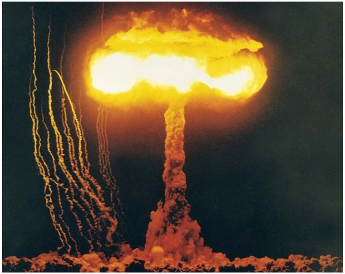
Chapter 10 - Nuclear Physics

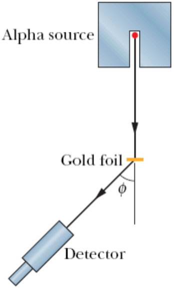


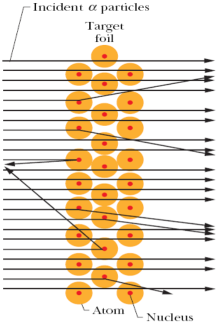
> “The release of atomic energy has not created a new problem. It has merely made more urgent the necessity of solving an ‘existing one.’ ”
>
> -Albert Einstein

David J. Starling
Penn State Hazleton
PHYS 214

The Nucleus

Ernest Rutherford proposed and discovered the nucleus in 1911.





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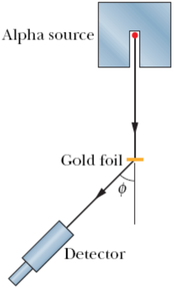
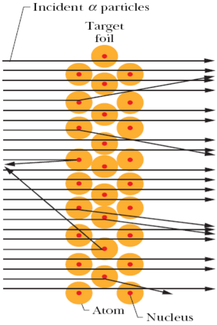
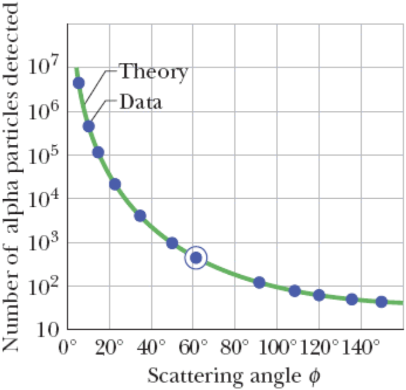




Alpha particles are positively charged helium nuclei ^{4}He.

The Nucleus

Their scattering angle theory matched predictions!



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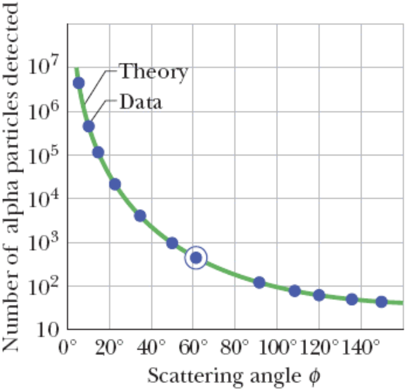
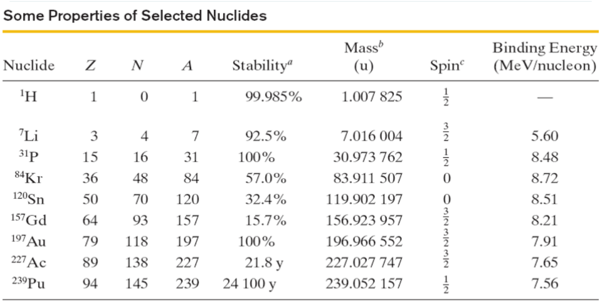


Geiger and Marsden conducted the experiments with Radon gas.

The Nucleus

Protons (Z) and Neutrons (N) combine to give the mass number (A) of the atom.



Some Properties of Selected Nuclides

Nuclide	Z	N	A	Stability[a]	Mass[b] (u)	Spin[c]	Binding Energy (MeV/nucleon)
^{1}H	1	0	1	99.985%	1.007 825	$\frac{1}{2}$	—
^{7}Li	3	4	7	92.5%	7.016 004	$\frac{3}{2}$	5.60
^{31}P	15	16	31	100%	30.973 762	$\frac{1}{2}$	8.48
^{84}Kr	36	48	84	57.0%	83.911 507	0	8.72
^{120}Sn	50	70	120	32.4%	119.902 197	0	8.51
^{157}Gd	64	93	157	15.7%	156.923 957	$\frac{3}{2}$	8.21
^{197}Au	79	118	197	100%	196.966 552	$\frac{3}{2}$	7.91
^{227}Ac	89	138	227	21.8 y	227.027 747	$\frac{3}{2}$	7.65
^{239}Pu	94	145	239	24 100 y	239.052 157	$\frac{1}{2}$	7.56

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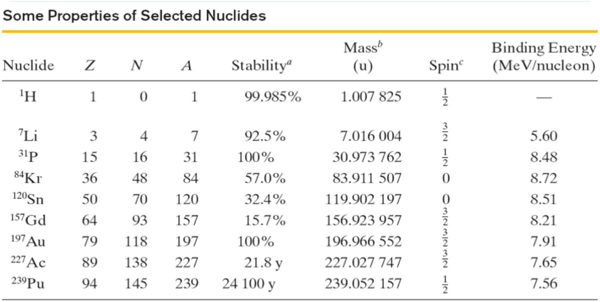

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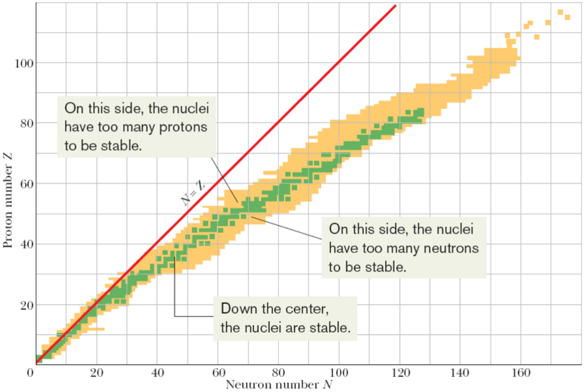
Note how the masses are not whole number multiples of Hydrogen.

The Nucleus

Atoms tend to have more neutrons than protons, and can have multiple stable isotopes.



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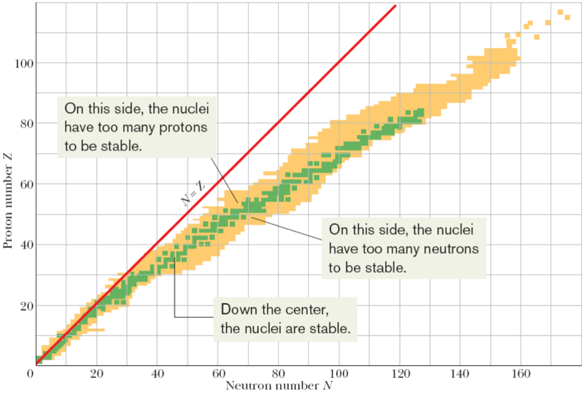


On this side, the nuclei have too many protons to be stable.

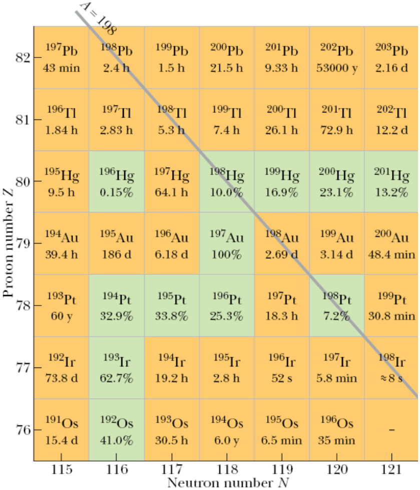
On this side, the nuclei have too many neutrons to be stable.

Down the center, the nuclei are stable.

Bismuth ($Z = 83$) is the largest stable nucleus.

The Nucleus

Stable nuclides have different abundances; radionuclides have different half-lives.



	115	116	117	118	119	120	121
82	^{197}Pb 43 min	^{198}Pb 2.4 h	^{199}Pb 1.5 h	^{200}Pb 21.5 h	^{201}Pb 9.33 h	^{202}Pb 53000 y	^{203}Pb 2.16 d
81	^{196}Tl 1.84 h	^{197}Tl 2.83 h	^{198}Tl 5.3 h	^{199}Tl 7.4 h	^{200}Tl 26.1 h	^{201}Tl 72.9 h	^{202}Tl 12.2 d
80	^{195}Hg 9.5 h	^{196}Hg 0.15%	^{197}Hg 64.1 h	^{198}Hg 10.0%	^{199}Hg 16.9%	^{200}Hg 23.1%	^{201}Hg 13.2%
79	^{194}Au 39.4 h	^{195}Au 186 d	^{196}Au 6.18 d	^{197}Au 100%	^{198}Au 2.69 d	^{199}Au 3.14 d	^{200}Au 48.4 min
78	^{193}Pt 60 y	^{194}Pt 32.9%	^{195}Pt 33.8%	^{196}Pt 25.3%	^{197}Pt 18.3 h	^{198}Pt 7.2%	^{199}Pt 30.8 min
77	^{192}Ir 73.8 d	^{193}Ir 62.7%	^{194}Ir 19.2 h	^{195}Ir 2.8 h	^{196}Ir 52 s	^{197}Ir 5.8 min	^{198}Ir ≈8 s
76	^{191}Os 15.4 d	^{192}Os 41.0%	^{193}Os 30.5 h	^{194}Os 6.0 y	^{195}Os 6.5 min	^{196}Os 35 min	–

The Nucleus

The radius of nuclides can be roughly approximated.

$$r = r_0 A^{1/3}$$

with $r_0 = 1.2$ fm and A the mass number.

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This only applies to spherical nuclides and not to unstable halo nuclides (e.g., ${}^{11}_{3}\text{Li}$).

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Atomic masses are reported in **atomic mass units** *with Carbon-12 defined to be 12 u.*

$$1 \text{ u} = 1.660538 \times 10^{-27} \text{ kg}$$

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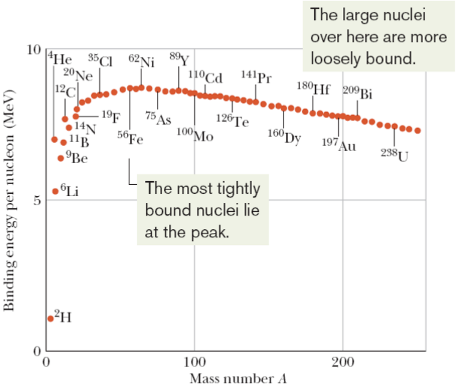
Therefore, the mass number of an atom and its atomic mass are very similar (e.g., ^{197}Au has a mass of 196.966522 u).

The Nucleus

It takes energy to pull protons and neutrons apart; therefore, they lose energy when they come together.



The large nuclei over here are more loosely bound.

The most tightly bound nuclei lie at the peak.

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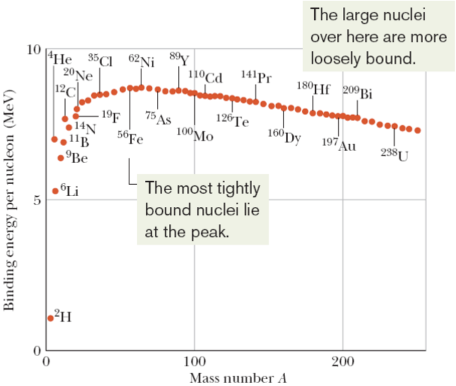

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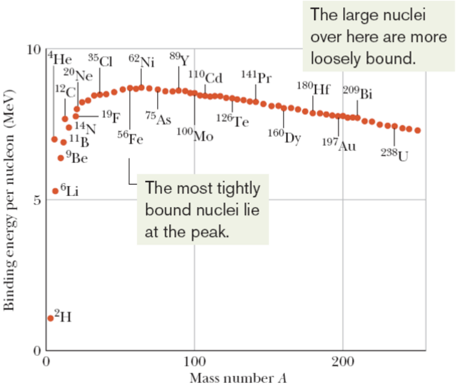

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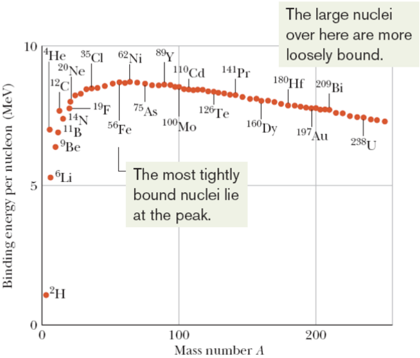
This change in energy is equivalent to a change in mass (via $E = mc^2$).

The Nucleus

The binding energy is just

$$\Delta E_b = \sum_i m_i c^2 - Mc^2 > 0.$$



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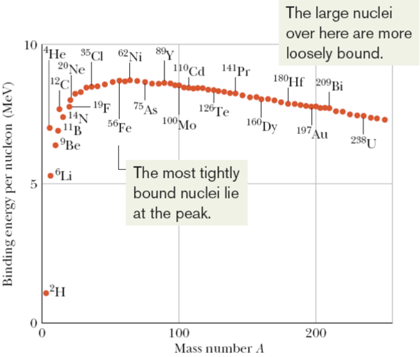

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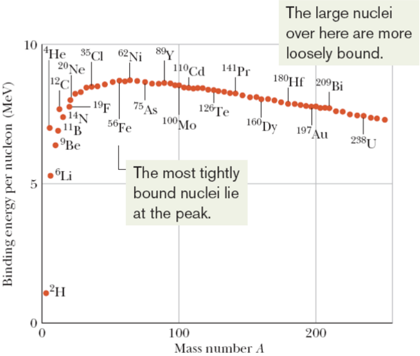

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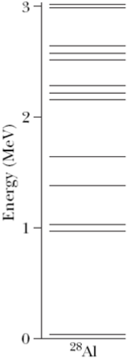
The mass excess is $\Delta \approx M - A$.

The Nucleus

Once formed, nuclides have energy levels similar to the electrons.



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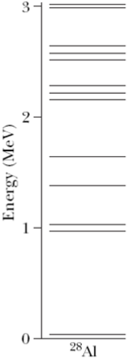

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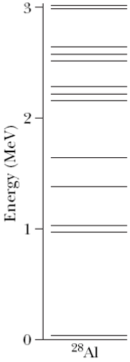

However, much more energy is required to excite the nucleus.

The Nucleus

Lecture Question 10.1

Which statement is true about the forces inside an atom?

(a) Gravity holds electrons, while the strong nuclear force holds nuclei together.

(b) Gravity holds electrons in their orbits and nuclei together.

(c) Gravity holds electrons, while the electromagnetic force holds nuclei together.

(d) The strong nuclear force holds electrons, while the electromagnetic force holds nuclei together.

(e) The electromagnetic force holds electrons, while the strong nuclear force holds nuclei together.

Radioactive Decay

Unstable nuclei decay into other nuclei. For a sample of N particles, the rate is proportional to N with decay constant λ.

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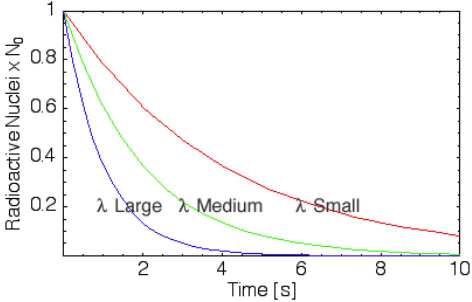
N &= N_0 e^{-\lambda t}
\end{aligned}$$

Radioactive Decay

The number of nuclei decays exponentially.



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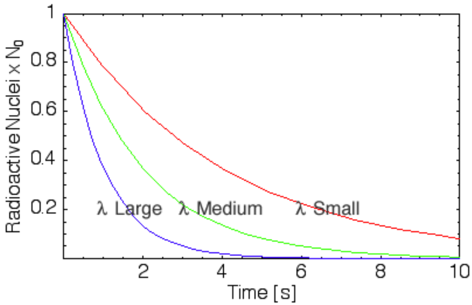

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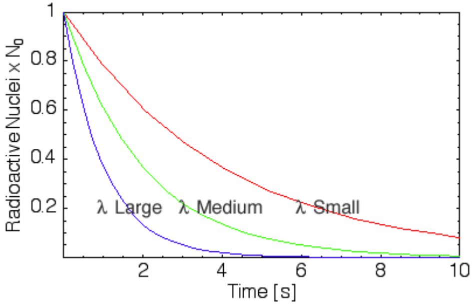

1 becquerel = 1 Bq = 1 decay per second
1 curie = 1 Ci = 3.7×10^{10} Bq

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The half-life is the time to reduce the nuclei number (or decay rate) by 1/2.

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The mean life time $\tau = 1/\lambda$ is when N has been reduced to N_0/e.

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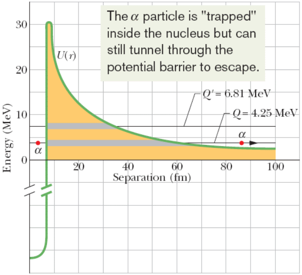

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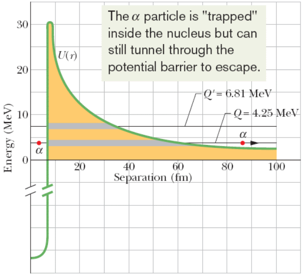

The α particle is "trapped" inside the nucleus but can still tunnel through the potential barrier to escape.

The alpha particle is bound within the ^{238}U nucleus but can tunnel out with some small probability, leaving behind a ^{234}Th nuclues.

Radioactive Decay

Beta decay is when a proton or neutron decays into the other, emitting an electron or positron to preserve charge.

$$\begin{aligned} {}^{32}_{15}\mathrm{P} &\rightarrow {}^{32}_{16}\mathrm{S} + e^{-} + \nu \\ {}^{64}_{29}\mathrm{Cu} &\rightarrow {}^{64}_{28}\mathrm{Ni} + e^{+} + \nu \end{aligned}$$

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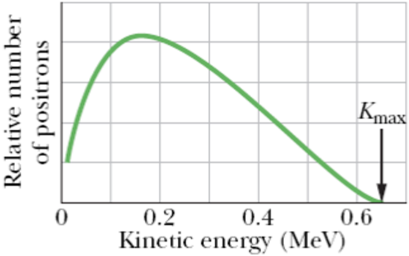
The half life for these reactions is 14.3 d and 12.7 h, respectively. The very low mass ν particle is a neutrino.

Radioactive Decay

Since two particles share the energy of beta emission, the positron/electron can have a range of energies.



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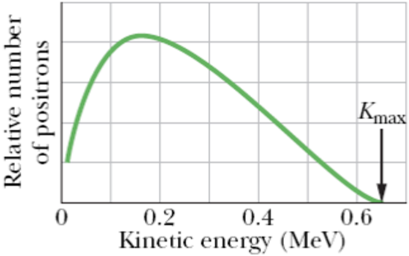
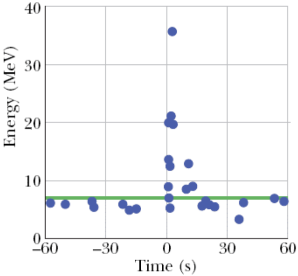


For beta decay of copper to nickel, the most probable positron emission energy is 0.15 MeV.

Radioactive Decay

Neutrinos interact very weakly with matter and so large detectors are required to see even the most massive supernova events.



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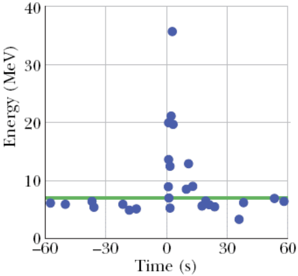
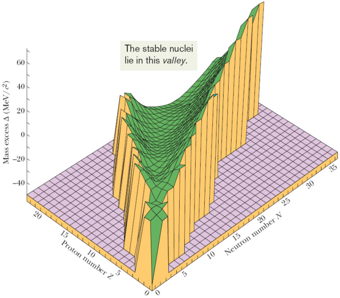
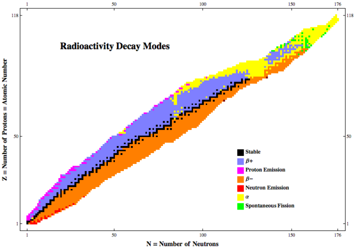


This data is from the Super-Kamiokande detector in Japan, 1000 m underground, holding 50,000 tons of ultra-pure water.

Radioactive Decay

Unstable nuclides decay toward stable ones over time; the nuclidic chart (abbreviated) helps understand how this works.





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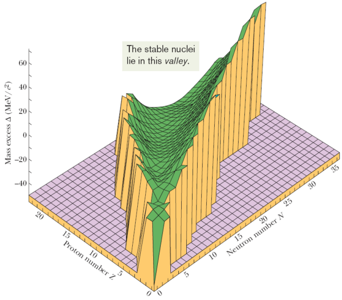
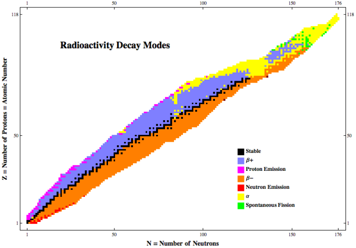
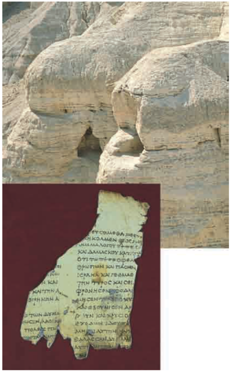

The stable nuclei lie in this *valley*.



Radioactive nuclides transform through alpha decay, beta decay, emission of protons or neutrons, or fission into daughter particles.

Radioactive Decay

Using the half-life of radioactive decay and measurements of various nuclides, we can date the age of objects.



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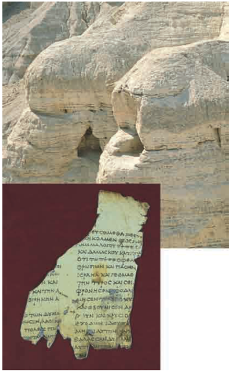

Radiocarbon dating places the age of the Dead Sea Scrolls from the West Bank at around 2,000 years old.

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- Absorbed Dose
  - Independent of type of radiation
  - 1 gray = 1 Gy = 1 J/kg
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  - Independent of type of radiation
  - 1 gray = 1 Gy = 1 J/kg
  - 1 Gy = 100 rad
- Dose Equivalent
  - Accounts for type of radiation for biological purposes
  - RBE factors (relative biological effectiveness)
  - 1 sievert = 1 Sv
  - 1 Sv = 100 rem

Radioactive Decay

There are two ways to measure radiation doses.

- Absorbed Dose
  - Independent of type of radiation
  - 1 gray = 1 Gy = 1 J/kg
  - 1 Gy = 100 rad
- Dose Equivalent
  - Accounts for type of radiation for biological purposes
  - RBE factors (relative biological effectiveness)
  - 1 sievert = 1 Sv
  - 1 Sv = 100 rem

Personal monitoring devices measure Dose Equivalent.

Radioactive Decay

Why does the nucleus behave like this?

- Collective Model
  - nucleons bounce around at random
  - short mean free path
  - helps describe nuclear reactions

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    - explains why some nuclei show “closed-shell effects”
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  - nucleons exist in stable quantum states
  - explains why some nuclei show “closed-shell effects”
  - collisions only occur for open quantum states
- Combined Model
  - combines features of previous models
  - shell of outside nucleons occupy quantized states
  - these nucleons interact with core and create “tidal waves”

Radioactive Decay

Lecture Question 10.2

When bismuth ^{211}Bi undergoes alpha decay, what nucleus is produced in addition to a helium nucleus?

(a) ^{207}Bi

(b) ^{207}Tl

(c) ^{209}Au

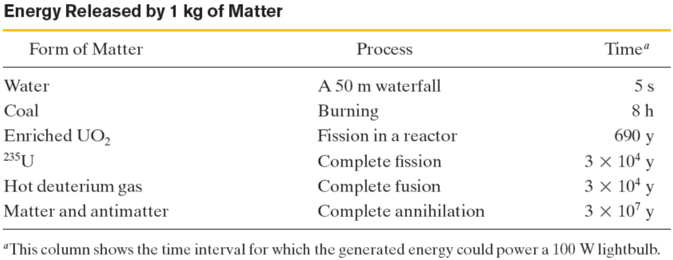
(d) ^{211}Au

(e) ^{209}Tl

The Nucleus
Radioactive Decay
Nuclear Fission
Nuclear Fusion

Nuclear Fission

Energy can be generated in a variety of ways.



Energy Released by 1 kg of Matter

Form of Matter	Process	Time[a]
Water	A 50 m waterfall	5 s
Coal	Burning	8 h
Enriched UO_2	Fission in a reactor	690 y
^{235}U	Complete fission	3×10^4 y
Hot deuterium gas	Complete fusion	3×10^4 y
Matter and antimatter	Complete annihilation	3×10^7 y

[a] This column shows the time interval for which the generated energy could power a 100 W lightbulb.

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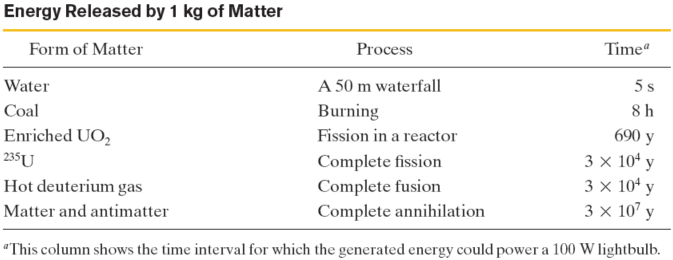

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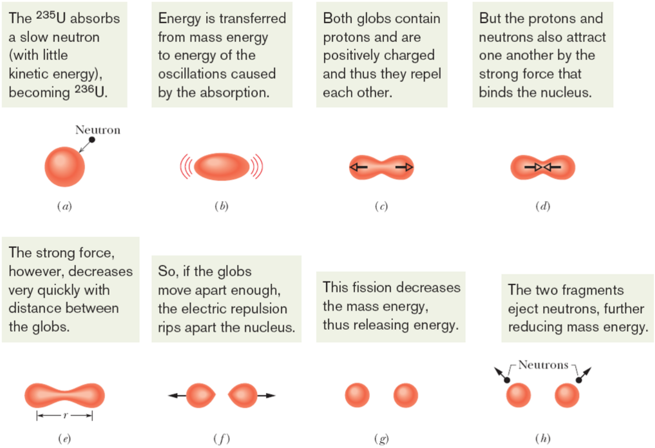
Nuclear reactions tend to release much more energy.

Nuclear Fission

Fission happens when a species becomes unstable.



The ^{235}U absorbs a slow neutron (with little kinetic energy), becoming ^{236}U.

Energy is transferred from mass energy to energy of the oscillations caused by the absorption.

Both globs contain protons and are positively charged and thus they repel each other.

But the protons and neutrons also attract one another by the strong force that binds the nucleus.

The strong force, however, decreases very quickly with distance between the globs.

So, if the globs move apart enough, the electric repulsion rips apart the nucleus.

This fission decreases the mass energy, thus releasing energy.

The two fragments eject neutrons, further reducing mass energy.

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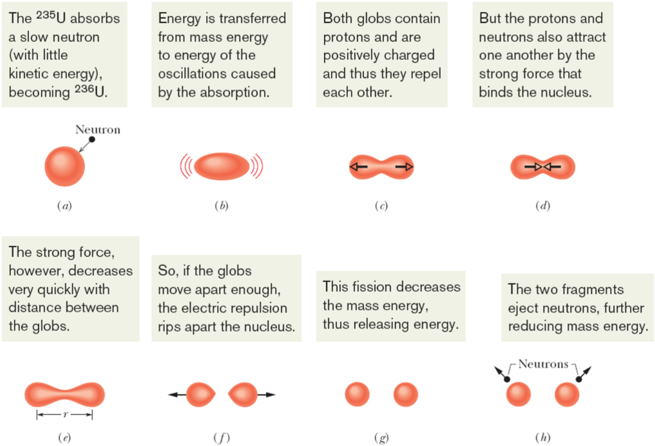

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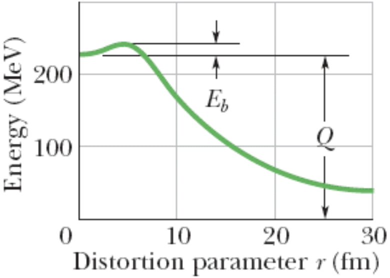
Energy is released by fast moving neutrons.

Nuclear Fission

As the nucleus distorts (r), the nuclide's potential energy varies.



Nuclear Fission

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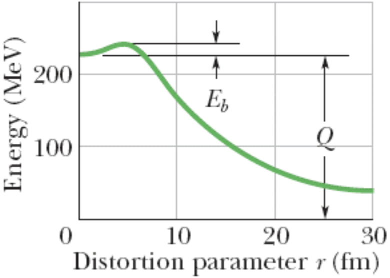
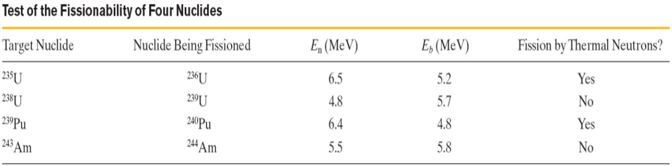


Once the distortion grows beyond ≈ 5 fm, the nuclear reaction occurs.

Nuclear Fission

When a neutron is captured, does the added energy exceed the potential barrier?



Test of the Fissionability of Four Nuclides

Target Nuclide	Nuclide Being Fissioned	E_n (MeV)	E_b (MeV)	Fission by Thermal Neutrons?
^{235}U	^{236}U	6.5	5.2	Yes
^{238}U	^{239}U	4.8	5.7	No
^{239}Pu	^{240}Pu	6.4	4.8	Yes
^{243}Am	^{244}Am	5.5	5.8	No

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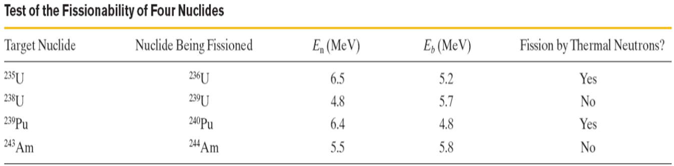

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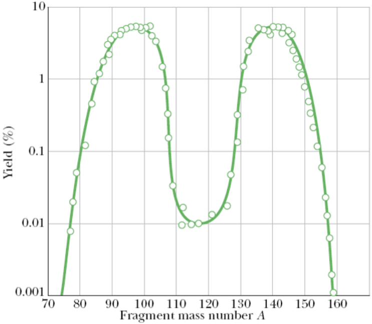
Only certain radionuclides are fissionable by neutron capture.

Nuclear Fission

When a radionuclide undergoes fission, its fragments can vary.



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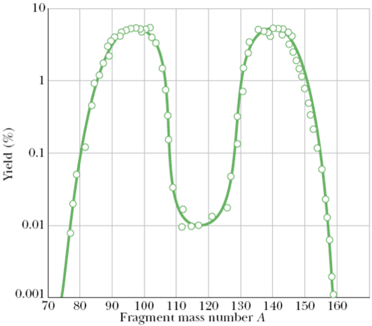

The most probable mass numbers are around $A \approx 95$ and $A \approx 140$.

Nuclear Fission

For $^{236}\mathrm{U}$*, when a neutron is ejected into a neighbor, we may get:*

$$^{235}\mathrm{U} + n + {}^{236}\mathrm{U} \longrightarrow {}^{140}\mathrm{Xe} + {}^{94}\mathrm{Sr} + 2n$$

Nuclear Fission

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But ^{140}Xe and ^{94}Sr are unstable and will decay further:

$$^{140}_{54}\mathrm{Xe} \xrightarrow{14\ \mathrm{s}} {}^{140}_{55}\mathrm{Cs} \xrightarrow{64\ \mathrm{s}} {}^{140}_{56}\mathrm{Ba} \xrightarrow{13\ \mathrm{d}} {}^{140}_{57}\mathrm{La} \xrightarrow{40\ \mathrm{h}} {}^{140}_{58}\mathrm{Ce}$$

$$^{94}_{38}\mathrm{Sr} \xrightarrow{75\ \mathrm{s}} {}^{94}_{39}\mathrm{Y} \xrightarrow{19\ \mathrm{m}} {}^{94}_{40}\mathrm{Zr}$$

Nuclear Fission

To calculate the energy released, you compare the binding energies before and after the reaction has completed.

$$Q = \sum_j \Delta E'_{ben,j} N'_j - \sum_i \Delta E_{ben,i} N_i$$

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- $\Delta E_{ben,i}$ is the binding energy per nucleon for species i
- N_i is the number of nucleons of species i
- Primes indicate after reaction
- Sum i is over initial nuclides (e.g., ^{236}U)
- Sum j is over final products (e.g., ^{140}Xe and ^{94}Sr)

Nuclear Fission

Consider previous example:

$$^{236}\mathrm{U} \longrightarrow {}^{140}\mathrm{Xe} + {}^{94}\mathrm{Sr} + 2n$$

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Nuclear Fission

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Binding energies: Uranium-236 (7.59 MeV), Xenon-140 (8.29 MeV) and Strontium-94 (8.59 MeV).

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$$\begin{aligned} Q &= \sum_j \Delta E'_{ben,j} N'_j - \sum_i \Delta E_{ben,i} N_i \\ &= (\Delta E_{^{140}Xe} \times 140 + \Delta E_{^{94}Sr} \times 94) - (\Delta E_{^{236}U} \times 236) \end{aligned}$$

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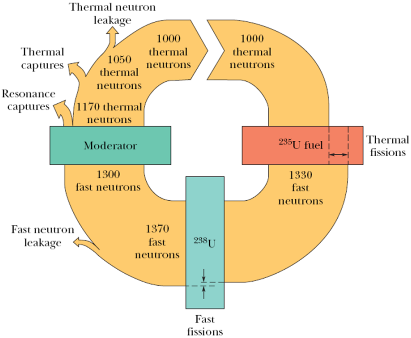
&= 8.29 \times 140 + 8.59 \times 94 - 7.59 \times 236 \\
&= 177 \text{ MeV}
\end{aligned}$$

Binding energies: Uranium-236 (7.59 MeV), Xenon-140 (8.29 MeV) and Strontium-94 (8.59 MeV).

Nuclear Fission

A nuclear reactor must operate in a stable configuration by managing neutron number and speed.



Nuclear Fission

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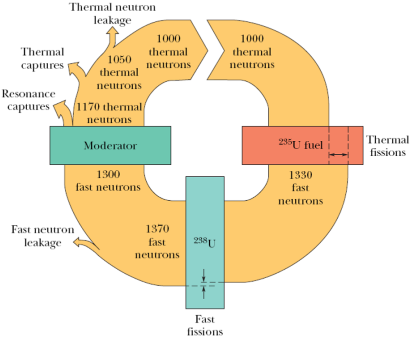


For fission, fast neutrons are not as effective as slow, thermal neutrons.

Nuclear Fission

The first man-made reactor was built on a squash court at the University of Chicago during World War II.

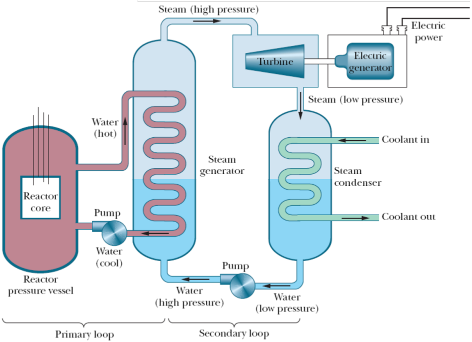
Nuclear Fission

The first man-made reactor was built on a squash court at the University of Chicago during World War II.

The fuel was lumps of Uranium embedded in blocks of graphite.

Nuclear Fission

So you spit a bunch of atoms. Now what?



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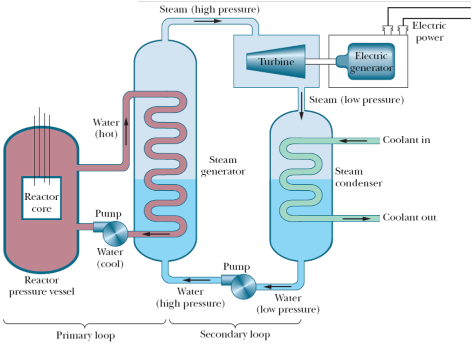


You heat water!

Nuclear Fission

Lecture Question 10.3

How many neutrons are released in the following reaction:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{88}_{38}\mathrm{Sr} + ^{136}_{54}\mathrm{Xe} + \underline{}\,^{1}_{0}\mathrm{n}$$

(a) 1

(b) 3

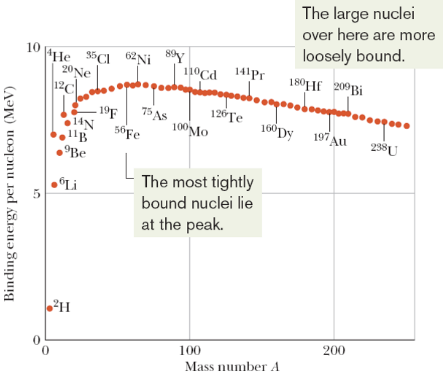
(c) 6

(d) 8

(e) 12

Nuclear Fusion

Nuclear fusion combines lighter atoms (with low ΔE_{ben}) to form heavier atoms (with higher ΔE_{ben}).

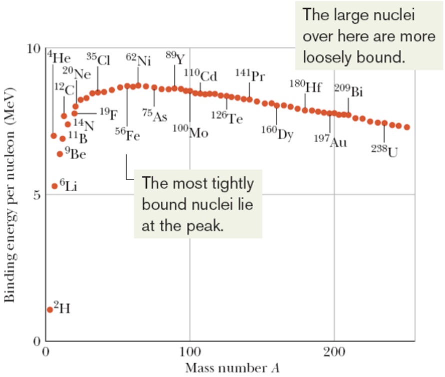


The large nuclei over here are more loosely bound.

The most tightly bound nuclei lie at the peak.

Nuclear Fusion

Nuclear fusion combines lighter atoms (with low ΔE_{ben}*) to form heavier atoms (with higher* ΔE_{ben}*).*



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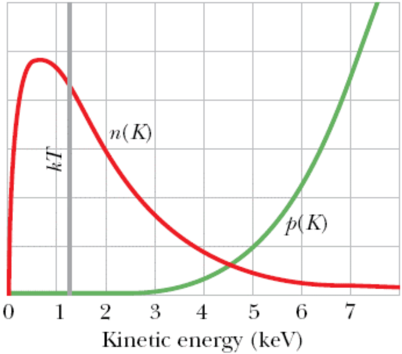
The most tightly bound nuclei lie at the peak.

Combining hydrogen into helium is how our sun produces so much energy.

Nuclear Fusion

Thermonuclear fusion is when the temperature of bulk matter is high enough for atoms to overcome Coulomb repulsion during collisions.



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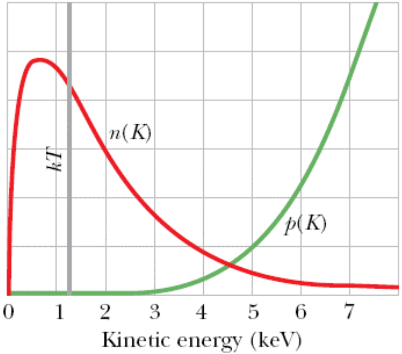
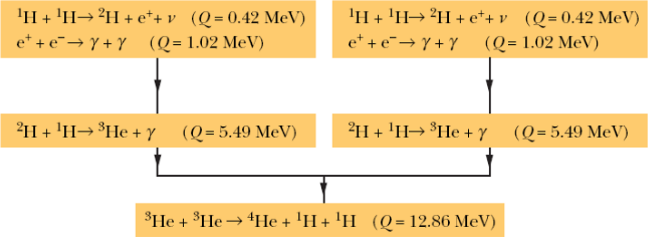


In the sun, hydrogen above 3 keV has an appreciable chance to fuse.

Nuclear Fusion

In the sun, six ^{1}H *atoms and an electron can produce one* ^{4}He *atom, two* ^{1}H *atoms, six photons and two neutrinos.*



$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu \quad (Q = 0.42\text{ MeV})$

$e^{+} + e^{-} \rightarrow \gamma + \gamma \quad (Q = 1.02\text{ MeV})$

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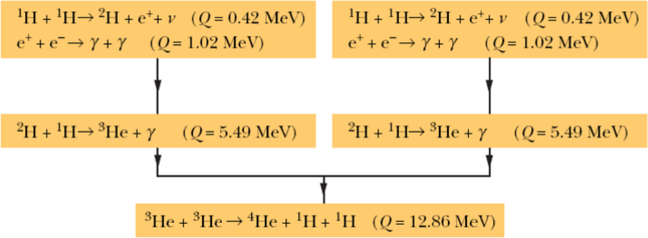

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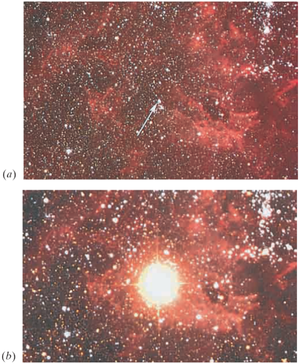
This proton-proton chain produces 26.7 MeV total.

Nuclear Fusion

When a star burns most of its hydrogen, it either begins to fuse Helium to create heavier elements, or begins to contract and die.



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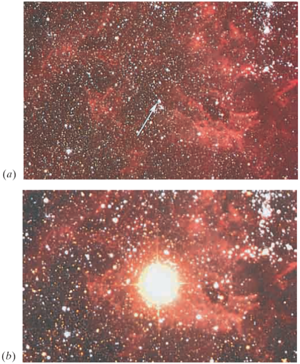

For very massive stars (e.g., Sanduleak), this death can result in a supernova followed by a neutron star, pulsar, black hole or total disintegration.

Nuclear Fusion

A controlled thermonuclear fusion reaction is possible using one of the following chains:

$$\begin{aligned}
{}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\xrightarrow{+3.27\ \mathrm{MeV}} {}^{3}\mathrm{He} + \mathrm{n} \\
{}^{2}\mathrm{H} + {}^{2}\mathrm{H} &\xrightarrow{+4.03\ \mathrm{MeV}} {}^{3}\mathrm{H} + {}^{1}\mathrm{H} \\
{}^{2}\mathrm{H} + {}^{3}\mathrm{H} &\xrightarrow{+17.59\ \mathrm{MeV}} {}^{4}\mathrm{He} + \mathrm{n}
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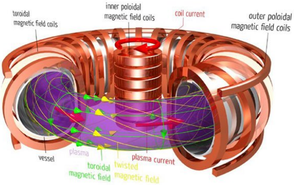
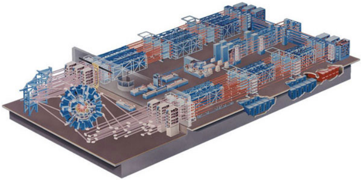
Requirements:

- High density
- High temperature
- Long confinement time

Nuclear Fusion

Nuclear fusion has two main research paths.





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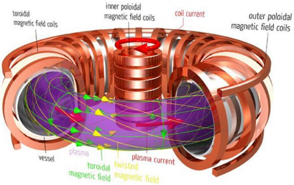
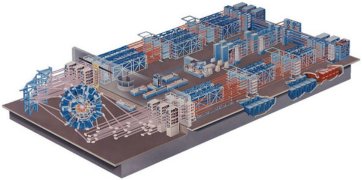
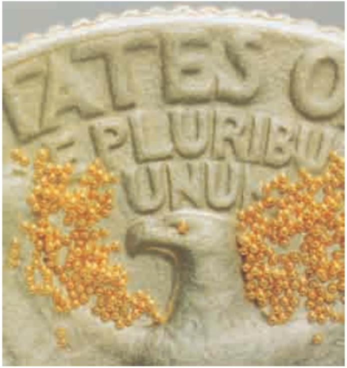




Magnetic confinement of hot plasma, and laser confinement of fuel pellets.

Nuclear Fusion

Deuterium (^{2}H) *and tritium* (^{3}H) *occur naturally in abundance and can be harvested from sea water.*



Nuclear Fusion

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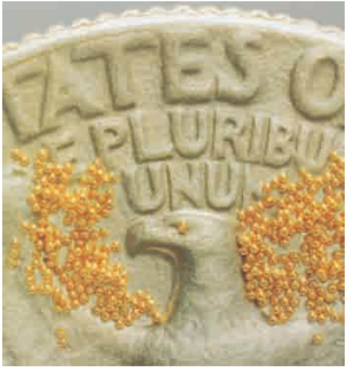

Formed into pellets, they can be fused via laser confinement.

Nuclear Fusion

Lecture Question 10.4

Consider the following nuclear fusion reaction and identify particle X.

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \longrightarrow ^{4}_{2}\mathrm{He} + \mathrm{X}$$

- **(a)** a photon
- **(b)** a proton
- **(c)** a neutron
- **(d)** a positron
- **(e)** an electron