Physics 228

Last Lecture:
Elementary Particle Physics
Cosmology

Help/Review Sessions:
Regular office hours this week (Th and Fr)
Monday May 8: 10 AM – 2 PM
Tuesday May 9: 11 AM – 3 PM

The final is Tuesday May 9, 4 PM - 7 PM in the College Ave Gym and Annex.

Please fill out online student evaluations (SIRS)!
Negative Energy States and Antiparticles

- **1928**: Paul Dirac finds negative energy states in his relativistic theory of quantum mechanics. Huh – negative energy??

- **1931**: Dirac realizes that negative energy states must be filled or electrons would fall into them (filled “Dirac sea”) He predicts that a hole (missing electron) in the Dirac sea would behave as a positively charged particle, which can annihilate with an electron.

- **1932**: Carl Anderson discovers this positive anti-electron and calls it “positron”.

- **All particles have antiparticles.**
With the concept of antiparticles, we see we can convert a photon into an electron-positron pair.

The picture to the right shows pair creation in a bubble-chamber.
Accelerators

Elementary particles are studied by slamming high-energy particles into other particles.

High-energy particles are produced in particle accelerators.

Synchrotron: Large Hadron Collider at CERN accelerates protons to 7 TeV (7 million MeV). Circumference: 17 miles!
In the Dirac sea picture, if the negative energy states correspond to positrons, why don’t these positrons annihilate all the electrons around us in one gigantic flash?

A. This would violate electron number conservation.
B. This would violate baryon number conservation.
C. This would violate energy conservation.
D. They actually annihilate each other all the time, creating the cosmic microwave background.
E. Positrons correspond to “holes” (missing electrons) in the sea of filled negative energy states. Once all holes are filled, no more positrons are available for annihilation.
From 1950, numerous (≈100) subatomic, strongly interacting particles were found.

We now understand these particles as being either “elementary” (electron, muon), or as bound states of elementary particles called quarks.
The Quark Model

In the early 1960s, Gell-Mann and others proposed that strongly interacting particles (hadrons) are made up of either 2 or 3 spin-1/2 "quarks". The quarks were named up, down, and strange.

The quarks have electric charges of $\pm \frac{1}{3} e$ or $\pm \frac{2}{3} e$, rather than being integral multiples of $e$. However, free quarks (or particles with fractional charge) are never observed.

Experimentally, scattering of electrons at high energy and momentum transfer from protons showed that the proton contained point-like particles.

Today we know of six types, or "flavors" of quarks: up, down, strange, charm, bottom, top.

The quarks inside hadrons interact (via the strong nuclear force) by exchanging virtual "gluons", just as EM interactions are mediated by exchange of virtual photons.
Quarks possess a type of charge which we call "color". Instead of two types (+ and -), there are three types of strong-interaction charges, called "red", "green" and "blue". Quarks interact by exchanging colored gluons.

Hadrons (baryons and mesons) are colorless. Three-quark hadrons, like the proton, are made of 1 red + 1 green + 1 blue quark. Two-quark hadrons like the π meson are made up of, e.g., red + anti-red quarks.
Hadrons

Particles made of the 3 generations of quarks are called "hadrons". Some, the baryons, are made of three quarks - or three antiquarks - while others, the mesons, are made of a quark + anti-quark pair.

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>d</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>c</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>s</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>t</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>b</td>
<td>4.2</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Baryons

Proton (p)

Neutron (n)

Mesons

Positive pion ($\pi^+$)

Positive kaon ($K^+$)
The leptons do not "feel" the strong force, so they do not bind into particles.

### Leptons

#### 1st generation
- \( \nu_L \) lightest neutrino*: \((0-0.13) \times 10^{-9}\)
- \( e \) electron: \(0.000511\)
- \( \nu_M \) middle neutrino*: \((0.009-0.13) \times 10^{-9}\)

#### 2nd generation
- \( \mu \) muon: \(0.106\)

#### 3rd generation
- \( \nu_H \) heaviest neutrino*: \((0.04-0.14) \times 10^{-9}\)
- \( \tau \) tau: \(1.777\)
All Known Fundamental Particles

What about gravity? “Gravitons” have been hypothesized, but not discovered.
In a neutral pi meson, up quarks are paired with anti-ups, and down quarks with anti-downs. Why don’t these quarks annihilate each other?

A. This would violate baryon number conservation
B. This would violate charge conservation
C. This would violate momentum conservation
D. This would violate energy conservation
E. They do annihilate, producing 2 photons. All conservation laws are satisfied.
Astrophysics and Cosmology

~100 billion to ~1 trillion stars in a galaxy!
Hubble Ultra Deep Field
There are more than 3000 galaxies in this image!

Because of the finite speed of light, as we look further out, we also look further back in time.
Gravitational Lensing

1. A Distant Source
   Light from a young, star-forming blue galaxy near the edge of the visible universe.

2. A Lens of Dark Matter
   Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3. Focal Point: Earth
   Most of the light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.
Expanding Universe and Hubble Constant

When we measure the speed at which galaxies are moving away from us vs. their distance, we find a linear relation.

(The speed is measured via the Doppler effect/red shift).

The slope, the Hubble constant $H_0$, has a value of $68+/-1.2$ km/s/Mpc.

Assuming a constant expansion rate, the age of the universe would be given by $1/H_0 \approx 14.4$ billion years.

$v = H r$
Cosmic Expansion and the Big Bang

(a) Points (representing galaxies) on the surface of a balloon are described by their latitude and longitude coordinates.

(b) The radius $R$ of the balloon has increased. The coordinates of the points are the same, but the distance between them has increased.

Balloon analogy: Points on the balloon move apart as it inflates. The speed of separation is proportional to the separation of the objects.

The rate of recession for any two points is proportional to the distance between them.

The universe may be infinite in size, but appears to be finite in age.
Cosmic Microwave Background Radiation

An initially dense, hot universe expanded and cooled leading to what we see today.

A hot free quark-gluon plasma cooled into hadrons and leptons, which decayed into protons + electrons + photons + neutrinos + trace heavier nuclei ($^2$H, $^3,^4$He...). Initially, this plasma was opaque to light. After ~380,000 years, neutral atoms formed making the universe transparent. This initial flash of light is seen today (red shifted by a factor ~1100) as the cosmic microwave background, confirming the big bang.

The present location of the atoms that emitted these photons marks the edge of the “observable universe”, which is finite.
Consider stars rotating around the center of their galaxy.

Assuming that the mass density of a galaxy is proportional to the observed brightness, the rotational velocity should decrease with radius.

However, the rotational velocity is observed to be approximately constant, implying more mass than is visible (stars).

We conclude that a large component of the mass of all galaxies is unobserved (“dark”) matter.
Galactic rotation curves can be explained if galaxies contain a lot of unobserved ("dark") matter. Some cosmologists believe that about 1/4 of the "stuff" in the universe is dark matter - vs 4% normal matter.

What about the rest?

About a decade ago studies of distant supernova showed that they were dimmer than expected. One possible explanation of this is that the universe’s expansion has been speeding up.

What could cause this acceleration? It is unknown, and called “dark energy”. According to some models, dark energy accounts for 73% of the total mass/energy of the universe.

Intrigued? Take Physics 341 and 342 (Principles of Astrophysics).

The End!