Honors Physics III

Lecture 21:
Fission and Fusion
Elementary Particles and Cosmology

http://www.physics.rutgers.edu/ugrad/273a

Weida Wu
Nuclear Reactions

- **Radioactivity**: spontaneous transmutation of nuclei.
- **Nuclear Reactions**: artificial transmutation of nuclei.
- First human made nuclear reactions (using alpha particles) by Rutherford:

  \[ \frac{4}{2}\text{He} + \frac{14}{7}\text{N} \rightarrow \frac{17}{8}\text{O} + \frac{1}{1}\text{H} \]

- Note: charge “Z” and mass number “A” must be conserved in every nuclear reaction. For example:
  \[ Z = 2 + 7 = 8 + 1 \quad A = 4 + 14 = 17 + 1 \]
- Abbreviation: \[ \frac{14}{7}\text{N(}\alpha, p\text{)}\frac{17}{8}\text{O} \quad \text{General: } X(a, b)Y \]
- Target X is usually at rest
- Energy conservation:

  \[ m_a c^2 + K_a + m_X c^2 = m_Y c^2 + K_Y + m_b c^2 + K_b \]
As always, we can define $Q$ as the **net kinetic energy released**.

$$Q \equiv K_Y + K_b - K_a$$

$$= (m_a + m_X - m_b - m_Y)c^2$$

Since it is always possible to have more than 2 nuclei in the final state: $a + X \rightarrow Y + b + c + d + ...$

$Q$ is the **(sum of incoming masses minus sum of outgoing masses) times $c^2$**.

- $Q>0 \Rightarrow$ exothermic
- $Q<0 \Rightarrow$ endothermic
- $Q=0 \Rightarrow$ elastic

Let’s review some examples of each of these.
Q-value examples

\[ a + X \rightarrow Y + b \]

\[ Q \equiv K_Y + K_b - K_a = (m_a + m_X - m_b - m_Y)c^2 \]

1) \[ \frac{2}{1} H + \frac{2}{1} H \rightarrow \frac{3}{2} He + \frac{1}{0} n \quad Q = + 3.27 \text{ MeV} \]
   - Q>0 ⇒ exothermic reaction
   - Some mass got converted to kinetic energy.
   - Q>0 reactions can occur with both target and projectile essentially at rest

2) \[ \frac{4}{2} He + \frac{14}{7} N \rightarrow \frac{17}{8} O + \frac{1}{1} H \quad Q = - 1.19 \text{ MeV} \]
   - Q<0 ⇒ endothermic reaction
   - Some kinetic energy got converted to mass!
   - Q<0 reactions cannot occur at rest.
   - Q = K_Y + K_b - K_a ⇒ if K_a =0, then Q<0 implies K_Y+K_b < 0 ⇒ impossible!
Q-value examples

\[ a + X \rightarrow Y + b \]

\[ Q \equiv K_Y + K_b - K_a = (m_a + m_X - m_b - m_Y) c^2 \]

3) \[ a + X \rightarrow a + X \quad Q = 0 \text{ MeV} \]

- \( Q=0 \Rightarrow \text{elastic collision} \)
Again, consider the following nuclear reaction:

\[ a + X \rightarrow Y + b \]

\[ Q = K_Y + K_b - K_a \]

Suppose that X starts off at rest (\( K_X = 0 \)) and the process is endothermic (\( Q < 0 \)).

What is the minimum value of \( K_a \) for the reaction to occur?

Take as an example:

\[ ^4_2\text{He} + ^{14}_7\text{N} \rightarrow ^{17}_8\text{O} + ^1_1\text{H} \]

Recall, here, \( Q = K_Y + K_b - K_a = (m_N + m_{\text{He}} - m_{\text{O}} - m_{\text{H}})c^2 = -1.19 \text{ MeV} \).

Well, naively, we can set \( K_b = K_Y = 0 \) (the minimum possible K.E.). So as long as \( K_a > -Q \), (e.g. \( K_a > 1.19 \text{ MeV} \)), then the process can occur.

So is the threshold is \( K_a = 1.19 \text{ MeV} \)?

- No, that’s incorrect. Why?
The problem is that while we have enforced energy conservation (that’s how we derived \( Q \)), we haven’t enforced momentum conservation.

If \( K_Y \) and \( K_b \) are 0, then their momenta are zero. However, \( K_X = 0 \) but \( K_a > 0 \). So momentum is not conserved in this reaction.

\[
a \rightarrow \quad X \quad Y \quad b
\]

\text{before} \quad \text{after}

In other words, if \( K_a = 1.19 \text{ MeV} \), then \( K_Y + K_b = 0 \Rightarrow K_Y = 0 \) and \( K_b = 0 \).

See 13.2 for non-relativistic approximation and problem #13 for relativistic consideration.
Nuclear Fission

- Natural Uranium is about 99.3% U-238 and 0.7% U-235.
- Neutrons make ideal projectiles for inducing fission

\[
\frac{1}{0}n + \frac{235}{92}U \rightarrow \frac{144}{56}Ba + \frac{89}{36}Kr + \frac{1}{0}n + \frac{1}{0}n + \frac{1}{0}n
\]

- Why is there an energy release?
- Well, do you remember where U is on the binding energy curve?
- Let’s look at the slope on curve of binding energy....
The energy release in the process on the previous page is about $Q \sim 200$ MeV.

- Compared with combustion of coal or oil: about a few eV per atom
Now since there are three neutrons produced per reaction, each neutron might hit another Uranium nucleus, producing yet more neutrons...

\[ \frac{1}{0}n + \frac{235}{92}U \rightarrow \frac{144}{56}Ba + \frac{89}{36}Kr + \frac{1}{0}n + \frac{1}{0}n + \frac{1}{0}n \]

\[ \rightarrow \text{stage: 1 2 3 4 5 ...} \]

\[ \# \text{reactions: 1 3 9 27 81 ...} \]

- 1 neutron in the first stage
- 3 neutrons in the second stage
- 9 neutrons in the third stage
- 27 neutrons in the fourth stage
- 81 neutrons in the fifth stage
- ...

This is the basis of a chain reaction. First achieved by Enrico Fermi in 1942.

Of course, this is idealized. Fission isn’t nearly so efficient...
Chain Reaction
What could make fission inefficient?

■ Sources of loss:

1) Competing reactions, eg:

\[ \frac{1}{0}n + \frac{235}{92}U \rightarrow \frac{140}{54}Xe + \frac{94}{38}Sr + \frac{1}{0}n + \frac{1}{0}n \]

2) Capture of neutrons by U-238, instead of U-235, followed by non-fission decay

3) Leakage of neutrons that don’t interact

■ Each of these can prevent a self-sustaining chain reaction.
Nuclear Reactors

- While nothing can be done about competing reactions (that’s determined by physics), one can deal with the other issues.

- For example, one can slow down neutrons to avoid U-238 capture. Often use D₂O (Deuterium Oxide, or heavy water) or Graphite as a “moderator” to slow them down.
Nuclear Fusion

![Diagram showing the relationship between average binding energy per nucleon and number of nucleons in a nucleus, with arrows indicating fusion and fission.]
Nuclear Fusion

- If light nuclei are forced together, they will fuse with a yield of energy because the mass of the combination will be less than the sum of the masses of the individual nuclei.

- If the combined nuclear mass is less than that of iron at the peak of the binding energy curve, then the nuclear particles will be more tightly bound than they were in the lighter nuclei, and that decrease in mass comes off in the form of energy.

- For elements heavier than iron, fission will yield energy.
Nuclear Fusion

- Fusion of hydrogen into helium releases energy: mass converted to kinetic energy:

\[
\begin{align*}
\frac{2}{1} H + \frac{2}{1} H & \rightarrow \frac{3}{1} H + \frac{1}{1} H \quad Q = 4.0 \text{MeV} \\
\frac{2}{1} H + \frac{2}{1} H & \rightarrow \frac{3}{2} He + \frac{1}{0} n \quad Q = 3.3 \text{MeV} \\
\frac{2}{1} H + \frac{3}{1} H & \rightarrow \frac{4}{2} He + \frac{1}{0} n \quad Q = 17.6 \text{MeV}
\end{align*}
\]

- Advantages over fission as a fuel:
  1) absence of radioactive waste
  2) plentiful supply of deuterons compared to U-235
Deuterium-Tritium

- The most promising of the hydrogen fusion reactions which make up the deuterium cycle is the fusion of deuterium and tritium.

- One of the major problems in obtaining energy from nuclear fusion is that the Coulomb repulsion force must be overcome before they can fuse.

- Accomplished by heating the fuel to extremely high temperatures

- Deuterium is available in large quantities from lakes and oceans and is inexpensive to extract

- Tritium is radioactive (half-life=12.3 years) and undergoes beta decay to He-3 and must be artificially produced.

\[
\begin{align*}
\frac{2}{1}H + \frac{2}{1}H & \rightarrow \frac{3}{1}H + \frac{1}{1}H \quad Q = 4.0\, MeV \\
\frac{2}{1}H + \frac{2}{1}H & \rightarrow \frac{3}{2}He + \frac{1}{0}n \quad Q = 3.3\, MeV \\
\frac{2}{1}H + \frac{3}{1}H & \rightarrow \frac{4}{2}He + \frac{1}{0}n \quad Q = 17.6\, MeV
\end{align*}
\]
Example

- World electric power consumption is $< 10^{20} \text{ J/year}$
- Oceans have $10^{24}$ grams of water
- 1 in 6000 water molecules is D$_2$O (deuterium oxide – heavy water)

If we extract D$_2$O and do fusion with 1% efficiency, for how long can the oceans supply our energy needs?
# molecules of water

\[
\begin{align*}
&= 6.02 \times 10^{23} \text{ molecules/mole} \times 10^{24} \text{ grams} \\
&= \frac{3 \times 10^{46}}{18 \text{ grams/mole}} \\
&= 3 \times 10^{46}
\end{align*}
\]

- 1 in 6000 is D\textsubscript{2}O and there are 2 deuterons in each, so

\[
\text{# deuterons} = \frac{3 \times 10^{46}}{6000} \times 2 = 10^{43}
\]

- Each reaction uses up to 2 deuterons and releases \( \sim 4 \text{ MeV} \), so the total energy available is:

\[
\frac{10^{43}}{2} \times 4 \text{ MeV} = 2 \times 10^{43} \text{ MeV} = 3 \times 10^{30} J
\]

- And at 1\% efficiency, this will last for:

\[
\frac{0.01 \times 3 \times 10^{30} J}{10^{20} J/\text{year}} = 3 \times 10^8 \text{ years}
\]
Nuclear Fusion

- Problems:

1) Fusion is very difficult to induce: must overcome the Coulomb repulsion, which was a helpful partner in fission

2) Controlled fusion not (yet) practical. Deuterium plasma doesn’t stay dense enough.
Fusion of two deuterons:

- The separation between two deuterons can be as little as $\sim 10^{-14}$ m in order for the attractive nuclear force to overcome the repulsive Coulomb force.

- Let’s calculate the potential energy (barrier) due to the repulsive force.

- Next estimate the effective temperature required in order for the deuteron to overcome the potential barrier.

- Assume $3/2 k T$ thermal kinetic energy per deuteron.
Part I: Potential energy:

\[ V = \frac{1}{4\pi \varepsilon_0} \frac{q_1 q_2}{r} \]

\[
= \frac{1}{4\pi (8.85 \times 10^{-12} \frac{C^2}{Nm^2})} \frac{(1.6 \times 10^{-19} C)^2}{10^{-14} m}
\]

\[ = 2.3 \times 10^{-14} J = 0.14 MeV \]

used : \[ 6.24 \times 10^{-12} MeV = 1 J \]

Part II: V is the Coulomb energy for a pair of deuterons. So per deuteron it is \[ 0.14 MeV / 2 = 1.1 \times 10^{-14} J \]

\[ 1.1 \times 10^{-14} J = 3/2 \ kT \]

So,

\[ T = \frac{2}{3} \frac{1.1 \times 10^{-14} J}{1.38 \times 10^{-23} J/K} = 5.3 \times 10^8 K \]

This is greater than the inside of the sun! (2 million K)
Proton-Proton cycle in the Sun

\[ \frac{1}{1}H + \frac{1}{1}H \rightarrow \frac{2}{1}H + e^+ + \nu_e \]

\[ \frac{1}{1}H + \frac{2}{1}H \rightarrow \frac{3}{2}He + \gamma \]

\[ \frac{3}{2}He + \frac{3}{2}He \rightarrow \frac{4}{2}He + \frac{1}{1}H + \frac{1}{1}H \]
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Lecture 21:
Elementary Particles and Cosmology

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Starting from a virus, the structure of matter can be divided into smaller and smaller entities down to the quark and to whatever lies beyond.
The Standard Model

The Standard Model is a good “theory”

- Matter: is made out of fermions
- Forces: are mediated by bosons
- Higgs boson (discovered in 2012): breaks the electroweak symmetry and gives mass to fermions and weak gauge bosons

- Experimentally verified its predictions to incredible precision
- But it does not explain everything…
The fundamental forces in nature responsible for all interactions:

1) Gravitation
2) Electroweak (electromagnetic and weak)
3) Strong

The electroweak is sometimes treated separately as the electromagnetic and the weak force thus creating **four fundamental forces**.

Gravity is more complicated, and least well understood.
We hope that a Grand Unified Theory will unify the strong, weak, and electromagnetic interaction. And maybe even gravity.
Practice Question 1

Which of the following statements is not true about the Standard Model?

A. The Standard Model is too complex to be fully discussed in a course/textbook of this level.
B. Most physicists think the Standard Model is the ultimate theory of particle physics.
C. The Standard Model explains hundreds of particles and the existence of quarks.
D. The Standard Model is a combination of the electroweak theory and quantum chromodynamics, but does not include gravity.
Practice Question 1

Which of the following statements is **not true** about the Standard Model?

A. The Standard Model is too complex to be *fully* discussed in a course/textbook of this level.

B. Most physicists think the Standard Model is the ultimate theory of particle physics. **Practically all physicists think the Standard Model will be superceded.**

C. The Standard Model explains hundreds of particles and the existence of quarks.

D. The Standard Model is a combination of the electroweak theory and quantum chromodynamics, but does not include gravity.
Lots of particles!

Baryons qqq and Antibaryons ¯qqq
Baryons are fermionic hadrons.
These are a few of the many types of baryons.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>proton</td>
<td>uud</td>
<td>1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>¯p</td>
<td>antiproton</td>
<td>¯udd</td>
<td>-1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>udd</td>
<td>0</td>
<td>0.940</td>
<td>1/2</td>
</tr>
<tr>
<td>Λ</td>
<td>lambda</td>
<td>uds</td>
<td>0</td>
<td>1.116</td>
<td>1/2</td>
</tr>
<tr>
<td>Ω⁻</td>
<td>omega</td>
<td>sss</td>
<td>-1</td>
<td>1.672</td>
<td>3/2</td>
</tr>
</tbody>
</table>

Mesons qq
Mesons are bosonic hadrons
These are a few of the many types of mesons.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺</td>
<td>pion</td>
<td>u¯d</td>
<td>+1</td>
<td>0.140</td>
<td>0</td>
</tr>
<tr>
<td>K⁻</td>
<td>kaon</td>
<td>s¯u</td>
<td>-1</td>
<td>0.494</td>
<td>0</td>
</tr>
<tr>
<td>ρ⁺</td>
<td>rho</td>
<td>u¯d</td>
<td>+1</td>
<td>0.776</td>
<td>1</td>
</tr>
<tr>
<td>B⁰</td>
<td>B-zero</td>
<td>d¯d</td>
<td>0</td>
<td>5.279</td>
<td>0</td>
</tr>
<tr>
<td>η_c</td>
<td>eta-c</td>
<td>c¯c</td>
<td>0</td>
<td>2.980</td>
<td>0</td>
</tr>
</tbody>
</table>
Classification of Particles: Leptons

- Exactly 6: e^−, ν_e, μ^−, ν_μ, τ^−, ν_τ
  - And their antiparticles
- All have spin 1/2
- Not affected by the strong interaction
- Decay ultimately to e^± and ν_e (anti-ν_e)
A few words on neutrinos

- We are already familiar with the electron neutrino that occurs in the beta decay of the neutron.
- Neutrinos have zero charge.
- Their masses are known to be very small. The precise mass of neutrinos may have a bearing on current cosmological theories of the universe because of the gravitational attraction of mass.
- All leptons have spin 1/2, and all three neutrinos have been identified experimentally.
- Neutrinos are particularly difficult to detect because they have no charge and little mass, and they interact very weakly.
### Table 14.3 The Leptons

<table>
<thead>
<tr>
<th>Particle Name</th>
<th>Symbol</th>
<th>Anti-particle</th>
<th>Mass (MeV/c²)</th>
<th>Mean Lifetime (s)</th>
<th>Main Decay Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$e^-$</td>
<td>$e^+$</td>
<td>0.511</td>
<td>Stable</td>
<td></td>
</tr>
<tr>
<td>$e$-Neutrino</td>
<td>$\nu_e$</td>
<td>$\bar{\nu}_e$</td>
<td>$&lt; 2.2 \times 10^{-6}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu^-$</td>
<td>$\mu^+$</td>
<td>105.7</td>
<td>$2.2 \times 10^{-6}$</td>
<td>$e^- \bar{\nu}<em>e \nu</em>\mu$</td>
</tr>
<tr>
<td>$\mu$-Neutrino</td>
<td>$\nu_\mu$</td>
<td>$\bar{\nu}_\mu$</td>
<td>$&lt; 0.17$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td>$\tau^-$</td>
<td>$\tau^+$</td>
<td>1776.8</td>
<td>$2.9 \times 10^{-13}$</td>
<td>$e^- \bar{\nu}<em>e \nu</em>\tau, \mu^- \bar{\nu}<em>\mu \nu</em>\tau$</td>
</tr>
<tr>
<td>$\tau$-Neutrino</td>
<td>$\nu_\tau$</td>
<td>$\bar{\nu}_\tau$</td>
<td>$&lt; 15.5$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 14.5 Quark Properties

<table>
<thead>
<tr>
<th>Quark Name</th>
<th>Symbol</th>
<th>Mass* (GeV/c^2)</th>
<th>Charge</th>
<th>Baryon Number</th>
<th>Strangeness S</th>
<th>Charm C</th>
<th>Bottomness B</th>
<th>Topness T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>u</td>
<td>0.0017 to 0.0033</td>
<td>2e/3</td>
<td>1/3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Down</td>
<td>d</td>
<td>0.0041 to 0.0058</td>
<td>-e/3</td>
<td>1/3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Strange</td>
<td>s</td>
<td>0.080 to 0.130</td>
<td>-e/3</td>
<td>1/3</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Charmed</td>
<td>c</td>
<td>1.18 to 1.34</td>
<td>2e/3</td>
<td>1/3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bottom</td>
<td>b</td>
<td>~4.4</td>
<td>-e/3</td>
<td>1/3</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>Top</td>
<td>t</td>
<td>172</td>
<td>2e/3</td>
<td>1/3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Antiquarks, $\bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$, and $\bar{t}$, have opposite signs for charge, baryon number, S, C, B, and T.

*The u, d, and s quark masses are estimates of so-called current-quark masses.


We don’t observe “free” quarks!
What happens if you try to pull apart two quarks?

- It requires so much energy, that you create another quark and antiquark to keep the products colorless!
- Called quark confinement
Hadrons

- These are particles that act through the strong force.
  - Made up of quarks

Two classes of hadrons: **mesons** and **baryons**

- **Mesons** are particles with integral spin having masses greater than that of the muon (106 MeV/$c^2$; note that the muon is a lepton and not a meson).

- All **baryons** have masses at least as large as the proton and have half-integral spins.
Classification of Particles: Baryons

- **Quark triplet bound states**
  - Think of a “bound state” like the Hydrogen atom, which is a proton-electron bound state

- **Can interact via the strong interaction** (what binds them together)

- **All fermions: half-integer spin**

- **Decay ultimately into proton and leptons**
Classification of Particles: 
Mesons

- quark-anti-quark bound state
- Can interact via strong interaction
- All bosons: integer spin
- Decay ultimately to $e^\pm$, $\nu_e$, anti-$\nu_e$

- Baryons and Mesons are collectively called Hadrons
Classification of Particles: Photons

- Is it’s own antiparticle
- Spin 1
- Stable
- Carrier of the electromagnetic force
Summary: Bosons and Fermions

- Photons, gluons, W\(^\pm\), and the Z\(^0\) are called **gauge bosons**, and are responsible for the strong and electroweak interactions.

- Gravitons are also bosons, having spin 2.

- Fermions exert attractive or repulsive forces on each other by exchanging gauge bosons, which are the force carriers.
The Higgs Boson

- One other boson that has been predicted since the ‘60s, and recently detected (in 2012), is necessary in quantum field theory to explain why the $W^{\pm}$ and $Z^0$ have such large masses, yet the photon has no mass.

- This boson is called the Higgs particle (or Higgs boson) after Peter Higgs, who is among first proposing the Higgs mechanism.
Cosmology
Evidence of the Big Bang

- **Steady state theory**: matter continuously created with net constant density.
- **Big Bang theory**: universe created from dense primeval fireball.
- Evidence for Big Bang theory:
  1) Hubble observed that the galaxies of the universe are moving away from each other at high speeds (between 1929-1952). The universe is apparently expanding from some primordial event.
  2) In 1964, Penzias and Wilson observe that a cosmic microwave background radiation permeates the universe.
  3) The predictions of the primordial nucleosynthesis of the elements agree with the known abundance of elements in the universe.
The Expanding Universe

- Doppler shift of light from other galaxies tell us their speed relative to us:

\[ \lambda = \lambda_0 \sqrt{\frac{1 + \beta}{1 - \beta}} \quad \text{where} \quad \beta \equiv \frac{v}{c} \]

- Usually discuss in terms of redshift \((z)\):

\[ z \equiv \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\lambda}{\lambda_0} - 1 = \sqrt{\frac{1 + \beta}{1 - \beta}} - 1 \]

- Most galaxies are red-shifted from us (particularly the distant ones)

- This means that most galaxies are receding from us.
Hubble’s Law

- The velocity that a galaxy is receding from us is proportional to its distance \( R \):
  \[ v = H_0 R \]

- The constant of proportionality is Hubble’s constant \( H_0 \)
- \( H_0 \) is about \( \sim 70 \text{ km/s/Mpc} = 0.0215 \text{ m/s/light-year} \)

- 1 Mpc (mega-parsec) = \( 3.26 \times 10^6 \) light years
  \[ = 3.1 \times 10^{22} \text{ m} \]

- (Beware: Hubble’s constant is not really constant. It’s been decreasing with time.)
Hubble’s Measurements

- The recessional velocity of astronomical objects is inferred from the shift toward lower frequencies (redshift) of certain spectral lines emitted by very distant objects.

- It is not necessary for Earth to be at the center of the universe to observe the expansion.
Example

- A galaxy is located 3000 Mpc from us.

a) How fast is it receding from us?

\[
\beta = \frac{v}{c} = \frac{H_0 R}{c} = \frac{(71 \text{ km/s/Mpc}) \cdot (3000 \text{ Mpc})}{3 \times 10^5 \text{ km/s}} = 0.71
\]

b) What is the redshift?

\[
z = \sqrt{\frac{1 + \beta}{1 - \beta}} - 1 = \sqrt{\frac{1.71}{0.29}} - 1 \approx 1.43
\]

c) What is the wavelength we would measure for the H\(_\alpha\) line (656 nm) emitted by the galaxy?

\[
\Delta \lambda = 1.43 \lambda_0 = 938 \text{ nm}
\]

\[
\lambda = \lambda_0 + \Delta \lambda = 656 \text{ nm} + 938 \text{ nm} = 1594 \text{ nm}
\]
Cosmic Microwave Background

- Because of the rapid expansion and cooling of the early universe, matter had decoupled from radiation at a temperature of 3000 K.

- That blackbody radiation characteristic of 3000 K several billion years ago has Doppler-shifted to 2.7 K today.

- Satellite measurements show a nearly isotropic 2.7 K radiation background.
  - Essentially all wavelengths included
  - Has precisely the Plank spectrum
  - Is isotropic

Very strong evidence of the Big Bang

- Discovered by Penzias and Wilson (in NJ!)
  - Nobel Prize in 1978
The Age of the Universe

- At what distance are galaxies receding from us at the velocity of light?

\[
\frac{v}{c} = 1 = \frac{H_0 R}{c} \quad \rightarrow \quad R = \frac{c}{H_0} = \frac{3 \times 10^5 \text{ km/s}}{71 \text{ km/s/Mpc}} \approx 4.2 \text{ Gpc}
\]

- How much time did it take for the light to travel?
  - 4.2 Gpc = 13.7 billion light years.

- That’s roughly how old we think the Universe is.
The Big Bang

- Let’s suppose that the expansion started at $t=0$. What happened since then?
  - At $t \approx 10^{-43}$ s, our understanding of physics is very speculative (requires quantum gravity, and all that).
  - At $t \approx 10^{-34}$ s, the Universe has a temperature of $10^{26}$ K. Photons and matter are in equilibrium.
    - $\gamma + \gamma \leftrightarrow$ particle + it’s antiparticle
    - Ratio of photons:nucleons $\sim 1:1$
    - CP violation leads to a slight excess of matter over antimatter
The Big Bang

- At $t \sim 10^{-6}$ s, $T \sim 10^{13}$ K.
- Matter exceeds antimatter by about one part in $10^9$.
- $kT \sim 1$ GeV, and no more nucleon pair production.
- Nucleons and antinucleons start to annihilate each other without any means of replacement. Eventually only a few are left over.
- This process is called baryogenesis.

Recall Boltzmann’s constant $k = 8.6 \times 10^{-11}$ MeV/K
The Big Bang

- **At t = 0.01 s, T = 10^{11} K**
  - Antinucleons have been annihilated
  - Most nucleons also, but a precious few are left over

- **At t ~ 1 s, T = 10^{10} K**
  - $kT < 1$ MeV, so no more $e^+e^-$ pair production
  - Electrons and positrons start to annihilate each other without replenishment.

- **By the time t ~ 6 s, T = 6 \times 10^9 K**
  - All of the positrons have annihilated and the ratio of photons to nucleons is about $10^8$ to 1. That won’t change much from now on.
The Big Bang

- At $t \sim 200$ s, $T \sim 10^9$ K
  - $kT \sim 0.1$ MeV, so the photons are no longer energetic enough to break up nuclei.
  - Nucleosynthesis begins.

- At $t \sim 300,000$ years, $T \sim 10^3$ K
  - $kT \sim 0.1$ eV, so photons can no longer keep electrons from binding with nuclei. Atoms start to form.
  - Photons stream freely. This is the source of the cosmic microwave background (CMB).
The Big Bang

- $T=13.5$ billion years (today), $T=2.7$ K
- The CMB is microwave and not $10^3$ K because the Universe has been expanding (cooling) since then, causing photons to redshift.

- Universe is expanding.
- Gravitational attraction of galaxies should be slowing the expansion.
- Will the expansion be reversed or continue forever?
Practice Question 1

- The cosmic microwave background radiation is due to:

A. neutrinos left over from the Big Bang.
B. electromagnetic radiation left over from the Big Bang itself.
C. the cooling of the universe to the point that photons no longer keep electrons from binding with nuclei, and atoms form.
D. remnants of CP violation.
Practice Question 1

- The cosmic microwave background radiation is due to:
  - The CMB radiation is photons, not neutrinos.
  - The CMB occurred a few hundred thousand years after the Big Bang.
  - CP violation is a matter/anti-matter asymmetry.

A. neutrinos left over from the Big Bang.
B. electromagnetic radiation left over from the Big Bang itself.
C. the cooling of the universe to the point that photons no longer keep electrons from binding with nuclei, and atoms form.
D. remnants of CP violation.