

## How The Universe Got That Way

13 billion years ago (more or less) the universe was born in what is termed the "big bang". It was a hot, dense soup of particles and photons. Now, the universe is a big, cold, largely empty space populated by galaxies, stars, planets—and you and me.

How did it get this way? And how did we figure this out?

These are the topics of this course.

Music: Woodstock by Joni Mitchell

### As you come in:

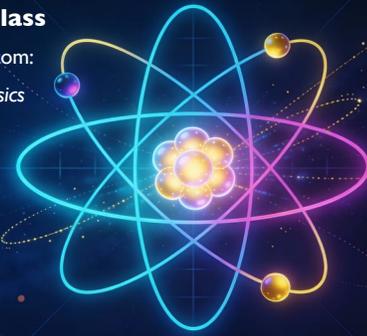
- Get a name tent
- Introduce yourself to your neighbors
- Start chatting
- Introduce yourself to me, if you'd like!

Brian Jones  
physicsjones@gmail.com

## Today's Class

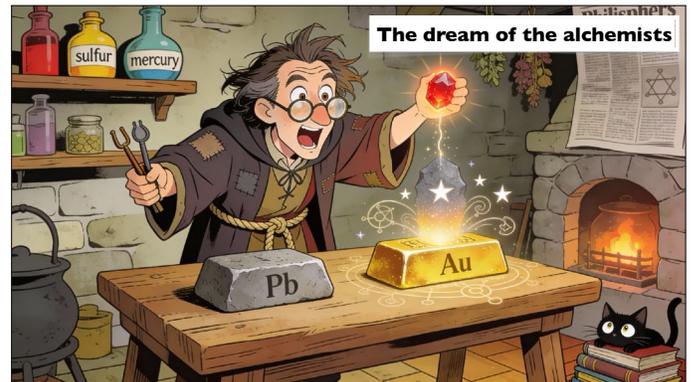
Inside the Atom:

Nuclear Physics



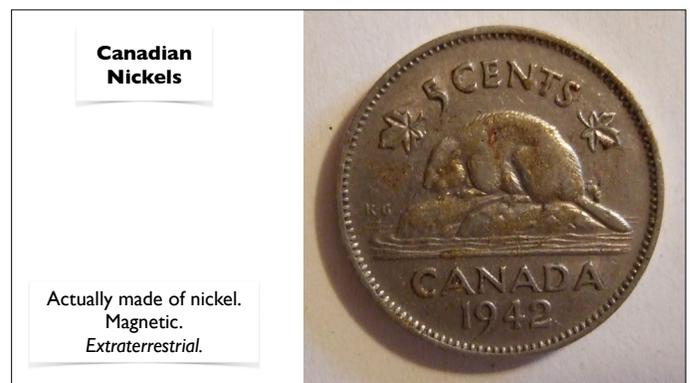
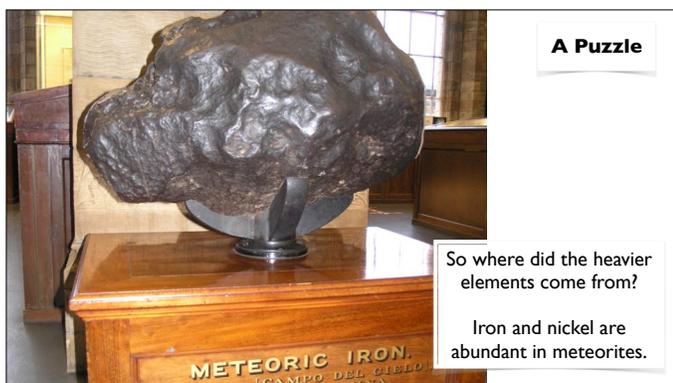
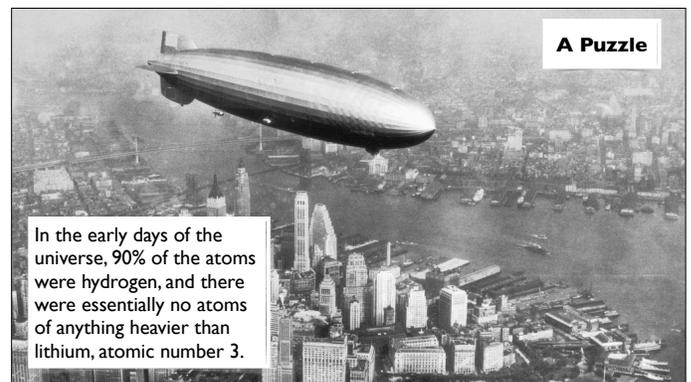
## Nuclear Physics

- Radiation and Radioactivity
- Nuclear Accounting
- Fission & Fusion
- Extreme Physics



### The Periodic Table of the Elements

|       |       |          |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|-------|-------|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1 H   |       |          |        |        |        |        |        |        |        |        |        |        |        |        |        |        | 2 He   |
| 3 Li  | 4 Be  |          |        |        |        |        |        |        |        |        |        | 5 B    | 6 C    | 7 N    | 8 O    | 9 F    | 10 Ne  |
| 11 Na | 12 Mg |          |        |        |        |        |        |        |        |        |        | 13 Al  | 14 Si  | 15 P   | 16 S   | 17 Cl  | 18 Ar  |
| 19 K  | 20 Ca | 21 Sc    | 22 Ti  | 23 V   | 24 Cr  | 25 Mn  | 26 Fe  | 27 Co  | 28 Ni  | 29 Cu  | 30 Zn  | 31 Ga  | 32 Ge  | 33 As  | 34 Se  | 35 Br  | 36 Kr  |
| 37 Rb | 38 Sr | 39 Y     | 40 Zr  | 41 Nb  | 42 Mo  | 43 Tc  | 44 Ru  | 45 Rh  | 46 Pd  | 47 Ag  | 48 Cd  | 49 In  | 50 Sn  | 51 Sb  | 52 Te  | 53 I   | 54 Xe  |
| 55 Cs | 56 Ba | * 71 Lu  | 72 Hf  | 73 Ta  | 74 W   | 75 Re  | 76 Os  | 77 Ir  | 78 Pt  | 79 Au  | 80 Hg  | 81 Tl  | 82 Pb  | 83 Bi  | 84 Po  | 85 At  | 86 Rn  |
| 87 Fr | 88 Ra | * 103 Lr | 104 Rf | 105 Db | 106 Sg | 107 Bh | 108 Hs | 109 Mt | 110 Ds | 111 Rg | 112 Cn | 113 Nh | 114 Fl | 115 Mc | 116 Lv | 117 Ts | 118 Og |
|       |       | * 57 La  | 58 Ce  | 59 Pr  | 60 Nd  | 61 Pm  | 62 Sm  | 63 Eu  | 64 Gd  | 65 Tb  | 66 Dy  | 67 Ho  | 68 Er  | 69 Tm  | 70 Yb  |        |        |
|       |       | * 89 Ac  | 90 Th  | 91 Pa  | 92 U   | 93 Np  | 94 Pu  | 95 Am  | 96 Cm  | 97 Bk  | 98 Cf  | 99 Es  | 100 Fm | 101 Md | 102 No |        |        |

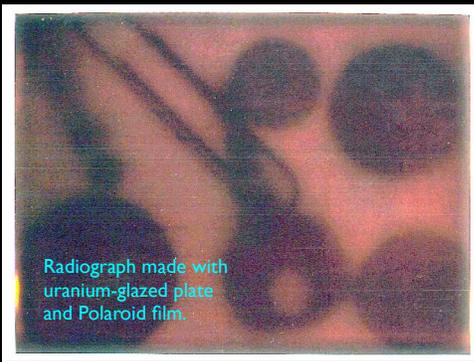


**Back to the story...  
The discovery of  
radioactivity**



**Nuclear Radiation is Ionizing Radiation**

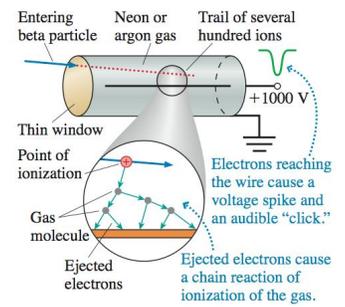
Radiation burn from cancer treatment



Radiograph made with uranium-glazed plate and Polaroid film.

**Measuring radioactivity**

Operation of Geiger counter



**People used to think that  
radiation was pretty sexy.**



Strangely, some folks still do....

**Measuring  
Radiation**

**Things To  
Test**

How far away can you be to detect the radiation?

How can you shield against the radiation?



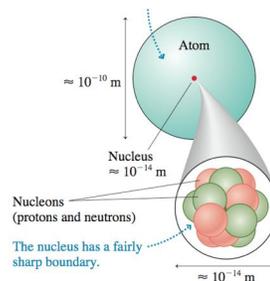
The cool orange color is from uranium.

**Where does the radiation come from?**



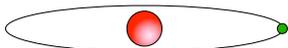
Things fall apart. Even atoms.

**Anatomy of an Atom**



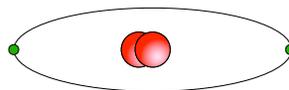
The nucleus is made of protons and neutrons. A cloud of electrons orbits the nucleus.

### The Simplest Atom



A hydrogen atom consists of a single positively charged proton and a negatively charged electron that "orbits" it.

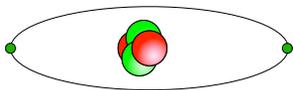
Of course, you can have elements with more protons in the nucleus.



#### Question

Do you see any problems with this nucleus?

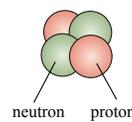
The neutrons are the "glue" that lets the nucleus hold together.



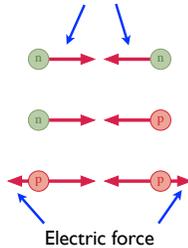
You need just the right number of neutrons, though. Too many or too few means the nucleus will be unstable.

### Holding it All Together

Helium nucleus

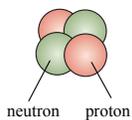


Strong nuclear force



### Holding it All Together

Helium nucleus



The number of neutrons in the nucleus can vary. The number of protons determines the **element**, the number of neutrons determines the **isotope**.

## Atomic Accounting

Number of protons + neutrons

Number of protons



## Isotopes

Helium has 2 stable isotopes.



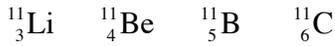
Tin has 10.



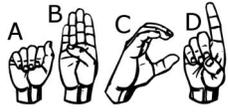
- ${}^{112}_{50}\text{Sn}$
- ${}^{114}_{50}\text{Sn}$
- ${}^{115}_{50}\text{Sn}$
- ${}^{116}_{50}\text{Sn}$
- ${}^{117}_{50}\text{Sn}$
- ${}^{118}_{50}\text{Sn}$
- ${}^{119}_{50}\text{Sn}$
- ${}^{120}_{50}\text{Sn}$
- ${}^{122}_{50}\text{Sn}$
- ${}^{124}_{50}\text{Sn}$

**Practice**

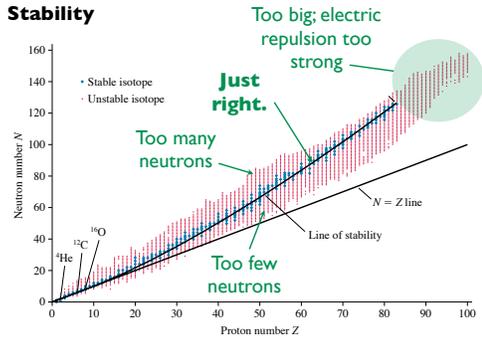
How many neutrons are in each of the following nuclei?



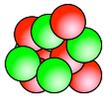
- A. 8
- B. 7
- C. 6
- D. 5



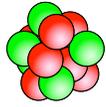
**Stability**



**Stability**



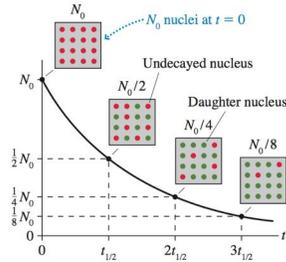
Stable



Not Stable

**You Light Up My Half Life**

Unstable nuclei decay in a very specific way.



$$N = N_0 \left[ \frac{1}{2} \right]^{t/t_{1/2}}$$

**Radioactive Dating**

A scrap of parchment from the Dead Sea Scrolls was found to have a  ${}^{14}\text{C}/{}^{12}\text{C}$  ratio that is 79.5% of the modern value.



This tells us the parchment is about 1900 years old.

$t_{1/2} = 5730 \text{ yr}$

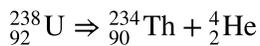
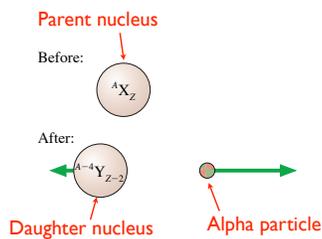
**A Puzzle**

All of the helium present when the earth was formed has escaped into space.

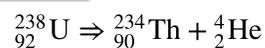
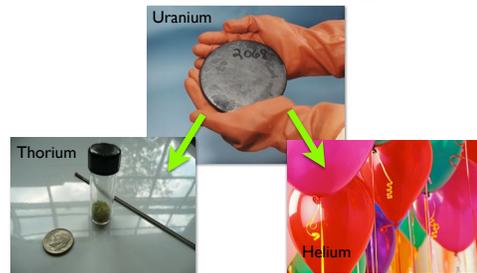
Why do we have helium at all?

**Alpha Decay**

Really large atoms tend to fall apart—and they often do so by ejecting a helium nucleus.



**When one uranium atom decays, you get two atoms!**



**Remember:**  
**Gravitational Time Dilation**

$$\frac{\Delta t \text{ (in gravitational field)}}{\Delta t \text{ (not in gravitational field)}} = \sqrt{1 - \frac{2GM}{rc^2}}$$

This is always less than 1.

Relativity Fact #2:  
Gravity affects time

**Strong gravity slows time down.**

We need a different formula for energy too.

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

Total energy of an object of mass  $m$  moving at speed  $u$

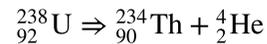
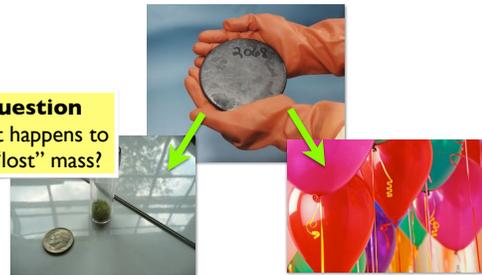
And when there is no motion, this reduces to the most famous equation in the world:

$$E = mc^2$$

Mass can be converted to energy, and vice versa.

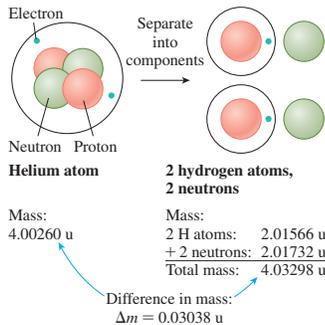
When uranium decays into thorium and helium, mass is "lost".

**Question**  
What happens to the "lost" mass?



**Fusion**

If you "build" a helium atom from two hydrogen atoms and two neutrons, the resulting atom has less mass than you started with.

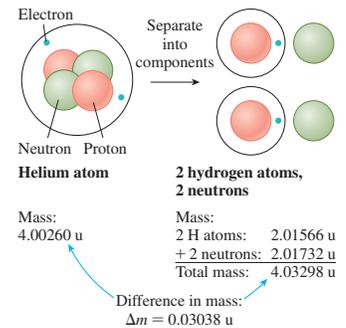


**Question**  
What happens to the "lost" mass?

**Energetic!**

The amount of energy you get this way is pretty incredible. Making a balloon's worth of helium releases an energy equivalent to 7,000 gallons of gas.

*That's more gas than I have burned in cars in my lifetime.*

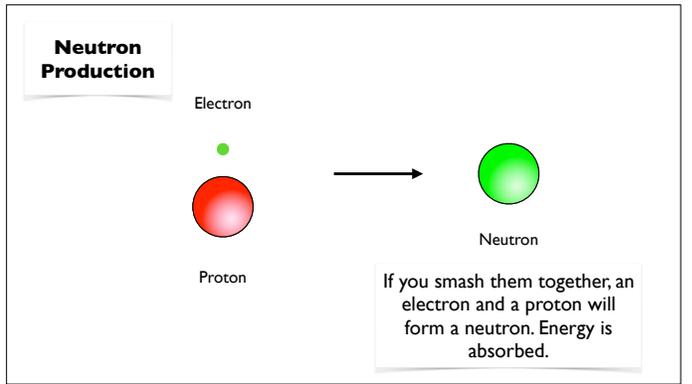
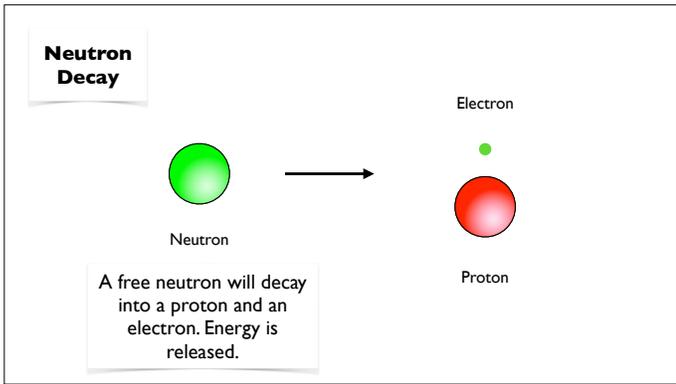


$$E = mc^2$$

In the core of the sun, hydrogen is being converted to helium. Mass is lost in this process. That's where the energy comes from.

The sun loses 350 billion tons of mass a day.





In the sun, 4 hydrogen atoms fuse to make 1 atom of helium. When it was formed, almost all of the atoms in the sun were hydrogen atoms. Now, about half the atoms in the sun's core are helium atoms.

**Question**  
The sun is about 4.6 billion years old. About how much longer will it continue?

In the sun, 4 hydrogen atoms fuse to make 1 atom of helium. When it was formed, almost all of the atoms in the sun were hydrogen atoms. Now, about half the atoms in the sun's core are helium atoms.

**Question**  
What happens then???

In the sun, 4 hydrogen atoms fuse to make 1 atom of helium. When it was formed, almost all of the atoms in the sun were hydrogen atoms. Now, about half the atoms in the sun's core are helium atoms.

**Betelgeuse**  
600 light-years away

When hydrogen in the core runs out, the sun can stabilize itself by fusing helium atoms.

**Question**  
What atom do you get when you combine 3 helium atoms? 4 helium atoms?

**Betelgeuse**  
600 light-years away

When hydrogen in the core runs out, the sun can stabilize itself by fusing helium atoms.

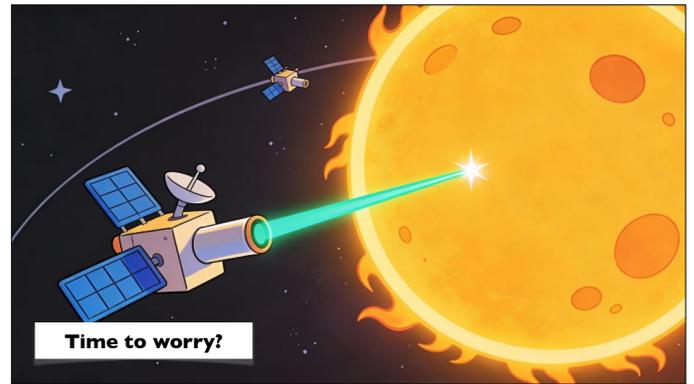
**Betelgeuse**  
600 light-years away

When this happens, the sun will balloon into a red giant.

Red giant stars are really big.

Sun  
1 pixel

Betelgeuse  
760 pixels



**Question**  
What happens when the star runs out of helium?

**White Dwarf**

Core supported by electron degeneracy.

**Neutron Star**

Core supported by neutron degeneracy.

**Black Hole**

Nothing stops the collapse.

**We Are Stardust**

**6 billion years ago.**

69. All the very heavy atoms found in the earth were created long ago by nuclear fusion reactions in a supernova, an exploding star. The debris spewed out by the supernova later coalesced to form the sun and the planets of our solar system. Nuclear physics suggests that the uranium isotopes  $^{238}\text{U}$  ( $t_{1/2} = 7.04 \times 10^8 \text{ yr}$ ) and  $^{235}\text{U}$  ( $t_{1/2} = 4.47 \times 10^8 \text{ yr}$ ) should have been created in roughly equal amounts. Today, 99.28% of uranium is  $^{238}\text{U}$  and 0.72% is  $^{235}\text{U}$ . How long ago did the supernova occur?

