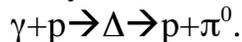


- 1) The speed of light in a medium of index of refraction n is c/n , where c is the speed of light in vacuum. Relativistic charged particles can travel in the medium with a velocity v such that $c/n < v < c$. In this case, the particle will emit visible light all along its trajectory. The light is emitted at an angle θ relative to the particle direction, with $\cos(\theta) = c/(nv)$. The index of refraction of water is 1.33 .

The relativistic energy E of a particle of rest mass m is

$$E = mc^2 \gamma \quad \gamma = [1 - \beta^2]^{-1/2} \quad \beta = v/c.$$

- The rest mass of the electron is $mc^2 = 0.511$ MeV. Find the β value (close to 1) of an electron of energy 5.11 MeV.
 - Find the Cerenkov angle for this electron in water.
 - What is the lowest energy electron that will produce Cerenkov light in water (this limit is $\beta = 1/n$ since the cosine function cannot be > 1).
- 2) An ultra-high energy cosmic ray proton can be slowed down by the following inelastic collision with the photons of the 3° K cosmic black body radiation (CBR)



The photons in the CBR have a typical energy of $2.5 \cdot 10^{-4}$ eV. The proton has a rest mass of $Mc^2 = 938 \cdot 10^6$ eV and the Δ -particle has a mass $M_\Delta c^2 = 1232 \cdot 10^6$ eV. Consider just the head on collision $\gamma + p \rightarrow \Delta$. Energy and momentum must be conserved in this reaction.

Energy Conservation $k + E = E_\Delta$.

Momentum Conservation $Pc - k = P_\Delta c$,

where k is the photon energy (and momentum times c), E is the proton energy, P is the proton momentum, E_Δ is the Delta energy and P_Δ is the Δ momentum. The following relativistic relation holds for any particle of mass m :

$$E^2 = (pc)^2 + (mc^2)^2.$$

- Using the energy and momentum conservation equations, as well as the energy-momentum-mass relation for the proton and Δ , find the minimum proton energy E such that the reaction $\gamma + p \rightarrow \Delta$ is allowed.