Free Neutrons, Fission and Spallation

Eron Cemal - Matteo Bianchini

29/01/2015

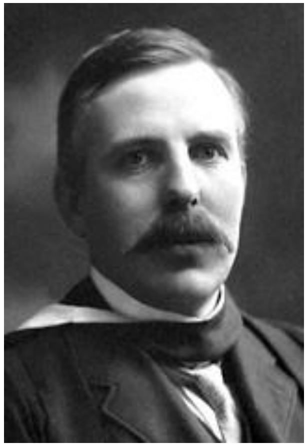
Overview

Part 1: The Neutron
- History and the neutron
- Intrinsic Properties
- Interactions: strong, weak, electromagnetic & gravity

Part 2: Neutron production
- Fusion reactions
- Fission reactions
- Spallation sources

Part 3: Neutrons capture and decay
- Where do neutrons go? Beta-decay & absorption
- Absorption materials
- Naturally occurring spallation in atmosphere and ^{14}C
- Neutrons in the universe

History: early days of the atom



Ernest Rutherford

- **1908**: proves that alpha radiation is He^{2+}
- **1911**: Rutherford's model of the atom → Idea of a nucleus

Problem: how to explain the difference between atomic number and measured atomic mass??

- **1920**: he suggests that a neutrally charged particle might exist in the nucleus

Nuclear electron hypothesis: he considered the required particle to be a neutral double of the p^+ consisting of an e^- closely orbiting a p^+. (This explained beta-radiation (e^-s) emitted from the nucleus).

Nuclear electrons hypothesis

Rutherford considered the required particle to be a neutral double of the p^+ consisting of an e^- closely orbiting a p^+. (This explained beta-radiation (e^-s) emitted from the nucleus).

SEVERAL PROBLEMS:
One for all, Heisenberg's uncertainty principle (**1927**): $\Delta x \cdot \Delta p \geq \frac{1}{2}\hbar$

It implies that an e^- confined to a region the size of an atomic nucleus (10^{-15} m) should have a kinetic energy of 10–100 MeV. This energy is larger than the binding energy of nucleons and larger than the observed energy of beta particles emitted from the nucleus.

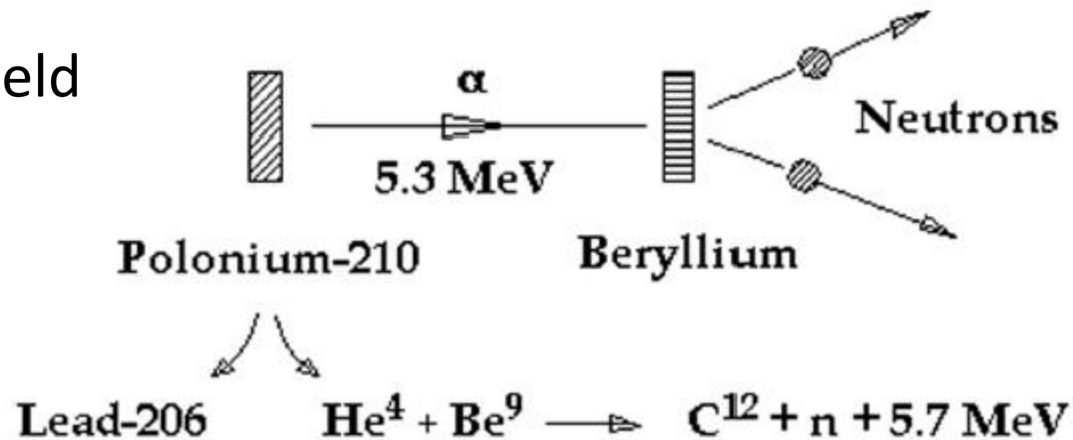
Discovery of the neutron

1931: **Bothe** and **Becker** (Giessen, Germany)

Very energetic α particle incident on light elements as Be, B, Li produced a radiation:

- highly penetrating
- Not influenced by electric field

→Initially it was thought to be gamma rays.



BUT **INCONSISTENT**

Radiation was actually too penetrating

When falling on paraffin (hydrogen-rich) it ejected protons of very high energy

History: Discovery of the neutron

$$^{9}Be + \alpha\ (^{4}He^{2+}) = {}^{12}C + {}^{1}n + 5.7\ MeV$$

James Chadwick (Cavendish Lab, Cambridge)

- 1920s: searched for Rutherford's neutral particle
- 1932: He repeated this reaction and showed that gamma-ray hypothesis was uncorrect.
- **NEUTRONS!**

Conservation of mass: the neutron exists and it shall have the same mass of the proton!

History: Discovery of the neutron

312 *NATURE* [FEBRUARY 27, 1932

Letters to the Editor

[*The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of* NATURE. *No notice is taken of anonym*

Po

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This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec.

tum responsible

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the two hypo-
evidence is in
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point.

J. CHADWICK.

1935: Chadwick won the Nobel Prize in Physics "for the discovery of the neutron".

Proton-neutron model of the nucleus

Neutron's existence is rapidly accepted.
1940: Heisenberg and Ivanenko propose a proton-neutron model of the nucleus
(But the exact nature of neutrons was not clear, and they still thought the neutron is a sort of proton-electron composite).

BUT could the model explain the origins of beta radiation from a nucleus?
i.e. how could an electron possibly be emitted from a nucleus composed by proton + neutron ?

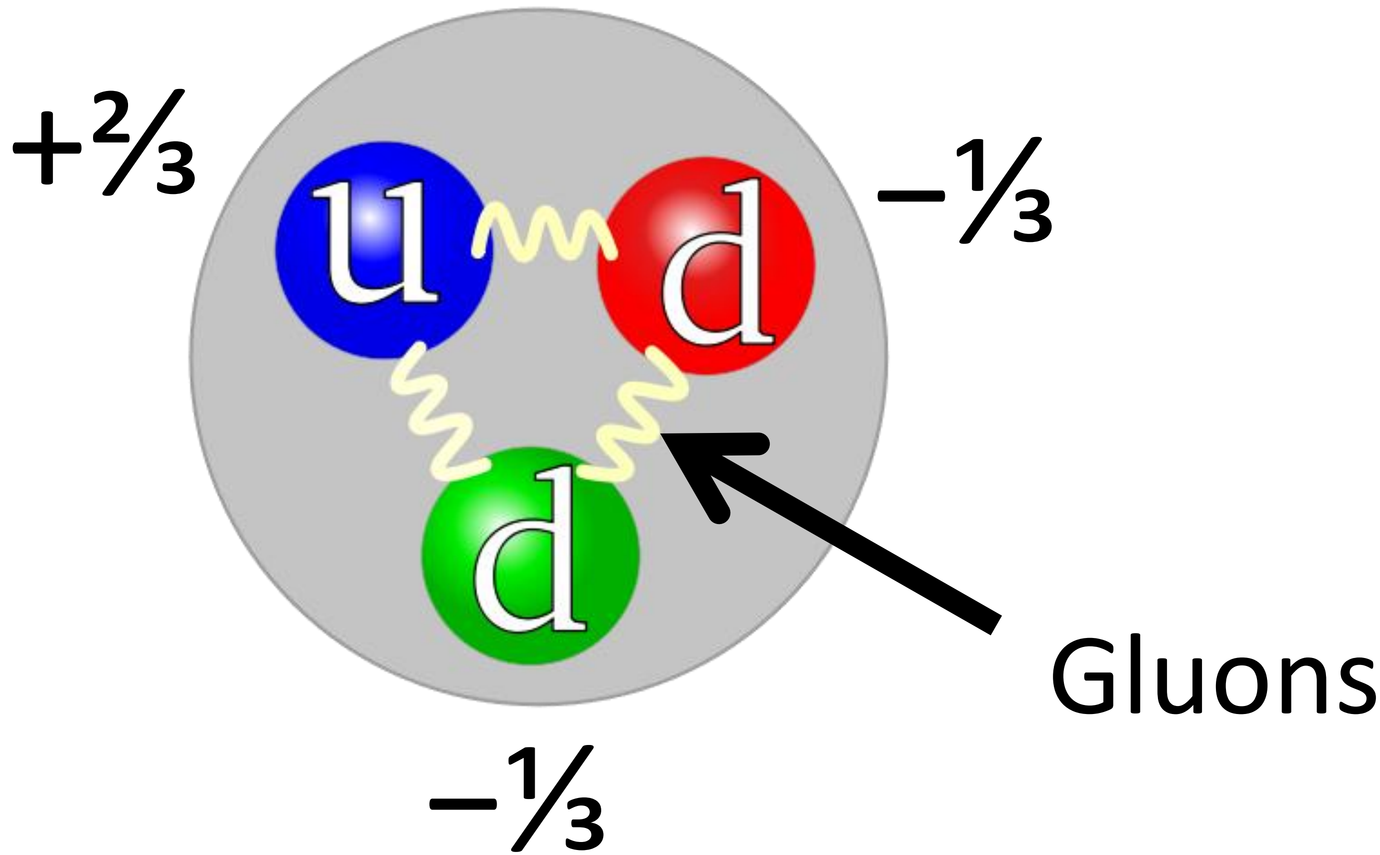
1934: Enrico Fermi: theory of beta-decay

SPOILER: $$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$$

Properties of a neutron

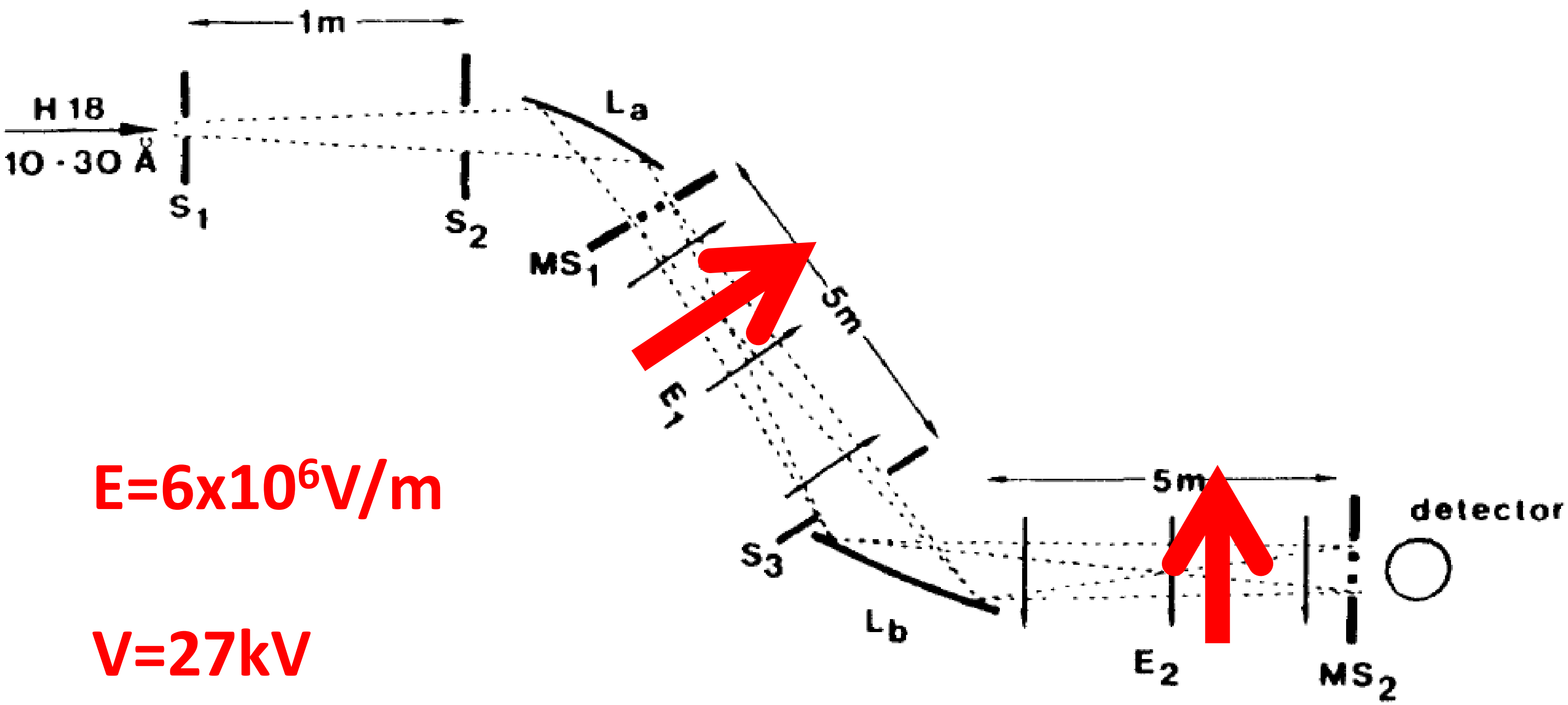
Property		
Quark structure	udd	
Electric charge	q_n=-0.2(8) x10^{-21}e	ILL(1987)
Electric dipole moment	dn>2.9x10^{-26} e cm	ILL(2006)
Mass	m_n=1.00866491600(43)u	ILL(1999)
Spin	1/2	
Magnetic moment	−1.91304272(45) μ_N	
Lifetime	880(1) s	

Neutron



http://upload.wikimedia.org/wikipedia/commons/8/81/Quark_structure_neutron.svg

Charge of Neutron



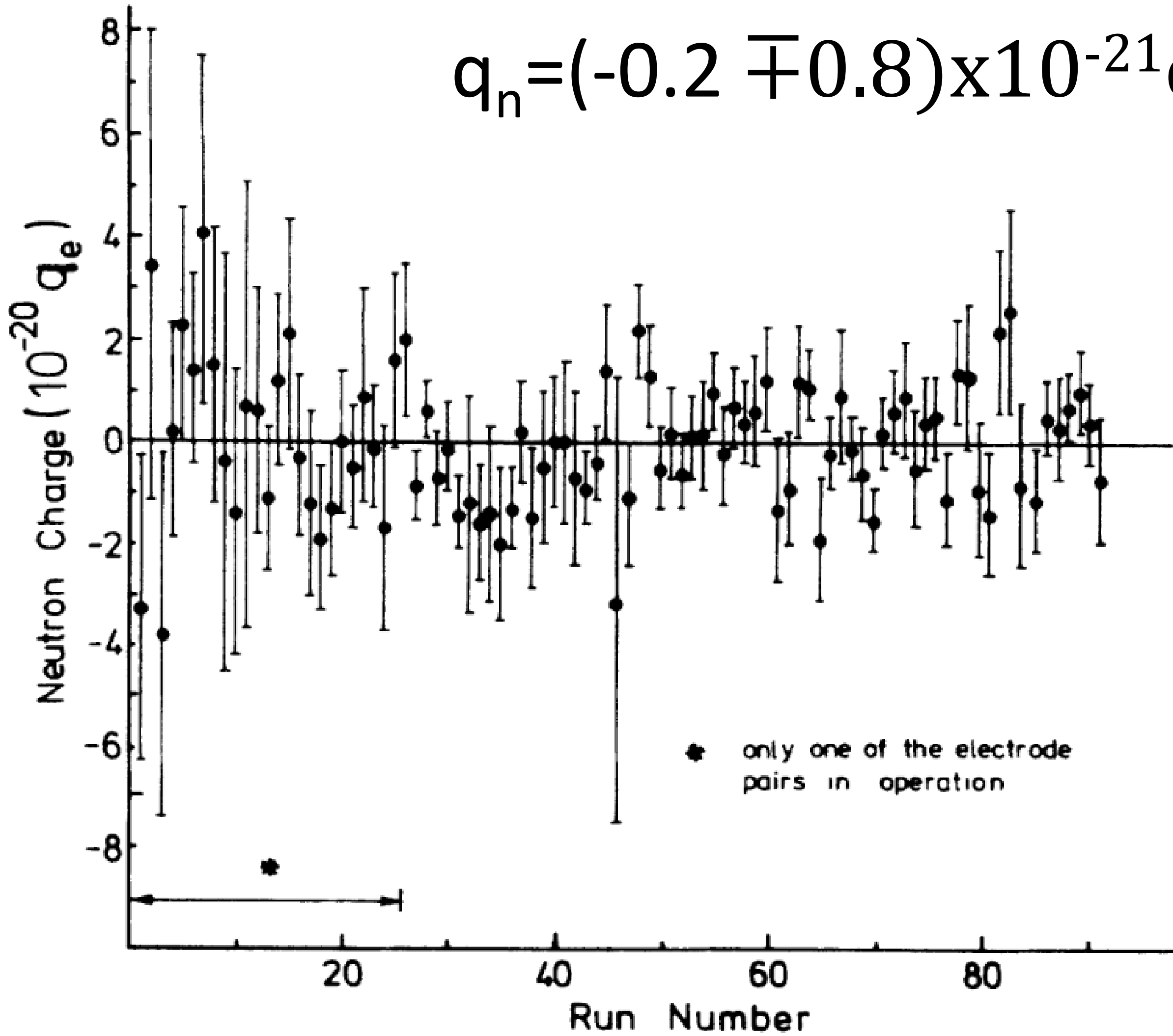
$E = 6 \times 10^6 V/m$

$V = 27 kV$

J Bauman et al PHYSICAL REVIEW D,**37**,11,(1988)

Charge of Neutron

$q_n = (-0.2 \mp 0.8) \times 10^{-21} e$



88 days (ILL)

J Bauman et al PHYSICAL REVIEW D,**37**,11,(1988)

Mass of neutron

$$p+n \rightarrow {}^{2}D+\gamma$$

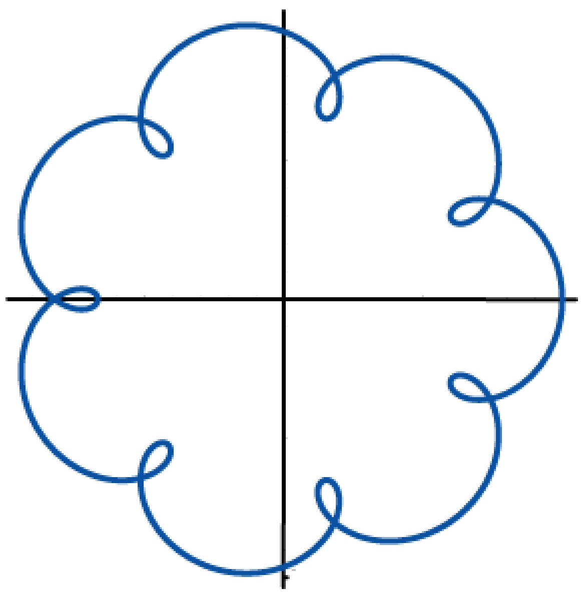
Mass known

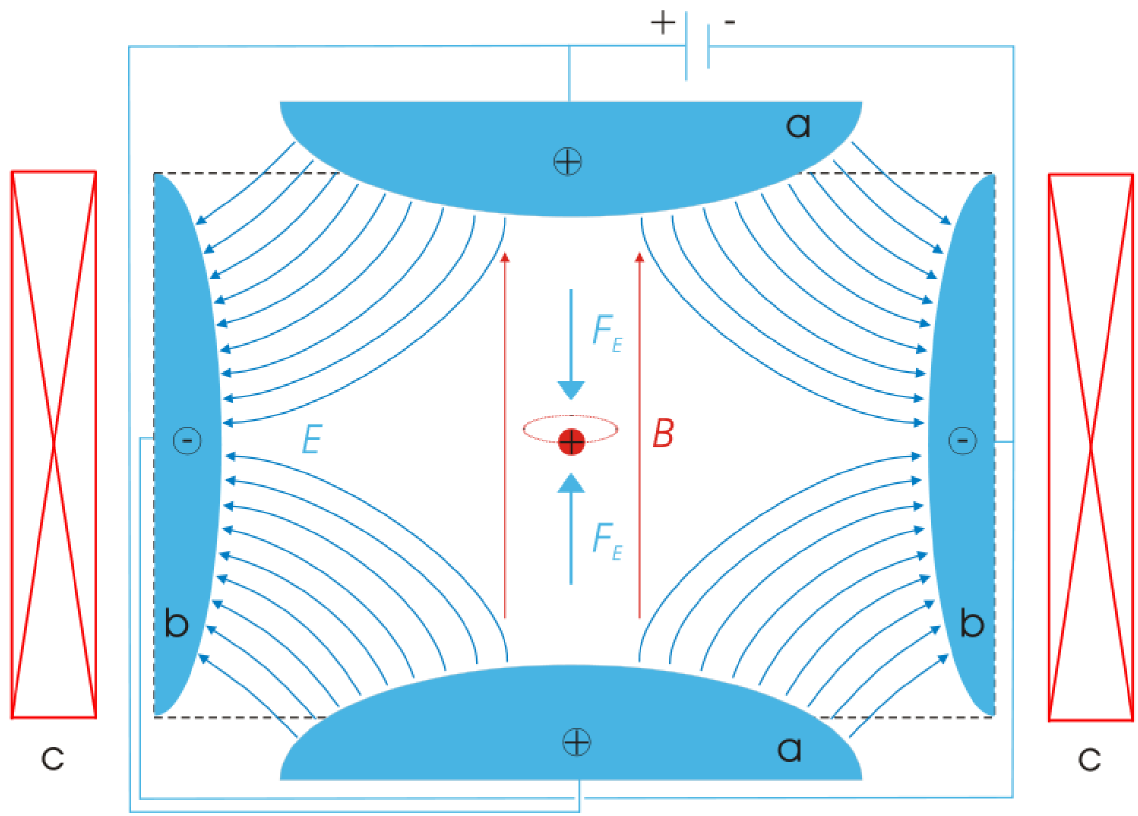
$\sim$2.2MeV

Mass of ^{1}H and ^{2}H

- Penning trap

ω_E, ω_B



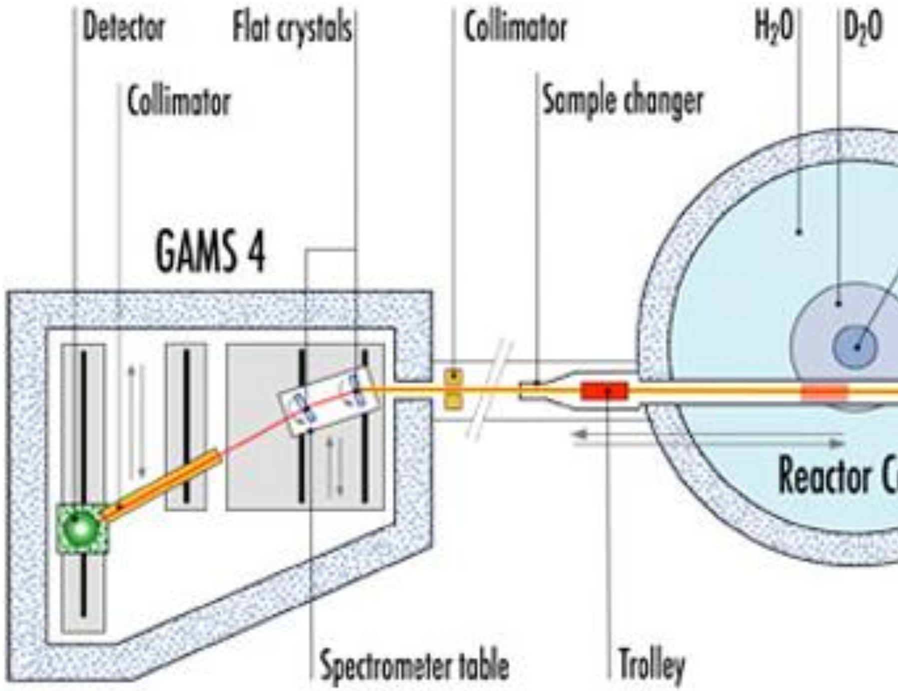


http://en.wikipedia.org/wiki/File:Penning_Trap.svg

GAMS4 (ILL+NIST)

- Perfect Si Crystals
- Lattice parameters
- Angles with interferometers
- Controlled environment

- θ_B=0.083202185(11)



Mass of neutron

2224566.14(41)eV

$$p + n \rightarrow {}^{2}D + \gamma$$

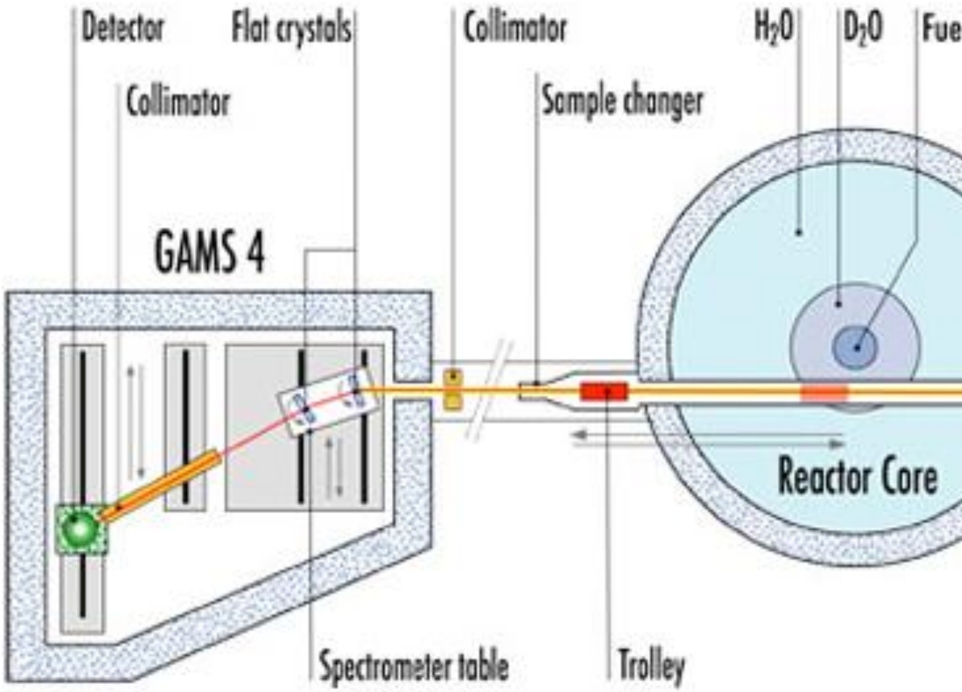
Therefore:

1.00866491600(43)u

Test of E=mc^2

$^{28}Si+n \rightarrow {}^{29}Si+\Sigma_i \gamma_i$

GAMS4 (ILL+NIST)



Accuracy= $4x10^{-7}$

Jentschel, M., et al, Eur. Phys. J. Special Topics **172**, 353 (2009)

Neutron spin

$s = \frac{1}{2}$

$s = 1$

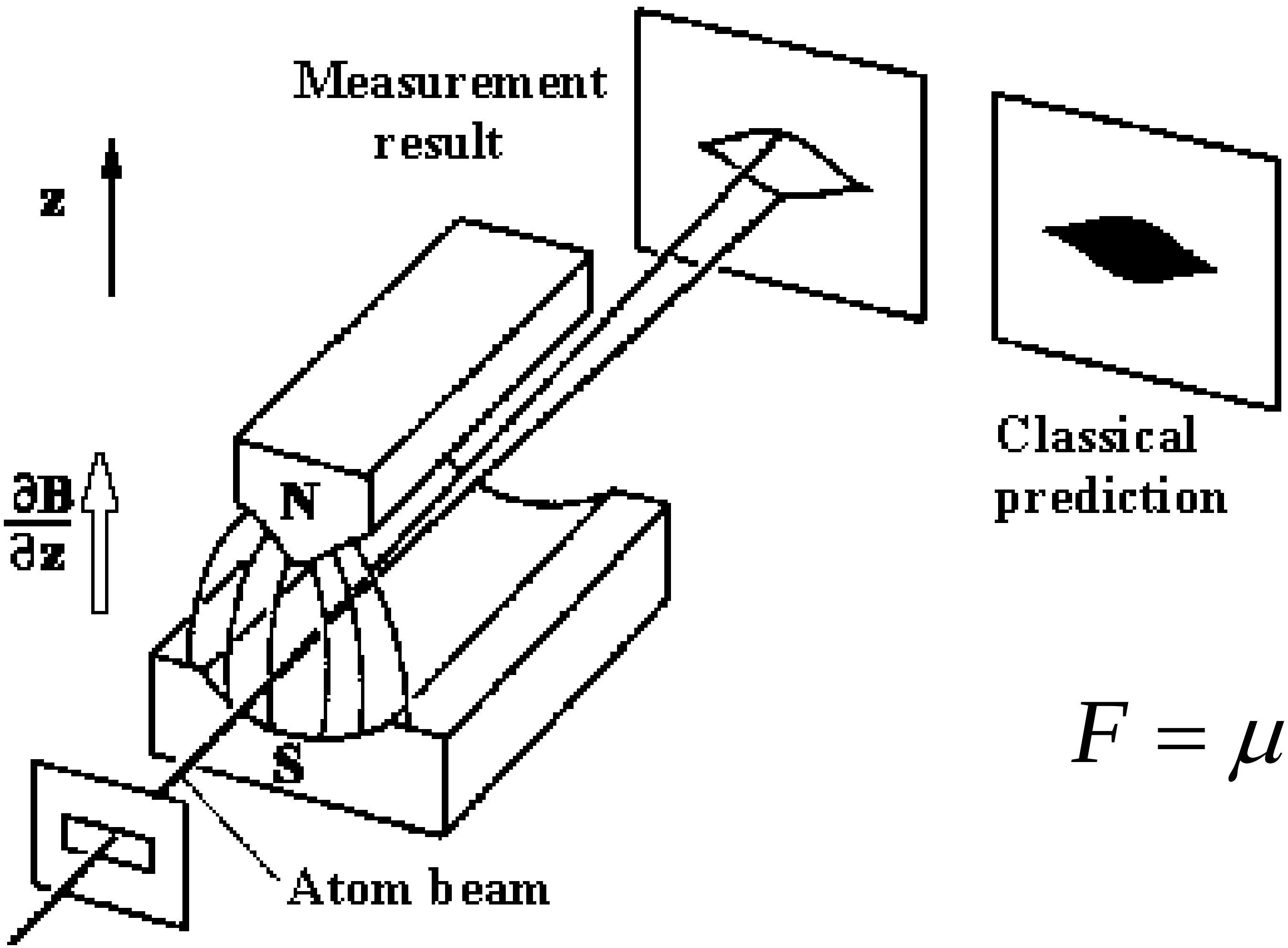
$$p + n \rightarrow {}^{2}D + \gamma$$

$s = ??$

$s = 0$

$\frac{1}{2}$ or $3/2$

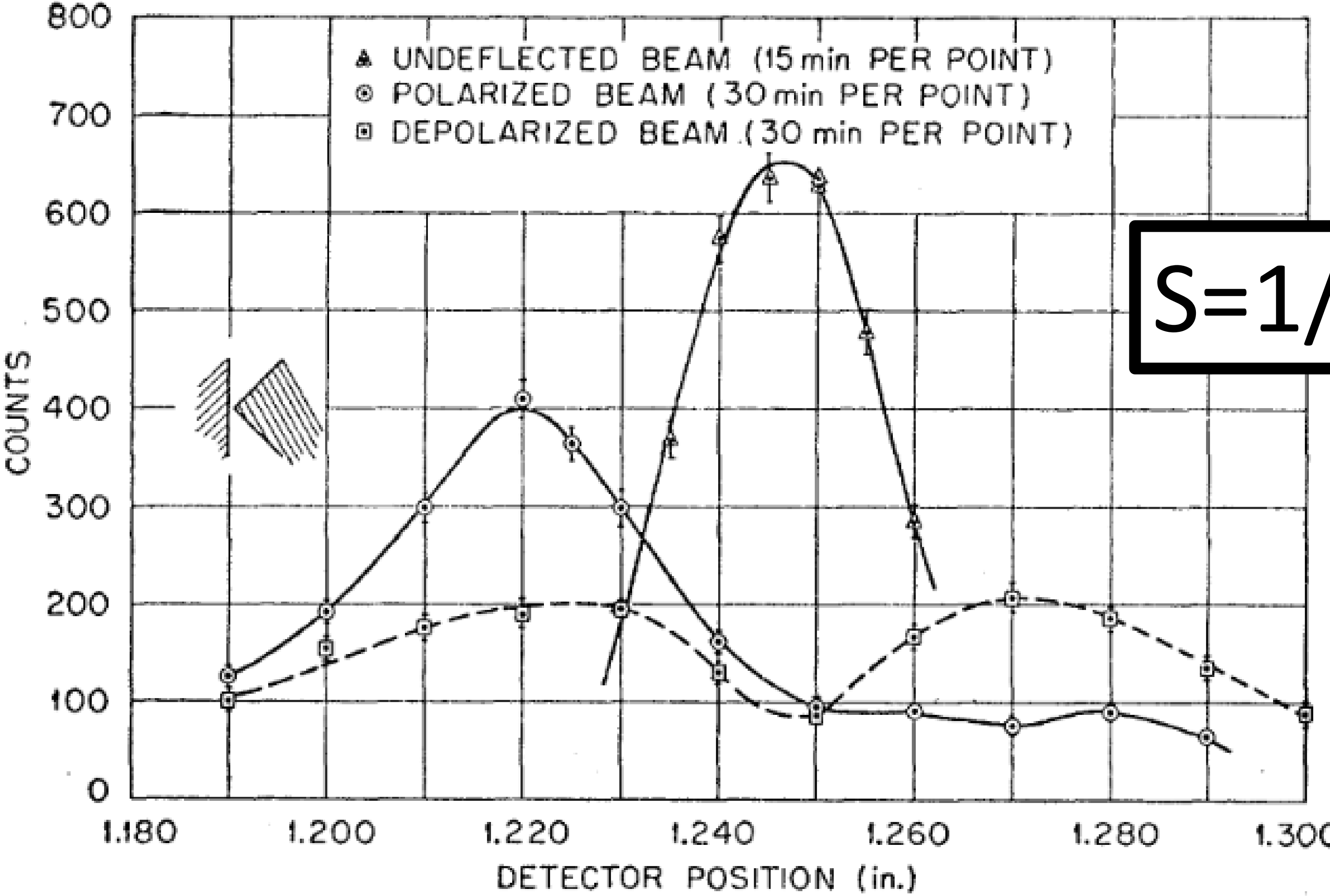
Stern-Gerlach



$$F = \mu \frac{\partial B}{\partial z}$$

http://www.pci.tu-bs.de/aggericke/PC3e_osv/Kap_II/Teil_3.gif

Stern-Gerlach



S=1/2

J. E. Sherwood Physical Review, **96**, (1954)

Magnetic moment

$2.793\ \mu_n$ $\qquad$ $0.857\ \mu_n$

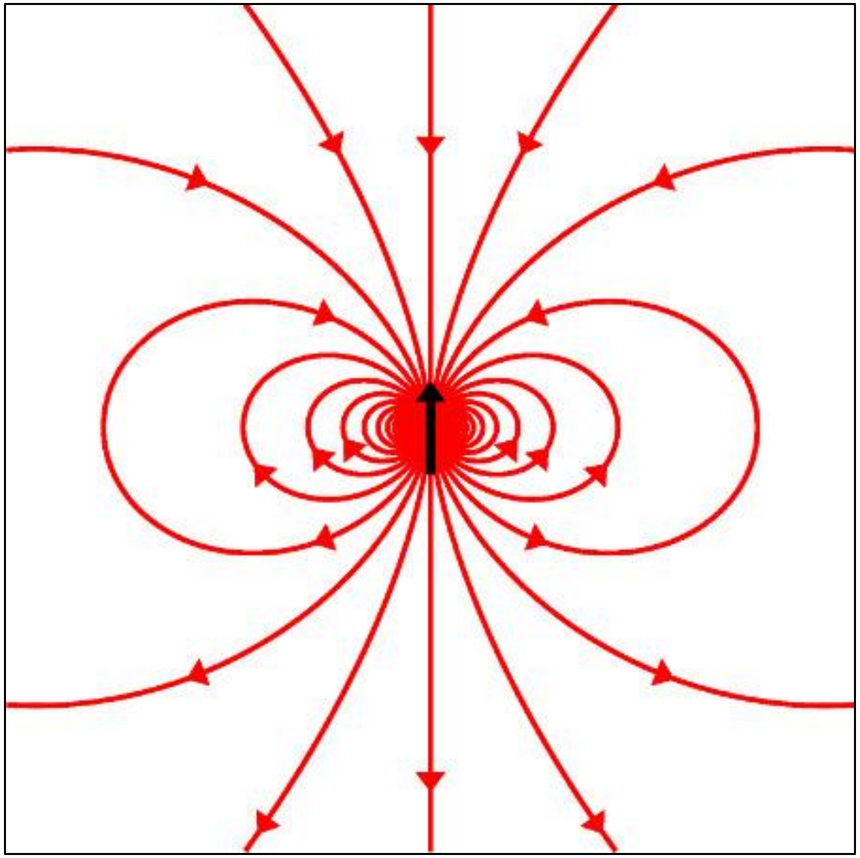
$$p+n \rightarrow {}^2D+\gamma$$

Therefore:

$-1.913\ \mu_N$

$\mu_N = e\hbar/2m_p$

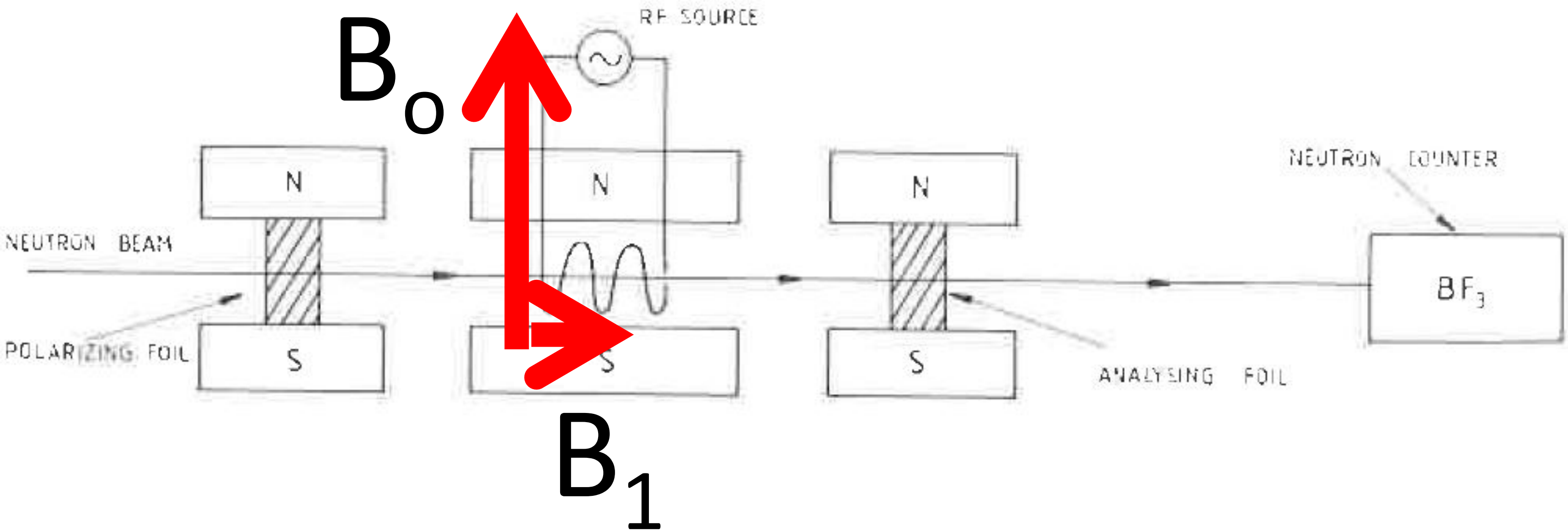
Magnetic moment



Spin and Mag. Moment anti parallel!

http://upload.wikimedia.org/wikipedia/commons/1/15/Neutron_spin_dipole_field.jpg

Rabi single coil resonance



Larmor

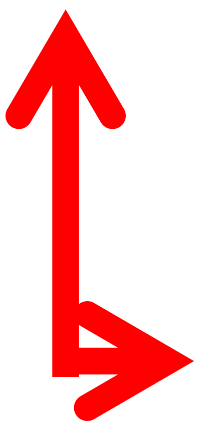
$\omega_o = \gamma_n B_o$

Now rotate B_1 ($<B_o$)

ω

Rabi single coil resonance

B_o



B_1

Larmor

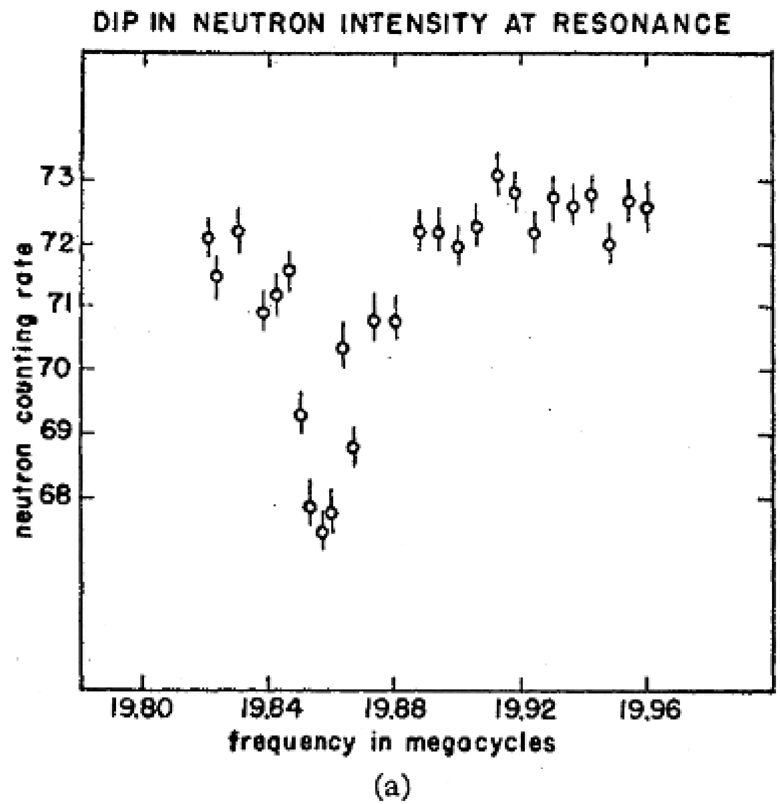
$\omega_o = \gamma_n B_o$

B_1 rotation

ω

Resonance

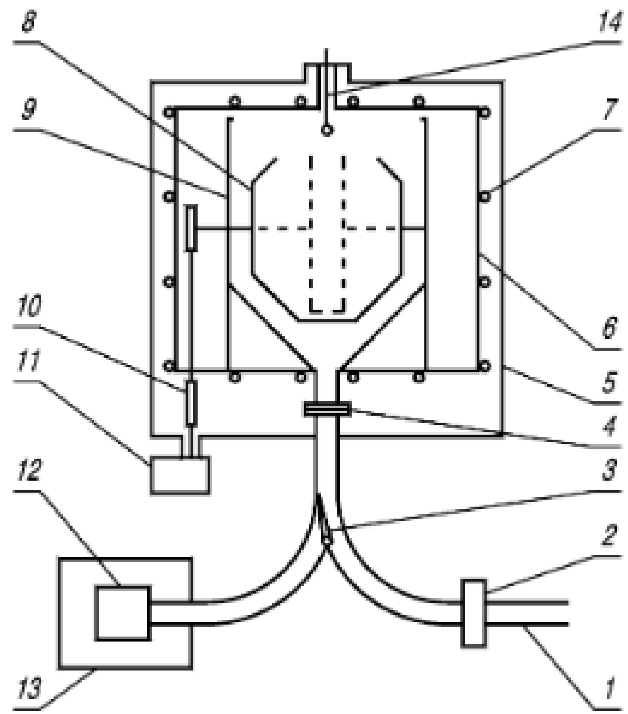
$\omega_o = \omega$



$\mu_n = -1.91304272(45)\ \mu_N$

Measuring lifetimes

- Beam method
  – Count n and p
- Bottle method
  – 100neV=> 1m high => 1.6 T
- **lifetime 880(1) s**

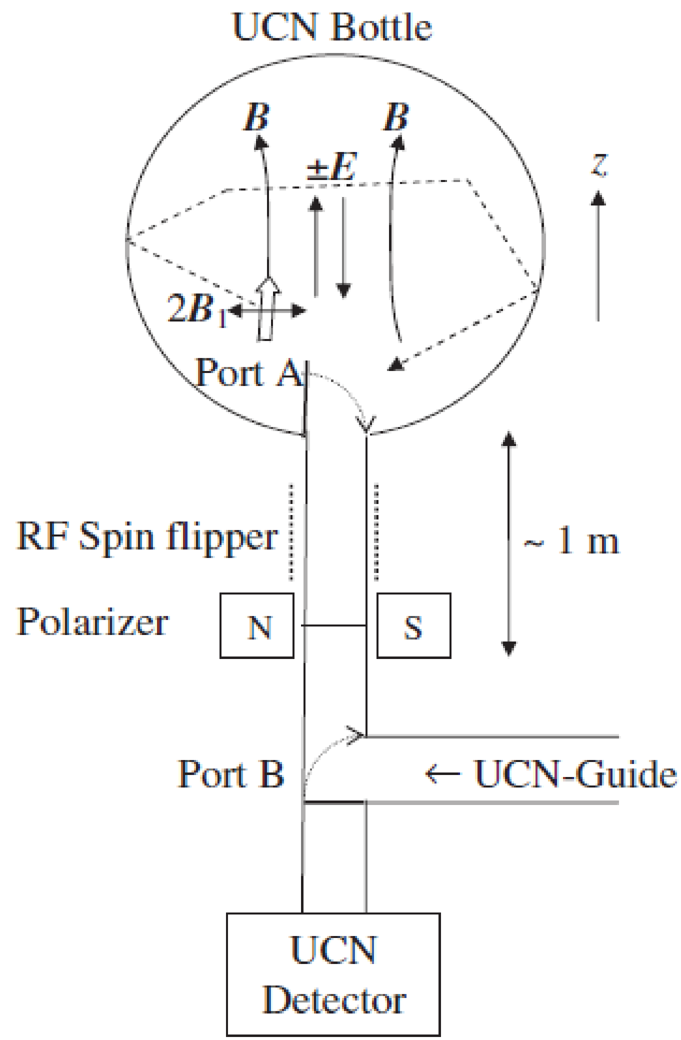


Electric Dipole Moment

- Why is it important?
- Baryogenesis: 10^4 more matter than antimatter
- Charge Parity (CP) violation during inflation
- Neutron must have electric dipole moment

Electric Dipole Moment

- **d_n=2.9x10^{-26} e cm**
- $\hbar\omega = 2\mu_n B \mp 2 d_n E$
- Ultra cold neutrons
- Limits are volume and density



Interactions

Interactions

UCN: Particle physics with "human dimensions"

Speed: some m/s

Jumps up to 2.5 m high

Magnetic field:
1 T may repel
UCN 0.6 m high

≈10 min half-life
≈15 min lifetime

Courtesy of
Koester Ulli

Interactions

Strong > EM > Weak > Gravity

$1 \quad : \quad 10^{-2} \quad : \quad 10^{-7} \quad : \quad 10^{-42}$

Typical distances:

$1\text{fm} \quad : \quad \infty \quad : \quad 0.01\text{fm} \quad : \infty$

Neutron's production

(α,n) and (γ,n) reactions

Nuclear Fusion

Nuclear Fission

Spallation

(α,n) and (γ,n) reactions

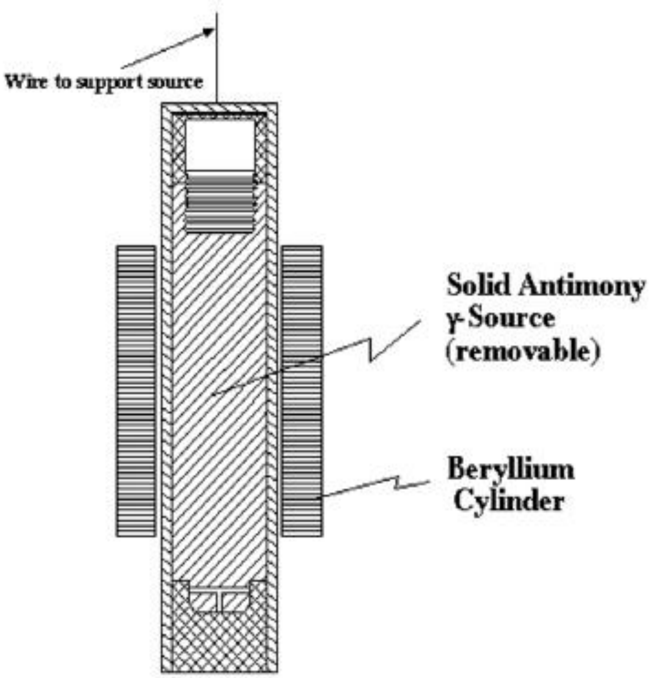
(α,n) $\longrightarrow$ Chadwick's reaction

$$^{9}\mathbf{Be} + \boldsymbol{\alpha}\ (^{4}\mathbf{He}^{2+}) = {}^{12}\mathbf{C} + {}^{1}\mathbf{n} + \mathbf{5.7\ MeV}$$

It is a sort of nuclear fusion reaction

(α,n) and (γ,n) reactions

(γ,n) → induced by gamma rays



$$^{124}\mathrm{Sb} = {}^{124}\mathrm{Te} + \beta^- + \nu + \gamma$$

$$^{9}\mathrm{Be} + \gamma = {}^{8}\mathrm{Be} + {}^{1}\mathrm{n} - 1.66\ \mathrm{MeV}$$

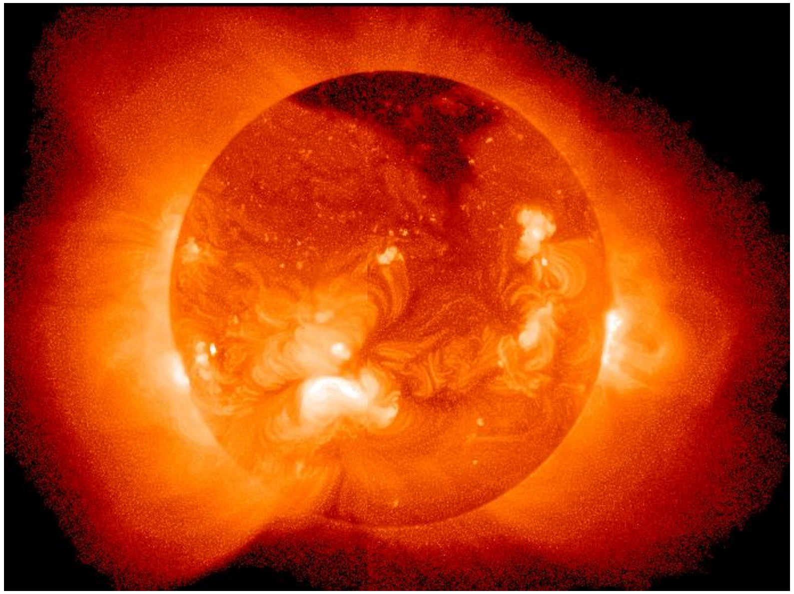
Immediately decomposing in 2 α particles

Useful because it can be easily turned on/off → reactor!

Cannot stay off too long (^{124}Sb half-life is 60 days)

Nuclear Fusion (to produce neutrons)

Fusion reactors produce neutrons:



- Artificial ones

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

3.5 MeV

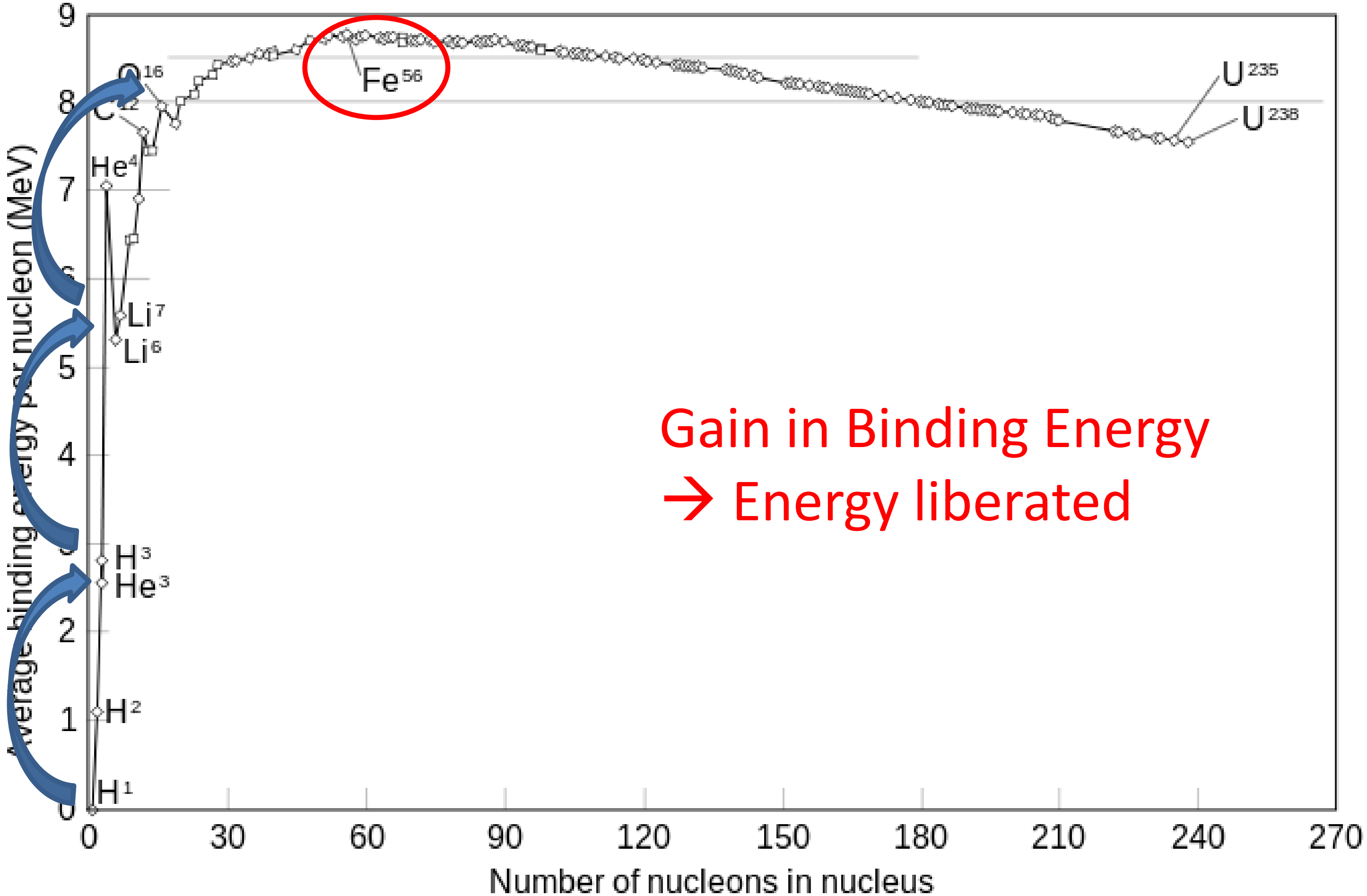
14 MeV ! (extremely energetic neutrons)

- Natural ones (stars)

Several fusion & decay reactions involved (proton-proton and CNO cycles)

$$^{13}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + ^{1}_{0}n$$

Average Binding Energy/nucleon



Gain in Binding Energy
→ Energy liberated

Nuclear Fission

Some history again…

1934: **Enrico Fermi** **(Rome)** bombards heavy elements with **neutrons** and finds them to be radioactive.

He reports the discovery to *Nature*, which refuses his paper because « too speculative »

ANNO V - VOL. I - N. 5 QUINDICINALE 15 MARZO 1934 - XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Then he publishes it on an Italian journal

Radioattività indotta da bombardamento di neutroni

Desidero riferire in questa lettera sopra alcune esperienze destinate ad accertare se un bombardamento di neutroni non determini dei fenomeni di radioattività susseguente analoghi a quelli osservati dai coniugi Joliot con bombardamento di particelle α.

Il dispositivo che ho usato è il seguente: La sorgente di neutroni è costituita da un tubetto di vetro contenente polvere di berillio ed emanazione. Usando circa 50 millicurie di emanazione, che mi sono stati forniti dal prof. G. C. Trabacchi che qui desidero ringraziare vivissimamente, si possono così ottenere oltre 100.000 neutroni al secondo, misti naturalmente a una intensissima radiazione γ, che però non dà alcun disturbo per esperienze di questo genere. Dei cilindretti contenenti l'elemento in esame sono sottoposti per un tempo variabile da alcuni minuti ad alcune ore alle radiazioni di questa sorgente.

Essi vengono poi rapidamente disposti attorno ad un contatore a filo, la cui parete esterna è formata da una foglia d'alluminio di spessore di circa 0.2 mm, tale quindi da permettere l'ingresso di eventuali raggi β nel contatore. Fino ad ora l'esperienza ha dato esito positivo per due elementi:

ALLUMINIO. — Un cilindretto di alluminio irradiato dai neutroni per un paio d'ore e posto successivamente attorno al contatore determina nei primi minuti un aumento assai considerevole degli impulsi, che crescono di 30 o 40 al minuto. L'effetto decresce col tempo riducendosi a metà in circa 12 minuti.

FLUORO. — Il fluoruro di calcio, irradiato per pochi minuti e portato poi assai rapidamente accanto al contatore determina nei primi momenti un aumento del numero degli impulsi. L'effetto si smorza rapidamente, riducendosi a metà in circa 10 secondi.

Una possibile interpretazione di questi fenomeni è la seguente. Il fluoro, bombardato coi neutroni, si disintegra emettendo particelle α. La reazione nucleare è probabilmente:

$$F^{19} + n^{1} \longrightarrow N^{16} + He^{4}$$

Si formerebbe così un azoto di peso 16 che, emettendo successivamente una particella β può trasformarsi in O^{16}. Una simile interpretazione potrebbe aversi per l'alluminio, conformemente alla possibile reazione nucleare:

$$Al^{27} + n^{1} \longrightarrow Na^{24} + He^{4}$$

Il Na^{24} così formato sarebbe un nuovo elemento radioattivo e si trasformerebbe in Ca^{24} con emissione di una particella β.

Se queste interpretazioni sono corrette, si avrebbe qui la formazione artificiale di elementi radioattivi che emettono normali particelle β, a differenza di quelli trovati dai Joliot che emettono invece positroni. In particolare nel caso dell'azoto si avrebbero due isotopi radioattivi: N^{13}, trovato dai Joliot, che emettendo un positrone si trasforma in C^{13}; ed N^{16} che, emettendo un elettrone si trasforma in O^{16}.

Sono in corso esperienze per estendere l'esame ad altri elementi e per studiare meglio le particolarità del fenomeno.

Roma, 25 *marzo* 1934-XII.

ENRICO FERMI

Fast neutron reactions
(do not make n gamma)

$$^{19}F + {}^{1}n \rightarrow {}^{16}N + {}^{4}He$$

$$\rightarrow {}^{16}O + e^{-}$$

$$^{27}Al + {}^{1}n \rightarrow {}^{24}Na + {}^{4}He$$

$$\rightarrow {}^{24}Ca + e^{-}$$

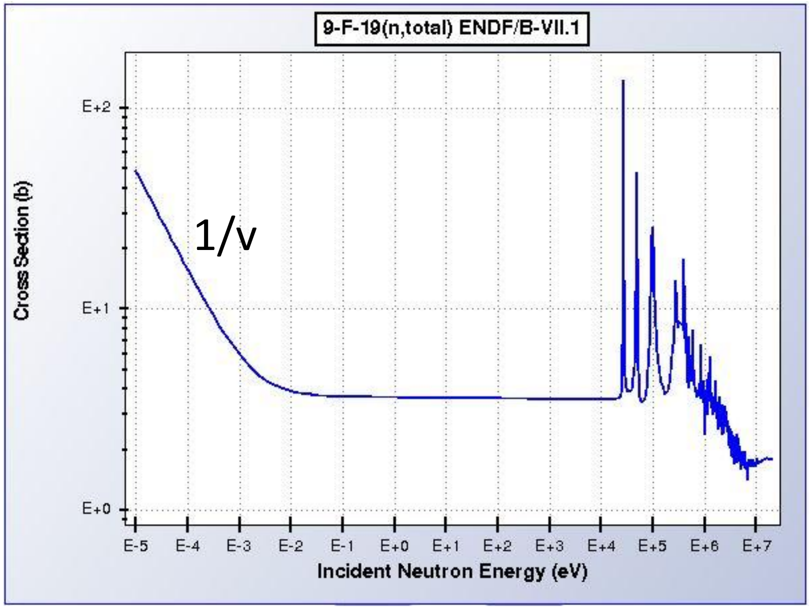
Nuclear Fission

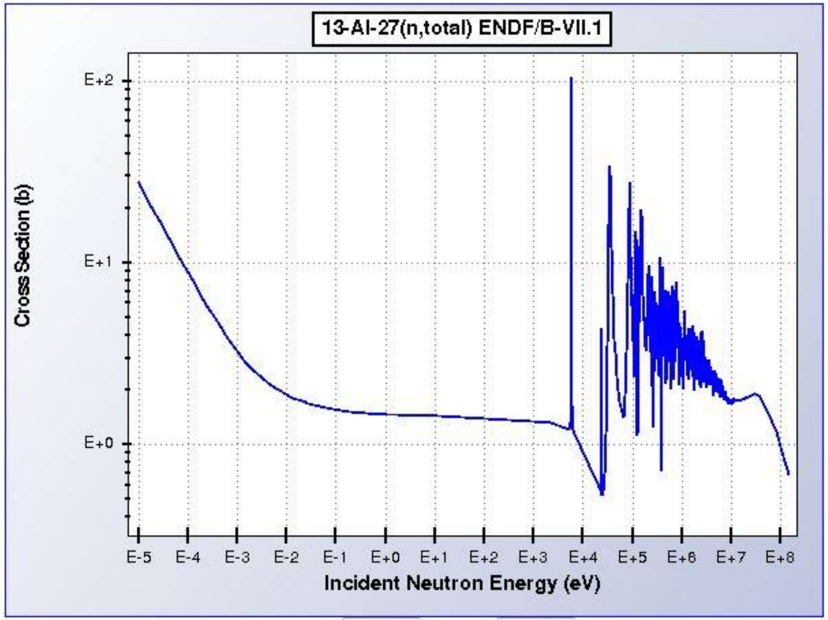
Some hystory again…

1934:Rome: **Enrico Fermi** bombards heavy elements with **neutrons** and finds them to be radioactive.

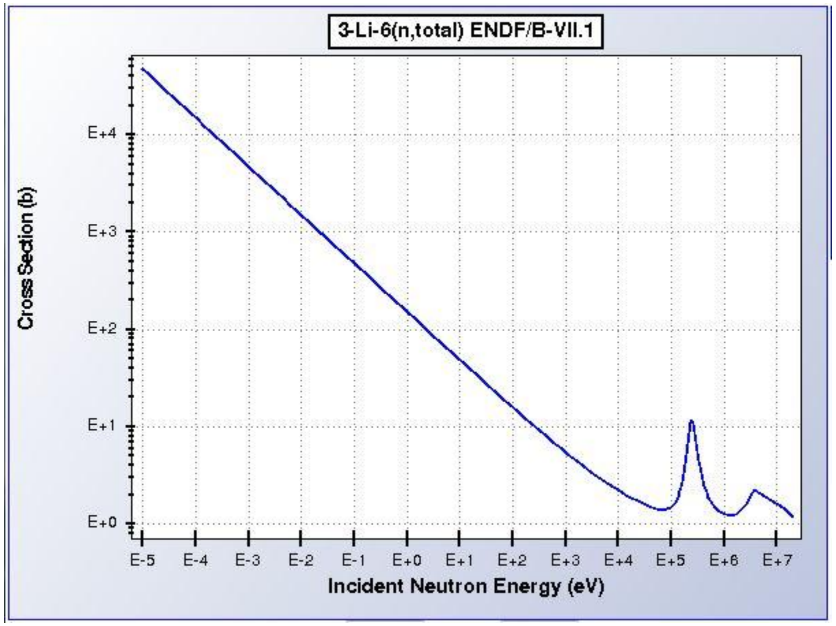
He induced radioactivity in **22** heavy elements.
He understood the difference between fast/slow neutrons: the cross section for interaction with nuclei is much larger for slow neutrons than for fast neutrons.

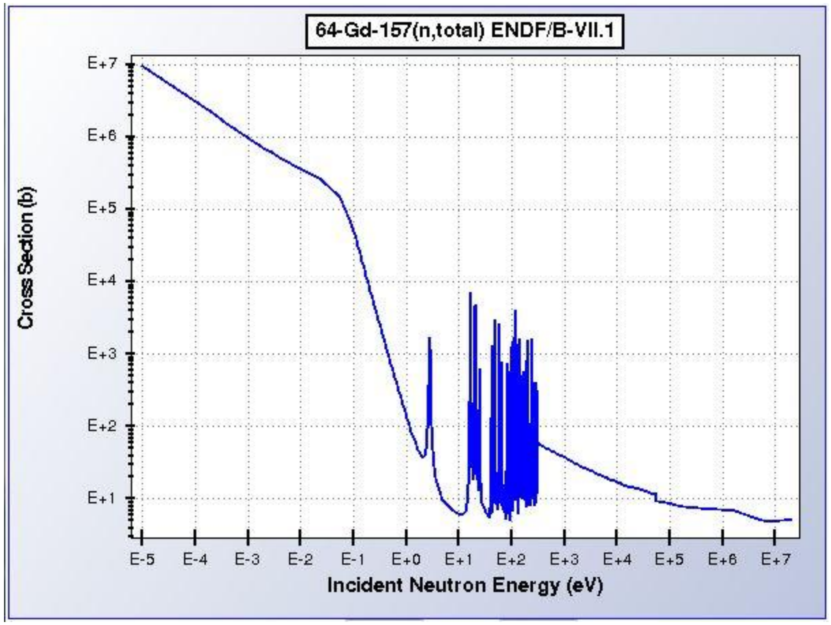
It seems that he was helped by different working tables in the lab (marble vs. wood) moderating neutrons in a different way…





Nuclear Fission





1935: Nobel Prize to Frederic Joliot et Irene Joliot-Curie *"in recognition of their synthesis of new radioactive elements"* (using α particles).

In **1938** Fermi received the Nobel Prize in Physics *"for his demonstrations of the existence of new radioactive elements produced <u>by neutron irradiation</u>, and for his related discovery of nuclear reactions brought about by slow neutrons"*.

Nuclear Fission

- **1938** (Berlin): Otto **Hahn** with Fritz **Strassman** and Lise **Meitner** bombarded **uranium** with neutrons, finding several products for this reaction.

- **1939**: Hahn and & coworkers understood they were observing **nuclear fission** (i.e. the fractionation of Uranium nuclei, as results on neutrons bombardement).

- The year later they also predicted the existence and liberation of additional neutrons during the fission process.

- **1939**: Frederic Joliot and his team proved that this phenomenon could be used to make a **chain reaction**.

- **1945**: Hahn received the 1944 **Nobel Prize in Chemistry** *"for his discovery of the fission of heavy atomic nuclei."*

Nuclear Fission

From **1939**, the history of the development of nuclear fission becomes history of WWII.

Scientists from Europe migrate to the US (Fermi amongst them) and many converge on the **Manhattan Project**.

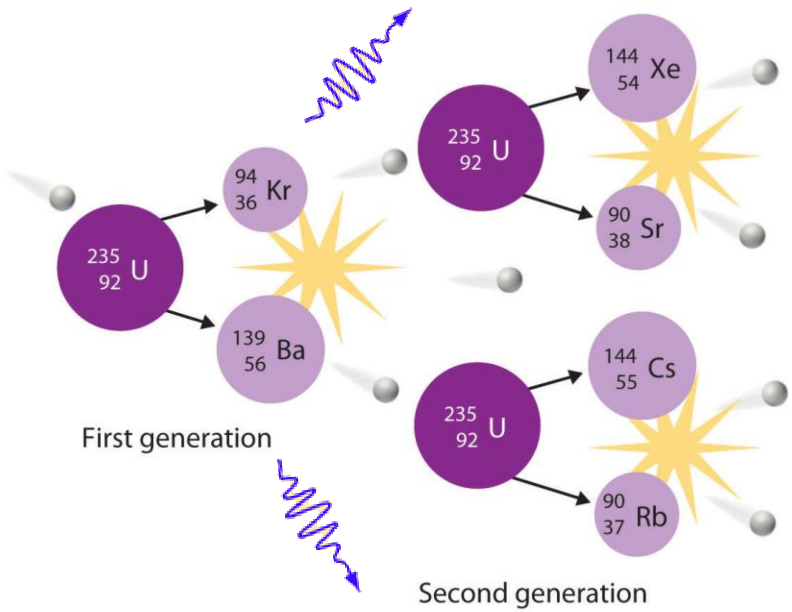
1942: University of Chicago: a team led by E. Fermi built the first working fission reactor named **Chicago Pile-1.**

It had a core of **Uranium Oxide** and as neutron moderator it used **graphite**.

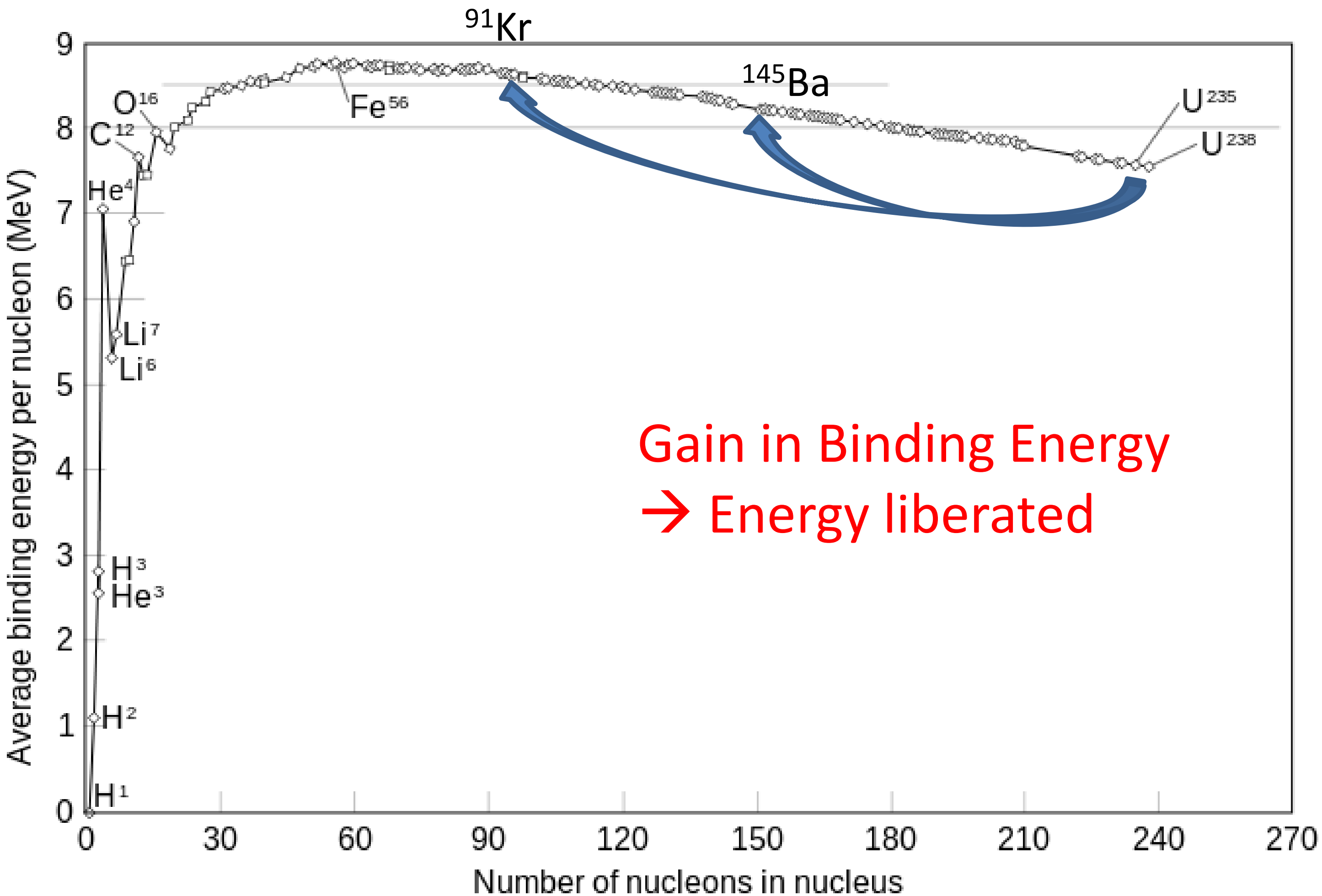
Nuclear Fission

$$^{235}_{92}U + ^{1}n \rightarrow ^{91}_{36}Kr^{*} + ^{145}_{56}Ba^{*} + Energy$$

$$^{91}_{36}Kr^{*} + ^{145}_{56}Ba^{*} \rightarrow ^{90}_{36}Kr + ^{144}_{56}Ba + 2n + \gamma$$



Nuclear Fission: Energy Gain



Nuclear Fission

Very energetic reaction, about **180-220 MeV** are liberated in the process, coming from a different mass between the initial one and the one of the products.

$$E = \Delta mc^2 \longrightarrow$$

Uranium loses about 0.1% of its weight

Energy immediately released in the form of:

- Kinetic energy of fission atoms products (about 180 MeV)
- Kinetic energy of emitted neutrons (about 2MeV / neutron)

In a second time:

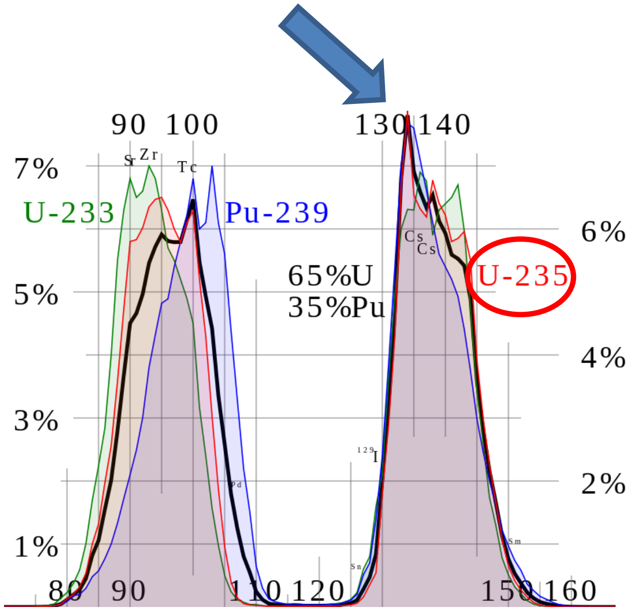
- Gamma Rays (about 7MeV)
- Beta (e^-)
- Delayed neutrons

Nuclear Fission Products

The exact fission fragments are not known a priori. An asymmetric-mass distribution can be found.

Nucleus modeled using a drop-like model: symmetric distribution.

Shell effects (Nuclear Shell Model): asymmetric distribution
More accurate, it describes the structure of the nucleus in terms of energy levels

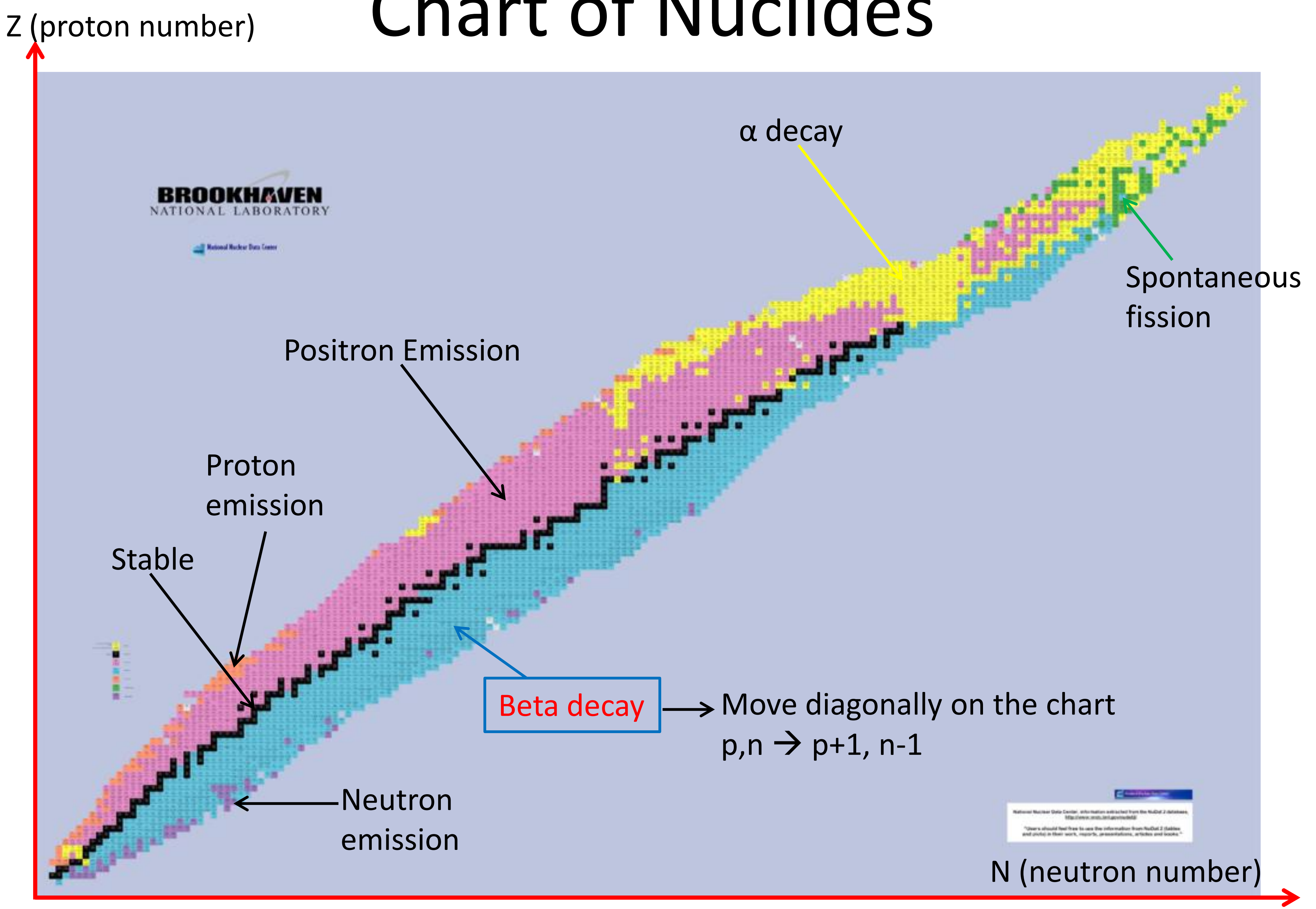


For some elements like ^{252}Cf a symmetric distribution is found. Not for U and Pu.

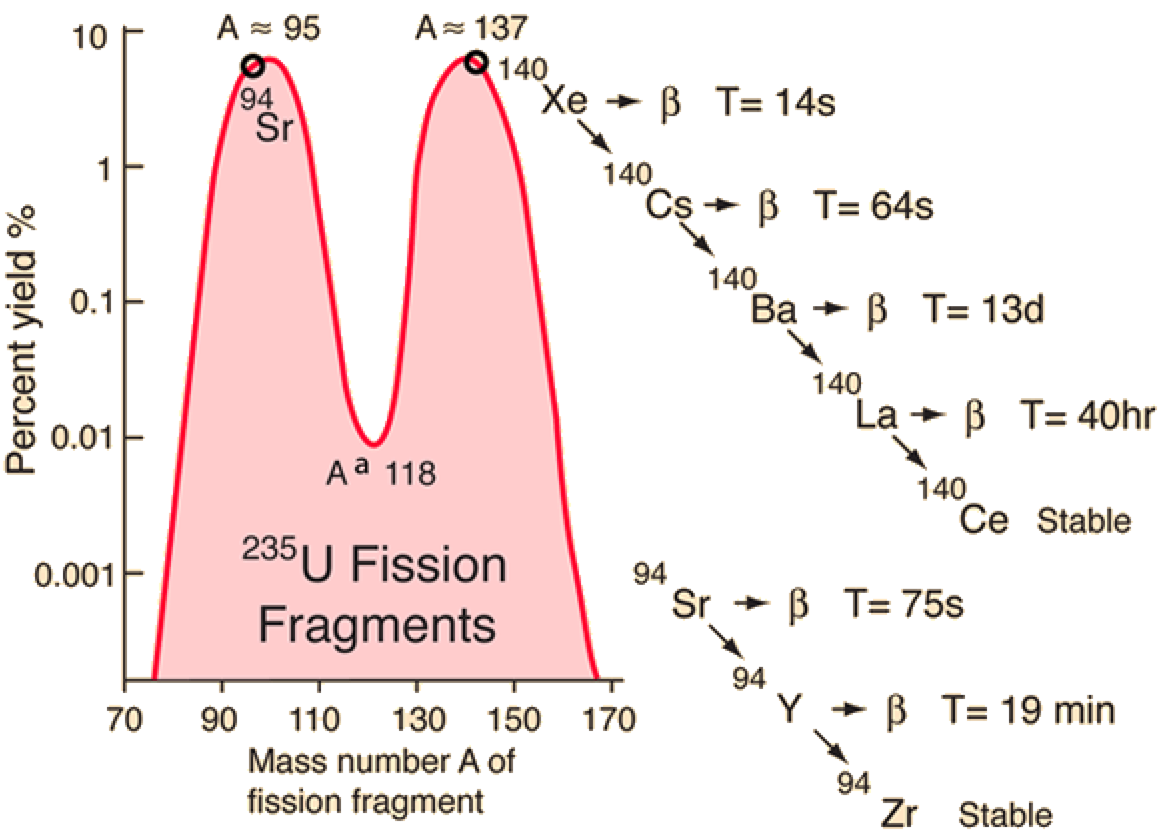
Difference in energy can be very small. Process not governed by energetic reasons.

$$\left.\begin{array}{l} ^{235}U+n \rightarrow {}^{118}Pd + {}^{118}Pd \ \ (199.769\ \text{MeV}) \\ ^{235}U+n \rightarrow {}^{100}Zr+{}^{136}Te \ \ (199.799\ \text{MeV}) \end{array}\right\} \approx 200\ \text{MeV}$$

Chart of Nuclides



Fission fragment decay



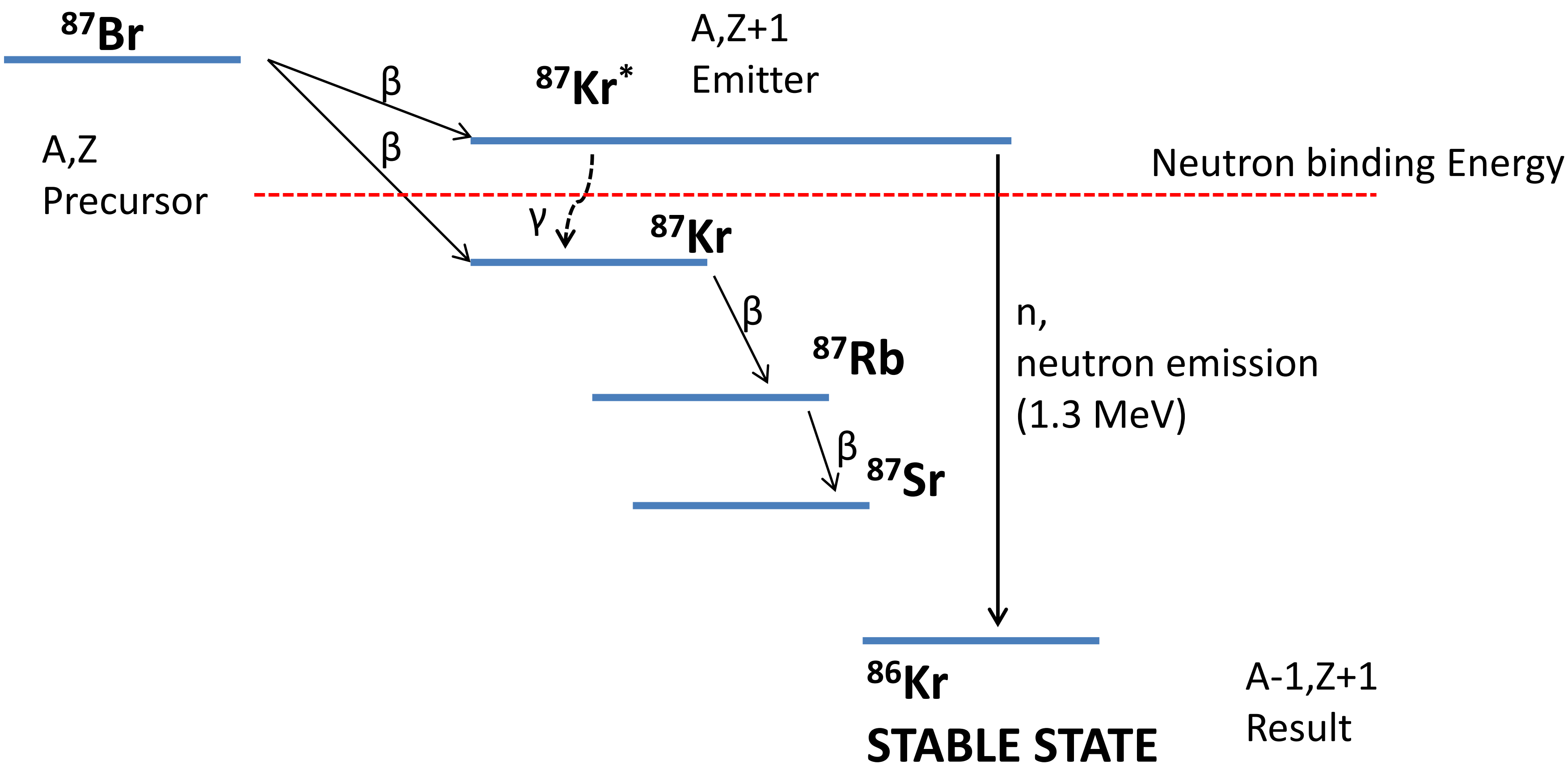
Several decay chains are possible

Sometimes the new element can also emit a neutron, which has a delay with respect to the initial fission instant

Makes reactor control possible to manage

Nuclear Fission: Beta-delayed neutrons

During the fission fragment decay chain, it is possible for some nuclei to undero a beta-n reaction, where after the beta process (n→p) the new atom is in a state so excited that the extra energy is bigger than the neutron binding energy, thus emitting a neutron.



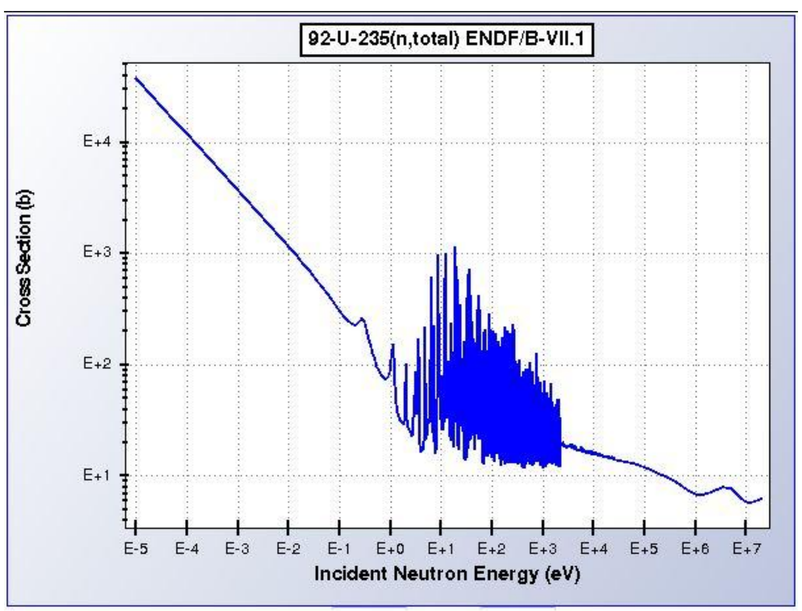
Nuclear Fission

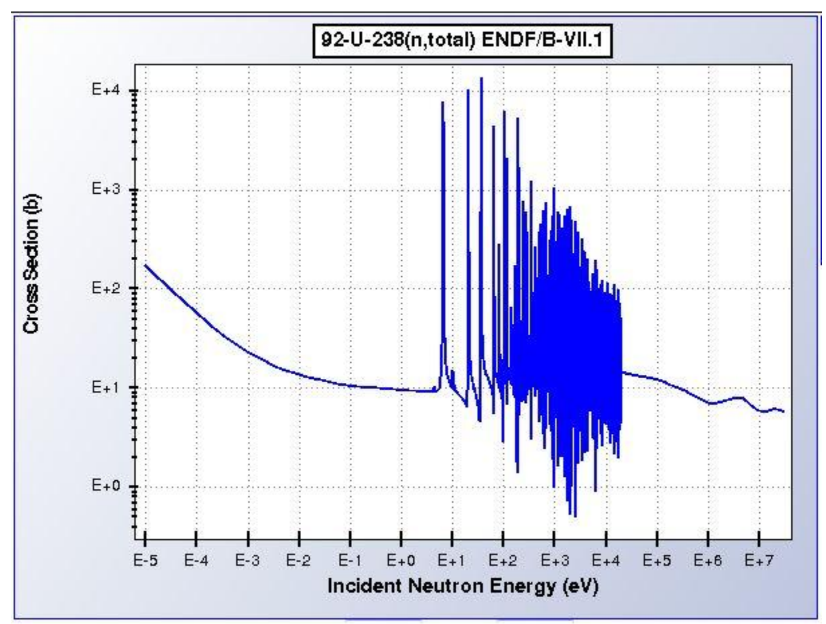
Several heavy elements (actinides region) may undergo either:

- **spontaneous fission**, a form of radioactive decay (quite rare for Uranium)
- **induced fission**, a form of nuclear reaction.

Isotopes that undergo fission when struck by a thermal, slow neutron: $\longrightarrow$ **fissile**.

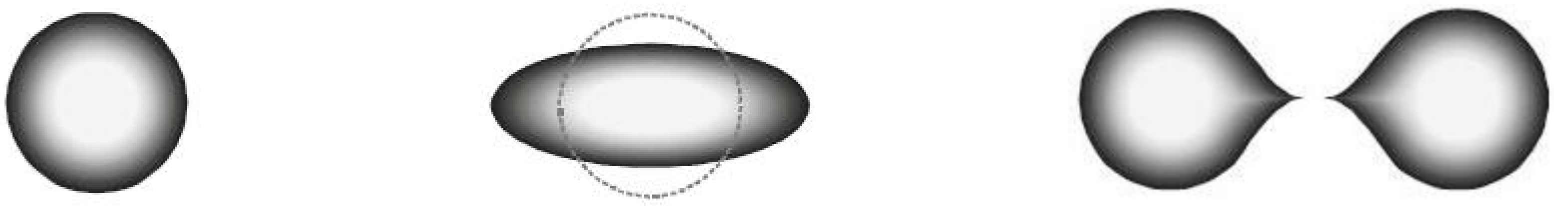
Uranium 235 is fissile. Uranium **^{235}U** is only 0.7% abundant in naturally found U.
The most common isotope is **^{238}U** which is not fissile.





Nuclear Fission

When initiating fission, the nucleus have to be deformed into an oval shape (same volume, bigger surface), so in fission a certain energy has to spent before it can be gained.
→**Energy barrier** (similar to a tunnelling effect, but it is a DEFORMATION ENERGY).



Neutron-pairing effect:
•Heavy isotopes with **odd** number of neutrons (as ^{235}U) gain extra energy upon neutron capture (about 2 MeV/n because it is energetically favorable to have spin pairs of neutrons (fermions)).
• Heavy isotopes having an **even** number of neutrons (as ^{238}U) do not beneficiate of such energy.

The extra energy due to neutron-pairing effect enormously facilitate overcoming such energy barrier, facilitating fission for ^{235}U.

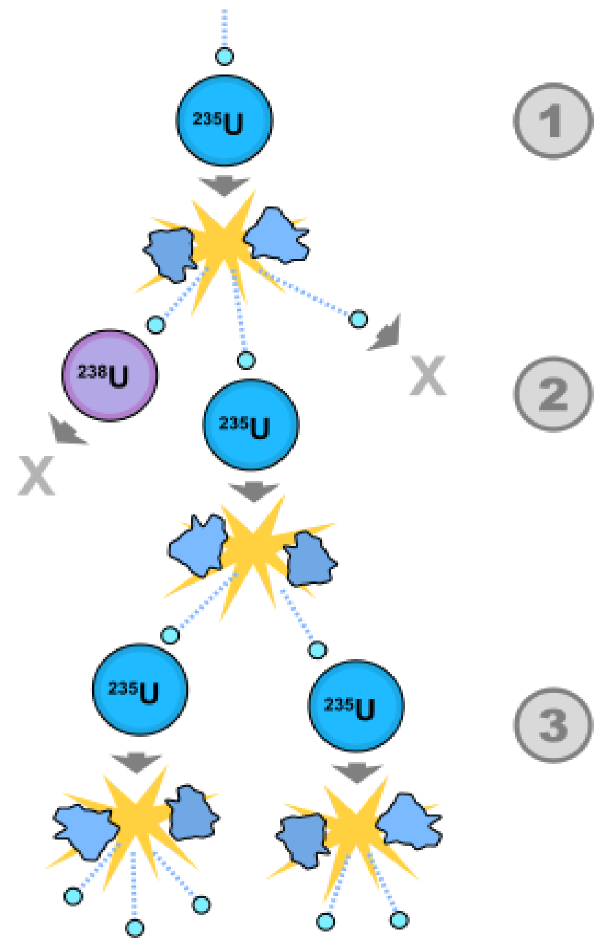
Chain reaction

➢ ^{235}U is fissile and can thus sustain a chain reaction. This can start because of spontaneus fission (or (γ,n) reaction). If the amount of U is small, the losses of neutrons are sufficient to stop the reaction. If the amount is significant, the amount of neutrons is sufficient to start a chain reaction, which can self-sustain. Such critical amount of material is called **critical mass**.

Mass ^{235}U > Critical Mass

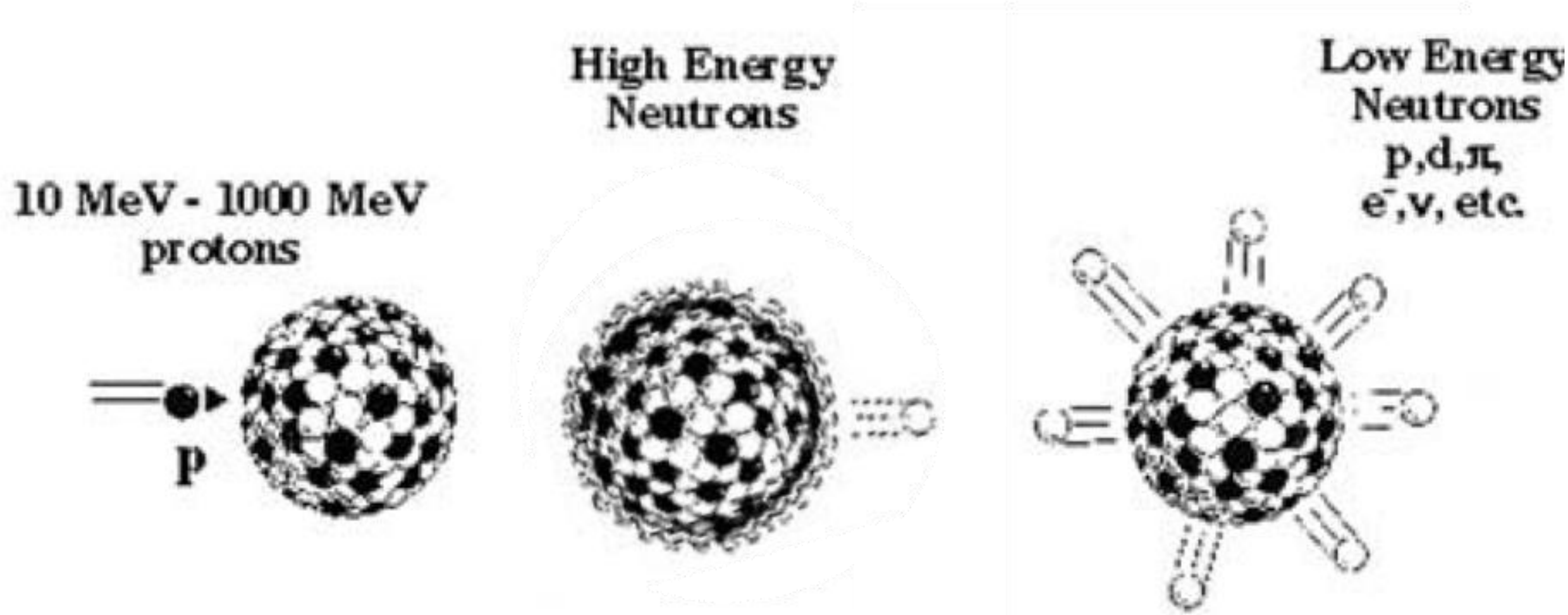
→neutron gain ≥ neutron losses

Chain reaction is sustained



Spallation sources

Spallation



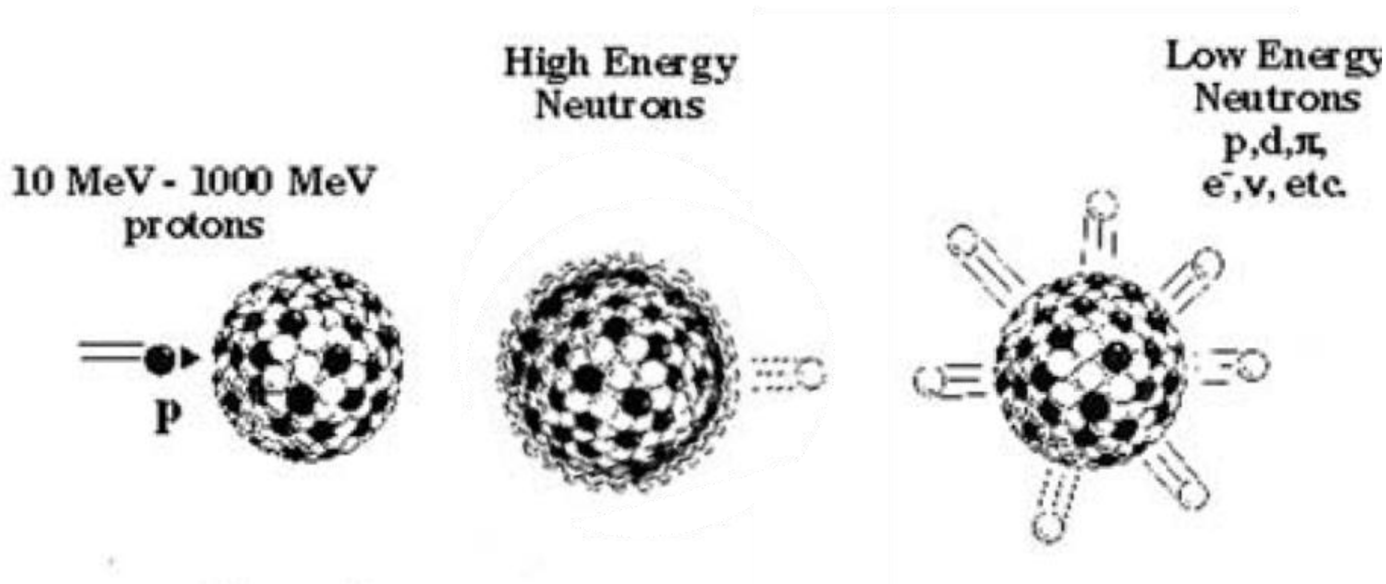
(1)Internal Cascade

(2)Intra nuclear Cascade

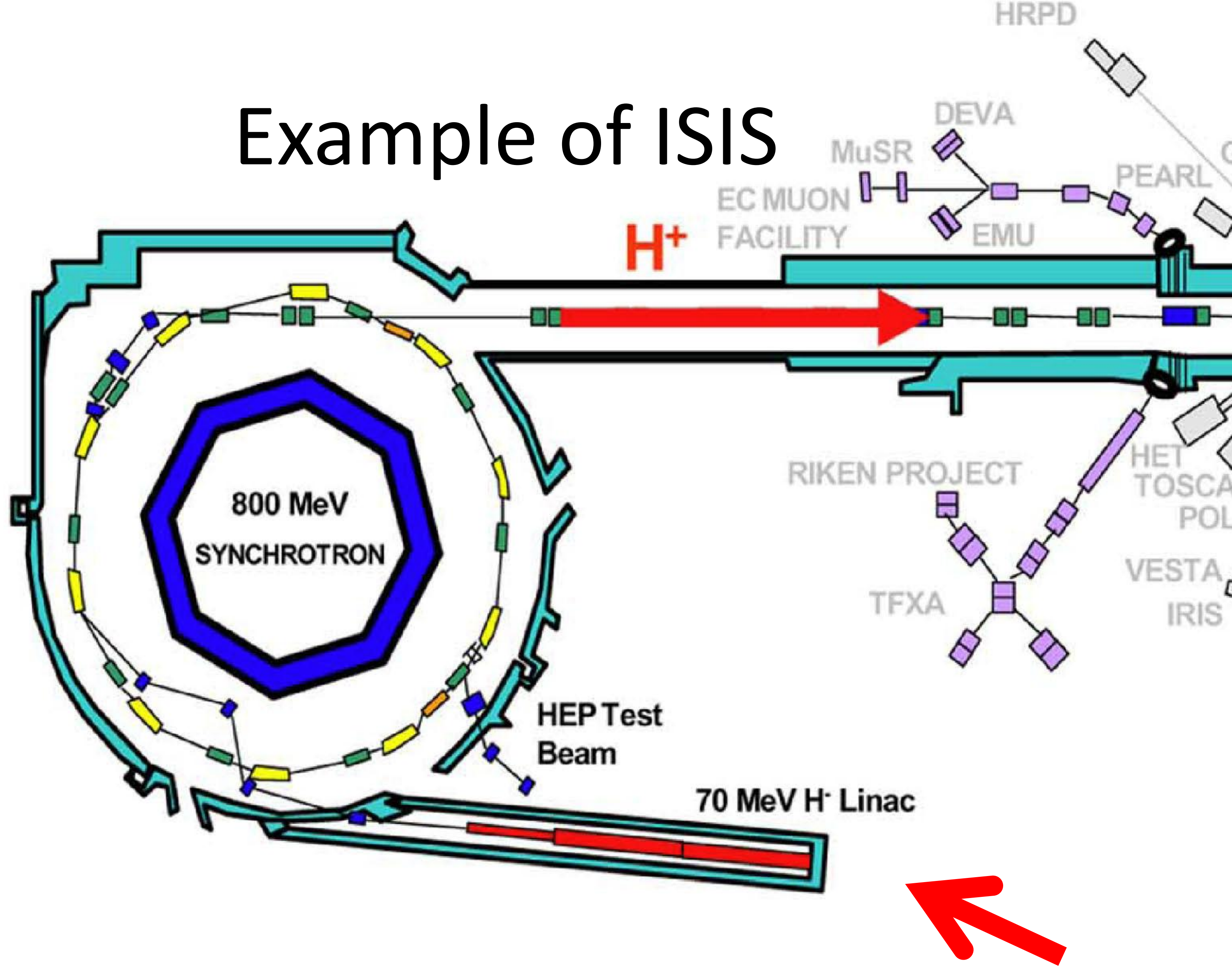
(3)Evaporation

Spallation Energies

$$^{208}_{82}Pb + p^{+} \rightarrow ^{185}_{79}Au + 20n + 3p^{+} - 173MeV$$

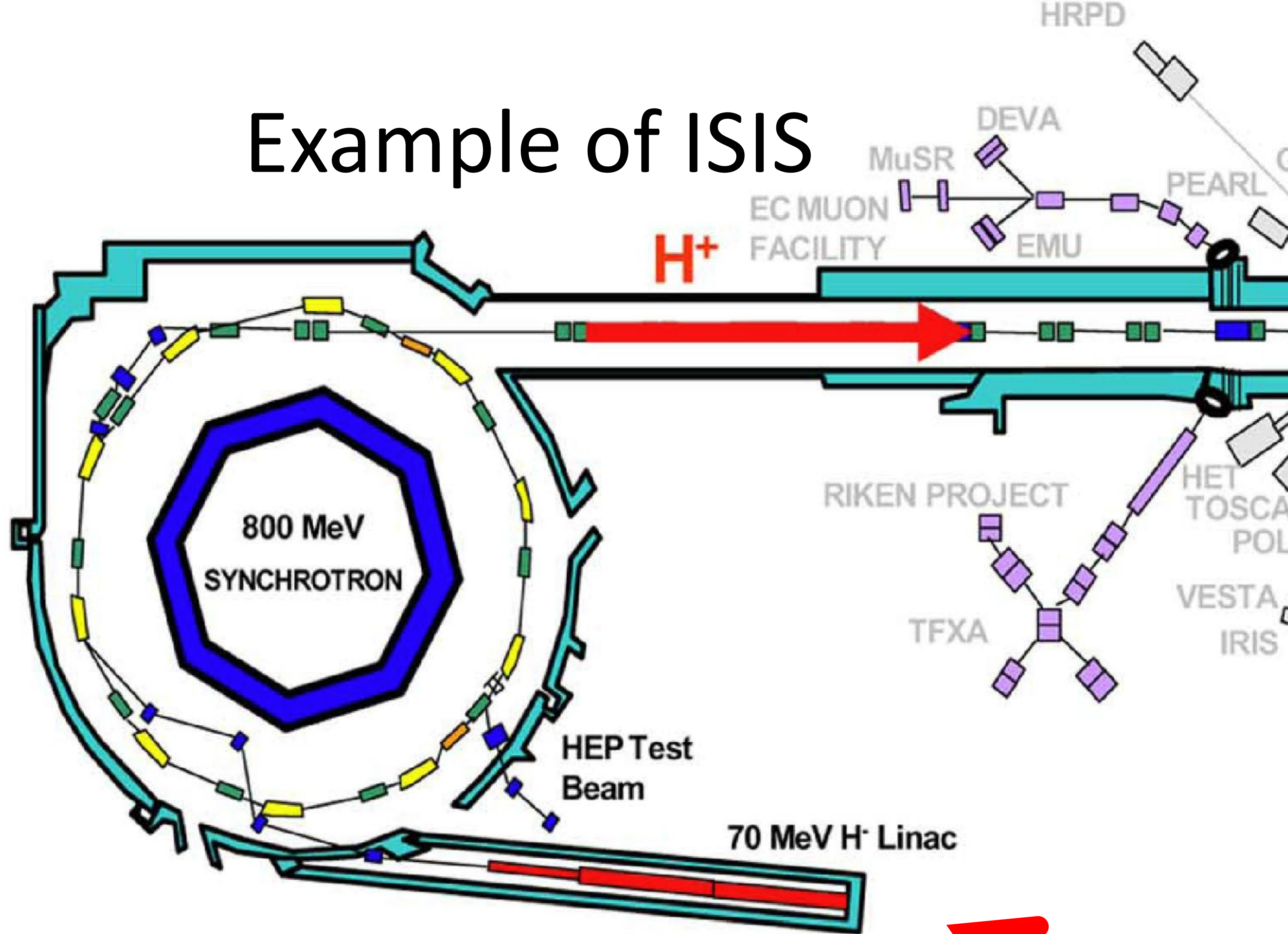


Example of ISIS



$H_2 \rightarrow H^-$

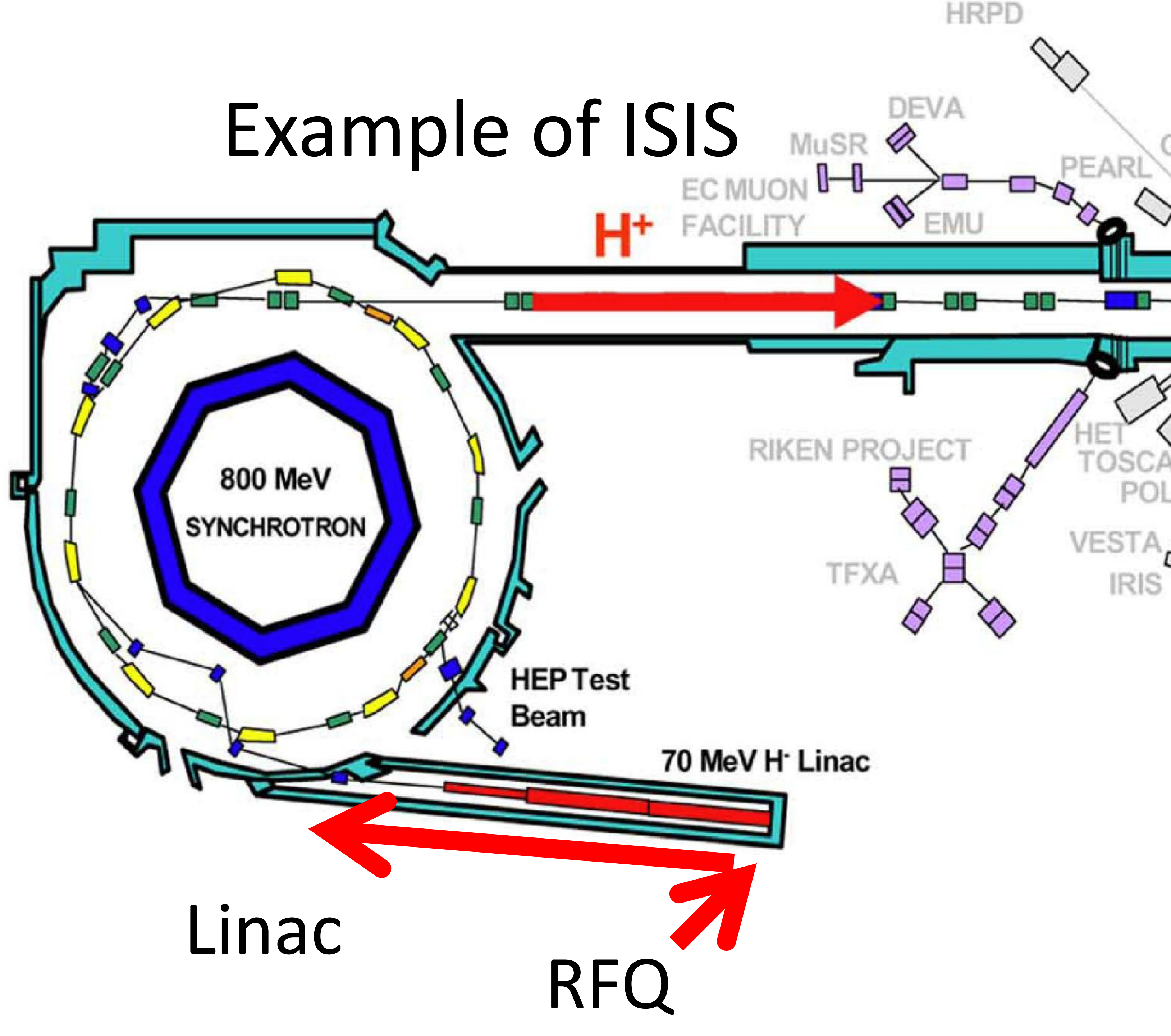
Example of ISIS



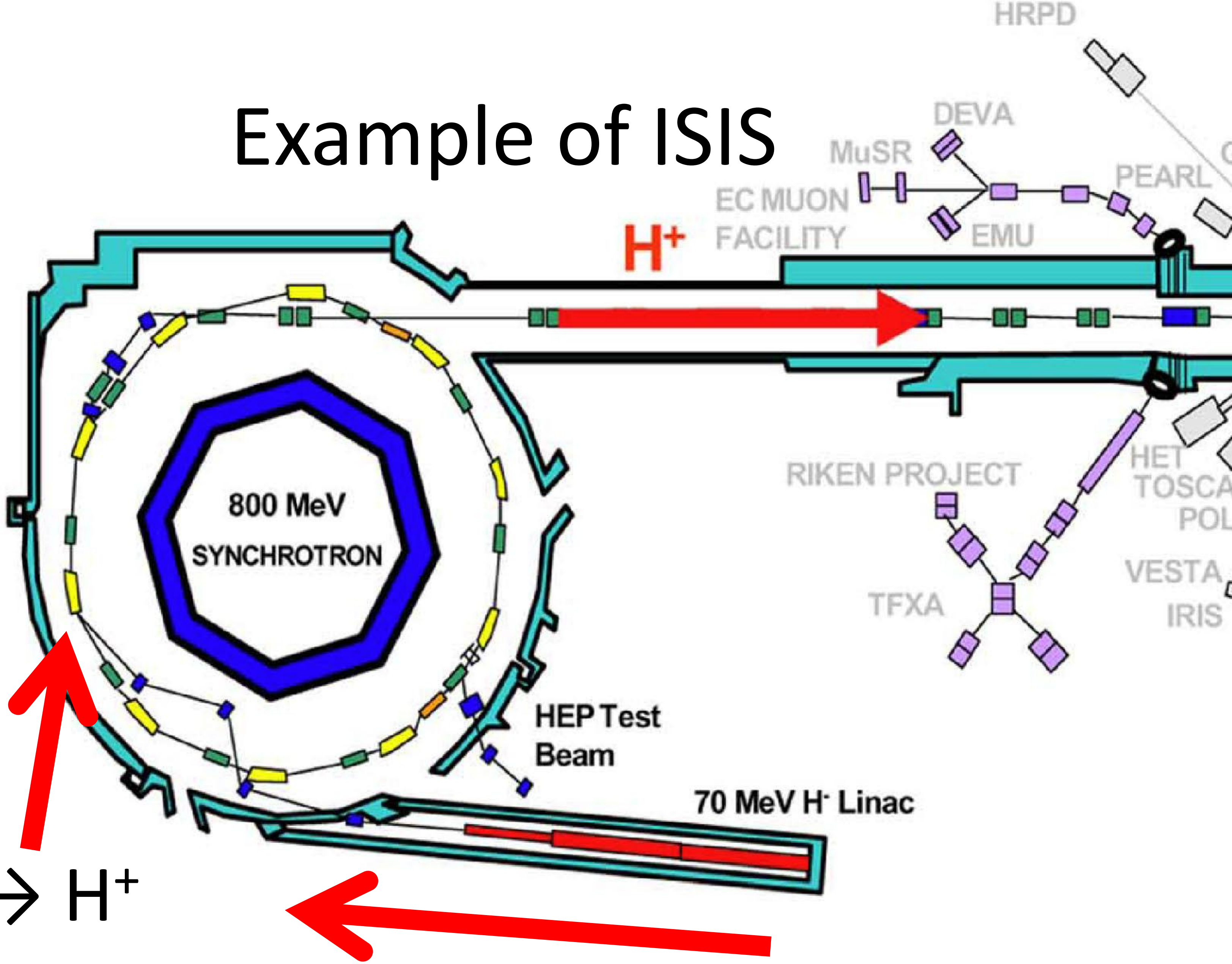
RFQ

$H_2 \rightarrow H^-$

Example of ISIS



Example of ISIS

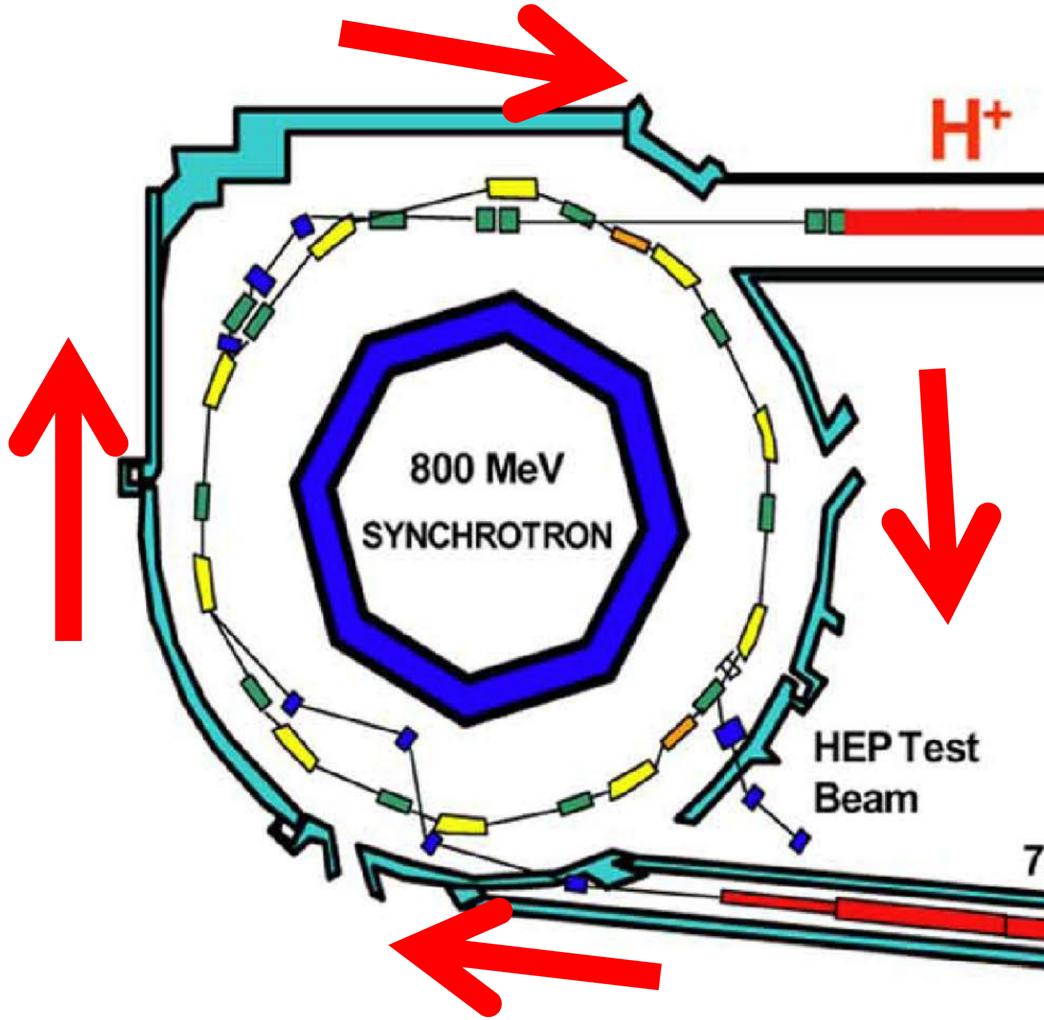


$H^- \rightarrow H^+$

Linac

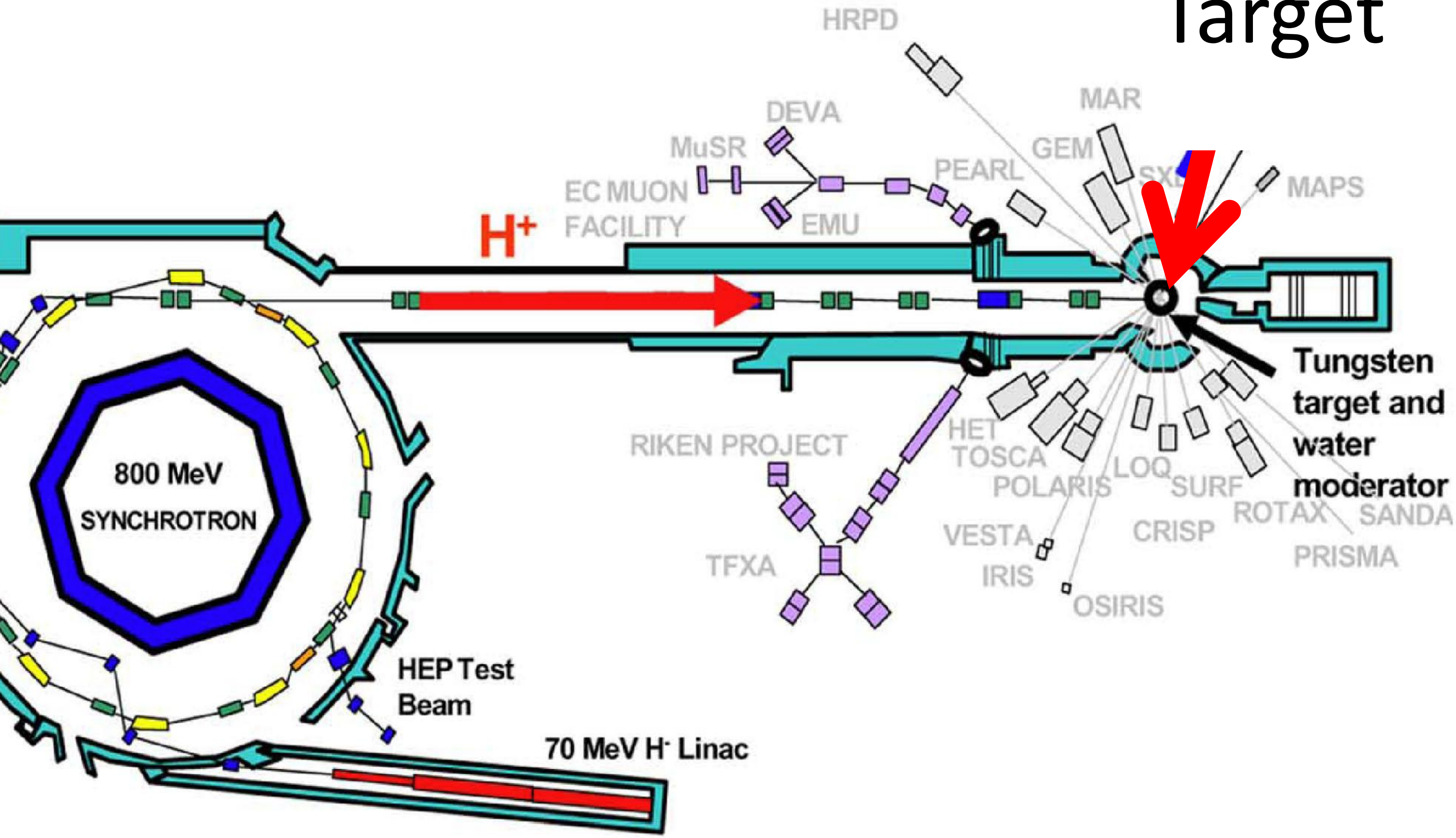
Example of ISIS

- $2.8x10^{13}$
- v=0.84c
- Focused
- Pulse 90ns wide

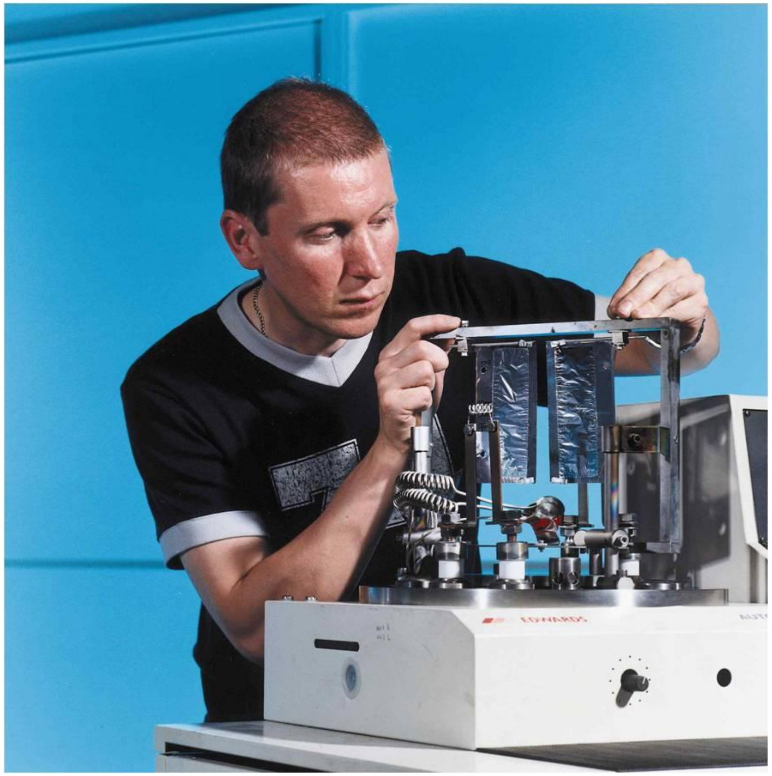


Example of ISIS

Tungsten Target



Foil / Target



http://www.isis.stfc.ac.uk/images/groups/accelerator-science/synchrotron-physics/foil12255.jpg

Neutron’s Production Review

1. Alpha-induced reactions (α,n)
2. Gamma-induced reactions – Photodissociation (γ,n)
3. Nuclear Fusion
4. Spontaneus Fission
5. Neutron Induced Fission
6. Beta-delayed neutron emission
7. Spallation

Where do neutrons go?

1934: Enrico Fermi published his paper on the process of beta decay.
He used an analogy with photons, which are also created/destroyed in atomic processes.

Free neutron decay, called **Beta-decay**

$$n^0 \rightarrow p^+ + e^- + \overline{\nu}_e$$

Lepton conservation

Continuous spectrum of e^- energies → 3-body process

Energy emission for this process is 0.782 MeV. Process mediated by the Weak Force

In fact, a free neutron is unstable and its half-life is now measured to be **611(1) secs [≈10 min]**

Other decays involving neutrons

Bound neutron decay, only for unstable nuclei

Inverse Beta-decay

$$p^+ + \bar{\nu}_e \rightarrow n^0 + e^+$$

It is a rare process but important for anti-neutrino detection!

Electron Capture also exixts

$$p^+ + e^- \rightarrow n^0 + \nu_e$$

Where do most neutrons go?

Above described processes are only a minority. Most neutron DO NOT disapper through decay.

They are **Absorbed** by nuclei of some elements in the periodic table

Nuclear cross sections include a scattering part (coherent+incoherent) and an absorption one

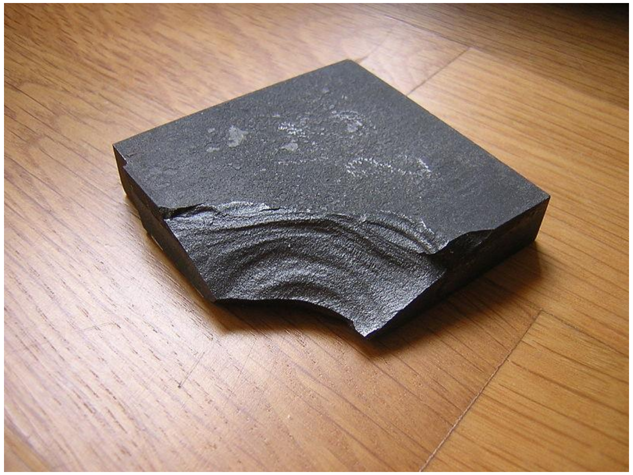
$$\sigma_T = \sigma_S + \sigma_A$$

Neutron Absorption (Capture)

Atom	σ_A (barns)
H, D	0.33, 0.000519
Li (^{6}**Li**, ^{7}Li)	**70.5** (**940**, 0.045)
B (^{10}B)	**767 (3835)**
Co	37.2
Rh	144.8
Cd	**2520**
In	193.8
Sm	**5922**
Gd, 155Gd, 157Gd	**49700**
U (^{235}**U**)	**7.57 (681)**

Shieldings @ ILL

B_4C

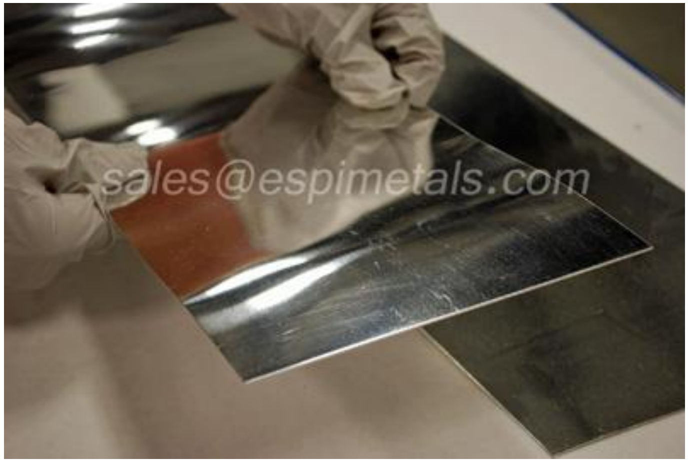


Tank armor, bullet proof vest material, neutron absorber

http://www.borflex.fr/materiau-flexible-radioprotection/

http://upload.wikimedia.org/wikipedia/commons/thumb/6/6f/Boron_carbide.JPG/800px-Boron_carbide.JPG

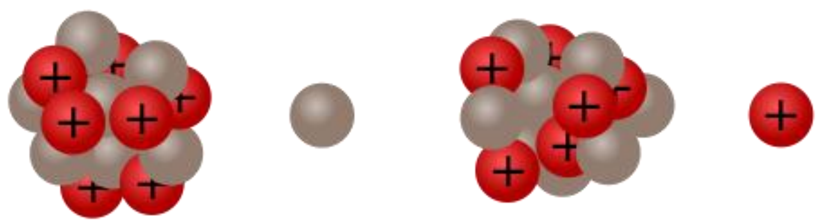
Cd



Gd (Gd_2O_3)

Naturally occurring spallation: formation of ^{14}C in the atmosphere

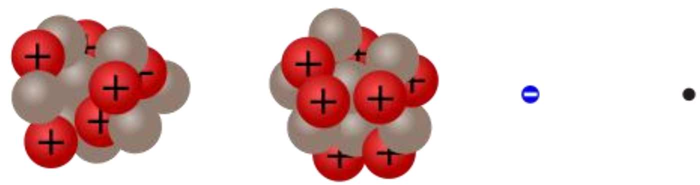
1- Cosmic rays (most p+ of 1GeV) produce neutron in the atmosphere (tropo- and stratosphere)
2- Neutrons are captured by nitrogen (most abundant gas in atmosphere)



$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}p$$

3- ^{14}C arrives on the surface. Natural atmospheric yield is estimated 20000-22000 Atoms/(m^2*s)

^{14}C decay



$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \overline{\nu} $$

Half-life of ^{14}C is 5730 years. ^{14}N is stable.

Exponential decay law

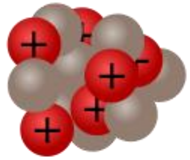
$$ N = N_0 \exp(-{}^{t}\!/\!_{\tau}) $$

N = amount of an isotope at time t
N_0 = amount at time t_0
τ = mean-life (half-life / log(2))

Radiocarbon dating

1949: technique developed by Willard Libby (University of Chicago)

Basic Idea: Plants and Animals fix atmospheric carbon during their life (in the form of $\mathbf{CO_2}$ (photosynthesis, food, …)).
When they die the amount of ^{14}C in them equals the one in the atmosphere.
Then no new ^{14}C is acquired, but the one present decays.



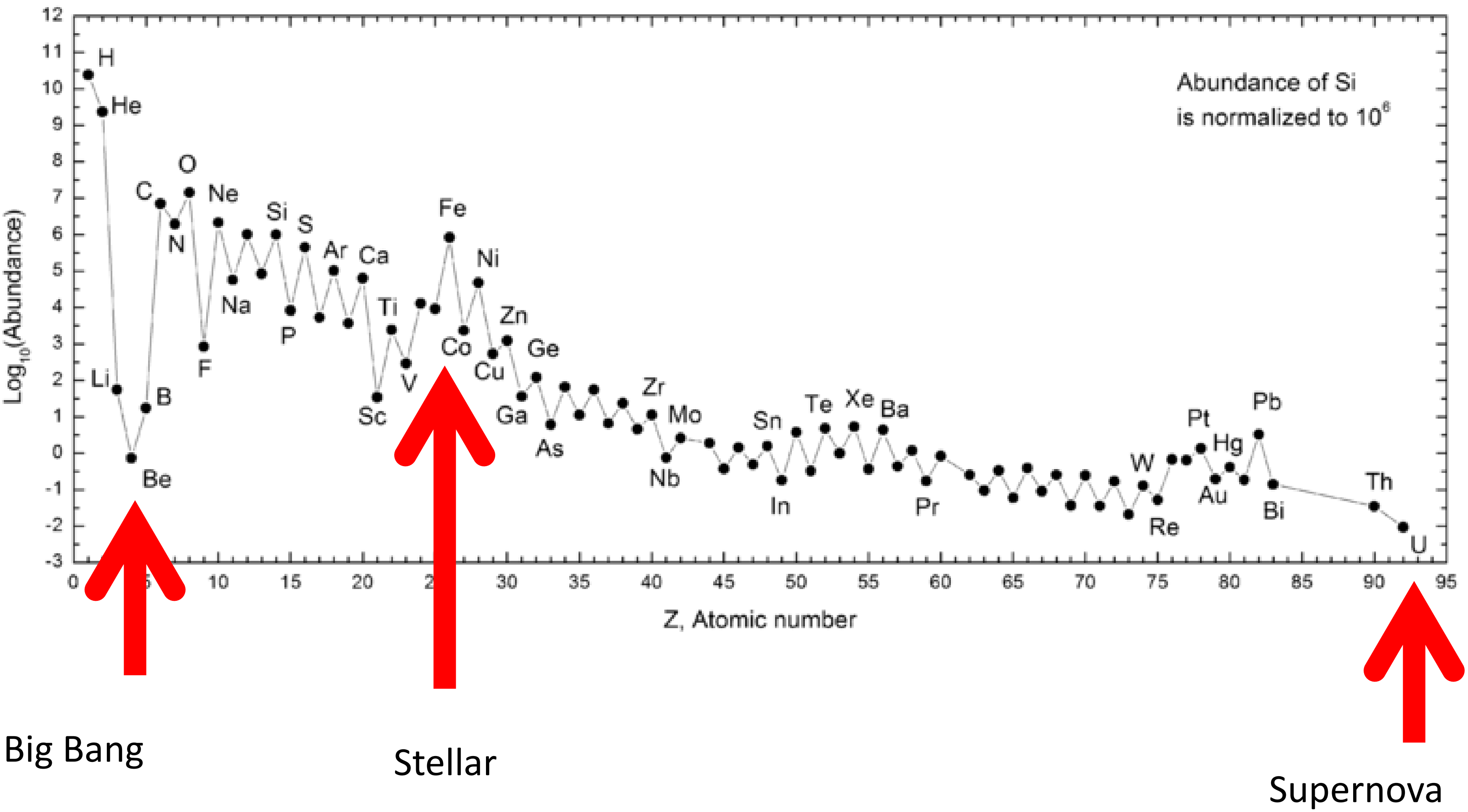
Libby estimated the radioactivity of ^{14}C to be 14 disintegrations/min per gram of C.
This allows estimating the age of archeologic findings up to 50000 years ago.

$$\text{Mol } ^{12}C = 10^{12} \cdot \text{Mol } ^{14}C$$

$$\text{Mol } ^{12}C > 10^{12} \cdot \text{Mol } ^{14}C$$

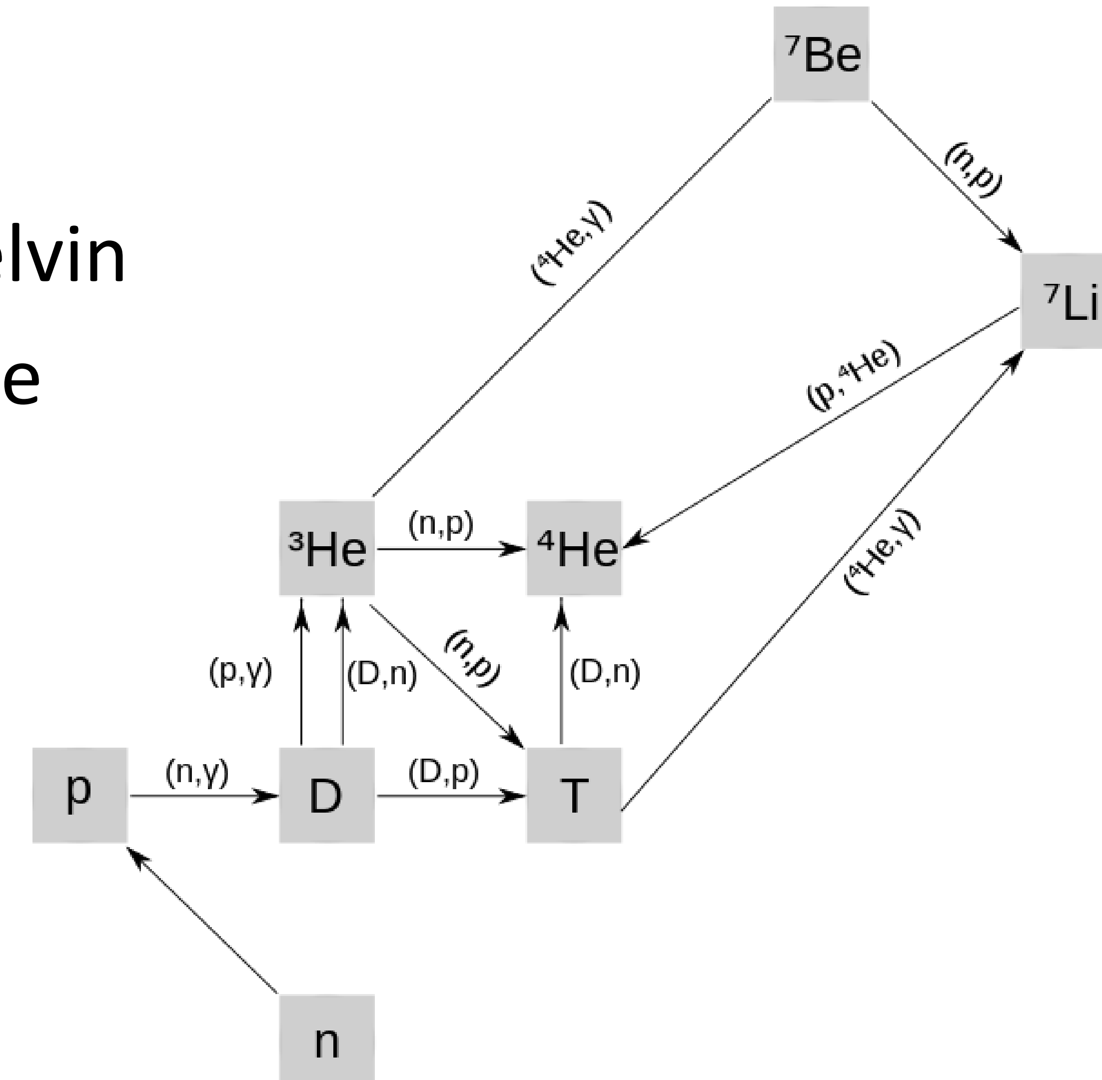
1960: Noble Prize to Willard Libby for *"his method to use carbon-14 for age determination in archaeology, geology, geophysics, and other branches of science"*.

Nucleosynthesis



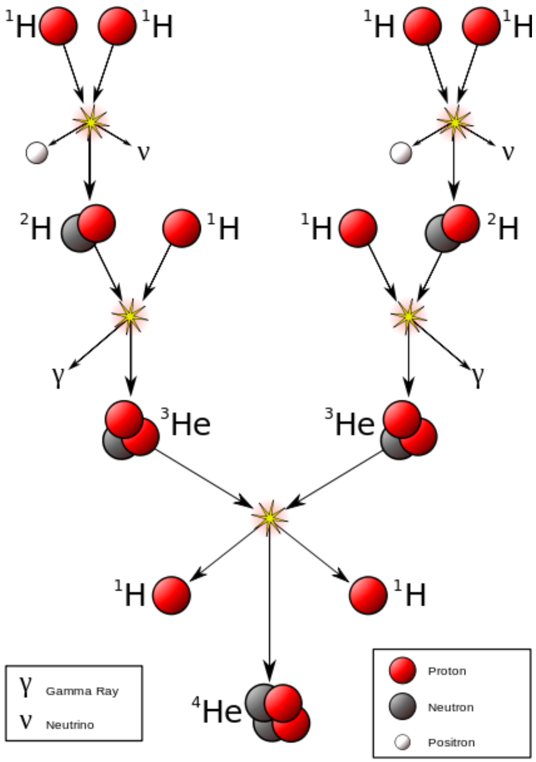
Big Bang Nucleosynthesis

- 10s-20min
- 116-1.6 gigaKelvin
- From H->^{7}Li,^{7}Be

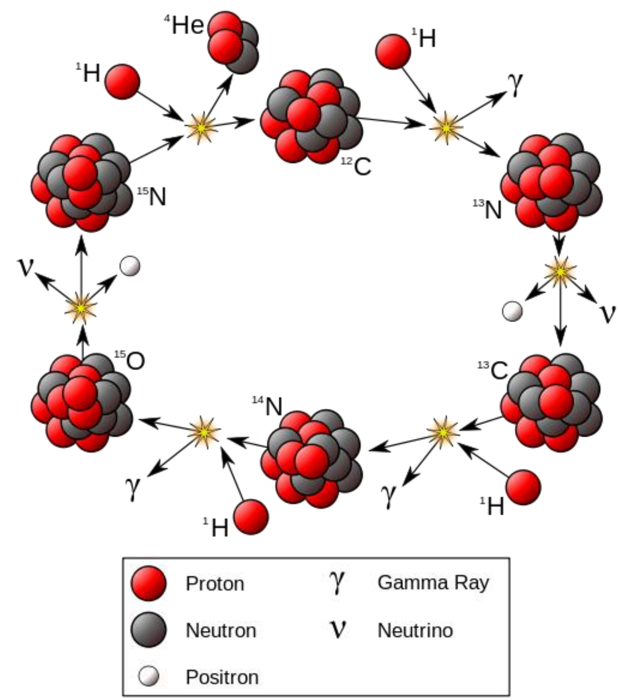


http://en.wikipedia.org/wiki/File:Scheme_of_nuclear_reaction_chains_for_Big_Bang_nucleosynthesis.svg

Stellar Nucleosynthesis, ^{4}He production



Light stars

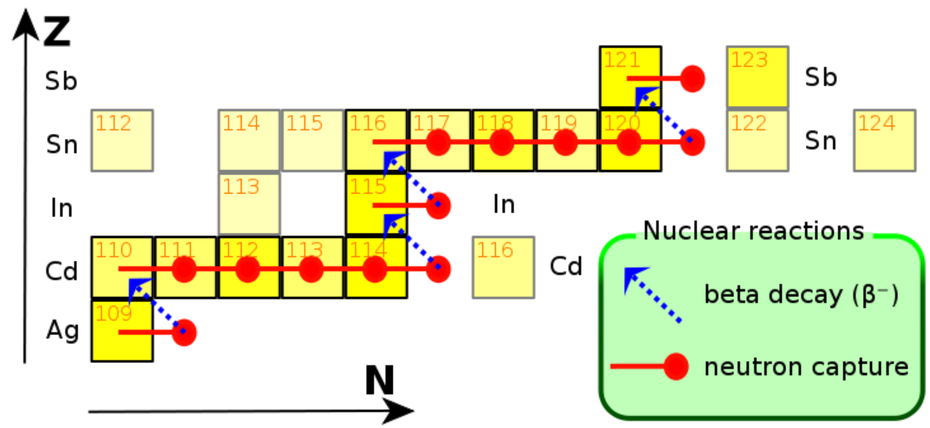


Heavier stars

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

Neutron Capture

- S-process (slow)
- R-process (rapid)
  - Extremely high neut. flux



http://en.wikipedia.org/wiki/File:S-process-elem-Ag-to-Sb.svg

Transmutation

- Easier to turn gold into lead!

$^{197}Au + n \rightarrow$ ^{198}Au (halflife 2.7 days) $\rightarrow$

$^{198}Hg + n \rightarrow$ $^{199}Hg + n \rightarrow$ $^{200}Hg + n \rightarrow$

$^{201}Hg + n \rightarrow$ $^{202}Hg + n \rightarrow$ ^{203}Hg (halflife 47 days)

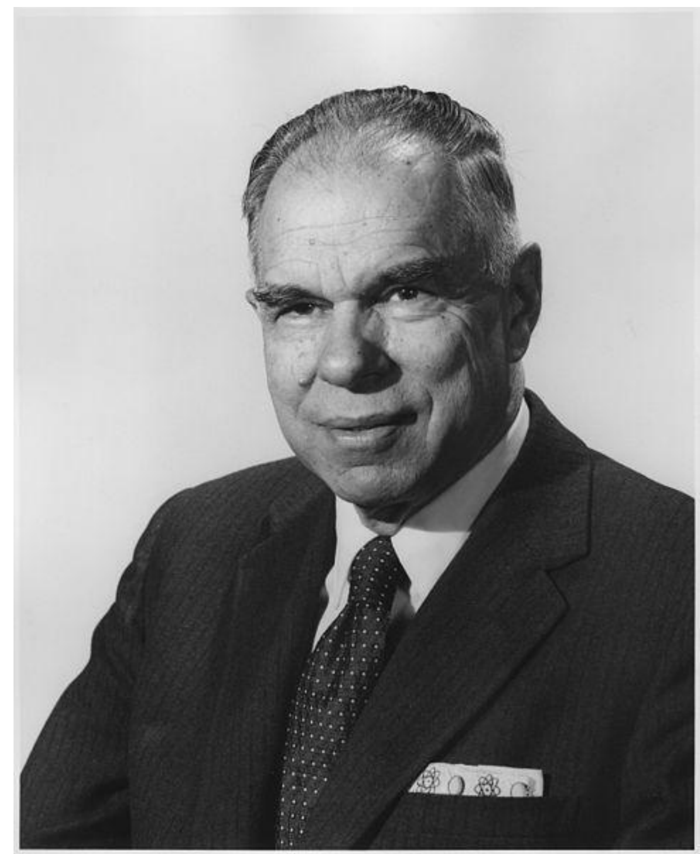
$\rightarrow$ $^{203}Tl + n \rightarrow$ ^{204}Tl (halflife 3.8 years) $\rightarrow$

^{204}Pb (halflife 1.4×10^{17} years)

Transmutation

- ${}_{83}Bi \rightarrow {}_{79}Au$ has been done

- 1000 atoms
- 5,000$ per hour
- 2 days



Thank you!

Thanks to Ulli Koester for his kind help!

More neutrons in the universe

NEUTRONS STARS are a type of compact star resulting from the gravitational collapse of a massive star after a supernova.

Proposed in **1934** by Walter Baade and Fritz Zwicky (2 year after Chadwick's discovery!)

Confirmed in **1967** by Iosif Shklovsky by pulsar observation.

Radiation from the pulsar PSR B1509-58, a rapidly spinning neutron star

NEUTRONS STARS are often spinning very rapidly, emitting electromagnetic radiation as **PULSARS**.

More neutrons in the universe

In **NEUTRONS STARS** gravitational force is so strong that neutrons are formed by the collapse of atoms ($p^+ + e^-$)
Gravitational force overcomes nuclear strong force!

Radiation from the pulsar PSR B1509-58, a rapidly spinning neutron star

NEUTRONS STARS are the densest and smallest stars known.
(12 km radius, mass of 2 Suns)

→$4*10^{30}$ kg condensed in 12 km instead of $7*10^5$ km

→Order of 10^{17} kg/m^3 ! (Sun is $1.4*10^3$ kg/m^3)

Gravitational force is so strong that due to relativistic effects, an observer on the surface would be able to see more than half of it.

More neutrons in the universe

Radiation from the pulsar PSR B1509-58, a rapidly spinning neutron star

Muse, 2010, Neutron Star Collision