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Nuclear Physics - I
Useful Book : Nuclear Physics,
Samuel S.M. Wong

Chap. 1

Introduction;

Nucl. Phys. : The study of the structure of nuclei and the interaction between nucleons.

The basic blocks { i) Protons
ii) Neutrons

N and P are two different aspects of the same particle. (The nucleon)

Fundamental Interactions;

4 - fundamental interaction in nature { Strong
Electromagnetic
Weak
Gravitation

The modern view of <u>force</u> between particles is based on <u>field theoretical</u> ideas.

A particle feels the presence of another one through the <u>exchange</u> of one or more <u>field quanta</u>, little "bundles" of energy.

Ex. — Charged particles: Field quantum = Photon (Boson)

Bosons: Particles governed by Bose-Einstein statistics. They may be absorbed and emitted by interacting particles without being constrained by Pauli exclusion principle.

Acc. to Heisenberg uncertainty principle:

$$\Delta E \, \Delta t \lesssim \hbar$$

ΔE: the energy of field quantum.
Δt: the Time duration that the state of particle changes.

Δt is very short $\xrightarrow{\text{then}}$ the particle cannot be observed
(For this reason the field quantum is called virtual particle.)

In contrast: A real particle has a definite energy and the amount can be measured in the laboratory.

An estimate of Range:

speed of field quanta $\approx c$ (assumption)

$$r_0 \simeq c\,\Delta t \simeq \frac{c\hbar}{\Delta E}$$

Δt: amount of time that the field quantum exists.

For a massive particle ($m \neq 0$) ; $E \geqslant mc^2$

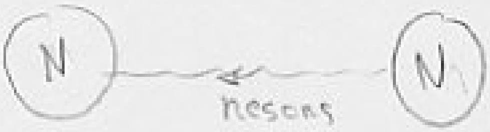
$$r_{0_{max}} = \frac{\hbar c}{E_{min}} = \frac{\hbar c}{mc^2} = \frac{\hbar}{mc}$$

$\hbar c \simeq 197$ Mev. fm ($fm = 10^{-15}$ m)

$\longrightarrow r_0 \approx 2$ fm if $mc^2 = 100$ Mev

If $m = 0 \longrightarrow r_0 \to \infty$ (as in the case of gravitational and electromagnetic interactions)

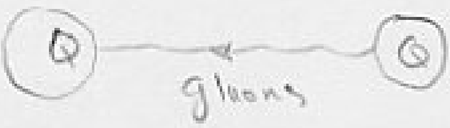
Field quanta in n-n (nucleon-nucleon) interaction are Mesons.



However; Nucleons and Mesons are not fundamental particles.

$$\text{Hadrons}\begin{cases}\text{nucleons}\\ \text{mesons}\\ --\\ --\\ --\\ --\\ \\ \\ --\end{cases}$$

Field quanta in Quark-Quark interaction are Gluons.



Quarks are the ultimate building blocks of nuclei.

Fundamental Interactions

Interaction	Field quantum	Range (m)	Relative strength	Typical Cross-section (m^2)	Typical time scale (s)
Strong	Gluon	10^{-15}	1	10^{-30}	10^{-23}
Weak	$W^{\pm}$ Z^{0}	10^{-18}	10^{-5}	10^{-44}	10^{-8}
Elec. Mag	Photon	∞	$\alpha = \frac{1}{137}$	10^{-33}	10^{-20}
Gravity	Graviton	∞	10^{-38}	—	—

Rest mass of $W^{\pm}$ and Z^{0} bosons $\sim$ 100 Gev (10^{11} ev)

while nucleon rest mass energy $\sim$ 1 Gev

$mc^2 = 10$ Gev $\longrightarrow r_0 \rightarrow 0$ (contact interaction)

a) Weak
b) Elec. Mag } interactions play an important role in nuclei.

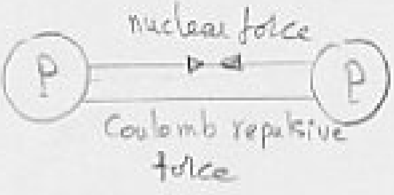
a)

In the absence of electromagnetic interactions nuclei having the same number of nucleons A but different Z and N are very similar to each other.

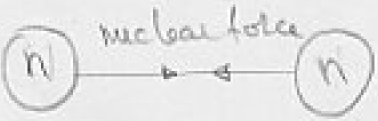
Strictly speacking this is true if the nuclear force is charge-indep. (the same for nn, pp, np interactions)

The nuclear forces are mainly <u>charge-indep.</u>, but not <u>completely</u>.

Coulomb interaction:



E_{pp}



E_{NN}

$E_{pp} < E_{nn}$

The Range of $\begin{cases} \text{Elec. Mag. Coulomb int.} : \text{long} \rightarrow E_c \sim (\text{number of } P)^2 \\ \text{Nucl. force} \quad : \text{Short} \rightarrow E_{nucl.} \sim (\text{" " nucleons}) \end{cases}$

The motion of proton $\xrightarrow{\text{Produces}}$ an electric current

The electric current $\xrightarrow{\text{"}}$ a mag. field

Mag. Dipole of the nucleus = Intrinsic mag. dipole moment of the nucleons + the above

As a result:

i) Nucleons can interact with an external El.-Mag. field, causing both emission and absorption of γ-rays.

ii) Also El.-Mag. interaction become an important consideration in the stability of *heavy* nuclei and understanding the *small* binding energy between members of an *isobar*.

Weak interaction is associated with β-decay ($e^{\pm}$)

$n_{free} \longrightarrow P + e + \bar{\nu}_e$

$P_{free} \not\longrightarrow n + e^{+} + \nu_e$ (not allowed, because of energy cons.)

$P_{bound} \longrightarrow n + e^{+} + \nu_e$

${}^{11}_{6}C \longrightarrow {}^{11}_{5}B + e^{+} + \nu_e$ (P_{bound})

A brief history of Nucl. Phys.

The beginning of nucl. Phys.:

1896: Becqurel → (blackend photographic plates)

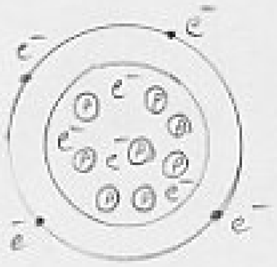
1898: Pierre & Mario Curie → seperated Radium ($Z=88$) from ore

They realized → Activity changes the chemical property.

Three different types of activity were stablished:

α, β, γ

1911: Rutherford ; Nuclear model for atom.



1920: Chadwick, determind
the radii of a few heavy nuclei $\simeq 10^{-14}$ m
$10^{-14} << 10^{-10}$ atomic radii

1932: Chadwick, Curie, Joliot: Disovary of Nuetron

1935: Yukawa ; Meson exchange theory of nucleon interaction

Puzzling point in α-decay:

$^{238}_{Z}U \longrightarrow \alpha + \cdots$ half-life ≃ 4.47 x10^9 Yr (long)

Kinetic eng. = 4.20 Mev

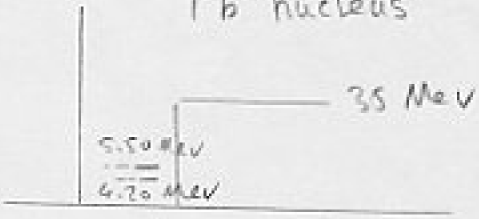
$^{238}_{Z+2}Pu \longrightarrow \alpha + \cdots$ " " ≃ 87.8 Yr

Kinetic eng. = 5.50 Mev

An estimate:

For $^{208}_{82}Pb$ Colomb barrier ≃ 35 Mev (the energy needed to bring an α-particle from infinity, close to Pb nucleus

Acc. to Classical consepts:



1- Difference in lifetime is 30-order of magnitude

2- For a particle having the energy 5.5 or 4.20 Mev, it is impossible to over come the 35 Mev barrier.

But { 1- Tunnelling effect
2- Wave nature of particle } solved the problem.

Acc. to classical consepts: α-particle must aquire an amount of energy, for exaple, through random collisions with the other constituents of the nucleus, to bring it to the Top of potential barrier, before it can be free from the nucleus.

If this were the case, $\multimap$ $KE_\alpha \geqq$ barrier height

Rutherford model was rejected;

Since an electron-proton pair has integer-spin

Then we must have $\longrightarrow$

$$\text{nucleus spin}\begin{cases}\text{integer} & \text{if charge of nucleus} = 2ne\\ \text{half-integer} & \text{'' \quad '' \quad ''} = (2n+1)e\end{cases}$$

But this is not true.

$$\text{Because nucleus spin}\begin{cases}\text{integer} & \text{for even number of nucleons}\\ \text{half-int.} & \text{'' \quad odd \quad '' \quad '' \quad ''}\end{cases}$$

1931 Pauli; proposed the neutrino ν particle;

1933 Fermi sloved the puzzle in nuclear β-decay

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

ΔE_{np} = const.

$E_{\bar{e}}$ = continuous spectrum of energy up to a maximum (endpoint energy)

There should be another particle to carry:
- 1- a unit of spin $\frac{1}{2}$
- 2- the remaining energy

ν: No charge ad almost massless

1957 Lee and Yang; parity violation in Weak interaction

It was confirmed by β-decay experiment on ^{60}Co;

it was observed → more electrons are emitted with momenta components opposite to the orientation of the nuclear spin than along it.

This is a clear violation of the invariance of operations under space inversion (broken symmetry).

$\left\{\begin{array}{l}\text{Strong}\\ \text{El.-Mag.}\end{array}\right.$ interactions are Known to conserve Parity;

i.e. : experiments give the same results whether they are viewed in right-handed coord. systems or left-handed coord. systems.

Possible future directions;

1) Measurement of neutrino mass
2) Relation between different types of neutrinos (neutrino oscillation)
3) " " neutrinos and antineutrinos (Majorna or Dirac Particles)

* Case (2) and (3) are also related to the question of whether the neutrino has a finite mass.

4) New technology, the possibility of building accelerators for heavy ions, new detection instruments will make it possible;

a) Creating new Particles in the lab.
b) Study of collision between heavy nuclei.
c) Revealing hidden Physical laws under special conds.
d) study of the laws of QED using the interaction results in the heavy ions collision (which involves interactions between intense Coulomb field.)

e) To reach high relativistic energy (several hundred GeV per nucleon). In such a collision of nuclei the nucleons inside nuclei may <u>lose</u> their identity and;

Consentration of hadronic matter $\xrightarrow{\text{may be regarded as}}$ plasma of $\left\{ \begin{array}{l} \text{Quarks} \\ \text{Gluons} \end{array} \right.$

f) Double-β decay (which has a bearing on the unification of all fundamental interactions, the central theme of grand unification theories)

For many nuclei;

$$(A,Z) \xrightarrow[\text{slow}]{} (A,Z+2) + 2e^- + \underbrace{\overset{?}{2\bar{\nu}_e}}_{\text{with or without}}$$

(because of second order weak int.)

For example;

$$^{76}Ge \longrightarrow {}^{76}Se + 2e^- + 2\bar{\nu}_e \qquad (\text{liftime} \sim 10^{21}\,\text{yr})$$

2) If the neutrinos are <u>Majorara</u> particles (neutrino = antineutrino), it may be possible to have <u>3</u> products on the right-hand side of eq. (instead of <u>5</u> product) (they annihilate each other).

$\xrightarrow{\text{leading to}}$ liftimes of double β-decay may be shortened greatly.

ii) On the other hand if, neutrinos are Dirac Particles (neutrino ≠ antineutrino), neutrinoless double B-decay is not possible.

But the is <u>no</u> neutrino in double B-decay.

g) Quark investigation

i) They are small (point like)
ii) Their effect can be observed at very short distances

1983, EMC effect (European Muon Collaboration), Lepton scattering is a good probe here to show:

$$\text{quark substructure for a} \begin{cases} \text{free nucleon} \\ \text{bound "} \end{cases}$$

Are they different or the same. We are not sure for some large uncertainties in the experimental data.

Free nucleons and bound nucleons behave somehow different and this is attributed to quarks.

One possibility is that:
The only effect of quarks in nuclei is a change of scale associated with the nucleons.

Meaning:

When a nucleon is imbeded in the nuclear medium, the quarks inside re-adjust themselves in such a way that all the nucleon properties scale in some straightforward manner such as, for example, a change of nucleon size.

If this is true, what is the scaling law?

h) Mesons:
Unlike the presence of quarks, there is very little doubt that mesonic currents exist in nuclei. The difficulty is that; the observed contributions seem to be too small.

Meaning:
Most of nuclear properties can be understood by considering bound nucleons to be essentially identical to free nucleons.

One possible explanation;

The apparent absence of a stronger effect from <u>mesonic</u> currents is that:

Their effects are, <u>to a large extent</u>, cancelled by other factors operating at the same time.

<u>If this is the case</u>;

Such cancellation cannot be simply attributed to an accident of nature;

Some <u>fundamental</u> symmetry must be operating here (waiting for us to <u>discover</u>).

2) Δ-Particle

Given sufficient energy (intermediate);

A nucleon $\xrightarrow{\text{may be excited into}}$ Δ-particle
(a strong resonance in the Pion-nucleon channel)

In this investigation one should have a good knowledge on nuclear wave functions at <u>smaller</u> distances (high momenta, high energy), and consequently <u>relativistic</u> treatment of <u>many-body</u> problem.

Because of the large amount of overlap between Nucl. Phy. and Particle Phys., the distinction between these two is quite meaningless.

$$\text{Today} \longrightarrow \text{subatomic Phys.} \begin{cases} \text{Nucl. Phys} \\ \text{Particle ''} \end{cases}$$

Distinction between different braches of subatomic Phys. are made on the basis of the energies involved:

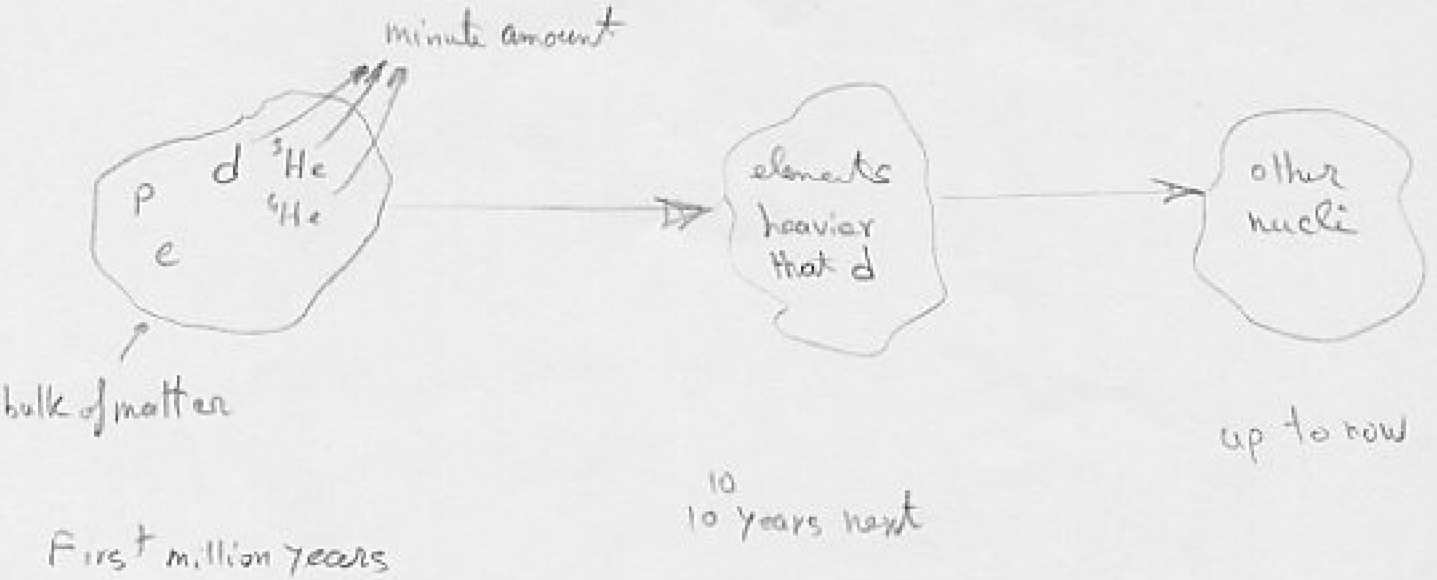
Elementary Particle — High energy Nucl. Phy	$\sim 10^{12}$ eV (TeV)
Intermediate energy Nucl. Phys.	10^{8} eV (100MeV) – 10^{9} eV (1GeV)
Low energy Nucl. Phys.	$\leqslant$ tens of MeV

The separation of energy is meaningful in one sense:

Energy (MeV)	Wavelength (fm) (involved scale)		
	Photon	Electron	Proton
0.1	1.2×10^4	3701	90
0.5	2.5×10^3	1421	40
1	1.2×10^3	872	29
10	1.2×10^2	118	9
100	1.2×10	12	2.8
1000	1.2	1	0.7

Nucleo-synthesis

Only a minimal amount of primordial nucleosynthesis took place in the first million years or so after the big bang, befor the end of the radiation era.



Hydrogen burning: (Proton burning)

In a typical young star like our own Sun:

$$4\,p \xrightarrow[\text{too small probability}]{\text{burning}} {}^4He + 2e^+ + 2\nu_e \qquad \underbrace{\text{energy converted} \ \% \ 0.7 \text{ of mass}}_{\text{most efficient energy production mechanism known.}}$$

Most likely process:

i) PPI chain;

(a) $p+p \longrightarrow d + e^+ + \underset{\substack{\downarrow \\ \text{balances the} \\ \text{lepton number}}}{\nu_e}$ (deuteron binding energy = 2.2MeV)

(b) $p+d \longrightarrow {}^3He + \gamma$ (p,γ) reaction

(c) ${}^3He + {}^3He \longrightarrow {}^4He + p + p$

(a,b,c) $\sim$ $4p \longrightarrow {}^4He + 2e^+ + 2\nu_e$ delivered energy = 28MeV

ii) PPII chain;

(a) ${}^3He + \overset{\nearrow\,\text{catalyst}}{{}^4He} \longrightarrow {}^7Be + \gamma$

(b) $e^- + {}^7Be \longrightarrow {}^7Li + \nu_e$

(c) $p + {}^7Li \longrightarrow {}^4He + {}^4He$

(a,b,c) $\sim$ $e^- + p + {}^3He \longrightarrow {}^4He + \nu_e + \gamma$

iii) ppIII chain;

$$p + {}^7Be \longrightarrow {}^8B + \gamma$$
$$ {}^8B \longrightarrow {}^8Be + e^+ + \nu_e$$
$$ {}^8Be \longrightarrow {}^4He + {}^4He$$

The interest of this reaction is in the high energy (7 MeV on the average) neutrino released in β^+-decay of ${}^8B$.

The energy is sufficient to change ${}^{37}Cl \xrightarrow{to} {}^{37}Ar$

$$\nu_e + {}^{37}Cl \longrightarrow e^- + {}^{37}Ar$$

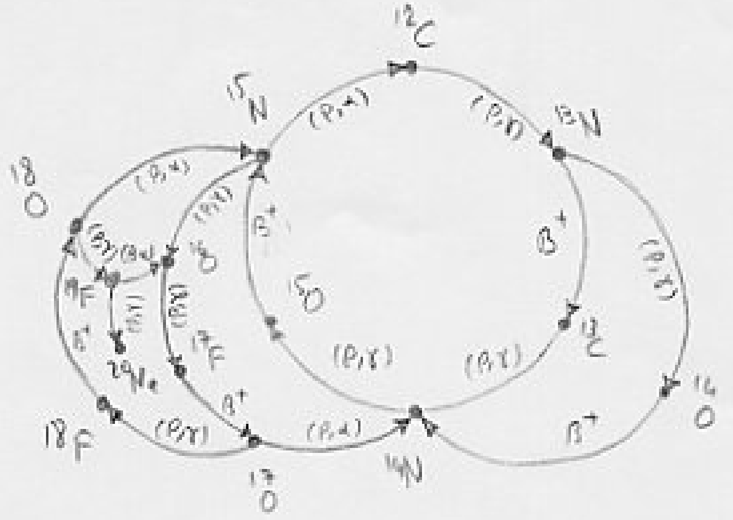
So;

The amount of change of ${}^{37}Cl$ in the chemical form C_2Cl_4 $\xrightarrow{\text{gives}}$ The rate of neutrino Production from ${}^8B$-decay

(C_2Cl_4 detector)

If sufficient amounts of heavier elements, such as ^{12}C, are present, a more efficient proton burning process may take place.

CNO cycle (carbon-nitrogen-oxygen):



$$^{12}C(p,\gamma)\,^{13}N(\beta^+)\,^{13}C(p,\gamma)\,^{14}N(p,\gamma)\,^{15}O(\beta^+)\,^{15}N(p,\alpha)\,^{12}C$$

The net result:

$$4p \longrightarrow {}^{4}He + 2\bar{e} + 2\nu_e$$

The process is more efficient with ^{12}C as the catalyst.

Side chains:

$^{13}N(p,\gamma)\,^{14}O(\beta^+)\,^{14}N \xrightarrow{\text{to}}$ the main CNO cycle

Similarly:

$^{15}N(p,\gamma)\,^{16}O(p,\gamma)\,^{17}F(\beta^+)\,^{17}O(p,\alpha)\,^{14}N \longrightarrow$ "

Again: a ^4He is made from 4-Protons.

^{17}O in the intermediate state:

$^{17}O(p,\gamma)^{18}F(\beta^+)^{18}O(p,\alpha)^{15}N$

^{18}O in the intermediate state:

$^{18}O(p,\gamma)^{19}F(p,\alpha)^{16}O$

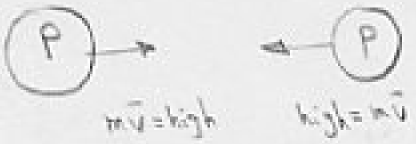
^{19}F in the intermediate state:

$^{19}F(p,\gamma)^{20}Ne$

In this way we see that heavior and heavior elements are produced by capturing protons one at time.

In order for PP chains and other nucleosynthesis reactions to take place both

high density (collision probability increases)
" temperature (energic collision)



Two protons with high $m\bar{v}$ overcome the Coulomb barrier to come enough close together (nuclear effective range)-

Ex. – Consider two nuclei, having proton numbers Z_1 and Z_2

The height of Coulomb barrier;

$$V_c = [\frac{1}{4\pi\epsilon_0}] \frac{(Z_1 e)(Z_2 e)}{R}$$

with [ ] : SI units
without [ ] : cgs =

$R > r_1 + r_2$

$$\alpha = [\frac{1}{4\pi\epsilon_0}] \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

$$V_c = \alpha \hbar c \frac{Z_1 Z_2}{R} \approx 1.44 \frac{Z_1 Z_2}{R(fm)} \text{ Mev}$$

$\alpha \hbar c \simeq 1.44$ Mev-fm

Between two protons, $(Z_1 = Z_2 = 1)$, with $R = 1 fm$

$\longrightarrow V_c \simeq 1$ Mev

It requires a temperature of the order of $T = \frac{E}{K} \simeq 10^{10}$ K

(where $K = 8.6 \times 10^{-11}$ Mev/K, Boltzman const.)

The interior of our sun $\ll 10^{10}$ K

(by three orders of magnitude)

$\longrightarrow$ Most of nuclear reactions must take place through barrier penetration due quantum mechanical tunnelling rather than by overcoming the Coulomb barrier.

For heavier nuclei, the Coulomb barrier is <u>even</u> higher.

$\longrightarrow$ even higher temperature is required.

The source of kinetic energy;

Gravitational contraction of a star; (the raw material for forming a star gradually coalesces into a <u>smaller</u> volume, $\xrightarrow{\text{the decrease in gravitational potential energy}}$ is converted into <u>heat</u>)

Helium <u>burning</u> and formation of nuclei up to A=56:

When most of the protons (in a young star) are converted into ^4He

$\longrightarrow$ star starts to cool down (due to radiation loss)

$\longrightarrow$ thermal pressure is reduced $\longrightarrow$ gravitational contraction again $\longrightarrow$ the star is heated up to a temp. > proton burning stage $\longrightarrow$ at 10^8 K (~ 10 keV) nuclear reactions containing ^4He begin to be significant, (next stage of nucleosynthesis).

$$3\,{}^4He \xrightarrow[\text{too small probability}]{\text{burning}} {}^{12}C$$

The majority of the reaction takes place in two stages:

$${}^4He + {}^4He \longrightarrow {}^8Be \quad \text{unstable}$$

lifetime $= 2.6\times10^{-16}$ s

But this lifetime is sufficiently long for the reaction:

$${}^4He + {}^8Be \longrightarrow {}^{12}C + \gamma$$

This is in part due to the large cross-section for the ${}^8Be(\alpha,\gamma)\,{}^{12}C$ reaction (in particular, to the 0^+ excited state in ${}^{12}C$ at 7.44 Mev).

From the point of view of nuclear structure:

a) 7.44 Mev state of ${}^{12}C$ (0^+): $\alpha - \alpha - \alpha$

b) Ground state of ${}^{12}C$:

$$\text{The wave func. of } (\alpha-\alpha-\alpha) \underset{\text{has large overlap}}{\approx} \text{The wave func. of } ({}^8Be + {}^4He)$$

The next process;

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

has large cross-section (since ^{16}O in the ground state has α-cluster structure wave func.)

Other tight nuclei with α-cluster structure; such as ^{20}Ne and ^{24}Mg are also formed by successive capture of α-particles.

Another stage of gravitational contraction $\longrightarrow$ $> 10^{9}$ K ($\sim$ 100eV average kinetic energy per particle)

$$
\begin{aligned}
^{12}C + ^{12}C &\longrightarrow ^{24}Mg + \gamma \\
&\longrightarrow ^{23}Na + p \\
&\longrightarrow ^{23}Mg + n \\
&\longrightarrow ^{20}Ne + \alpha \\
&\longrightarrow ^{16}O + \alpha + \alpha
\end{aligned}
$$

At even higher temp. :

$$
\begin{aligned}
^{16}O + ^{16}O &\longrightarrow ^{32}S + \gamma \\
&\longrightarrow ^{31}P + p \\
&\longrightarrow ^{31}S + n \\
&\longrightarrow ^{28}Si + \alpha \\
&\longrightarrow ^{24}Mg + \alpha + \alpha
\end{aligned}
$$

The reaction; $^{12}C + {}^{16}O$ is not considered;
(because when the temperature rise enough for this reaction most of ^{12}C is exhusted before.)

The process of forming successively heavior elements through exothermic thermonuclear reactions stops around mass $A=56$ (^{56}Fe and ^{56}Ni).

nucl. binding energy reaches Max. at $A=56$

The net binding energy is the result of balance between:

$$\begin{cases} \text{1- attractive nucl. forces} \approx \text{No. of nucleons} \\ \text{2- repulsive Coulomb "} \approx (\qquad\qquad)^2 \end{cases}$$

Since;

$$F_{n-p} > F_{nn} \text{ or } F_{pp}$$

(F: nuclear force)
(because P and n are not identical)
(and can be closer together

$$\longrightarrow N_p \approx N_n \quad \text{for } A<56 \text{ (N: number)}$$

But for $A>56$, electrostatic repulsion become significant factor (because of large amount of positive charge)

An estimate:

Consider a uniformaly charged sphere of radius R with total charge (Ze)

$$E_c = \left[\frac{1}{4\pi\epsilon_0}\right] \underset{\substack{\uparrow \\ \text{charges centered} \\ \text{at origin}}}{\frac{(Ze)^2}{R}} = \alpha\hbar c \, \frac{Z^2}{R} \longrightarrow \alpha\hbar c \, \underset{\substack{\uparrow \\ \text{uniformaly charged}}}{\frac{Z(Z-1)}{R}}$$

$$R = 1.2\, A^{1/3}\ \text{fm}$$

$$\longrightarrow E_C = 1.3\ \text{Gev} \quad \text{for } {}^{208}\text{Pb}$$

$$\text{or} \quad E_C/A = 6.5\ \text{Mev} \qquad \text{energy per nucleon}$$

This value should be compared with:

Max. binding energy per nucleon ≈ 9 Mev   for $A = 56$

Sources of heavy nuclei:

Heavy nuclei $A > 56$

These nuclei cannot be formed by exothermic processes

$\xrightarrow{\text{So}}$ No thermonuclear reaction can take place once all the nuclei are converted to $A = 56$.

Gravitational contraction again $\longrightarrow$ No thermal pressure generated by nuclear reactions

$\longrightarrow$ No reduction of gravitational attraction

$\longrightarrow$ i) If the star is small, it will stop shining when all the gravitational energy is released (gentle end)

ii) In massive stars the gravitational force is overwhelming that $\xrightarrow{\text{collapse}}$ in order of seconds

$\longrightarrow$ compression of matter $\longrightarrow$ density of star > nuclear density

(for a short time ~ fraction of second)

A part of gravitational energy $\xrightarrow{\text{is transformed into}}$ Potential energy
(in the form of
super-compressed
nuclear matter)

Since;

Nuclear matter is rather stiff against compression

→ the excess potential energy $\xrightarrow{\text{will cause}}$ the star to explode in the form of supernova

→ such explosion is the source of heavy nuclei.

The probability for a particle having Kinetic energy E in a given stellar temp. T, is given by the Boltzman factor;

$$P(E) \sim e^{-E/KT}$$

$\xrightarrow{\text{then}}$ at any given T, there is finite probability that a charged particle with enaugh energy to tunnell through the Coulomb barrier of a heavy nucleus.

→ Formation of heavier nuclei by capture.

(endothermic reaction)

The process;

$$(A=56) + {}^{4}He \xrightarrow[\text{Too small probability}]{} \text{Heavier nucleus}$$

As an example; let us estimate the probability for α-particle capture of ^{204}Hg to form ^{208}Pb.

The height of Coulomb barrier!

$$V_c = \alpha \hbar c \frac{Z_1 Z_2}{R} \simeq 1.44 \frac{Z_1 Z_2}{R(fm)} \text{ Mev}$$

$$\left\{ \begin{array}{l} Z_1 = 2 \\ Z_2 = 80 \\ R = 1.2 A^{1/3} = 5.9 fm \end{array} \right. \longrightarrow V_c \simeq 32 \text{ Mev}$$

(while for capturing α-particle by ^{52}Fe to form ^{56}Ni,)
$V_c \simeq 15$ Mev

Acc. quantum mechanical tunnelling effect;

P ~ expotentialy decrease with V_c

α-capture probability

⟶ The amount of heavy nuclei produced in this way is minuscule.

Other process must be responsible for the production of the bulk of the observed heavy nuclei.

One way is neutron capture (no Coulomb barrier present).

i) Under normal stellar conditions the neutron flux is too small for this process (slow process: s-process)

ii) During the supernov explosion, the neutron flux is extremely high and neutron capture becomes an important process (rapid process: r-process).

But;

The relative amounts of all the elements observed cannot be explained by the main process of nucleosynthesis. (for example; Lithium, Beryllium and Boron, are more abundant than would be expected from stellar sources)

More complicated procedures must be invoked.

The study of Nuclear Physics:

a) One of the source of information is radioactive nuclei,

The information can be obtained from:

- i) Elements created in the laboratory
- ii) Liftime of the excited states
- iii) Relation between initial and final states

b) Detection of solar neutrinos is another source of information. (Detectors are located in sattelites and in underground mines)

(a) and (b) are passive observation.

c) Accelerators makes it possible;

- i) To form new states
- ii) To " new elements

All charged particles can in principle be accelerated.
But { high intensity / good energy resolution } are also essential.

In this respect → Electron accelerators have an advantge.

Hadronic probes are also used in accelerators:

A- Light ions:

1- nucleons
2- deuteron (one P, one n)
3- triton (one P, two n)
4- ^3He
5- α-particle

Each one is good for a special kind of study.

For example:

I) $\alpha_{spin} = 0$ $\alpha_{isospin} = 0$

$\longrightarrow$ α-particle scattering is ideal for exciting a nucleus without changing the isospin.

II) Deutrons are loosely bound systems of protons and neutrons $\xrightarrow{\text{they are useful}}$ for transferring a nucleon to the target nucleus.

B- Heavy ions;

They can Create;

1- New and exotic nuclei
2- intense elec.-Mag. fields
3- even quark-gluon plasma

They are capable;

1- of transferring large amount of <u>mass</u> and <u>angular momentum</u>
2- to create states of extremely high angular momentum.

C- Mesons; are another hadronic Probes.

<u>Nuclear force</u> is known to be mediated by <u>mesons</u>.

Meson scattering and meson absorption $\xrightarrow{\text{give}}$ some information.

D- Antiprotons

Precision in antiproton scattering off nucleons and nuclei is <u>far less</u> than what can be obtained with protons.

Lepton probes:

Weak interaction, or lepton, probes are used for certain types of nuclear studies (Ex.: EMC effect).

a) Electron is a lepton, but, its interaction with nuclei is dominated by its charge.

⟶ Weak interaction effects are overshadowed by El.-Mag. interactions.

b) Neutrinos, being neutral leptons, are more useful.

The usefulness of neutrino scattering is limited by the small reaction cross section.

15 order of mag. < strong int. at low energies

Although nuclear models are very successful in correlating large amounts of experimental data, we are not yet at the stage of having an unified all-encompassing theory of nuclear structure and nuclear reaction.
Perhaps the nature of strong interaction is complicating the many-body problem.

Commonly used units:

Length $1\ \text{fm} = 10^{-15}\ \text{m}$ (femtometer)

area $1\ \text{fm}^2$ (typical area: cross section of strong int. process)

″ $\text{barn} = 10^{-28}\ \text{m}^2$

″ $\text{millibarn} = 10^{-1}\ \text{fm}^2$

″ $\text{microbarn} = 10^{-4}$ ″

$M_{\text{nucleon}} = 1.67 \times 10^{-27}\ \text{kg}$ $\quad M_n = M_p\left(1 + \frac{0.14}{100}\right)$

Atomic mass unit: u or amu, $u = 1.6605402 \times 10^{-27}\ \text{kg}$

$1\ \text{Mev} = 1.60217733 \times 10^{-13}\ \text{J}$

$M_n = 939.56563\ \text{Mev}$

Large variety of time scales:

Long time scale (like liftime $\sim 10^{9}\ \text{yr}$) is not typical of nuclear interaction.

For lifetimes of the order 10^{-15} to $10^{-23}\ \text{s}$, it is more convenient to represent them in terms of their inverse in energy units.

$\Delta E\, \Delta t = \hbar \longrightarrow \Delta E \sim \frac{\hbar}{\Delta t}$ $\quad \Gamma = \frac{\hbar}{\overline{T}}$ width in probability distribution of the energy

$\overline{T}$: lifetime (mean life) $\quad \hbar = 6.58 \times 10^{22}\ \text{Mev-s}$

$\overline{T} = 10^{-23} \longrightarrow \Gamma = 100\ \text{Mev}$, $\overline{T} = 10^{-15} \longrightarrow \Gamma = 1\ \text{ev}$