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 $^{14}\text{C}$
• 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 $\alpha$ particle incident on light elements as Be, B, Li produced a radiation:
- highly penetrating
- Not influenced by electric field

$\rightarrow$ 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

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

James Chadwick (Cavendish Lab, Cambridge)

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

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

1935: Chadwick won the Nobel Prize in Physics “for the discovery of the neutron”.
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: \[ n^0 \rightarrow p^+ + e^- + \bar{v}_e \]
## Properties of a neutron

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quark structure</td>
<td>udd</td>
<td></td>
</tr>
<tr>
<td>Electric charge</td>
<td>$q_n = -0.2(8) \times 10^{-21} e$</td>
<td>ILL(1987)</td>
</tr>
<tr>
<td>Electric dipole moment</td>
<td>$d_n &gt; 2.9 \times 10^{-26} e \text{ cm}$</td>
<td>ILL(2006)</td>
</tr>
<tr>
<td>Mass</td>
<td>$m_n = 1.00866491600(43) \text{ u}$</td>
<td>ILL(1999)</td>
</tr>
<tr>
<td>Spin</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>Magnetic moment</td>
<td>$-1.91304272(45) \mu_N$</td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td>880(1) s</td>
<td></td>
</tr>
</tbody>
</table>
Charge of Neutron

\[ q_n = (-0.4 \pm 1.1) \times 10^{-21} \ e \] for 88 days (ILL)

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

\[ E = 6 \times 10^6 \text{V/m} \]
\[ V = 27 \text{kV} \]
Charge of Neutron

\[ q_n = (-0.2 \pm 0.8) \times 10^{-21} e \]

88 days (ILL)

Mass of neutron

\[ p + n \rightarrow ^2D + \gamma \]

Mass known \(\sim 2.2\text{MeV}\)
Mass of $^1\text{H}$ and $^2\text{H}$

- Penning trap

$\omega_E, \omega_B$

GAMS4 (ILL+NIST)

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

$$\theta_B = 0.083202185(11)$$
Mass of neutron

\[ p + n \rightarrow ^2D + \gamma \]

Therefore:
\[ 1.00866491600(43)u \]

2224566.14(41)eV
Test of $E=mc^2$

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

GAMS4 (ILL+NIST)

Accuracy = $4 \times 10^{-7}$

Neutron spin

\[ p + n \rightarrow ^2 D + \gamma \]

\[ s = \frac{1}{2} \] or \[ 3/2 \]

\[ s = 1 \]

\[ s = \text{??} \]

\[ s = 0 \]
Stern-Gerlach

Measurement result

Classical prediction

\[ F = \mu \frac{\partial B}{\partial z} \]
Stern-Gerlach


S=1/2
Magnetic moment

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

Therefore:

- $2.793 \mu_n$
- $0.857 \mu_n$

$\mu_N = e\hbar/2m_p$

$\therefore -1.913 \mu_N$
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 $B_1 (<B_o)$

$$\omega$$
Rabi single coil resonance

Larmor
\[ \omega_o = \gamma_n B_o \]

B₁ rotation
\[ \omega \]

\[ \mu_n = -1.91304272(45) \mu_N \]

Resonance
\[ \omega_o = \omega \]
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

- $d_n = 2.9 \times 10^{-26} \text{ e cm}$
- $\hbar \omega = 2 \mu_n B \mp 2d_n E$
- Ultra cold neutrons
- Limits are volume and density
Interactions
Interactions

UCN: Particle physics with “human dimensions”

Speed: some m/s

Magnetic field: 1 T may repel UCN 0.6 m high

Jumps up to 2.5 m high

≈ 10 min half-life
≈ 15 min lifetime

Courtesy of Koester Ulli
Interactions

Strong > EM > Weak > Gravity

\[ 1 : 10^{-2} : 10^{-7} : 10^{-42} \]

Typical distances:

\[ 1\text{fm} : \infty : 0.01\text{fm} : \infty \]
Neutron’s production

$(\alpha,n)$ and $(\gamma,n)$ reactions

Nuclear Fusion

Nuclear Fission

Spallation
(α,n) and (γ,n) reactions

(α,n) → Chadwick’s reaction

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

It is a sort of nuclear fusion reaction
(α,n) and (γ,n) reactions

(γ,n) induced by gamma rays

\[ \text{Reactions:} \]

\[ { }^{124}\text{Sb} = { }^{124}\text{Te} + \beta^- + \nu + \gamma \]

\[ { }^{9}\text{Be} + \gamma = { }^{8}\text{Be} + { }^1\text{n} - 1.66 \text{ MeV} \]

Immediately decomposing in 2 α particles

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

Cannot stay off too long (\({ }^{124}\text{Sb}\) half-life is 60 days)
Nuclear Fusion (to produce neutrons)

Fusion reactors produce neutrons:

- Artificial ones
  \[ \frac{2}{1}D + \frac{3}{1}T \rightarrow \frac{4}{2}He + \frac{1}{0}n \]
  - 3.5 MeV
  - 14 MeV (extremely energetic neutrons)

- Natural ones (stars)
  \[ \frac{13}{6}C + \frac{4}{2}He \rightarrow \frac{16}{8}O + \frac{1}{0}n \]
  - Several fusion & decay reactions involved (proton-proton and CNO cycles)
Average Binding Energy/nucleon

Gain in Binding Energy
→ Energy liberated
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».
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 susseguiti analoghi a quelli osservati dai contigui 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 state fornite dai proi. 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 fiore, la cui parete esterna è formata da una foglia d'alluminio di spessore di circa 0,2 mm, tale 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.

FILTRO. — Il fuoriuscito di calcio, irradiato per pochi minuti e portato poi assai rapidamente accanto al contatore determina nei primi minuti 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 fuoriuscito, bombardato con neutroni, si disintegra emettendo particelle α. La reazione nucleare è probabilmente:

\[ F + n \rightarrow N + He \]

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

\[ Al + n \rightarrow Na + He \]

Il Na così formato sarebbe un nuovo elemento radioattivo e si trasformerebbe in Ca anno di emissione di una particella B.

Se queste interpretazioni sono corrette, si avrebbe qui la formazione artificiale di elementi radioattivi che emettono normalmente particelle B, a differenza di quelli trovati dai Joliot che emettono invece positroni. In particolare nel caso dell'azoto si avrebbero due isotopi radioattivi: Nα, trovati dai Joliot, che emettendo un positrone si trasformano in C, e Nβ, che, emettendo un elettrone si trasforma in Oβ.

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

Then he publishes it on an Italian journal

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 history 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...

![Graph 1](image1.png)

![Graph 2](image2.png)
Nuclear Fission


In 1938 Fermi received the Nobel Prize in Physics "for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, 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

\[
\begin{align*}
\frac{235}{92}U + 1n &\rightarrow \frac{91}{36}Kr^* + \frac{145}{56}Ba^* + \text{Energy} \\
\frac{91}{36}Kr^* + \frac{145}{56}Ba^* &\rightarrow \frac{90}{36}Kr + \frac{144}{56}Ba + 2n + \gamma
\end{align*}
\]
Nuclear Fission: Energy Gain

Gain in Binding Energy ➔ Energy liberated
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.

\[ E = \Delta mc^2 \]

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.

$^{235}$U+n $\rightarrow$ $^{118}$Pd + $^{118}$Pd (199.769 MeV)

$^{235}$U+n $\rightarrow$ $^{100}$Zr + $^{136}$Te (199.799 MeV)

$\approx$ 200 MeV
Chart of Nuclides

- **α decay**
- **Spontaneous fission**
- **Positron Emission**
- **Proton emission**
- **Stable**
- **Neutron emission**

**Move diagonally on the chart**

$\text{p,n} \rightarrow \text{p+1, n-1}$

**Z (proton number)**

**N (neutron number)**
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 undergo a beta-n reaction, where after the beta process ($n \rightarrow p$) the new atom is in a state so excited that the extra energy is bigger than the neutron binding energy, thus emitting a neutron.

\[
\begin{align*}
^{87}\text{Br} & \xrightarrow{\beta} ^{87}\text{Kr}^* & \text{A,Z+1 Emitter} \\
\text{A,Z Precursor} & \xrightarrow{\beta} ^{87}\text{Kr} & \text{Neutron binding Energy} \\
& \xrightarrow{\gamma} ^{87}\text{Kr} & \text{n, neutron emission (1.3 MeV)} \\
& \xrightarrow{\beta} ^{87}\text{Rb} & \text{A-1,Z+1 Result} \\
& \xrightarrow{\beta} ^{87}\text{Sr} & \\
& \xrightarrow{\beta} ^{86}\text{Kr} & \text{STABLE STATE}
\end{align*}
\]
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: \( \rightarrow \text{fissile} \).

Uranium 235 is fissile. Uranium \(^{235}\text{U}\) is only 0.7% abundant in naturally found U. The most common isotope is \(^{238}\text{U}\) 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 $^{235}\text{U}$) 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 $^{238}\text{U}$) do not beneficiate of such energy.

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

- $^{235}\text{U}$ is fissile and can thus sustain a chain reaction. This can start because of spontaneous fission (or $(\gamma,n)$ 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**.

\[
\text{Mass } ^{235}\text{U} > \text{Critical Mass}
\]

→ neutron gain $\geq$ neutron losses

Chain reaction is sustained
Spallation sources
Spallation

1. Internal Cascade
2. Intra nuclear Cascade
3. Evaporation

10 MeV - 1000 MeV protons

High Energy Neutrons

Low Energy Neutrons, p, d, π, e^−, ν, etc.
Spallation Energies

\[
\frac{208}{82} Pb + p^+ \rightarrow ^{185}_{79} Au + 20n + 3 p^+ - 173 MeV
\]
Example of ISIS

\[ H_2 \rightarrow H^- \]
Example of ISIS

$H_2 \rightarrow H^-$
Example of ISIS

Linac

RFQ
Example of ISIS

$H^- \rightarrow H^+$

Linac
Example of ISIS

- $2.8 \times 10^{13}$
- $v = 0.84c$
- Focused
- Pulse 90ns wide
Example of ISIS

Tungsten Target
Neutron’s Production Review

1. Alpha-induced reactions ($\alpha,n$)
2. Gamma-induced reactions – Photodissociation ($\gamma,n$)
3. Nuclear Fusion
4. Spontaneous 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**

\[
 n^0 \rightarrow p^+ + e^- + \bar{\nu}_e
\]

- **Lepton conservation**
- Continuous spectrum of e\(^-\) energies \(\rightarrow\) 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** \([\approx 10\text{ min}]\)
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 exists

\[ p^+ + e^- \rightarrow n^0 + \nu_e \]
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)

<table>
<thead>
<tr>
<th>Atom</th>
<th>$\sigma_A$ (barns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H, D</td>
<td>0.33, 0.000519</td>
</tr>
<tr>
<td>Li ($^6\text{Li}$, $^7\text{Li}$)</td>
<td>70.5 (940, 0.045)</td>
</tr>
<tr>
<td>B ($^{10}\text{B}$)</td>
<td>767 (3835)</td>
</tr>
<tr>
<td>Co</td>
<td>37.2</td>
</tr>
<tr>
<td>Rh</td>
<td>144.8</td>
</tr>
<tr>
<td>Cd</td>
<td>2520</td>
</tr>
<tr>
<td>In</td>
<td>193.8</td>
</tr>
<tr>
<td>Sm</td>
<td>5922</td>
</tr>
<tr>
<td>Gd, 155Gd, 157Gd</td>
<td>49700</td>
</tr>
<tr>
<td>U ($^{235}\text{U}$)</td>
<td>7.57 (681)</td>
</tr>
</tbody>
</table>
Shieldings @ ILL

B₄C

Tank armor, bullet proof vest material, neutron absorber

Cd

Gd (Gd₂O₃)

http://www.borflex.fr/materiau-flexible-radioprotection/
http://upload.wikimedia.org/wikipedia/commons/thumb/6/6f/Boron_carbide.JPG/800px-Boron_carbide.JPG
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)

$$^{14}_7\text{N} + ^0_1\text{n} \rightarrow ^{14}_6\text{C} + ^1_1\text{p}$$

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

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

Exponential decay law

$$N = N_0 \exp\left(-\frac{t}{\tau}\right)$$

$N = $ amount of an isotope at time $t$

$N_0 = $ amount at time $t_0$

$\tau = $ 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 CO₂ (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.

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

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

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

Stellar

Supernova
Big Bang Nucleosynthesis

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

![Diagram of nuclear reaction chains for Big Bang nucleosynthesis](http://en.wikipedia.org/wiki/File:Scheme_of_nuclear_reaction_chains_for_Big_Bang_nucleosynthesis.svg)
Stellar Nucleosynthesis, $^4\text{He}$ production

Light stars

Heavier stars

Neutron Capture

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

• Easier to turn gold into lead!

\[ ^{197}\text{Au} + n \rightarrow ^{198}\text{Au} \text{ (halflife 2.7 days)} \rightarrow ^{198}\text{Hg} + n \rightarrow ^{199}\text{Hg} + n \rightarrow ^{200}\text{Hg} + n \rightarrow ^{201}\text{Hg} + n \rightarrow ^{202}\text{Hg} + n \rightarrow ^{203}\text{Hg} \text{ (halflife 47 days)} \rightarrow ^{203}\text{Tl} + n \rightarrow ^{204}\text{Tl} \text{ (halflife 3.8 years)} \rightarrow ^{204}\text{Pb} \text{ (halflife } 1.4 \times 10^{17} \text{ years)} \]
Transmutation

• $^{83}_{33}\text{Bi} \rightarrow ^{79}_{79}\text{Au}$ 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.

**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!

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

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

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