POLICIES

Attendance:

- Up to four excused absences (two with notes from parent/guardian)
- Valid excuses:
  - illness, family emergency, tests or athletic/academic competitions, mass transit breakdowns, hurricanes. **Snow.**
- Invalid excuses:
  - sleeping in, missing the train

Please no cell phones.

Ask questions!
1. Introduction
2. History of Particle Physics
3. Special Relativity
4. Quantum Mechanics
5. Experimental Methods
6. The Standard Model - Overview
7. The Standard Model - Limitations
8. Neutrino Theory
9. Neutrino Experiment
10. LHC and Experiments
11. The Higgs Boson and Beyond
12. Particle Cosmology
WHAT IS PARTICLE PHYSICS?

Particle physicists explore the most basic components of our natural world: Particles!

Not *just* particles though, also the forces between particles and their interactions: How they become the things we see around us.

And sometimes, this leads us from the littlest things to the biggest things: The Big Bang, the large scale structure of the universe, the interiors of stars and even extra dimensions of space.
ATOMIC EXCITATION

• An atom is excited when it has the potential to spontaneously produce energy. This happens when one or more of the electrons occupy a higher-energy state; when the electron returns to a lower energy state, the energy difference is given off in the form of radiation.

• The lowest energy state is the ground state.
IONIZATION

- **Ion**: positively or negatively charged particle (or part of atom)
- Ions can be produced when enough energy is given to remove one or more electrons from an atom:
IONIZATION

- **Ion**: positively or negatively charged particle (or part of atom)
- Ions can be produced when enough energy is given to remove one or more electrons from an atom:
- **Ionization energy** is the energy necessary to strip an atom of all its electrons.
DETECTING PARTICLES

When charged particles pass through matter, they ionize atoms in their path, liberating charges, and causing the emission of detectable light (scintillators) or the formation of tracks of droplets (cloud/bubble chambers). This is how we “see” them.

- Experimental physicists use many kinds of particle detectors, including:
  - Geiger counters
  - Cloud chambers*
  - Bubble chambers*
  - Spark chambers*
  - Photographic emulsions*
  - Wire chambers
  - Cherenkov counters
  - Scintillators
  - Photomultipliers
  - Calorimeters

- NOTE: most of these instruments are sensitive to electrically charged particles only Neutral particles cannot be directly detected easily.

* Less common these days...
Particle physics tries to identify elementary particles and deduce the quantitative force laws that most simply describe their behavior.

A vital force law: Lorentz Force Law, the force on an electric charge $q$ placed in an electromagnetic field (electric field $E$ and magnetic field $B$):

$$\vec{F} = q (\vec{v} \times \vec{B} + \vec{E})$$

- Charge of the particle
- Velocity of the particle
- Magnetic field
- Electric field (\(= 0\) here, since we haven’t turned one on)
ELECTRIC FIELDS

• You can define the electric field according to what it does to test (electric) charges.

• The electric field $E$ in a region of space in which a test charge $q$ gets accelerated by a force $F$, is given by:

$$ F = qE $$

In other words, if you put a charge $q$ in an electric field $E$, that charge will experience a force proportional to $q$ along the direction of $E$. 
• Every electric charge is also the source of an electric field.
• According to classical physics, this is how charges attract and repel each other: each charge detects the field of the other, and then responds according to the force law:

\[ F = qE \]

• At the quantum level, this view has been replaced by the model of mediator exchange, which we flesh out later in the course…
MEASURING ELECTRIC FIELDS

A basic particle accelerator:

- Consider the parallel-plate capacitor...

Two metal plates are given equal but opposite charges $+Q$ and $-Q$, creating a potential difference $V$, or drop in voltage, between them.

The charges set up a uniform electric field $E$ between the plates.

A test charge in this region gets accelerated.

- This is the principle behind every particle accelerator; pass charges through an electric field to increase their kinetic energy.
Energy Units

The electron-Volt (eV)

Basic unit of energy in particle physics: electron-Volt (eV)

- The eV is the energy acquired by one electron accelerated (in a vacuum) through a potential difference of one Volt.

Comparison with more familiar units:

- $1 \text{ eV} = 1.602 \times 10^{-19} \text{ Joule}$

Also unit of mass: $E=mc^2$ → in natural units (c=1): $E=m$

And momentum: $E=pc$ → in natural units (c=1): $E=p$

(Note: 1 Joule is roughly the energy it takes to lift a 1 kg object 10 cm off the ground.)
MAGNETIC FIELDS

• According to the Lorentz Force Law, the magnetic force on a charge \( q \) is:

\[
\vec{F} = q (\vec{v} \times \vec{B})
\]

• **NOTE**: the magnetic force is perpendicular to both the direction of the field and the velocity of the (positive) test charge (right-hand rule). If \( v \) and \( B \) are perpendicular to each other, the charge’s trajectory will bend into a circle.

• **NOTE**: if the charge is stationary \( (v=0) \), the magnetic force on it is zero. Magnetic fields only affect moving charges (currents).

• **NOTE**: the direction of the particle’s path depends on the sign of its charge!
Electric charges moving in uniform magnetic fields travel in circular paths. The path’s radius of curvature yields important information:

\[ F_{\text{magnetic}} = F_{\text{centripetal}} \]
\[ \frac{q}{c} |\vec{v} \times \vec{B}| = m \frac{v^2}{r} \]
\[ \vec{v} \times \vec{B} = vB \text{ if } \vec{v} \text{ is perpendicular to } \vec{B}. \]
\[ \frac{qvB}{c} = m \frac{v^2}{r} \]
\[ r = \frac{m v c}{qB} \]
\[ r = \frac{pc}{qB} \]

By measuring the radius of curvature of a charge’s path, physicists can determine both the momentum and the sign of the charge.

This is a primary means of particle identification in experiments!
MEASUREMENT APPLICATION
**MEASUREMENT APPLICATION**

- **Pixel Detector**: innermost detector for measuring the position of particles. It is within a magnetic field so we also measure the momentum.

- These are an example of a **Semiconductor Detectors**: essentially solid state ionization chambers. Absorbed energy creates electron-hole pairs (negative and positive charge carriers) which under an applied electric field move towards their respective collection electrodes, where they induce a signal current.
Late 1800’s to today:

Discoveries of particles, particle properties fundamental symmetries and the Standard Model.

From Classical physics...

to Modern Physics...

to Particle Physics today.
THE BIG PICTURE

This picture and these forces summarize the Standard Model of particle physics.

<table>
<thead>
<tr>
<th>INTERACTION</th>
<th>DESCRIPTION</th>
<th>MEDIATOR</th>
<th>STRENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRONG</td>
<td>binds quarks in protons and neutrons, and protons and neutrons in nuclei</td>
<td>gluon</td>
<td>1</td>
</tr>
<tr>
<td>EM</td>
<td>all extra-nuclear physics (atoms, molecules, chemistry, etc)</td>
<td>photon</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>WEAK</td>
<td>nuclear β decay</td>
<td>$W^\pm, Z^0$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>GRAVITY</td>
<td>all types of particles</td>
<td>graviton</td>
<td>$10^{-39}$</td>
</tr>
</tbody>
</table>

“This most incomprehensible thing about the universe is that it is comprehensible.”
LATE 1800’s

- **Atoms were the fundamental particles of nature.** Mendeleev’s Periodic Table summarizes patterns and scientists used these patterns to search for “missing” elements.

- Chemists and physicists were classifying the known (and yet-to-be discovered) elements according to their chemical properties.

- Trends in the periodic table suggest some underlying atomic structure: i.e., atoms are composites of smaller, more “fundamental” particles that determine chemical behavior.

![Periodic Table of the Elements](image.png)
“The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote... Our future discoveries must be looked for in the sixth place of decimals.”

-Albert Abraham Michelson, 1894
THE 1890’s

• New, unstable elements (radioactivity) were being investigated by M. Curie, P. Curie, H. Becquerel, E. Rutherford, et al.

• Radioactivity: describes the emission of particles from atomic nuclei as a result of nuclear instability. The fact that atoms seemed to spontaneously split apart also suggests they are not fundamental particles.

• At the time, it was known that unstable elements tended to emit three types of particles, differentiated by electric charge:

1) Alpha particles ($\alpha$): +2 electric charge; about 4x proton mass
2) Beta particles ($\beta$): -1 electric charge; about 1/1800 proton mass
3) Gamma particles ($\gamma$): electrically neutral
THE 1890’s

The α-particle, as it turns out, is just He$^{+2}$, the nucleus of a helium atom. It is emitted in decays like:

\[ ^{218}_{84} Po \rightarrow ^{214}_{82} Pb + \alpha \]

The β-particle is an electron (not known until 1897). A β-decay example:

\[ ^{234}_{90} Th \rightarrow ^{234}_{91} Pa + \beta \]

The γ-particles are photons, emitted in such decays as:

\[ ^{137}_{Ba} \rightarrow ^{137}_{Ba} + \gamma \]
For a number of years, scientists had generated “cathode rays” by heating filaments inside gas-filled tubes and applying an electric field.

- **Recall**: we know cathode rays have electric charge, because they can be deflected by magnetic fields.

- **Question**: are cathode rays some kind of charged fluid, or are they made of charged particles (like ions)?

- **In 1897, J.J. Thomson attempted a measurement of the charge/mass ratio of cathode rays to see if they were particles.**
DISCOVERY OF THE ELECTRON, 1897

- Put a cathode ray into a known electric or magnetic field.

- Measure the cathode ray’s deflection.

- If cathode rays are composed of discrete charges, their deflection should be consistent with the Lorentz Force Law:

$$\vec{F} = q (\vec{v} \times \vec{B} + \vec{E})$$
DISCOVERY OF THE ELECTRON, 1897

- Thomson found that cathode ray deflections were consistent with the Lorentz Force, and could be particles ("corpuscles") after all.

- The charge to mass ratio $e/m$ was significantly larger than for any known ion (over $1000x$ $e/m$ of hydrogen). This could mean two things:
  
  (1) The charge $e$ was very big.

  (2) The mass $m$ was very small.

- Independent measurements of $e$ (oil drop experiment) suggested that, in fact, cathode rays were composed of extremely light, negatively charged particles.

- Thomson called his corpuscle’s charge the electron (from the Greek “amber”); eventually, this term was applied to the particles themselves, whose mass is:

  $m_e = 0.511 \text{ MeV/c}^2 = 9.15 \times 10^{-31} \text{ kg}$
Thomson correctly believed that electrons were fundamental components of atoms (e.g., responsible for chemical behavior).

He knew atoms were electrically neutral, so he concluded that the negatively charged point-like electrons must be embedded in a “gel” of positive charge such that the entire atom is neutral.

Thomson: electrons are contained in an atom like “plums in a pudding”.
Test of Thomson’s theory of atomic structure (1909-1913):

Recall: scattering two particles and measuring the deflection gives information about particle structure and interaction.

Thomson’s Model

Rutherford’s Model
RUTHERFORD EXPERIMENT

The Gold Foil Experiment

- Most a-particles were not scattered at all, but a few were scattered through angles of 90° or more!

- Rutherford: large-angle scattering is exactly consistent with Coulomb repulsion of two small, dense objects.

- Conclusion: scattered particle beam is evidence of a dense, compact, positively-charged structure (located at the center of the atom).
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DISCOVERY OF THE NUCLEUS (1911)

- Rutherford’s efforts formed one of the truly great experiments of modern physics.
- He quickly understood that he discovered a new nuclear model of the atom, saying of the result:
  
  “It was quite the most incredible event that ever happened to me in my life. It was almost as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

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THE BOHR ATOM (1914)

- New atomic model: localized positive charge and electron “cloud”
- Also results from spectroscopy:
THE BOHR ATOM (1914)

• New atomic model: localized positive charge and electron “cloud”

• Also results from spectroscopy:

Recall: When you excite a gas, it emits radiation in certain discrete wavelengths (spectral lines) according to Balmer’s formula:

$$\frac{1}{\lambda} = R \left( \frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$$
THE BOHR ATOM (1914)

• In 1914, N. Bohr developed a simple atomic model that perfectly explained the phenomenon of spectral lines.

• The three main ideas:

1) The electron moves in uniform circular motion, with the centripetal force provided by its Coulomb attraction to the nucleus:

\[ F_{\text{centripetal}} = m_e \frac{v^2}{r} = \frac{e^2}{r^2} = F_{\text{Coulomb}} \]

2) The angular momentum of the electron in its orbit is quantized, satisfying the constraint:

\[ m_e v r = n \hbar, \quad n \text{ is an integer} \]

3) Therefore, the electron can have only a discrete spectrum of allowed energies:

\[ E = \frac{1}{2} m_e v^2 - \frac{e^2}{r} = -\frac{1}{n^2} \left( \frac{m_e e^4}{2\hbar^2} \right) \]
In the context of the Bohr model, the discrete spectra seen in atomic spectroscopy make perfect sense.

The electron occupies discrete orbits in the hydrogen atom.

When hydrogen is excited in an electric field, the electron jumps into a higher energy orbit.

Eventually, the electron will return to a lower energy state. Once this happens, light must be emitted to conserve the energy of the whole system.
DISCOVERY OF THE NEUTRON (1932)

- In the Bohr atomic model, atoms consisted of just protons and electrons.

- However, there was a major problem: most elements were heavier than they should have been.

(He charge is $+2e$, but weighs $4m_p$;
Li charge $+3e$, but weighs $7m_p$; etc.)

- To account for the missing mass in heavier elements, nuclei had to contain other particles comparable in mass to the proton ($1 \text{ GeV}/c^2$) but with no electric charge.

- The mysterious massive, neutral particle inside atomic nuclei eluded detection until 1932, when J. Chadwick observed the neutron in an $\alpha$-Be scattering experiment.
1927: New Wrinkle…

Antimatter

- P. Dirac attempted to combine quantum mechanics with the relativistic energy formula:

\[ E = \sqrt{\not{p}^2 c^2 + m^2 c^4} \]

- **PROBLEM**: the theory allows both positive and negative energy solutions!

\[ E_+ = +\sqrt{\not{p}^2 c^2 + m^2 c^4} \]
\[ E_- = -\sqrt{\not{p}^2 c^2 + m^2 c^4} \]

- Dirac’s interpretation: the positive solutions are ordinary particles; the negative solutions are antimatter.

- But was anti-matter real, or just a mathematical artifact?
ANTIMATTER (1932)

In 1932, C. Anderson observed the anti-electron (positron), validating Dirac’s theory.

Feynman’s explanation of negative energies: they are the positive energy states of anti-particles!

Anti-matter is a universal feature of quantum field theory; all particles have matching anti-particles.

Anti-particles have the same mass as their particle partners, but opposite quantum numbers (charge, lepton number, etc.)

Notation: particle $e^-, p$
antiparticle $e^+, \bar{e}, \bar{p}$

Discovery of the positron in a cloud chamber by C. Anderson
Image: J. Griffiths, Intro to Elementary Particles
A new particle, the field quantum

The discovery of the photon, the quantum of the electromagnetic field, marked a major departure from classical physics.

As with the developing picture of the atom, it took several decades (and several incontrovertible experiments) before physicists accepted the existence of the photon.

But before we get into that, let’s talk about what classical physics actually had to say about electromagnetism.
Work by J.C. Maxwell in the mid/late 1800s: the EM field could be understood in terms of four equations:

\[ \oint E \cdot dA = \frac{Q}{\varepsilon_0} \]
\[ \oint B \cdot dA = 0 \]
\[ \oint E \cdot ds = -\frac{d\Phi}{dt} \]
\[ \oint B \cdot ds = \mu_0 \varepsilon_0 \frac{d\Phi}{dt} + \mu_0 I \]

These are Maxwell’s equations in the vacuum, relating the electric and magnetic field.
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\[ \oint E \cdot ds = -\frac{d\Phi_E}{dt} \]
\[ \oint B \cdot ds = \mu_0 \varepsilon_0 \frac{d\Phi_B}{dt} + \mu_0 I \]
Maxwell’s equations predict self-propagating, transverse electric & magnetic (electromagnetic) waves, aka light, which travel at speed $c=3\times10^8\text{m/s}$ and have frequency $f=c/\lambda$. Electromagnetic waves transport energy stored in the propagating fields through empty space.
CLASSICAL ELECTRODYNAMICS

A beautiful theory…

The implications of the Maxwell Equations – namely, the appearance of electromagnetic fields to observers in different inertial reference frames – inspired scientists (Poincaré, Einstein) to develop special relativity.

But,

when trying to explain thermal radiation (light emitted by hot objects), the theory completely fails!
FAILURE OF CLASSICAL ELECTRODYNAMICS

- When light is emitted by hot objects, the intensity of the light always varies continuously with the wavelength – unlike atomic spectra – and the spectrum has a characteristic shape.

- Examples of blackbodies: stars, light filaments, toaster coils, the universe itself!

- This so-called blackbody spectrum (or Planck spectrum) always peaks at a wavelength that depends on the surface temperature of the object.
FAILURE OF CLASSICAL ELECTRODYNAMICS

“Ultraviolet catastrophe”

- A study of blackbody radiation with classical E&M and statistical mechanics (the Rayleigh-Jeans Law) predicts that the emitted intensity varies with frequency and temperature as:

\[ I_\nu(T) \propto \frac{k_B T}{c^3} \nu^2 \]

- This means that as the light frequency increases into the UV, the intensity becomes infinite!

- This nonsensical answer was such an embarrassment for the theory that physicists called it the “ultraviolet catastrophe”.

[Diagram showing the transition from classical to quantum behavior]
In 1900, using arguments from statistical mechanics (the theory of bodies in thermal equilibrium), M. Planck derived a theoretical curve that fit the blackbody spectrum perfectly:

\[ I_\nu(T) \propto \frac{h}{c^3} \frac{\nu^3}{e^{h\nu/k_BT} - 1} \]

However, to get this result, Planck had to assume that thermal radiation is quantized; that is, it’s emitted in little “packets” of energy, photons, proportional to the frequency \( \nu \):

\[ E = h\nu \]

The quantity \( h \), called Planck’s constant, was determined from the fit to the blackbody spectrum. It turned out to be a fundamental constant of nature, and has the value:

\[ h = 4.1357 \times 10^{-15} \text{ eV} \cdot \text{s} \]
Are photons real?

- In order to explain blackbody emission spectra, Planck needed to assume that thermal radiation is emitted in bundles whose energy comes in integral multiples of $h\nu$.

- This suggested that light could actually be quantized (it’s a particle). But most of the experimental evidence (and Maxwell’s Equations) at the time said that light is a wave.

- So is light a particle, or a wave? As it turns out, light can behave like a particle if you are performing the right kind of experiment!

- At first, Planck did not really believe in the light quantum, and most physicists did not accept its existence until faced with undeniable evidence from two phenomena:
  1) The photoelectric effect
  2) Compton scattering

Evidence for light particles!
PHOTOELECTRIC EFFECT

In the 1800’s, it was discovered that shining light onto certain metals liberated electrons from the surface.

Experiments on this photoelectric effect showed odd results:

1) Increasing the intensity of the light increased the number of electrons, but not the maximum kinetic energy of the electrons.

2) Red light did not liberate electrons, no matter how intense it was!

3) Weak violet light liberated few electrons, but their maximum kinetic energy was greater than that for more intense long-wavelength beams!

In 1905, A. Einstein showed that these results made perfect sense in the context of quantization of the EM field, where photon energy is proportional to frequency. If photons of energy $E=\hbar \nu$ strike electrons in the surface of the metal, the freed electrons have a kinetic energy:

$$K = \hbar \nu - \phi$$

The work function $\phi$ is a constant that depends on the metal.
In 1923, A.H. Compton found that light scattered from a particle at rest is shifted in wavelength by an amount:

$$\lambda_f - \lambda_i = \lambda_c (1 - \cos \theta)$$

Here, $\lambda_c = \frac{h}{mc}$ is the Compton wavelength of the target mass $m$.

There is no way to derive this formula if you assume light is a wave, but if you treat the incoming light beam like a particle with energy $E = h\nu$, Compton’s formula drops right out!

Hence, the Compton Effect proved to be the decisive evidence in favor of the quantization of the EM field into photons.
FIELD QUANTIZATION

When is field quantization important and observable?

- Even on the atomic scale, quantization of the EM field is a tiny effect.
- In a bound state (like H = proton + electron), huge numbers of photons are streaming back and forth, effectively "smoothing out" the EM field in the atom.
- Only in elementary particle processes involving single photons (Compton scattering, photoelectric effect) does field quantization become important.
NUCLEAR FIELDS

- Field quantization, once accepted for the electromagnetic field, was quickly applied to other calculations.
- One was the physics of the atomic nucleus, which gets very complicated after hydrogen.
- QUESTION: How are protons in heavy atoms bound inside the 1 fm “box” of the nucleus? Shouldn’t the electrostatic repulsion of the protons blow the nucleus apart?
NUCLEAR FORCE MODEL (1934)

- Evidently, some force is holding the nucleus together: the “strong force.”
- Inside the nucleus, the strong force has to overwhelm the EM force, but outside, on the atomic scale, it should have almost no effect.
- How to accomplish this? Assume the strong force has a very short range, falling off rapidly to zero for distances greater than 1 fm.
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- How to accomplish this? Assume the strong force has a very short range, falling off rapidly to zero for distances greater than 1 fm.

\[ F_{\text{strong}} \propto -\frac{1}{r^2} e^{-r/a} \]

Here \( a \sim 1 \text{ fm} \) limits the range.