Chapter S4: Building Blocks of the Universe
S4.1 The Quantum Revolution

• Our goals for learning:
  • How has the quantum revolution changed our world?
How has the quantum revolution changed our world?
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 nature?
  - What are the fundamental forces in nature?
What are the basic properties of subatomic particles?

Fundamental Particle Classification

- **Fermions**
  - **Quarks**
    - Examples: up quark, down quark (protons and neutrons are made of quarks)
  - **Leptons**
    - Examples: electrons, neutrinos

- **Bosons**
  - Examples: photons, gluons
Particle Accelerators

• Much of our knowledge about the quantum realm comes from particle accelerators.

• Smashing together high-energy particles produces 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.
Orientation of Spin

- Particles can have spin in integer or half-integer multiples of $\hbar/2\pi$.
- Particles with half-integer spin have two basic spin states: up and down.
What are the fundamental building blocks of nature?
Fermions and Bosons

- Physicists classify particles into two basic types, depending on their spin (measured in units of $\hbar/2\pi$).
- **Fermions** have half-integer spin ($1/2, 3/2, 5/2, \ldots$).
  - Examples: electrons, protons, neutrons
- **Bosons** have integer spin ($0, 1, 2, \ldots$).
  - Example: photons
Fundamental Particles

**Fundamental Particle Classification**

- **Fermions**
  - Quarks
    - Examples: up quark, down quark (protons and neutrons are made of quarks)
  - Leptons
    - Examples: electrons, neutrinos

- **Bosons**
  - Examples: photons, gluons
Quarks

Protons and neutrons are made of quarks.

- Up quark \((u)\) has charge \(+2/3\).
- Down quark \((d)\) has charge \(-1/3\).

\[\text{Total charge: } +\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1\]

\[\text{Total charge: } +\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0\]

- 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 \( E = mc^2 \).

An electron and a positron (antielectron) collide, resulting in annihilation in which all their energy emerges as a pair of photons.
Matter and Antimatter

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

- The energy of two photons combines to create an electron and a positron.

  - 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 force.
  • Weak force is $10^{-5}$ times electromagnetic force.
  • Gravity is $10^{-43}$ times electromagnetic force.

• 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 nature?
  • 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

\[
\text{Uncertainty in location} \times \text{Uncertainty in momentum} \approx \text{Planck's constant } (h)
\]
Energy and Time

\[
\text{Uncertainty in energy} \times \text{Uncertainty in time} \approx \text{Planck's constant } (h)
\]
What is the exclusion principle?

spin up

spin down
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 Key Quantum Effects in Astronomy

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?

**a** When there are many more available quantum states (chairs) than electrons (people), an electron is unlikely to try to enter the same state as another electron. The only pressure comes from the temperature-related motion of the electrons, which is thermal pressure.

**b** When the number of electrons (people) approaches the number of available quantum states (chairs), finding an available state requires that the electrons move faster than they would otherwise. This extra motion creates degeneracy pressure.
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 the same quantum state (including momentum) at the same time.
- There must be an effect that limits how much matter can be compressed—degeneracy pressure.
Auditorium Analogy for Degeneracy Pressure

When there are many more available quantum states (chairs) than electrons (people), an electron is unlikely to try to enter the same state as another electron. The only pressure comes from the temperature-related motion of the electrons, which is thermal pressure.

- 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.
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 their electrons from being squeezed into a smaller space.

- *Neutron degeneracy pressure* is what supports neutron stars against gravity—quantum laws prevent their neutrons from being squeezed into a smaller space.
How is quantum tunneling crucial to life on Earth?
Quantum Tunneling

- A person in jail does not have enough energy to crash through the bars of a cell.
- Uncertainty principle allows subatomic particle to "tunnel" through barriers because of uncertainty in energy.
Quantum Tunneling and Life

- At the core 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 occasionally tunnel through the electromagnetic energy barrier.
How empty is empty space?

Most of Space

a Pairs of virtual electrons and positrons can pop into existence, as long as they annihilate each other before they can be detected.
Virtual Particles

Most of Space

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

a Pairs of virtual electrons and positrons can pop into existence, as long as they annihilate each other before they can be detected.

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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*.

Pairs of virtual electrons and positrons can pop into existence, as long as they annihilate each other before they can be detected.
Do black holes last forever?

Space Near a Black Hole

b Near the event horizon of a black hole, this same process leads to the creation of real particles, not just virtual ones. The energy to make these particles comes at the expense of the black hole, which loses as much mass as the new particles gain.
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.

b Near the event horizon of a black hole, this same process leads to the creation of real particles, not just virtual ones. The energy to make these particles comes at the expense of the black hole, which loses as much mass as the new particles gain.
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 they 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."