Physics 294H

- Professor: Joey Huston
- email:huston@msu.edu
- office: BPS3230
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
  - **Help-room hours: 12:40-2:40 Monday (note change); 3:00-4:00 PM Friday**
  - **36.73 hand-in problem for next Wed**
- Quizzes by iclicker (sometimes hand-written)
- Average on 2nd exam (so far)=71/120
- **Final exam Thursday May 5 10:00 AM – 12:00 PM 1420 BPS**
- Course website: www.pa.msu.edu/~huston/phy294h/index.html
  - lectures will be posted frequently, mostly every day if I can remember to do so

Lorentz transformations

$$x' = \gamma (x - vt)$$

$$y' = y$$

$$z' = z$$

$$t' = \gamma (t - \frac{vx}{c^2})$$

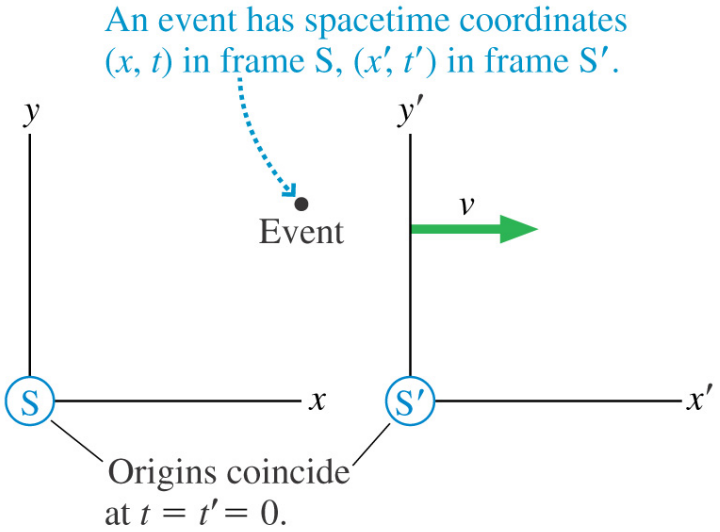
$$x = \gamma (x' + vt')$$

$$y' = y$$

$$z' = z$$

$$t = \gamma (t' + \frac{vx'}{c^2})$$

These transformation equations leave Maxwell's equations invariant.



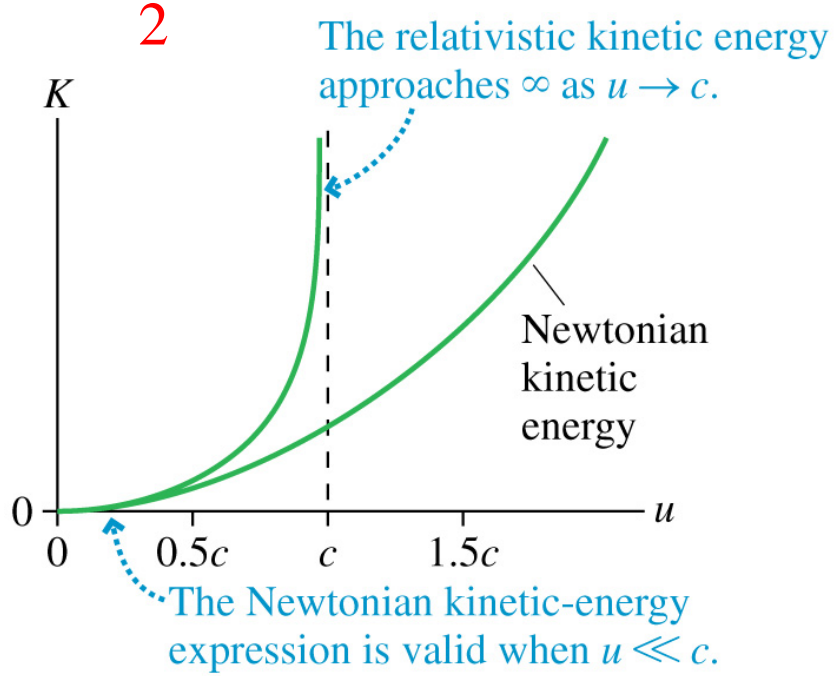
Causality, Lorentz transformations and the speed of light

- Consider two causally related events: A *causes* B.
- If A causes B, then it must be the case that $t_A < t_B$.
- Suppose that there exists some kind of causal influence between A and B that can travel at speed $u > c$.
- In this case, then, we can use the Lorentz transformations to show that there exists a reference frame S′ in which $t_B' < t_A'$.
- In S′, event B happens before A, even though A causes B!
- This would be like you being born before your mother was born!
- No causal influence of any kind (particle, wave or even information) can travel faster than c.

energy

$$\gamma_p mc^2 = \frac{mc^2}{\sqrt{1-\frac{u^2}{c^2}}} \approx \left(1+\frac{1}{2}\frac{u^2}{c^2}\right)mc^2 = mc^2 + \frac{1}{2}mu^2$$

- $E=\gamma_p mc^2=E_o+K$
  =rest energy + kinetic energy
- $K=(\gamma_p-1)mc^2$
- Kinetic energy goes to $1/2mu^2$ when $u<<c$
- $E_o=mc^2$ (rest energy)
- $E^2-(pc)^2=E_o^2$



Convenient to quote particle energies in eV

1 eV = 1.6 X 10^{-19} J

m_e=9.11X10^{-31} kg

$m_e c^2$=(9.11X10^{-31} kg)(3.0X10^8 m/s)^2 = 8.2X10^{-19} J

=(8.2X10^{-14} J)/(1.6X10^{-19} J/eV)=0.511 MeV

iclicker question

Suppose that a pitcher can throw a fastball at u = 1.2c. This would give $u^2/c^2 = 1.44$; the total energy equation, below, would then have the square root of a negative number.

$$E = \frac{mc^2}{\sqrt{1 - u^2/c^2}} = \gamma mc^2$$

Choose the correct statement:

A. The resulting energy would be imaginary indicating that the ball is actually stationary.
B. The resulting energy would be equal to that of a photon traveling at 1.4c.
C. Nothing can ever be accelerated to a speed greater than c.

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Answer: C, It would take an infinite amount of energy for a baseball to reach the speed of light. Nothing can ever be made to move faster than c.

An electron has rest energy 0.5 MeV. An electron traveling at $0.968c$ has $\gamma_p = 4$. The electron's kinetic energy is

A. 1.0 MeV.

B. 1.5 MeV.

C. 2.0 MeV.

D. 4.0 MeV.

E. I would need my calculator and several minutes to figure it out.

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A. 1.0 MeV.

✔ B. 1.5 MeV. $K = (\gamma_p - 1)E_0$

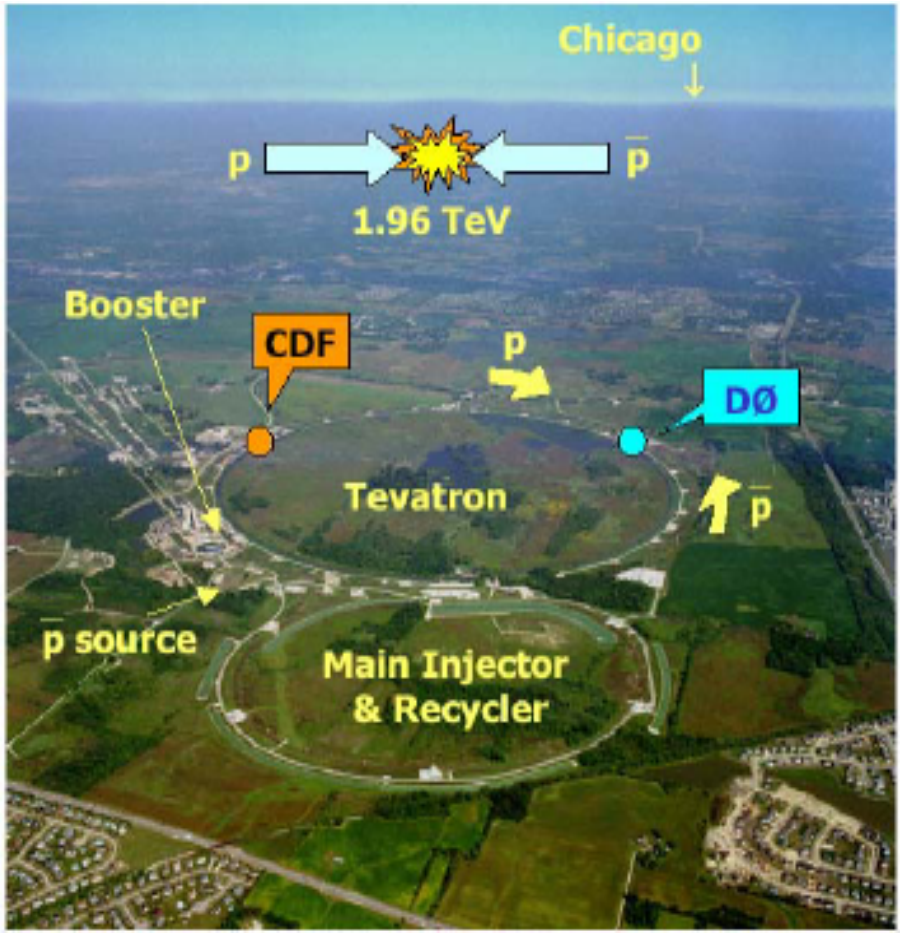
C. 2.0 MeV.

D. 4.0 MeV.

E. I would need my calculator and several minutes to figure it out.

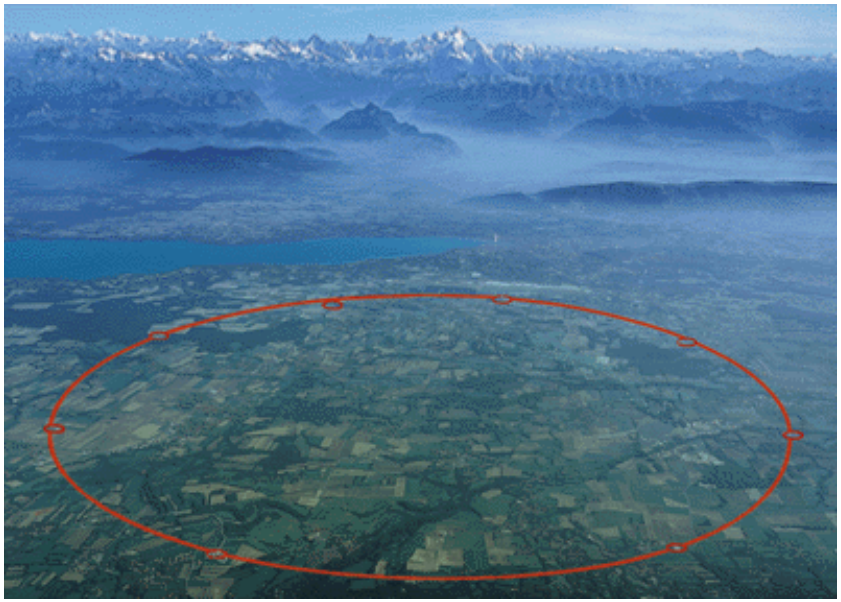
Fermilab accelerator

- The protons and anti-protons ~~are~~ used to be accelerated to an energy of 980 GeV (billion electron-volts)
  - i.e. their total energy is about 1000 times their rest mass energy
  - or γ is about 1000

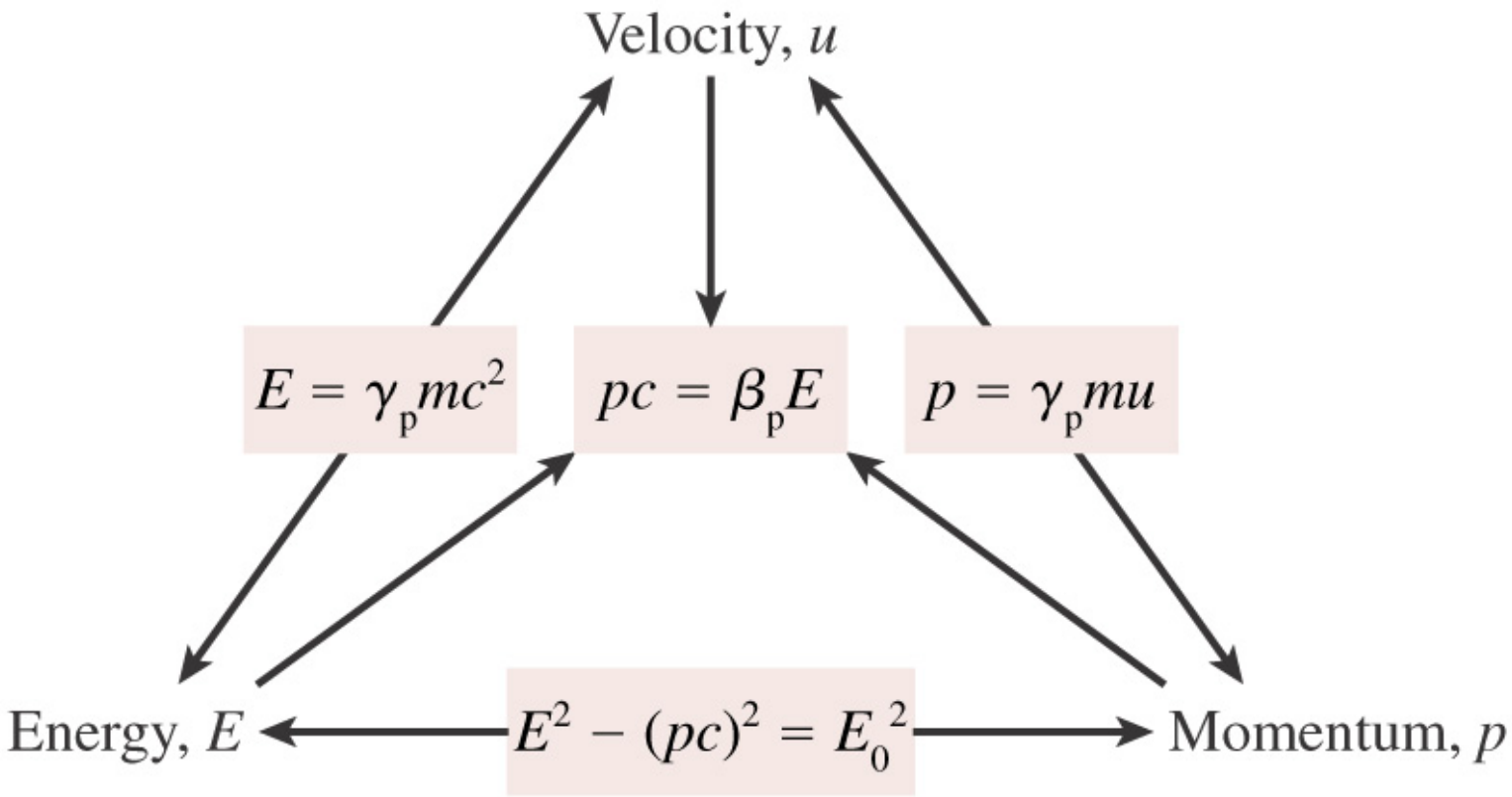


CERN accelerator

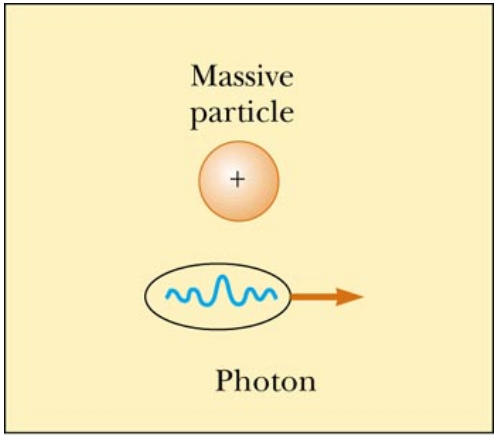
- The proton beams are accelerated to 6.5 TeV (trillion electron-volts)
  - i.e. their total energy is about 6500 times their rest mass
  - γ is ~6500



Velocity-energy-momentum triangle



Pair production and annihilation



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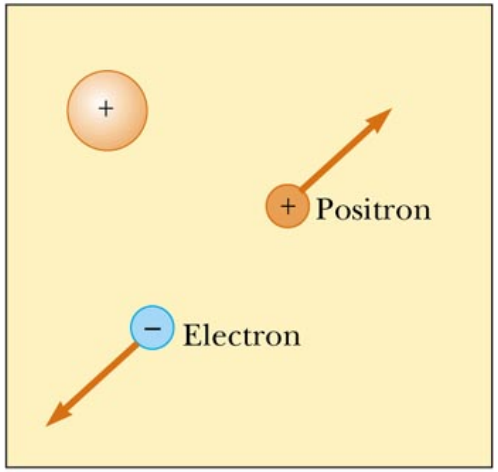

After

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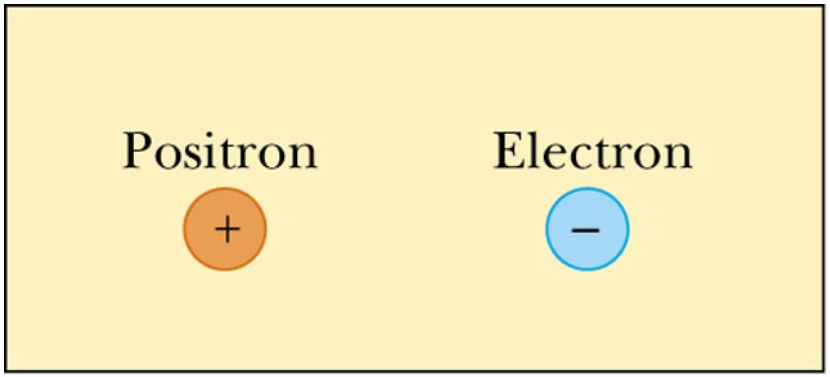

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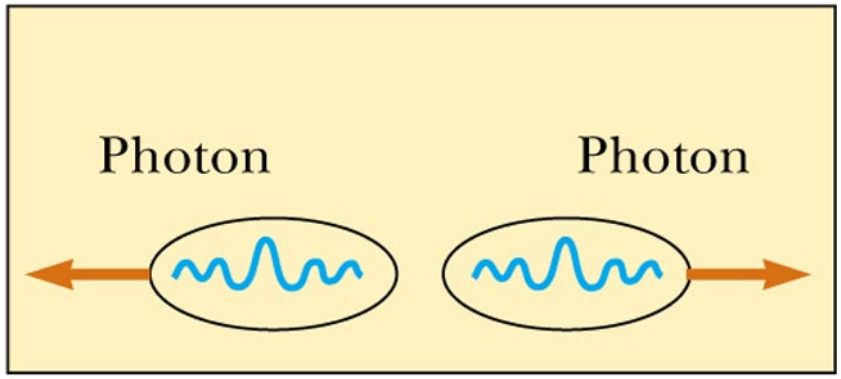

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$E=mc^2$

Einstein's Gedanken Experiment

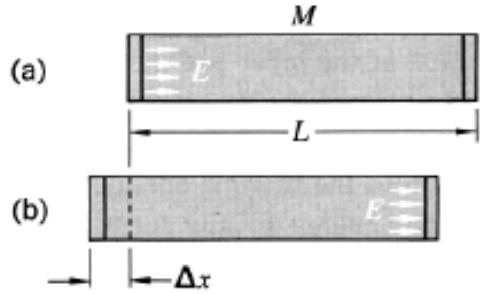
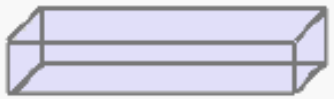


Fig. 1–4 Einstein's box—a hypothetical experiment in which a box recoils from its initial position (a) to a final position (b) as a result of a burst of radiant energy traveling from one end of the box to the other.

If radiation E is emitted from the left end of the box, the box must recoil to the left with a calculable momentum. Hence the box moves a calculable distance before the radiation is absorbed at the other end, and the box stops.

Since the center of mass can not move, the radiation must have transferred mass.



Here is the problem: Light has no mass, only momentum.

how can this happen?

The Algebra

recoil of box due to light momentum → $Mv = \frac{E}{c}$ $\quad v = \frac{E}{Mc}$

time light is in flight → $\Delta t = \frac{L}{c}$

distance box moves → $\Delta x = v\Delta t = \frac{EL}{Mc^2}$

center of mass doesn't move → $0 = -M\Delta x + mL$

plug in for Δx → $\frac{EL}{c^2} = mL$

solve → $E = mc^2$

E is energy transmitted from one end of the box to the other. m is the mass transferred as a result.

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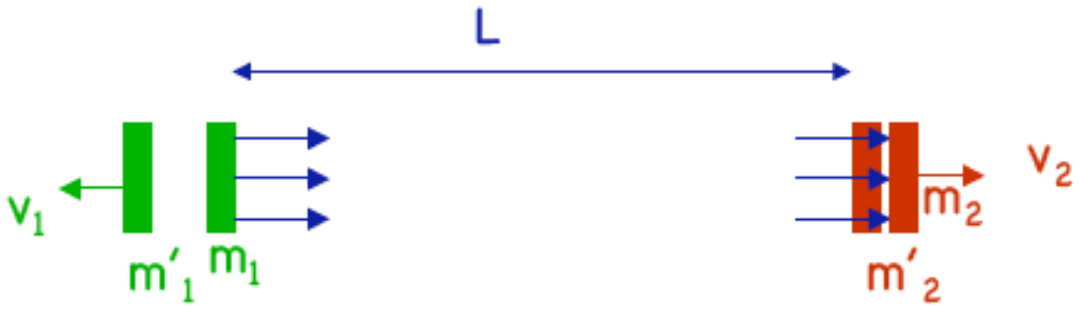
Year of Physics, March 10, 2005, slide 11

..but there's a problem with this derivation

Mein Gott, Einstein was wrong

Relativistically Correct Derivation



This takes into account the fact that recoil m_1 has a reduced mass and m_2 an increased mass.

Complicated proof, but answer is the same.

Cockroft and Walton

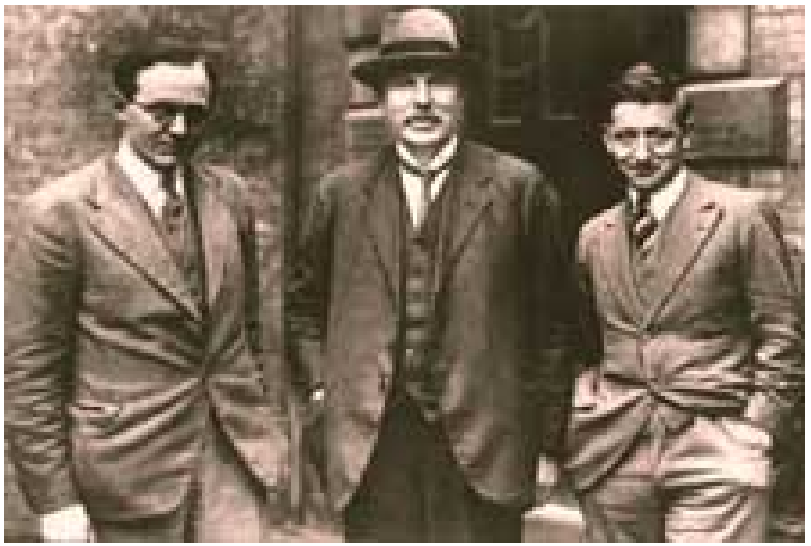
What does $\Delta E = \Delta M c^2$ mean?

The Δ means "change in". When a particle has no energy its mass is its "rest mass" M_0. Adding energy increases the mass. So simply put the energy-mass relation means that adding energy (for example kinetic) increases the mass.

However because c is so huge, the ΔM is usually very small. That is why the relation was not verified until 1932, and yes it was in nuclear physics.

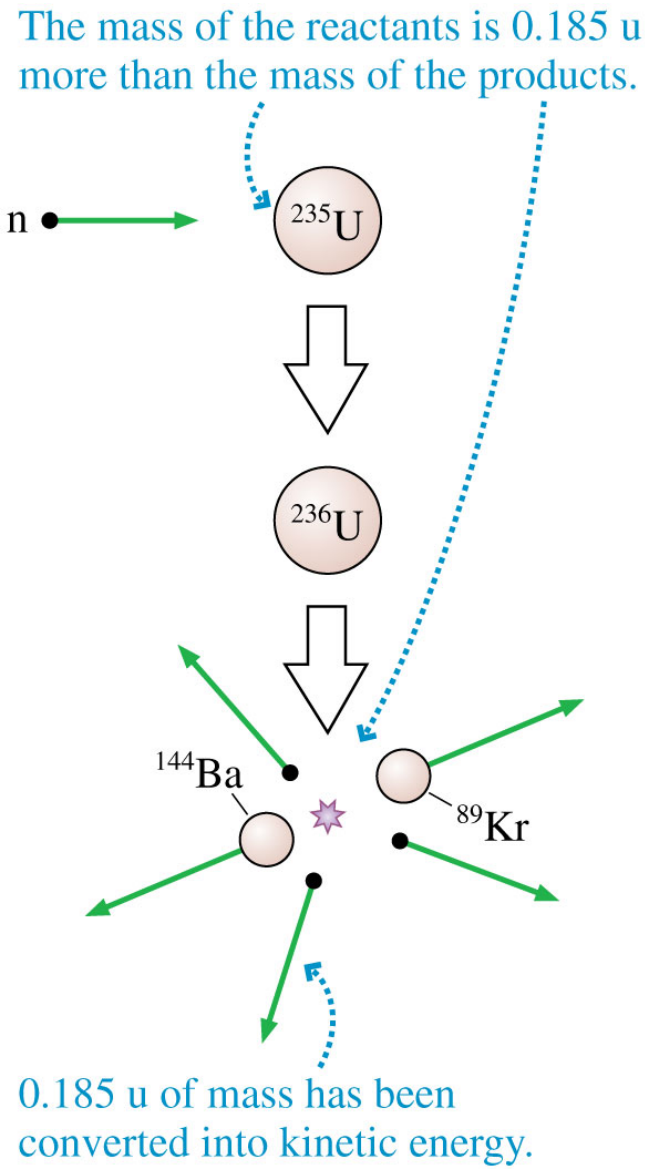
$$^{1}H + {}^{7}Li \rightarrow {}^{4}He + {}^{4}He + Q$$

The Q was found the be just what you would calculate from the masses.



Ernest Rutherford

Nuclear fission

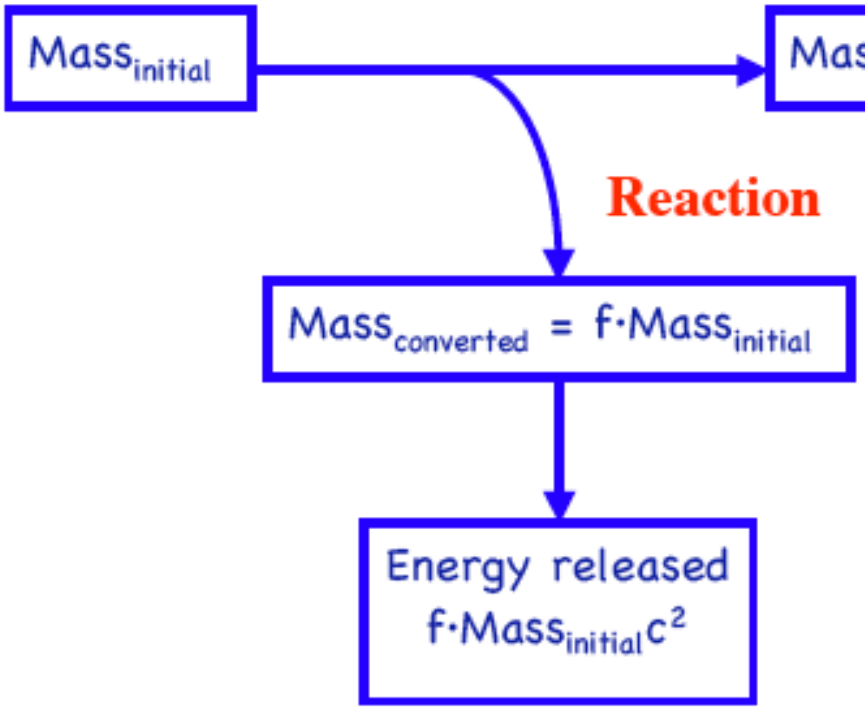


- Probably the most well-known application of the conservation of total energy is **nuclear fission.**
- A ^{235}U nucleus absorbs a neutron and then quickly fragments into two smaller nuclei and several extra neutrons.
- Mass has been lost and converted to an equivalent amount of kinetic energy in the fission products.
- This generates heat.

What Powers the Sun?

Nuclear reactions power the stars (and the sun)

- All energy, gravitional, chemical, or nuclear comes from mass



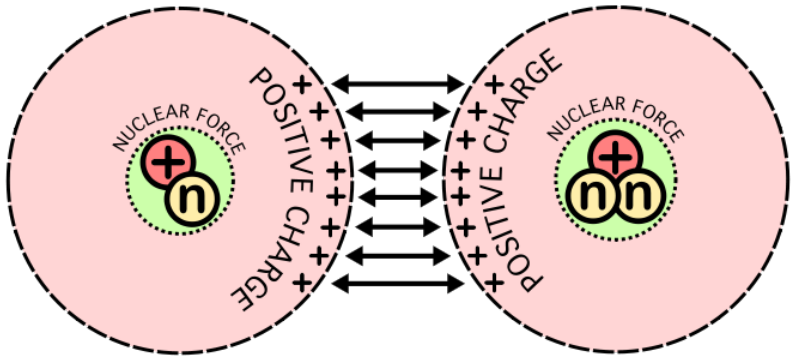
$f_{chem} \sim 1.5 \times 10^{-10}$ 2200 y

$f_{gravity} \sim 7.5 \times 10^{-6}$ 10^7 y

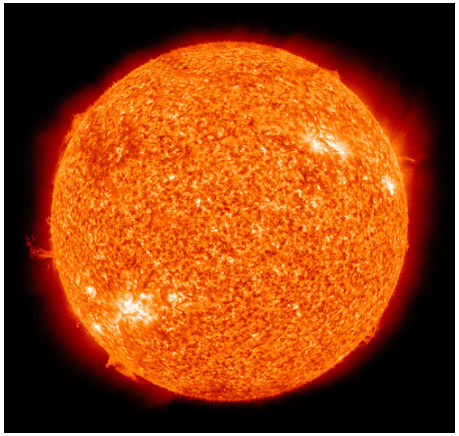
$f_{fusion} \sim$ ~~1.0×10^{-3}~~ .007 10^{11} y

No other source lasts lifetime of sun (4.5×10^9 yr)

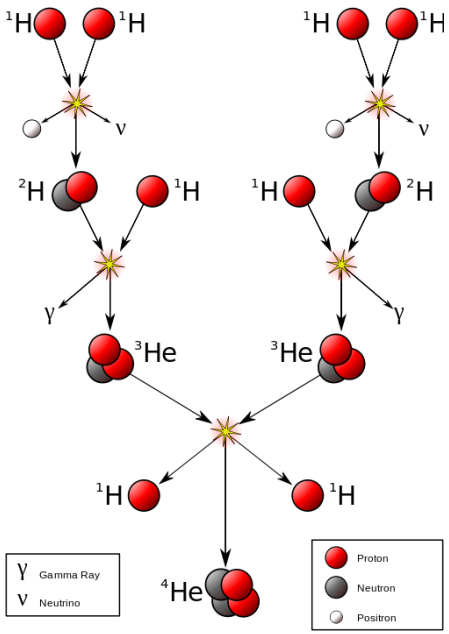
Fusion in the sun



The electrostatic force between the positively charged nuclei is repulsive, but when the separation is small enough, the quantum effect will tunnel through the wall. Therefore, the prerequisite for fusion is that the two nuclei be brought close enough together for a long enough time for quantum tunnelling to act.



The sun is a main sequence star, and thus generates its energy by nuclear fusion of hydrogen nuclei into helium. In its core, the sun fuses 620 million metric tons of hydrogen each second.



proton-proton chain

about 4 million tons of mass are converted to energy each second