EP228 Particle Physics

Topic 5
Cosmic Connection

Department of
Engineering Physics
University of Gaziantep

Course web page
www.gantep.edu.tr/~bingul/ep228

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Content

- Cosmic Rays
- Big-Bang
- Cosmic Microwave Background
- Greisen–Zatsepin–Kuzmin Limit (GZK Cutoff)
- Dark-Matter
- Dark Energy
- Exercises
Cosmic Rays
Early Attempts
Cosmic Rays

- Cosmic rays are energetic particles which do not originate from Earth.

- **Primary Cosmic Rays** originate from energetic processes on the Stars and travel interstellar medium.

- The cosmic radiation comes from Sun and outside the solar system (such as rotating neutron stars, supernovae)

- High energy primary cosmic rays collide with particles high in the atmosphere and cause jets of secondary particles known as **air shower**.
The primary cosmic radiation includes all stable charged particles and nuclei with lifetimes of order $10^6$ years or longer.

Electrons / Positrons
Protons / Antiprotons
Helium
Lithium
Beryllium
Boron
Carbon
Oxygen
Iron
Galactic Cosmic Rays

Solar Energetic Particles
(Solar Particle Events or Coronal Mass Ejections)

Galactic Cosmic Rays
- Major components of the primary cosmic radiation.
  * Protons ~ 90%
  * He ~ 9%
  * e\(^-\)s and other nuclei ~ 1%

- Note that some cosmic rays can have energies of over

\[10^6 \text{ GeV} = 1000 \text{ TeV} = 1 \text{ PeV}.

far higher than LHC protons (7 TeV)
AMS Experiment

The experimental challenge

DIRECT ≠ EASY!
May 19, 2011: AMS installation completed.
In 3 years we have collected 50 billion events.
This is much more than all Cosmic Rays collected over last century.
AMS Experiment

Positron Flux Data with AMS

E^3 Flux [GeV^3/(s sr m^2 GeV)]

Energy [GeV]
Cosmic Rays in Atmosphere

When primary cosmic rays hit Earth's atmosphere at around 30,000 m above the surface, the impacts cause nuclear reactions which produce pions, kaons and other unstable mesons called air shower.

\[ p + {O^{16}} \rightarrow n + \pi \]
\[ n + {N^{14}} \rightarrow p + {C^{14}} \]

This is important for radio carbon dating.
Cosmic Muons

- The newly produced (many) charged pions, quickly decay into muons.

\[
\begin{align*}
\pi^+ & \rightarrow \mu^+ + \nu_\mu \\
\pi^- & \rightarrow \mu^- + \bar{\nu}_\mu
\end{align*}
\]

and neutral pions decay mostly to two photons:

\[\pi^0 \rightarrow \gamma \gamma\]

- Many of these muons are able to reach the surface of the Earth. Since muons do not interact strongly with the atmosphere and the relativistic effect of time dilation.
Cosmic Muons

- Muons are ionizing radiation.
- Muons may easily be detected by many types of particle detectors such as: *Bubble Chambers* or *Scintillation detectors.*
Spectrum of muons at $\theta = 0^\circ$ (♦, ■, ▼, ▲, ×, +) and $\theta = 75^\circ$ ◊.
Muon charge ratio

\[ \frac{F_{\mu^+}}{F_{\mu^-}} \]

\[ p_\mu \quad [\text{GeV/c}] \]
Muon vertical intensity
Big-Bang

- Cosmological model to explain the universe today

- Expanding Universe …
  - Hubble Red shift (1924)
  - Cosmic Background (1964)
  - Temperature of the universe in Kelvin:

\[ T \approx 10^{10} / \sqrt{t} \]

\( t \) is the time in seconds.

Age of the universe is:
13.798 +- 0.037 billion years.

\[ T = 3 \text{ K} \]
Cosmic Background Radiation (CBR)

- Expanding universe cools down.
- CBR is the thermal radiation assumed to be left over from the "Big Bang" of cosmology.

With a traditional optical telescope, the space between stars and galaxies (the background) is completely dark. However, a sufficiently sensitive radio telescope shows a faint background glow, almost exactly the same in all directions.
Cosmic Background Radiation (CBR)

- WMAP data:
  The detailed, all-sky picture of the infant universe created from nine years of WMAP data. The image reveals 13.77 billion year old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become the galaxies. The signal from our Galaxy was subtracted using the multi-frequency data. This image shows a temperature range of ±200 microKelvin.
CBR & GZK cutoff

GZK cutoff is a theoretical upper limit on the energy of cosmic rays coming from "distant" sources.

Consider an ultra-relativistic proton ejected from a star. This proton may collide with a microwave from CBR photon and the following reactions can occur:

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ p + \gamma \rightarrow p + \pi^0 \]

Here, energy of the microwave photon is about:

\[ E_\gamma = kT = 2.63 \times 10^{-10} \, \text{MeV} \]
CBR & GZK cutoff

Question:
What is the threshold energy of proton starting the reaction?

\[ p + \gamma \rightarrow n + \pi^+ \]

Answer:

\[ E_p = \frac{(m_n c^2 + m_\pi c^2)^2 - (m_p c^2)^2}{4 E_{\gamma}} = 3 \times 10^{20} \text{ eV} \]

Above this energy no primary cosmic ray can be found.
CBR & GZK cutoff

Differential Flux $\times E^{2.5}$

$\left( m = 2.5 \times 10^{-16} \text{ GeV} \right)$

Energy of Nucleus (eV)

$10^{11}$ $10^{12}$ $10^{13}$ $10^{14}$ $10^{15}$ $10^{16}$ $10^{17}$ $10^{18}$ $10^{19}$ $10^{20}$

$10^0$ $10^1$ $10^2$ $10^3$ $10^4$
Hubble’s Law

- Speed of galaxies receding from the Earth is approximately proportional to their distance from the Earth.

\[ v = H \times d \]
Dark Energy

- 73% DARK ENERGY
- 23% DARK MATTER
- 3.6% INTERGALACTIC GAS
- 0.4% STARS, ETC.
Dark Matter

- Do not radiate and reflect electromagnetic wave
- Interacts with visible material

\[
\frac{mv^2}{r} = G \frac{mM}{r^2} \quad \rightarrow \quad v = \left(\frac{GM}{r}\right)^{1/2}
\]
End of Universe

- Critical Density

\[ \rho_c = \frac{3H^2}{8\pi G} \]

\[ = 10^{-26} \ \text{kg} \ \text{m}^{-3} \]

\[ = 10 \ \text{Hidrojen} \ \text{m}^{-3} \]

[nasa.gov]
Consider you have cosmic muon detector (counter) of square shape whose one side is 30 cm. Assume that the detection efficiency is 90%.

1. Estimate number of muons that will be detected by your counter at the see level per steradian in 1 hour using the figure on page 8.

2. In problem 1, assuming the muon charge ratio is $F_+/F_- = 1.3$, calculate number of positive muons which will be detected.

3. Consider that you place your counter at a level of 5 km under the Earth surface. Using the figure on page 11, compute how many hours you should wait to count 20 muons per steradian.

4. Show that GZK cutoff for the proton in the reaction $p + \gamma \rightarrow n + \pi^+$ is given by:

$$E_p = \frac{(m_n c^2 + m_\pi c^2)^2 - (m_p c^2)^2}{4E_\gamma}$$