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MAGNETIC PHOTON SPLITTING AND GAMMA-RAY BURST SPECTRA

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ABSTRACT

The splitting of photons into two photons becomes both possible and significant in magnetic fields in excess of 10^{12} Gauss. Below the threshold energy $2m_ec^2$ for single-photon pair production, splitting can be an astrophysically-observable phenomenon evident in gamma-ray burst spectra. In such circumstances, it has been found that magnetic photon splitting reprocesses the gamma-ray burst continuum by degrading the photon energy, with a net effect that is quite similar to pair cascade reprocessing of the spectrum. Results are presented for the spectral modifications due to splitting, taking into account the different probabilities for splitting for different polarization modes. Unpolarized and polarized pair cascade photon spectra form the input spectra for the model, which calculates the resulting splitting-reprocessed spectra numerically by solving the photon kinetic equations for each polarization mode. This inclusion of photon polarizations is found to not alter previous predictions that splitting produce a significant flattening of the hard X-ray continuum and a bump at MeV energies below a pair production turnover. The spectrum near the bump is always strongly polarized. The spectra of bursts detected by GRO may provide observational confirmation of magnetic photon splitting.

INTRODUCTION

Magnetic photon splitting $\gamma \rightarrow \gamma\gamma$ is an exotic and comparatively recent prediction of quantum electrodynamics in strong magnetic fields: the first correct calculations of the reaction rate were performed by Bialynicka-Birula and Bialynicki-Birula (1970), Adler *et al.* (1970) and Adler (1971). When $B = 0$, splitting is kinematically possible but is forbidden by a charge conjugation symmetry of QED known as Furry's theorem (e.g. see Jauch and Rohrlich, 1980). The theorem states that ring diagrams that have only external lines corresponding to photons, and that have an odd number of vertices, contribute zero to the interaction matrix elements. This symmetry is broken by the presence of an external field. The splitting of photons is therefore a purely quantum effect, and has appreciable reaction rates only when the magnetic field is at least a significant fraction of the quantum critical field $B_c = m_e^2c^3/(e\hbar) = 4.413 \times 10^{13}$ Gauss. Neutron stars, and especially gamma-ray bursts (GRB) associated with neutron stars, with their high γ-ray luminosities, therefore provide good environments for testing for the existence of splitting.

The potential importance of magnetic photon splitting, suggested by Baring (1988) and Mitrofanov *et al.* (1986), has been explored in detail by Baring (1991) in the context of spectral implications for gamma-ray bursts. Splitting was found to degrade the photon continuum in a manner similar to the reprocessing effect of a pair cascade. In magnetized neutron star environments, where $B \gtrsim 10^{12}$ Gauss, $\gamma \rightarrow \gamma\gamma$ produces a flattening of the hard X-ray continuum and a broad bump at energies around 1 MeV (Baring, 1991). This feature is potentially observable, and if detected, would be a significant verification of QED in strong magnetic fields. In particular, the instruments aboard the GRO mission have the capability to make such a detection. In the model of Baring (1991), the source of continuum photons was generated by a synchrotron radiation pair cascade initiated by some quasi-isotropic injection of non-thermal electrons.

Here the basic nature of the splitting process is reviewed, and the spectral modifications to the GRB continuum reconsidered: the new development in this work is the inclusion of an exact treatment of the individual polarization states of the photons participating in the splitting process. This extension of the work in Baring (1991) is an important step, particularly since it has long been recognized that splitting may be an important polarizing mechanism in neutron star sources such as pulsars (Adler *et al.*, 1970; Usov and Shabad, 1983). It is found here that consideration of the photon polarization states does not qualitatively change the spectral reprocessing nature of $\gamma \rightarrow \gamma\gamma$, and that the MeV bump still appears. However, the resultant spectra are strongly polarized by the splitting process, and any detailed GRB spectral model should include the photon polarizations in order to make quantitative predictions even for observational detections without polarimetric capability.

In this paper, it is convenient to use a simple dimensionless notation for various quantities in relativistic, magnetized environments. Therefore all magnetic fields will be expressed hereafter in units of the critical field B_c, and all photon and particle energies will be scaled by $m_e c^2$.

MAGNETIC PHOTON SPLITTING

Photon splitting is a third-order QED process that must have a reaction rate that is strongly dependent on the magnetic field strength. The calculation of its rate by standard QED techniques is both difficult and laborious, because of the complications introduced by the presence of the field. The most formidable difficulty is the complicated form for the electron propagator in the external field, which renders the evaluation of the general expression for the splitting rate analytically intractable. The earliest research on this process therefore specialized to the low photon energy $\varepsilon \ll 1$ (in units of $m_e c^2$), low field ($B \ll 1$) limit where dramatic simplifications can be made. This limit corresponds to the case of small dispersion. Since the presence of a magnetic field polarizes the vacuum, dispersive effects naturally occur. However when the field is low ($B \lesssim 0.1$) and the energy of photons that are splitting is moderate ($\varepsilon \lesssim 1$) these dispersive effects are small: this corresponds to the situation in gamma-ray bursts (Baring, 1991). The most general calculation of splitting valid for any values of ε and B was performed by Stoneham (1979).

The calculations of Bialynicka-Birula and Bialynicki-Birula (1970), Adler *et al.* (1970) and Adler (1971) were all in this limit of low dispersion. An expression for the splitting rate for this case, averaged over all photon polarizations, was obtained by Papanyan and Ritus (1972). For the splitting of photons of energy $\varepsilon m_e c^2$ with $\varepsilon \ll 1$ into photons of energies $\omega m_e c^2$ and $(\varepsilon - \omega) m_e c^2$, their result can be expressed as an optical depth for an emission region of size R (see Baring, 1991):

$$\tau_{sp}(\varepsilon, \omega) \approx \frac{3\alpha_f^3}{\pi^2} \left(\frac{19}{315}\right)^2 \frac{R}{\lambda_c} B^6 \sin^6\theta \, \omega^2 (\varepsilon - \omega)^2 \quad . \tag{1}$$

Here $\alpha_f \approx 1/137$ is the fine structure constant, $\lambda_c = \hbar/(m_e c)$ is the Compton wavelength, and θ is the angle of propagation of the photon that splits with respect to the field lines. This is also the propagation angle for both of the produced photons: by energy and momentum conservation the splitting process is collinear in the absence of dispersive effects. The total rate for photon splitting is obtained by integrating eq. (1) over ω, yielding

$$\tau_{sp}(\varepsilon) \approx \frac{\alpha_f^3}{10\pi^2} \left(\frac{19}{315}\right)^2 \frac{R}{\lambda_c} B^6 \varepsilon^5 \sin^6\theta \quad . \tag{2}$$

For neutron star atmospheres, $\tau_{sp}(\varepsilon)$ can be greater than unity if θ is not too small.

Adler (1971) observed that in the low-energy limit, the splitting rate had the same field dependence but a different magnitude for different combinations of the initial and final photon polarizations. Therefore, photon splitting must be a powerful polarizing mechanism. The polarization-dependent rates can be taken from eq. (23) of Adler (1971), which can be related to eq. (1), using the optical depth notation preferred here, via

$$\tau_{\perp\to\parallel\parallel} = \frac{1}{2}\tau_{\parallel\to\perp\parallel} = \left(\frac{13}{24}\right)^2 \tau_{\perp\to\perp\perp} = \frac{1}{6}\left(\frac{26}{19}\right)^2 \tau_{sp}(\varepsilon,\omega) \quad , \tag{3}$$

The photon polarization labelling convention of Stoneham (1979) is adopted here (this standard form was not used by Adler, 1971): the label $\parallel$ refers to the state with the photon's *electric* field vector parallel to the plane containing the magnetic field and the photon's momentum vector, while $\perp$ denotes the photon's electric field vector being normal to this plane. The splitting modes $\perp\to\perp\parallel$, $\parallel\to\perp\perp$ and $\parallel\to\parallel\parallel$ are forbidden in the low energy, low dispersion limit.

In order for photon splitting to have observable effects in gamma-ray burst spectra, not only must its optical depth in the GRB emission region exceed unity, but it must not also be dominated by any other photon absorption process. Its main rival as a mechanism for gamma-ray attenuation is single-photon pair production $\gamma \to e^+e^-$, which has a kinematic threshold at $\varepsilon \sin\theta = 2$. Above this threshold, which is strongly dependent on θ, the reaction rate for $\gamma \to e^+e^-$ is so great that it totally dominates photon splitting and renders the GRB emission region opaque to gamma rays (e.g. Baring, 1989). Therefore, as was deduced by Baring (1991), there is a small but significant energy range below the pair production threshold for which photon splitting can act effectively to modify the gamma-ray spectra, provided that θ is not small. This is sufficient for photon splitting to create observable effects in the MeV continuum of burst sources.

SPLITTING EFFECTS IN GAMMA-RAY BURST SPECTRA

The principal effect of photon splitting on a gamma-ray spectrum is to reprocess the spectrum by degrading the energies of the photons. A pile-up of photons might therefore be expected at energies near where the splitting optical depth in eq. (2) drops below unity, which is about 0.5 MeV when $\theta \approx \pi/2$ and $B \approx 0.1$. To determine the modifications that photon splitting makes to the gamma-ray burst continuum, it is appropriate to numerically solve the time-independent kinetic equations for the two photon polarization states. The solution then has two equilibrium populations, $n_\perp(\varepsilon)$ and $n_\parallel(\varepsilon)$, for the different polarizations. In the simplest model, photons can be injected into the neutron star magnetosphere with some energy distribution $q(\varepsilon)$ for a specific emission angle θ and then be allowed to split or escape from the emission region (the effect of pair production can be included in $q(\varepsilon)$). Since photon splitting is a collinear process, the kinetic equation can be solved separately for each θ, and then integrated over emission angles.

The kinetic equations can be written down quickly: the injection rates (possibly polarized) are $q_{\perp,\parallel}(\varepsilon)/t_{\rm esc}$ and the photon escape rates are $n_{\perp,\parallel}(\varepsilon)/t_{\rm esc}$, where $t_{\rm esc} = R/c$ is the photon escape time for the emission region. Note that here spatial and angular diffusion of the photons due to splitting is negligible because $\gamma \to \gamma\gamma$ is an angle-preserving process. Since photon splitting absorbs photons and also creates them at lower energies, it provides both source and loss terms to the kinetic equations. If σ denotes the polarization modes $\perp$ and $\parallel$, the loss terms are the absorption rates $\tau_\sigma(\varepsilon) n_\sigma(\varepsilon)/t_{\rm esc}$ ($\tau_\sigma(\varepsilon)$ is defined in eq. (4b)), while the source terms are proportional to the integral of the spectral rates in eq. (3) when weighted by the photon populations $n_\sigma(\varepsilon)$. The kinetic equations are therefore integral equations. Scaling by $t_{\rm esc}$, these equations assume the form

$$n_\sigma(\varepsilon)\{1 + \tau_\sigma(\varepsilon)\} = q_\sigma(\varepsilon) + 2\int_\varepsilon^\infty d\omega \sum_{\sigma',\sigma''} \tau_{\sigma'\to\sigma\sigma''}(\omega,\varepsilon)\, n_{\sigma'}(\omega) \quad , \qquad (4a)$$

for $\sigma = \perp , \parallel$, where

$$\tau_\sigma(\varepsilon) = \sum_{\sigma',\sigma''} \int_0^\varepsilon \tau_{\sigma\to\sigma'\sigma''}(\varepsilon,\omega)\, d\omega \qquad (4b)$$

is the absorption optical depth for polarizations $\sigma = \perp , \parallel$, obtained using eq. (3). Note that the term with the integral includes an extra factor of two to account for the duplicity of photons created in the splitting process. If the photon polarizations are unobservable, these two integro-differential equations reduce to one.

The injection spectrum $q(\varepsilon)$ is chosen to be a typical output of the synchrotron pair cascade model of Baring (1989). The continuum spectrum is therefore formed by synchrotron radiation, though it could also be produced by other mechanisms such as inverse Compton scattering and curvature radiation. For synchrotron photons supplied by non-thermal electrons, generally a power-law continuum results, though this is truncated due to the strong absorption of gamma-rays by pair production $\gamma \to e^+e^-$ (Baring, 1989). A canonical spectrum representing the injection expected from a synchrotron pair cascade is then

$$q_\sigma \;=\; \frac{Q_\sigma \varepsilon^{-(1+\alpha)}}{1+\tau_{pp}(\varepsilon)} \quad , \qquad \sigma = \perp, \parallel \; , \tag{5}$$

where the optical depth of the emission region (of size R) to single-photon pair production can be obtained from Baring (1991):

$$\tau_{pp}(\varepsilon) \;\approx\; \alpha_{\rm f}\,\frac{R}{\lambda_c}\,B\sin\theta\,\frac{3\varepsilon_\perp^2-4}{2\varepsilon_\perp^2(\varepsilon_\perp+2)^2}\,\sqrt{\frac{\varepsilon_\perp^2-4}{\phi(\varepsilon_\perp)\mathcal{L}(\varepsilon_\perp)}}\;\exp\biggl\{-\frac{\phi(\varepsilon_\perp)}{4B}\biggr\} \quad . \tag{6a}$$

Here $\varepsilon_\perp = \varepsilon\sin\theta$ and

$$\phi(\varepsilon_\perp) \;=\; 4\varepsilon_\perp - (\varepsilon_\perp^2-4)\mathcal{L}(\varepsilon_\perp) \qquad , \qquad \mathcal{L}(\varepsilon_\perp) \;=\; \log_e\biggl(\frac{\varepsilon_\perp+2}{\varepsilon_\perp-2}\biggr) \quad . \tag{6b}$$

This approximation is valid for $2 < \varepsilon_\perp \ll 1/B$, i.e. near the threshold for pair production. The spectral index α of the injection in eq. (5) is independent of the polarization state since synchrotron radiation and most other radiation mechanisms do not produce polarization-dependent indices from non-thermal electrons. Validity of an injection such as in eq. (5) requires that the pair cascade spectrum is generated much faster than the photons can split. This injection is therefore physically reasonable because synchrotron radiation and pair production generally have much shorter timescales than does photon splitting.

The solutions of eq. (4) for an unpolarized injection of photons from a pair cascade are displayed in Fig. 1. The reprocessing effect of magnetic photon splitting generates an absorption of photons just below the pair production threshold and an overproduction of photons at lower energies. The net effect is a flattening of the hard X-ray continuum and a broad spectral bump around 0.5 MeV when the photon emission angle is $\theta = \pi/2$. This bump appears in both polarization states and is qualitatively similar to the prediction made in the work of Baring (1991), where consideration of the photon polarizations was neglected. It is clearly an observable feature, and is moved to higher energies and becomes less prominent as θ decreases. The pair production truncations to the hard gamma-ray spectrum are evident in Fig. 1 and generally occur at energies $\varepsilon \sim 2/\sin\theta$ for $B = 0.1$. The polarization $\mathcal{P}(\varepsilon)$ of the photons at energy ε is given by

$$\mathcal{P}(\varepsilon) = \left|\frac{n_\perp(\varepsilon) - n_\parallel(\varepsilon)}{n_\perp(\varepsilon) + n_\parallel(\varepsilon)}\right| \quad , \tag{7}$$

and is clearly quite large in Fig. 1. In fact, in the idealized situation that the emission region has an enormous optical depth to $\gamma \to \gamma\gamma$, repeated splitting of photons generates a strongly-polarized photon population, 5/7 of which is in the $\perp$ state: this result can be obtained from a close consideration of eqs. (3) and (4). This preferential polarization of the continuum, corresponding to $\mathcal{P} = 3/7$, is realized near the $\gamma \to e^+e^-$ cutoff for the $\sin\theta = 1.0$ case in Fig. 1.

The photon injection from a synchrotron pair cascade will not be unpolarized, as assumed in Fig. 1, so a more realistic injection is needed. Standard synchrotron radiation

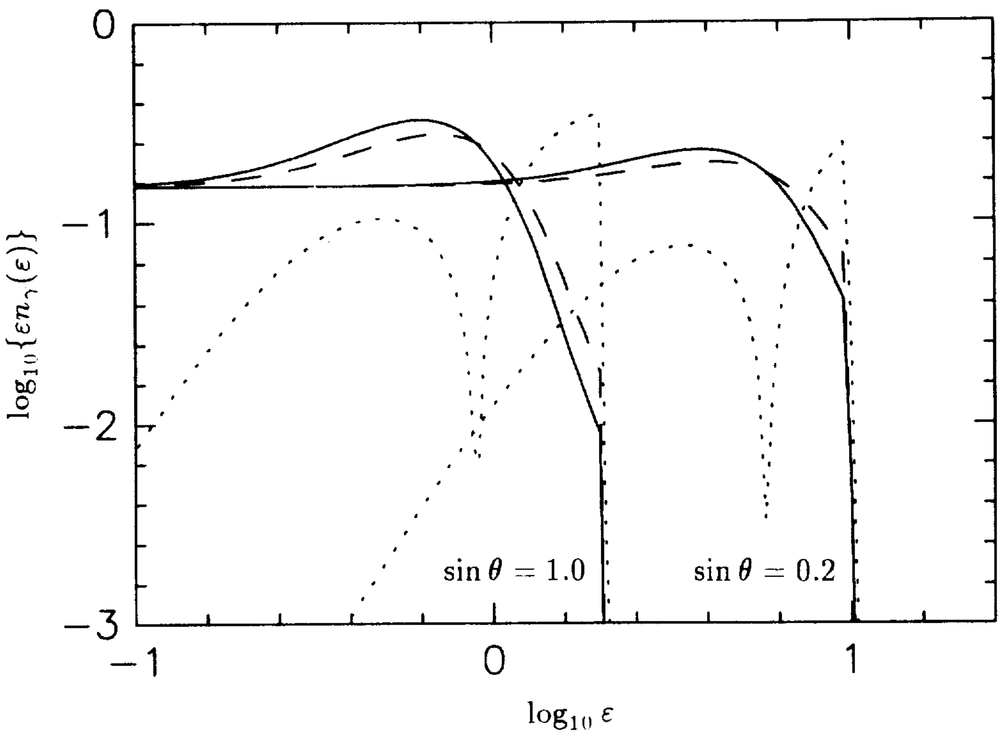

Fig. 1: The solutions of the photon kinetic equations in eq. (4), illustrating the reprocessing effects of splitting for different emission angles θ. The polarization components $n_\perp(\varepsilon)$ (solid curves) and $n_\parallel(\varepsilon)$ (dashed curves) of the photon spectrum are shown. The injected photon spectrum is a truncated power-law as in eq. (5) with $\alpha = 0$, and is unpolarized ($Q_\perp = Q_\parallel$). The field is $B = 0.1$. The dotted curves depict the polarization $\mathcal{P} = |(n_\perp - n_\parallel)/(n_\perp + n_\parallel)|$. Reducing θ clearly diminishes the reprocessing and polarization effects of splitting.

theory for power-law electrons predicts that a synchrotron spectrum of index α will have a corresponding polarization $\mathcal{P} = (\alpha+1)/(\alpha+5/3)$ (e.g. see Bekefi, 1966), independent of the photon energy. This corresponds to $n_\perp(\varepsilon)/n_\parallel(\varepsilon) = 3\alpha + 4$, which for $\alpha = 0$ is 4. The pair production process only generates non-thermal pairs and so does not influence the synchrotron polarization. Fig. 2 shows the photon splitting-reprocessed spectrum for the case of a synchrotron injection spectrum that is polarized according to the above prescription (i.e. $Q_\perp/Q_\parallel = 3\alpha + 4$). Clearly the synchrotron polarization tends to dominate the emergent photon polarization, without affecting the prominence of the splitting bump. However, in contrast to Fig. 1, near the pair production cutoff, where photon splitting is most effective, $\gamma \to \gamma\gamma$ actually acts to *depolarize* the synchrotron radiation towards the value of $\mathcal{P} = 3/7$ that is "preferred" by magnetic splitting.

Modelling gamma-ray burst spectra could plausibly include an integration over emission angles θ: indeed observations are unlikely to sample just a single value of θ. This can be represented by an enveloping of spectra like those in Fig. 1, resulting in Fig. 3 when summed over polarizations. The angular distribution of radiation is chosen for

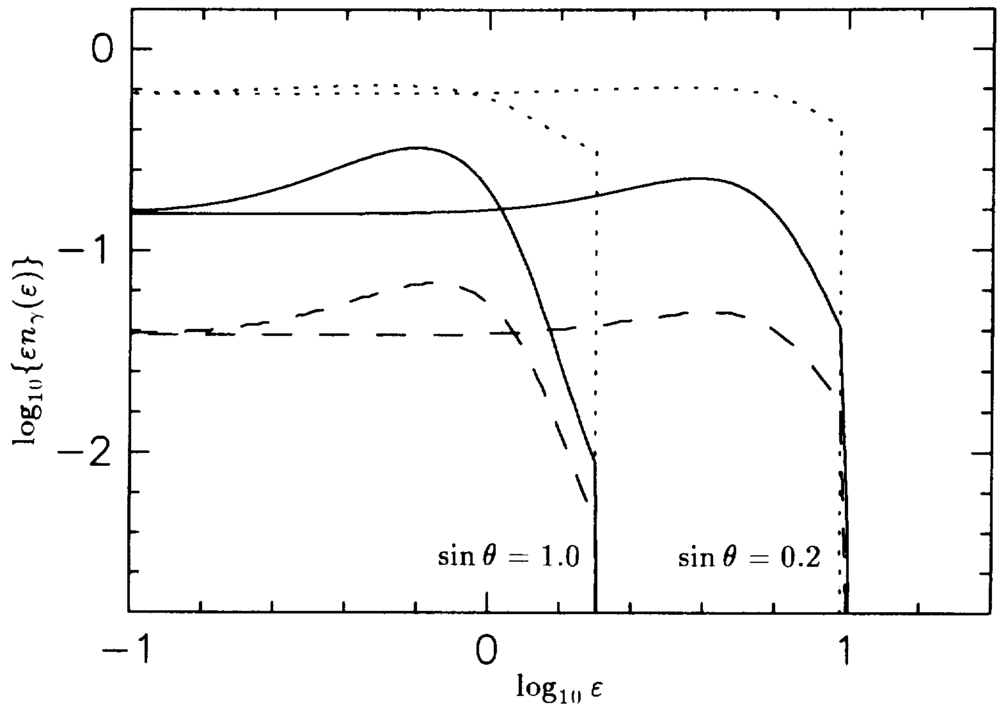

Fig. 2: The solutions of the photon kinetic equations in eq. (4), for a case almost identical to that depicted in Fig. 1: here the photon injection is again a truncated power-law with $\alpha = 0$, but this time it is polarized as would be expected from synchrotron radiation (i.e. $Q_\perp/Q_\parallel = 3\alpha + 4 = 4$). The reprocessing due to splitting is again evident, however now the polarization is mostly determined by the synchrotron process.

convenience (see Baring, 1991) to be $\phi(\sin\theta) = \sin^\kappa\theta$, and negative values of κ occur in models where the emitting electrons cool in energy and decrease their pitch angle during their synchrotron emission lifetime (this amounts to a pile-up of electrons with small pitch angles). The high-energy spectral break is by an index (see Baring, 1991) of $(1 + \alpha + \kappa)$, which becomes zero when $\kappa = -(1+\alpha)$. It is due to the enveloping of the pair production cutoffs for different θ. The photon splitting bump in the continuum around 1 MeV, which is still polarized, remains very prominent. The bump appears near 1 MeV because the dominant contribution to the splitting reprocessing comes from $\theta \approx \pi/2$: it is unlikely to be confused with a two-photon pair annihilation line because it is so broad (Baring, 1991).

In conclusion, magnetic photon splitting can produce a significant bump in the gamma-ray spectrum of GRBs, a prediction that is not altered by the accurate treatment of the photon polarization states that is presented here. The instruments aboard the GRO mission have the capability to detect this feature in burst sources, which would then be an important verification of the theory of quantum electrodynamics in strong magnetic fields.

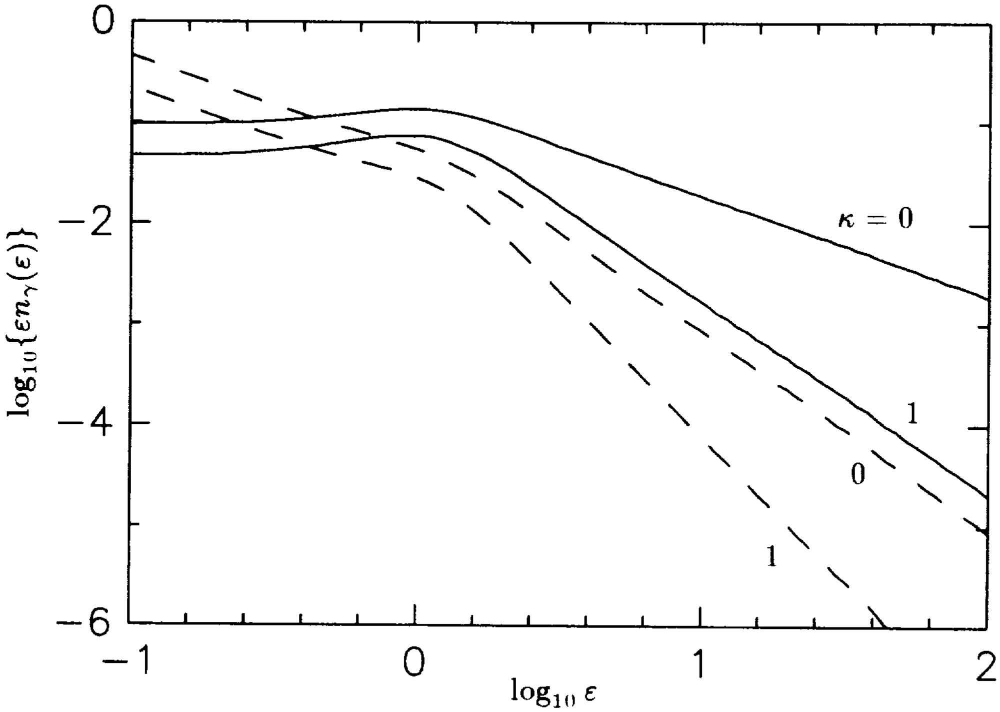

Fig. 3: Photon spectra resulting from an integration over emission angles and a sum over photon polarizations of spectra like those in Fig. 1, for $B = 0.1$. The sum is weighted by the angular distribution $\phi(\sin\theta) \propto \sin^\kappa\theta$, with κ as labelled. The photon injections are unpolarized ($Q_\perp = Q_\parallel$), truncated power-laws as in eq. (5), with $\alpha = 0$ (solid lines) and $\alpha = 1$ (dashed lines). The splitting bump is more pronounced for flatter spectra, and the overall spectral break is $(1 + \alpha + \kappa)$.

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