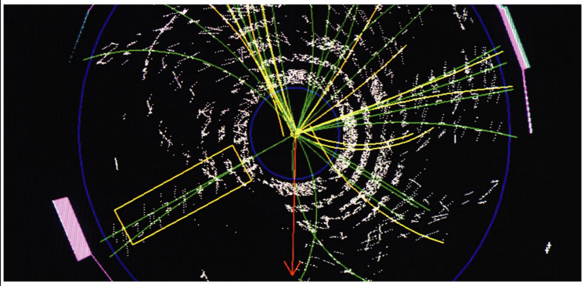
# Chapter S4
# Building Blocks of the Universe



# Agenda

- Announce:
  - Pass back “Waves on a String” “Parallax I”
- Errors vs Uncertainty
- deGrasse Tyson
- Review Ch. 11—Jovian Planets
- Ch. S4—Building Blocks


# Errors vs Uncertainty

- Uncertainty & Error:
  - Always present to some degree
  - “Better” equipment/design can help make small
- Uncertainty:
  - Allowance for inherent inability to **measure** exactly
- Error:
  - Real world **phenomena** which you know are there, you cannot eliminate, but which you cannot account for
  - Examples: friction, wind resistance, imperfect weighting of dice,

# Leonids

- Night

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- A year
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- Yes
- No

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- Yes
- **No – because there is no free oxygen**

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- Escape into space
- Condense and make rain
- Condense and make clouds
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- Indicate a magnetic field is present
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- Infrared radiation
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1. Plausible. Saturn's moons also show impact craters and volcanoes.
2. Plausible. Saturn's atmosphere originated from the volatiles in impactors that were released via volcanic activity.
3. Implausible. No impactors would survive the immense pressures at the depth of Saturn's core.
4. Implausible. Any large impactor approaching Saturn would be broken up by tidal forces.
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## S4.1 The Quantum Revolution

- Our goals for learning
- How has the quantum revolution changed our world?

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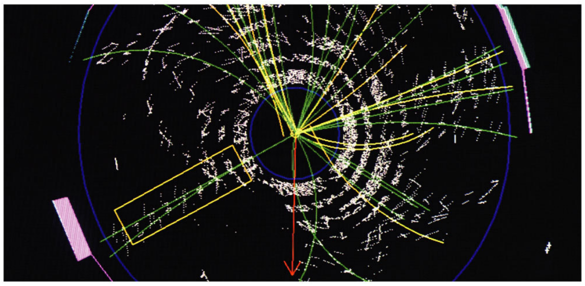


## The Quantum Realm

- Light behaves like particles (photons)
- Atoms consist mostly of empty space
- Electrons in atoms are restricted to particular energies
- The science of this realm is known as *quantum mechanics*

## Surprising Quantum Ideas

- Protons and neutrons are not truly fundamental—they are made of *quarks*
- Antimatter can annihilate matter and produce pure energy
- Just four forces govern all interactions: gravity, electromagnetic, strong, and weak
- Particles can behave like waves
- Quantum laws have astronomical consequences

## Quantum Mechanics and Society

- Understanding of quantum laws made possible our high-tech society:
  - Radios and television
  - Cell phones
  - Computers
  - Internet

## What have we learned?

- How has the quantum revolution changed our world?
  - Quantum mechanics has revolutionized our understanding of particles and forces and made possible the development of modern electronic devices

## S4.2 Fundamental Particles and Forces

- Our goals for learning
- What are the basic properties of subatomic particles?
- What are the fundamental building blocks of matter?
- What are the fundamental forces in nature?

## What are the basic properties of subatomic particles?

## Particle Accelerators

- Much of our knowledge about the quantum realm comes particle accelerators
- Smashing together high-energy particles produces showers of new particles

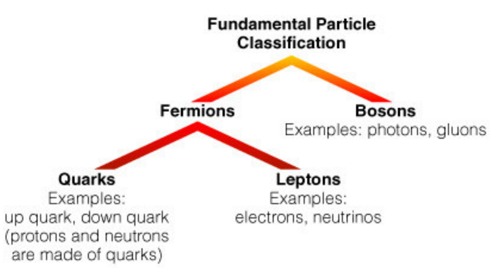
## Properties of Particles

- Mass
- Charge (proton +1, electron -1)
- Spin
  - Each type of subatomic particle has a certain amount of angular momentum, as if it were spinning on its axis

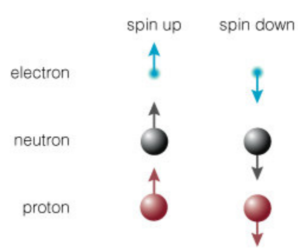
## Fermions and Bosons

- Physicists classify particles into two basic types, depending on their spin (measured in units of $h/2\pi$)
- *Fermions* have half-integer spin (1/2, 3/2, 5/2,…)
  - Electrons, protons, neutrons
- *Bosons* have integer spin (0,1,2,…)
  - Photons

## Fundamental Particles




## Orientation of Spin




- Fermions with spin of 1/2 have two basic spin states: up and down

## What are the fundamental building blocks of matter?


## Quarks


- Protons and neutrons are made of quarks
- *Up quark* (u) has charge +2/3
- *Down quark* (d) has charge -1/3

## Quarks and Leptons

- Six types of quarks: up, down, strange, charmed, top, and bottom
- Leptons are not made of quarks and also come in six types
  - Electron, muon, tauon
  - Electron neutrino, mu neutrino, tau neutrino
- Neutrinos are very light and uncharged

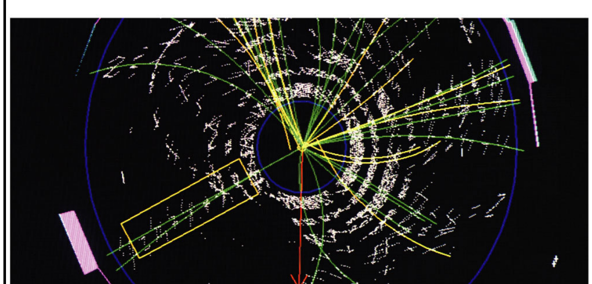
## Matter and Antimatter


- Each particle has an antimatter counterpart
- When a particle collides with its antimatter counterpart, they annihilate and become pure energy in accord with $E = mc^2$

## Matter and Antimatter


- Energy of two photons can combine to create a particle and its antimatter counterpart (pair production)

## What are the fundamental forces in nature?



## Four Forces

- Strong Force (holds nuclei together)
  - Exchange particle: gluons
- Electromagnetic Force (holds electrons in atoms)
  - Exchange particle: photons
- Weak force (mediates nuclear reactions)
  - Exchange particle: weak bosons
- Gravity (holds large-scale structures together)
  - Exchange particle: gravitons

## Strength of Forces

- Inside nucleus:
  - strong force is 100 times electromagnetic
  - weak force is $10^{-5}$ times electromagnetic force
  - gravity is $10^{-43}$ times electromagnetic
- Outside nucleus:
  - Strong and weak forces are unimportant

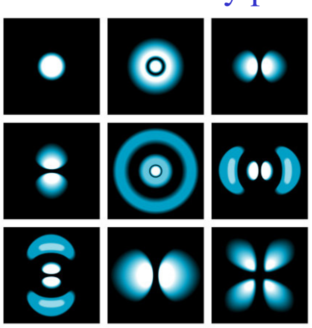
## What have we learned?

- What are the basic properties of subatomic particles?
  - Charge, mass, and spin
- What are the fundamental building blocks of matter?
  - Quarks (up, down, strange, charmed, top, bottom)
  - Leptons (electron, muon, tauon, neutrinos)
- What are the fundamental forces in nature?
  - Strong, electromagnetic, weak, gravity

## S4.3 Uncertainty and Exclusion in the Quantum Realm

- Our goals for learning
- What is the uncertainty principle?
- What is the exclusion principle?

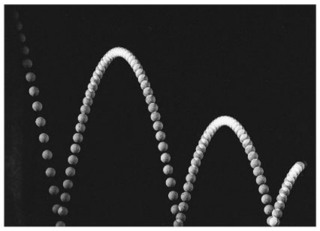
## What is the uncertainty principle?



## Uncertainty Principle

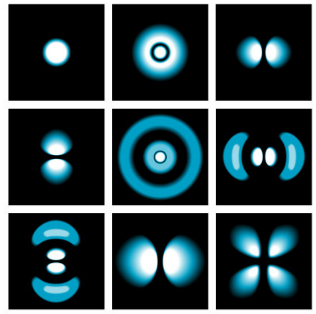
- The more we know about where a particle is located, the less we can know about its momentum, and conversely, the more we know about its momentum, the less we can know about its location

## Position of a Particle



- In our everyday experience, a particle has a well-defined position at each moment in time
- But in the quantum realm particles do not have well-defined positions

## Electrons in Atoms



- In quantum mechanics an electron in an atom does not orbit in the usual sense
- We can know only the probability of finding an electron at a particular spot

## Electron Waves


- On atomic scales, an electron often behaves more like a wave with a well-defined momentum but a poorly defined position

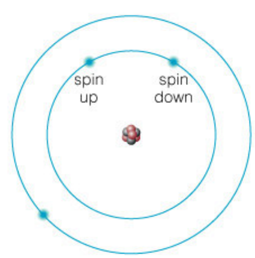
## Location and Momentum

Uncertainty in location X Uncertainty in location = Planck's Constant (*h*)

## Energy and Time

Uncertainty in energy X Uncertainty in time = Planck's Constant (*h*)

## What is the exclusion principle?



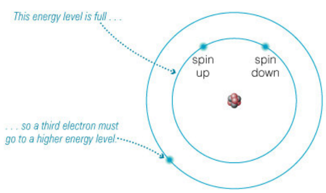
## Quantum States

- The *quantum state* of a particle specifies its location, momentum, orbital angular momentum, and spin to the extent allowed by the uncertainty principle

## Exclusion Principle

- Two fermions of the same type cannot occupy the same quantum state at the same time

## Exclusion in Atoms




- Two electrons, one with spin up and the other with spin down can occupy a single energy level
- A third electron must go into another energy level

## What have we learned?

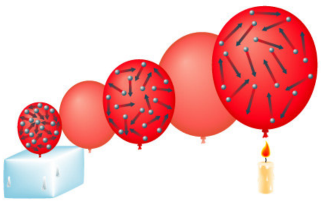
- What is the uncertainty principle?
  – We cannot simultaneously know the precise value of both a particle's position and its momentum
  – We cannot simultaneously know the precise value of both a particle's energy and the time that it has that energy
- What is the exclusion principle?
  – Two fermions cannot occupy the same quantum state at the same time

## S4.4 The Quantum Revolution

- Our goals for learning
- How do the quantum laws affect special types of stars?
- How is "quantum tunneling" crucial to life on Earth?
- How empty is empty space?
- Do black holes last forever?

## How do the quantum laws affect special types of stars?

## Thermal Pressure

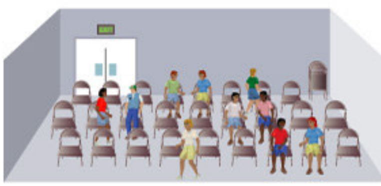


- Molecules striking the walls of a balloon apply *thermal pressure* that depends on the temperature inside the balloon
- Most stars are supported by thermal pressure

## Degeneracy Pressure

- Laws of quantum mechanics create a different form of pressure known as *degeneracy pressure*
- Squeezing matter restricts locations of its particles, increasing their uncertainty in momentum
- But two particles cannot be in same quantum state (including momentum) at same time
- There must be an effect that limits how much matter can be compressed—degeneracy pressure

## Auditorium Analogy



- When the number of quantum states (chairs) is much greater than the number of particles (people), it's easy to squeeze them into a smaller space

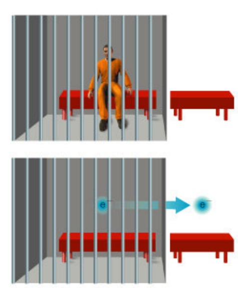
## Auditorium Analogy

- When the number of quantum states (chairs) is nearly the same as the number of particles (people), it's hard to squeeze them into a smaller space

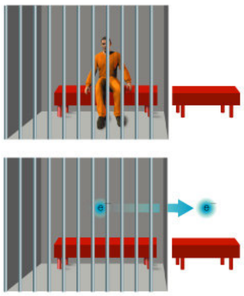
## Degeneracy Pressure in Stars

- *Electron degeneracy pressure* is what supports white dwarfs against gravity—quantum laws prevent its electrons from being squeezed into a smaller space
- *Neutron degeneracy pressure* is what supports neutron stars against gravity—quantum laws prevent its neutrons from being squeezed into a smaller space

## How is "quantum tunneling" crucial to life on Earth?



## Quantum Tunneling

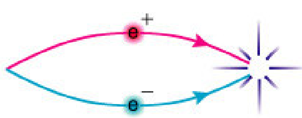


- Person in jail does not have enough energy to crash through the barrier
- Uncertainty principle allows subatomic particle to “tunnel” through barriers because of uncertainty in energy

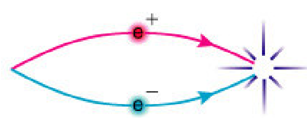
## Quantum Tunneling and Life

- At the core temperature of the Sun, protons do not have enough energy to get close enough to other protons for fusion (electromagnetic repulsion is too strong)
- Quantum tunneling saves the day by allowing protons to tunnel through the electromagnetic energy barrier

## How empty is empty space?

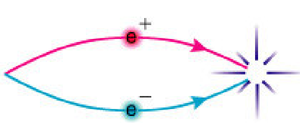


## Virtual Particles



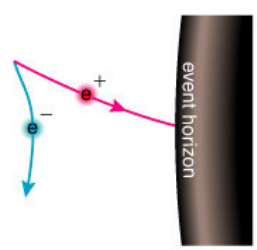
- Uncertainty principle (in energy & time) allows production of matter-antimatter particle pairs
- But particles must annihilate in an undetectably short period of time

## Vacuum Energy

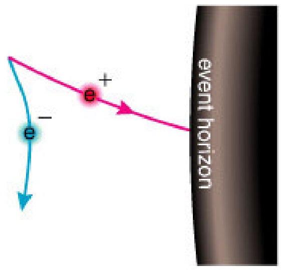


- According to quantum mechanics, empty space (a vacuum) is actually full of virtual particle pairs popping in and out of existence
- The combined energy of these pairs is called the *vacuum energy*

## Do black holes last forever?

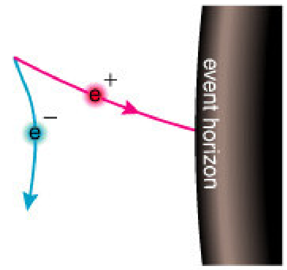


## Virtual Particles near Black Holes




- Particles can be produced near black holes if one member of a virtual pair falls into the black hole
- Energy to permanently create other particle comes out of black hole's mass

## Hawking Radiation




- Stephen Hawking predicted that this form of particle production would cause black holes to "evaporate" over extremely long time periods
- Only photons and subatomic particles would be left

## What have we learned?

- How do the quantum laws affect special types of stars?
  - Quantum laws produce degeneracy pressure that supports white dwarfs and neutron stars
- How is "quantum tunneling" crucial to life on Earth?
  - Uncertainty in energy allows for quantum tunneling through which fusion happens in Sun

## What have we learned?

- How empty is empty space?
  - According to quantum laws, virtual pairs of particles can pop into existence as long as the annihilate in an undetectably short time period
  - Empty space should be filled with virtual particles whose combined energy is the vacuum energy
- Do black holes last forever?
  - According to Stephen Hawking, production of virtual particles near a black hole will eventually cause it to "evaporate"