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Particle interactions in matter at the terascale: The cosmic-ray experience

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ABSTRACT

Cosmic-rays with energies up to 3×10^{20} eV have been observed, as have astrophysical neutrinos with energies above 1 PeV. In this talk, I will discuss some of the unique phenomena that occur when particles with TeV energies and above interact with matter. The emphasis will be on lepton interactions. The cross-sections for electron bremsstrahlung and photon pair conversion are suppressed at high energies, by the Landau–Pomeranchuk–Migdal (LPM) effect, lengthening electromagnetic showers. At still higher energies (above 10^{20} eV), photonuclear and electronuclear interactions dominate, and showers become predominantly hadronic. Muons interact much less strongly, so can travel long distances through solids before losing energy. Tau leptons behave similarly, although their short lifetime limits how far they can travel. The hadronic interaction cross-section is believed to continue to increase slowly with rising energy; measurements of cosmic-ray air showers seem to confirm this prediction.

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1. Introduction

Over the past 100 years, physicists have followed the cosmic-ray energy spectrum upward in energy. Modern large-acceptance detectors like the Flys Eye and Auger detector have observed cosmic-rays with energies up to 3×10^{20} eV. These cosmic-rays manifest themselves as particle showers, containing trillions of lower-energy particles, which cascade downward through the atmosphere. These cascades develop through hadronic and electromagnetic interactions which convert particle energy into additional particles.

Despite much effort, cosmic-rays are not yet well understood. We do not yet know their source(s) or their composition. Are they protons or heavier nuclei? The answer to this question requires a detailed understanding of the reactions that shape shower development. Several experiments are trying to determine their origin, by searching for cosmic neutrinos produced in these accelerators [1]. This requires an accurate understanding of how leptons interact with matter.

These neutrinos may be produced in astrophysical sources. Many possible sources have been proposed, ranging from active galactic nuclei (galaxies with supermassive black holes at the center) to gamma-ray bursts (the collapse of supermassive stars, and/or collisions involving blacks holes and neutron stars). One common, although not universal, feature of these models is that the neutrino spectrum is fairly hard, with the flux usually scaling as E_ν^{-2}; this E_ν^{-2} is assumed in most experimental studies. For an E_ν^{-2} spectrum, astrophysical neutrino detectors like IceCube and ANTARES are most sensitive to TeV and PeV neutrinos. As will be discussed below, IceCube has observed two neutrino events with energies slightly above 1 PeV (10^{15} eV), ushering in the era of terascale neutrino astrophysics.

Neutrinos are also produced when cosmic-ray protons with energies above 4×10^{19} eV interact with the 3 K microwave blackbody radiation and are photo-excited to the Δ^+ resonance. The Δ^+ decays, eventually producing neutrinos, mostly with energies in the 10^{17}–10^{20} eV range. Other experiments have searched for these Greisen, Zatsepin and Kuzmin (GZK) neutrinos, but are not yet sensitive enough to make definitive statements. They have, however, set flux limits for neutrinos with energies up to 10^{25} eV.

This writeup will review some of the unique physics that appears in particle interactions at the terascale, and thus relevant to cosmic-ray and astrophysical neutrino studies. I will emphasize phenomena that are unique to particle interactions in bulk matter, and are absent with individual atomic targets. These phenomena are most prominent in reactions involving photons and leptons, particularly electrons.

2. Electron and photon interactions

At energies above ≈ 50 MeV, electrons and photons interact predominantly through bremsstrahlung (braking radiation) and pair production respectively. In bremsstrahlung, an electron or positron interacts with a target nucleus and emits a photon, while in pair production, a photon interacts with a target and converts into an e^+e^- pair. These reactions share one key kinematic feature:

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as the incident particle energy increases, the longitudinal momentum transfer ($q_{||}$) from the target nucleus decreases. For bremsstrahlung of a photon with energy k from an electron with energy E [2],

$$q_{||} = \frac{km^2}{2E(E-k)} \quad (1)$$

where m is the electron mass. Per the uncertainty principle, the reaction is delocalized over a distance known as the formation length,

$$l_f = \hbar/q_{||} \quad (2)$$

For pair production, the situation is similar. For a pair with an invariant mass M_{ee},

$$q_{||} = \frac{M_{ee}^2}{2k} \quad (3)$$

with the formation length calculated the same way. Most pairs are produced with masses just above threshold, $M_{ee} \approx> 2m$ [3]. Throughout this review, E refers to electron energy, and k refers to photon energy, for both bremsstrahlung and pair production.

For very high energy particles, the formation length can reach macroscopic distances. For example, for a 10^{18} eV photon producing a 1 MeV (i.e. at threshold) pair, $l_f = 20$ cm. For bremsstrahlung, even longer formation lengths are possible. For a 10^{15} eV electron emitting a 1 GeV photon, the formation length is over a kilometer. When the formation length is longer than the inter-atomic distance a single electron or photon may interact simultaneously with multiple atomic targets, with the amplitudes adding, rather than the cross-sections. These delocalized interactions can lead to rather non-intuitive behavior.

For bremsstrahlung, the photon radiation depends only on the total electron multiple Coulomb scattering (MCS) in the formation length. This mean scattering angle accumulates as the square root of the number of scatterers, so scales as $\sqrt{l_f}$. Per standard electrodynamics [4]

$$\frac{d^2N}{dkd\Omega} = \frac{Z^2e^2\Gamma^4|\Delta\vec{v}|^2(1+\theta^4k^4)}{\pi^2c^3(1+\theta^2k^2)^4} \quad (4)$$

where N is the number of photons emitted, Z is the atomic number of the target atoms, e the electrical charge, Γ the projectile Lorentz boost, and $\Delta\vec{v}$ and θ the change in velocity and direction as the particle travels through the formation zone. When $\Gamma\theta < 1$, the $\sqrt{l_f}$ dependence leads to the same radiation as for independent scattering. However, when $\Gamma\theta > 1$, the denominator in Eq. (4) rises rapidly, and the radiation is less than it would be if the electron interacted independently with each target atom [5].

One can calculate the suppression fairly simply using an expanded version of Eq. (1) [2]. An additional term can account for the reduced longitudinal momentum due to multiple scattering (the momentum times $[1-\cos(\theta)]$). Multiple scattering is usually treated with a Gaussian approximation. Since the θ depends on l_f, and also partly determines it (by reducing the longitudinal momentum), some algebra leads to a quadratic equation for l_f. Radiation is suppressed by the ratio of the formation length with multiple scattering to that without it. When

$$\frac{k}{E} < \frac{E-k}{E_{LPM}} \quad (5)$$

bremsstrahlung is suppressed. Here, $E_{LPM} = 7.7X_0$ TeV/cm is a material dependent constant; X_0 is the radiation length. E_{LPM} decreases rapidly with increasing density and atomic number, so LPM suppression is most important in dense media. For example, E_{LPM} is 2.5 TeV in gold and 4.3 TeV in lead. For water, important for astrophysical neutrino detectors, $E_{LPM} = 278$ TeV. When k is smaller than in Eq. (5), the radiation is suppressed by $\sqrt{k}$, so $d\sigma/dk \approx 1/\sqrt{k}$. More detailed quantum–mechanical calculations have borne out the semi-classical derivation sketched out above. Fig. 1 shows the bremsstrahlung differential cross-section for a variety of different electron energies.

For $E \gg E_{LPM}$, the cross-section is greatly reduced except when $k \approx E$, and the electron typically transfers most of its energy to a photon. Pair production behaves similarly. For $k > E_{LPM}$, the cross-section is suppressed as $1/\sqrt{k}$. Symmetric pairs are the most suppressed, leaving pairs where the electron or positron takes most of the energy. Fig. 2 shows the pair production cross-section and normalized electron energy loss ($1/E dE/dx$). When $E \gg E_{LPM}$ an electron usually transfers most of its energy to a photon, which in turn transfers most of its energy to an electron or positron. Since all of these interactions are subject to LPM suppression, the shower develops much more slowly than for unsuppressed (Bethe–Heitler) cross-sections.

Bremsstrahlung photons can also interact with the medium, via forward Compton scattering. In more classical language, the dielectric constant of the medium differs from one, slowing down the photon. One way to understand this effect is to treat the photon as having a mass, $\hbar\omega_p$, where ω_p is the plasma frequency of the medium. In solid or liquid media, $\hbar\omega_p$ is 20–60 eV. Creating a massive photon requires additional momentum transfer from the medium, reducing the formation length and suppressing the emission. In solids, the photon mass significantly increases $q_{||}$ when $k/E < 10^{-4}$, and the bremsstrahlung cross-section is suppressed by the factor

$$\frac{k^2}{k^2 + (\gamma\hbar\omega_p)^2} \quad (6)$$

For $k < \gamma\hbar\omega_p$, the cross-section is strongly reduced, as $(\gamma\hbar\omega_p)^2/k^2$, and the bremsstrahlung cross-section scales as $d\sigma/dk \approx k$ The usual infrared divergence has naturally disappeared, and the total bremsstrahlung cross-section is finite! Of course, if the photon interacts in other ways, then these interactions can also suppress bremsstrahlung. For optical or X-ray photons, atomic physics plays a big role in regulating bremsstrahlung [6]. At very high energies, photon pair production limits the formation length to the photon interaction length (including the LPM effect), suppressing bremsstrahlung by the ratio of the pair production length to the unsuppressed formation length. An improved treatment adds an additional term to Eq. (1) to account for the finite pair production length [7].

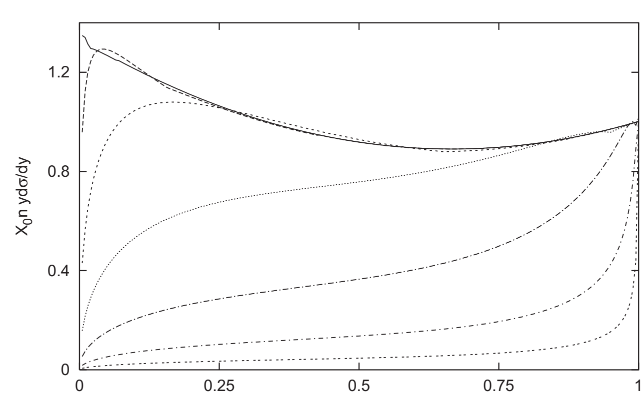

Fig. 1. The differential bremsstrahlung cross-section for different electron energies, in terms of $y = k/E$. For lead targets, the curves correspond to electron energies of 10 GeV (solid line, top), 100 GeV (moving downward), 1 TeV, 10 TeV, 100 TeV, 1 PeV and 10 PeV (bottom curve). The y-axis shows the normalized cross-section times photon energy, $yd\sigma/dy \cdot 1/X_0$. From Ref. [2].

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