Cosmic Rays, Physics, and Relativity

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Outline

• What are cosmic rays?

• Open issues in particle physics and some experiments addressing them (Auger, Fermi, LHC).

• The Standard Model of Particle Physics

• Einstein’s Relativity allows cosmic muons (which are unstable) to survive long enough to penetrate the atmosphere.
Cosmic Rays

- High energy particles coming from space (galactic or extragalactic).

- As a natural source of high energy particles, cosmic rays were critical to the discovery of the muon and many other particles in bubble chambers in the 1930s and 40s.

- Radio-carbon dating. Activated carbon created by cosmics:
  \[ n + ^{14}N \rightarrow p + ^{14}C \]
  \[ ^{14}C \rightarrow ^{14}N + e^- + \nu_e \]
Cosmic Rays

• In the 1930s and 40s, a wide variety of investigations confirmed that the primary cosmic rays are mostly protons, and the secondary radiation produced in the atmosphere is primarily electrons, photons and muons.

• On the ground we detect secondary particles created in a showers in the Earth’s atmosphere.
Cosmic Detector

- A muon comes streaking invisibly through the sky.
- It passes through the plastic scintillator, emitting light.
- The light triggers a Photomultiplier Tube (PMT), read by digital electronics.
Cosmic Ray Spectrum

many passing through you per second

10 cm$^{-2}$ s$^{-1}$

1 m$^{-2}$ s$^{-1}$

1 m$^{-2}$ yr$^{-1}$

1 km$^{-2}$ yr$^{-1}$

energy of a fast ball in baseball put into the kinetic energy of a single particle

Flux $F$ (m$^2$ sr s GeV$^{-1}$)

Energy $E$ (eV)

$E^{2.6} F(E)$ [GeV$^{1.6}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$]
Mysteries in Cosmic Rays

Some unanswered questions about cosmic rays:

- Are Active Galactic Nuclei (AGN) the source of ultra-high-energy cosmic rays?

- Does dark matter annihilation show up in high-energy cosmic rays? Dark matter is the unexplained part (85%) of matter observed gravitationally to exist in galaxies but hasn’t been seen to interact with other matter otherwise.

- Is the Greisen–Zatsepin–Kuzmin (GZK) limit obeyed? A cosmic upper-limit for the energy of a cosmic ray due to interactions with the CMB that would violate Relativity otherwise.
Pierre Auger Observatory

Highest energy cosmic ray observatory

Mendoza Province, Argentina

observes secondary cosmic rays in atmospheric showers
Fermi Gamma-ray Space Telescope observes primary cosmic photons (gamma-rays) from space.
Large Hadron Collider

- 27 km circumference
- 1232 dipoles: 15 m, 8.3 T
- 100 tons liquid He, 1.9 K
- p-p collisions at $\sqrt{s} = 7-8$ TeV
- inst. luminosity = $10^{32}-10^{34}$ cm$^{-2}$s$^{-1}$

- $10^{11}$ protons / bunch
- 1000 bunches/ beam
- 20 MHz, 50 ns bunch spacing
- 1-40 interactions / crossing
- $0.5 \times 10^9$ interactions / sec

Geneva, Switzerland
ATLAS is a 7 story tall, 100 megapixel camera, taking pictures of proton-proton collisions 20 million times per second, saving 10 million GB of data per year. The collaboration involves more than 3000 scientists and world-wide grid computing.
Particle physics deals with the fundamental particles that make up atoms.

**Standard Model**

- **Quarks**
  - u (up) (1964)
  - c (charm) (1974)
  - t (top) (1995)
  - d (down) (1964)
  - s (strange) (1964)
  - b (bottom) (1977)

- **Leptons**
  - e (electron) (1897)
  - μ (muon) (1936)
  - τ (tau) (1975)

- **Gauge bosons**
  - gluin (1979)
  - W\(^\pm\) (1983)
  - Z (1983)
  - γ (photon) (1900)

- **Higgs boson**
  - H (Higgs) (2012?)

**Chemistry deals with interactions among atoms.**

**Periodic Table of Elements**

- electron <10\(^{-16}\) cm
- proton (neutron) <10\(^{-16}\) cm
- quark <10\(^{-16}\) cm
- atom ~10\(^{-8}\) cm
- nucleus ~10\(^{-12}\) cm
- ~10\(^{-13}\) cm

**Figure 2.1:** An illustration of the field content of the Standard Model. The numbers in parentheses denote the year the particle for that field was discovered. Note that the fermions are only grouped into doublets for their left-chiral parts. The right-chiral parts are SU(2)\(_L\) singlets. The structure of the gauge group representations is shown in more detail in Figure A.3 in Appendix A.

2.3 The search for the Higgs boson

2.3.1 Before the start-up of the LHC

Several generations of colliders and fixed-target experiments have contributed to the experimental support for the SM and for searching for new physics, each successively climbing in energy to gain sensitivity to physics at higher energy scales. Figure 2.2 shows a plot the e\(^{\#}\) effective energy of collisions probed if it were a fixed-target experiment as a function of the time the experiment began taking data.

By the year 2000, LEP had reached its highest energy of \(p_s = 209\) GeV, and combined searches of the LEP experiments excluded a SM Higgs with a mass less than 114 GeV in 2003 [17]. Figure 2.3 (left) shows the upper limit on the ratio of the coupling for Higgs decays through \(H \rightarrow ZZ\) \(^\ast\) compared to the SM as a function of the Higgs mass.
Higgs Boson Discovery

• On July 4, 2012, the ATLAS and CMS experiments at the LHC announced the discovery of a new particle, consistent with the SM Higgs boson.

• The Higgs boson is critical to the SM, and was the last and final particle in the model to be found.

• The LHC is currently shutdown for upgrades but will start “Run 2” next spring (2015).

• The goals include measuring the properties of the Higgs better and continuing to search for new physics.

• It’s a very exciting time for particle physics!
In 1905, Einstein revolutionized our understanding of space and time by realizing that they are part of a combined manifold, spacetime.

His studies were motivated by trying to understand how the speed of light and the equations of EM could be invariant in any frame of reference.

In 1916, Einstein extended this to account for gravitational effects in the general theory of relativity.

Clocks tick slower (time differences are smaller) in a moving frame of reference or in a gravitational potential well.
Time Dilation

Lorentz transformations along 1-spatial dimension

\[
\begin{pmatrix}
  t' \\
  x'
\end{pmatrix} = \gamma \begin{pmatrix}
  1 & -\frac{v}{c^2} \\
  -v & 1
\end{pmatrix} \begin{pmatrix}
  t \\
  x
\end{pmatrix}
\]

where \( \gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} = \frac{E}{mc^2} \geq 1 \)

\[
t' = t\gamma - \gamma xv/c
\]

\[
\Delta t' = t'_{2} - t'_{1} = \gamma \Delta t
\]

Since \( \gamma \geq 1 \), time the boosted (lab) frame always measures a longer time than the rest frame.
Note that muons are unstable. The average lifetime of a muon in its rest-frame is $\tau = 2.2 \times 10^{-6}$ s.

Even if they were traveling at approximately the speed of light: $ct \approx 650$ m

So naively, most muons that get created in cosmic showers ~ 10 km high in the atmosphere, should have decayed before reaching earth.

But for a muon with $E=1$ GeV, $\gamma = E/m = 1\text{GeV}/100\text{MeV} = 10$

$$\Delta t' = \gamma \Delta t$$

$\Rightarrow$ time dilation stretches out the observed lifetime of the muons by a factor of 10:

$\gamma ct \approx 6.5$ km
Summary

• Cosmic rays have historical importance in discoveries in particle physics, as the particle accelerator nature gave us for free.

• They are also related to unanswered questions in physics and astronomy now.

• The two modern pillars of physics are quantum mechanics (particles physics) and relativity (Einstein’s theory of space–time).

• For those of you that want to learn more physics, nature has told us a really cool and surprising story that will rock your intuition.