Energy

Class 34: Where $E = mc^2$ comes from.
Lab 6 & 7 were due.

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Today: Relativity; (a little review)
Energy concerns
Doing HW with energy and momentum
General Relativity

Started Thursday at 1600 ends Saturday
Did going over some of the problems last Wednesday in class help or was it too little too fast?

- A. Yes     B. No     C. Maybe

- Do you want to talk about any of the current HW?
Suppose we are on our way to Proxima Centauri, which is 4.2 ly away (in the reference frame of the earth). We are in a space ship which is traveling with a speed of $c$. When we are half-way there, we send a signal to both the earth and Proxima Centauri. The signals travel at the speed of light $c$. In the reference frame of the earth and Proxima Centauri, both signals travel 2.1 ly and thus arrive at their destinations at the same time.

(a) In our reference frame, how long does it take for the signal to reach earth? Remember that in our reference frame, the distance between earth and Proxima Centauri is less than 4.2 ly because of length contraction.
HW27-3. Suppose we are on a space ship generating a beam of electrons. In our reference frame, the electrons are traveling in the +x direction with a speed of 0.87c. Our spaceship passes by the earth. In the earth’s reference frame, the space ship is traveling in the +x direction with a speed of [03] c.

Approach is much like the problem we just did. But now a are electrons, b earth and d spaceship. 

\[ V_{ab} = \frac{V_{ad} + V_{db}}{1 + \frac{V_{ad}V_{db}}{C^2}} \]

\( V_{ad} = 0.87c; \ V_{db} = [03] \) ;
Constant Force (begin at rest)

\[ F = p/t \]

\[ p = Ft \]

\[ \gamma \mu u = Ft \]

\[ u \ll c \implies u \text{ increases} \]

\[ u \rightarrow c \implies \gamma \text{ increases} \]

\[ t = \gamma \mu u / F \]

as \( u \rightarrow c \), \( \gamma \rightarrow \infty \), \( t \rightarrow \infty \)

\( u \) never reaches \( c \).
Speed of Light, Notes

• The “speed of light” is the speed limit of the universe. (Or is it the other way around?)

• It is the maximum speed possible for energy and information transfer.

• Any object with mass must move at a lower speed.
Did you complete at least 70% of Chapter 39:7-10?

A. Yes
B. No

What is an eV? How do we use them?
Relativistic Energy

- The definition of kinetic energy requires modification in relativistic mechanics.
- \( K = \gamma mc^2 - mc^2 = (\gamma - 1)mc^2 \)
  - This matches the classical kinetic energy equation when \( u << c \)
  - The term \( E_0 = mc^2 \) is called the rest energy of the object and is independent of its speed,
  - The term \( \gamma mc^2 \) is the total energy, \( E \), of the object and depends on its speed and its rest energy.
Relativistic Energy – Consequences

- A particle has energy by virtue of its mass alone
  - A stationary particle with zero kinetic energy has an energy proportional to its inertial mass
  - This is shown by $E = K + mc^2$
- A small mass corresponds to an enormous amount of energy
Rest Energy

- **Electron**: $E_0 \equiv mc^2 = 0.511$ MeV
- **Proton**: $E_0 \equiv mc^2 = 938$ MeV
Consider an electron and a proton, each with a kinetic energy of 1 MeV. Which particle is moving at relativistic speeds? (pp)

A. electron
B. proton

We will show it on transparency.
HW 28-1 If a particle’s kinetic energy is equal to $[01]$ times its rest energy, find its velocity.

- 1st find total energy from rest energy & $[01]$
- This gives you gamma
- Use $\gamma$ to get $v/c \equiv \beta = \sqrt{1-\gamma^{-2}}$
- Example 39.12 B
28-2. Find the work required to increase the velocity of an electron by 0.0100c (a) if its initial velocity is [02] c and (b) if its initial velocity is [03] c. Remember that the work done is equal to the change of kinetic energy.

Hint: 1st find total energy (E1) from [02]
- This gives you gamma
- Use gamma to get v/c
- Now increase v/c by 0.0100 and get total E2.
- \( \Delta E = E2 - E1 = \) change of kinetic energy
Example of the Fly’s Eye

- \( K = 50 \text{ J} \approx 3 \times 10^{20} \text{ eV} \)
- \( \gamma = \frac{K}{mc^2} + 1 = 6 \times 10^{14} \)
- \( \beta = \sqrt{1 - \gamma^{-2}} = \)
- Try it on your Calculator.

But how do we solve it? M-G Stanley Knows
I am the very model of a modern major general

• I'm very well acquainted, too, with matters mathematical,
  I understand equations, both the simple and quadratical,
  About binomial theorem I'm teeming with a lot o' news,
  With many cheerful facts about the square of the hypotenuse.

ALL join in:
With many cheerful facts about the square of the hypotenuse.

• Gilbert & Sullivan
  http://math.boisestate.edu/gas/pirates/web_op/kar/pp13.kar
  Pirates of Penzance. You owe it to yourself to see it some time.

But how do we use the Binomial Theorem?
Energy and Relativistic Momentum

It is useful to have an expression relating total energy, $E$, to the relativistic momentum, $p$

- $E^2 = p^2c^2 + (mc^2)^2$

When the particle is at rest, $p = 0$ and $E = mc^2$

Massless particles ($m = 0$) have $E = pc$

- The mass $m$ of a particle is independent of its motion and so is the same value in all reference frames

- $m$ is often called the invariant mass
HW 28-4. We accelerate electrons between two parallel plates a few cm apart. We apply [05] MV across the plates. When an electron begins at rest at one plate, it arrives at the other plate with a kinetic energy of [05] MeV. [KE = qV; q is charge & V voltage.]

(a) Find the velocity of the electron. [0.960, 0.990c] 1st find total energy from rest energy & [05]; You can use an eV approach. I will show.

• This gives you gamma
• Use gamma to get v/c
Parallel Plate Capacitor
(b) Find the momentum of the electron.

\[ E^2 = p^2 c^2 + (mc^2)^2; \text{ you know } E \text{ and } mc^2. \]
(c) The electric field between the plates is equal to 2.15 MV/m. This produces a constant force of $3.44 \times 10^{-13}$ N on the electron as it travels from one plate to the other. Find the amount of time it takes for the electron to travel from one plate to the other. Remember that the force is the time derivative of the momentum. [3.00, 5.00 ns]

BTW, Electric field = $F/q$; where q is charge. • $dp/dt = F$ : $\Delta p = F \Delta t$; use p from part b.
General Relativity (includes gravity)

Object in Free fall is equivalent to an inertial frame of reference without gravity.

Accelerating in free fall

“Weightless”
Consider the space shuttle in orbit around the Earth. Is the shuttle in an inertial frame of reference? (pp)

A. yes
B. no
Consider a box in free-fall. A laser in the box shoots a beam from one side of the box to the other. In the ref. frame of the box, the laser beam will be: (pp)

A. curved upward
B. curved downward
C. not curved
In our reference frame the beam droops

- It happens near stars, too
- http://www.theory.caltech.edu/people/patricia/lclens.html
Gravitational lensing

http://www.nature.com/nature/journal/v417/n6892/fig_tab/417905a_F1.html
Gravity disappears

- Space tells matter how to move.
- Matter tells space how to curve.
  - John Wheeler.

Question:
- Can the other Forces disappear?
The Gravitational Lens G2237 + 0305

The European Space Agency's Faint Object Camera on board NASA's Hubble Space Telescope has provided astronomers with the most detailed image ever taken of the gravitational lens G2237 + 0305—sometimes referred to as the "Einstein Cross". The photograph shows four images of a very distant quasar which has been multiple-imaged by a relatively nearby galaxy acting as a gravitational lens. The angular separation between the upper and lower images is 1.6 arc seconds. The quasar seen here is at a distance of approximately 8 billion light years, whereas the galaxy at a distance of 400 million light years is 20 times closer. The light from the quasar is bent in its path by the gravitational field of the galaxy. This bending has produced the four bright outer images seen in the photograph. The bright central region of the galaxy is seen as the diffuse central object.
Gravitational lensing


Canonical: Use “canonical” when you mean “usual” or “standard.” As in, “the canonical example of talking like a physicist is to use the word ‘canonical.’”

Orthogonal: Use “orthogonal” to refer to things that are mutually-exclusive or can’t coincide. “We keep playing phone tag — I think our schedules must be orthogonal”

Empirical Data: Any actual personal experience becomes “empirical data.” i.e. a burn on your hand is empirical data that the stove is hot.

Ground State: You’re not being lazy, you are in your ground state.

Extrapolation: A semi-educated guess is an extrapolation.

Ideal Case: You aren’t ignoring details, you are taking the ideal case.

Vanishingly small: A tiny amount is “vanishingly small.”
• Potential Well: Stuck in a meeting is “trapped in a potential well,” though you hope you can “tunnel out.”
• Black hole: If there is no escape, you are trapped by a black hole, from which there is no escape.
• Photons: It’s not light, they are photons. Turning on the lamp becomes emitting photons.
• Exercise to Reader: The rest is history becomes “the rest is left as an exercise to the reader…”
• Not even wrong. Someone is making an argument using assumptions that are known to be wrong, or are making an argument that can’t be falsified. Courtesy Wolfgang Pauli. “Wait, he’s assuming Ron Paul can still win the Republican nomination? That’s not even wrong.”
• For very small values of. This one, I’m afraid, I can best explain by example. “So there are four of us going to dinner.” “Three.” “Okay, so there are four of us for very small values of four.”
• Super position: If something seems to act like something else, I say that it’s in a “superposition of the two states”. Other good words to add to your vocabulary:
• Discontinuity     Renormalize     Positive & negative work
• God Particle     Dark Energy     Space-time continuum