CHAPTER 33: ATOMIC NUCLEUS AND RADIOACTIVITY
04/10/19 & 04/15/19

RADIOACTIVITY: ALPHA, BETA, AND GAMMA RAYS

- In 1896 it was discovered that some elements spontaneously emit highly energetic rays that are similar to but somewhat different than the emission of light, or even X-rays.
    - These rays could pass through certain amounts of material such as paper wrapped around film.
    - These rays are not the result of electron energy level transitions, but rather from drastic changes within the atomic core, or nucleus.
    - The emission of energetic rays due to changes in the atomic nucleus is called ***radioactivity***.
        - All elements with atomic number greater than 82 (lead) are radioactive.
- Three types of radiation from radioactive elements:
    - α: Alpha rays
        - positive electric charge (+2e)
        - alpha particles are actually helium nuclei (2 protons + 2 neutrons)
        - stopped by a few sheets of paper
    - β: Beta rays
        - negative electric charge (-1e)
        - beta particles are actually electrons
        - stopped by a sheet of aluminum
    - γ: Gamma rays
        - neutral
        - gamma rays are actually very high energy electromagnetic radiation (photons)
        - stopped by many centimeters of lead
- FIGS. 33.3, 33.4

THE NUCLEUS

- Properties of the nucleus
    - Made up of nucleons – positively charged protons and neutral neutrons
    - One quadrillionth of an atom’s volume (rest is mostly empty space)
    - Accounts for almost all of the atom’s mass (nucleons are 2000 times more massive than electrons)
    - Between $1\text{-}7\times10^{-15}$ meter radius
    - Has energy levels similar to orbital electron energy levels but with much higher energies
- Gamma rays are emitted when there is a transition between energy levels within the nucleus.
- Alpha particles are emitted when a collection of two protons and two neutrons “wanders outside” the nucleus.
    - Nucleons move somewhat freely within the nucleus.

    - Clusters of 2 protons and 2 neutrons have a probability cloud within the nucleus similar to the electron probability cloud within the atom.
    - A tiny part of the alpha particle's probability wave extends outside the nucleus. Once outside, the alpha particle gets pushed away by electric repulsion.
- Beta particles are emitted when a neutron transforms into a proton.

RADIATION DETECTION

- High energy particles such as alphas, betas, and gammas interact with matter.
    - The high energy particles knock electrons from atoms, leaving a trail of free electrons and positively charged ions.
    - This ***ionization*** is responsible for the damage caused to cells in the body from doses of high energy radiation.
    - It also allows us to detect radioactivity with various types of detectors.
        - FIG. Geiger Counter
        - FIG. Cloud Chamber
        - DEMO: Cloud Chamber

ISOTOPES

- An element is defined by the number of protons in its nucleus – its ***atomic number***.
- The number of neutrons in an element's nucleus can vary.
    - Atoms with the same number of protons, but different numbers of neutrons are called ***isotopes*** of a given element.
    - The number of protons plus neutrons is the ***atomic mass number***.
- Hydrogen isotopes:
    - FIG. 33.5
    - Common: 1 proton, 0 neutrons: ${}^{1}_{1}\mathrm{H}$
    - Deuterium: 1 proton, 1 neutron: ${}^{2}_{1}\mathrm{H}$
        - 1 in 6000 atoms
        - H_2O made with deuterium is called "heavy water"
    - Tritium: 1 proton, 2 neutron: ${}^{3}_{1}\mathrm{H}$
        - 1 in 10^{17} atoms
        - Radioactive
- Three naturally occurring isotopes of uranium:
    - Most common: ${}^{238}_{92}\mathrm{U}$ or U-238

TRANSMUTATION

- When a nucleus emits radiation, does it stay the same element?
    - Alpha? No.
        - FIG. ${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$
    - Beta? No.
        - FIG. ${}^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e}$
    - Gamma? Yes.

        - $^{60}_{28}\mathrm{Ni} \to ^{60}_{28}\mathrm{Ni} + ^{0}_{0}\gamma$
- The changing of one chemical element to another is called ***transmutation***.
    - Natural: through radioactivity
        - FIG. 33.14
    - Artificial: by bombarding elements with particles
        - FIG. $^{14}_{7}\mathrm{N} + ^{4}_{2}\mathrm{He} \to ^{17}_{8}\mathrm{O} + ^{1}_{1}\mathrm{H}$

WHY ATOMS ARE RADIOACTIVE

- Positively charged protons are packed close together in a nucleus. Why aren't nuclei burst apart by the huge repulsive electrical forces?
    - There is another stronger force that binds them together.
- The ***strong force*** (or strong interaction) binds protons and neutrons together.
    - It is an attractive force.
    - It is more than 100 times stronger than electromagnetism.
    - It has a very short range. It only acts over distances of a few nucleon diameters (~10^{-15} m).
- Nucleus stability
    - Stable nuclei are non-radioactive; unstable nuclei are radioactive.
    - For protons close together (i.e. small nuclei), the strong force wins out over the electric force. For protons farther apart (opposite sides of large nuclei), the electric forces dominate.
        - Larger nuclei are more unstable.
        - FIG. 33.8
    - Neutrons play a large role in nuclear stability.
        - A proton and neutron are bound more tightly than 2 protons or 2 neutrons.
            - Many of the first 20 elements have equal numbers of protons and neutrons and are stable.
        - In larger nuclei, since protons repel each other electrically, a nucleus can be made more stable by replacing some protons with neutrons.
            - Too many extra neutrons will separate the protons too much, making the nucleus unstable.
            - $^{56}_{26}\mathrm{Fe}$ is very stable, $^{238}_{92}\mathrm{U}$ is still unstable (radioactive).

HALF-LIFE

- The rate of radioactive decay of an element is measured in terms of a characteristic time called the ***half-life***.
    - Half-life: the time it takes for half of an original quantity of a radioactive isotope to decay.
    - FIG. 33.9
        - After one half-life, one half of the isotope atoms are left.
        - After two half-lives, one quarter of the isotope atoms are left.
        - After three half-lives, one eighth of the isotope atoms are left, etc.

- Half-lives of different isotopes vary widely from less than a millionth of a second to several billion years.
    - $^{238}_{92}\mathrm{U}$: half-life is 4.5 billion years.
- The shorter the half-life, the greater the decay rate.

CARBON DATING

- Naturally occurring carbon is mostly $^{12}_{6}\mathrm{C}$, but one in every billion atoms of carbon is $^{14}_{6}\mathrm{C}$, which is produced by cosmic rays hitting nitrogen atoms in the atmosphere, and it is radioactive (it is a beta emitter).
    - FIG. $^{14}_{7}\mathrm{N}+^{1}_{0}\mathrm{n}\rightarrow^{14}_{6}\mathrm{C}+^{1}_{1}\mathrm{H}$, $^{14}_{6}\mathrm{C}\rightarrow^{14}_{7}\mathrm{N}+^{0}_{-1}\mathrm{e}$
- All carbon can join with oxygen to make carbon dioxide, which is taken in by all plants and animals while they are alive.
    - The carbon-14 in the organism is constantly undergoing radioactive decay, but more carbon-14 is constantly being taken in. All living plants and animals have a fairly constant level of radioactive carbon-14 in them.
- When an organism dies, carbon-14 stops being taken in, and the percentage of carbon-14 starts decreasing at a rate given by its half-life of 5730 years.
    - After an organism has been dead for 5730 years, only half of the carbon-14 that was present in the organism remains.
    - FIG. 33.18
- Archaeologists can calculate how old wooden tools or skeletons are by measuring the current level of radioactivity (as far back as 50,000 years ago).
    - Dating of older, non-living things can be done using other radioactive isotopes such as uranium.

IMPORTANT BENEFITS OF RADIOACTIVITY

- Tracers: low-level radioactive materials used to diagnose a system
    - FIGS. 33.15, 33,16
    - Leaks, fertilizer, digestion, medicine, etc.
- Food irradiation: using high-energy gamma rays to kill food pathogens and eliminate food-borne illnesses without adversely affecting the food
    - FIG. 33.17
- Medical treatment: strong, concentrated doses of radiation are used to destroy cancer cells

EFFECTS OF RADIATION ON HUMANS

- Our exposure to radioactivity:
    - FIG. 33.19
    - Natural background radiation: 75%. Radioactivity is nothing new. It is natural and has been around on Earth as long as there has been an Earth. It warms the Earth's interior (molten layers, volcanoes, geysers, etc.).
        - Earth: radon gas, minerals in the Earth's crust, etc. (brick houses worse than wood).
        - Cosmic rays

            - Exposure higher with greater altitude (Denver gets twice the exposure from cosmic rays as New Orleans)
            - 2 cross-country flights = 1 chest X-ray
    - Food and water: 8%.
        - carbon-14, potassium-40 give 8000 radioactive decays per second in our bodies.
    - Man-made sources: 17%.
        - Medical X-rays: 15%
        - Consumer products: 2%
        - Coal and nuclear power plants and weapons tests: < 0.003%
            - Coal plants: 23,000 tons of radioactive waste per year directly into the air.
            - Nuclear plants: 10,000 tons per year contained.
- Biological damage from radiation
    - Ionization from radiation leaves a trail of electrons, ions, and broken atoms and molecules.
    - The ions and molecular fragments can break apart other molecules or create new molecules that are harmful to cells
    - Our bodies are good at repairing this damage as long as there is not too much of it at one time, i.e. the dose of radiation is not too intense.
    - If the damaged molecule is DNA, defective genetic information can be passed on to offspring cells. This is a *mutation*.
        - This is how cancer can develop.
        - If the DNA mutation occurs in reproductive cells in the gonads, the mutation can be passed on to the next generation.

CHAPTER 34: NUCLEAR FISSION AND FUSION 04/17/19

NUCLEAR FISSION

- If a neutron is absorbed by a very large nucleus, such as uranium-235, it can deform the nucleus enough so that the nuclear forces that hold the nucleus together are overwhelmed by the electrical repulsion between protons. When this happens, the nucleus splits in two. This is ***nuclear fission***.
  - FIG. 34.1
  - VIDEO: ${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{91}_{36}\text{Kr} + {}^{142}_{56}\text{Ba} + 3\left({}^{1}_{0}\text{n}\right)$
    - Note that three escaping neutrons are produced (on average it is ~2.5). These neutrons can then cause three other uranium nuclei to fission, releasing nine neutrons that could each fission another uranium nucleus releasing 27 neutrons, etc. This sequence is called a ***chain reaction***.
      - FIG. 34.2
- The mass of the fission fragment nuclei plus the extra neutrons is less than the mass of the original uranium nucleus and neutron. The tiny difference in mass (~0.1% of the mass) is converted into energy according to Einstein's $E=mc^2$.
  - Most of the released energy is kinetic energy of the fragments and neutrons; a smaller amount is gamma radiation.
  - A typical fission reaction releases 200,000,000 electron volts (eV) (or 200 MeV) of energy. This is really, really, really big for one nucleus!
    - Energy of one water drop falling over Niagara Falls: 4 eV
    - Energy of one TNT molecule exploding: 30 eV
    - Energy of one gasoline molecule oxidizing: 30 eV
- In a small chunk of U-235, a chain reaction would not occur. Ejected neutrons travel a certain average distance before encountering another nucleus. For a small chunk of uranium, an ejected neutron would be more likely to escape through the surface of the chunk before it hit another nucleus and caused another fission. On average, less than one neutron per fission would start another fission. The reaction dies out. For a bigger chunk (baseball-sized or so), the ratio of volume to surface area is bigger and on average more than one neutron per fission would start another fission before escaping. The chain reaction would grow.
  - FIG. 34.3
  - The ***critical mass*** is the amount of mass necessary for one fission to produce on average one additional fission. Less mass, the reaction dies out; more mass, the chain reaction builds up explosively.
  - FIG. 34.5, gun-type uranium fission bomb

NUCLEAR FISSION REACTOR

- The fast neutrons released by fissioning U-235, which is rare in ordinary uranium metal (0.7% of U atoms), are easily captured by the more common, non-fissioning U-238. Slow neutrons are more likely to be captured by U-235 than by U-238.
- Nuclear reactors use chunks of ordinary uranium separated by a material such as graphite (carbon) that slows neutrons to make a chain reaction with ordinary uranium. A nuclear reactor consists of:

  - FIG. 34.9
  - Nuclear fuel: for example, uranium enriched to ~3% U-235; the material that undergoes fission
  - Moderator: Low mass nucleus material (e.g. graphite or heavy water) that slows or "moderates" the neutrons to make fission more likely
  - Control rods: rods made of a neutron absorbing material, such as boron, that are inserted to reduce the number of neutrons available for fission, and thus control the reaction rate.
  - Two separate water systems to transfer the fission heat energy to a steam turbine which generates electric power (separate to avoid radioactivity transfer to turbine).
- About 20% of US electricity generated from fission power plants
- Benefits of nuclear fission reactor power
  - 1 kg of uranium fuel produces more energy than 30 freightcarloads of coal
  - Elimination of massive amounts of pollution from fossil fuel plants
- Drawbacks of nuclear fission reactor power
  - Waste products are radioactive. Disposal is a major challenge.
  - Danger of nuclear weapon proliferation (e.g. North Korea, etc.)
  - Risk of release of large amounts of radioactivity in the case of a major accident (e.g. Chernobyl)

MASS-ENERGY EQUIVALENCE

- Nucleons have more mass when they are separated from each other than they do when they are bound together in a nucleus.
  - It would take work to separate nucleons from the nucleus. The energy you put into them has to go somewhere – it becomes more mass according to $E=mc^2$.
  - When you put them back together, the mass that they "lose" goes into binding energy holding them together.
- Nuclear mass increases with atomic number simply because you are increasing the number of nucleons. This is not surprising.
  - FIG. 34.15
- The *mass per nucleon* also changes with atomic number though. This is surprising.
  - Greatest mass per nucleon is for hydrogen because there is no binding energy to other nucleons that reduces the proton's mass.
  - As nucleons are added, the mass per nucleon drops until we reach iron, which holds its nucleons tighter than any other element. Therefore it has more binding energy, and less mass per nucleon.
  - Above iron, atoms have more and more mass (and less binding energy) per nucleon.
  - FIG. 34.16
- A nuclear reaction that has products with less mass than before the reaction gives off energy. One that has products with more mass requires input energy.
  - Fission of heavy nuclei produces fragments "down the hill" on the right side of the graph, meaning the products have less mass per nucleon.

    - FIG. 34.17: $_{0}^{1}\mathrm{n}+{}_{92}^{235}\mathrm{U}\rightarrow{}_{36}^{91}\mathrm{Kr}+{}_{56}^{142}\mathrm{Ba}+3\left({}_{0}^{1}\mathrm{n}\right)$

NUCLEAR FUSION

- Nuclear fusion is combining nuclei. Energy is given off if two small nuclei are fused to make a larger nucleus. This is moving “down the hill” on the left side of the graph.
  - FIG. 34.19
  - The hill is steeper on the left which means that more energy per nucleon is given off for a fusion reaction that for a fission reaction. ~0.7% of the mass is converted to energy.
    - U-235 fission: 200 MeV, or 0.74 MeV per nucleon
    - Hydrogen fusion: 17.6 MeV, or 3.5 MeV per nucleon
  - Gram for gram of fuel, fusion produces much more energy than fission because there are many more hydrogen atoms in a gram than uranium atoms in a gram.
- For fusion reaction to occur, the nuclei must collide at very high speeds, corresponding to extremely high temperatures, such as those found in the sun.
  - The sun’s burning is nuclear fusion.
  - FIG. 34.22: A fusion bomb (thermonuclear, or hydrogen bomb) requires a fission bomb to ignite it.
- Benefits of fusion reactor power
  - More energy per gram of fuel
  - Can’t have a reactor meltdown
  - No pollution, radioactive or otherwise
- Drawbacks of fusion reactor power
  - We have not achieved a working reactor yet

CHAPTER 35: SPECIAL THEORY OF RELATIVITY
04/22/19 & 04/24/19

EINSTEIN'S REVOLUTIONARY THEORY OF SPACETIME

- Einstein noted that Maxwell's equations for electromagnetism described completely different physics depending if charges were moving or not. He felt that the laws of physics should be independent of motion.
- He succeeded in making Maxwell's equations independent of motion by completely redefining how we think about space and time.
    - The very measurements of space and time depend on the relative motion of the observer.
    - When we move, not only do we alter our position in space, but we also change the flow of time.
        - e.g. the length of a rocket ship *and* the speed of its clocks change when it moves fast – space and time are both altered by motion.
    - The connection between space and time leads to a connection between energy and mass: $E=mc^2$.

MOTION IS RELATIVE

- All motion is relative to some observer. There is no absolute motion.
- A place from which motion is observed and measured is called a ***frame of reference***.
    - We have to choose a frame of reference from which to make any measurement of motion.
    - There is no absolute frame of reference.
    - Example: throwing a ball from a moving vehicle.

POSTULATES OF THE SPECIAL THEORY OF RELATIVITY

- **All laws of nature are the same in all uniformly moving frames of reference.**
    - There is no experiment that can be devised to determine a state of uniform motion (i.e. there is no absolute motion),
        - Accelerated motion is easy to detect, however.
- **The speed of light in free space has the same measured value for all observers, regardless of the motion of the source or the motion of the observer; that is, the speed of light is a constant.**
    - You cannot travel with a beam of light. Light is always measured by all observers in all frames of reference to be 300,000 km/sec.
    - Example: rocket ship leaving a flashing space station at 0.5 c.

SPACETIME

- To understand relativity, we need to stop thinking about space and time as separate entities, and start thinking of them tied together in a concept called *spacetime*.
    - Our space is 3-dimensional: distance along the x, y, and z coordinate axes define a point in space. Lengths along these axes define the size of an object. The object exists in space.

  - Objects also exist in a fourth dimension: time.
    - Example: paper airplane,
  - Objects exist in spacetime.
  - Spacetime is different for observers in different reference frames (if there is relative motion between them). Their measurements of space and time will not agree.
    - However, they will still measure the same speed for light, c. This constant ratio of space and time unifies all different realms of spacetime.

SIMULTANEITY

- Two events are simultaneous if they occur at the same time. However, events that are simultaneous in one reference frame need not be in another reference frame moving relative to the first.
  - FIG. 35.4 and 35.5

TIME DILATION

- Time is stretched for reference frames in motion.
  - FIG. 35.8, 35.9, 35.10
    - Vertical light in a horizontally moving rocket.
    - An observer in the rocket with the clock (same reference frame) sees normal vertical operation of the clock.
    - A stationary observer sees the light in the clock take a longer, diagonal path between mirrors.
      - To keep the speed of light constant, the longer distance traveled by the light must be divided by a longer time peiod for the light to travel.
      - This stretching out of time is called ***time dilation***.
        - Time dilation occurs for all clocks, not just light clocks. It is part of the nature of time, not the mechanics of the clocks.
  - Derive the equation for time dilation from the light clock geometry.
    - $t = \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}},\ \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}},\ \mathrm{t} = \gamma t_0$
    - γ is the Lorentz Factor
      - always greater than or equal to 1
      - $v = 0,\ \gamma = 1,\ \mathrm{t} = t_0$
      - $v = 0.5c,\ \gamma = 1.15,\ \mathrm{t} = 1.15t_0$
      - $v = 0.995c,\ \mathrm{t} = 10t_0$
      - Moving clocks run slow; they run on a different time.
      - If someone is moving relative to our reference frame, we see each other's clocks running slow.

TWIN TRIP

- Consider two identical twins. One takes a high-speed round-trip rocket journey while the other stays at home. The traveler will return home younger than his stay-at-home twin. How is this so if time dilation tells us that when there is relative motion between two frames, each sees the other's clocks run slow?
- Spaceship moving between Earth and Pluto:
    - Earth and Pluto at rest relative to each other
        - Earth flashes light at 3 minute interval toward Pluto
        - Pluto observes flashes at 3 min intervals
    - Rocket traveling from Earth to Pluto
        - Rocket still measures speed of flashes to be c, but the frequency of the flashes will be greater or less depending if the rocket is approaching or receding from light source.
        - Suppose rocket is receding at a speed fast enough for the frequency of light flashes to decrease to half – they are observed by the rocket at 6 min intervals. This is due both to time being altered by motion and to the extra distance that succeeding light flashes have to travel to "catch up" to the rocket, which has moved away since the previous flash reached it.
    - Rocket flashes a beacon every time a flash from Earth reaches it.
        - This happens every 6 min according to the clocks on the rocket.
        - Since both flashes continue to travel to Pluto at the same speed, c, they both reach Pluto together and an observer on Pluto sees them at 3 min intervals.
        - A 6 minute interval on the approaching rocket is seen as a 3 minute interval on the stationary Pluto.
    - What if Earth flashed every 6 min?
        - The rocket would observe flashes every 12 min.
        - What if the Earth and rocket reference frames are interchanged?
            - Stationary rocket flashes every 6 min, and receding Earth observes them every 12 min.
        - So what about receding rocket flashing at 6 min intervals?
            - Stationary Earth observes them at 12 min intervals.
    - Effect of moving away is the opposite of the effect of approaching.
        - This is a reciprocal relationship for frequencies (doubling/halving, tripling/thirding, quadrupling/quartering for approaching/receding) at relativistic speeds
- Twin trip, using the same speeds as in the previous, Earth-rocket-Pluto example. Traveling twin recedes from Earth for 1 hour, turns around immediately, and approaches Earth returning in 1 hour – 2 hour trip according to the clocks in the rocket.
    - FIGS. 35.17, 35.18
    - Rocket emits flashes every 6 min
    - Rocket receding for 1 hour, starting at noon.
        - 10 flashes at 6 min intervals; Rocket – 1 hour, 1 PM

        - Earth sees these 10 flashes at 12 min intervals; Earth – 2 hours 2 PM
    - Rocket turns on a dime and approaches Earth, returning in 1 hour
        - 10 flashes at 6 min intervals: Rocket – 1 hour, 2 PM
        - Earth sees these 10 flashes at 3 min intervals: Earth – 0.5 hours, 2:30 PM
- Check twin trip result from other reference frame's perspective. Earth emits flashes every 6 min.
    - FIGS. 35.19, 35.20
    - Rocket recedes for 1 hour, observes flashes every 12 min – 5 flashes.
    - Rocket approaches for 1 hour, observes flashes every 3 min – 20 flashes
    - Rocket: 2 hour trip, 25 flashes
    - Earth 25 flashes at 6 min intervals – 2.5 hours
- Both twins agree on the results.
    - One (the traveler) ages less than the other because the stay-at-home has stayed in a single reference frame while the traveler has been in two reference frames separated by acceleration (turning around), effectively experiencing two different realms of time that are both different from the stay-at-home's realm of time.

ADDITION OF VELOCITIES

- Adding ordinary velocities:
    - $V = v_1 + v_2$
    - Walk 1 km/h down the aisle of a 60 km/h train: V=61 km/h
- Adding relativistic velocities:
    - $V = \dfrac{v_1 + v_2}{1 + \frac{v_1 v_2}{c^2}}$
    - Spaceship at 0.5 c fires a rocket at 0.5 c: V=0.8c, not 1c
        - No material object can travel as fast or faster than light
    - Spaceship at 0.5 c fires a laser beam at c: V=c!

LENGTH CONTRACTION

- When objects move through spacetime, space as well as time changes.
    - Space is contracted, making objects appear shorter as they move past at relativistic speeds – this is ***length contraction***.
    - FIGS. 35.22, 35.23
    - $L = L_0 \sqrt{1 - \frac{v^2}{c^2}}$
        - If one travels at the speed of light, all distance are contracted to 0! Travel would happen instantaneously!
            - Photons travel from one place to another instantaneously from their perspective.

RELATIVISTIC MOMENTUM

- Classical momentum: $p = mv$
- Relativistic momentum: $p = \gamma mv$, $p = \dfrac{mv}{\sqrt{1 - \dfrac{v^2}{c^2}}}$
    - As speed approaches c, momentum increases without limit – it approaches infinity!
    - It would take an infinite impulse to push an object to the speed of light. Or, equivalently, an infinite amount of energy to accelerate an object to the speed of light. IMPOSSIBLE!
        - MATERIAL OBJECTS CANNOT REACH THE SPEED OF LIGHT!!!

SPACE TRAVEL

- Theoretically, we could travel into the future of our stay-at-home friends (i.e. the twin trip).
- At 99.999% of c, a one year trip for astronauts would cover a distance of 200 light years – 200 years would pass on Earth!
- Two technological problems prevent this:
    - Ships traveling at those speeds would need billions of time more energy than the space shuttle.
    - There is no way known to shield intense particle bombardment due to ramming into interstellar particles at those speeds (it would be like sitting in a huge particle accelerator beam!).
- We can’t go back into the past. That would require faster than light travel.

CHAPTER 36: GENERAL THEORY OF RELATIVITY 04/29/19

- Special Theory of Relativity: the “special” is in the name because this theory only deals with the special case of uniformly moving (non-accelerating) reference frames.
  - 1st Postulate of STR: All laws of physics are the same in all uniformly moving reference frames.
- General Theory of Relativity: 10 years later, Einstein extended his conviction that the laws of nature should be the same in all reference frames to accelerating reference frames as well. General Relativity is a new theory of gravitation, because underlying it is the idea that the effects of gravitation and acceleration cannot be distinguished from one another (much like in STR, how different states of uniform motion cannot be distinguished).

PRINCIPLE OF EQUIVALENCE

- DRAW: Compare dropping balls while standing on Earth with dropping balls in a spaceship accelerating at 9.8 m/s^2.
  - On Earth: what is the value of g? What happens to a dropped ball? How far will it fall in 1 s?
  - In spaceship away from gravity: If there were no acceleration, what would happen to a dropped ball? Where would it be in 1 s? With the ship accelerating at 9.8 m/s^2, what happens to a dropped ball? Where would the floor/you/the ball be in 1 s?
    - FIG. 36.3
- ***Principle of Equivalence***: observations made in an accelerated reference frame are indistinguishable from observations made in a Newtonian gravitational field.
  - Applies to mechanics, optics, electromagnetics – all physical phenomena.

BENDING OF LIGHT DUE TO GRAVITY

- FIG. 36.4: Ball thrown across an accelerating spaceship in a gravity-free region. From the outside it follows a straight path. From inside it follows a curved path that looks just like gravity pulling it down. This would not be surprising since the inside observer “feels” the “gravity” from the ship’s acceleration.
- FIG. 36.5: Light ray shooting across an accelerating spaceship in a gravity-free region. Looks exactly like a thrown ball! Straight path from outside, curved path inside! The light’s path has been deflected by acceleration.
  - According to the principle of equivalence, if light can be deflected by acceleration, it must be deflected by gravity. How?
    - Gravity pulls on energy of light because energy is equivalent to mass ($E=mc^2$).
    - The deeper explanation is that, gravity, or more precisely the presence of mass, bends or warps spacetime.
- How do we know gravity bends light? The effect in Earth’s gravitational field is too tiny to be measured.
  - FIG. 36.7: Has been confirmed by measuring the deflection of star light around the sun during every eclipse since 1919!

GRAVITY AND TIME: GRAVITATIONAL RED SHIFT

- In STR, time slows down in moving reference frames. Gravity and acceleration also cause time to slow.
  - FIG. 36.9: clocks on a rotating disk.
    - Clock in center runs the same as ground clock because there is no relative motion between their reference frames.
    - Clock on the rim is slower than the ground clock (due to STR time dilation from moving reference frames) and the center clock (due to stronger centrifugal force, i.e. acceleration, on the rim clock even though center and rim clocks are in the same reference frame.
    - Principle of equivalence: if acceleration causes time to slow, so does gravity.
      - FIG. 36.10: a clock at the surface of the Earth runs slower than one farther away where gravity is weaker.
- Gravity slows down all "clocks" including the vibrational frequencies of atoms that emit light. An atom on the sun emits light of a lower frequency than light emitted by an atom of the same element on Earth. The shifting of light lower, toward the red end of the spectrum, is called the ***gravitational red shift***.
  - Gravity pulls on photons. The photons lose energy (but not speed!). Lower energy means lower frequency – red shift!
    - The gravity of black holes causes photons to lose all of their energy, red-shifting to a frequency of zero – they cannot escape! This is consistent with time stopping for the photon.

GRAVITY, SPACE AND A NEW GEOMETRY

- The ratio of circumference to diameter of a rotating disk is not π.
  - FIG. 36.12: Length contraction (from STR) tells us that a measuring stick at the rim (moving fast) will be much more contracted than one at the center (moving very slowly). A stick along the radius is not contracted at all (disk motion is perpendicular to the radius).
  - The ratio of circumference to radius will vary depending on the speed of rotation and size of the disk.
  - Acceleration = gravity, so gravity can change the geometry of the disk as well. Measurements of distance depend on the strength of gravitational fields.
- Gravity causes space to be non-Euclidean (space doesn't have a flat geometry)
  - Circumference/diameter of a circle is not π.
  - Angles in a triangle do not add up to 180º.
  - Shortest distance between two points is not a "straight" line.
  - FIG. 36.13
    - Flat space (Euclidean): angles in a triangle add to 180º
    - Closed space (spherical): angles in a triangle add to more than 180º
    - Open space (saddle-shaped): angles in a triangle add to less than 180º
  - Lines forming the triangles in open and closed space are not 3-dimensionally "straight", but they are the "straightest" or shortest

distances between two points. These kinds of lines are called *geodesics* and light paths follow geodesics in 4-dimensional spacetime.

    - FIG. 36.14: closed space example with star in between three planets, open space example with three stars to the outside of three planets.

- In general relativity, gravitational fields bend and twist, or warp, spacetime.
  - The presence of mass produces curved 4-dimensional spacetime
    - Like a heavy ball in the middle of a waterbed. What paths would a rolled marble take?
    - DEMO: marble on 2-dimensional “spacetime” frame.

NEWTONIAN AND EINSTEINIAN GRAVITATION

- Correspondence principle: General relativity reduces to Newtonian gravity for weak gravitational fields.
  - Computing trajectories for space probes uses only Newtonian gravity.
- Quantum Theory ↔ Newtonian Physics ↔ Relativity
(Very light and small) (ordinary, everyday scale) (Very massive and large)
|←————————————?————————————→|
- Linking quantum theory with relativity is perhaps the biggest puzzle facing physics today.