NUCLEAR CHEMISTRY

IN ONE HOUR!

Outline

1. Nuclear Periodic Table
   - A. Predict decay modes
   - B. Valley of Stability
   - C. Binding Energy/A
2. Radioactivity
   - A. Alpha decay
   - B. Beta minus decay
   - C. Beta plus decay
   - D. Gamma decay
   - E. Other decay modes
   - F. Kinetics of radioactive decay
3. Nuclear Reactions
   - A. Simple reactions
     - i. Why do we need accelerators?
   - B. Fission
   - C. Fusion
4. Your Choice
   - A. Nuclear energy
   - B. Nuclear weapons
   - C. Nucleosynthesis
   - D. History of nuclear science

NUCLIDE CLASSIFICATIONS

1. **Stable nuclides -do not undergo radioactive decay**
   a. 264 known stable nuclides
   b. examples: ^{12}C, ^{4}He, ^{2}H, ^{208}Pb , etc.

2. **Primary radionuclides -radioactive and have been here on Earth since it was formed**
   a. Have long half-lives, $t_{1/2}$
   b. 26 primary radionuclides are known
   c. examples: ^{238}U- $t_{1/2} = 4.5 \times 10^9$ yr , ^{40}K- $t_{1/2} = 1.3 \times 10^9$ yr , ^{87}Rb $t_{1/2} = 4.8 \times 10^{10}$ yr

3. **Secondary natural radionuclides -radioactive nuclides formed from the decay of primary radionuclides**
   a. $t_{1/2}$ too short for them to have been here since Earth formed
   b. 38 secondary radionuclides are known
   c. examples: ^{226}Ra $t_{1/2} = 1600$ yr, ^{234}Th $t_{1/2} = 24.1$ days, ^{222}Rn $t_{1/2} = 8.0$ days

NUCLIDE CLASSIFICATIONS

4. induced natural radionuclides -formed by cosmic rays

a. induced radionuclides have a short $t_{1/2}$ but are continuously formed by cosmic ray interactions with terrestrial nuclides

b. 10 induced radionuclides are known

c. examples: ^{3}H - $t_{1/2}$ = 12.3 yr , ^{14}C- $t_{1/2}$ = 5730 yr

d. ^{3}H and ^{14}C formed from cosmic rays interacting with ^{14}N in the stratosphere

5. artificial radionuclides –all are man made by nuclear reactions

a. artificial radionuclides have a variety of $t_{1/2}$'s
b. more than 2000 artificial radionuclides are known

c. examples: ^{60}Co - $t_{1/2}$ = 5.27 yr, ^{137}Cs - $t_{1/2}$ = 30.1 yr, ^{24}Na - $t_{1/2}$ = 14.96 hr

NUCLIDE CLASSIFICATIONS

6. Mass classifications of nuclides

a. **Isotopes –nuclides that have equal numbers of protons**
   ^{12}C, ^{13}C, ^{14}C

b. **Isotones - nuclides that have equal numbers of neutrons**
   ^{14}C, ^{15}N, ^{16}O

c. **Isobars - nuclides that have equal mass numbers**
   ^{11}B, ^{11}C, ^{11}N

d. **Isomers – nuclides with the same Z, N, and A but different excitations ^{99}Tc or $^{99}Tc^{*}$ and $^{99\text{-}m}Tc$**
   1) usually have a relatively long difference in $t_{1/2}$
   2) $^{99\text{-}m}Tc$ $t_{1/2}$ = 6.02 hr
   3) ^{99}Tc- $t_{1/2}$ = 2 x 10^5yr

Nuclear Periodic Table

16											S 26 0.012s	S 27 0.021s	S 28 0.125s	S 29 0.187s	S 30 1.178s
15											P 25 0.0368s	P 26 0.0437s	P 27 0.26s	P 28 0.2703s	P 29 4.142s
14									Si 22 0.029s	Si 23 0.0423s	Si 24 0.14s	Si 25 0.22s	Si 26 2.234s	Si 27 4.16s	Si 28 92.2297
13									Al 21 0.0428s	Al 22 0.0911s	Al 23 0.446s	Al 24 2.053s	Al 25 7.183s	Al 26 7.17e+05y	Al 27 100
12								Mg 19 4e-12s	Mg 20 0.0908s	Mg 21 0.122s	Mg 22 3.875s	Mg 23 11.32s	Mg 24 78.99	Mg 25 10	Mg 26 11.01
11								Na 18 0.0347s	Na 19 0.435s	Na 20 0.4479s	Na 21 22.49s	Na 22 2.603y	Na 23 100	Na 24 15h	Na 25 59.1s
10							Ne 16	Ne 17 0.1092s	Ne 18 1.666s	Ne 19 17.22s	Ne 20 90.48	Ne 21 0.27	Ne 22 9.25	Ne 23 37.24s	Ne 24 3.38m
9							F 15 0.14s	F 16 1e-19s	F 17 1.075m	F 18 1.83h	F 19 100	F 20 11.16s	F 21 4.158s	F 22 4.23s	F 23 2.23s
8						O 12	O 13 0.00858s	O 14 1.177m	O 15 2.037m	O 16 99.757	O 17 0.038	O 18 0.205	O 19 26.88s	O 20 13.51s	O 21 3.42s	O 22 2.25s
7						N 11 0.09s	N 12 0.011s	N 13 9.965m	N 14 99.632	N 15 0.368	N 16 7.13s	N 17 4.173s	N 18 0.619s	N 19 0.271s	N 20 0.13s	N 21 0.095s
6			C 8	C 9 0.1265s	C 10 19.31s	C 11 20.39m	C 12 98.93	C 13 1.07	C 14 5700y	C 15 2.449s	C 16 0.747s	C 17 0.193s	C 18 0.092s	C 19 0.049s	C 20 0.014s
5				B 8 0.77s	B 9 8.5e-19s	B 10 19.9	B 11 80.1	B 12 0.0202s	B 13 0.01736s	B 14 0.0125s	B 15 0.0105s		B 17 0.00508s		B 19 0.00292s
4				Be 7 53.22d	Be 8 6.7e-17s	Be 9 100	Be 10 1.51e+06y	Be 11 13.81s	Be 12 0.0213s		Be 14 0.00484s				
3				Li 6 7.59	Li 7 92.41	Li 8 0.8399s	Li 9 0.1783s		Li 11 0.0087s						
2		He 3 0.000137	He 4 99.9999		He 6 0.8067s		He 8 0.1191s								
1	H 1 99.9885	H 2 0.0115	H 3 12.32y												
0		n 1 10.23m													

protons

neutrons

Nuclear Periodic Table

Isotopes – nuclei with constant Z

- ^{9}C, ^{10}C, ^{11}C, ^{12}C, ^{13}C, ^{14}C, ^{15}C, ^{16}C, ^{17}C, ^{18}C, ^{19}C, ^{20}C

Isotones – nuclei with constant N

- ^{11}Li, ^{12}Be, ^{13}B, ^{14}C, ^{15}N, ^{16}O, ^{17}F, ^{18}Ne, ^{19}Na, ^{20}Mg, ^{21}Al, ^{22}Si

Isobars – nuclei with constant A

- ^{13}O, ^{13}N, ^{13}C, ^{13}B

Find these various nuclide series on chart of nuclides

- Is there a pattern?

Nuclear Periodic Table

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6			C 8	C 9 0.1265s	C 10 19.31s	C 11 20.39m	C 12 98.93	C 13 1.07	C 14 5700y	C 15 2.449s	C 16 0.747s	C 17 0.193s	C 18 0.092s	C 19 0.049s	C 20 0.014s
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4				Be 7 53.22d	Be 8 6.7e-17s	Be 9 100	Be 10 1.51e+06y	Be 11 13.81s	Be 12 0.0213s		Be 14 0.00484s				
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0		n 1 10.23m													

protons

neutrons

Nuclear Periodic Table

https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

Binding Energy

- *Q value* is the nuclear analog to ΔH_{rxn} in Chemistry
- Sign of this number tells you whether reaction is endo- or exoergic
- *Binding energy* is the nuclear analog to ΔH_f^0 in Chemistry
- Binding energy indicates how well a given nucleus is held together (bound)
- For nuclei the binding energy is given by the *Q* value for the reaction that forms a nucleus from its component pieces
- Definition of *Q* value

$$\mathbf{Q} = \left(\sum \mathbf{masses}_{\mathbf{reactants}} - \sum \mathbf{masses}_{\mathbf{products}}\right)\ \mathbf{931.5\ MeV / amu}$$

or

$$\mathbf{Q} = \sum \Delta_{\mathbf{mass\ reactants}} - \sum \Delta_{\mathbf{mass\ products}}$$

BINDING ENERGY

- To calculate the binding energy of a nucleus use this basic equation

$$\mathbf{Z\,m_H + N\,m_n \rightarrow \text{an atom of } {}^{A}E + \text{energy}}$$

or

$$E_B = [(Z\,m_H + N\,m_n) - M_E\,]931.5 \text{ MeV/amu}$$

or

$$E_B = (Z\,\Delta_{mass}H + N\,\Delta_{mass}n) - \Delta_{mass\ product\ nuclide}$$

Binding Energy

- Calculate the binding energy of ^{19}F

$$E_B = [\ 9\ (7.289) + 10\ (8.071)] - (-1.4871)\ \text{MeV}$$
$$= [\ 65.601 + 80.711 + 1.4871]\ \text{MeV}$$
$$= 146.311 + 1.4871\ \text{MeV}$$
$$= 147.798\ \text{MeV}$$

Binding Energy

- ***IMPORTANT NOTE***
  - ***The nuclear chemistry definition is the reverse of the P-chem and gen chem definition***
  - ***products – reactants***
- **In the nuclear scheme:**
  - **$Q > 0$ means exoergic**
  - **$Q < 0$ means endoergic**

Valley of Stability

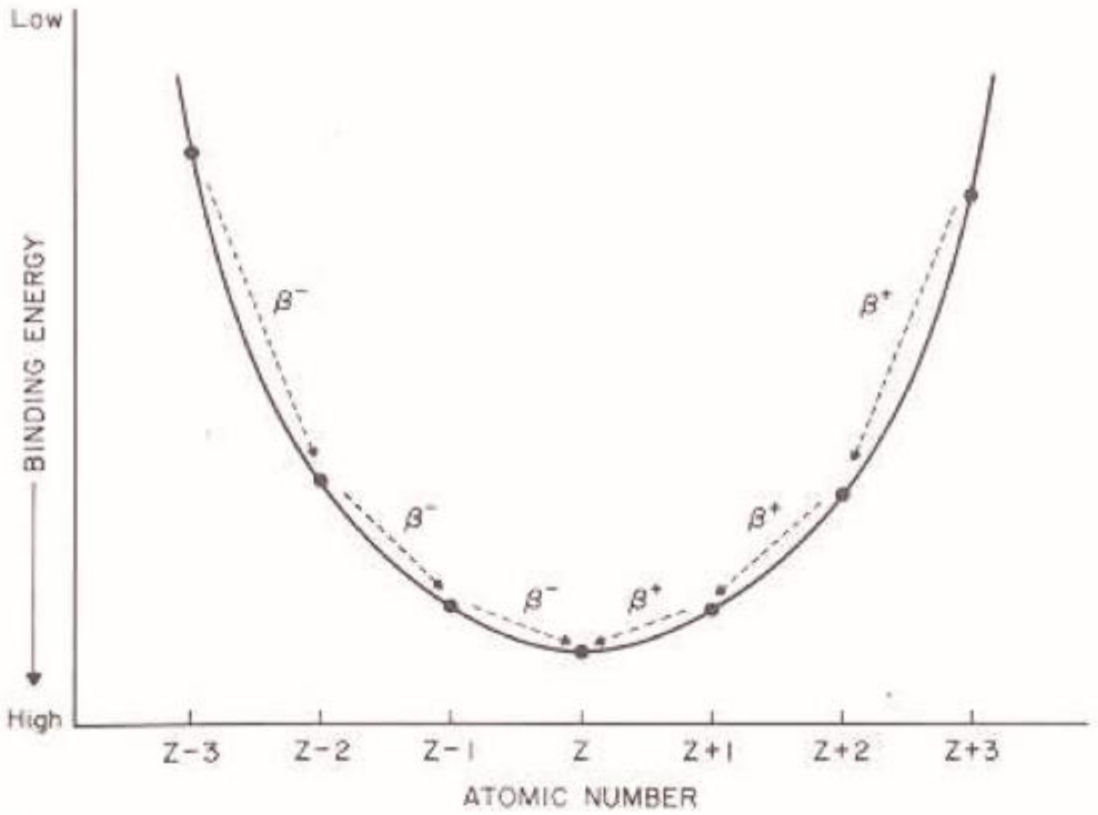

Figure 3.9. Binding energy parabola for a set of odd-*A* isobars. Electron capture can be an alternative to positron emission on all binding energy parabolas.

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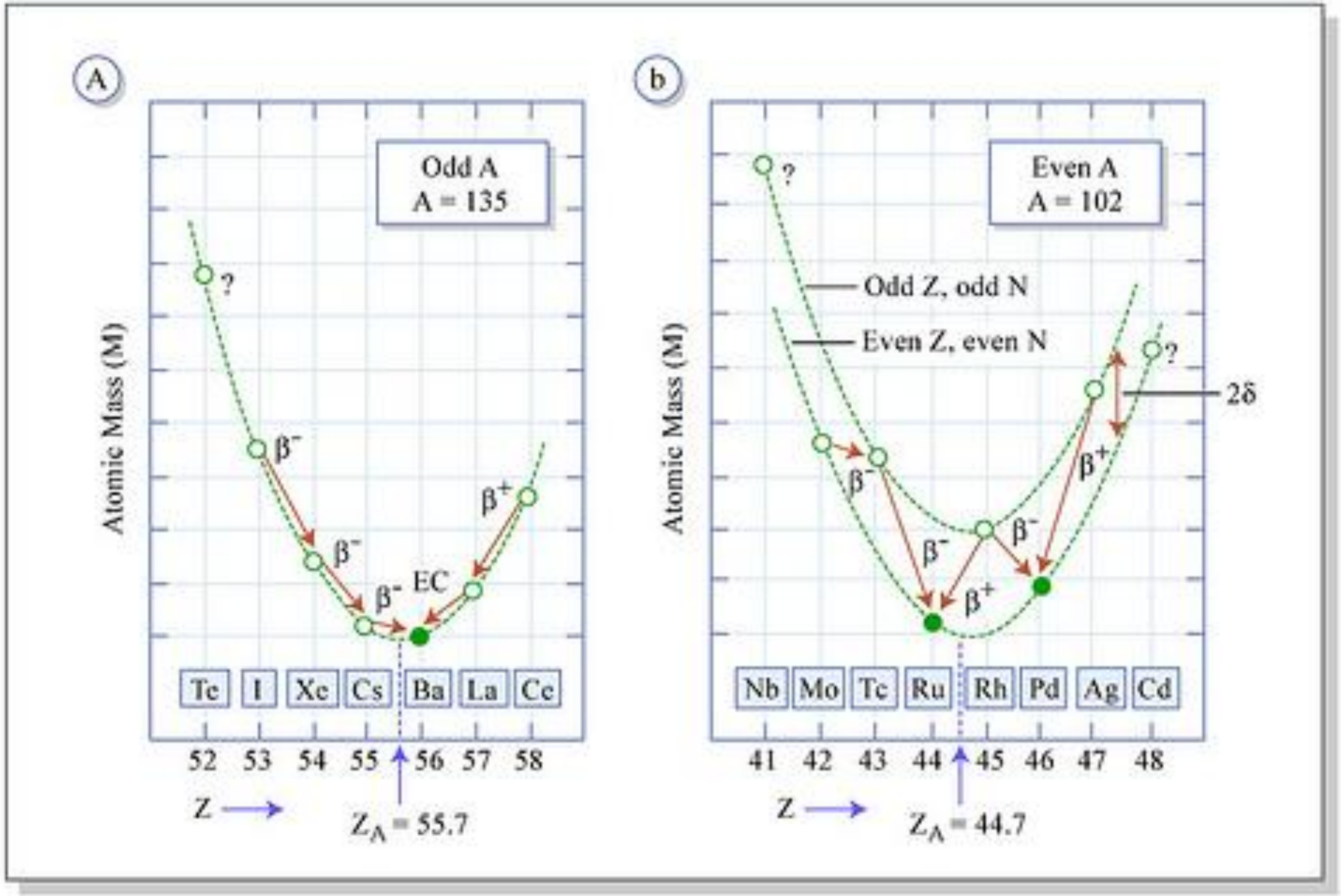
Valley of Stability

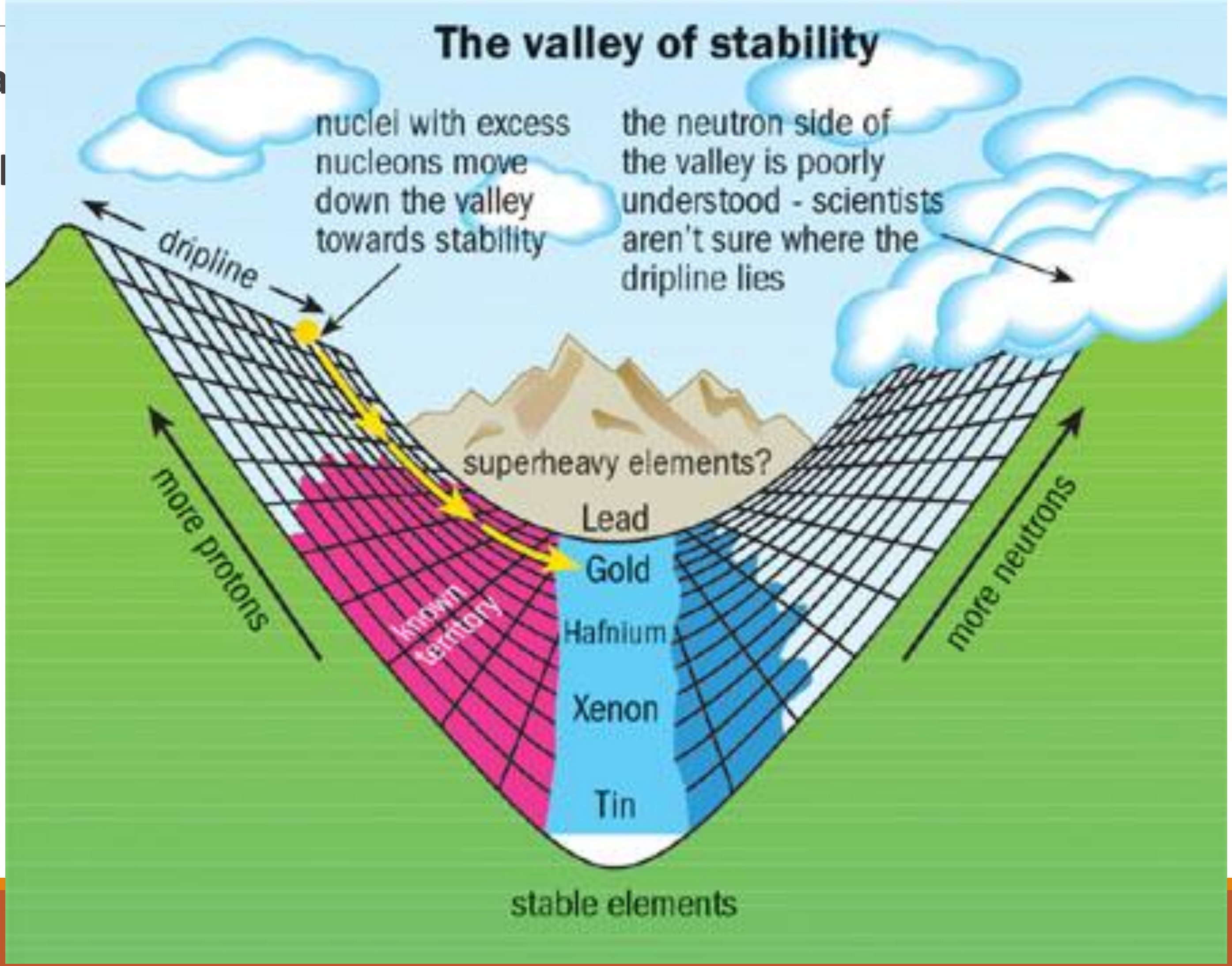
Two pa



Valley of Stability

Plot ma

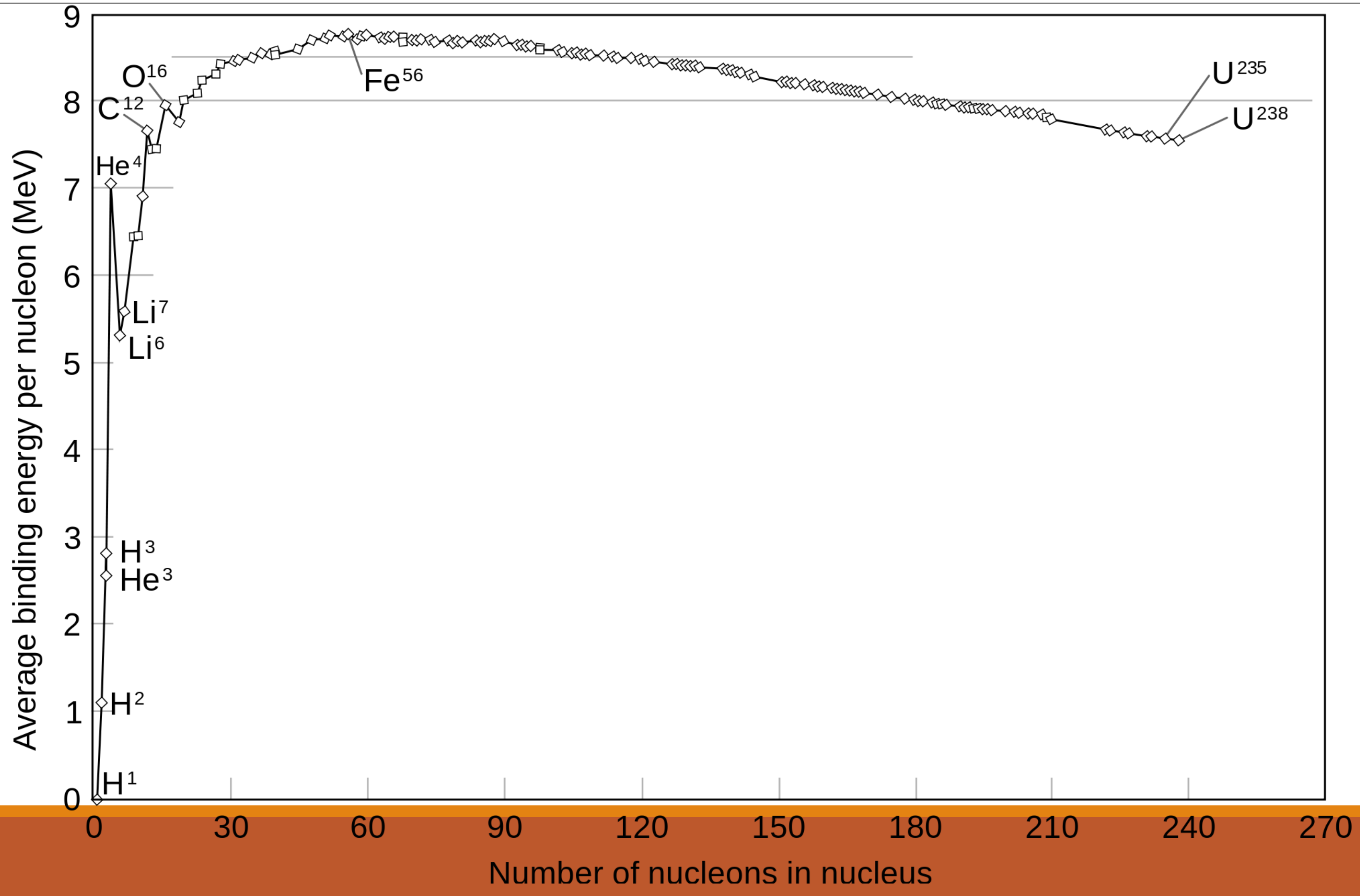
3-D grap



Binding Energy per Nucleon or BE/A

- Binding energy per nucleon or BE/A
- Relative indication of how well each nucleon is bound to the nucleus
- BE/A for ^{19}F is given by
  - 147.798 MeV ÷ 19 = 7.779 MeV
- The higher BE/A value the more stable the nucleus

Binding Energy per Nucleon or BE/A



Radioactivity

A. **Alpha decay**

- Nucleus spontaneously emits a $^{4}He^{2+}$ particle
- For example:
- $^{210}Po \longrightarrow {}^{206}Pb^{2-} + {}^{4}He^{2+}$ $t_{1/2} = 138$ days
- Alpha decay primarily occurs in heavy nuclei
  - All nuclides heavier than ^{209}Bi can alpha decay (among other possibilities)

Radioactivity

B. Beta minus decay

- Nucleus spontaneously emits a β^- (an electron)
  - Converts a neutron into a proton
- Neutron rich nuclides undergo β^- decay
  - Have too many neutrons relative to protons
- $^{90}Sr \longrightarrow {}^{90}Y + \beta^- + \bar{\nu}$ $t_{1/2} = 29.1$ y
- $^{32}P \longrightarrow {}^{32}S + \beta^- + \bar{\nu}$ $t_{1/2} = 14.3$ d

Radioactivity

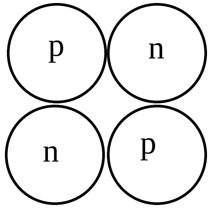
C. Beta plus decay

- Nucleus spontaneously emits a β^+ (a positive electron or positron)
  - Converts a proton into a neutron
- Proton rich nuclides undergo β^+ decay
  - Have too many protons relative to neutrons
- $^{22}Na \rightarrow {}^{22}Ne + \beta^+ + \nu$ $t_{1/2}$ = 2.60 y
- $^{11}C \rightarrow {}^{11}B + \beta^+ + \nu$ $t_{1/2}$ = 20.36 m

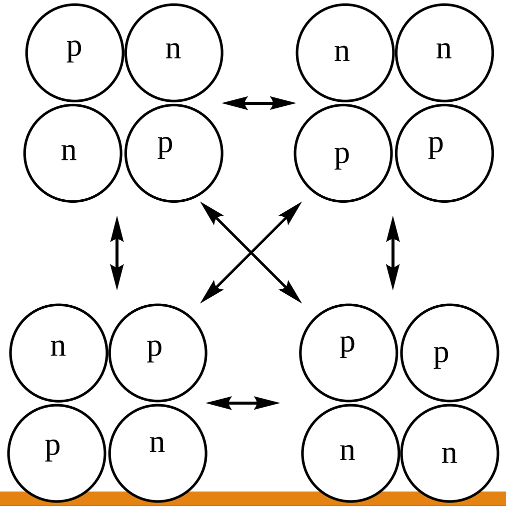
Radioactivity

How does a proton become a neutron and vice versa?

Is this how you envision a ^{4}He nucleus?



Think about it more like this.

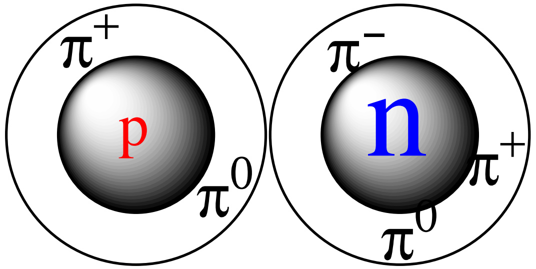


Radioactivity

How does nature pull off this trick?

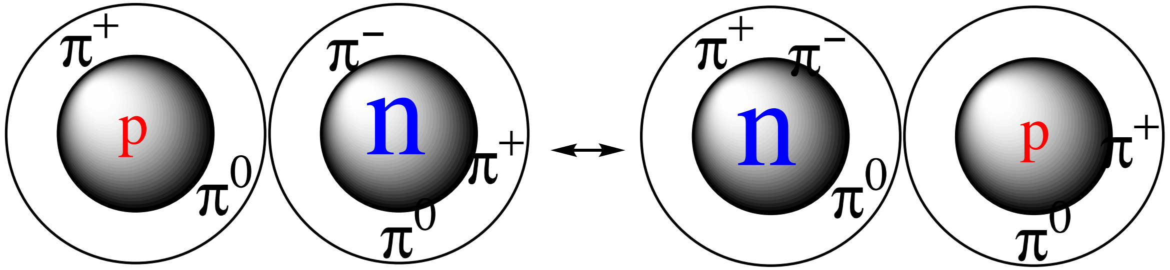
- Pi-mesons (or pions) are the answer!
- There are three types of pions, π^+ π^- π^0
- All three have a rest mass of 0.149867 amu
  - Protons have a rest mass of 1.007276 amu
  - Neutrons have a rest mass of 1.008665 amu

Pion number and charge determines what's a proton or neutron



Radioactivity

Pions are constantly moving (exchanging) from one particle to another.



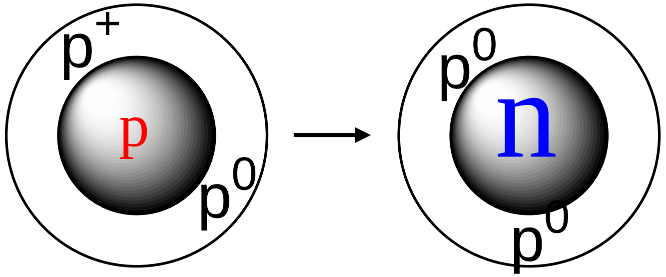
Pion exchange force is what holds nuclei together.
Called the STRONG force.

Radioactivity

In beta decay pions convert from π^+ or π^- to π^0

Positron decay illustration

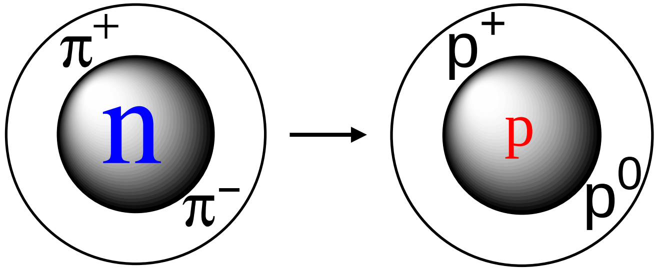
$$\pi^+ \longrightarrow \pi^0 + \beta^+ + \nu$$



Radioactivity

Negatron decay illustration

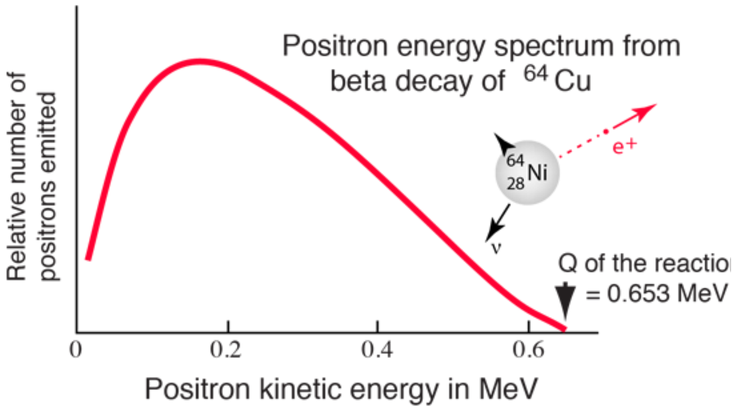
$$\pi^- \longrightarrow \pi^0 + \beta^- + \bar{\nu}$$

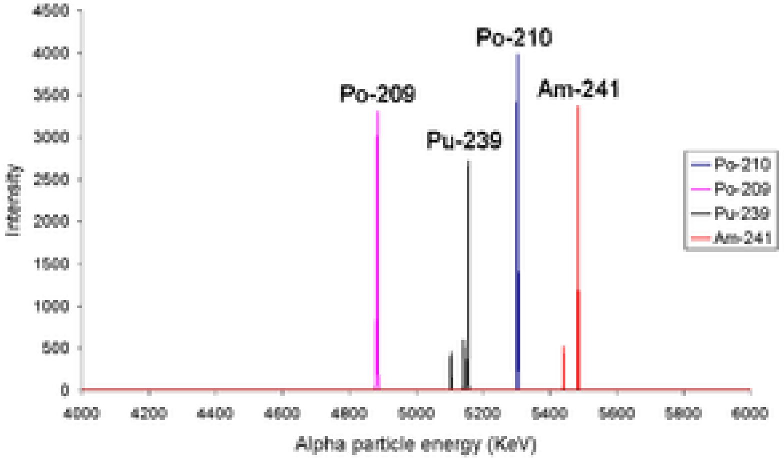


Radioactivity

What is that ν thing?

- It is the symbol for a neutrino
- Proposed in the 1920's by Wolfgang Pauli to explain why beta decay spectra are continuous, not discrete





Radioactivity

Enrico Fermi proposed the name neutrino, Italian for “little neutral one”

Definitively ”discovered” by Fred Reines and Clyde Cowan in 1956

Neutrino properties

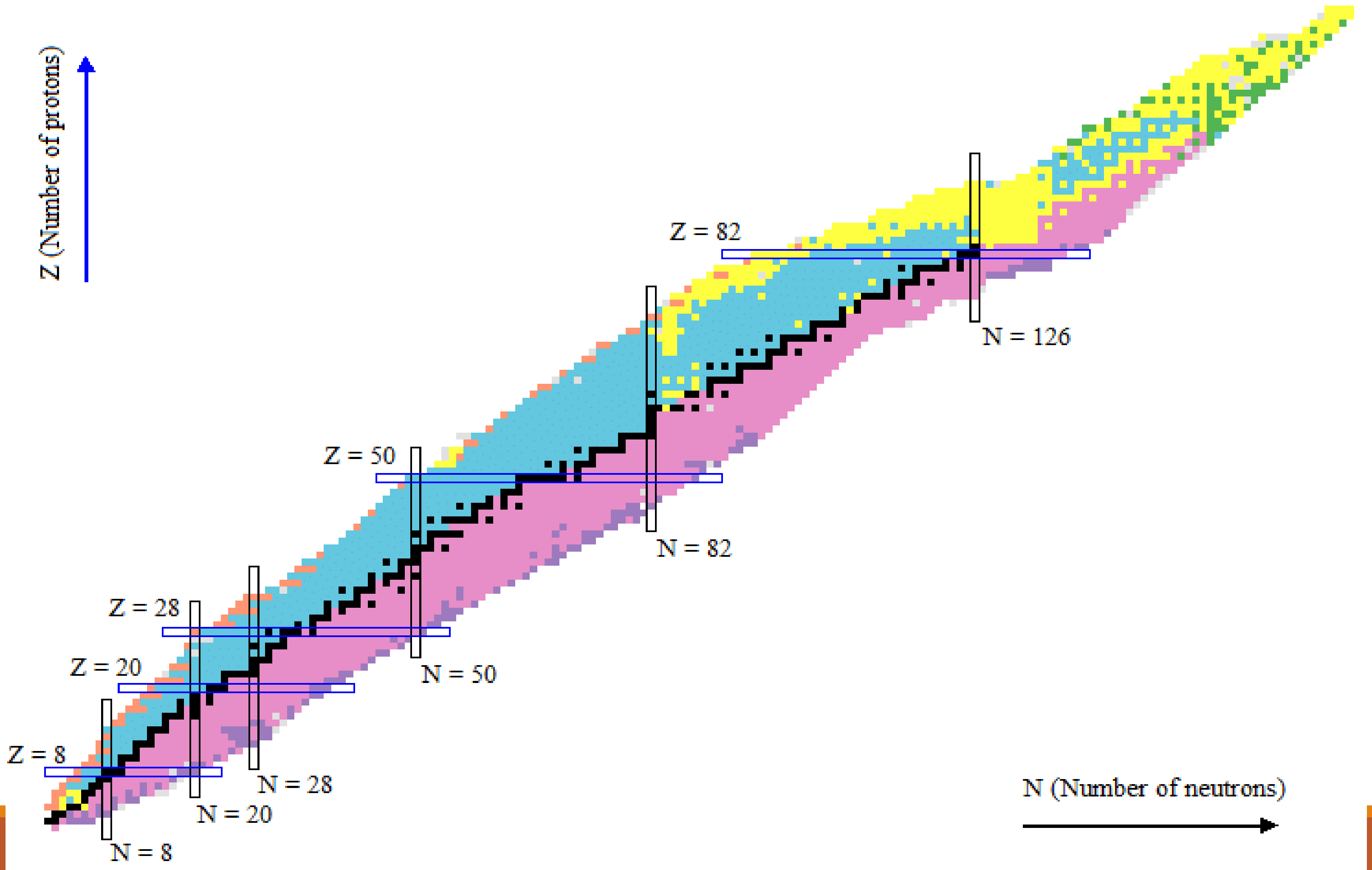
- Zero charge
- Mass of ~1.1 eV or 1.2 x 10^{-9} amu

Radioactivity

D. Gamma decay

- Nucleus spontaneously emits a highly energetic light photon (electromagnetic radiation)
  - Nuclear equivalent of atomic emission spectrum
- All nuclei can undergo gamma decay
  - Yes, even stable nuclides!
- $^{60}Co^* \longrightarrow {}^{60}Co + h\nu$ $t_{1/2} = 0.30$ ps E = 1.17 MeV & $t_{1/2} = 0.71$ ps with an E = 1.33 MeV
- $^{16}O^* \longrightarrow {}^{16}O + h\nu$ $t_{1/2} = 6.7\ \mu s$ with E = 6.05 MeV
- By comparison, the violet colored light in the H emission spectrum has an E = 3.03 eV

Radioactivity



Radioactivity

E. **Other forms of Radioactive Decay**

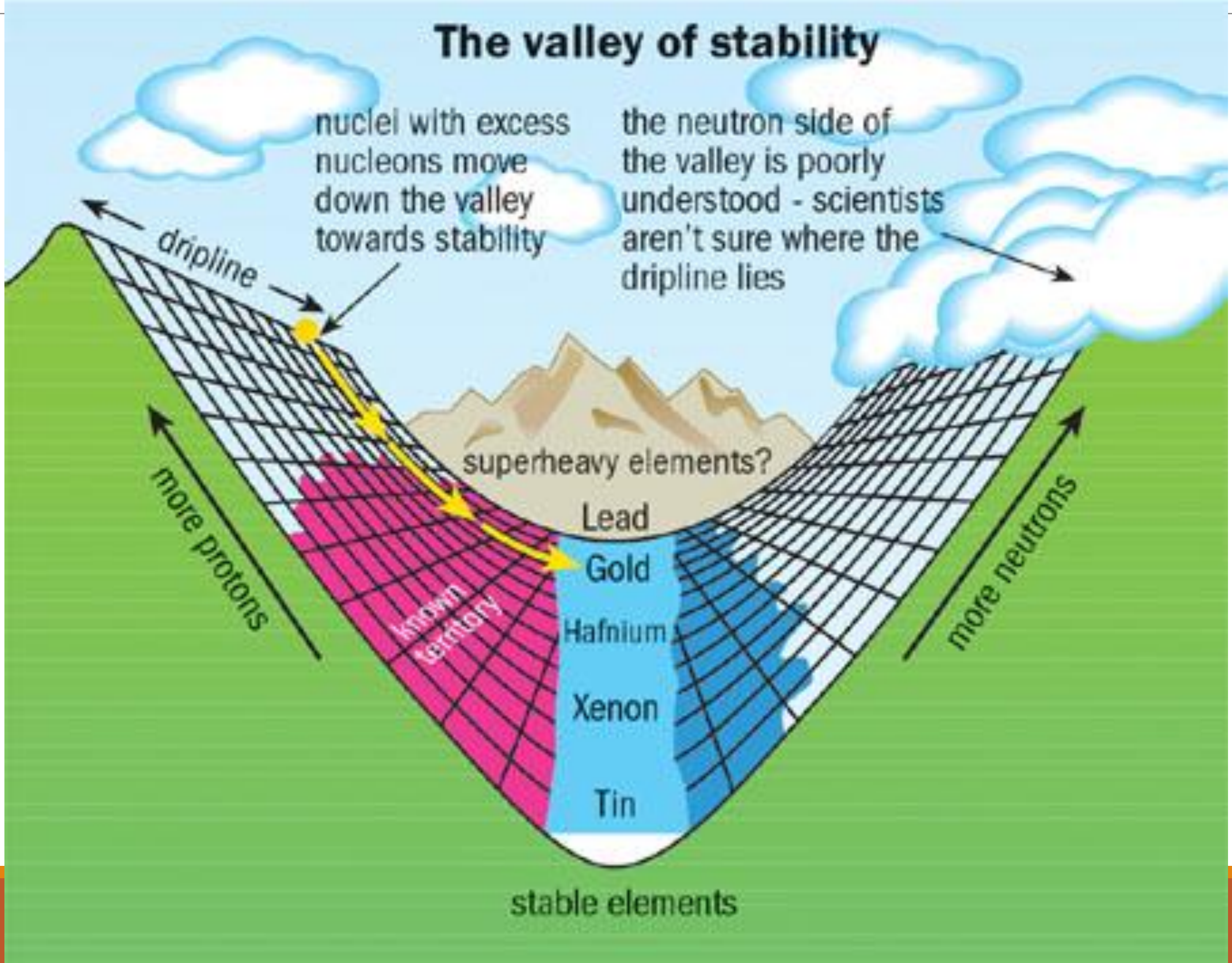
- Spontaneous fission (nucleus splits into two pieces) VERY heavy nuclei like ^{252}Cf do this
- Proton emission – VERY rare but has been seen in ^{53m}Co and a few other nuclides
- Neutron emission – also rare but seen in very neutron rich fission products
- Heavy particle emission – ^{12}C and ^{16}O emission seen in a few heavy alpha emitting nuclides

Radioactivity

F. **Kinetics of Radioactive Decay**

- All radioactive decay obeys first order kinetics
- $A = A_0e^{-kt}$ or $\ln(A/A_0) = -kt$
  - A = remaining amount of nuclide
  - A_0 = initial amount of nuclide
  - k = radioactive decay constant
  - t = time since decay started
- Decay constant and half life are related
  - $t_{1/2} = 0.693/k$

Radioactivity



Nuclear Reactions

Somewhat like chemical reactions in that the reacting species:

1. Must collide with one another
2. Have enough kinetic energy for the reaction to occur
   - (Unlike chemical reactions orientation is not a significant factor.)

- Nuclear reactions are balanced by ensuring that protons and mass are conserved
- Neutron induced reactions do not require that the neutron be accelerated
- $^{235}U + n \longrightarrow {}^{145}Ba + {}^{88}Kr + 3n$
- 92 p 56 p 36 p
- 235 + 1 = 145 + 88 + 3

Nuclear Reactions

Charged particle reactions using p, ^{3}H, ^{12}C, etc. require acceleration so that the positively charged nuclei will come into contact and exchange pieces

$^{12}C + ^{3}He \rightarrow ^{14}N + ^{1}H$

$^{12}C + ^{3}He \rightarrow ^{11}C + ^{4}He$

Two important nuclear reactions are fission and fusion

- Fission – one big nucleus splits into two smaller nuclei
- $^{235}U + n \rightarrow ^{145}Ba + ^{88}Kr + 3n$
- Fusion – two smaller nuclei merge into one larger nucleus
- $^{20}Ne + ^{20}Ne \rightarrow ^{40}Ca$

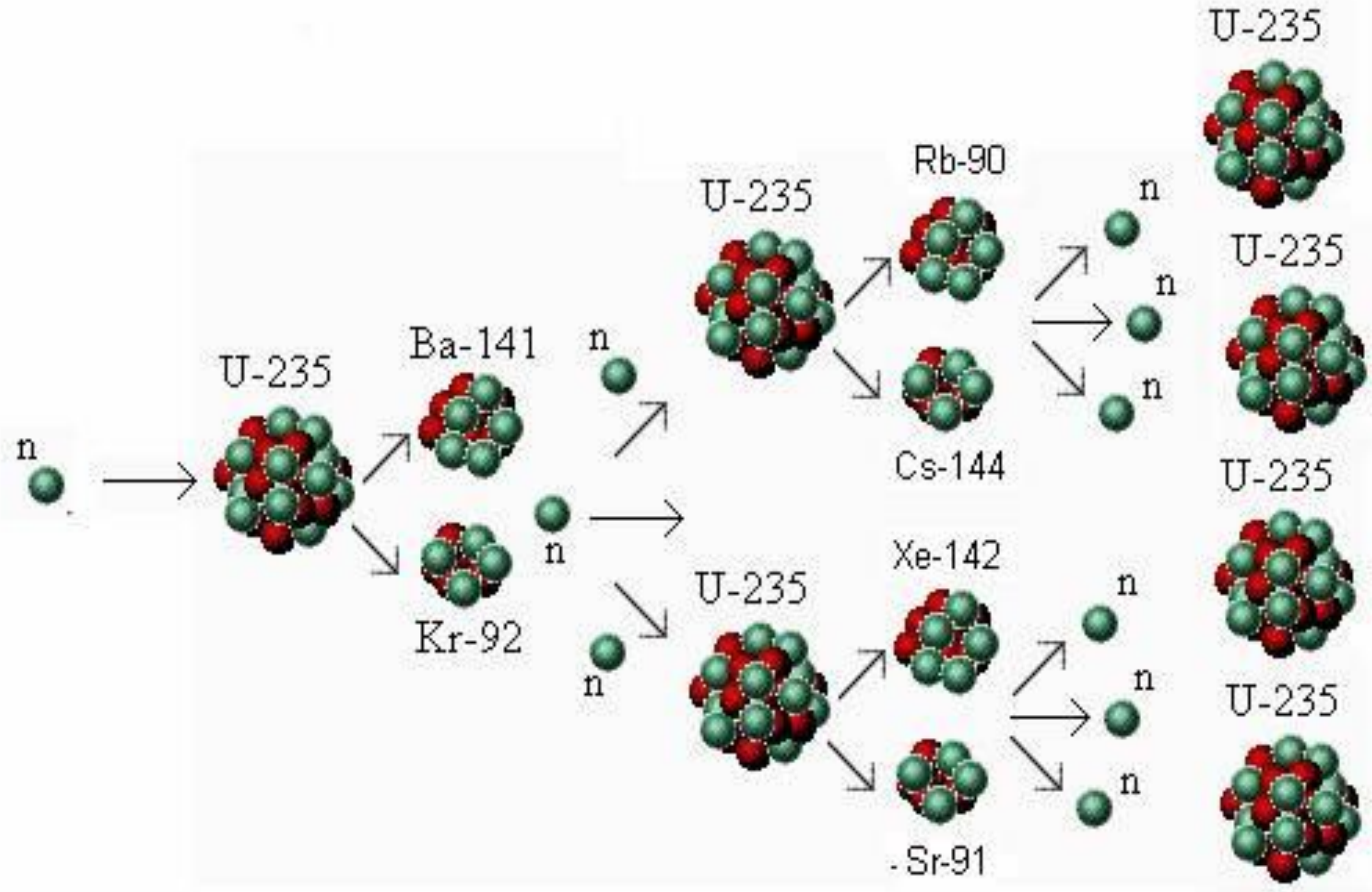
Your Choice

A. Nuclear energy
B. Nuclear weapons
C. Nucleosynthesis
D. History of nuclear science

A. Nuclear Energy

Nuclear Reactors

1. Military weapons reactors are designed to produce fissile isotopes for use in nuclear weapons.
    1. Hanford, WA
    2. Savannah River Site, SC
2. Nuclear power reactors are designed to generate heat which is used to generate electricity
    1. Military versions used in aircraft carriers and submarines
    2. Civilian versions used around the country (and world) to generate electricity
    3. In US ~ 15% of electricity is reactor generated
    4. In France ~ 70% of electricity is reactor generated


n
U-235
Ba-141
Kr-92
n
n
n
U-235
U-235
Rb-90
Cs-144
Xe-142
Sr-91
n
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n
n
n
U-235
U-235
U-235
U-235

Nuclear Reactors

6. We can express the chain reaction characteristics using the multiplication factor, *k*

$$k = \frac{\text{Number of neutrons in the n+1 generation}}{\text{Number of neutrons in the n generation}}$$

7. If $k < 1$, chain reaction is subcritical and not self sustaining
   A. Reaction will fizzle
8. If $k = 1$, chain reaction is critical and self sustaining
   A. Ideal for reactors
9. If $k > 1$, chain reaction is supercritical and will run out of control
   A. Great for weapons but very bad for reactors!

Reactor Components

Nuclear Fuel

- ^{232}Th, ^{233}U, ^{235}U, ^{238}U, and ^{239}Pu can be used
  - ^{233}U, ^{235}U, and ^{239}Pu have large thermal neutron capture cross sections
  - ^{232}Th and ^{238}U have large fast neutron capture cross sections
- ^{235}U is the most commonly used fuel
  - Physical forms – U metal, UO_2, or UC
  - UO_2 is used most commonly
- ^{238}U and ^{232}Th can be used to make other fuels

$$^{238}\text{U} + \text{fast n} \rightarrow {}^{239}\text{U} \xrightarrow{b^- \; 23.5\text{min}} {}^{239}\text{Np} \xrightarrow{b^- \; 2.36 \text{ days}} {}^{239}\text{Pu}$$

$$^{232}\text{Th} + \text{fast n} \rightarrow {}^{233}\text{Th} \xrightarrow{b^- \; 22.3\text{min}} {}^{233}\text{Pa} \xrightarrow{b^- \; 27.0 \text{ days}} {}^{233}\text{U}$$

  - Basis for breeder reactors

Fuel Cladding

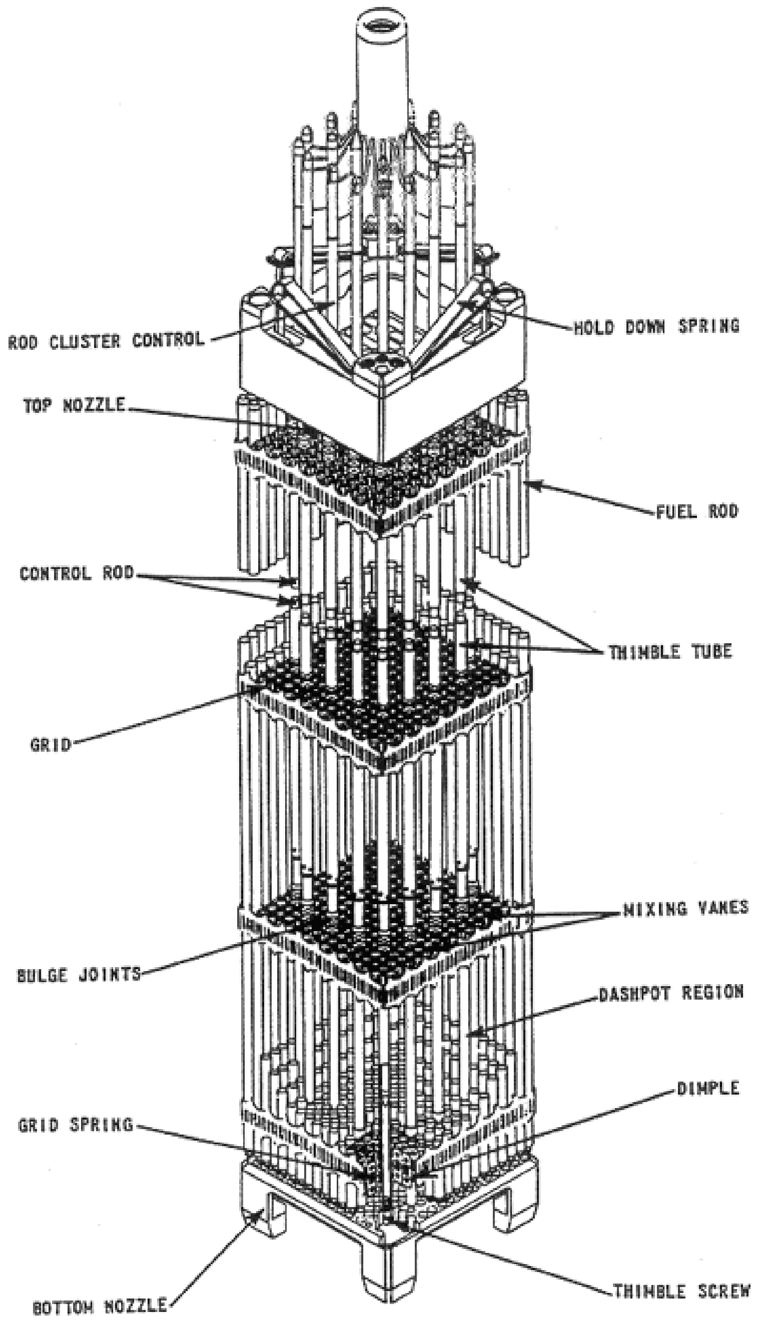
Fuel Rods

- Assemblies of $UO_2(s)$ inside metal tubes
- Tubes are from ~ 1 yd to 10 or 15 yd in length
- Couple of inches in diameter

Packed into bundles containing several rods

Tubes are made of Zr alloyed with Ni, Cr, Fe, and S

- At high T these tubes are catalysts for water decomp



Reactor Fuel Assembly

Moderators

Required to slow neutrons to thermal velocities

- Typically contain lots of protons which neutrons scatter from to slow down

Commonly used moderators

- $^{1}H_2O$, $^{2}H_2O$ and C (graphite)

$^{1}H_2O$ is cheap, plentiful, and easy to purify

- Has relatively high neutron capture cross section
- Requires enriched U fuel

$^{2}H_2O$ is expensive to separate from regular water

- Much lower neutron capture cross section (0.16% that of $^{1}H_2O$)
- Can use natural fuel

Graphite is cheap, plentiful, and easy to purify

- Much poorer moderator
- First few reactors used it
- Last one in US (Hanford, WA) shut down in the 1980's

Coolants

Removes heat from fission reactions

- Heat transfer to power generator

Common coolants include CO_2, He, H_2O (both heavy and light), and alkali metals like Na(*l*)

In the US regular water is most commonly used for both moderator and coolant

Reactor Types

Fast Breeder Reactors

- Fast refers to the neutrons
- Generate fuel as they operate

Use conventional U fuel either enriched or natural

After reactor has been in operation for a few months

- ^{235}U is depleted, ^{238}U is still present and some ^{239}Pu has been made

Fuel rods are removed and chemically processed to obtain ^{238}U and ^{239}Pu

New fuel rods are prepared with ^{239}Pu surrounded by ^{238}U

- Neutrons from ^{239}Pu fission initiate this reaction sequence
- $^{238}U + n \rightarrow {}^{239}U \rightarrow {}^{239}Np + \beta^- \rightarrow {}^{239}Pu + \beta^-$

Reactor Types

Thermal Breeder Reactors

Core is ^{233}U surrounded by ^{232}Th

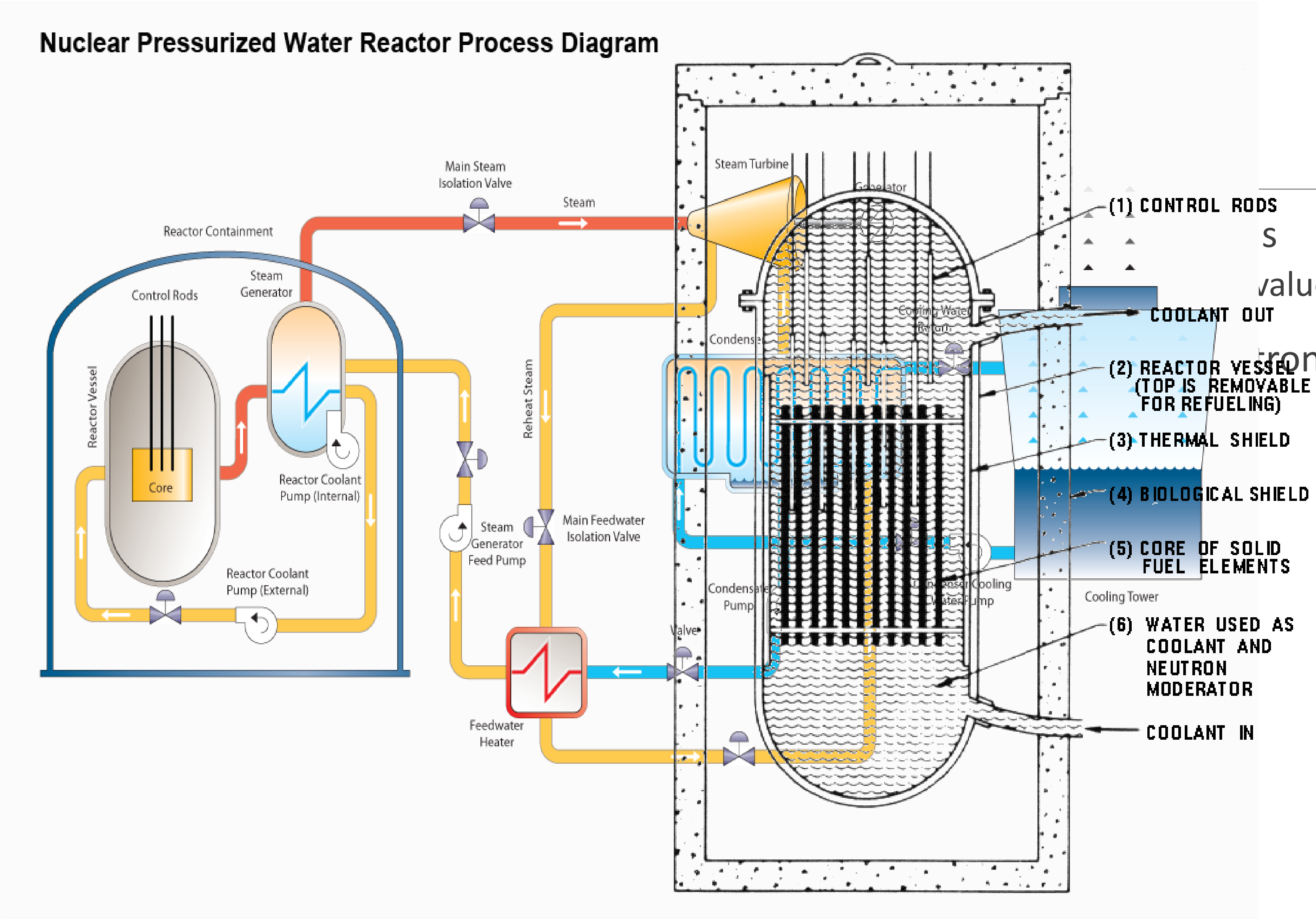
Fission neutrons from ^{233}U captured by ^{232}Th to initiate this reaction sequence

- $^{232}Th + n \rightarrow {}^{233}Th \rightarrow {}^{233}Pa + \beta^- \rightarrow {}^{233}U + \beta^-$

Reactor Types

Power Reactors

- Light water reactors
  - Most common type
- Pressurized water reactors
  - Capped to increase pressure, raise water temperature, and increase thermal efficiency
- Boiling water reactors
  - Operate with water at 100^0C



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Reactor Pictures

Reactor Pitfalls

Theoret

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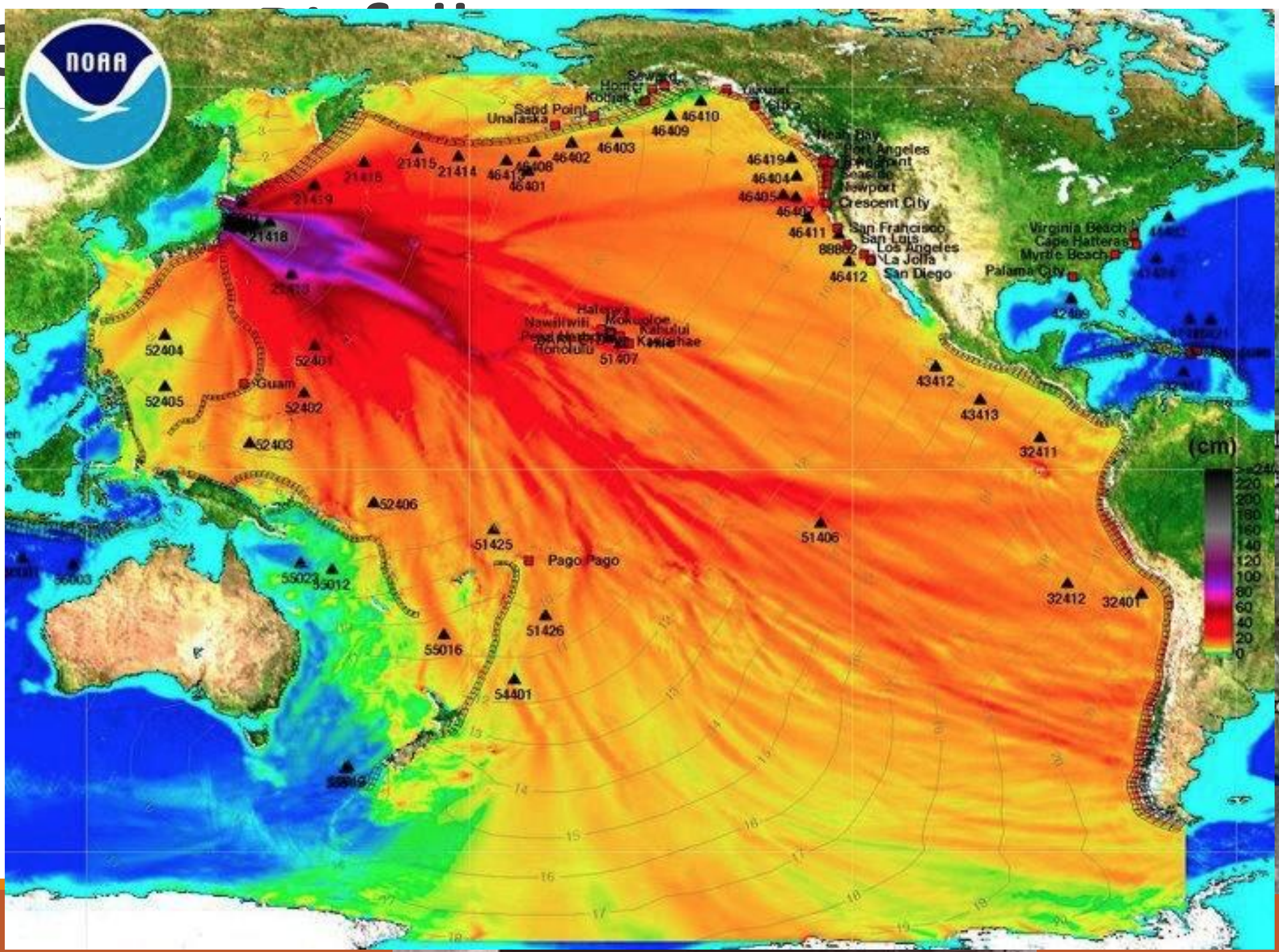
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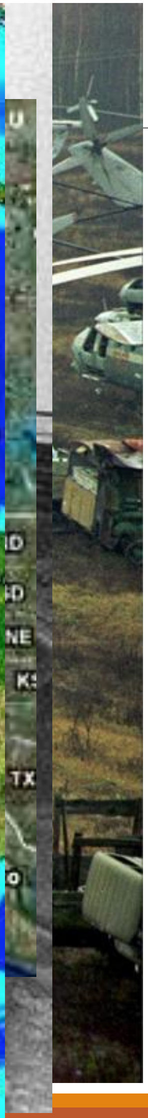
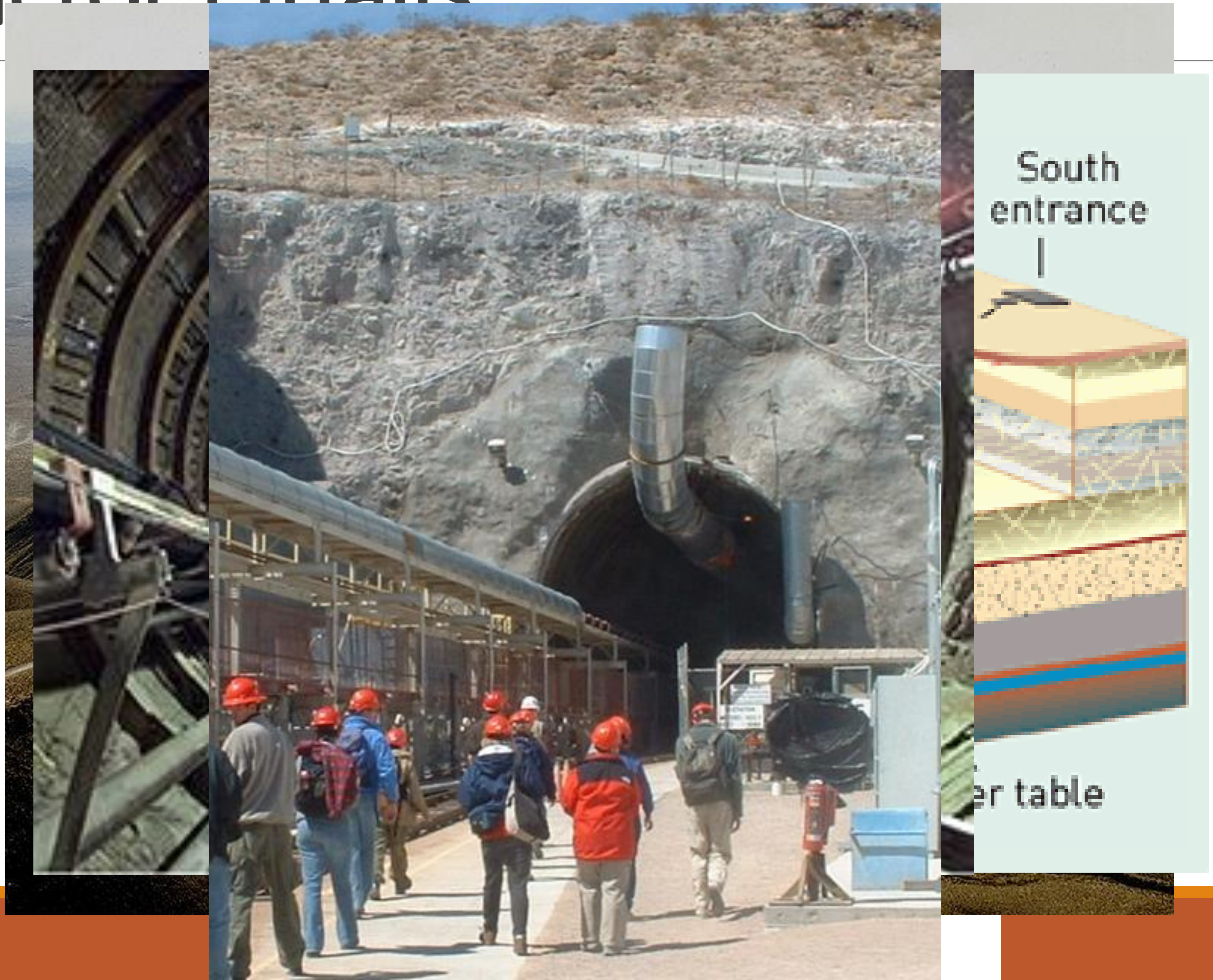


Reactor Pitfalls

Waste d



Nuclear Reactor Pluses

Power generated from nuclear fission does not add to global warming

- No CO_2 emissions
- Compared to coal-fired plants nuclear energy is very clean

Much longer term energy source than fossil fuels

It is possible to engineer nuclear power plants that are fail-safe

B. Nuclear Weapons

Nuclear Fission Weapons

Nuclear reactors are designed so that they cannot undergo a nuclear explosion

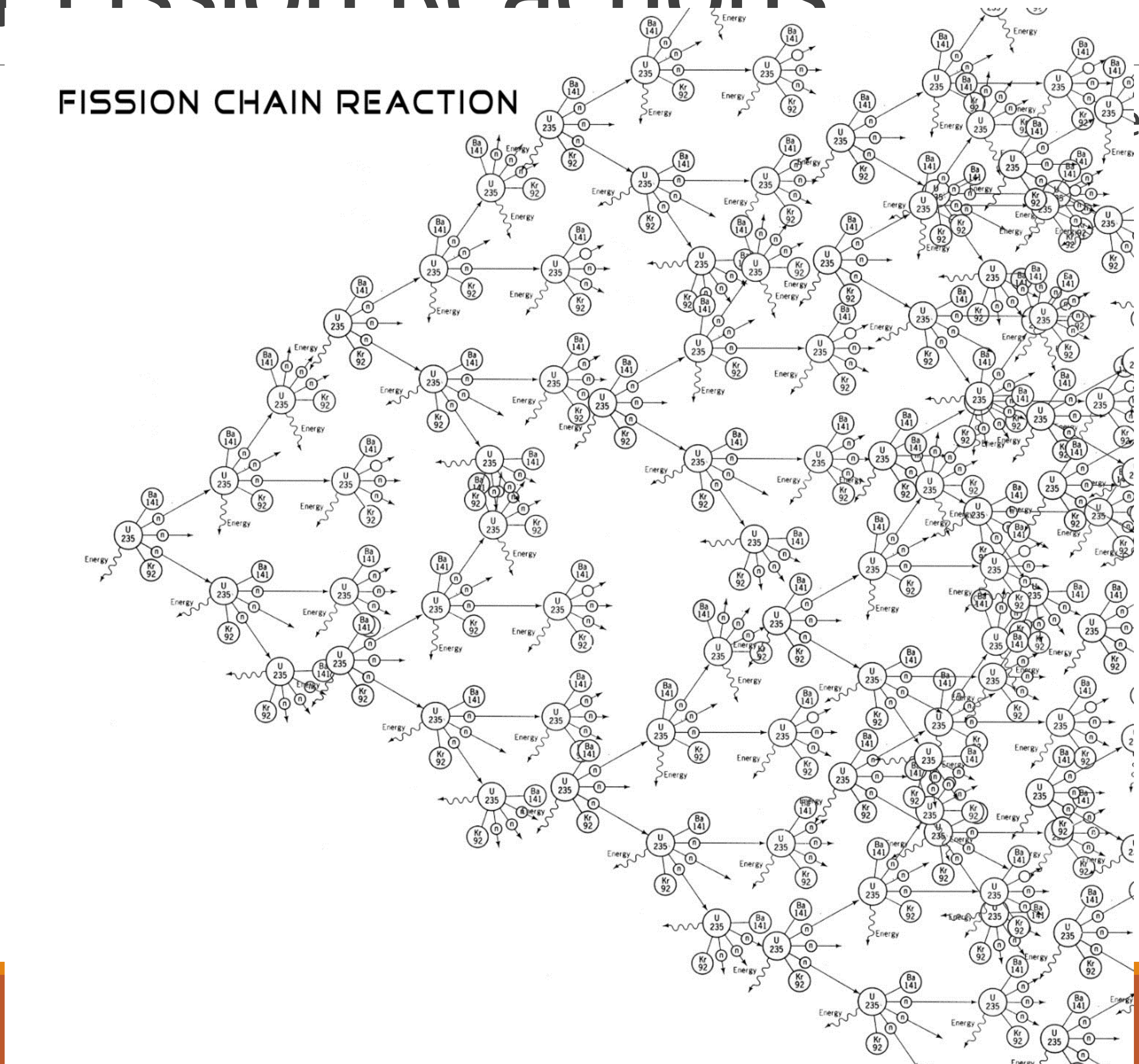
- Fissile material is too far apart
- Cannot sustain a chain reaction

Nuclear fission weapons require a critical mass of 90% pure ^{235}U or ^{239}Pu

Critical mass – sufficient quantity of material that fission neutrons cannot escape without initiating another fission reaction

Nuclear Fission Reactions

Chain reaction –



2 or 3 more, etc.

Nuclear Fission Weapons

U consists of the following isotopes all of which are radioactive

Isotope	% Abundance	$t_{1/2}$
^{238}U	99.275%	4.5×10^9 yr
^{235}U	0.720%	7.04×10^8 yr
^{234}U	0.0054%	2.45×10^5 yr

^{233}U also exists in very small amounts with a $t_{1/2}$ of 1.59×10^5 yr

To make a weapon the U must be enriched from 0.720% ^{235}U to 90% ^{235}U

Nuclear Fission Weapons

Nuclear Fission Weapons

In July 194 , NM

Nuclear Fission Weapons

Hiroshi

Little Bo

Casu

- 6
- 6

Nuclear Fission Weapons

Nagasaki

Fat Man

Casualtie

- 39,000
- 25,000

Nuclear Fission Weapons

USSR builds a nuclear weapon in 1949

- Starts the Cold War

Countries that possess nuclear weapons

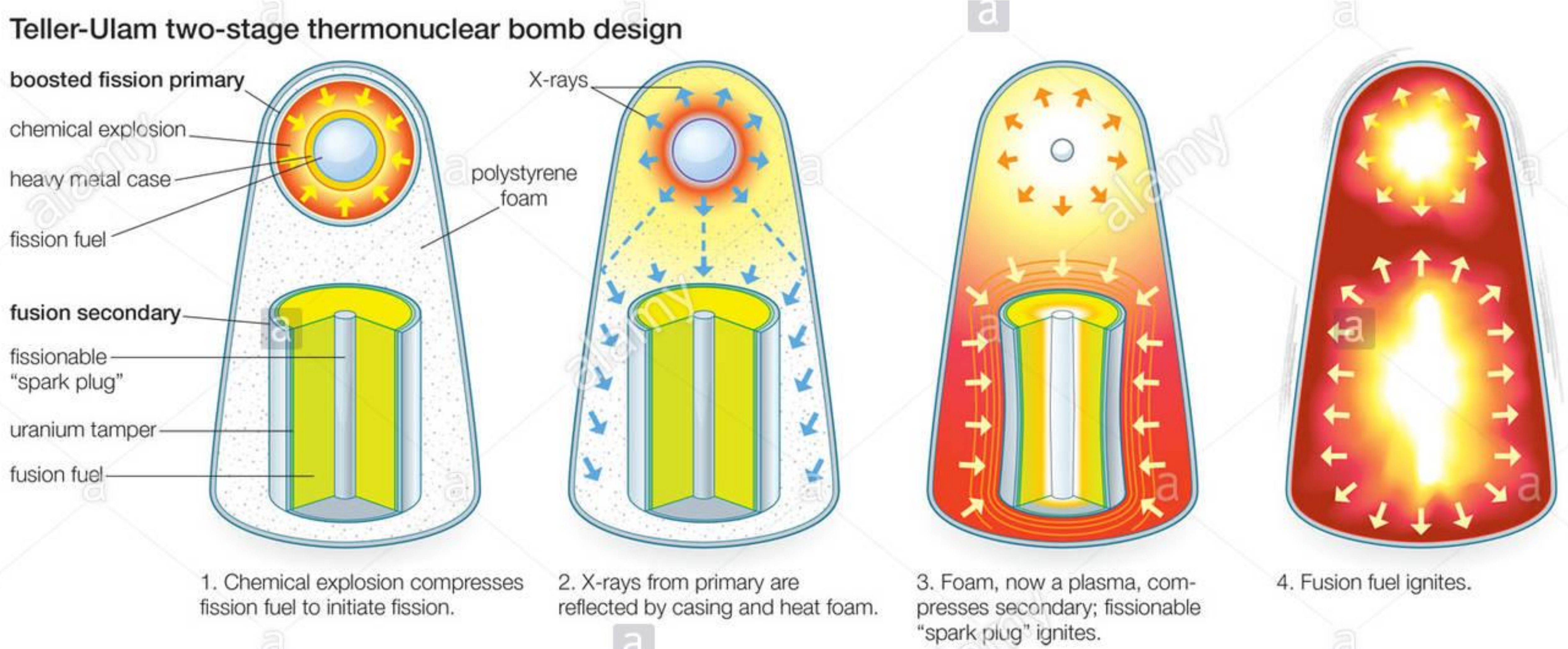
- USA
- Russia
- Britain
- France
- Israel
- China
- India
- Pakistan
- North Korea
- (South Africa)

Nuclear Fusion Weapons

First ther

- Cranks


US AIR FORCE
Peacekeeper MX


Teller-Ulam two-stage thermonuclear bomb design
boosted fission primary
chemical explosion
heavy metal case
fission fuel
polystyrene foam
X-rays
fusion secondary
fissionable "spark plug"
uranium tamper
fusion fuel
1. Chemical explosion compresses fission fuel to initiate fission.
2. X-rays from primary are reflected by casing and heat foam.
3. Foam, now a plasma, compresses secondary; fissionable "spark plug" ignites.
4. Fusion fuel ignites.

C. Nucleosynthesis

Primordial Nucleosynthesis

Big Bang Theory

A. Seminal paper by Alpher, Bethe, and Gamow in 1948
B. Further work by numerous others

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. BETHE
Cornell University, Ithaca, New York

AND

G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas

Primordial Nucleosynthesis

Universe started ~ 13 to 15 billion years ago

1. **All matter, energy, space and time were contained in a single immensely dense and extremely small point**
2. **At ~10^{-43} s after the explosion (singularity) occurs, all matter was compressed into a sphere the size of the point of a needle with a density of ~10^{90} kg/cm^3**
3. **Universal T was ~10^{32} K**
4. **All 4 physical forces are united in a single force**
5. **As the explosion proceeds, the universe expands and cools**
   a. **4 forces begin to separate themselves over the next ~ 10^{-8} s**
   b. **some particles have been generated including leptons, quarks, leptoquarks, and gravitons**
   c. **Universe inflates tremendously over the time frame 10^{-35} to 10^{-33} s and the strong force separates from the electroweak force – gluon appears**
   d. **From 10^{-33} to 10^{-6} s all four forces finally separate and electrons, positrons, neutrinos, and antineutrinos begin their existence**
      ① **Matter dominates over antimatter**
      ② **Protons and neutrons are formed**

Primordial Nucleosynthesis

D. Nucleosynthesis era 1 to 5 min after the explosion

1) universe has cooled to 10^9 K and nuclei can begin to form (thermal E < strong force)
2) universe consists of a very hot plasma containing electrons, positrons, neutrinos, antineutrinos, neutrons, and protons

E. Nuclear reactions begin making some new nuclei and elements

1) $p + n \rightarrow d + \gamma$
2) $d + n \rightarrow t + \gamma$ (tritium rapidly decays away)

F. He formation begins

1) $p + d \rightarrow {}^3He + \gamma$
2) ${}^3He + {}^3He \rightarrow {}^4He + 2p$

G. Elements with A = 5 or 8 are all very unstable with short half lives, this blocks the direct synthetic route for heavier elements

1) ${}^8Be$ $t_{1/2} \sim 7 \times 10^{-17}$ s
2) ${}^5Li$ $t_{1/2} \sim 3 \times 10^{-22}$ s
3) ${}^5He$ $t_{1/2} \sim 7.6 \times 10^{-22}$ s

Primordial Nucleosynthesis

D. Only ^{7}Li is stable enough to withstand these conditions

1) $^{4}He + ^{3}H \rightarrow ^{7}Li$ or
2) $^{4}He + ^{3}He \rightarrow ^{7}Be$
3) $^{7}Be + e^{-} \rightarrow ^{7}Li + \nu$

E. Within 5 minutes after the Big Bang, the Universe has cooled to the point that further nuclear reactions are impossible and only these elements have been formed

1) ^{1}H ~ 76% of the early universe
2) ^{4}He ~ 24% of the early universe
3) Trace amounts of ^{3}He, ^{2}H, and ^{7}Li
4) This explains the early portion of the cosmic abundance curve but where did the rest of the stuff come from?

F. Elemental synthesis stops for ~ 10^{6} years and the universe cools off some more

1) matter dominates radiation
2) electrons and nuclei can finally combine to form atoms

G. Universe continues its expansion and cooling to the point that we have a nearly constant 3K microwave radiation cosmic background

Stellar Evolution

1. Big Bang explosion spews matter and energy over Universe then gravity begins to contract clumps
   1) Big Bang was not symmetric otherwise there would be no coagulation into galaxies and stars, etc.

2. Protostars are made as H and He gases condense into a sphere raising temperature and density high enough to initiate fusion reactions

3. Three different star populations
   1) Population III stars
      a. First generation stars
      b. Have no starting material except H, He and some Li
      c. Extremely massive with very short lives of a few thousand to few million years
      d. Nuclear reactions inside them made some heavier elements which were then ejected into the interstellar medium and used in subsequent stars
      e. No population III stars exist today
   2) Population II stars
      a. Second generation stars
      b. These stars contained ~ 1% heavier elements then H and He (from the pop III stars) when they are formed
      c. This changes some of the synthetic pathways that are available to them
      d. A few of these stars are still with us but mostly as remnants
   3) Population I stars
      a. Third generation stars
      b. Begin life with 2-5% heavier elements than H and He
      c. Sun is a population I star
         a. Most abundant stars in the sky

Stellar Evolution

4. Evolutior

A. Evo

B. mas
can

C. sma

D. Her

1) I

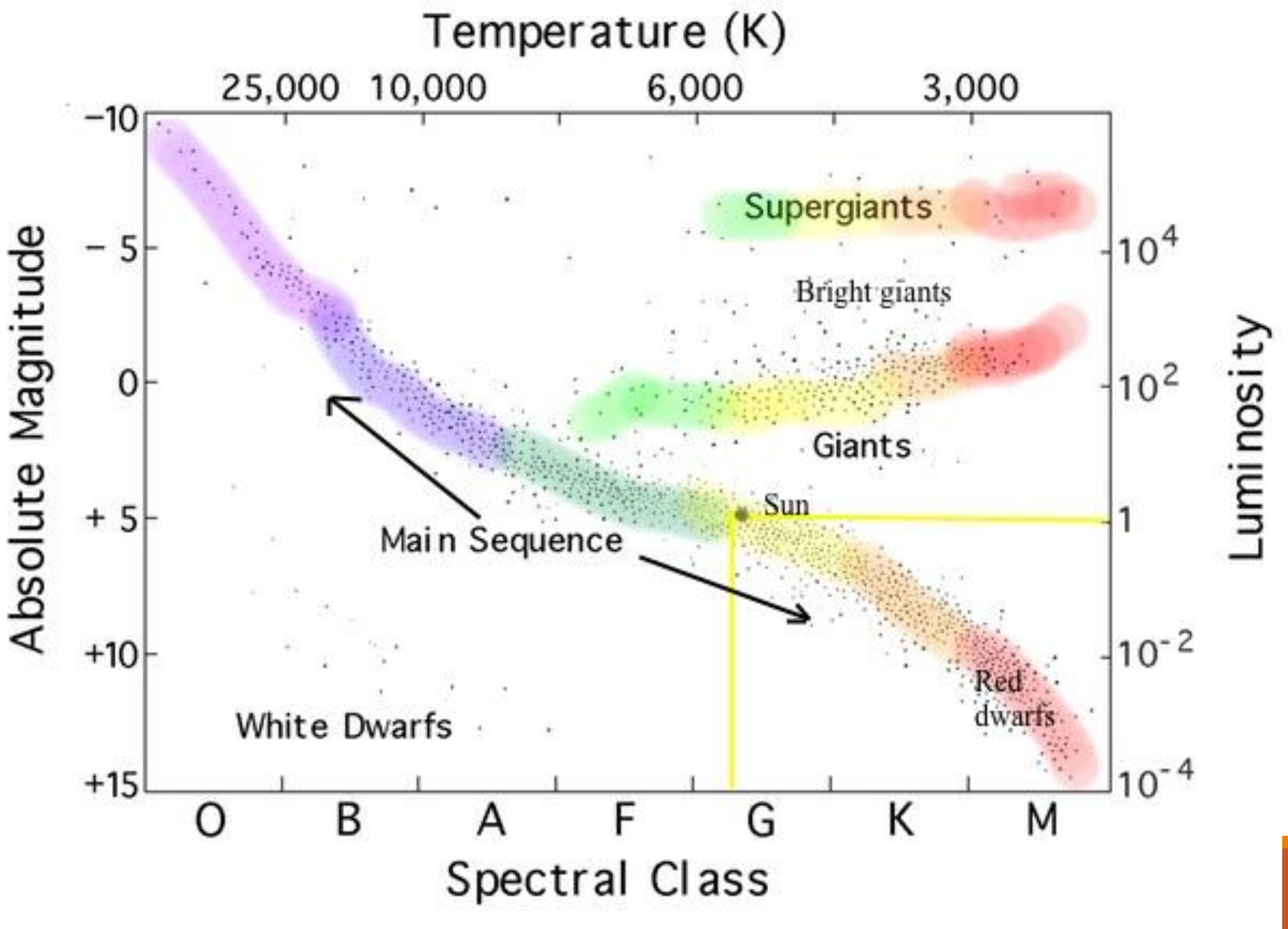
2) I

3) I

4) I

5) I

6) I



Stellar Evolution

Main Sequence Stars

- Most stars are found in a diagonal band on the H-R diagram called the main sequence
- Stars spend the majority of their lives on the main sequence

Blue supergiants

- Massive stars that are exceedingly hot
- Producing majority of their light in the UV

Red Supergiants and Red Giants

- Massive, large diameter stars that are cooler
- Emit a lot of their light in the red-IR region

White dwarfs

- Very small stars that are relatively hot

As a star reaches the end of its lifetime it moves from the main sequence into the red supergiant or red giant region

- Once it passes through the red giant or supergiant phase, it has two options available to it
  - If the mass is < 1.4 solar masses it becomes a white dwarf
  - If it is truly a massive star > 3 solar masses, then it will become a nova or supernova
    - If the core that remains after the explosion has a mass of 1.4-3 solar masses, it becomes a neutron star
    - If the core has a mass > 3 solar masses it will form a black hole

Stellar Nucleosynthesis

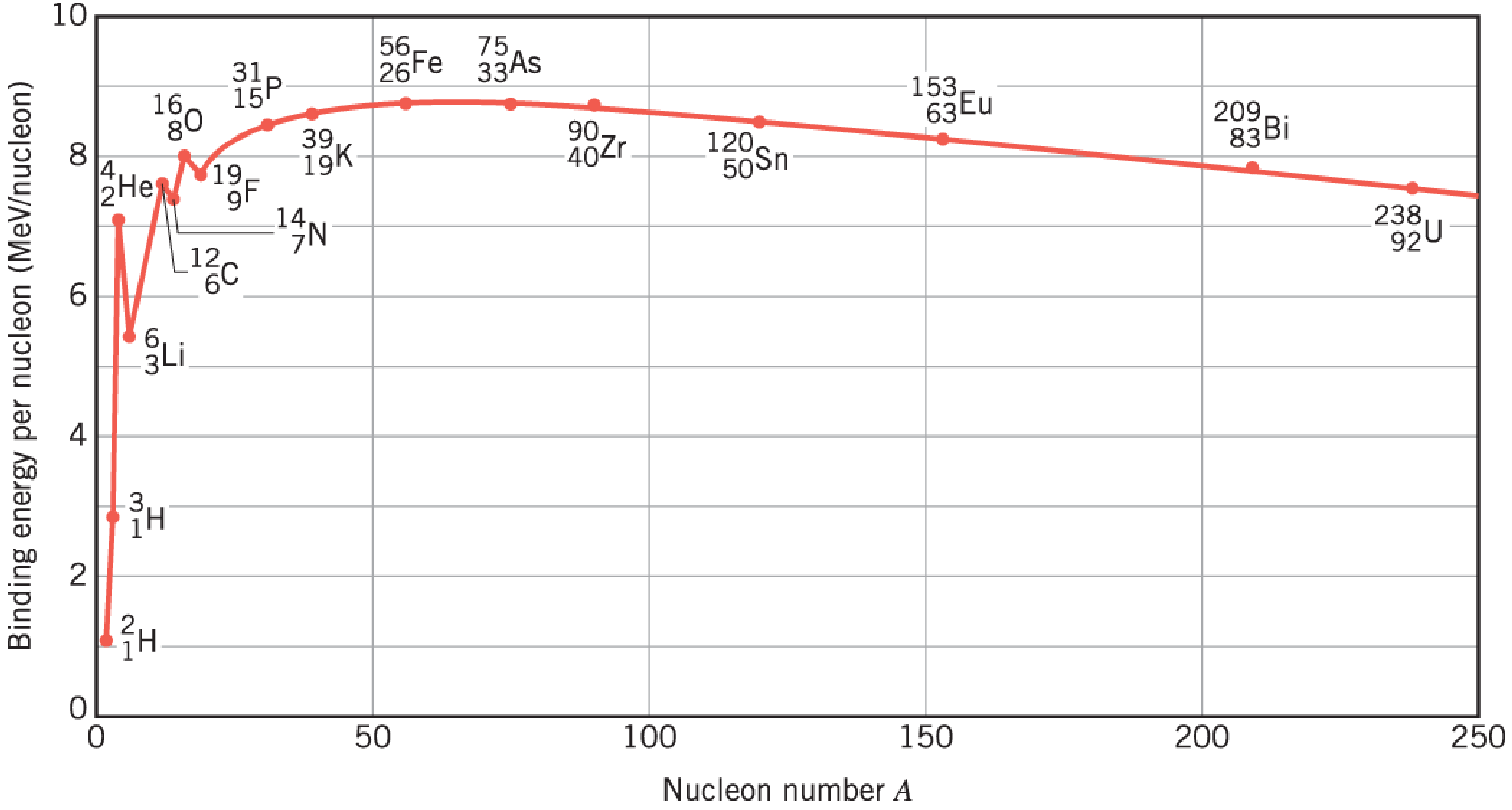
1. Main sequence hydrogen fusion reactions
2. Once star has reached an internal T of ~108 K
3. ppI sequence
   a) $p + p \rightarrow d + \beta^{-} + \nu$
   b) $p + p + e^{-} \rightarrow d + \nu$
   c) $p + d \rightarrow {}^{3}He + \gamma$
   d) ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$
4. Net result 4 p → 4He + energy

Stellar Nucleosynthesis

5. If the star has sufficient He and high T ppII sequence is possible
   a) $^{3}He + ^{4}He \rightarrow ^{7}Be + \gamma$
   b) $^{7}Be + e^{-} \rightarrow ^{7}Li + \nu$
   c) $^{7}Li + p \rightarrow ^{8}Be + \gamma \rightarrow ^{4}He + ^{4}He$

6. One last pp possibility is the ppIII chain
   a) $^{7}Be + p \rightarrow ^{8}B + \gamma$
   b) $^{8}B \rightarrow ^{8}Be + \beta^{+} + \nu$
   c) $^{8}Be \rightarrow ^{4}He + ^{4}He$

Stellar Nucleosynthesis



Wien's Law

$\lambda_{peak}\,T = 2.898 \times 10^{-3}$ mK

Stellar Nucleosynthesis

7. CNO Bi-cycle first recognized by Hans Bethe
   A. $^{12}C + p \rightarrow {}^{13}N + \gamma$
   B. $^{13}N + e^{-} \rightarrow {}^{13}C + \nu$
   C. $^{13}C + p \rightarrow {}^{14}N + \gamma$
   D. $^{14}N + p \rightarrow {}^{15}O + \gamma$
   E. $^{15}O + e^{-} \rightarrow {}^{15}N + \nu$
   F. $^{15}N + p \rightarrow {}^{12}C + {}^{4}He$
      1) C and N isotopes catalyze the formation of ^{4}He from 4 p's

8. Another possible CNO cycle is
   A. $^{15}N + p \rightarrow {}^{16}O + \gamma$
   B. $^{16}O + p \rightarrow {}^{17}F + \gamma$
   C. $^{17}F + e^{-} \rightarrow {}^{17}O + \nu$
   D. $^{17}O + p \rightarrow {}^{14}N + {}^{4}He$

Stellar Nucleosynthesis

He burning

A. Over time the core becomes He rich - p to p interactions become too diffuse to sustain fusion

B. Core contracts and heats initiating new more exoergic fusion reactions than H fusion
   1) Even though the core contracts, the star expands to accommodate the increased energy flow from He fusion reactions
   2) Star evolves from main sequence to red giant or red supergiant phase

C. Triple alpha process
   1) ^{8}Be has a short half-life (~10^{-17} s) not much is around at any one point in time
   2) In a red giant star enough ^{8}Be present to form an equilibrium concentration of ^{8}Be leading to these He burning reactions
      a. $^{4}He + ^{4}He \rightarrow ^{8}Be$
      b. $^{8}Be + ^{4}He \rightarrow ^{12}C + \gamma$

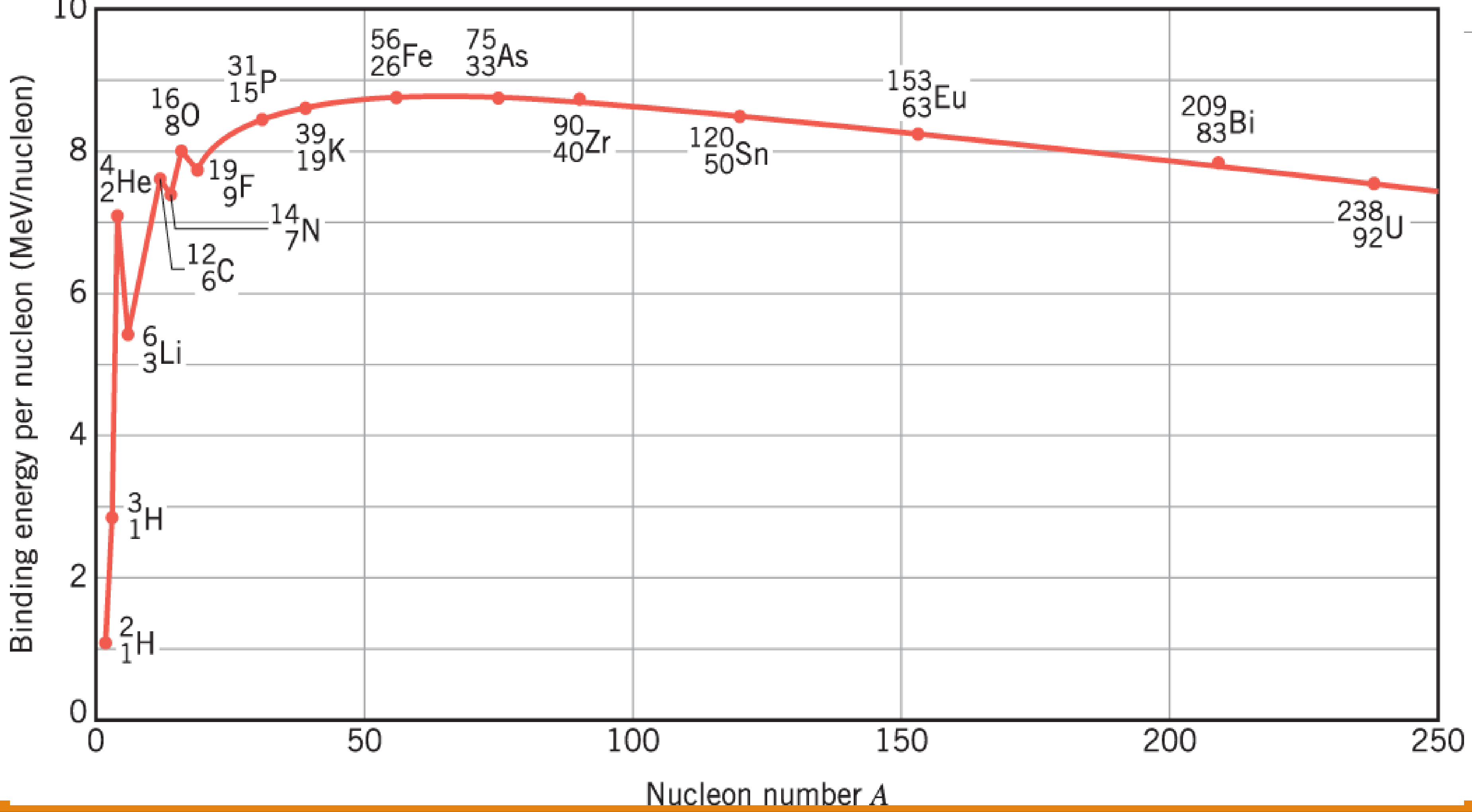
D. Carbon fusion reaction
   1) $^{12}C + ^{4}He \rightarrow ^{16}O$

E. C fusion is the end of the line for He burning
   1) He burning leaves the star's core relatively rich in C and O
   2) He burning is much shorter than the main sequence lasting perhaps for only a few thousand to million years
   3) Eventually the core becomes saturated in C and O shutting off the He burning sequence

F. Core contracts and heats

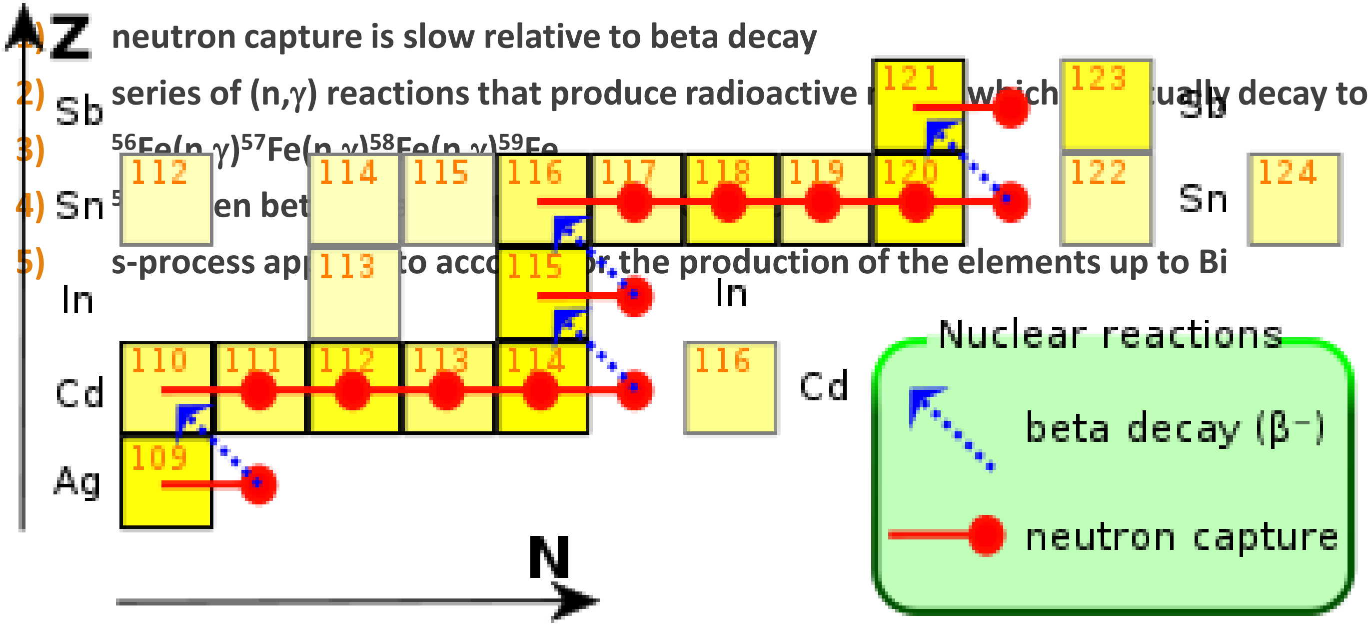
G. Star's exterior contracts to initiate the next batch of reactions

Stellar Nucleosynthesis



Stellar Nucleosynthesis

11. **Elements heavier than Fe and Ni are made via the r- and s-neutron capture processes**
    - A. slow or s-process
        1) neutron capture is slow relative to beta decay
        2) series of (n,γ) reactions that produce radioactive n… which …ually decay to stable nuclides
        3) $^{56}Fe(n,\gamma)^{57}Fe(n,\gamma)^{58}Fe(n,\gamma)^{59}Fe$
        4) …en bet…
        5) s-process app… to acc… for the production of the elements up to Bi



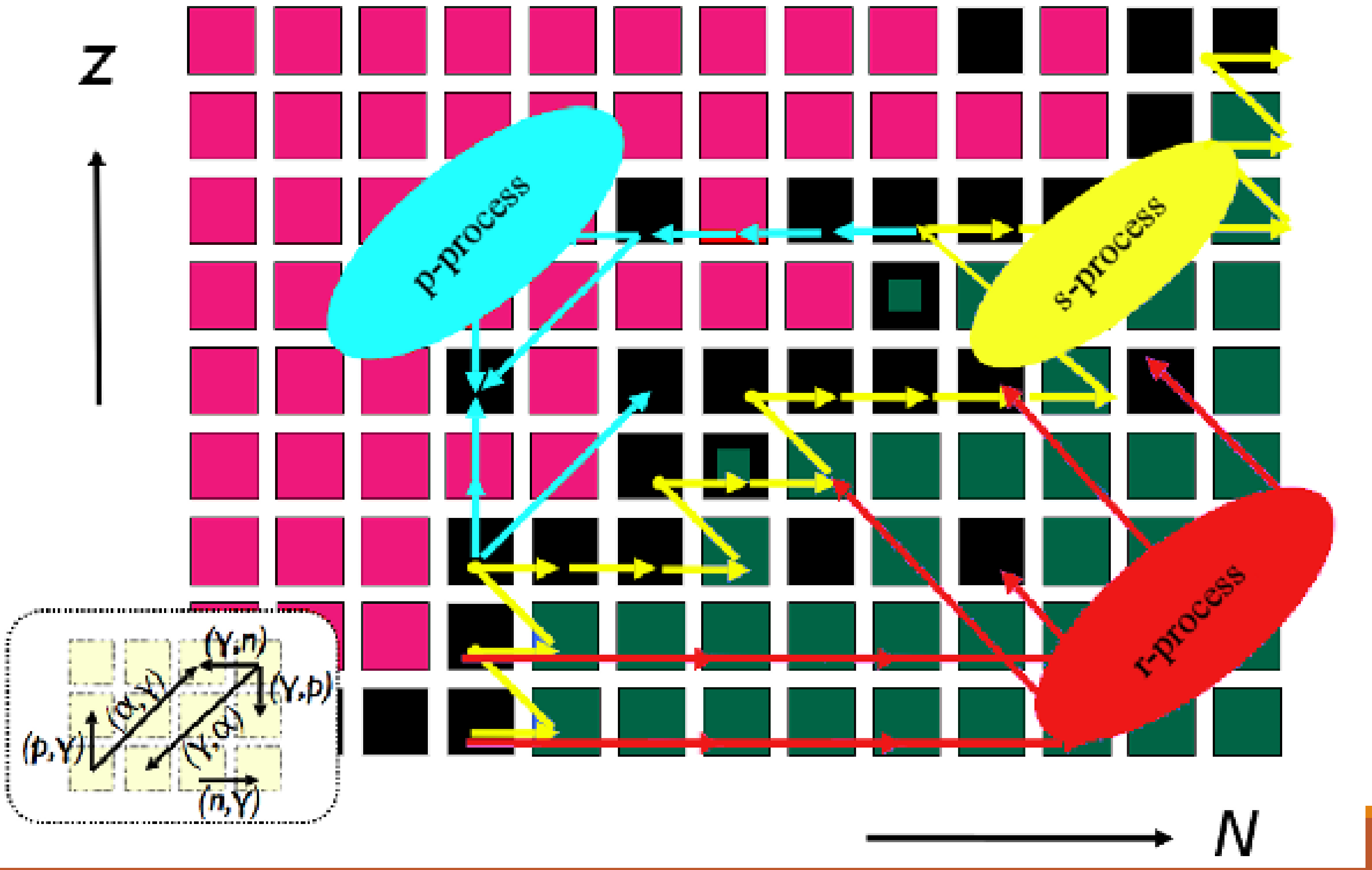
Stellar Nucleosynthesis

B. rapid or r-process

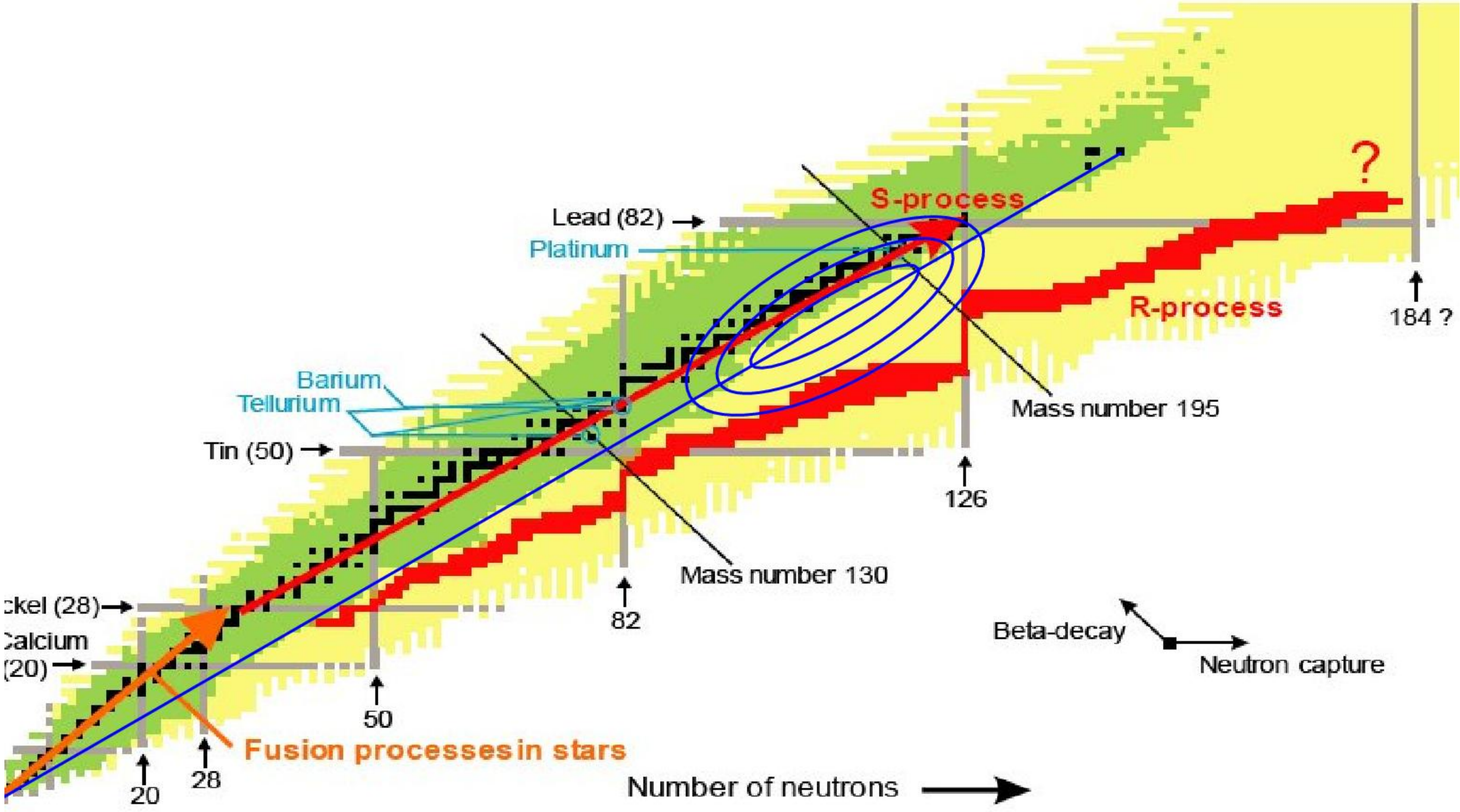
1) Rapid capture of as many as 20 to 50 neutrons before the nucleus beta decays
   a. Yields nuclei that are excessively neutron rich
2) Such high neutron fluxes can only occur during a supernova explosion
3) Synthesizes the heaviest elements like U and Th as well as some nuclei that the s-process cannot generate such as ^{116}Cd
4) Peaks in the cosmic abundance curve at N = 50 and 126 are double humped due to the r- and s-processes making slightly different A value nuclides

Stellar Nucleosynthesis

C.



Stellar Nucleosynthesis



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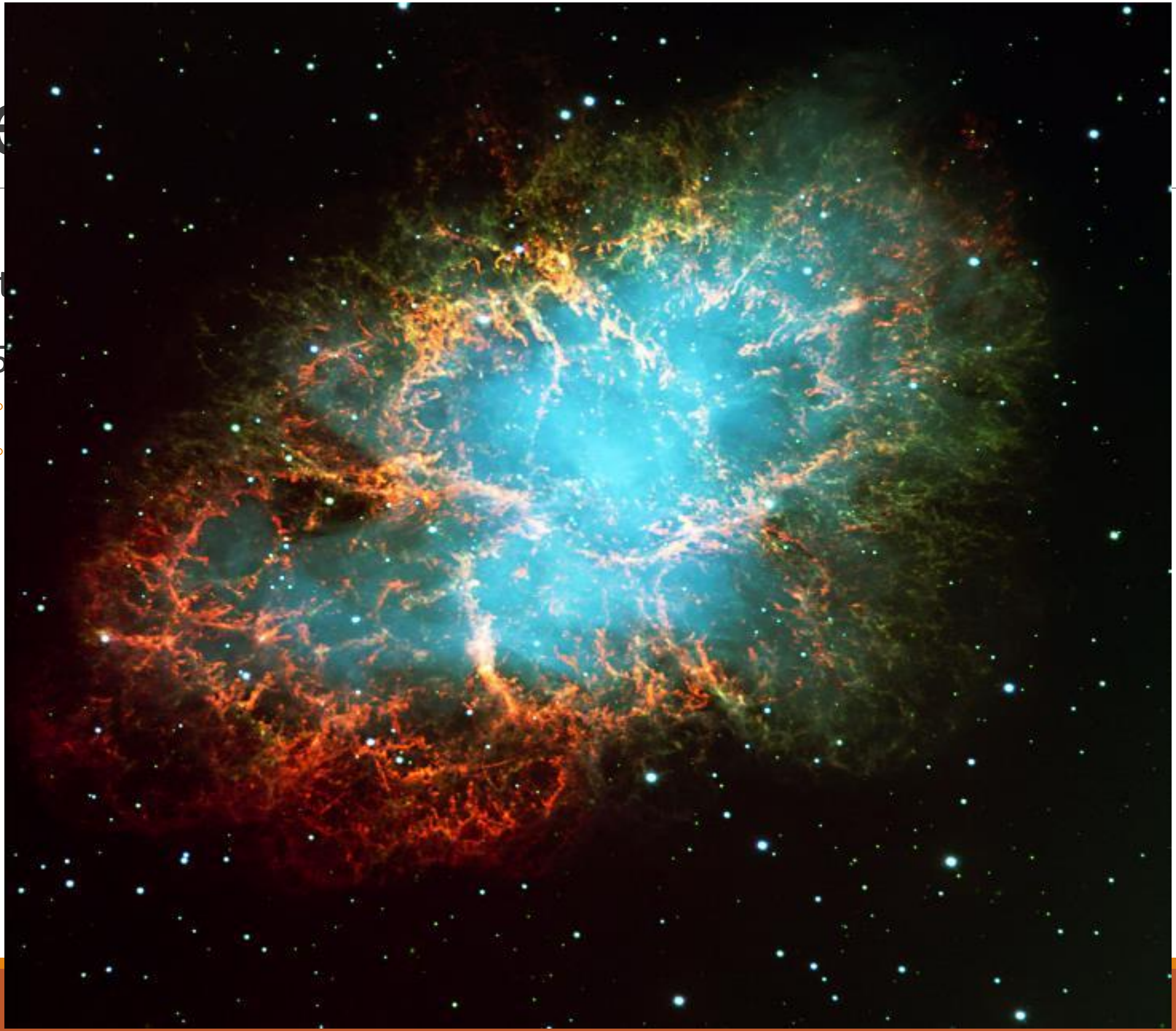
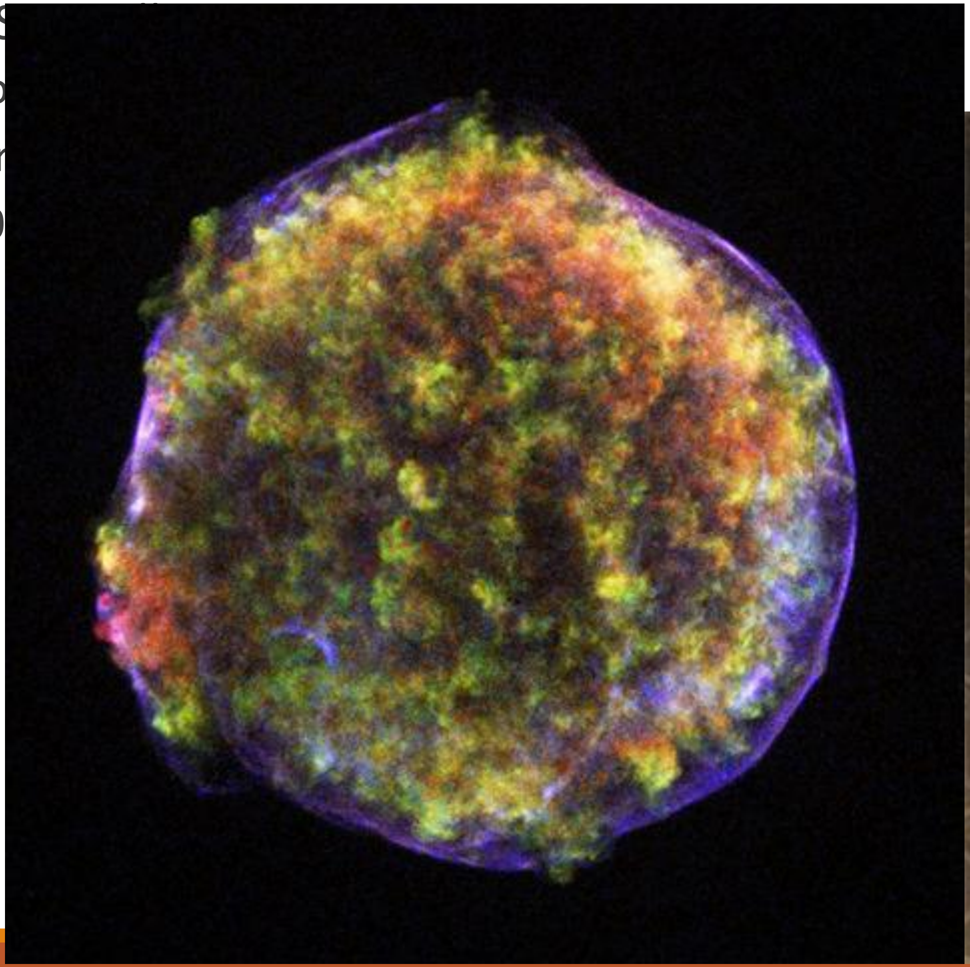


Supernovae

1572 – S

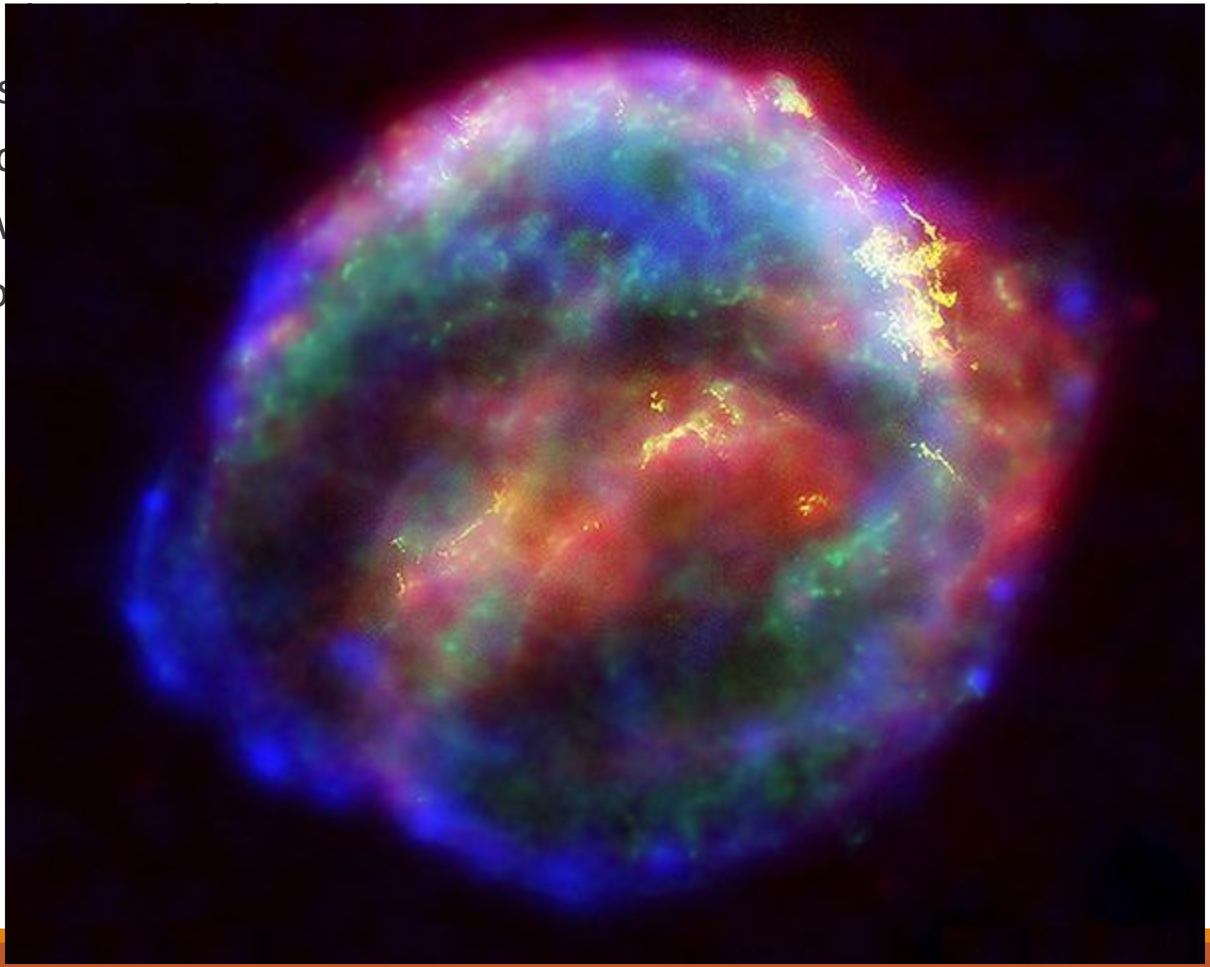
- Tycho
- Occur
- 10,00



Supernovae

1604 – Seen Around

- Johannes Kepler des
- Occurred in Ophiuc
- 20,000 light years av
- Visible in daylight fo



Stellar Nucleosynthesis

Supernovae

A. Type I Supernovae

1) occur as one star steals mass from another nearby star until it reaches a critical mass and the star undergoes a supernovae explosion

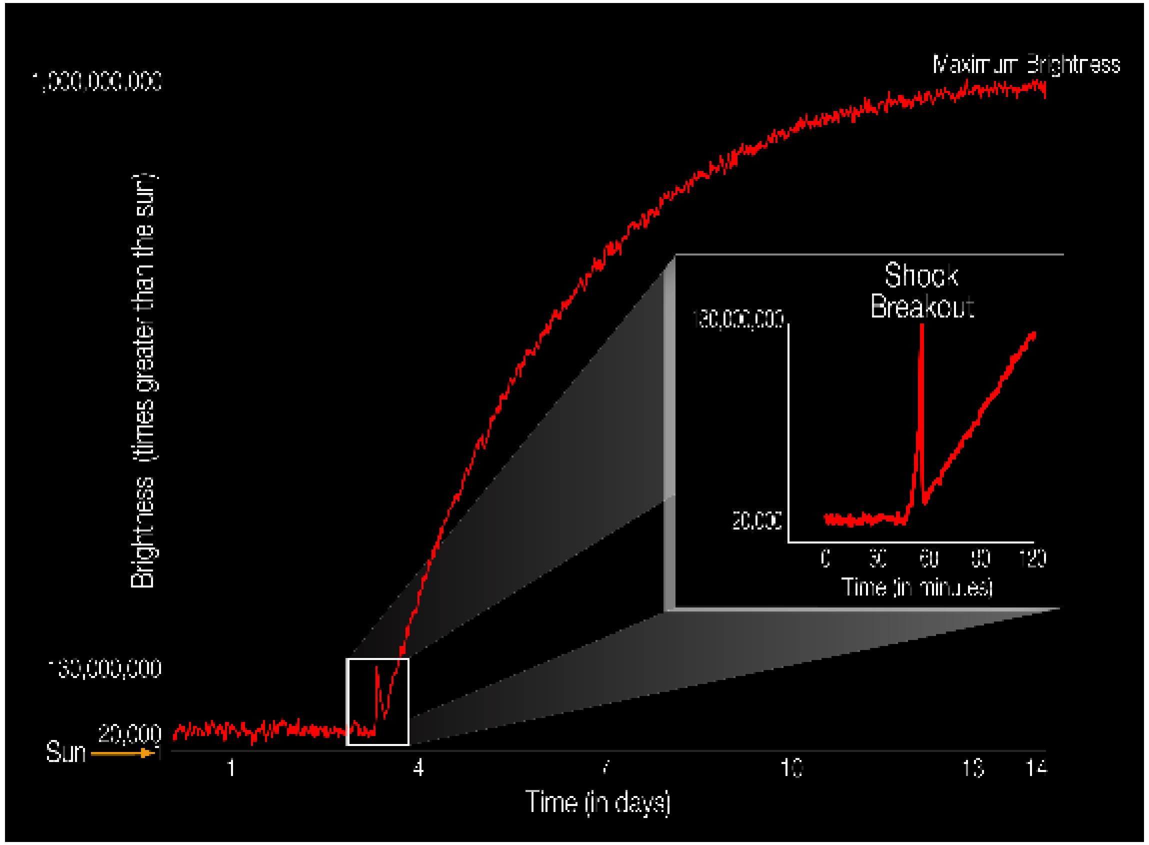
B. Type II supernovae are the final step in the evolution of massive stars (> 10 solar masses)

1) Fe-Ni core reaches 1.4 solar masses or more that cannot support itself
2) Rapidly collapses from a radius ½ that of Earth to 100 km
3) Core density reaches nuclear density, ~ 10^{14} g/cm^3
4) Nuclear strong force ceases to be attractive becoming repulsive

Stellar Nucleosynthesis

1) Core collapse takes a few 10th's of a second
   a. Outer core edges traveling ~70,000 km/s (0.25 c)
2) Photodisintegration reactions occur converting protons to neutrons
   a. Generates an enormous neutrino flux of ~16.8×10^{57} neutrinos
   b. Energy released in the neutrino flux is ~ 6.7×10^{46} J
3) Core rebounds through a hydrodynamic bounce
   a. ~ 0.7 solar masses of ^{56}Ni are made inside the core
   b. Takes about 20 ms for the shock wave to exit the core but ~ 2 hours for it to get out of the star
   c. Neutron star, pulsar, or a black hole remains from the core
4) Neutron star formation releases an amount of energy equal to 100 times that of the sun's entire lifetime E output or ~ same amount of energy emitted in the visible universe in 1 sec

March 2016, Kepler Telescope



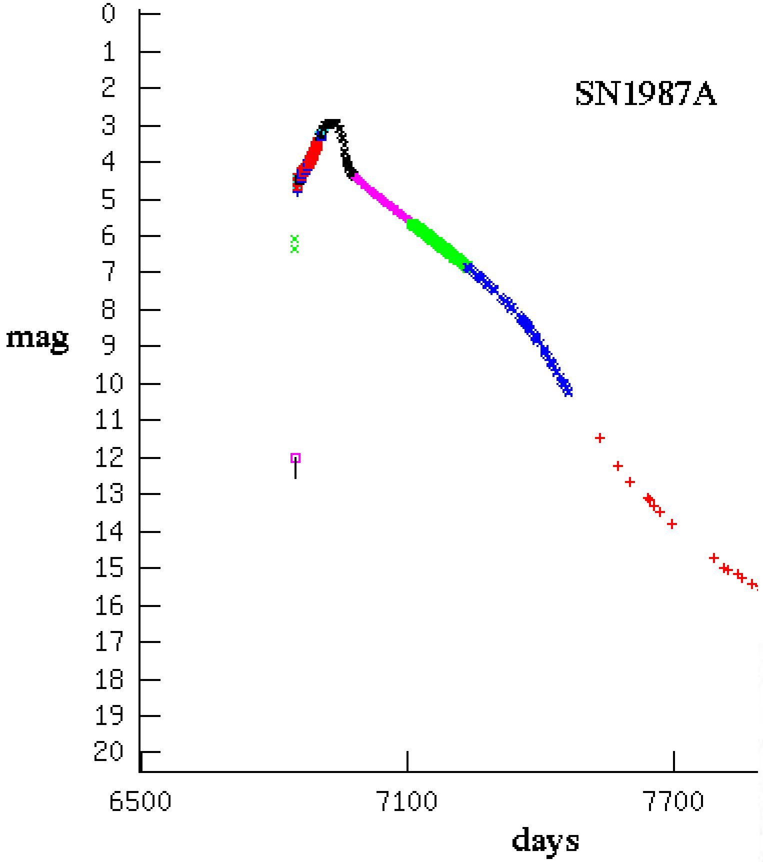
March 2016, Kepler Telescope

Supernova Shock Breakout Simulation

Stellar Nucleosynthesis

SN 1987A

Bolometric Decay Curve



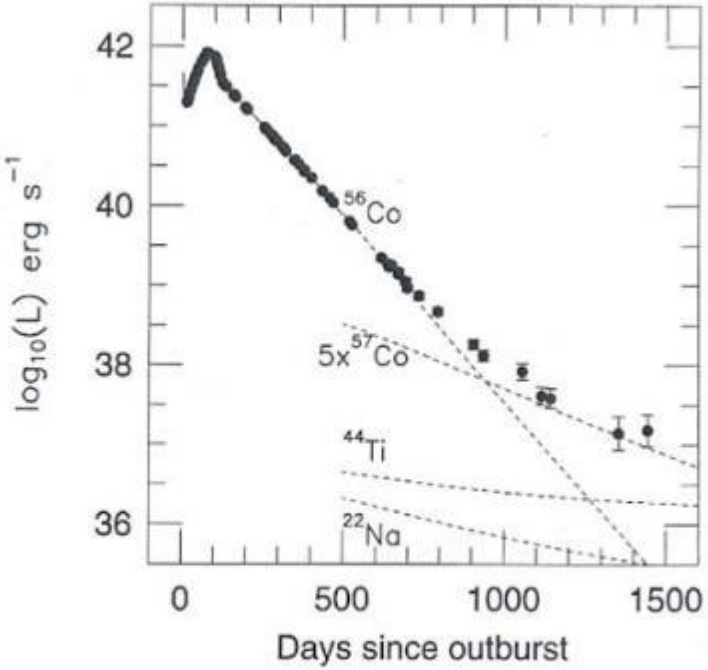
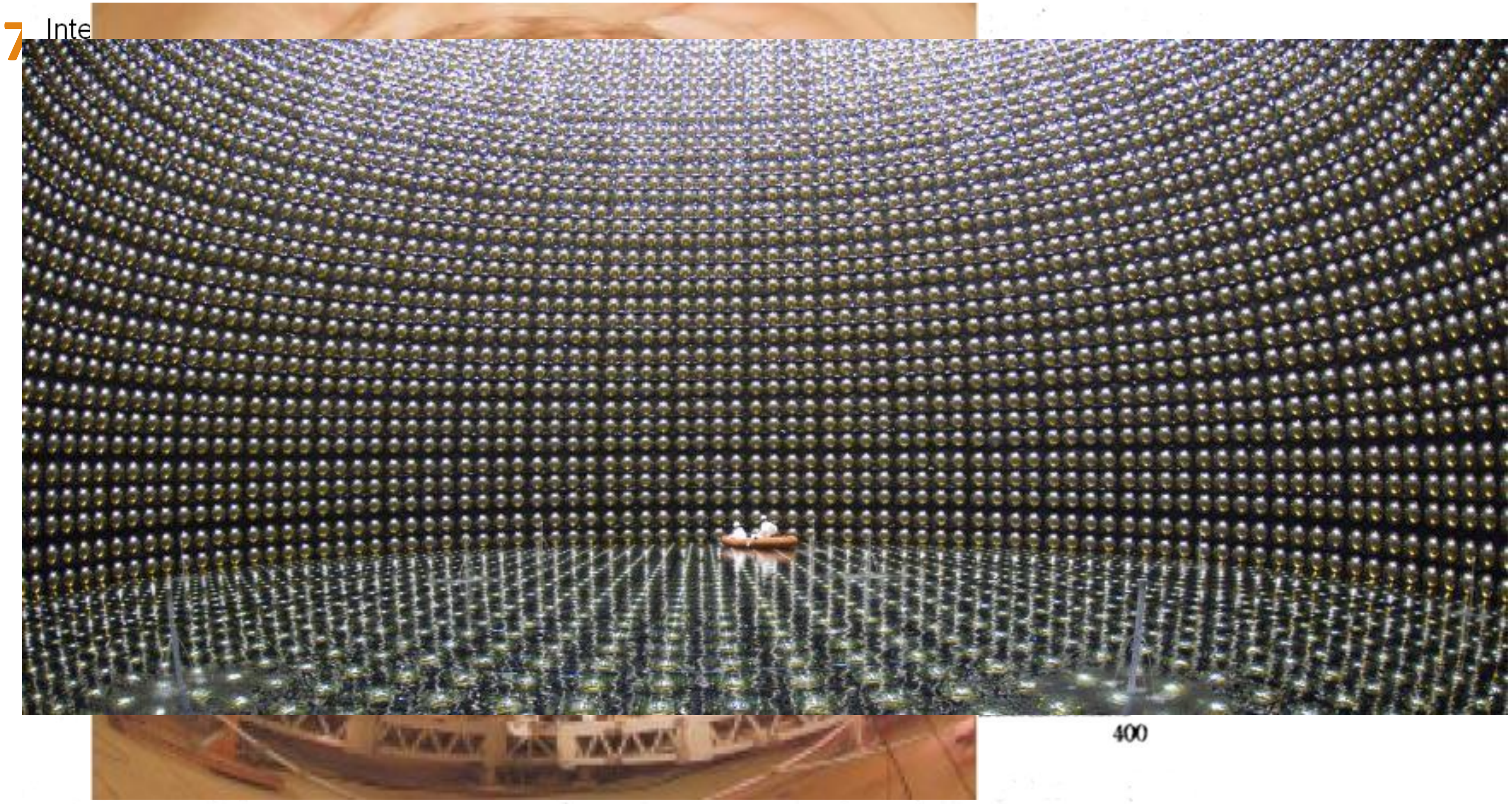


Figure 13.20 The bolometric light curve of SN 1987A through the first 1444 days after the explosion. The dashed lines show the contributions expected from the radioactive isotopes produced by the shock wave. The initial masses are estimated to be $^{56}_{28}$Ni (and later $^{56}_{27}$Co), 0.075 $M_\odot$; $^{57}_{27}$Co, 0.009 $M_\odot$ (five times the solar abundance); $^{44}_{22}$Ti, 1×10^{-4} $M_\odot$; and $^{22}_{11}$Na, 2×10^{-6} $M_\odot$. (Figure from Suntzeff et al., *Ap. J. Lett.*, *384*, L33, 1992.)

Stellar Neutrino Detection



1987-2-23 7:35:35 a.m. (world standard time)

Stellar Nucleosynthesis

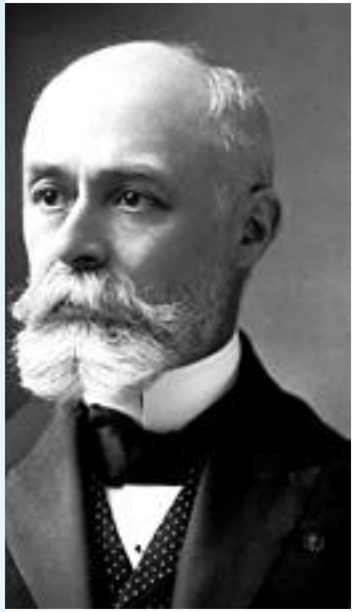
18. Synthesis of Be, B, and Li
    A. These elements cannot be synthesized in either stellar nucleosynthesis or by supernovae explosion
    B. Several theories as to their production have been made
        1) Spallation reactions in the interstellar medium
        2) Neutron flux from SN explosion impinging upon a H shell
        3) Cosmic ray reactions in the interstellar medium

D. History of Nuclear Science

Some Seminal Historic Events

Antoine H

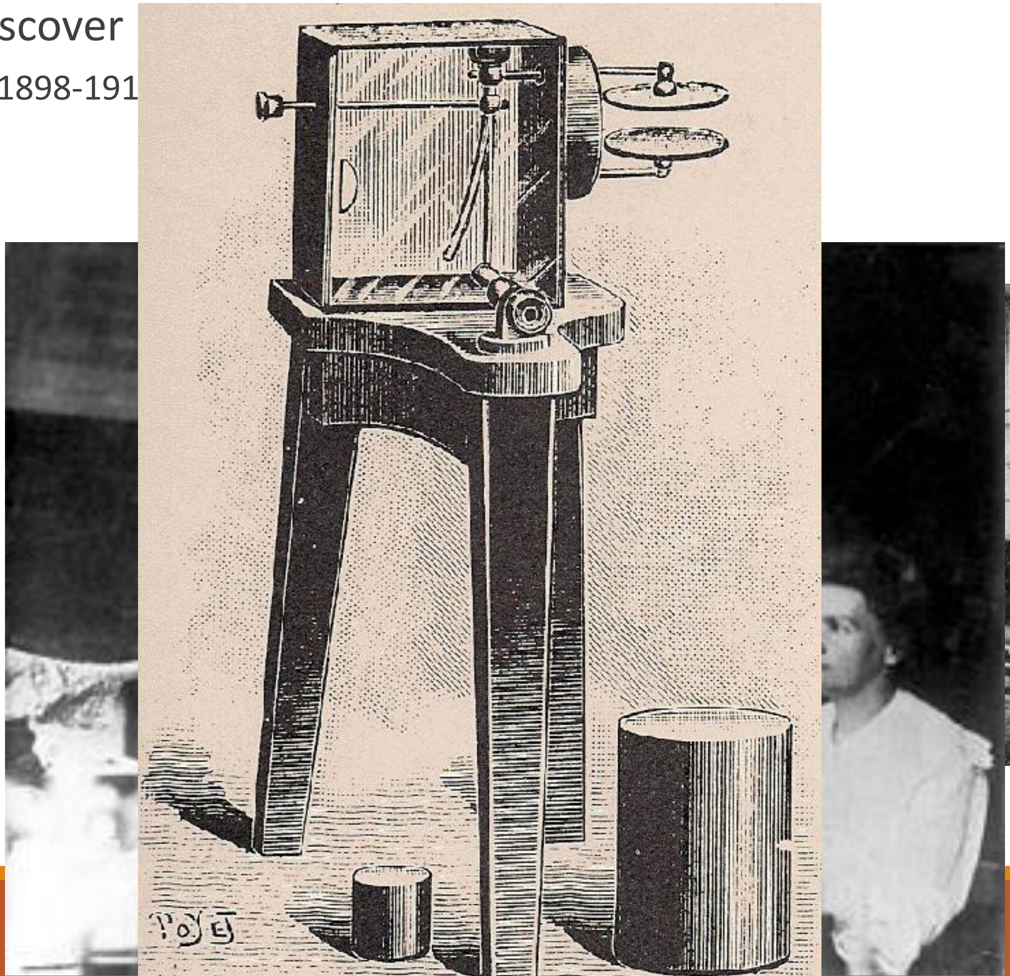
- Accider

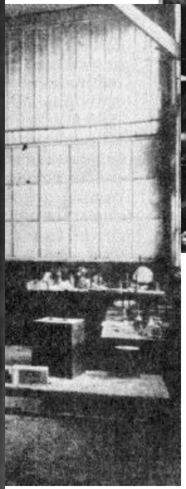


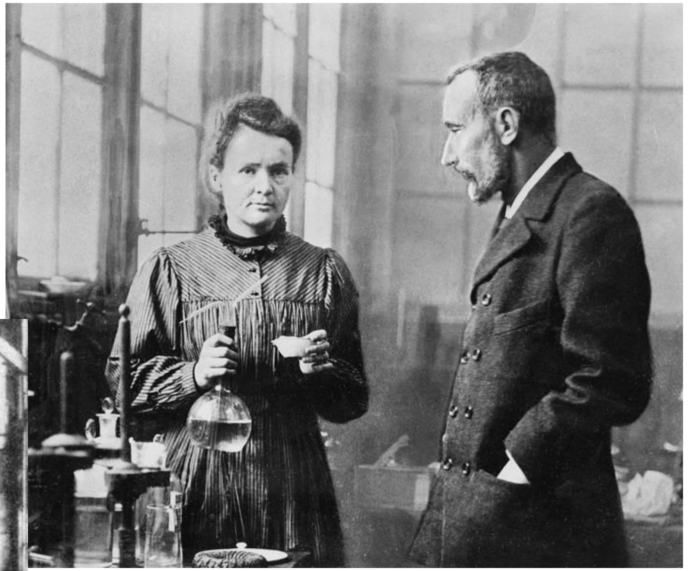
Some Seminal Historic Events

Pierre and Marie Curie

- Discover
  - 1898-191







Some Se… c Events

Ernest R…

Discov…

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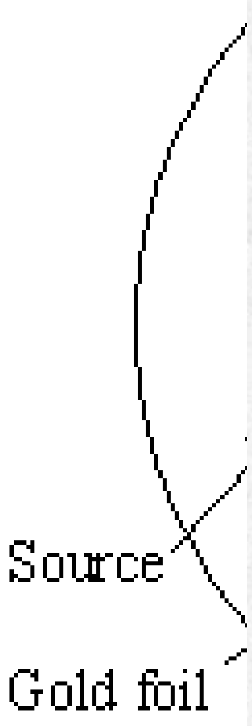
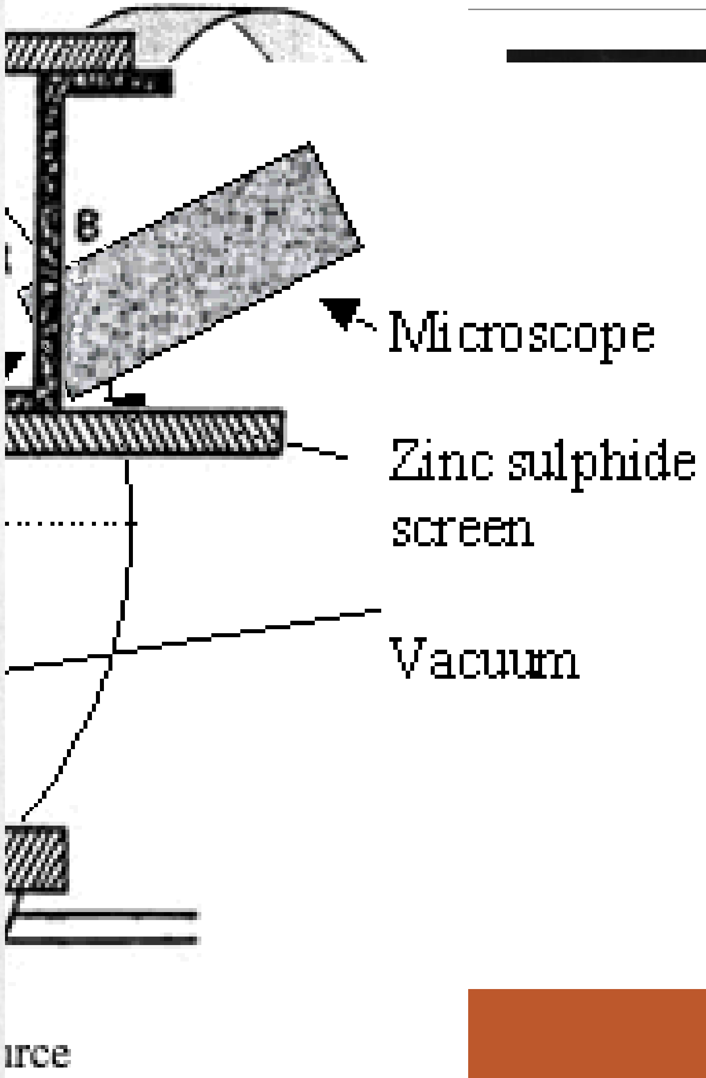




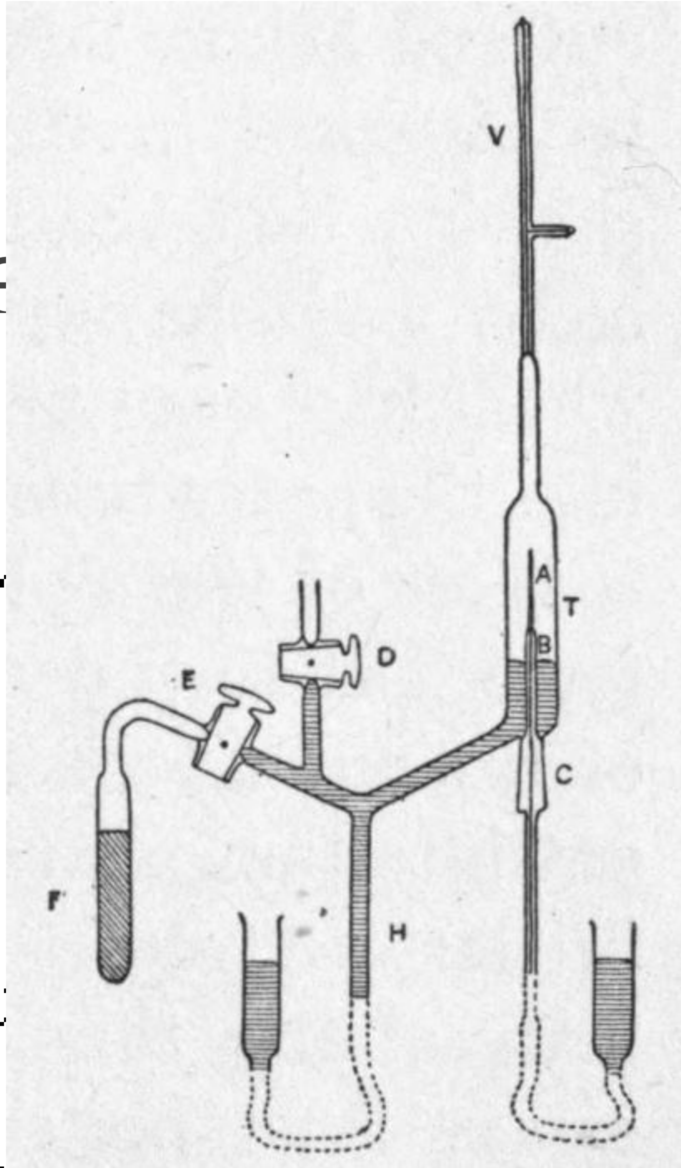


FIG. 7.—APPARATUS USED IN EXPERIMENT BY RUTHERFORD AND ROYDS.

Elementary Particles

1. Protons and Neutrons are not elementary particles
   - They are composed of other smaller particles
   - Can "see" these elementary particles in high energy nuclear reactions
2. Electron is an elementary particle

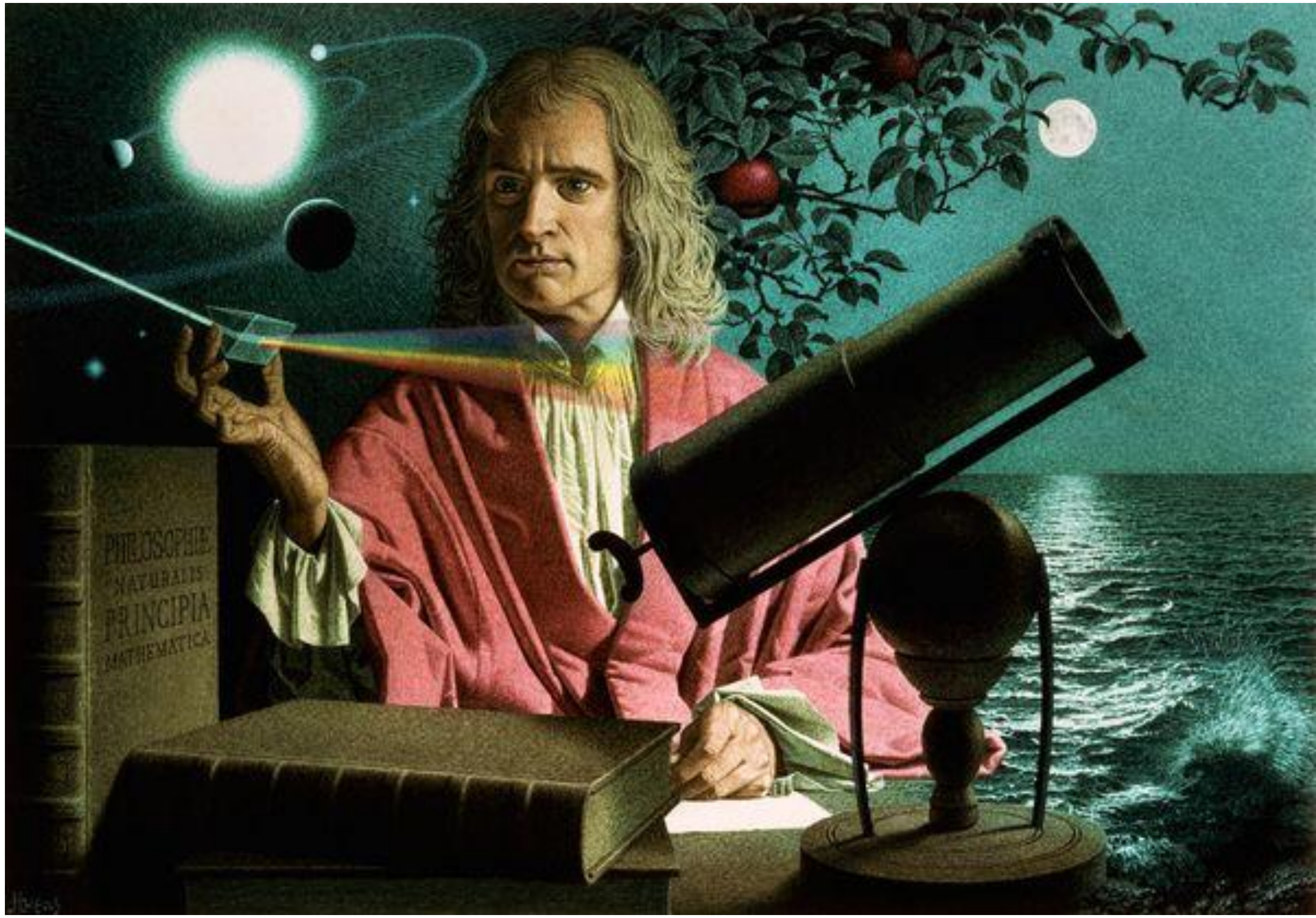
Four Fundamental Forces of Nature

1. Gravity
2. Weak force
3. Electromagnetic force
4. Strong force

Force	Relative Strength	Range	Exchange Particle	Spin	Rest Mass
Gravity	1	Very long (~ ∞)	Graviton	2	0
Weak	10^{25}	Very short	W^+, W^-, Z^0	1	80 – 90 GeV
Electromagnetic	10^{36}	long	Photon	1	0
Strong (nuclear)	10^{38}	10^{-14}	Gluon	1	0

Gravity

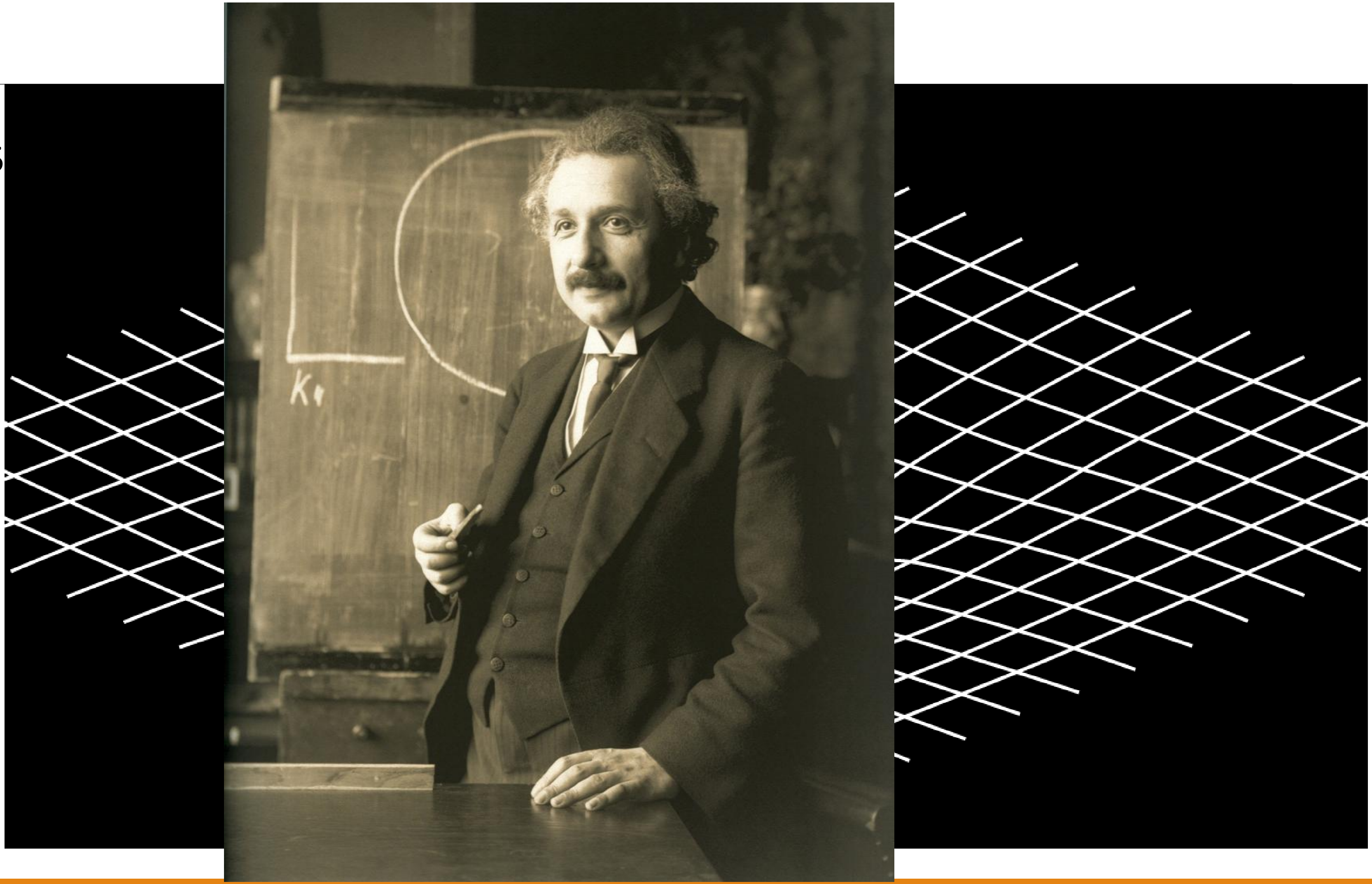
1. **First calculated by Isaac Newton -1600’s**



$$F_g = \frac{G \times m_1 \times m_2}{r^2}$$

Gravity

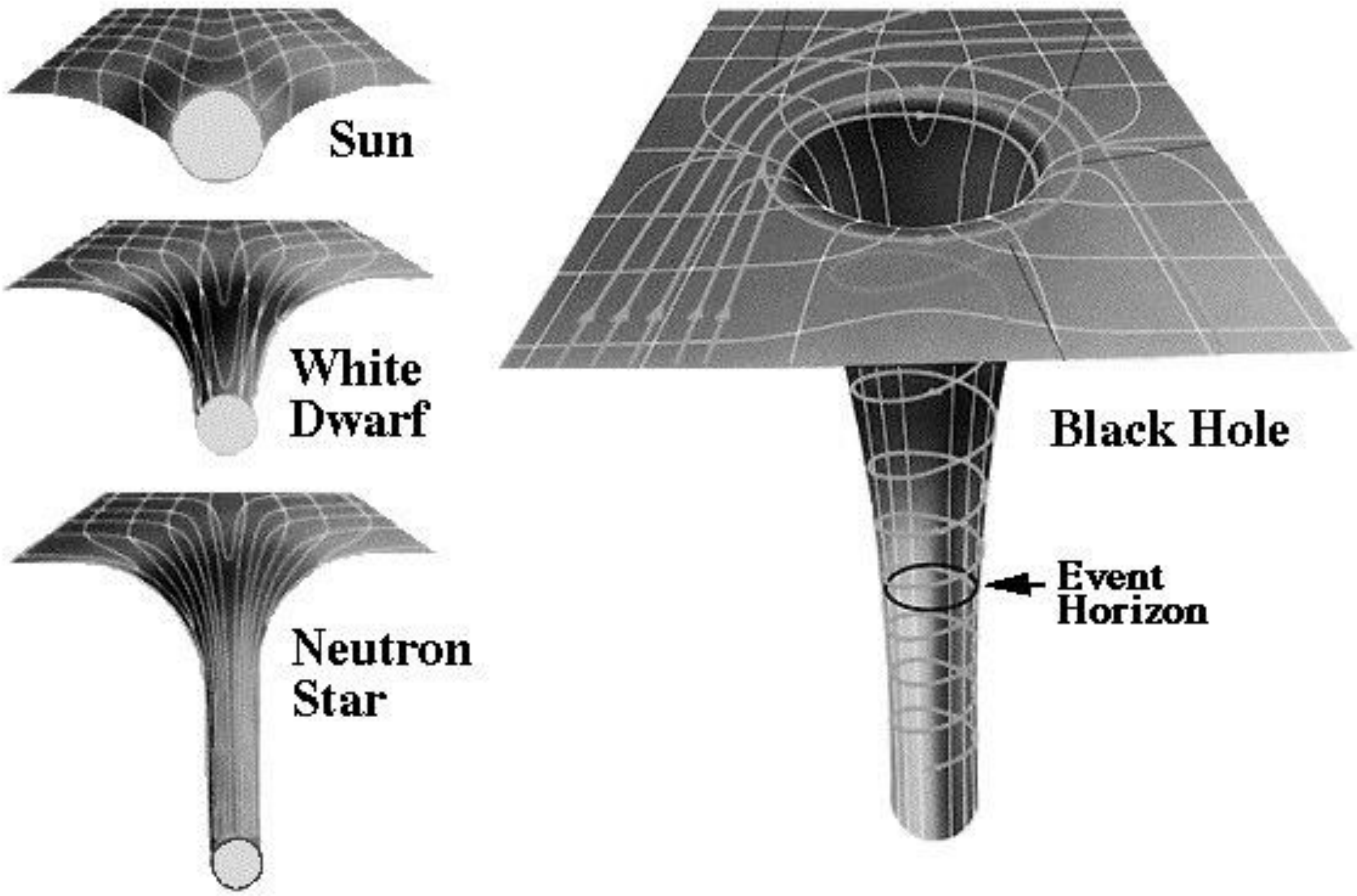
Explained by Einstein 1915



Gravity

https://www.youtube.com/watch?v=LoaOHvy5AcA

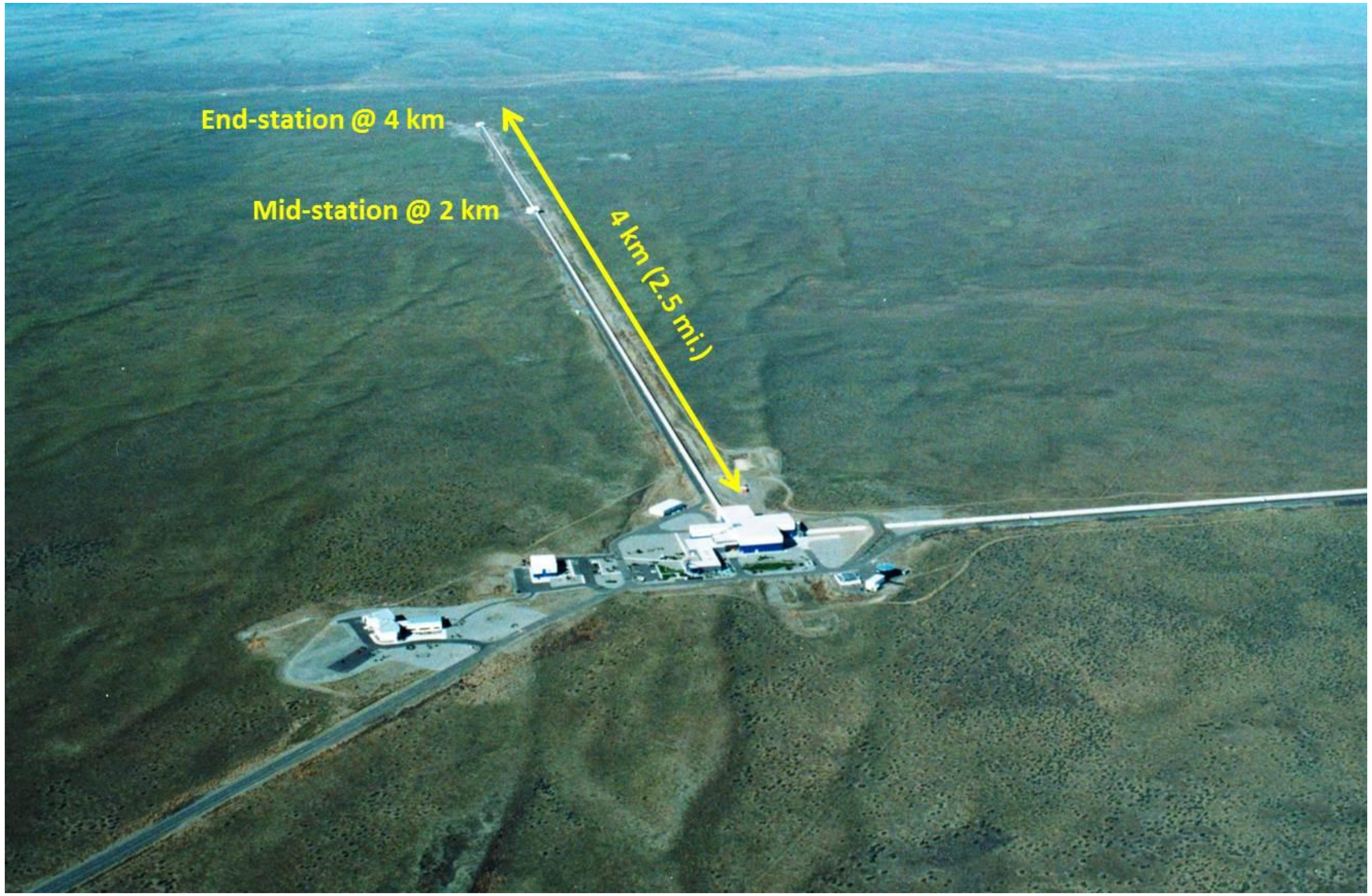
Gravity



Gravity

1. Table 2.1 has this interesting tidbit
   - graviton† †Not yet detected.
2. How would you design and build an experiment to detect gravitons (warping of space-time)?

LIGO – Laser Interferometer Gravity Wave Observatory



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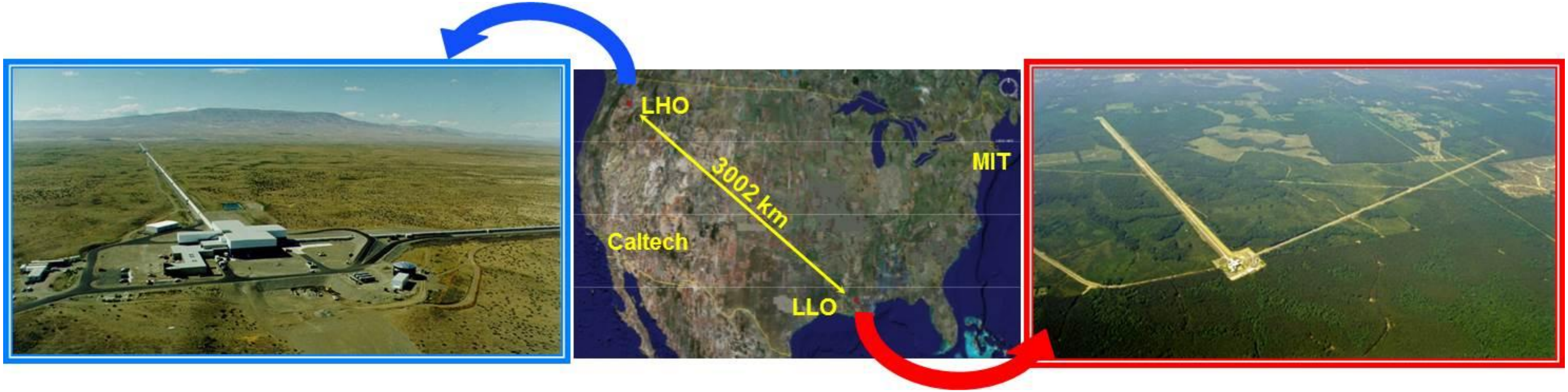

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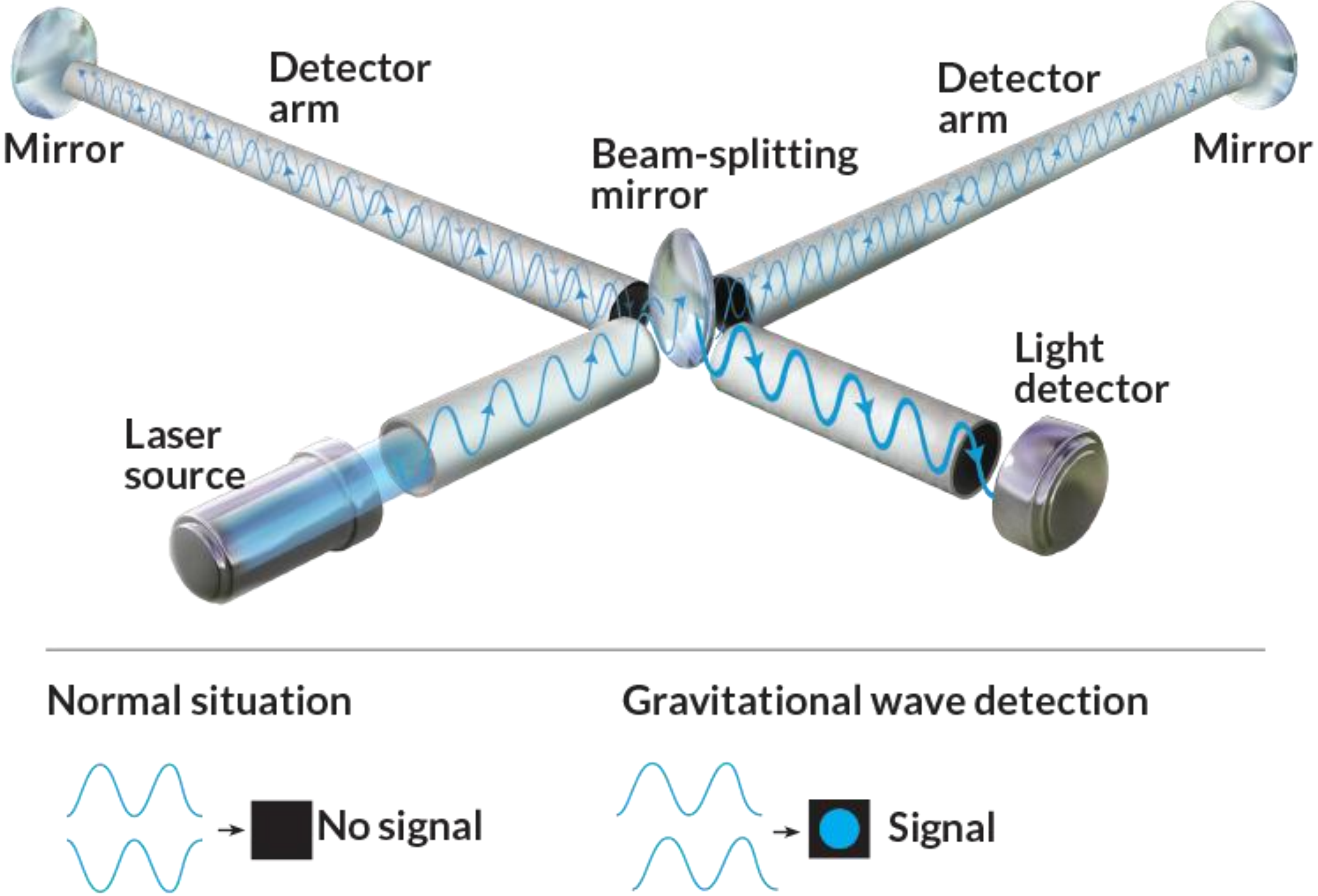
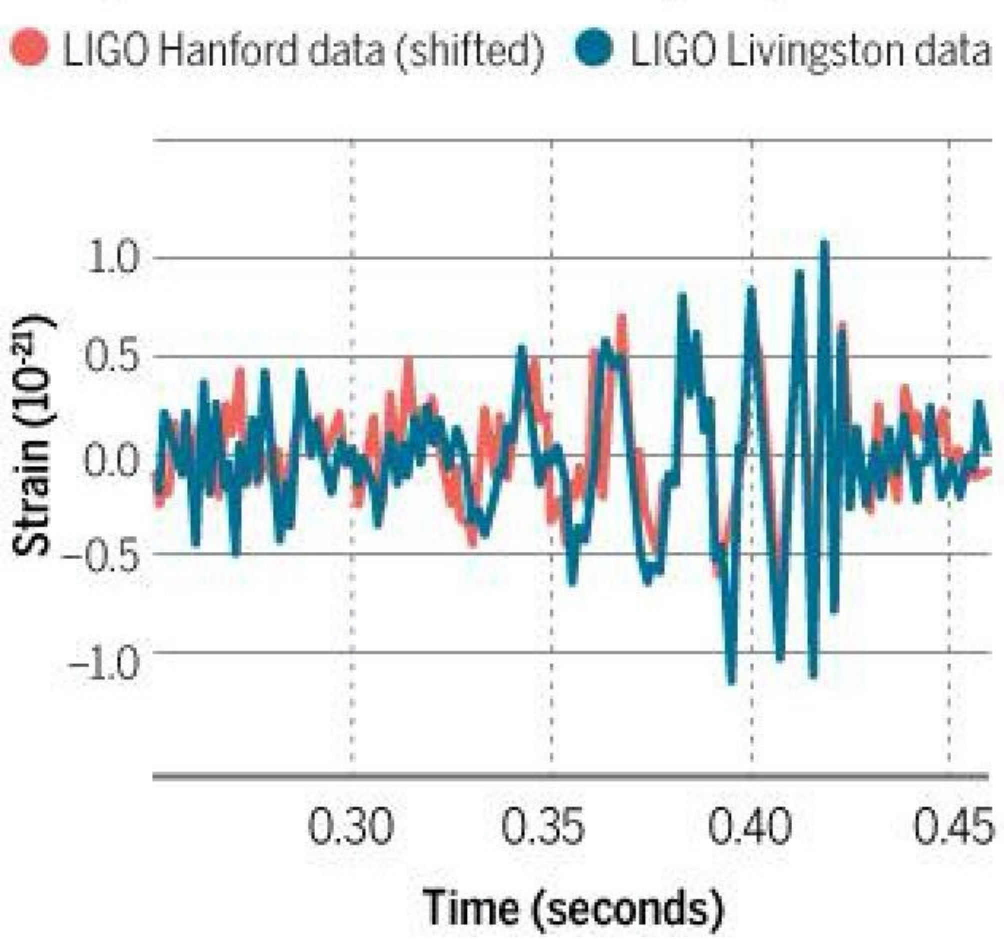


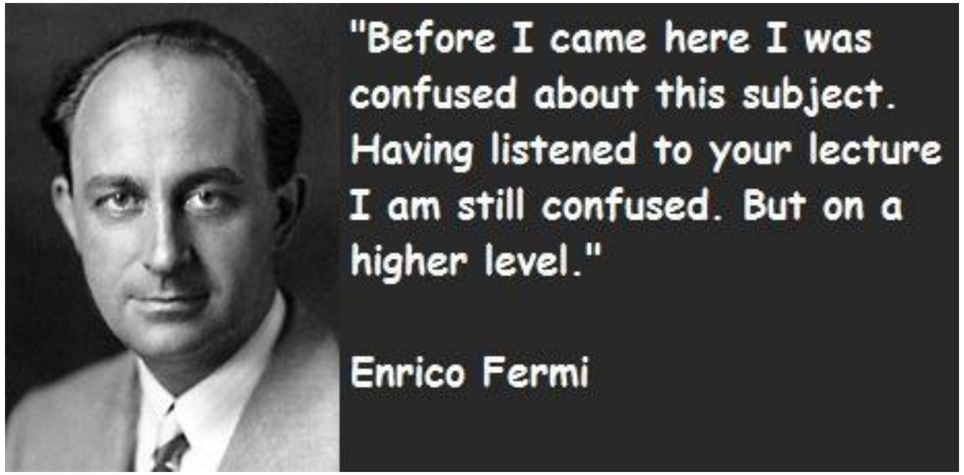
LIGO – Laser Interferometer Gravity Wave Observatory



14 September 2015, at 9:50:45 universal time—4:50 a.m. in Louisiana and 2:50 a.m. in Washington

Weak Force

1. Shortest ranged force - fm or less (1 fm = 10^{-15} m)
2. Weaker than strong and electromagnetic force but stronger than gravity
3. Cause of β radioactive decay
4. Lepton interactions
   - Electrons, muons, and neutrinos
5. Proposed by Enrico Fermi -1930's
   - Still being studied



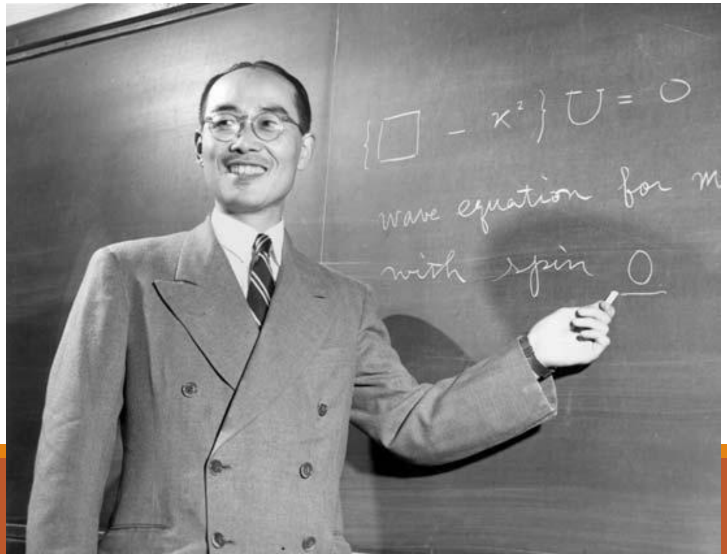
Electricity and Magnetism

1. **Long ranged force**
2. **Second strongest force**
3. **Holds atoms and molecules together**
4. **Explained by James Clerk Maxwell -1830's**
   - **Recognized that electricity and magnetism are manifestations of the same force**
5. **Described by Coulomb's Law**

$$F_e = \frac{-k_e \times z_1 \times z_2}{r^2}$$

Strong Force

1. Very short ranged force -1 fm ~ 10^{-15} m
2. Strongest force in nature ~ 10^{38} x stronger than gravity
3. Holds nuclei together
4. Proposed by Yukawa – 1930's
   - Still being studied
5. Has the shortest interaction time ~10^{-23} S



The Neutrino

- Predicted by Pauli – 1927
- Named by Fermi – 1928
- Confirmed by Reines and Cowan – 1956
- We will frequently use the electron neutrino both the matter and antimatter version
  - β^- decay emits $\bar{\nu}$
  - β^+ decay emits ν
- All neutrinos have spin, no charge
- Neutrinos oscillate between each flavor $\nu_e \leftrightarrows \nu_\mu \rightleftarrows \nu_\tau$
- Neutrino flux at Earth's surface is 6.5 x 10^{10} s^{-1} m^{-2}
- It does not appear that the neutrino rest mass is sufficient to close the Universe

HOW DO THESE FORCES INTERACT WITH EACH OTHER?

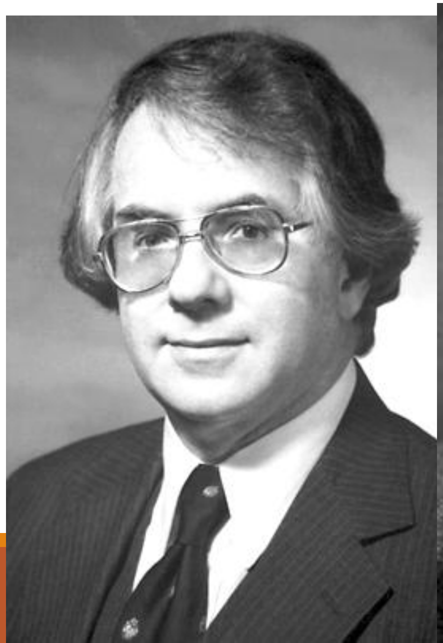
1. **Glashow, Weinberg, and Salam**

   electroweak interactions -1960's

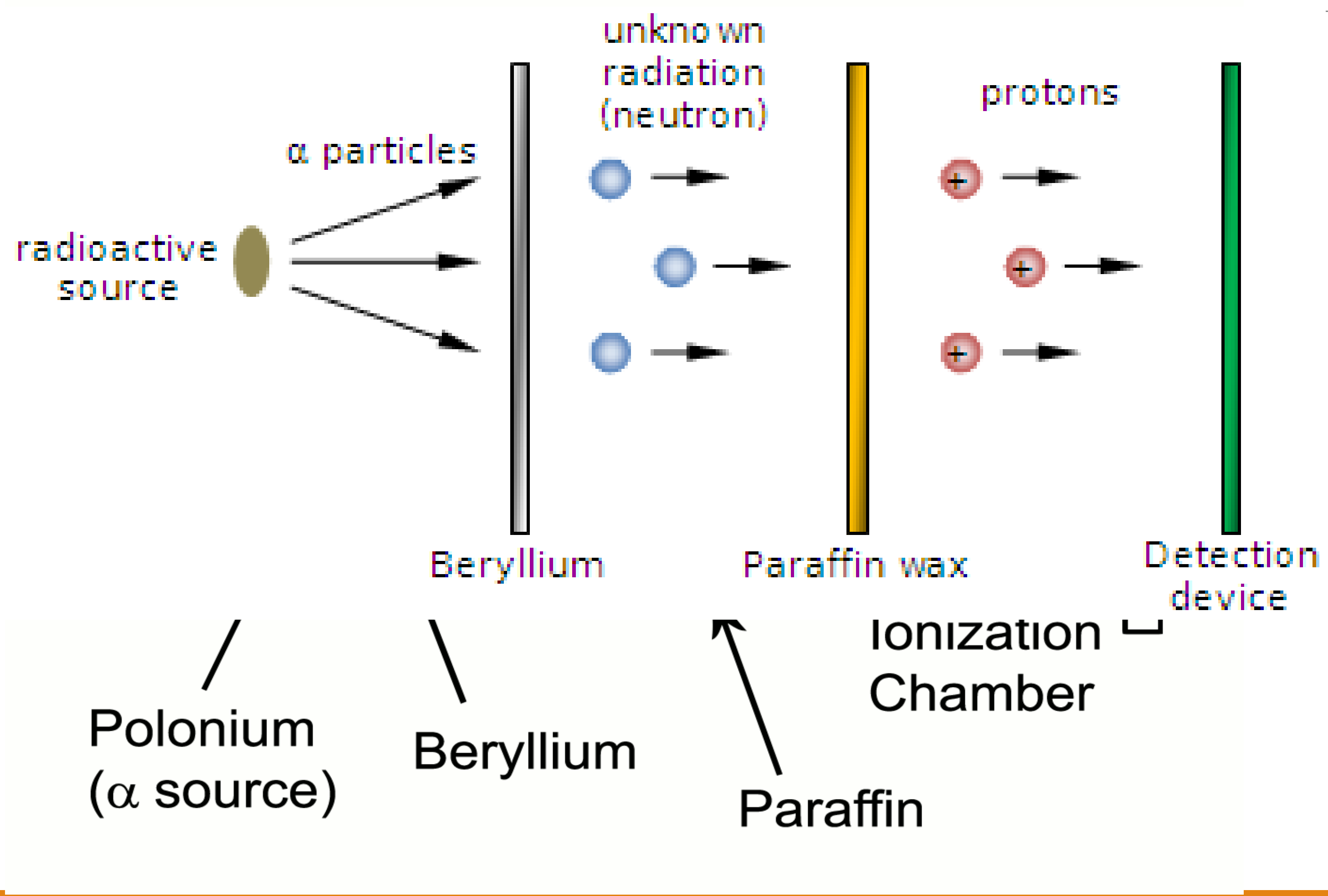
2. **Murray Gell-Mann**

   description of strong force -QCD -1970's

3. **Today we are looking for a Grand Unified Theory (GUTs)**

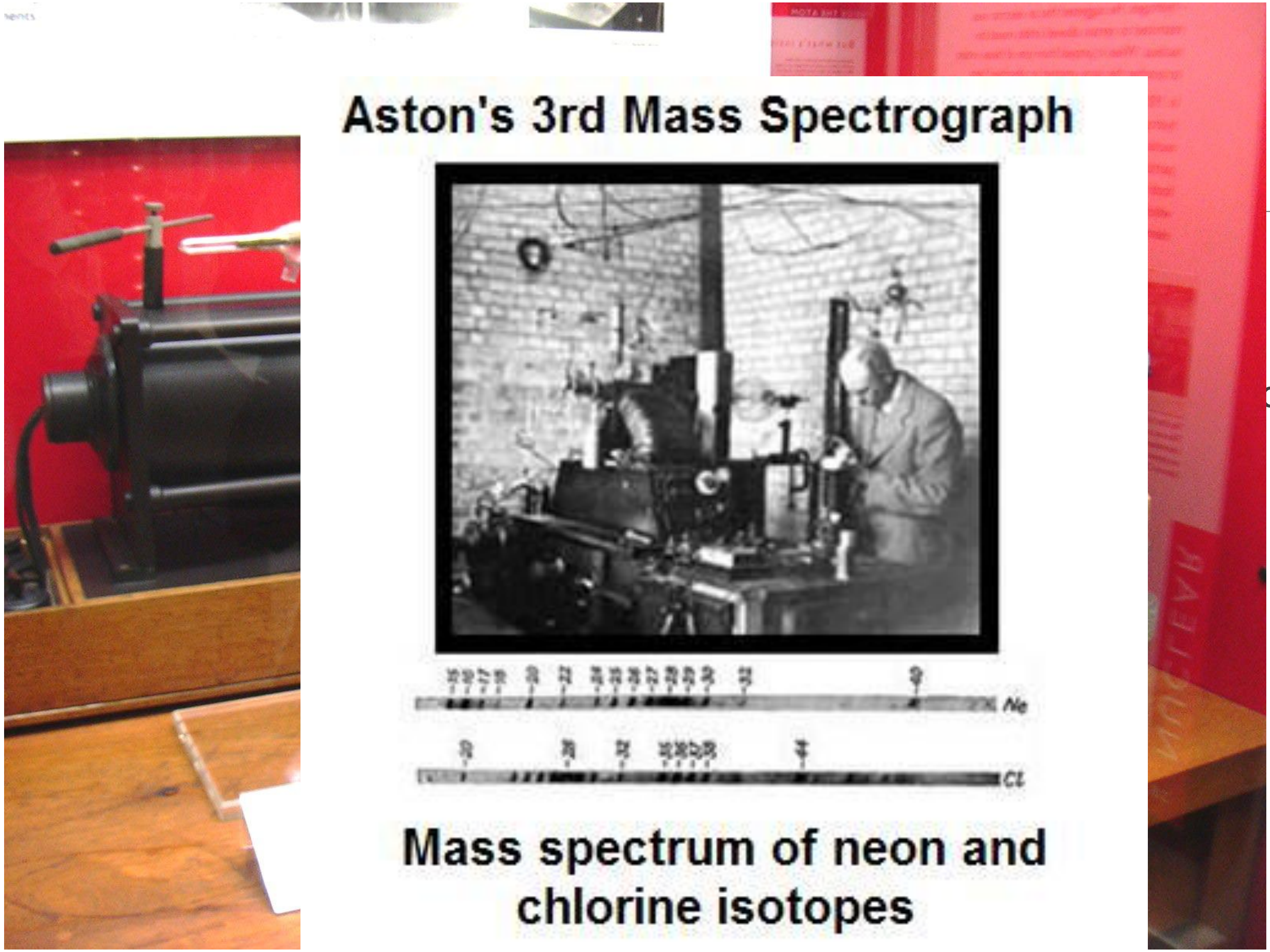


History of Nuclear Chemistry and Physics



Summary of Electron, Proton, and Neutron Properties

Particle	Charge/mass (C/g)	Charge (C)	Mass (kg)	Mass (amu)	Mass (MeV)
Electron	-1.759×10^{8}	-1.602×10^{-19}	9.109×10^{-31}	0.00055	0.511
Proton	$+9.58 \times 10^{4}$	$+1.602 \times 10^{-19}$	1.673×10^{-27}	1.00728	938.272
Neutron	0.00	0.00	1.675×10^{-27}	1.00867	939.566
1 amu = 931.5 MeV					


Aston's 3rd Mass Spectrograph
Ne
Cl
Mass spectrum of neon and chlorine isotopes