Course policies

● Classes from 10:00 AM to 12:30 PM (10 min break at ~ 11:10 AM).
  ● Attendance record counts.
    – Up to four absences
    – Lateness or leaving early counts as half-absence
    – Send email notifications of all absences to shpattendance@columbia.edu.

● Please, no cell phones during class

● Please, ask questions!

● Lecture materials + Research Opportunities + Resources to become a particle physicist
  ● https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram
## Schedule

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<td>The Standard Model - Limitations</td>
<td>Yeon-jae</td>
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<td>Neutrino Theory</td>
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<td>Neutrino Experiment</td>
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<tr>
<td></td>
<td>24</td>
<td>No classes, SHP break</td>
<td>Edward</td>
</tr>
<tr>
<td>December</td>
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<td>LHC and Experiments</td>
<td>Yeon-jae</td>
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<td></td>
<td>8</td>
<td>The Higgs Boson and Beyond</td>
<td>Yeon-jae</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Particle Cosmology</td>
<td>Edward</td>
</tr>
</tbody>
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Announcements

• The Admissions Office of Columbia College and the School of Engineering will be conducting special information sessions and campus tours for SHP students and their parents:
  • Saturday, October 27, 2018 at 12:45 pm
    One house Information session in room 301 Pupin followed by an optional campus tour.
  • Saturday, November 17, 2018 at 12:45 pm
    One house Information session in room 301 Pupin followed by an optional campus tour.
  • No RSVP necessary – All Welcome.
QUICK REVIEW: QUANTUM MECHANICS
PARTICLES AND WAVES
WHAT IS QUANTUM MECHANICS?

• Quantum mechanics is the study of nature at very small scales – specifically when the energies and momenta of the system are of the order of Planck’s constant:

\[ \hbar = \frac{\hbar}{2\pi} = 6.6 \times 10^{-16} \text{ eV s} \]

• On a quantum level, particles exhibit a number of non-classical behaviors:
  1. Quantization of energy, momentum, charge, spin, …
  2. Particles exhibit wave-like effects: interference, diffraction, …
  3. Systems can exist in a superposition of states
THE DE BROGLIE HYPOTHESIS

• de Broglie’s suggestion was a bold statement about the symmetry of Nature.

• Proposal: the wave aspects of matter are related to its particle aspects in quantitatively the same way that the wave and particle aspects of light are related.

• Hypothesis: for matter and radiation, the total energy ($E$) of a particle is related to the frequency ($f$) of the wave associated with its motion by:

$$E = hf$$

• If $E=pc$ (recall SR), then the momentum $p$ of the particle is related to the wavelength $\lambda$ of the associated wave by the equation:

$$p = \frac{h}{\lambda}$$
ELECTRON DIFFRACTION

• Scattering electrons off crystals also creates a diffraction pattern!

• Electron diffraction is only possible if electrons are waves.

• Hence, electrons (matter particles) can also behave as waves.

Diffraction pattern created by scattering electrons off a crystal. (This is a negative image, so the dark spots are actually regions of constructive interference.) Electron diffraction is only possible if electrons are waves.
UNDERSTANDING MATTER WAVES

• Let’s think a little more about de Broglie waves.

• In classical physics, energy is transported either by waves or by particles.
  • Particle: a definite, localized bundle of energy and momentum, like a bullet that transfers energy from gun to target.
  • Wave: a periodic disturbance spread over space and time, like water waves carrying energy on the surface of the ocean.

• In quantum mechanics, the same entity can be described by both a wave and a particle model:
  • Electrons scatter like localized particles, but they can also diffract like extended waves.
QUANTUM WAVES SUMMARIZED

• An elementary particle like a photon can act like a particle (Compton scattering) or a wave (diffraction), depending on the type of experiment / observation.

• If it’s acting like a particle, the photon can be described by its position and momentum $x$ and $p$. If it’s acting like a wave, we must describe the photon with a wave function $\psi(x,t)$.

• Two waves can always be superimposed to form a third:
  • $\psi = \psi_1 + \psi_2$.
  • This is what gives rise to interference effects like diffraction.

• The wave function for a moving particle (a traveling wave) has a simple sinusoidal form.
  • But how do we interpret $\psi(x,t)$ physically?
INTERPRETATION OF THE WAVE FUNCTION

• We have seen that a particle can be described by a wave function \( \psi(x, t) \).

• For any wave, we define the wave’s intensity \( I \) to be:
  \[
  I = |\psi(x, t)|^2 = \int \psi(x, t) \psi(x, t)^* \, dx
  \]
  where the asterisk signifies complex conjugation. Note that for a plane wave this is a constant:
  \[
  I = |\psi(x, t)|^2 = |A|^2
  \]

• Let’s use the concept of intensity and a simple thought experiment to get some intuition about the physical meaning of the de Broglie wave function.
THE DOUBLE SLIT EXPERIMENT

• **Experiment**: a device sprays an electron beam at a wall with **two small holes** in it. The size of the holes is close to the electrons’ wavelength $\lambda_{dB}$.

• Behind the wall is a screen with an **electron detector**.

• As electrons reach the screen, the detector counts up **how many electrons** strike **each point** on the wall.

• Using the data, we plot the **intensity** $I(x)$: the number of electrons arriving per second at position $x$.
THE DOUBLE SLIT EXPERIMENT

• The classical result:

If electrons were classical particles, we would expect the intensity in front of each slit to look like a bell curve, peaked directly in front of each slit opening.

• When both slits are open, the total intensity $I_{1+2}$ on the screen should just be the sum of the intensities $I_1$ and $I_2$ when only one or the other slit is open.
THE DOUBLE SLIT EXPERIMENT

• In reality:
  
  ![Diagram of the double slit experiment]

• When we perform the real experiment, a strange thing happens.
• When only one slit is open, we get the expected intensity distributions.
• But when both slits are open, a wave-like diffraction pattern appears.
• Electrons act* like waves!

  *When fired through two slits placed a de Broglie wavelength apart.
In terms of waves, the wave function of an electron at the screen when only slit 1 is open is $\psi_1$, and when only slit 2 is open it’s $\psi_2$.

- Hence, the intensity when only one slit is open is either $I_1 = |\psi_1|^2$ or $I_2 = |\psi_2|^2$.

- With both slits open, the intensity at the screen is $I_{1+2} = |\psi_1 + \psi_2|^2$, not just $I_1 + I_2$!

- When we add the wave functions, we get constructive and destructive interference; this is what creates the diffraction pattern.
IS THERE A CONTRADICTION?

• We now understand the wave function in terms of the probability of a particle being some place at some time.
  • However, there is another problem to think about.

• Since the electrons diffract, they are waves; but when they hit the screen, they interact like particles. And if they are particles, then shouldn’t they only go through one slit at a time?

• If this is the case, how can an electron’s wave undergo double slit interference when the electron only goes through one slit?
  • Seems impossible…

• To test what’s going on, suppose we slow down the electron gun so that only one electron at a time hits the wall.

• We then insert a device over each slit that tells us if the electron definitely went through one slit or the other.
DESTROYING THE INTERFERENCE PATTERN

- We add electron detectors that shine light across each slit.
- When an electron passes through one of the slits, it breaks the beam, allowing us to see whether it traveled through slit 1 or slit 2 on its way to the detector.
- **Result**: if we try to detect the electrons at one of the two slits in this way, the interference pattern is **destroyed**! In fact, the pattern now looks like the one expected for classical particles.
COMPLEMENTARITY

• Why did the interference pattern disappear?

• Apparently, when we used the light beam to localize the electron at one slit, we destroyed something in the wave function $\psi(x,t)$, that contributes to interference.

• **Principle of Complementarity (N. Bohr):** if a measurement proves the wave character of radiation or matter, it is impossible to prove the particle character in the same measurement, and vice-versa.

• The link between the wave and particle models is provided by the probability interpretation of $\psi(x,t)$: the wave function gives the probability of finding the particle at some position.
THE UNCERTAINTY PRINCIPLE

• There seems to be some fundamental constraint on quantum mechanics that prevents matter from acting wave-like and particle-like simultaneously.

• Moreover, it appears that our measurements can directly affect whether we observe particle or wave-like behavior.

• These effects are encapsulated in the Uncertainty Principle.

• Heisenberg: quantum observations are fundamentally limited in accuracy.
THE UNCERTAINTY PRINCIPLE

• According to classical physics, we can (at the same instant) measure the position $x$ and momentum $p_x$ of a particle to infinite accuracy if we like. We’re only limited by our equipment.

• However, Heisenberg’s uncertainty principle states that an experiment cannot simultaneously determine the exact values of $x$ and $p_x$.

• Quantitatively, the principle states that if we a particle’s momentum $p_x$ to an accuracy $\Delta p_x$, and its position $x$ to within some $\Delta x$, the precision of our measurement is inherently limited such that:

$$\Delta p_x \Delta x \geq \frac{\hbar}{2}$$
USING THE UNCERTAINTY PRINCIPLE

• Does the Uncertainty Principle mean that we can’t measure position or momentum to arbitrary accuracy?

• No. The restriction is not on the accuracy to which $x$ and $p_x$ can be measured, but rather on the product $\Delta p_x \Delta x$ in a simultaneous measurement of both.

• The Uncertainty Principle implies that the more accurately we know one variable, the less we know the other. If we could measure a particle’s $p_x$ to infinite precision, so that $\Delta p_x = 0$, then the uncertainty principle states:

$$\Delta x \geq \frac{\hbar}{2 \Delta p_x}$$

$$\Delta p_x \to 0, \quad \Delta x \to \infty$$

• In other words, after our measurement of the particle’s momentum, we lose all information about its position!
THE UNCERTAINTY PRINCIPLE

• The Uncertainty Principle also applies to measurements of energy $E$ and the time $t$. It states that:

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

• Example: estimate the mass of virtual particles confined to the nucleus (see Lecture 2 on estimating Yukawa’s meson mass).

• Example: $\Delta t$ could be the time during which a photon of energy spread $\Delta E$ is emitted from an atom.

• This effect causes spectral lines in excited atoms to have a finite uncertainty $\Delta \lambda$ ("natural width") in their wavelengths.

Atomic spectral lines, the result of transitions that take a finite time, are not thin “delta function” spikes, but actually have a natural width due to the Uncertainty Principle.
UNCERTAINTY AND THE DOUBLE SLIT

• Now that we know the Uncertainty Principle, we can understand why we can’t “beat” the double slit experiment and simultaneously observe wave and particle behavior.

• Our electron detector Compton scatters light off of incoming electrons.

• When an electron passes through one of the slits, we observe the scattered photon and know that an electron went through that slit.

• When this happens, the photon transfers some of its momentum to the electron, creating uncertainty in the electron’s momentum.
UNCERTAINTY AND THE DOUBLE SLIT

• If we want to know the slit used, the photon’s wavelength must be smaller than the spacing between the two slits.

• Hence, the photon has to have a large momentum (remember, $\lambda=h/p$).

• As a result, a lot of momentum gets transferred to the electron - enough to effectively destroy the diffraction pattern.

If the wavelength of the scattering photon is small enough to pinpoint the electron at one of the slits, the resulting momentum transfer is large enough to “push” the electron out of the interference minima and maxima. The diffraction pattern is destroyed.
UNCERTAINTY AND THE DOUBLE SLIT

• If we try to pinpoint the electron at one of the slits, its momentum uncertainty gets so big that the interference pattern vanishes.

• Can you think of a way to get around this problem?

• We could use lower energy photons; but that dropping of the photon momentum simultaneously increases the photon wavelength...

• It turns out, that just when the photon momentum gets low enough that electron diffraction reappears, the photon wavelength becomes larger than the separation between the two slits (see Feynman Lectures on Physics, Vol. 3).

• This means we can no longer tell which slit the electron went through!
WHY THE UNCERTAINTY PRINCIPLE

• Let’s review what we have said so far about matter waves and quantum mechanics.

• Elementary particles have associated wave functions $\psi(x,t)$. The intensity of the wave, $I(x) = |\psi(x,t)|^2$, gives the probability of finding the particle at position $x$ at time $t$.

• Quantum mechanics places a firm constraint on the simultaneous measurements we can make of a particle’s position and momentum: $\Delta p \Delta x \geq \hbar / 2$.

• This last concept, the Uncertainty Principle, seems very mysterious. However, it turns out that it is just a natural consequence of the wave nature of matter: all waves obey an Uncertainty Principle!
WAVE FUNCTIONS SHOULD BE FINITE

- If a wave function is infinite in extent, like $\psi = A \sin(2\pi(x/\lambda - vt))$, the probability interpretation suggests that the particle could be anywhere: $\Delta x = \infty$.
- If we want particles to be localized to some smaller $\Delta x$, we need one whose amplitude varies with $x$ and $t$, so that it vanishes for most values of $x$. But how do we create a function like this?
BUILDING WAVE PACKETS

• In order to get localized particles, their corresponding wave functions need to go to zero as $x \rightarrow \pm \infty$. Such a wave function is called a wave packet.

• It turns out to be rather easy to generate wave packets: all we have to do is superimpose, or add up, several sinusoids of different wavelengths or frequencies.

• Recall the Principle of Superposition: any wave $\psi$ can be built up by adding two or more other waves.

• If we pick the right combination of sinusoids, they will cancel at every $x$ other than some finite interval (Fourier Theorem).
THE CONTINUUM LIMIT

• So, evaluating a sum of sinusoids like:

\[ \psi = \sum_k A_k \cos (kx) \]

where \( k \) is an integer that runs between \( k_1 \) and \( k_2 \), we can reproduce any periodic function.

• If we let \( k \) run over all values between \( k_1 \) and \( k_2 \) — that is, we make it a continuous variable — then we can finally reproduce a finite wave packet.

By summing over all values of \( k \) in an interval \( \Delta k = k_1 - k_2 \), we are essentially evaluating the integral

\[ \psi = \int_{k_1}^{k_2} dk A(k) \cos (kx) \]

In such a “continuous sum”, the component sinusoids are all in phase near \( x = 0 \). Away from this point, in either direction, the components begin to get out of phase with each other. If we go far enough out, the phases of the infinite number of components become totally random, and cancel out phases of component sinusoids completely.
CONNECTION TO UNCERTAINTY

• So, we can sum up sinusoids to get wave packets.
  • What does this actually mean?

• Intuition: we want a wave function that is non-zero only over some finite interval Δx.

• To build such a function, we start adding sinusoids whose inverse wavelengths, k = 2π/λ, take on values in some finite interval Δk.

• Here’s the point: as we make the interval Δk bigger, the width of the wave packet Δx gets smaller. This sounds like the Uncertainty Principle!
Precisely determined momentum

A sine wave of wavelength $\lambda$ implies that the momentum is precisely known. But the wavefunction and the probability of finding the particle $\Psi^*\Psi$ is spread over all of space!

Adding several waves of different wavelength together will produce an interference pattern which begins to localize the wave.

But that process spreads the momentum values and makes it more uncertain. This is an inherent and inescapable increase in the uncertainty $\Delta p$ when $\Delta x$ is decreased.

http://hyperphysics.phy-astr.gsu.edu
WAVE-RELATED UNCERTAINTIES

• As we sum over sinusoids, making the range of k values Δk larger, we decrease the width of the resulting function.

• In fact, there is a fundamental limit here that looks just like the position-momentum uncertainty relation.

• For any wave, the minimum width Δx of a wave packet composed from sinusoids with range Δk is Δx=1/(2Δk), or:

\[ \Delta x \Delta k \geq \frac{1}{2} \]

• There is a similar relation between time and frequency:

\[ \Delta t \Delta \omega \geq \frac{1}{2} \]
CONNECTION TO QUANTUM MECHANICS

• If \( k = \frac{2\pi}{\lambda} \), and \( \lambda = \frac{h}{p} \), then the uncertainty relation for waves in general tells us:

\[
\Delta x \Delta k \geq \frac{1}{2} \implies \Delta x \frac{2\pi}{\Delta \lambda} \geq \frac{1}{2} \implies \Delta x \frac{2\pi \Delta p}{h} \geq \frac{1}{2} \\
\Delta x \Delta p \geq \frac{h}{2}
\]

• We recover the Heisenberg uncertainty relation!

• By a similar argument, we can show that the frequency-time uncertainty relation for waves implies the energy-time uncertainty of quantum mechanics.

• Hence, there is nothing really mysterious about the Uncertainty Principle; it arises rather naturally from properties of (localized) waves.
SUMMARY

- Quantum mechanics is the physics of small objects.
  - Its typical energy scale is given by Planck's constant.
- In quantum mechanics, variables like position, momentum, energy, etc. tend to take on discrete values (often proportional to $h$).
- Matter and radiation can have both particle and wave-like properties, depending on the type of observation.
- The Uncertainty Principle tells us that there is a fundamental limit to the precision with which we can measure certain pairs of observables.
- Objects can never be wavelike or particle-like simultaneously.
EXPERIMENTAL METHODS IN PARTICLE PHYSICS

HOW WE STUDY PARTICLES IN THE LAB
TODAY’S AGENDA

• What do we want to know and what do we measure?

• Passage of particles through matter:
  • Ionization
  • Scintillation
  • Cherenkov radiation

• Particle detectors

• Modern experiments
STANDARD MODEL PARTICLE PROPERTIES
WHAT WE WANT TO KNOW

- Particle properties:
  - Mass
  - Spin
  - Charge

- Particle interactions:
  - What happens when particles collide with each other?
    - What are the interaction products?
  - With what probability do different types of interactions occur?
    - How long does it take for an unstable particle to decay?
      - … and what particles does it decay to?
    - Are there extremely rare interactions that we haven’t measured yet?

- Do new particles exist that we don’t know about yet?
  - Can we produce them in high energy collisions?
WHAT WE MEASURE

• Particle **trajectories**
  • … and how they **bend** in **magnetic** fields

• Particle **energies**

• **Events:**
  • **Collection** of particle tracks and energy deposits resulting from an interaction.
  • **Topology:** what particles are produced in the event
  • **Angles** between particles, imbalances in **momentum**, etc…

WHEN TWO APPLES COLLIDE, THEY CAN BRIEFLY FORM EXOTIC NEW FRUIT. PINEAPPLES WITH APPLE SKIN, POMEGRANATES FULL OF GRAPES, WATERMELON-SIZED PEACHES.

THESE NORMALLY DECAY INTO A SHOWER OF FRUIT SALAD, BUT BY STUDYING THE DEBRIS, WE CAN LEARN WHAT WAS PRODUCED.

THEN, THE HUNT IS ON FOR A STABLE FORM.

xkcd.com
WHAT WE ACTUALLY MEASURE

- Particles interact with **detector materials** and either:
  - **Change** the material’s properties in an observable way, or
  - Produce some kind of **disturbance** in the medium.
    - Such as emission of **light** or inducing an **electrical signal** on an electrode.

- “Vintage” techniques:
  - Chemical imprints left on **photographic** plates.
  - “**Clouds**” in supersaturated vapours.
  - Traces of “**bubbles**” in superheated liquids.
  - **Sparks** in a gas with a very high electric field applied to it.
WHAT WE ACTUALLY MEASURE

• **Modern** techniques:
  
  • **Electrical signals** induced by *moving charges* close to electrodes.
  • **Light** that is converted into *electrical signals*.
  • Very small **vibrations** in crystalline structures (heat), converted into *electrical signals*.
    • Mostly used for dark matter searches.
  • **Acoustic** signals picked up by very sensitive microphones and converted into *electrical signals*. (Very rare!)

• Electrical signals are “**digitized**”:
  
  • Read in by a **computer** system and stored in **digital** format.
  • Some experiments generate very large amounts of **data**.
    • Significant storage and computing challenges!
PARTICLE INTERACTIONS WITH MATTER
FIRST EXPERIMENTS IN PARTICLE PHYSICS

• By 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, which were differentiated by their electric charge.

<table>
<thead>
<tr>
<th>Electric charge</th>
<th>Mass</th>
</tr>
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<tbody>
<tr>
<td>Alpha (α)</td>
<td>+2</td>
</tr>
<tr>
<td></td>
<td>4 x Mp</td>
</tr>
<tr>
<td>Beta (β)</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>1/1800 x Mp</td>
</tr>
<tr>
<td>Gamma (γ)</td>
<td>Neutral</td>
</tr>
</tbody>
</table>
PASSAGE OF PARTICLES THROUGH MATTER

- Alpha, beta, gamma radiation:
  - Classified according to how they bend in a magnetic field.
  - Also differentiated by how easily they can be stopped.

Why do different particles have different penetrating power?
PASSAGE OF PARTICLES THROUGH MATTER

- Alpha, beta, gamma radiation:
  - Classified according to how they bend in a magnetic field.
  - Also differentiated by how easily they can be stopped.

Charged particles interact more frequently. They ionize matter (directly) and lose energy in the process.

Neutral particles interact less often, losing less energy. They ionize matter indirectly.
STOPPING POWER

The graph shows the stopping power [MeV cm²/g] as a function of the momentum [MeV/c] for muon beams on copper (μ⁺ on Cu). The graph includes various processes such as Anderson-Ziegler, Bethe, radiative effects, nuclear losses, and radiative losses. The graph also illustrates minimum ionization and the energy loss at various momentum values, such as $E_{\mu c}$.

The horizontal axis represents the momentum in MeV/c, GeV/c, and TeV/c, while the vertical axis shows the stopping power in MeV cm²/g.
STOPPING POWER

Changes rapidly with Z

Little dependence on Z

Radiative effects reach 1%

Nuclear losses

Anderson-Ziegler

Lindhard-Scharff

Momentum

Stopping power [MeV cm²/g]

βγ

[MeV/c]

[GeV/c]

[TeV/c]

E_{μc}

Radiative losses

Without δ
PARTICLE DETECTION

- Different particles undergo different interactions, leading to different detector signatures.
- Exploit this to identify particle types.

<table>
<thead>
<tr>
<th>Particles</th>
<th>Type of interaction</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrinos</td>
<td>weak (very rarely)</td>
<td>missing energy, interaction products</td>
</tr>
<tr>
<td>electrons</td>
<td>electromagnetic</td>
<td>track and electromagnetic shower</td>
</tr>
<tr>
<td>muons</td>
<td>electromagnetic</td>
<td>penetrating track</td>
</tr>
<tr>
<td>p, K, π</td>
<td>electromagnetic, strong, weak</td>
<td>track and hadronic shower</td>
</tr>
<tr>
<td>photons</td>
<td>electromagnetic</td>
<td>electromagnetic shower</td>
</tr>
<tr>
<td>neutrons, K⁰</td>
<td>strong, weak</td>
<td>hadron shower</td>
</tr>
</tbody>
</table>
LAYERED DETECTORS

**Photons**
- No ionization in low density tracker

**Electrons**
- Ionize tracker, radiative losses lead to shower

**Muons**
- Minimum ionizing particles, little energy loss

**Charged hadrons**
- Fully absorbed in dense hadronic calorimeter

**Neutral hadrons**
- No direct ionization

**Non-destructive measurement**

**Destructive measurements**

C. Lippmann – 2003
PARTICLE DETECTION
1. MEASUREMENT BY ELECTROMAGNETIC ENERGY LOSS

• Applies to all charged particles
**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:

![Diagram showing ionization process](image)
IONIZATION

Bethe energy loss formula

\[- \frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left( \frac{e^2}{4\pi \varepsilon_0} \right)^2 \left[ \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]\]

\[- \frac{dE}{dx}\] Energy loss per distance traveled

\[\beta = \frac{v}{c}\] Particle velocity

\[z\] Particle charge (in units of electron charge)

\[n\] Density of electrons in material

\[I\] Mean excitation potential of material

\[\varepsilon_0\] Vacuum permittivity

\[e\] Electron charge

\[m_e\] Electron mass

\[c\] Speed of light in vacuum

Minimum Ionizing Particles
**IONIZATION**

Bethe energy loss formula

\[- \frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left( \frac{e^2}{4\pi \varepsilon_0} \right)^2 \left[ \ln \left( \frac{2 m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]\]

- \(- \frac{dE}{dx}\) Energy loss per distance traveled
- \(\beta = \frac{v}{c}\) Particle velocity
- \(z\) Particle charge (in units of electron charge)
- \(n\) Density of electrons in material
- \(I\) Mean excitation potential of material
- \(\varepsilon_0\) Vacuum permittivity
- \(e\) Electron charge
- \(m_e\) Electron mass
- \(c\) Speed of light in vacuum

\[p = \frac{1}{\sqrt{1 - \beta^2}} m\]
SCINTILLATION

• Scintillation is the *emission of light* of a characteristic wavelength spectrum, following the *absorption of radiation*.
  • The emitted radiation is usually less energetic than that absorbed.

• Scintillation *occurs in*:
  • Some types of *organic molecules* with complicated electronic structures
    • p-Terphenyl: C_{18}H_{14}
    • “PPO”: C_{15}H_{11}NO
  • *Inorganic* crystals and gases / liquids
    • NaI, CaF_{2}
    • He, Ar, Xe
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.
CHERENKOV RADIATION

- Cherenkov effect: a charged particle moving faster than the speed of light in a medium \( v > c/n \) emits Cherenkov radiation.

As a particle passes through matter, the surrounding atoms polarize and depolarize, and a weak electromagnetic wave spreads out from the position of the particle. For a particle traveling more slowly than light, wave-fronts originating at different times can never meet, and no interference is possible.

For a particle traveling faster than light, the wave-fronts do overlap, and constructive interference is possible, leading to a significant, observable signal.
CHERENKOV RADIATION

- Cherenkov effect: a charged particle moving faster than the speed of light in a medium ($v > c/n$) emits Cherenkov radiation.

Duck moving slower than the speed at which water waves travel.  

Bullet moving faster than the speed at which air waves travel – the speed of sound.
CHERENKOV RADIATION

• In a medium of refractive index \( n \), the speed of light is \( c/n \), and there is no reason why the speed of the particle, \( \beta c \), cannot be greater than \( c/n \).

\[
\cos \theta_c = \frac{\frac{c}{n} t}{\beta c t} = \frac{1}{\beta n}
\]

• A highly relativistic particle passing through a medium is observed to emit visible light known as Cherenkov radiation if \( \beta > 1/n \). As can be seen from the above diagram, a cone of light radiates out from each point on the particle's track.

• The Cherenkov cone angle is related to the particle's \( \beta \).
CHERENKOV RADIATION

• The characteristic blue glow of nuclear reactors is due to Cherenkov radiation.
**LIGHT DETECTION**

- A photomultiplier tube (PMT) is a commonly used instrument for detecting visible photons.
- Basic of operation: photoelectric effect
  - Single photons converted to electrons and multiplied to a measurable electronic signal.
LIGHT DETECTION

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LIGHT DETECTION

• Light falls on a photocathode and a photoelectron is emitted (photoelectric effect).
  • Quantum Efficiency depends on cathode and wavelength (QE~25%).
• Photoelectron focused and accelerated towards the first dynode by electric field.
• Photoelectron strikes dynode and several electrons are emitted (on average n~5).
• Several dynodes (~10) give high gain (10^7).
• High speed: few nanoseconds transit time!
• Gain can be much lower in magnetic fields, depending on orientation.
PHOTON INTERACTIONS IN MATTER

- Photoelectric effect ✓
- Compton scattering ✓
- Pair production (today)

• How does each process contribute to the total energy loss?
PHOTON INTERACTIONS IN MATTER

- Absorption coefficient of Al
  \[ Z = 13 \]

- Absorption coefficient of Pb
  \[ Z = 82 \]

Higher Z materials favour photon absorption by photoelectric effect

Probability of interaction depends on number of protons (Z)
PHOTON INTERACTIONS IN MATTER
PAIR PRODUCTION

• Dominant process at high energy – above 4 MeV for lead (material dependent).

Pair production in a bubble chamber
ELECTRON INTERACTIONS IN MATTER: BREMSTRAHLUNG

Bremsstrahlung: $e Z \rightarrow Z e \gamma$

Electromagnetic radiation produced by the deceleration of an electron, when deflected by an atomic nucleus.

$$X_0 [\text{cm}] = \frac{716}{\rho \left[ \frac{g}{cm^3} \right]} \frac{A}{Z} \frac{1}{(Z + 1) \ln (287/\sqrt{Z})}$$

$X_0$ is the mean distance over which a high-energy electron loses all but $1/e$ of its energy.

$\text{Pb: } X_0 = 0.56 \text{ cm}$

$\text{Si: } X_0 = 8.9 \text{ cm}$
PAIR PRODUCTION AND BREMSSTRAHLUNG

• Pair production and Bremsstrahlung radiation are complementary processes: both lead to electromagnetic showers.

• Very similar Feynman diagrams

• Just two arms swapped

• At high energy: $\sigma_\gamma = \frac{7}{9} \sigma_e$
ELECTROMAGNETIC SHOWERS

• The number of particles increases as a $2^N$, where $N$ is the number of $X_0$ over which the shower has developed.

• $X_0$ is the “radiation length”.

• The length of the shower depends on the primary electron energy.
ELECTROMAGNETIC SHOWERS

• Cloud chamber image of a shower between lead plates.
PARTICLE DETECTION MEASUREMENT BY HADRONIC ENERGY LOSS

• Hadronic interactions have high **multiplicity**:
  • Shower is to 95% contained in ~7λ at 50 GeV (1.2 m of iron).

• Hadronic interactions produce π⁰:
  • π⁰→γγ, leading to **local EM showers**.

• Some energy loss in nuclear breakup and neutrons (“**invisible** energy”)

• Stronger **fluctuations** in a hadronic shower:
  • **Worse** energy resolution.
HADRONIC VS EM SHOWERS

Gamma shower

Hadronic shower
HADRONIC VS EM SHOWERS
ASIDE
A NOTE ABOUT CROSS-SECTIONS

• A measure of interaction probability in particle physics.

• “Effective area of collision”

• Used to calculate predicted interaction rates:

\[ N = \Phi \times \sigma \]

- **Interaction rate**: events/second
- **Flux of incoming particles**: particles/cm²/second
- **Cross-section**: cm²
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A NOTE ABOUT CROSS-SECTIONS

- A measure of interaction probability in particle physics.
- “Effective area of collision”
- Used to calculate predicted interaction rates:

\[ N(E) = \Phi(E) \times \sigma(E) \]

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A NOTE ABOUT CROSS-SECTIONS

• Example:

\[ r = 7 \text{ fermi} = 7 \times 10^{-15} \text{ m} \]
\[ A = \pi r^2 = 154 \text{ fermi}^2 = 1.54 \times 10^{-28} \text{ m}^2 \]
\[ A = 1.54 \text{ barns} \]
\[ 1 \text{ barn} = 10^{-28} \text{ m}^2 = 100 \text{ fm}^2 \]

A 6 MeV alpha particle approaching a gold nucleus with an impact parameter equal to the gold nuclear radius of 7 fm would be scattered through an angle of almost 140°. We would say that the cross section for scattering at or greater than 140° is 1.54 barns.
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• Example:

• Rutherford worked out the scattering cross-section for alpha particles of kinetic energy $KE$ scattering off a single nucleus with atomic number $Z$. The cross-section for scattering at a greater angle than some chosen angle is:

$$\sigma = \pi Z^2 \left(\frac{ke^2}{KE}\right)^2 \left(1 + \cos \theta \right) \left(1 - \cos \theta \right)$$

Depends on chosen angle (geometric nature of cross-section).
Increases with $Z^2$, the number of protons in a nucleus.
Depends on $k$, the Coulomb force constant (strength of electromagnetic interaction).
Decreases with the kinetic energy squared ($KE^2$) of the incoming particle.
DETECTING PARTICLES
PARTICLE DETECTORS

• Detectors usually specialize in:
  • Tracking: measuring positions / trajectories / momenta of charged particles, e.g.:
    • Silicon detectors
    • Drift chambers
  • Calorimetry: measuring energies of particles:
    • Electromagnetic calorimeters
    • Hadronic calorimeters

• But they can also be a combination.
PARTICLE DETECTORS

• Design Criteria:
  • Coverage and hermeticity:
    • Captures all particles produced in an interaction.
    • No holes, no cracks, no dead regions.
  • Resolution:
    • Resolve all particles (high granularity, each “granule”/channel read out individually).
    • Measure energies and directions with high precision.
  • Constraints:
    • Cost and available technology.
ENERGY RESOLUTION

- The ability to differentiate amounts of energy deposition.

- Quantitatively described by the **full width at half maximum**:

\[
\text{FWHM} = 2\sqrt{\ln 2}\sigma \approx 2.35\sigma
\]

- It determines when two peaks can be separated.
ENERGY RESOLUTION

\[ \int L \approx 1.5 \text{ pb}^{-1} \]

\[ \frac{dN_{\mu\mu}}{dm_{\mu\mu}} \text{ [GeV}^{-1}] \]

\[ 10^0 \quad 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \]

\[ m_{\mu\mu} \text{ [GeV]} \]

\[ \omega/\rho \quad \phi \quad J/\psi \quad \psi' \quad Y(1S) \quad Y(2S) \quad Z \]

**ATLAS** Preliminary

Data 2010, \( \sqrt{s} = 7 \text{ TeV} \)
CHERENKOV DETECTORS

The Cerenkov radiation from a muon produced by a muon neutrino event yields a well-defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.
CHERENKOV DETECTORS

• Super-Kamiokande in Japan.
  • The world’s largest neutrino detector!
NEUTRINO DETECTION AT SUPER-K

• Electrons and muons resulting from neutrino interactions in the water
NEUTRINO DETECTION AT SUPER-K
IONIZATION DETECTOR

- Drifting electrons should not be trapped:
  - Use noble gas, e.g. Ar.
- Want large primary ionization yield:
  - Ar gives 25 ions/cm at normal T, p for a minimum ionizing particle.
- The primary electrons may ionize further atoms:
  - ×3 or ×4 increase.
- Xe and/or higher pressure are even better (and more expensive).

Induced electrical signal on anode can be measured to estimate number of drift electrons: Elost to ionization.
IONIZATION DETECTOR

• Geiger counter
TIME PROJECTION CHAMBER

• Exploits ionization energy losses of charged particles.
• Electrons are drifted onto a fine grained plane of wires, and the particle trajectories can be mapped out, along with their ionization energy loss, $dE/dx$
TIME PROJECTION CHAMBER

• MicroBooNE liquid argon TPC at Fermilab
SCINTILLATION DETECTORS

• Emitted light depends on detector material.
  • Usually in the visible to UV range.

• Sometimes requires the use of wavelength-shifting materials to shift UV light to visible, so it can be efficiently measured by commonly used photomultiplier tubes.
MODERN EXPERIMENTS
PARTICLE SOURCES

• Particle physics experiments use different sources of particles

• Artificial beams produced in accelerators
  • Colliders – beams are made to collide against each other.
    • Highest energy interactions from artificial sources
  • Beams are aimed at fixed targets / detectors
    • Lower energy, but typically more intense

• Natural sources
  • Particles resulting from cosmic ray interaction in the atmosphere
  • Radioactive sources
  • Astrophysical sources
  • Dark matter?


PARTICLE COLLIDERS AROUND THE WORLD

<table>
<thead>
<tr>
<th>Location</th>
<th>Facility</th>
<th>Year</th>
<th>Interaction</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC, California</td>
<td>SLC</td>
<td>1989-1998</td>
<td>$e^-e^+$</td>
<td>50 GeV $e^-$ and 50 GeV $e^+$</td>
</tr>
<tr>
<td></td>
<td>PEP II</td>
<td>1997-2008</td>
<td>$e^-e^+$</td>
<td>9.0 GeV $e^-$ and 3.1 GeV $e^+$</td>
</tr>
<tr>
<td>Fermilab, nr Chicago</td>
<td>Tevatron</td>
<td>1987-2009</td>
<td>$p \bar{p}$</td>
<td>980 GeV $p$ and 980 GeV $\bar{p}$</td>
</tr>
<tr>
<td>CERN, Geneva</td>
<td>LEP</td>
<td>1989-2000</td>
<td>$e^-e^+$</td>
<td>$E_{CM}$: 89 to 206 GeV</td>
</tr>
<tr>
<td></td>
<td>LHC</td>
<td>2008-...</td>
<td>$p \bar{p}$</td>
<td>$E_{CM}$: 14 TeV</td>
</tr>
<tr>
<td>DESY, Hamburg</td>
<td>HERA</td>
<td>1990-2007</td>
<td>$e^-p$</td>
<td>920 GeV $p$ and 30 GeV $e^-$</td>
</tr>
<tr>
<td>KEK, near Toyko</td>
<td>KEKB</td>
<td>1999-...</td>
<td>$e^-e^+$</td>
<td>8.0 GeV $e^-$ and 3.5 GeV $e^+$</td>
</tr>
<tr>
<td>Brookhaven National Lab, Long Island</td>
<td>RHIC</td>
<td>2000-...</td>
<td>AuAu, CuCu</td>
<td>200 GeV/nucleon</td>
</tr>
</tbody>
</table>
CERN’S ACCELERATOR COMPLEX

ATLAS

- p (proton)
- ion
- neutrons
- \( \bar{p} \) (antiproton)
- electron
- proton/antiproton conversion

HiRadMat

n-ToF

2011

2001

ALICE

LHC

2008 (27 km)

ATLAS

SPS

1976 (7 km)

CMS

LHCb

AWAKE

2016

East Area

CTF3
A GENERAL PURPOSE DETECTOR

beam pipe

tracking and vertexing

EM calorimeter

hadronic calorimeter

muon chambers
THE CMS DETECTOR

15 m

22 m
A SLICE OF CMS
MAGNET SYSTEMS

• Solenoid and toroidal magnets.

• Solenoid coils in CMS and ATLAS:
  • Field direction along beam axis.
  • Homogenous field inside the coil.
  • e.g. CMS superconducting magnet
    • \( I = 20 \text{ kA}, B = 4T \)
    • Temperature 4K.

• For comparison, Earth’s magnetic field at surface is ~50 \( \mu T \).
EVENT SIGNATURES

Higgs → 4 muons

Charged particles bend in the magnetic field

The lower the particle momentum the more they bend.

Straight tracks from high momentum particles are the most interesting!
A REAL EVENT
T2K: ND280
A GENERAL PURPOSE NEUTRINO DETECTOR

- Beam of neutrinos produced at the J-PARC proton accelerator in Japan

[Diagram of T2K: ND280 detector with components such as UA1 Magnet, U0D, Barrel ECal, Downstream ECal, P0D, TPCs, Plastic scintillator, and Argon gas.]
THE ND280 DETECTOR
WITH MAGNET OPEN FOR MAINTENANCE
A NEUTRINO INTERACTION IN ND280
WHAT ABOUT DARK MATTER?

• Does not interact through weak, electromagnetic, or strong force.

• But it **might interact**, very very weakly.

• We need very “quiet” (cryogenic, deep underground) detectors to see dark matter interactions.
  • Scattering off of nuclei $\rightarrow$ transfer of kinetic energy.
THE LUX DARK MATTER EXPERIMENT

- The Large Underground Xenon (LUX) and XENON-1t experiments look for evidence of weakly interacting massive particle (WIMP) dark matter interactions.

- A few hundred to a ton of liquid xenon as the TPC medium.

- Aim to directly detect galactic dark matter in underground laboratories about 1 mile deep.

- The detectors are shielded from background particles by a surrounding water tank and the earth above.

- This shielding reduces cosmic rays and radiation interacting with the xenon.
PARTICLE DETECTORS AT THE SOUTH POLE
PARTICLE DETECTORS AT THE SOUTH POLE

Why do we go to such remote places for science?
ICE FISHING FOR SPACE NEUTRINOS!

- IceCube detector at the South Pole
  - A neutrino detector: a neutrino telescope.
- Looks for extra-terrestrial sources of neutrinos.
  - Like taking an “X-ray” picture of the Universe.
- Use the Antarctic ice as a Cherenkov detector!
ICE FISHING FOR SPACE NEUTRINOS!

• Made up of strings of thousands of basketball-sized photon detectors
  • Digital Optical Modules

*IceCube in Scale: The dashed lines above represent the portion of the cables that have DOMs attached*
THE ICECUBE DETECTOR

IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

IceCube detector
86 strings of DOMs, set 125 meters apart

Digital Optical Module (DOM)
5,150 DOMs deployed in the ice

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation–managed research facility

150 m

DeepCore

DOMs are 17 meters apart

60 DOMs on each string

Antarctic bedrock
ICECUBE PHYSICS

• Used to study extra-galactic, extremely high-energy sources.
  • Neutrinos, being nearly massless and without charge, are ideal messengers. They carry directional information.
  • Charged particles are bent by magnetic fields, neutrons decay before reaching the earth and high-energy photons are absorbed.

• E.g. gamma ray bursts: hadronic or electromagnetic origin?

• Can only be done in the South Pole!

• Vast, extremely clean ice; it’s there for free!
  • Recall, detector constraints: cost and detector technology
BERT, ERNIE AND MANY OTHERS

• In 2013, IceCube announced that it had detected 28 neutrinos likely originating from outside the Solar System.
  • These are ultra-high energy (PeV) neutrino events.
APPLICATION OF SCINTILLATION DETECTORS

- Cosmic ray muon detection
COSMIC RAY MUON DETECTION
COSMIC RAY MUON DETECTION

• Measurement of the muon lifetime

1. Measure $t_{\text{decay}}$ (difference between muon signal and decay signal in the second scintillator paddle) of a sample $N_0$ of low energy muons.

2. Fit the data to an exponential curve of the form:

$$N(t) = N_0 e^{-t/T}$$

where $T = \text{muon lifetime}$
COSMIC RAY MUON DETECTION

- Measurement of the muon lifetime

  Lifetime $T$:
  $T = 2.29\mu s$
  $T_{th} = 2.1970\mu s$

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   where $T =$ muon lifetime
THE ATLAS DETECTOR

Muon Detectors  Tile Calorimeter  Liquid Argon Calorimeter

Toroid Magnets  Solenoid Magnet  SCT Tracker  Pixel Detector  TRT Tracker

25 m

44 m
THE ATLAS DETECTOR
THAT’S ALL FOR THIS WEEK

• Next week:
  • An overview of the Standard Model
BONUS
SOLID-STATE DETECTORS
SOLID-STATE DETECTORS
COLLIDER EXPERIMENTS

LHC Experiments underground
WHY BUILD THE LARGE HADRON COLLIDER?

- Large accelerator complex:
  - Long-lived charged particles can be accelerated to high momenta using electromagnetic fields.
  - The LHC accelerates protons and heavy ions; older generation accelerators collided e.g. protons - anti-protons, and electrons - positrons, ...

- Why accelerate particles?
  - High beam energies $\rightarrow$ high $E_{CM}$ $\rightarrow$ more energy to create new particles!
  - Higher energies probe physics at shorter distances. De Broglie wavelength:

$$\frac{\lambda}{2\pi} = \frac{h c}{p c} \approx \frac{197 \text{ MeV fm}}{p \text{ [MeV/c]}}$$

  - e.g. 20 GeV/c probes a distance of 0.01 fm.

- An accelerator complex uses a variety of particle acceleration techniques to reach the final energy.
PROTON-PROTON COLLISIONS
PROTON-PROTON COLLISIONS

• Quantum Chromodynamics theory is expressed in terms of quarks and gluons (partons)
  • We are colliding composite objects.
• At the LHC energies, quarks and gluons collide and the actual collision energy is a fraction of the total:

\[ \sqrt{\hat{s}} \ll \sqrt{s} = E_{\text{cm}} = 2E_p \]
CERN
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

• Founded in 1954. Currently operates a network of six accelerators.

• A few of the scientific and computing achievements:
  • Neutral currents in Gargamelle bubble chamber
  • W/Z bosons in UA1 and UA2 experiments
  • The World Wide Web!
SCINTILLATION

- Depending on the particle dE/dx, the fast and slow states are occupied differently.
- The relative intensities in the light output of these states depend on the ionizing particle type.
- This property of scintillators allows for pulse shape discrimination: it is possible to identify which particle was detected by looking at the scintillation light times.
SCINTILLATION

• *Pulse shapes* can be used to **discriminate** among different particle types:
ASIDE
A NOTE ABOUT CROSS-SECTIONS

• A measure of interaction probability in particle physics.

• “Effective area of collision”

• Used to calculate predicted interaction rates:

\[ N = \Phi \times \sigma \]

- Interaction rate: events/second
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SCINTILLATION DETECTORS

- Light output and type of particles / radiation.

particle energy [MeV]

NE-102 = common plastic scintillator