

However, there are other paths for protons to produce astrophysical radiation — direct collision of proton with another proton (or nucleus). This produces variety of unusual particles, such as neutral pion, π^0 .

π^0 is 2 quarks; superposition of up & anti-up ($u\bar{u}$) & down & anti-down ($d\bar{d}$). π^0 is its own antiparticle, so can directly decay into two photons.

Pions are lightest mesons, π^0 has $m_0^2 = 135 \text{ MeV}$.

If a relativistic proton has sufficient energy,

$p + p \rightarrow p + p + \pi^0$ is possible.

Must conserve both energy & momentum. We can automatically conserve momentum by using the center-of-mass frame. In that frame, we write an equation for E before vs. E after, assuming all particles stationary after; & both protons at γ before;

$$2\gamma m_p c^2 = 2m_p c^2 + m_\pi c^2$$

Use $m_p c^2 = 938 \text{ MeV}$, $m_\pi c^2 = 135 \text{ MeV}$. Then

$$2\gamma (938 \text{ MeV}) = 2(938 \text{ MeV}) + 135 \text{ MeV}$$

$$\gamma = \frac{2 \times 938 + 135}{2 \times 938} = 1.072$$

From $\gamma = \frac{1}{\sqrt{1 - (\frac{v}{c})^2}}$, can show

$$v = c\sqrt{1 - 1/\gamma^2}, \text{ so for } \gamma = 1.072, v = 0.36c.$$

Transform back to "lab" frame (where one proton is stationary), using

$$u_x = \frac{u'_x + v}{1 + vu'_x/c^2} \quad (\text{from transforms of } x, t)$$

$$u_x = \frac{(0.36 + 0.36)c}{1 + (0.36)^2} = 0.64c \quad \text{So protons at } > 0.64c \text{ can produce pions in collisions}$$

A neutral pion decays into two photons, each of $\frac{135}{2} = 68$ MeV in the pion's rest frame. However, the transformation to our observer frame will ~~dramatically~~ boost their energy, by factor γ .

Gamma-ray spectrum of galaxy

Observed γ -ray spectrum of galaxy shows peak at ~ 1 GeV from pion decay.

Contributions from IC, bremsstrahlung, & extragalactic background.

Another decay process relevant for X/ γ -rays; positron annihilation. Positrons produced in many radioactive decays, decelerated by bremsstrahlung until directly annihilate an electron, or form positronium with an electron.

If positronium has antiparallel spins, annihilates to make 2 photons, each of 511 keV.

If has parallel spins, must decay into 3 photons, each up to 511 keV.

511 keV line

Line shape thus includes sharp 511 keV peak & decreasing continuum below.

Positron annihilation strongest near Galactic Plane, with known sources including pulsars & SNRs.

Fermi map

High-quality maps of recent Fermi satellite identify diffuse emission (IC, pions — which correlate with density of target matter that is, molecular clouds —, and brems) & point sources (pulsars, SNR, AGN).

Suggestion of another γ -ray component at Galactic Center.

Spatial γ -ray dist

Can extrapolate observed γ -ray emission from disk & bulge of galaxy to predict flux at Galactic center.

Extended source of emission required around Galactic Center.

No astrophysical source of γ -rays can fully explain this — best candidate would be large numbers of radio pulsars, but not easy to produce enough.

Spectral distr.

Consistent with ρ^2 distribution, ^{predicted for dark matter} suggesting self-annihilation of dark matter.

Spectrum consistent with decay of ~ 8 GeV particles to taus (τ^+ , τ^- leptons), which decay to γ -rays & neutrinos, etc.

If true, represents first clear detection of dark matter. May be consistent with claimed detections of DM by DAMA and COGENT DM-detectors.

Possible support from WMAP. Annihilating DM may produce relativistic electrons, producing synchrotron radiation.

WMAP fg, haze

WMAP sees a "haze" near Galactic center that looks like synchrotron radiation.

Origin of these electrons uncertain, but could be DM.

Galactic center is most obvious place to look for indirect evidence of DM, e.g. annihilations. Also using small satellite galaxies, looking in X-ray & γ -rays.