Electron Spectra at ω=1 (z=0) Propagated from Source Spectra Proportional to $E_e^{-\Gamma}$ for Γ=1.5. ω_i=1/3.5, $\phi(\omega) \simeq 1$ and $E_B \simeq 3.5$ MeV as Explained in the Text.

Figure 2 - Calculated Electron Spectra at ω=1 (z=0) for Source Spectra with Γ=2.5.

Figure 3 - Bremsstrahlung γ-Ray Spectra at ω=1 (z=0) from Electron Source Spectra with Γ=1.5.

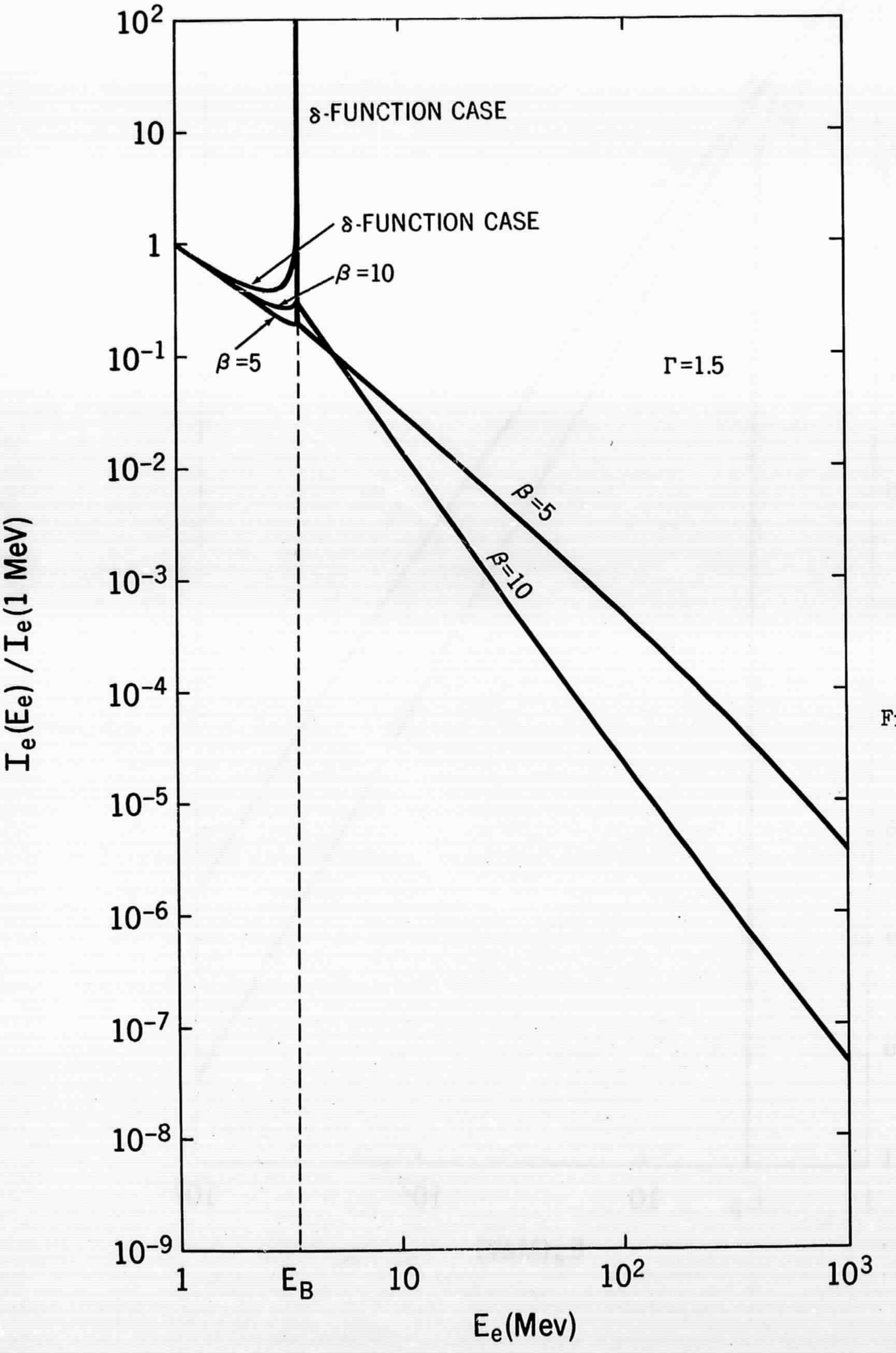
Figure 4 - Bremsstrahlung γ-Ray Spectra at ω=1 (z=0) from Electron Source Spectra with Γ=2.5.

Figure 5 - Spectral Index Γ' as a function of Energy for the Electron Spectra Given in Figure 1.

Figure 6 - Spectral Index Γ' as a Function of Energy for the Electron Spectra Given in Figure 2.

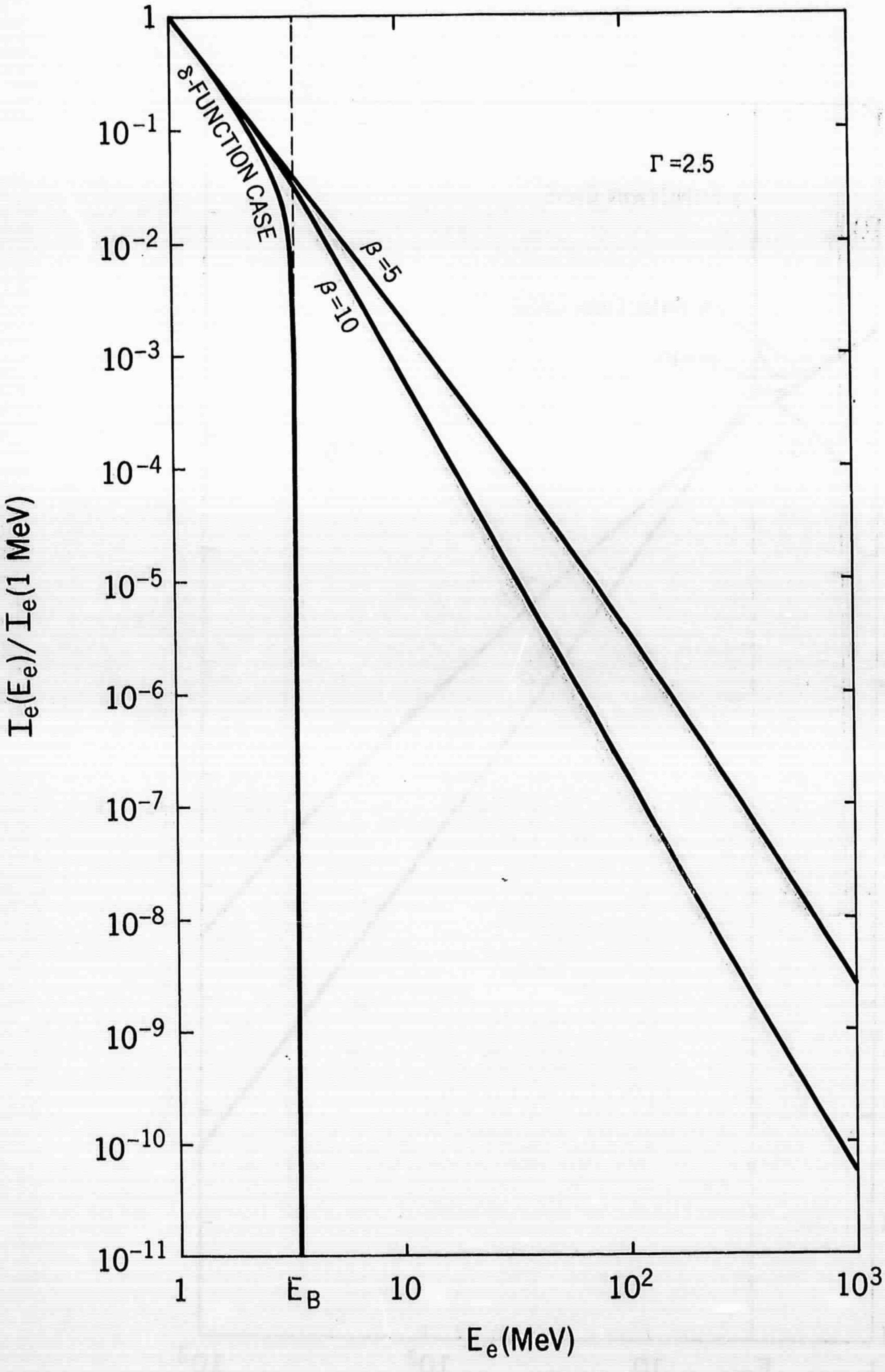
Figure 7 - Spectral Index Γ' as a Function of Energy for the γ-Ray Spectra Given in Figure 3.

Figure 8 - Spectral Index Γ' as a Function of Energy for the γ-Ray Spectra Given in Figure 4.



δ-FUNCTION CASE
δ-FUNCTION CASE
β =10
β =5
Γ=1.5
β =5
β =10
$I_e(E_e) / I_e(1\ MeV)$
E_e(Mev)
E_B
1
10
10^2
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}

Fig. 1



1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$I_e(E_e)/I_e(1\ MeV)$
δ-FUNCTION CASE
$\Gamma = 2.5$
$\beta = 5$
$\beta = 10$
1
E_B
10
10^2
10^3
E_e(MeV)

Fig. 2

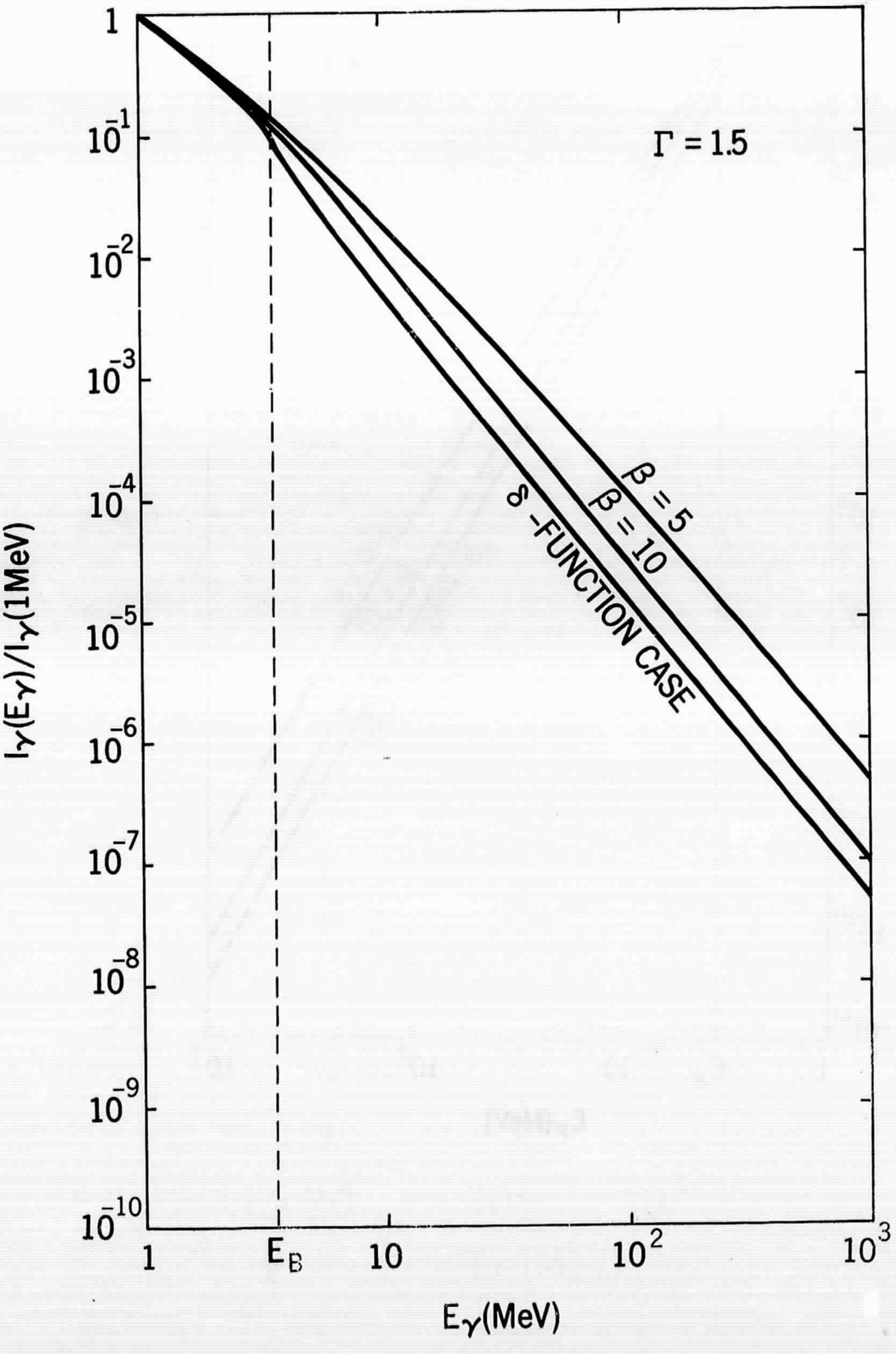

1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$I_\gamma(E_\gamma)/I_\gamma(1\,MeV)$
$\Gamma = 1.5$
$\beta = 5$
$\beta = 10$
δ -FUNCTION CASE
1
E_B
10
10^2
10^3
E_γ(MeV)

Fig. 3

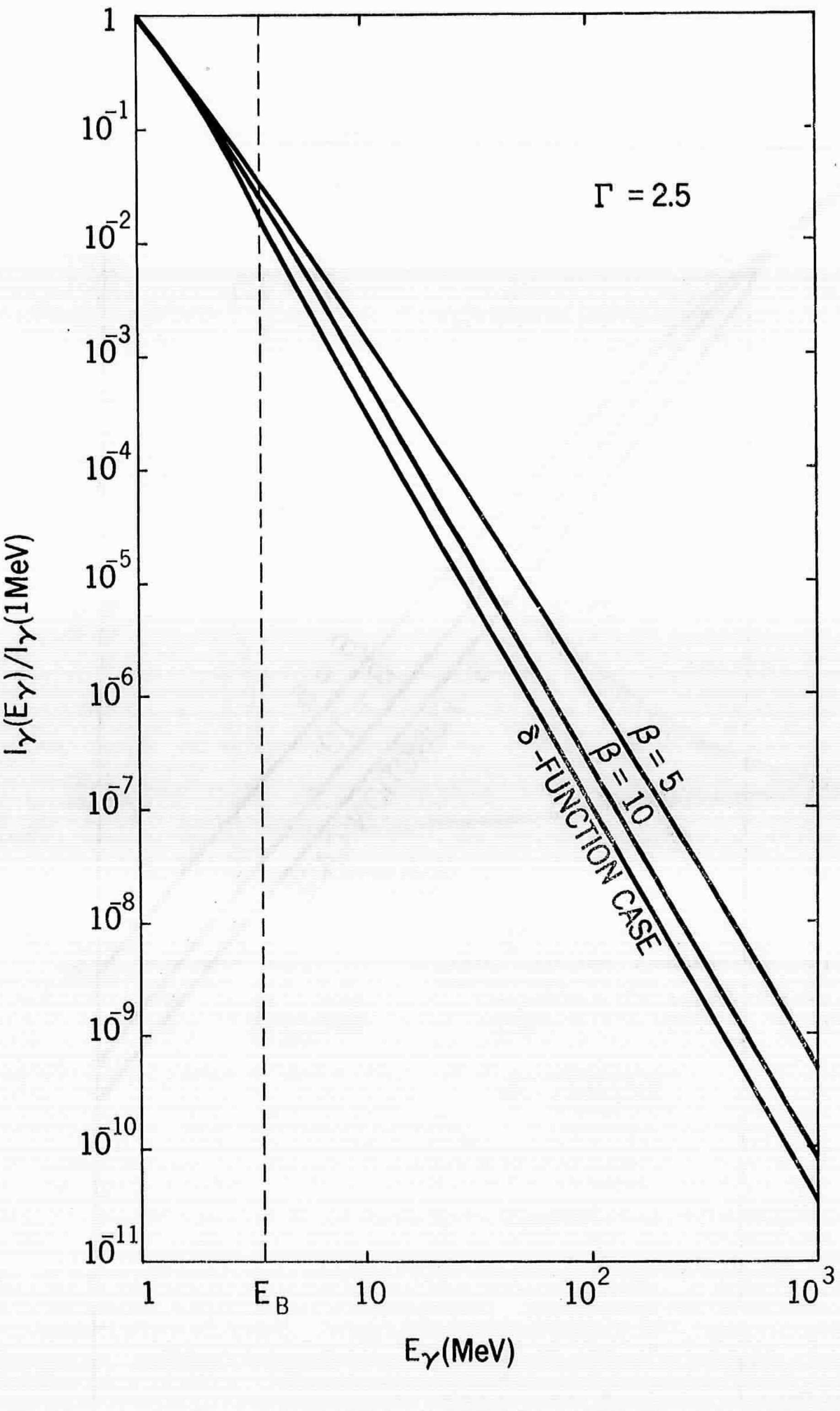

1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$I_\gamma(E_\gamma)/I_\gamma(1\,\mathrm{MeV})$
$\Gamma = 2.5$
$\beta = 5$
$\beta = 10$
δ-FUNCTION CASE
1
E_B
10
10^2
10^3
E_γ(MeV)

Fig. 4

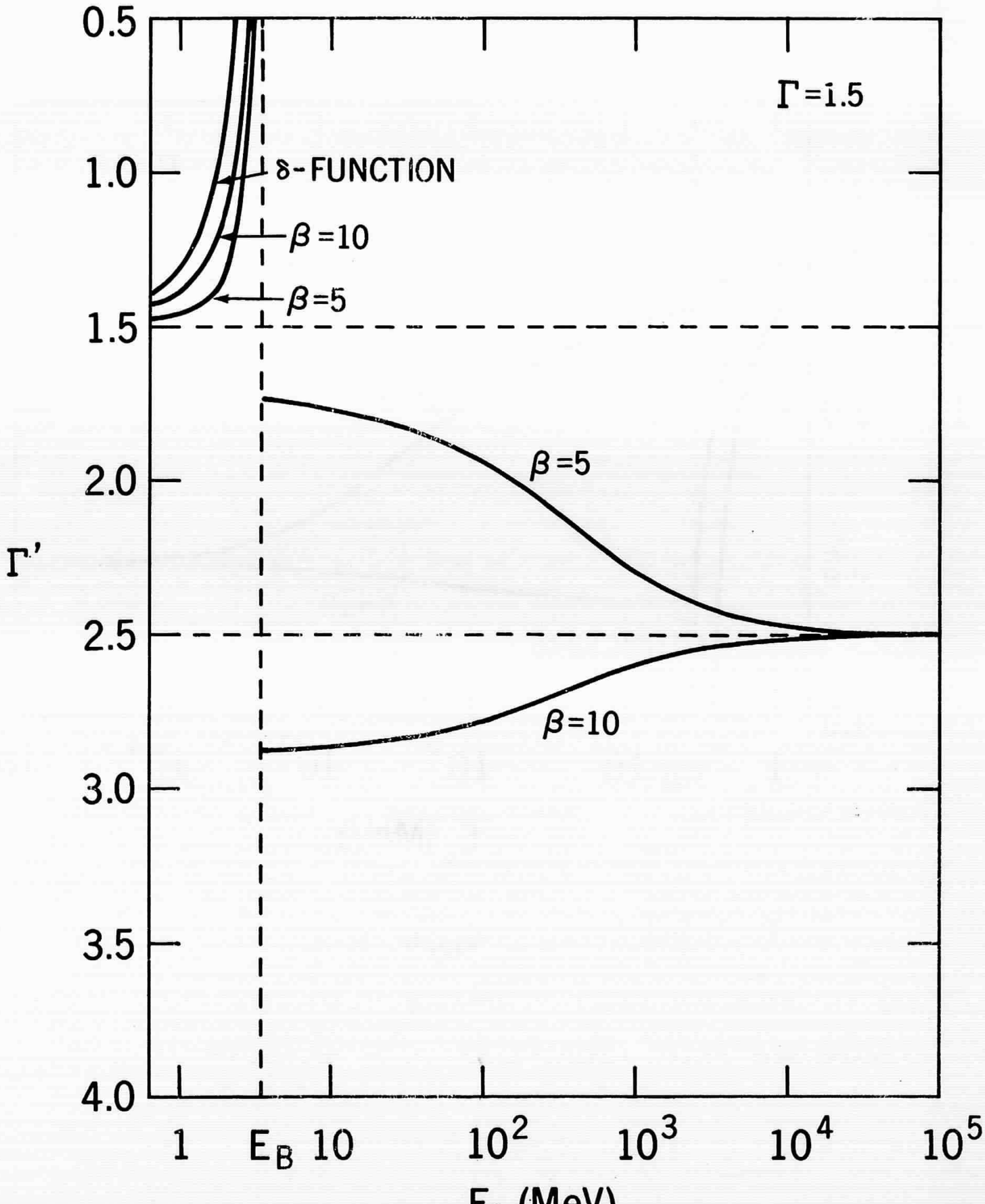

0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Γ'
Γ=1.5
δ-FUNCTION
β=10
β=5
β=5
β=10
1
E_B
10
10^2
10^3
10^4
10^5
E_e (MeV)

Fig. 5

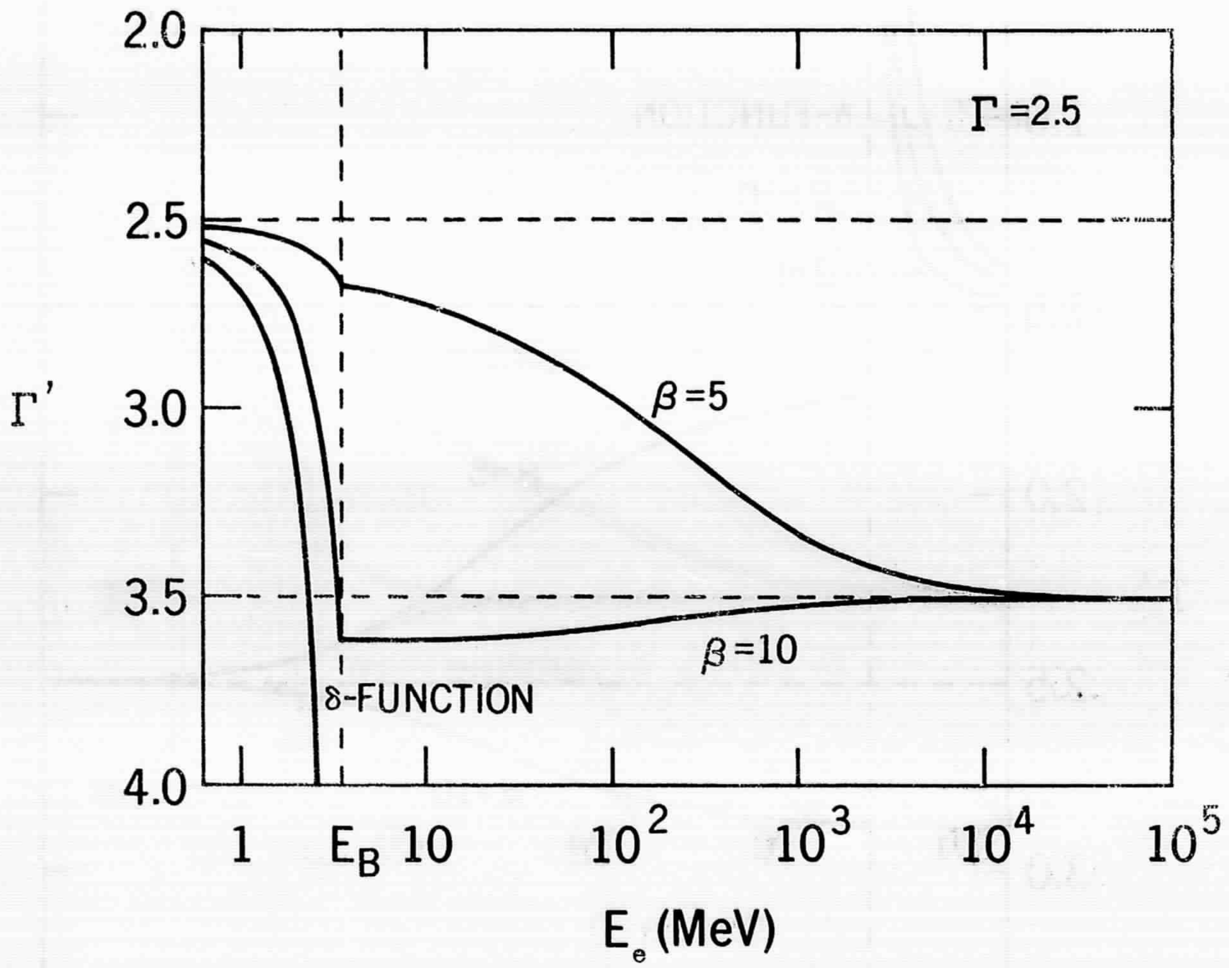
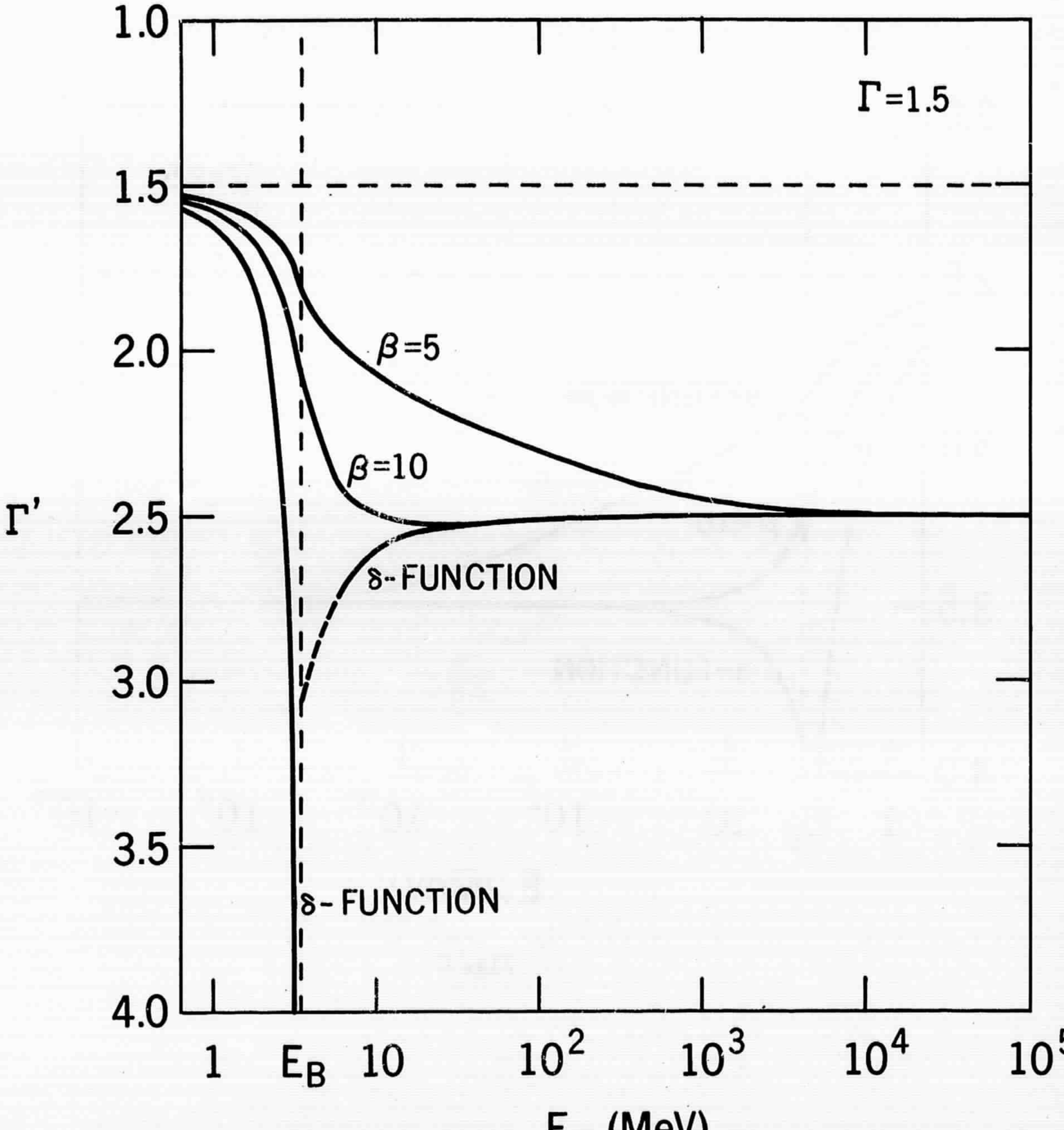
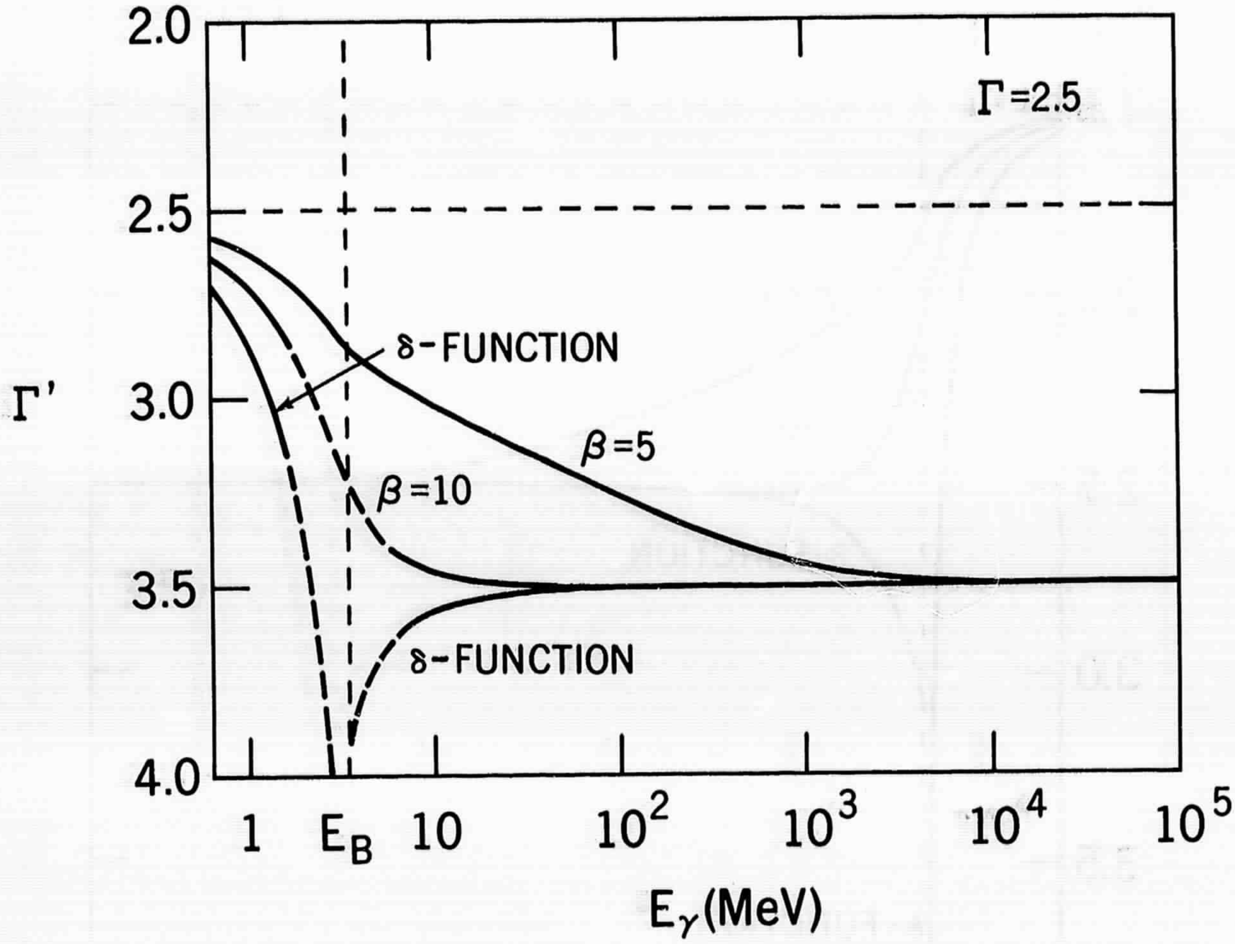

2.0
2.5
3.0
3.5
4.0
Γ'
Γ =2.5
β =5
β =10
δ-FUNCTION
1
E_B 10
10^2
10^3
10^4
10^5
E_e (MeV)

Fig. 6



Γ=1.5
β=5
β=10
δ-FUNCTION
δ-FUNCTION
Γ'
1.0
1.5
2.0
2.5
3.0
3.5
4.0
1
E_B
10
10^2
10^3
10^4
10^5
E_γ (MeV)

Fig. 7



2.0
2.5
3.0
3.5
4.0
Γ'
Γ=2.5
δ-FUNCTION
β=5
β=10
δ-FUNCTION
1
E_B
10
10^2
10^3
10^4
10^5
E_γ(MeV)

Fig. 8