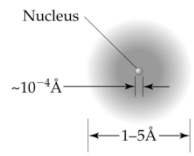
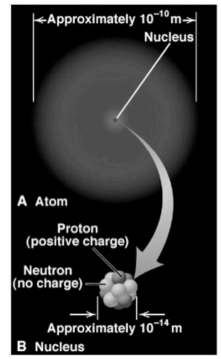
Nuclear Chemistry

General Features of the Atom

Anders Jöns Ångström
(1814-1874)
1 Å = 10 picometers = 0.1 nanometers = 10^{-4} microns = 10^{-8} centimeters





~ 0.1 nm

Nucleus = 1/10,000 of the atom

- *1 nm = 10 Å*
- *An atom vs. a nucleus ~10,000 x larger*

NUCLEAR CHEMISTRY

- *Nuclear Particles:*

	Mass	*Charge*	*Symbol*
PROTON	*1 amu*	*+1*	*H+, ${}^{1}_{1}H$, ${}^{1}_{1}p$*
NEUTRON	*1 amu*	*0*	*${}^{1}_{0}n$*

Atomic Identity & Mass

Atomic Number and Mass

- ***Carbon-13***
- *Atomic Number = 6 (atom's identity)*
- *Atomic Mass = 13 (isotope 13; C-13 or 13-C or ${}^{13}C$)*
- *6 protons; # neutrons = 13 - 6 = 7*
- *Symbol:*

$${}^{13}_{6}C$$

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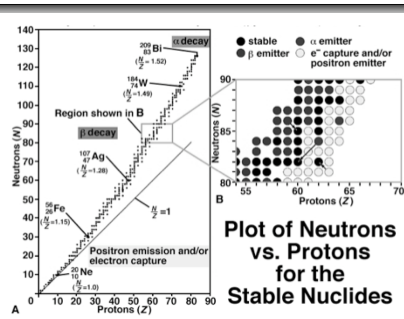
http://www.nndc.bnl.gov/chart/

Nuclides



Number of Stable Nuclides

Elements 48 through 54

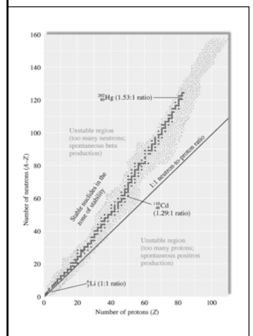
Element	Atomic Number (*Z*)	Number of Nuclides
Cd	**48**	**8**
In	49	2
Sn	**50**	**10**
Sb	51	2
Te	**52**	**8**
I	53	1
Xe	**54**	**9**

Magic numbers are 2, 8, 20, 28, 50, or 82 protons or neutrons.
Even numbers of protons and neutrons are more stable than odd.

Distribution of Stable Nuclides

Protons	Neutrons	Stable Nuclides	%
Even	Even	157	58.8
Even	Odd	53	19.9
Odd	Even	50	18.7
Odd	Odd	7	2.6
	Total =	267	100.0%

QUESTION



A nuclide made of 75 protons and 130 neutrons would most likely exhibit which of the following properties?

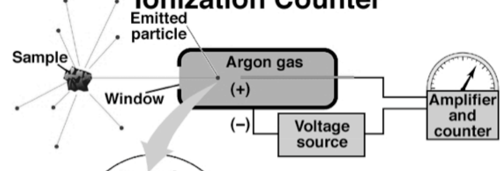
A. Stable (not radioactive).
B. Change into another nuclide with a higher *Z* value
C. Change into another nuclide with a lower *Z* value
D. Keep the same *Z* value with a higher isotopic mass.

Nuclear Decay / Radioactivity

- Unstable nuclei “decay” i.e. they lose particles which lead to other elements and isotopes.
- The elements and isotopes produced may also be unstable and go through further decay.

■ Nuclear decay reactions conserves mass.

Detection of Radioactivity by an Ionization Counter



Nuclear Particles emitted from unstable nucleii

- Emitted Particles:

	Mass	Charge	Symbol
alpha particle	4 amu	+2	$^{4}_{2}He^{2+}$; $(^{4}_{2}He)$; $^{4}_{2}\alpha$
beta particle	very small	-1	$^{0}_{-1}e$ $^{0}_{-1}\beta$
gamma	very very small	0	γ
positron	very small	+1	$^{0}_{+1}\beta$

QUESTION

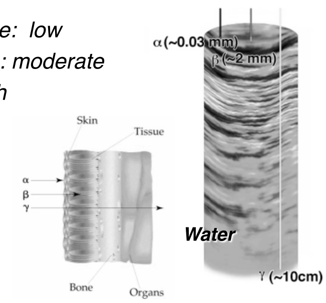
What should be placed in the blank to balance the following nuclear equation:

$$^{15}_{8}O \rightarrow ^{15}_{7}N + \_\_\_$$

A. Gamma ray
B. Alpha particle
C. Positron
D. $^{0}_{-1}\beta$

Nuclear Penetrating Power

- alpha particle: low
- beta particle: moderate
- gamma: high
- X-rays?



http://www.civildefensemuseum.com/southrad/conversion.html

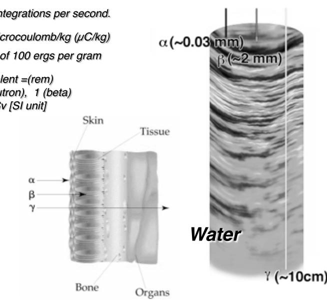
Nuclear Energy Units

1 curie = 37 billion disintegrations per second.

1 roentgen (R) = 258 microcoulomb/kg (μC/kg)

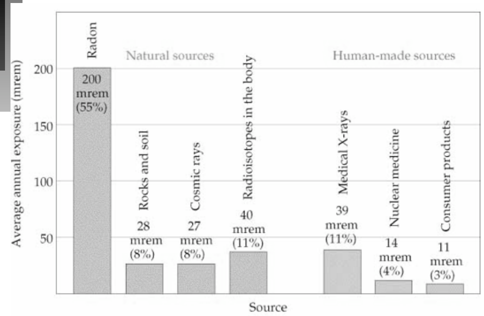
1 rad is the absorption of 100 ergs per gram

Rad x Q = dose equivalent =(rem)
Q = 20 (alpha), 10 (neutron), 1 (beta)
1 rem = 0.01 Sievert Sv [SI unit]



Exposure to Radiation

100 mrem = 1 mSv



QUESTION

Which of the following is not a factor in determining the biological effects of radiation exposure?

A) The energy of the radiation
B) The age of the organism at which the exposure occurs
C) The penetrating ability of the radiation
D) The chemical properties of the radiation source
E) The ionizing ability of the radiation

NUCLEAR STABILITY
Patterns of Radioactive Decay

- Alpha decay (α) –**heavy isotopes**
- Beta decay (β^-) –**neutron rich isotopes**
- Positron emission (β^+)–**proton rich isotopes**
- Electron capture–**proton rich isotopes**

x-rays

- Gamma-ray emission (γ)
- Spontaneous fission–**very heavy isotopes**

Alpha Decay–Heavy Elements

- $^{238}U \rightarrow {}^{234}Th + \alpha + e$
  $t_{1/2} = 4.48 \times 10^9$ years
- $^{210}Po \rightarrow {}^{206}Pb + \alpha + e$
  $t_{1/2} = 138$ days
- $^{256}Rf \rightarrow {}^{252}No + \alpha + e$
  $t_{1/2} = 7$ ms

For Cobalt 60 predict the alpha decay product:

$^{60}_{27}Co$ ---->$^{4}_{2}He$ + ?

Beta Decay–Electron Emission

- $n \rightarrow p^+ + \beta^- +$ Energy

- $^{14}C \rightarrow {}^{14}N + \beta^- +$ Energy
  $t_{1/2}$= 5730 years
- ? $\rightarrow {}^{90}Y + \beta^- +$ Energy
  $t_{1/2}$= 30 years
- $^{247}Am \rightarrow {}^{247}Cm + \beta^- +$ Energy
  $t_{1/2}$= 22 min
- $^{131}I \rightarrow$? $+ \beta^- +$ Energy
  $t_{1/2}$ = 8 days

Electron Capture–Positron Emission

$p^+ + e^- \rightarrow n$ + Energy = Electron capture

$^{51}Cr + e^- \rightarrow {}^{51}V$ + Energy

$t_{1/2}$ = 28 days

$p^+ \rightarrow n + e^+$ + Energy = Positron emission

$^{7}Be \rightarrow {}^{7}Li + \beta^+$ + Energy

$t_{1/2}$ = 53 days

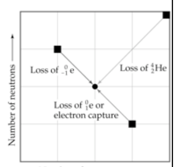
? $+ e^- \rightarrow {}^{177}Ir$ + Energy

$^{144}Gd \rightarrow$? $+ \beta^+$ + Energy

Nuclear Decay

Predict the Particle or element:

- *Thallium 206 decays to Lead 206. What particle is emitted?*
- *Cesium 137 goes through Beta decay. What element is produced and what is its mass?*
- *Thorium 230 decays to Radium 226. What particle is emitted?*



QUESTION

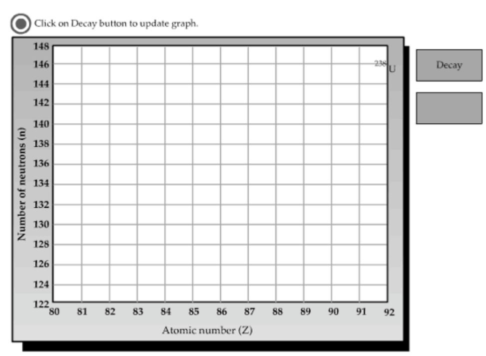
In a particular nuclear decay scheme, a nuclide releases an alpha particle, a beta particle and eventually another alpha particle. Which of the following correctly predicts the resulting effect on the mass and the atomic number of the original nuclide?

A. The atomic mass number decreases by 7; *Z* decreases by 4.
B. The atomic mass number decreases by 8; *Z* decreases by 4.
C. The atomic mass number decreases by 5; *Z* decreases by 8.
D. The atomic mass number decreases by 8; *Z* decreases by 5.

Nuclear Decay Series

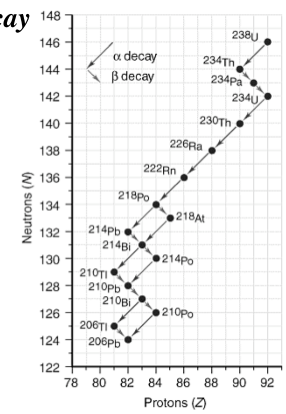
- *If the nuclei produced from radioactive decay are unstable, they continue to decay until a stable isotope results.*
- *An example is Radium which produces Lead*

$$^{226}_{88}Ra \text{-->} \text{-->} \text{-->} \text{-->} {}^{206}_{82}Pb$$



http://chemconnections.org/general/movies/U-238DecaySeries/U-238DecaySeries.html

The ^{238}U Decay Series



Nuclear Decay Measurement

- *Decay can be measured with an instrument that detects "disintegrations". The rate can be obtained by "counting" them over a period of time. e.g. disintegrations / second (dps)*
- *The rate of decay follows first order kinetics*
- *The rate law produces the following equation for the half life:*

$$t_{1/2} = 0.693 / k$$

QUESTION

The rate constant for the beta decay of thorium-234 is 2.88 × 10^{-2}/day. What is the half-life of this nuclide?

A) 53.1 days
B) 1.22 days
C) 0.693 days
D) 24.1 days
E) 101 days

Radiodating Methods

- *Three isotopes are currently used:*
  Carbon-14 half life 5,730 yrs
  Potassium-40 half life 1.3 x 10^9 yrs
  Uranium-238 half life 4.47 x 10^9 yrs
- *The age of samples can be determined by using their respective rate constants and the following equation:*

$$\ln\left[\frac{A}{A_0}\right] = -kt$$

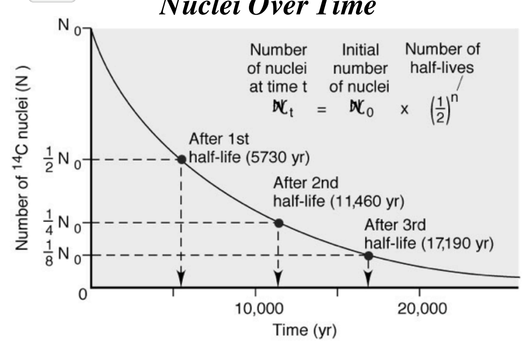
NOTE: Many other methods are employed which use various isotopic ratios

QUESTION

Iron is found in hemoglobin in humans and mammals. Iron–59 (a beta emitter) is used in several protocols that study red blood cells. The half-life of the nuclide is approximately 45.1 days. If Ed Viesturs received a dose of iron–59 at base camp during his ascent of Mt. Everest without bottled oxygen, what theoretical percent would remain in his system after 30.0 days assuming his body did not excrete any of the administered dose?

A. 35.3% remains
B. 63.1% remains
C. 66.5% remains
D. 158%

Decrease in Number of ^{14}C Nuclei Over Time

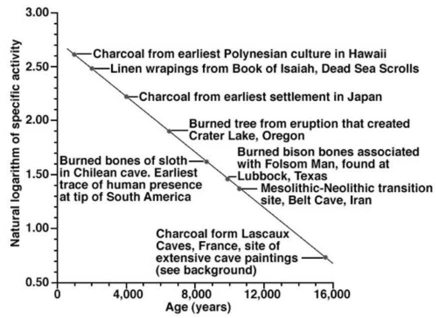


QUESTION

The number of half-lives needed for a radioactive element to decay to about 6% of its original activity is (choose nearest number):

A) 2
B) 3
C) 4
D) 5
E) 6

Radiocarbon Dating for Determining the Age of Artifacts



QUESTION

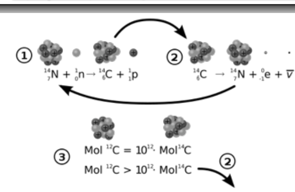
In an archeological dig an ancient looking wood fragment arrangement is thought to be the remains of a campfire. A small sample is dated using radiocarbon techniques. All wood is radioactive, but how radioactive (in betas/minute/gram) would the sample be if it were 7 500 years old? Note: the half-life of C–14 is 5 730 years and current carbon samples typically average 13.6 counts per minute per gram.

A. 34 CPM/g
B. 4.7 CPM/g
C. 5.5 CPM/g
D. Less than 1 CPM/g

Radiocarbon: Biological Steady State

Geo- Biogenesis of ^{14}C in living organisms

http://en.wikipedia.org/wiki/Radiocarbon_dating



#1: Formation of Carbon-14 in the upper atmosphere
#2: Beta decay of Carbon-14
#3: $^{14}C/^{12}C$ in living organisms; [Photosynthesis produces a steady state ratio of $^{14}C/^{12}C$ while living.]
In dead organisms, C-14 decays by first order kinetics as in #2; the ratio and concentration of C-14 decreases following a first order rate law.

QUESTIONS

The half-life of C–14 is accepted as 5730 years with carbon samples disintegrating on average at 13.6 counts per minute per gram.

These values are fixed by the reaction kinetics and are constants that will not change.

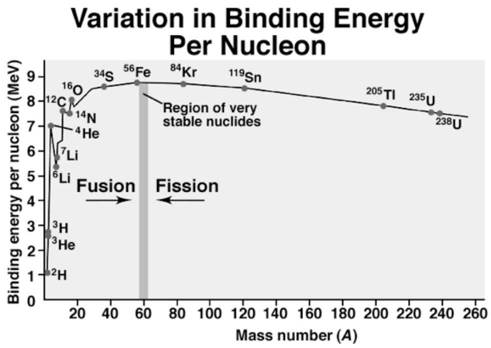
A. TRUE B. FALSE

The ratio of $^{14}C/^{12}C$ taken up by plants in photosynthesis has been constant from millions of years ago to today.

A. TRUE B. FALSE

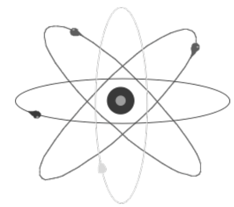
Nuclear Reactions

- *The mass of the visible universe is 73% H_2 and 25% He. The remaining 2%, "heavy" elements, have atomic masses >4.*
- *The "heavy" elements are formed at very high temperatures ($T>10^6$ °C) by FUSION, i.e. nuclei combining to form new elements.*
- *There is an upper limit to the production of heavy nuclei at A=92, Uranium.*
- *Heavy nuclei split to lighter ones by FISSION*



NUCLEAR ENERGY

- *EINSTEIN'S EQUATION FOR THE CONVERSION OF MASS INTO ENERGY*
- $E = mc^2$
- m = *mass (kg)*
- c = *Speed of light*
  c = *2.998 x 10^8 m/s* ($c = 2.998 \times 10^8$ m/s)



Mass ⇔ Energy

Electron volt (ev)

The energy an electron acquires when it moves through a potential difference of one volt:

Slide 9

$1\ ev = 1.602 \times 10^{-19} J$

Binding energies are commonly expressed in units of *megaelectron volts* (Mev)

$1\ Mev = 10^6\ ev = 1.602 \times 10^{-13} J$

A particularly useful factor converts a given mass defect in atomic mass units to its energy equivalent in electron volts:

$1\ amu = 931.5 \times 10^6\ ev = 931.5\ Mev$

Calculating Binding Energy eg. per Nucleon of Deuterium

GIVEN: Deuterium has a mass of 2.01410178 amu.

Hydrogen atom mass = 1 x 1.007825 amu = 1.007825 amu
Neutron mass = 1 x 1.008665 amu = 1.008665 amu
2.016490 amu

Mass difference = theoretical mass - actual mass
= 2.016490 amu - 2.01410178 amu = **0.002388 amu**

Calculating the binding energy per nucleon:

$$\frac{\text{Binding energy}}{\text{Nucleon}} = \frac{-0.002388 \text{ amu} \times 931.5 \text{ Mev/amu}}{2 \text{ nucleons}}$$

= **-1.1123 Mev/nucleon**

QUESTION

The Fe–56 nuclide is one of the most stable known. Given the following information, calculate the binding energy per nucleon for this important nuclide. The mass of Fe–56 nucleus = 55.90421 amu. The mass of a proton = 1.0078 amu; and the mass of a neutron = 1.0087 amu.

(1.66×10^{-27}kg = 1 amu;
$c = 3.00 \times 10^8$ m/s 1 MeV = 1.60×10^{-13} J)

A. 9.3 MeV/n
B. 3.1×10^{-9} MeV/n
C. 20.0 Mev/n
D. This involves $E = mc^2$, but I do not get any of these answers.

Practice problems with solutions:
http://chemconnections.org/general/chem121/Problems%20calculating%20mass%20defect.pdf

QUESTIONS

In accurately calculating the binding energy per nucleon for any atom the number of significant figures in mass numbers can be four or larger.

A) TRUE B) FALSE

In accurately calculating the binding energy per nucleon for any atom the number of decimal places in mass numbers can be four or larger.

A) TRUE B) FALSE

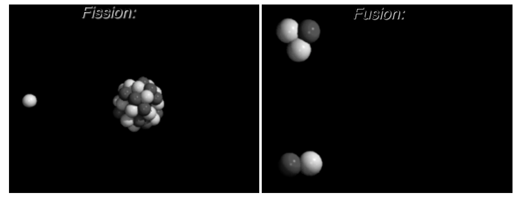
http://physics.nist.gov/cgi-bin/Compositions/stand_alone.pl

Nuclear Reactions

- *Fission and Fusion reactions are highly exothermic (1 Mev / nucleon).*
- *This is 10 ^{6} times larger than "chemical" reactions which are about 1 ev / atom.*
- *Nuclear fission was first used in a chain reaction:*

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n$$

Nuclear Reactions:



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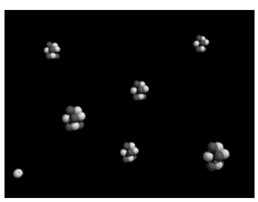
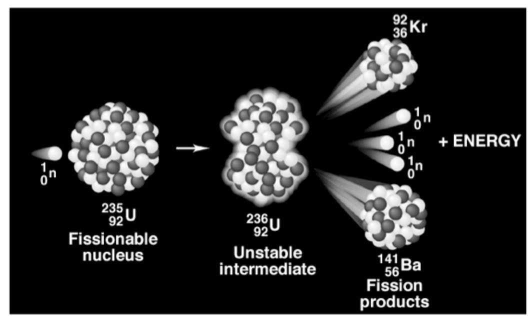
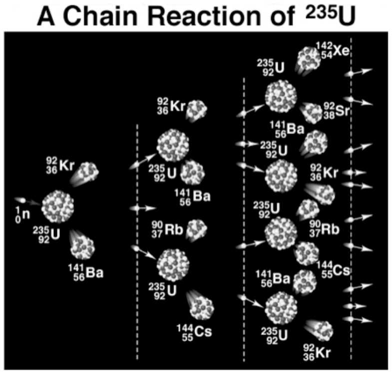


Induced Fission of ^{235}U



A Chain Reaction of ^{235}U



Nuclear Reactions / Fission

- *The Fission Chain Reaction proceeds geometrically: 1 neutron -> 3 -> 9 -> 27 -> 81 etc.*
- *1 Mole of U-235 (about 1/2 lb) produces 2 x 10^{10} kJ which is equivalent to the combustion of 800 tons of Coal!*
- *Commercial nuclear reactors use fission to produce electricity....Fission bombs were used in the destruction of Hiroshima and Nagasaki, Japan, in August 1945.*

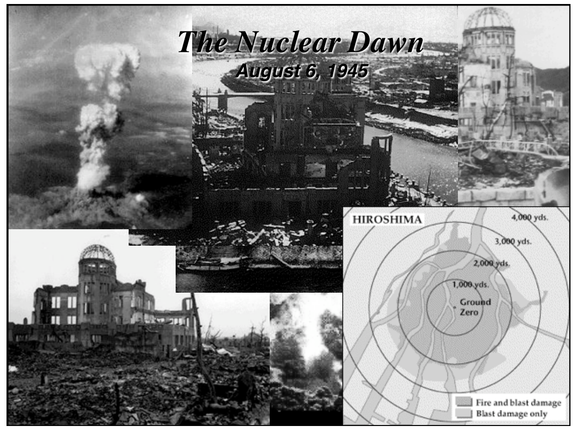
Nuclear Reactions / Fission

President Truman / Hiroshima

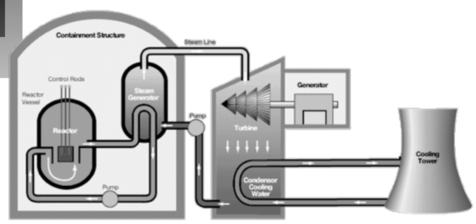
http://hiroshima.mapping.jp/ge_en.html

August 6, 1945

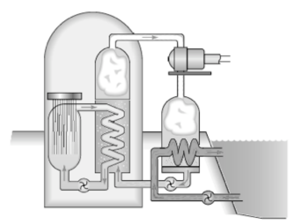
http://hiroshima.mapping.jp/ge_en.html



Nuclear Power Plant



Nuclear Power Plant

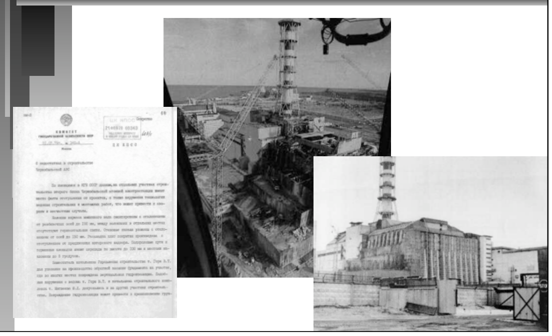


http://chemconnections.org/general/movies/NuclearPowerPlant/NuclearPowerPlant.html

Worldwide Nuclear Power Plants

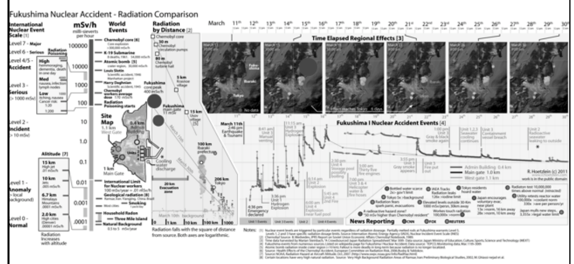
Chernobyl, Ukraine

April,1986 and April,2001



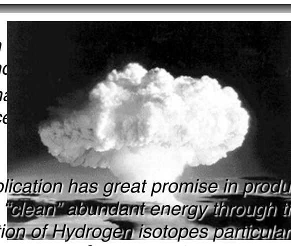
Nuclear Plant Disaster
March 2011
Fukushima, Japan

Fukushima Radiation



1 millisievert (mSv) = 100 mrem
0.01 Sievert (Sv) = 1 rem

Nuclear Reactions / Fusion

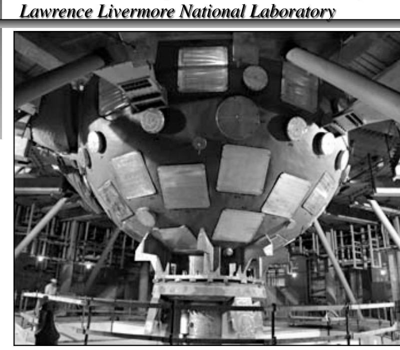


- *Fusion ... try of the sun and ...*
- *It too ha... t yet found a peace...*

■*The application has great promise in producing relatively "clean" abundant energy through the combination of Hydrogen isotopes particularly from ^2H, deuterium and ^3H, tritium: (NIF/National Ignition Facility, LLNL & ITER, France)*

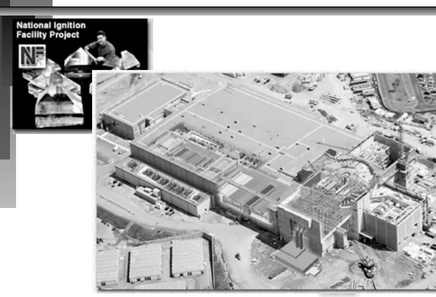
$$^2H + ^3H \rightarrow ^4He + ^1_0n + 18.38MeV$$

National Ignition Facility
Lawrence Livermore National Laboratory



Crystals for the Classroom
http://crystals.llnl.gov

National Ignition Facility
Lawrence Livermore National Laboratory



https://lasers.llnl.gov/

Hydrogen Burning in Stars and Fusion Reactions

$^1H + ^1H \rightarrow$ $^2H + \beta^+ + 1.4$ Mev

$^1H + ^2H \rightarrow$ $^3He + 5.5$ Mev

$^2H + ^2H \rightarrow$ $^3He + ^1n + 3.3$ Mev

$^2H + ^2H \rightarrow$ $^3H + ^1H + 4.0$ mev

$^2H + ^3H \rightarrow$ $^4He + ^1n + 17.6$ Mev ← Easiest! Highest cross-section!

$^2H + ^3He \rightarrow$ $^4He + ^1H + 18.3$ Mev

ITER: International Thermonuclear Experimental Reactor

Research and engineering project which is currently building the world's largest and most advanced experimental tokamak nuclear fusion reactor in the south of France.

iter

china eu india japan korea russia usa

http://www.iter.org/

QUESTION

How much energy is released when 2.50 metric tons of $^2H_2$ gas undergoes the following nuclear fusion reaction?

$$^2H + ^2H \rightarrow ^3He + ^1n$$

(1 metric ton = 1000 kg, c = 2.9979 × 10^8 m/s, 1 amu = 1.66054 × 10^{-27} kg)

Particle	Mass (amu)	
Neutron	1.008665	A. 3.69 × 10^{17} J B. 5.42 × 10^{-18} J
^2H	2.01400	C. 5.39 × 10^{64} J D. 1.84 × 10^{17} J
^3He	3.01603	E. 1.34 × 10^{71} J

Helium "Burning" Reactions in Stars

$^{12}C + ^4He \rightarrow ^{16}O$

$^{16}O + ^4He \rightarrow ^{20}Ne$

$^{20}Ne + ^4He \rightarrow ^{24}Mg$

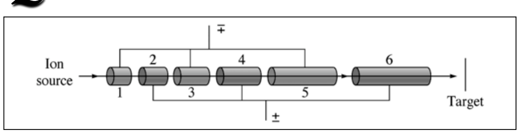
$^{24}Mg + ^4He \rightarrow ^{28}Si$

$^{28}Si + ^4He \rightarrow ^{32}S$

$^{32}S + ^4He \rightarrow ^{36}Ar$

$^{36}Ar + ^4He \rightarrow ^{40}Ca$

QUESTION



Uranium–238 can be transformed into Californium–244 if it is correctly bombarded by carbon–12. What else would be emitted as the californium forms?

A. Two alpha particles
B. Six neutrons
C. Three beta particles
D. Six beta particles