The Physics of Cosmic Rays

QuarkNet
summer workshop
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Something Totally New

- Marie Curie determines that radioactivity has nothing to do with chemistry...
- Nobel prizes in 1903 and 1911!
Discoveries of Cosmic Rays

• Viktor Hess studied the “electrification of air” using electrometers.
• Ionization from radioactive decay would deposit charge on the electrometer.
• But no matter how well they were made, they “leaked”.
• Leakage rate was the same in the middle of a lake, but lower in a cave...
In 1912 Viktor Hess carried three electrometers to an altitude of 5300 meters in a balloon flight:

- Ionization rate decreased up to ~700 m
- Above 700 m then it increased with altitude. At 5300 m the ionization rate is 4 \times \text{rate at ground level}
- "The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."
Open Questions

• Same intensity at night ➔ not from the sun!
• Were they charged like beta rays or uncharged like gamma rays?
• Do they come down or go up? How do you know for sure?
• Electrometers can’t easily answer these questions...
Compton argued strongly against the suggestion that they were photons!
In 1911, Wilson developed the “expansion cloud chamber” which used saturated water vapor.

In the classroom, we would normally use a “diffusion cloud chamber” using saturated alcohol vapor.
Images of Cosmic Rays

Anderson discovers the “positive electron” in 1933.

⇒ Anti-matter!
Discovery of other particles

Anderson and Neddermayer got very good at measuring energy and mass. By triggering a camera using two Geiger counters they obtained this picture, published in 1938:

- Curved too much to be a proton.
- Traveled too far to be an electron.
- It must have intermediate mass...

\[
\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu
\]
Charged Pions and Kaons

- Charged particles also expose stacks of photographic emulsion
- The pion had been predicted to explain strong nuclear forces
- Not a muon: pions interacted with nuclei
- Another strange particle was observed with about $\frac{1}{2}$ the mass of the proton
- Strangely, they were always produced in pairs and also interacted with nuclei

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]

\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]
The Known Particles in 1950

<table>
<thead>
<tr>
<th>symbol</th>
<th>particle</th>
<th>mass</th>
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<tbody>
<tr>
<td>p</td>
<td>proton</td>
<td>938 MeV/c^2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>940 MeV/c^2</td>
</tr>
<tr>
<td>(\pi^\pm)</td>
<td>pion</td>
<td>140 MeV/c^2</td>
</tr>
<tr>
<td>(V^0, V^\pm)</td>
<td>???</td>
<td>???</td>
</tr>
<tr>
<td>(e^\pm)</td>
<td>electron</td>
<td>0.511 MeV/c^2</td>
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<tr>
<td>(\mu^\pm)</td>
<td>muon</td>
<td>106 MeV/c^2</td>
</tr>
<tr>
<td>(\nu)</td>
<td>neutrino</td>
<td>0?</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>photon</td>
<td>0</td>
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</tbody>
</table>
Back to Cosmic Rays

• In 1938, Pierre Auger was studying cosmic rays in the Alps.
• He observed that two detectors located many meters apart detected particles at exactly the same time.
• Discovery of Extensive Air Showers:
  – secondary particles produced in the collision of a high energy primary particle with air
  – he estimated the energies of some of the primary particles to be $10^{15}$ eV
• Rossi (USA) and Zatsepin (Russia) constructed arrays of detectors to study air showers.
The State of the Art

Detect Cherenkov light when a muon passes through a tank of water
Air Showers

- Primary particles are mostly protons
- They interact with nuclei of atoms in the upper atmosphere producing showers of pions
- Neutral pions decay immediately to photons, photons produce e⁺e⁻ pairs
- Pions also interact with nuclei, but also decay to muons
- Muons do not interact with nuclei:
  - They lose energy as the ionize air
  - but many reach sea level
Properties of Primary Particles

- Primary composition:
  - 90% protons
  - 9% helium nuclei
  - 1% electrons
  (depends on energy)
- Charged particles deflected by magnetic fields
  - Near the earth’s magnetic field
  - In the galaxy’s magnetic field
  - In the magnetic fields between galaxies
- Local magnetic field caused by earth’s dipole (latitude effect) and by the solar wind (day/night effect)
- When cosmic rays arrive, they generally don’t point back to their source.
Do they come from the sun?

- The “solar wind” consists of hot particles with enough kinetic energy to escape the sun’s gravity:
  \[ v = \sqrt{\frac{2GM}{r}} \]  
  (618 km/s)

- Most have energies less than a few GeV
- These don’t produce extensive air showers!
- Do produce neutrons...
How big is the “footprint”?  

Typically a few km across, but not 10’s of km.  

This is about the size of Lafayette...
Energy Spectrum

- Lots are low energy
- Some are high energy
  - Possibly accelerated in magnetic fields around stars
- Very few are ultra high energy
  - about 1 per square km per century with energy $> 10^{20}$ eV
  - Probably come from within our own galaxy...
Greisen-Zatsepin-Kuzmin cutoff

- High energy photons can break apart protons:
  \[ \gamma + p \rightarrow N + \text{pions} \]
- Equivalently, at very high energies, a proton can “collide” with a low energy photon
- The universe is full of low energy photons
  - the cosmic microwave background radiation
- Very high energy protons can’t travel too far without interacting with the CMB photons

Typical sizes of galactic clusters
Recent Experiments think they see this...
Figure 4: Fractional difference between the combined energy spectrum of the Pierre Auger Observatory and a spectrum with an index of 2.6. Data from HiRes stereo measurements [20] are shown for comparison.
In total **27 events** measured at $E > 57$ EeV
out of which **20 correlate**
5.6 expected ($p=0.21$)
Net chance for isotropic distr. $P < 10^{-5}$
Darker colors indicate larger exposure
More Recent Work
Connection with Lightning?

• The electric fields in clouds is not strong enough to ionize the air
• Something else must trigger lightning
• An extensive air shower *could* produce enough ionization to start the runaway breakdown resulting in lightning
• But this hasn’t been conclusively demonstrated...

➤ See [Scientific American article](http://www.scientificamerican.com), January 2008.
Summary

• Who would have thought that leaky electrometers would lead here?
• Led to the birth of accelerator based particle physics
• Still a very active topic of research today
• The Fermilab cosmic ray detector can emulate many of these studies.