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SUPRATHERMAL PROTON BREMSSTRAHLUNG

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With the advent of X-ray and gamma ray astronomy, there has been a revival of theoretical interest and study of those physical processes capable of producing energetic photons.

One such process that has been studied recently is suprathermal proton bremsstrahlung. In this process, a suprathermal proton, or if you prefer, simply an energetic proton, strikes a relatively motionless electron in a background plasma and causes the electron to radiate.

We are interested in knowing for this process the differential cross section as a function of energy of the emitted photon. This cross section has been calculated by several authors using a method that I will discuss very briefly in just a moment. I have calculated this cross section by a method that I believe is considerably superior to the conventional one in the case of relativistic collisions, and in doing this I believe I have been able to correct a rather serious error regarding the relativistic cross section only, that existed in the literature.

To understand the conventional method of calculating this cross-section, it is convenient to view this collision process from the point of view of the incoming fast proton. If you sit on this proton, in this frame of reference, what you see is that a fast electron comes whizzing by, is deflected in the proton's coulomb field, and in so doing radiates photons. Viewed from this frame, the process is just plain old bremsstrahlung, a simple process which has been known for a long time; the cross section of this process is described quite well by the Bethe-Heitler formula. The conventional approach, therefore, is to first view the process in the proton's rest frame, using the Bethe-Heitler formula, or a generalization of it, to obtain a resulting photon spectrum.

This result is then transformed, using the Lorentz transformation, back into the laboratory frame, in which it is the electron rather than the proton that is at rest. When the velocity of the incoming proton is much less than the velocity of light, the effect of the Lorentz transformation in this procedure on the photon's energy, in other words, the Doppler shift, is quite small. In fact, you can neglect it.

In this case, the cross section in the laboratory frame is really quite simple and, as Boldt and Serlemitsos (Ref. 1) here at Goddard have shown, it is simply the Bethe-Heitler formula, the same one you started with for bremsstrahlung in the first place, only with the provison that you must understand that the kinetic energy in this formula must refer to the kinetic energy of the electron as viewed in the proton's rest frame.

However, now, when the proton's velocity approaches that of light, the doppler shift actually becomes quite important in this transformation, and one must in fact keep track of the emission angles as well as the energy of the emitted photons in order to correctly transform the spectrum back into the laboratory frame.

This is in fact a very complicated and tricky procedure, and one that really requires a computer. The procedure has been attempted by Brown (Refs. 2 and 3), who obtained rather surprising result. He found that the total cross section for the process exhibited a rather sharp peak at a proton energy of 3.2 nJ (20 GeV), and then fell off rather rapidly above that energy. From this he deduced that the process could be responsible for a significant amount of the cosmic gamma rays seen above 0.2 pJ (1 MeV) or so by Vette et al. (Ref. 4) on the ERS 18 satellite.

This result actually was rather surprising because there is no characteristic energy of 3.2 nJ (20 GeV) in the quantum electrodynamics of electrons or protons. It is rather difficult to see how one could get a resonance of this kind in this type of a process.

It occurred to me that there was really a very much simpler way of calculating this cross section. The basic method one can use is called the Weizsäcker-Williams method, but as you might have guessed was actually first used by Fermi (Ref. 5).

In this approach, one begins by noticing the fact that in the rest frame of the electron, the coulomb field of the incoming proton is distorted, if you wish by the Lorentz transformation, such that it strongly resembles a plane pulse of radiation. Figure 1 shows what the fields, the electric and magnetic fields of either a stationary charge or a rapidly moving charge, would look like to someone watching them go by.

Actually one can exploit the similarity of this field for the moving charge to a radiation pulse by Fourier analyzing this pulse and considering the results obtained to represent the spectrum of simply an incoming burst of photons. You just pretend they are real photons. The radiation process is then considered to be nothing more than the Compton scattering of these photons off the stationary electron.

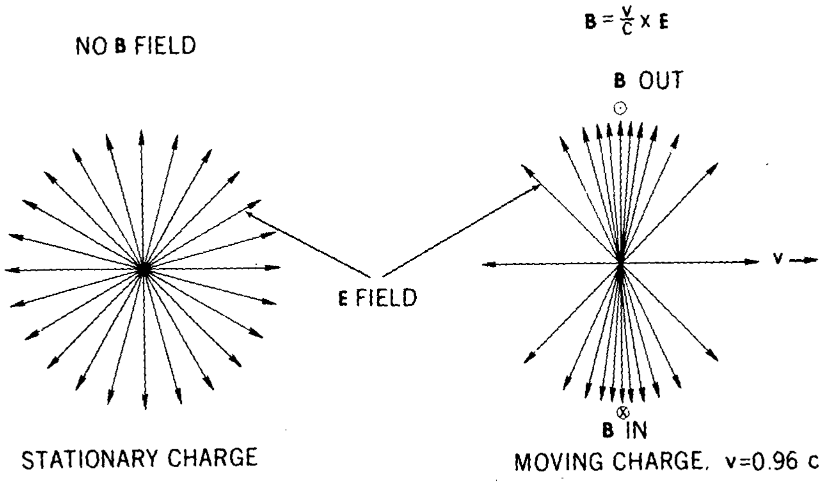

Figure 1–Electromagnetic field of stationary and moving charges.

Now, at this point you are essentially through with the calculation. There is no Lorentz transformation to perform, and there is no angle to consider. The only thing to do is to integrate the well-known cross sections for Compton scattering over the spectrum of these incoming photons.

The expression obtained from this is a single integral, and the expression for this incoming photon spectrum can be found in Jackson's book on classical electrodynamics (Ref. 6), among other places. The integral can be done analytically in fact, and the result can be obtained in a closed form. The results of the calculation are shown in Figure 2 as simple curves.

The cross sections are plotted as functions of the photons energy on the lower axis; the number labeling each curve is the proton's kinetic energy in nanojoules (gigaelectron volts).

One thing we should note is that these curves go smoothly right through 3 nJ (20 GeV) without a ripple. So I believe that the resonance that appeared in the earlier work does not exist. I think it was an artifact of the extremely complicated computation procedure that was needed in that method. This actually is the most pronounced difference between my result and those of Brown's, but it is by no means the only difference.

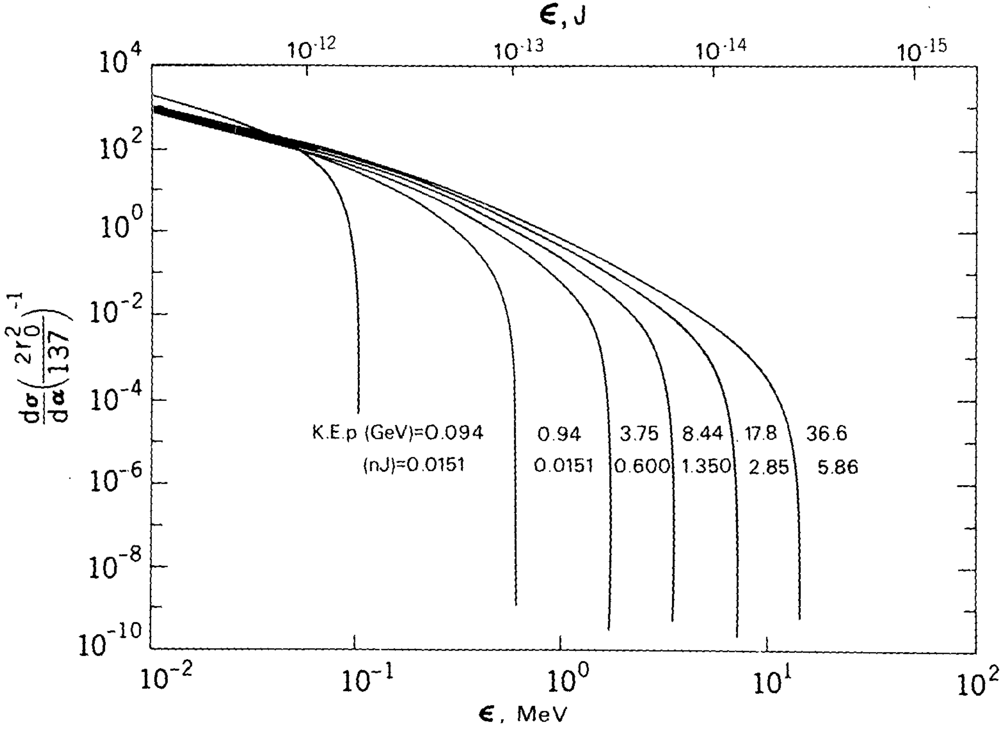

Figure 2–Results of calculations.

As I said, the expressions for these curves are a bit complicated, but for photons energies above about 0.2 pJ (1 MeV), the various curves obey an approximate scaling law rather well. Those with a practiced eye might actually be able to see that these curves essentially just displace along a diagonal line, as you go to high-energy protons.

But from the scaling law it is possible to deduce the photon spectrum that would arise from an inverse power law spectrum of protons. This actually can be done very quickly, using a method that I discussed about 4 yr ago at the cosmic ray conference in Calgary, and the result is that one would obtain an inverse power law spectrum of photons that is one power steeper than that of the incoming protons.

Since you would not expect a proton spectrum to be much flatter than E^{-2} you would not expect the photons spectrum resulting from this process to be much flatter than E^{-3}, which is in fact rather steeper than I believe is seen in gamma ray spectra around this energy. Therefore, you would not expect this process to contribute too significantly, at least not over any reasonable band of photon energies.

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