Introduction to Atomic Nuclei

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- The nucleus
- Chart of nuclides
- Nuclear force
- Nuclear structure and excitations
- Radioactivity and fission
- Nuclear reactions and accelerators
- Quark structure of nucleus
- Phases of nuclear matter
- Origin of the elements
- Applications of nuclear science

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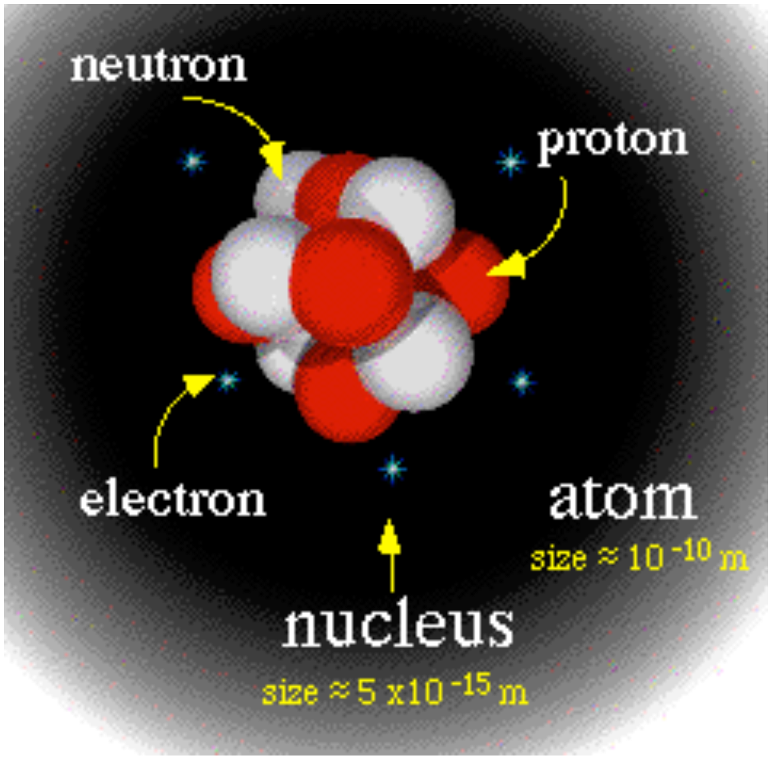
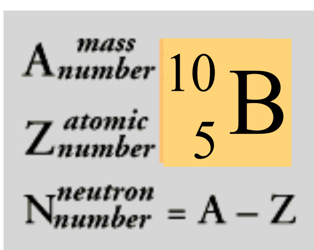
Nucleus: Discovered by Ernest Rutherford in 1911 in alpha particles scattering from atoms. It is the core of the atom, where most of its mass and all of its positive charge is concentrated. Except for ^{1}H, the nucleus consists of a combination of protons and neutrons.





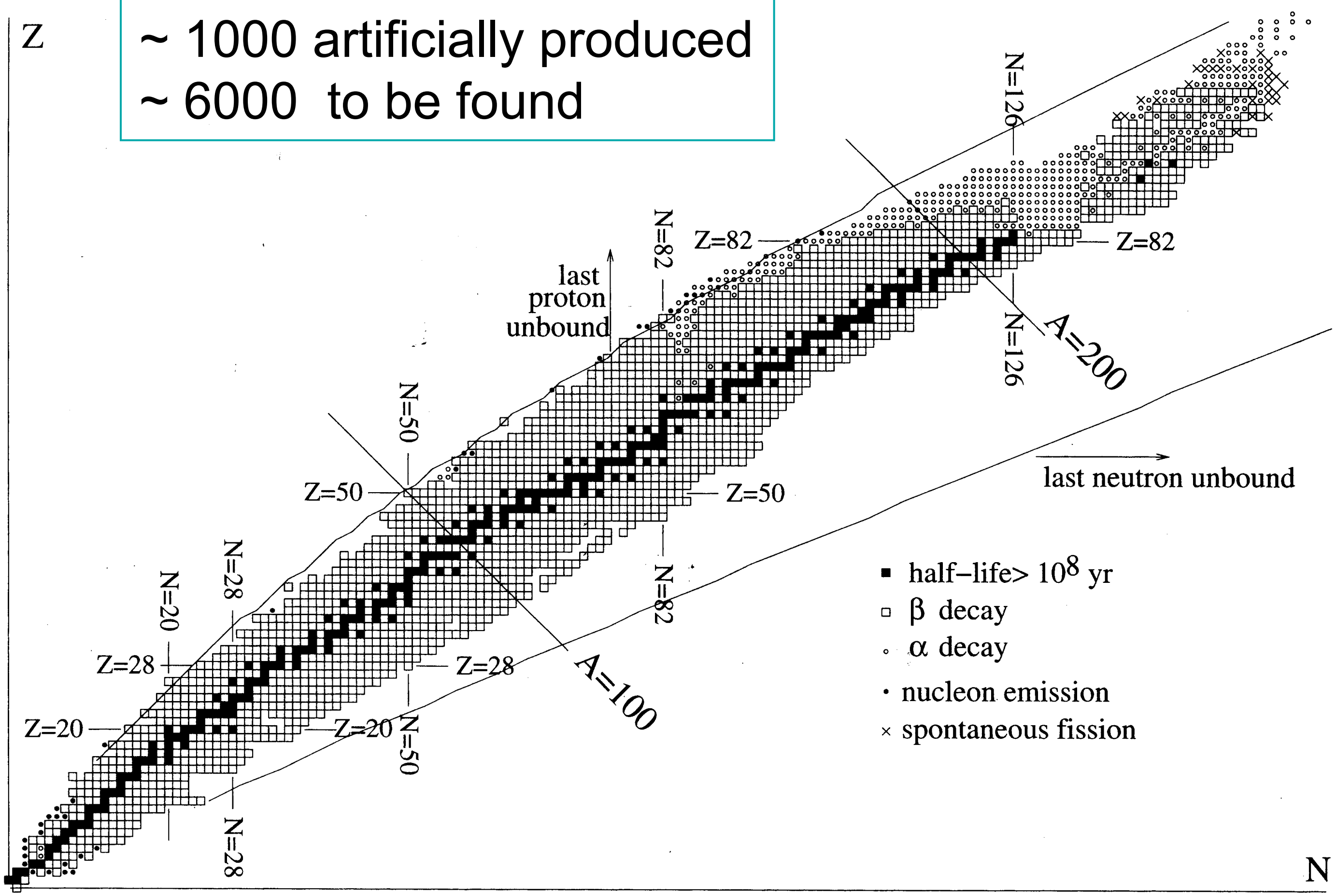
Proton: Nucleus of the hydrogen atom; carries same amount of charge ($\sim 1.6 \times 10^{-19}$ C) as electron but opposite sign; weights ($\sim 1.67 \times 10^{-27}$ kg or 938 MeV/c^2) about 2000 times heavier than the electron; has spin =1/2 ħ.
(Planck constant ħ~ 1×10^{-34} J·sec)

Neutron: discovered by James Chadwick in 1933; does not have charge; spin=1/2 ħ; slightly heavier than proton; half-life~10 min ($n \rightarrow p + e^{-} + \bar{\upsilon}_e$).

Nucleon: either proton or neutron

Chart of the Nuclides

~ 300 in nature
~ 1000 artificially produced
~ 6000 to be found



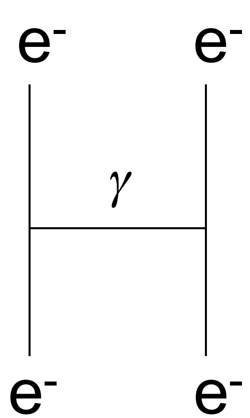
Magic numbers: 2, 8, 20, 28, 50, 82, 126 are neutron and/or proton numbers in nuclei with greater binding energy and stability.

Nuclear force

Nucleus is bounded by strong short-range attractive force between nucleons resulting from the exchange of the **pion** (π), first proposed by Hideki Yukawa in 1935 but was not found until 1947 by Cecil Powell.

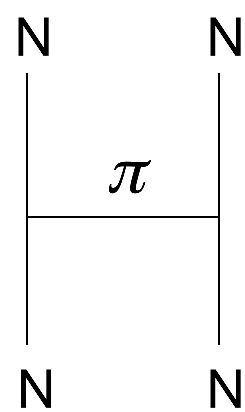
Pion: mass ~ 1/7 of proton mass; has three different charges (e,0,-e); zero spin.

Coulomb potential



$$\rightarrow V(r) \propto \frac{1}{r}$$

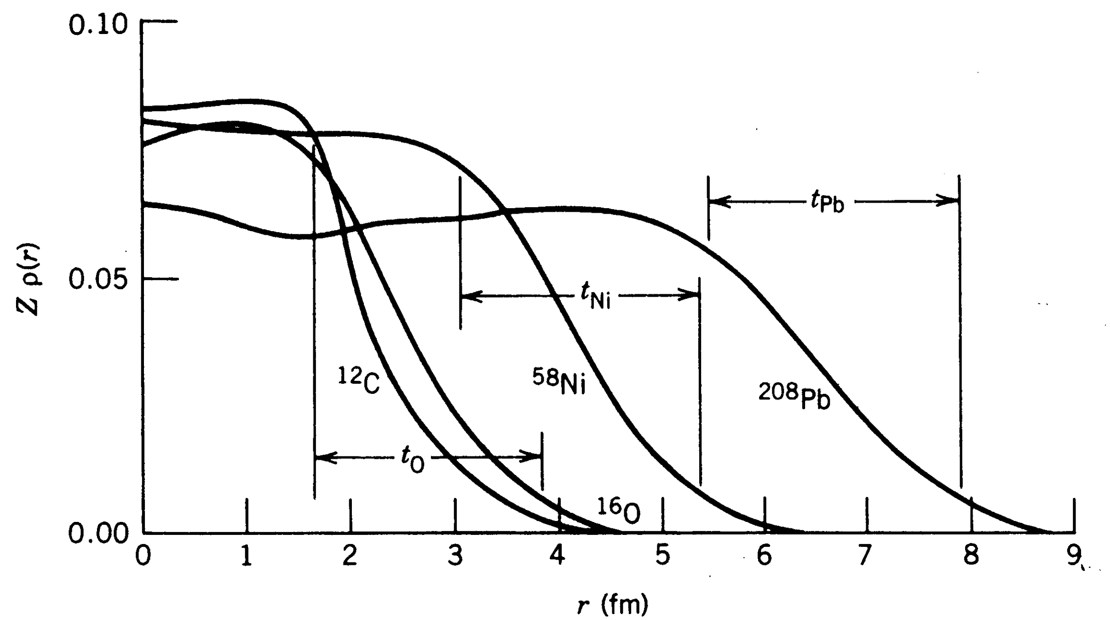
Nuclear potential



$$\rightarrow V(r) \propto \frac{e^{-(m_\pi c/\hbar) r}}{r}$$

Nuclear potential is ~ 100 times stronger than the Coulomb potential between electrons due to photon (γ) exchange.

Nuclear size can be measured from electron scattering as shown by Robert Hofstadter in 1957.



Woods-Saxon form $$\rho(\mathrm{r}) = \frac{\mathrm{c}}{1 + \mathrm{e}^{(\mathrm{r}-\mathrm{R})/\mathrm{a}}}$$

Central nuclear density
$\rho_0 \sim Ac \sim A/Z \cdot Zc \sim 0.16\ \mathrm{fm}^{-3}$

Diffuseness a~0.5 fm
Surface thickness t=(4ln3)a~2.3 fm

Radius $R \sim 1.2\ A^{1/3}$ fm

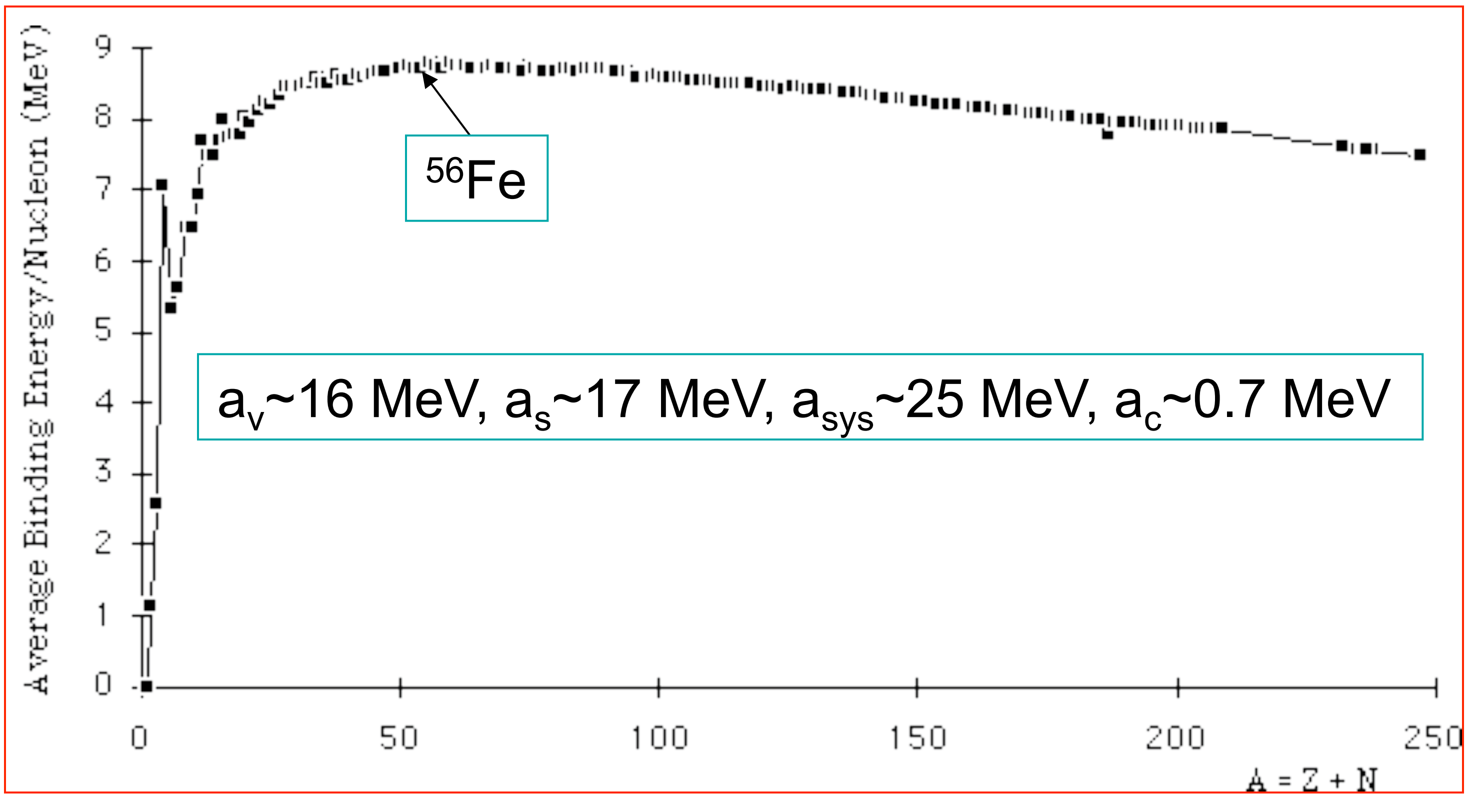
Nuclei behave like liquid drops !

Nuclear mass can be expressed by liquid drop formula as suggested by Weizsäcker (1935); Bethe & Bacher (1936).

Binding energy: Minimum energy required to dissociate a nucleus into its constituent protons and neutrons; ~ 8 MeV per nucleon.

$$B \equiv [Zm_p + Nm_n - {}^{A}_{Z}m]c^2$$

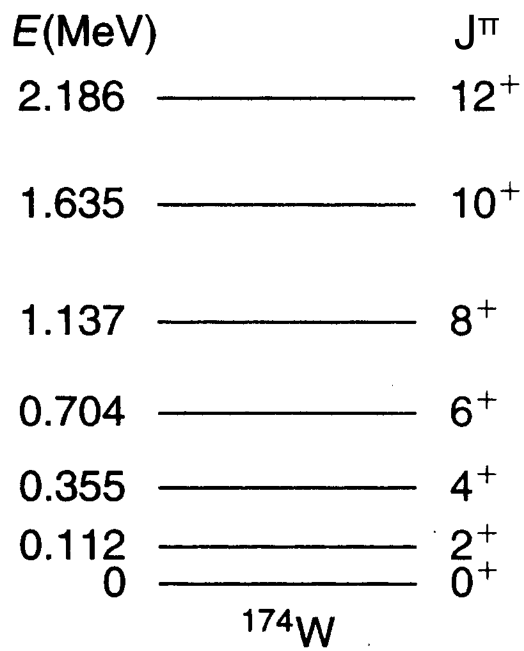
$$\cong a_v A - a_s A^{2/3} - a_{sys}\frac{(N-Z)^2}{A} - a_c \frac{Z^2}{A^{1/3}}$$



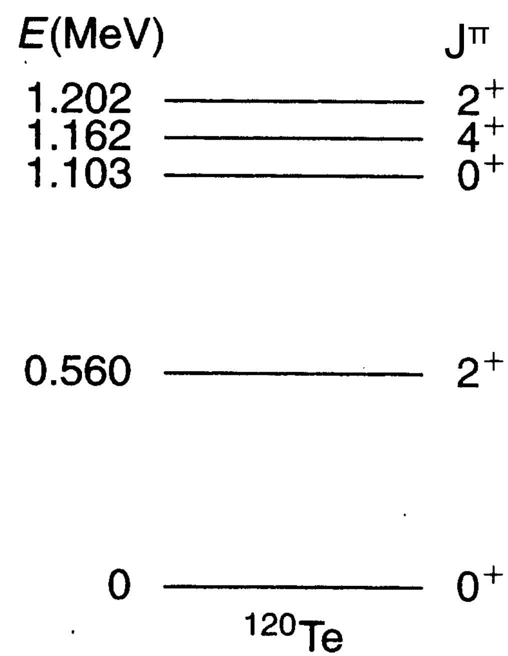
a_v~16 MeV, a_s~17 MeV, a_{sys}~25 MeV, a_c~0.7 MeV

Collective model: A large number of nucleons can execute collective motions; introduced by Bohr, Mottelson & Rainwater in ~1950 for understanding nuclear rotational and vibrational excitations.

Rotational excitations



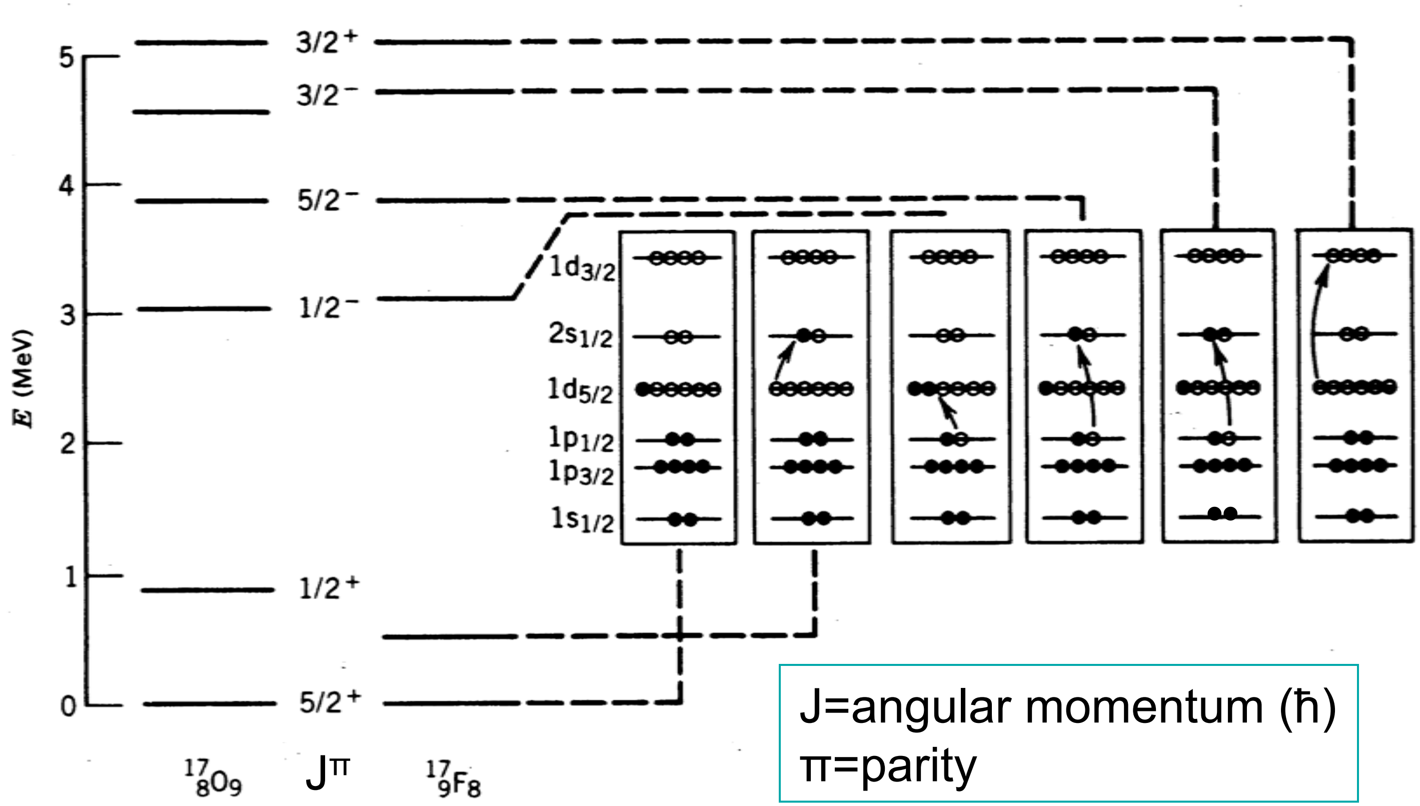
Quadrupole vibrational excitations



$$E_J = \frac{J(J+1)\hbar^2}{2I}, \quad J=0, 2, 4, \cdots$$

J=angular momentum (ħ)
π=parity; I=moment of inertia

Shell model: Nucleons occupy shell-like orbits inside nucleus; proposed by Maria Meyer & Hans Jensen in ~1949 to explain the magic numbers and the single-particle excitations in nuclei.



J=angular momentum (ħ)
π=parity

Protons and neutrons are fermions which satisfy the **Pauli exclusion principle** (proposed by Wolfgang Pauli in 1933) that no two fermions can occupy same quantum state.

Radioactivity

- **Alpha decay**: the nucleus releases an alpha particle (^{4}He)

$$^{235}_{92}\mathrm{U} \rightarrow {}^{231}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}, \quad \tau_{1/2} \approx 7\times10^{8}\ \mathrm{yr}$$

- **Beta decay**: the nucleus either emits an electron and antineutrino or a positron and neutrino

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}, \quad \tau_{1/2} \approx 5730\ \mathrm{yr}$$

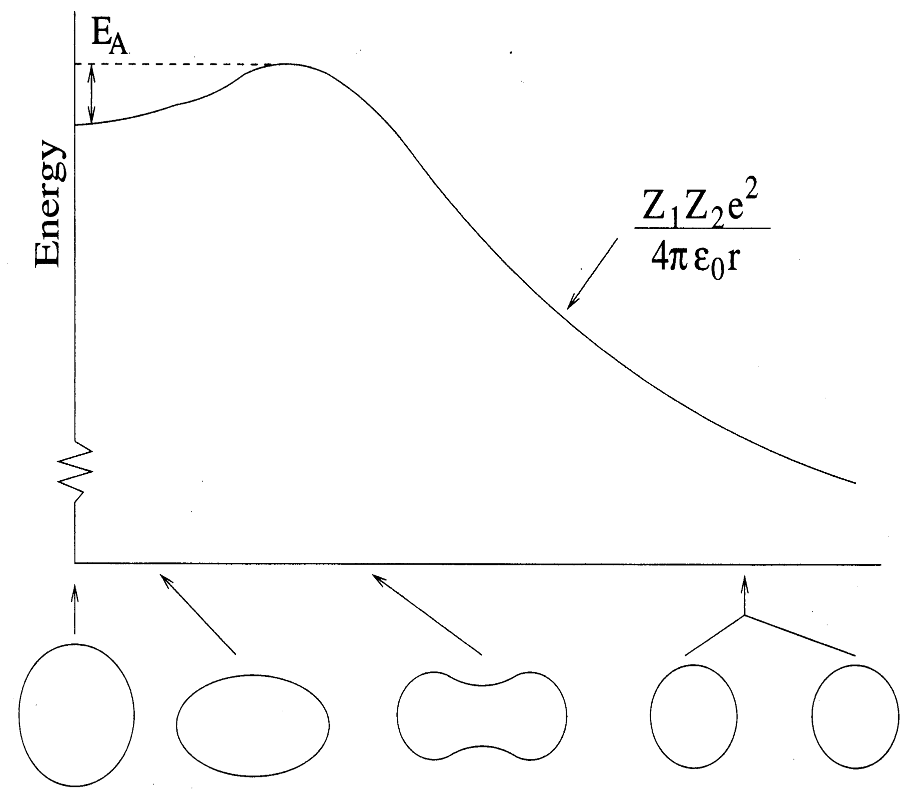
$$^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + \mathrm{e}^{+} + \nu_{\mathrm{e}}, \quad \tau_{1/2} \approx 110\ \mathrm{min}$$

- **Gamma decay**: the nucleus lower its internal energy by emitting a photon

$$^{174}_{74}\mathrm{W}^{*}(0.112\ \mathrm{MeV}) \rightarrow {}^{174}_{74}\mathrm{W} + \gamma, \quad \tau_{1/2} \approx 1.14\ \mathrm{ns}$$

Fission: A nucleus can split into two large fragments; discovered by Hahn and Strassman in 1939; and explained by Meitner and Frisch as well as Bohr and Wheeler in same year.

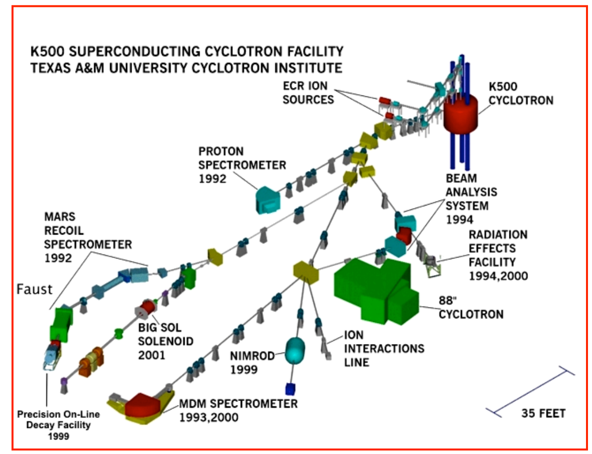
$$n + {}^{235}_{92}U \rightarrow {}^{134}_{54}Xe + {}^{100}_{38}Sr + n$$



Fission occurs as a result of quantum tunneling through the fission barrier. Normally, ^{235}U decays by alpha emission with only ~$7X10^{-9}$ probability for fission due to a high fission barrier. A thermal neutron is needed to induce the fission by exciting the nucleus, leading to a lower fission barrier thus a larger tunneling probability.

Nuclear reactions and accelerators

With energetic particles (e^-,p,d,π,···) from Van de Graff generator (~1931), cyclotrons (invented by Ernest Lawrence ~1939) and modern accelerators, we can study the properties of nuclei and create new isotopes, e.g.

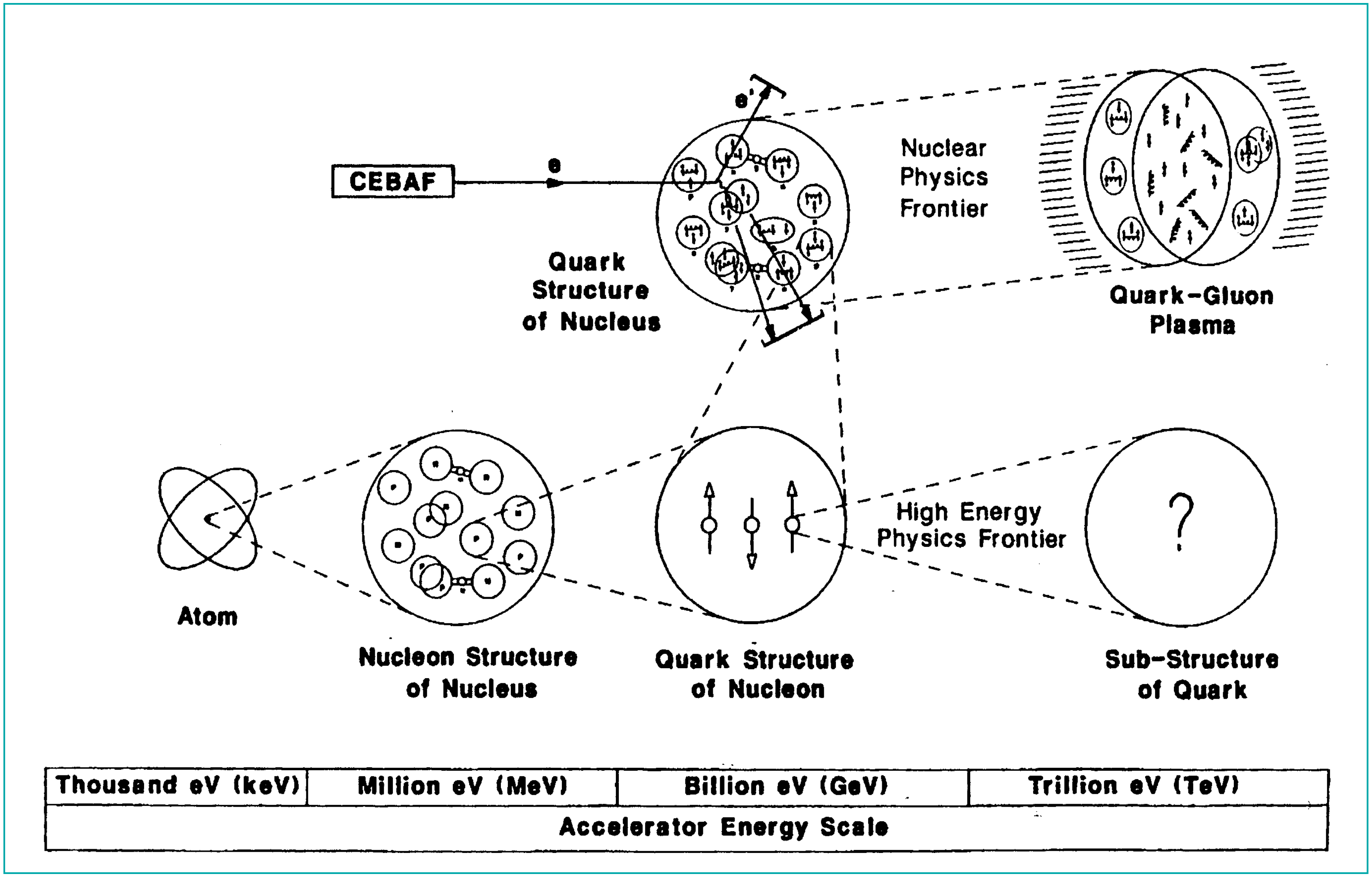


Continuous Electron Beam Accelerator Facility (CEBAF) @ Thomas Jefferson National Laboratory 6 GeV (upgrade to 12 GeV)
- Excited states of p & n
- Quark effects in nuclei

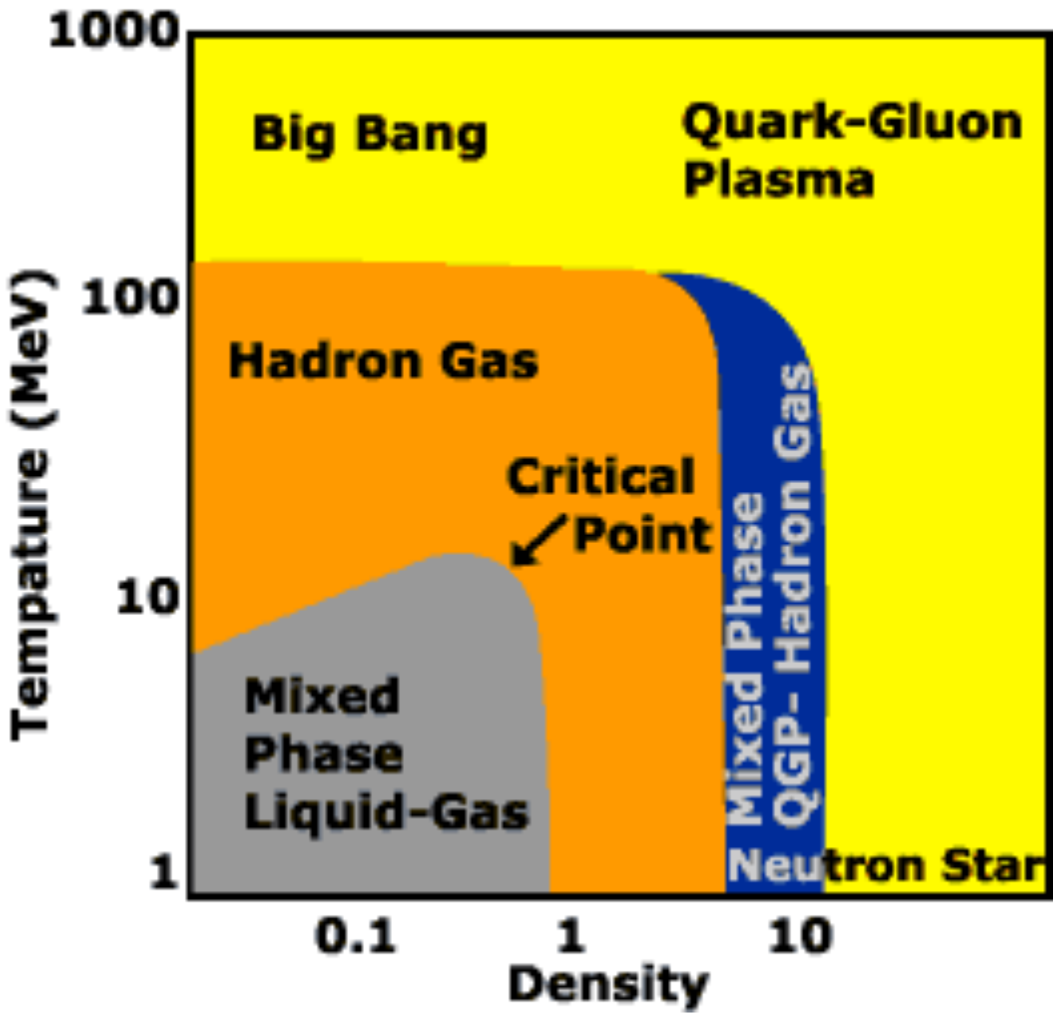
Relativistic Heavy Ion Collider (RHIC) @ Brookhaven National Laboratory
p+p, Au+Au@100 GeV/A
- Quark-gluon plasma
- Proton structure

TAMU K500 Super-conducting Cyclotron
Variety of beams <100 MeV/A
- Nuclear collective motions
- Exotic nuclei
- Hot nuclei
- Nuclear reactions relevant to nucleosynthesis

Quarks inside nuclei



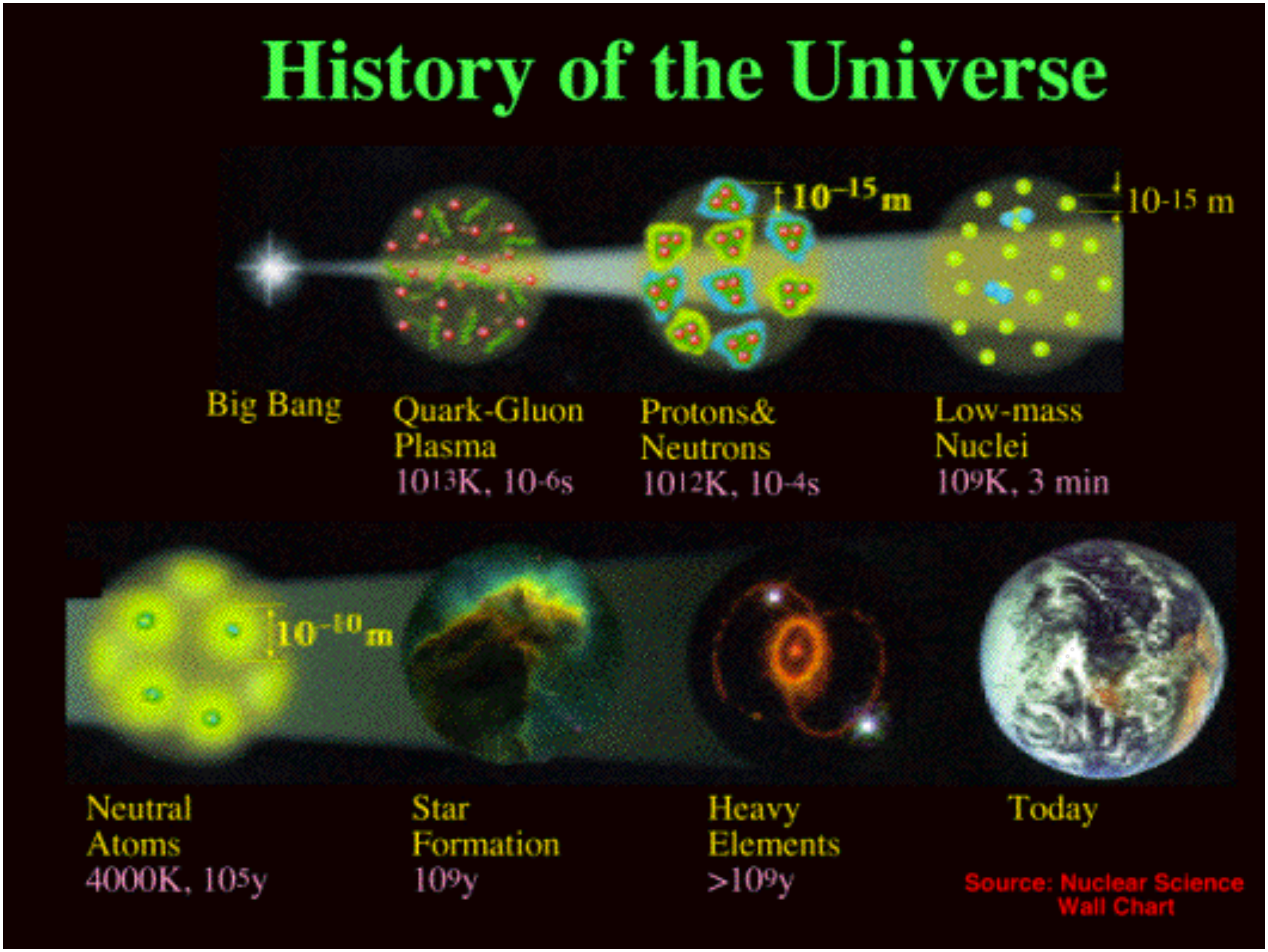
Phases of nuclear matter



As nuclei are heated, they transform from a liquid to a gas of nucleons. With further heating, nucleons are excited to their resonances (N and Δ) and emit pions (π) and kaons (K) as well as other meson resonances (ρ, ω, K*), forming a hadronic gas. At extreme high temperature, hadrons dissolve into a plasma of quarks and gluons. Under compressions, nucleons inside nuclei lose their identity and form a dense matter of quarks.

Heavy ion collisions make it possible to heat and compress the nuclear matter and thus study the properties of nuclear matter under extreme conditions.

Origin of the elements



Nuclear reactions during the first three minutes

- kT > 800 keV: neutrons and protons were in chemical equilibrium

$$\boxed{\frac{\rho_{\mathrm{n}}}{\rho_{\mathrm{p}}} \approx 0.2 \quad \text{at } kT \approx 800\,\mathrm{keV}}$$

- 800 keV > kT > 60 keV: neutrons decayed freely ($\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^{-} + \bar{\upsilon}_{\mathrm{e}}$)

$$\boxed{\frac{\rho_{\mathrm{n}}}{\rho_{\mathrm{p}}} \approx 0.1 \quad \text{at } kT \approx 60\,\mathrm{keV}}$$

- 60 keV > kT > 30 keV: nucleosynthesis occurred

$$\mathrm{n} + \mathrm{p} \rightarrow {}^{2}\mathrm{H} + \gamma$$

$${}^{2}\mathrm{H} + \mathrm{n} \rightarrow {}^{3}\mathrm{H} + \gamma \quad \text{or} \quad {}^{2}\mathrm{H} + \mathrm{p} \rightarrow {}^{3}\mathrm{He} + \gamma$$

$${}^{2}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \gamma$$

$${}^{3}\mathrm{He} + \mathrm{n} \rightarrow {}^{4}\mathrm{He} + \gamma \quad \text{or} \quad {}^{3}\mathrm{H} + \mathrm{p} \rightarrow {}^{4}\mathrm{He} + \gamma$$

Premodial He/H ratio

$$\rightarrow \frac{\rho_{\mathrm{He}}}{\rho_{\mathrm{H}}} \approx 0.25$$

Absence of stable nuclei at A=5 or 8 prevents the production of heavy elements during big bang nucleosynthesis.

Nuclear reactions inside stars: proposed by Hans Bethe in 1939

Hydrogen burning (7×10^6 y)

Common to all chains

$$p + p \rightarrow d + e^+ + \nu_e$$
$$d + p \rightarrow {}^3\mathrm{He} + \gamma$$

PPI-chain

$${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + p + p$$

PPII-chain

$${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$$
$${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \gamma$$
$${}^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$

PPIII-chain

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

Helium burning (5×10^5 y)

$${}^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^8\mathrm{Be}$$
$${}^4\mathrm{He} + {}^8\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + \gamma$$
$${}^4\mathrm{He} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + \gamma$$

CNO cycle

$${}^{12}\mathrm{C} + \mathrm{p} \rightarrow {}^{13}\mathrm{N} + \gamma$$
$${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \mathrm{e}^+ + \nu_\mathrm{e}$$
$${}^{13}\mathrm{C} + \mathrm{p} \rightarrow {}^{14}\mathrm{N} + \gamma$$
$${}^{14}\mathrm{N} + \mathrm{p} \rightarrow {}^{15}\mathrm{O} + \gamma$$
$${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + \mathrm{e}^+ + \nu_\mathrm{e}$$
$${}^{15}\mathrm{N} + \mathrm{p} \rightarrow {}^{12}\mathrm{C} + {}^4\mathrm{He}$$

Carbon burning (600 y)

$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$
$$\rightarrow {}^{23}\mathrm{Na} + \mathrm{p}$$
$$\rightarrow {}^{23}\mathrm{Mg} + \mathrm{n}$$
$$\rightarrow {}^{20}\mathrm{Ne} + {}^4\mathrm{He}$$
$$\rightarrow {}^{16}\mathrm{O} + {}^4\mathrm{He} + {}^4\mathrm{He}$$

Neon burning (1 y)

$${}^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^4\mathrm{He}$$
$${}^{20}\mathrm{Ne} + {}^4\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

Oxygen burning (6 mon)

$${}^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{32}\mathrm{S} + \gamma$$
$$\rightarrow {}^{31}\mathrm{P} + \mathrm{p}$$
$$\rightarrow {}^{31}\mathrm{S} + \mathrm{n}$$
$$\rightarrow {}^{28}\mathrm{Si} + {}^4\mathrm{He}$$
$$\rightarrow {}^{28}\mathrm{Mg} + {}^4\mathrm{He} + {}^4\mathrm{He}$$

Silicon burning (1 d)

$${}^{28}\mathrm{Si} + {}^{28}\mathrm{Si} \rightarrow {}^{56}\mathrm{Ni} + \gamma$$
$${}^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} + \mathrm{e}^+ + \nu_\mathrm{e}$$
$${}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe} + \mathrm{e}^+ + \nu_\mathrm{e}$$

Time scales for stars of 25 solar mass

Precollapse structure of massive stars

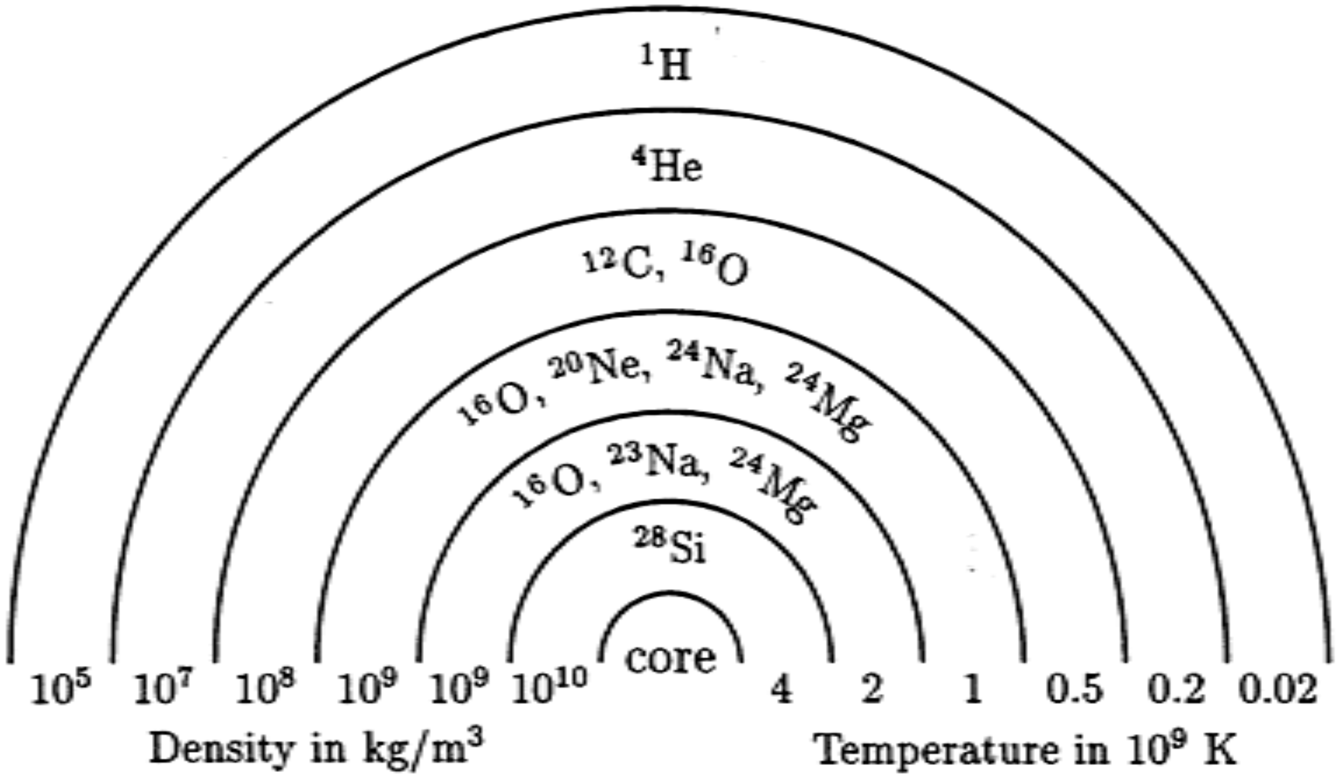
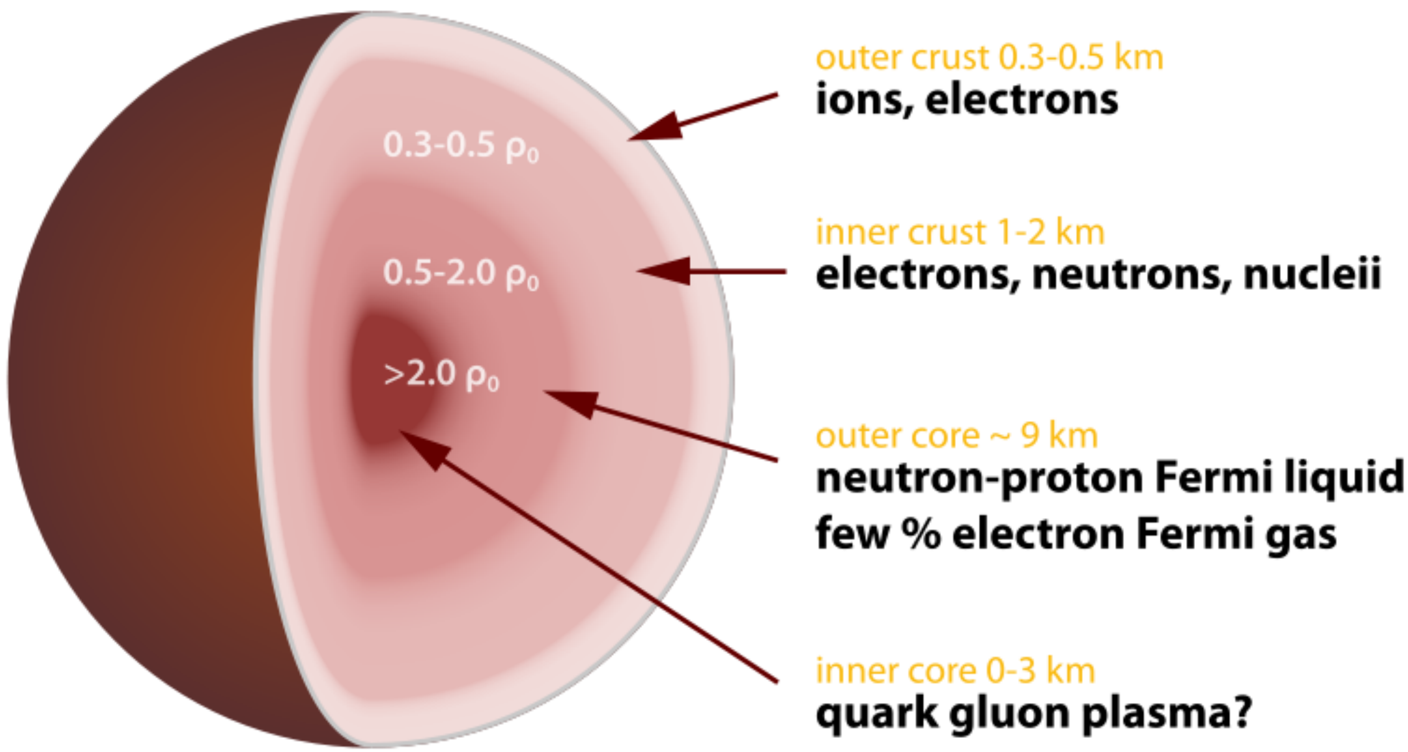


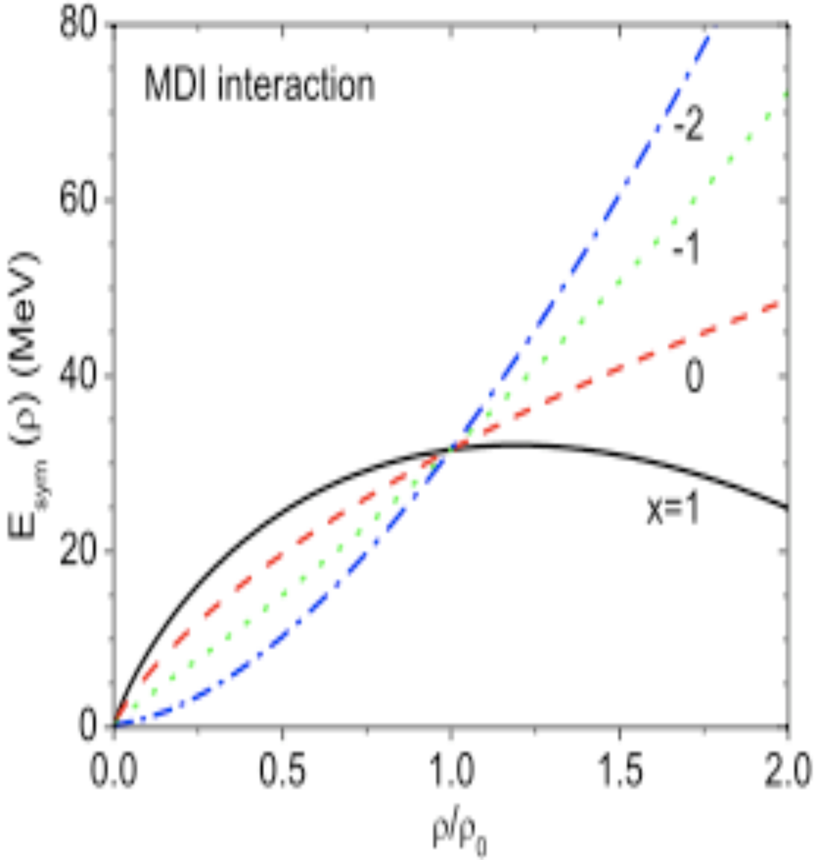
Figure 10-6: Schematic diagram showing the dominant nuclear components, temperature, and density in different layers of a massive star prior to supernova explosion [120].

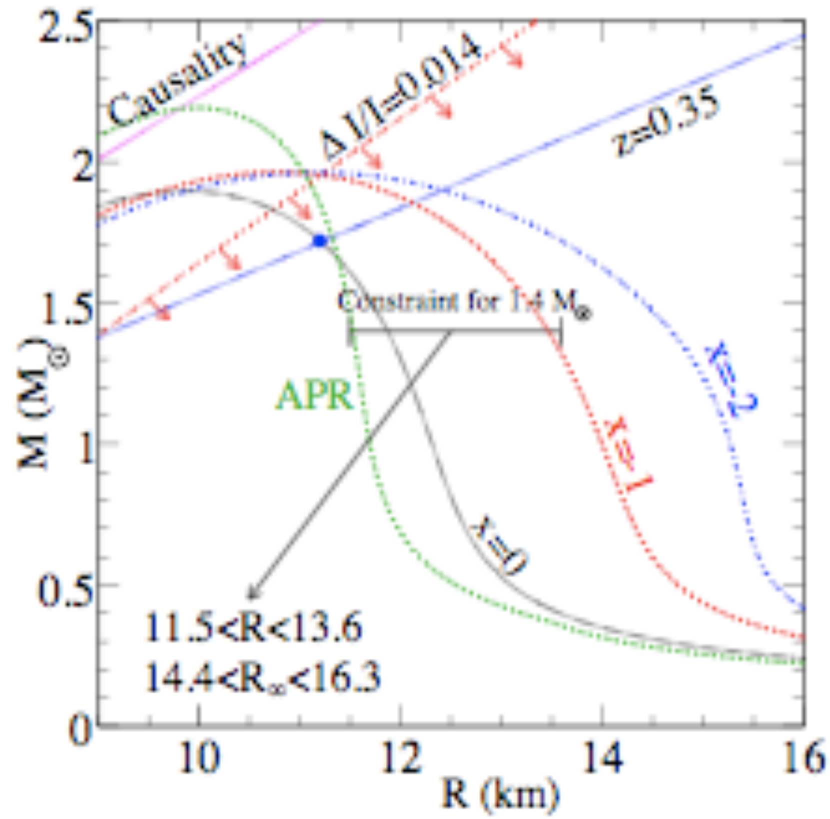
Through neutron captures and beta decays in supernova or neutron-star collisions, nuclei heavier than Fe can be produced (Burbidge, Burbidge, Fowler, and Hoyle, 1957).

Structure of Neutron stars



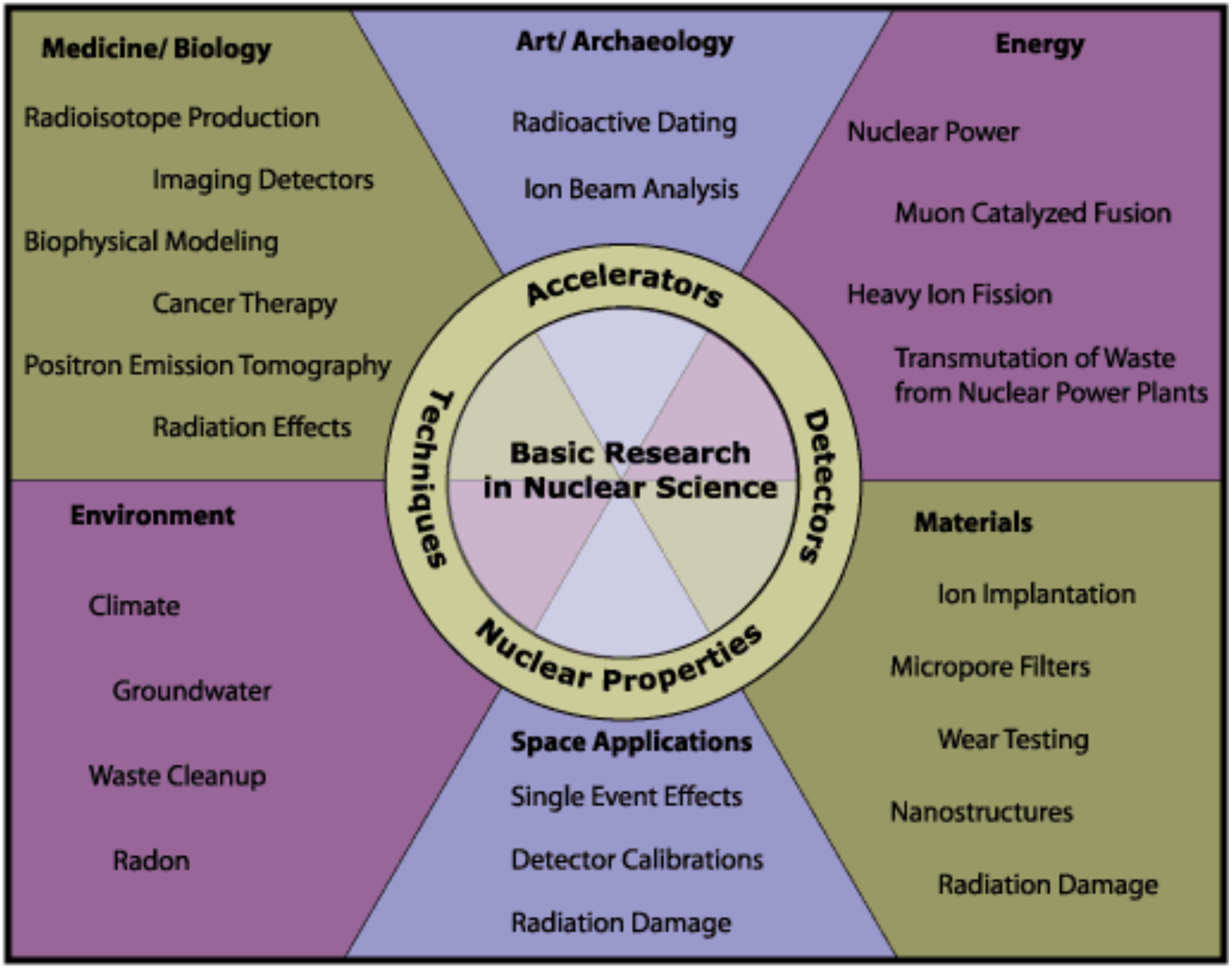
Mass-radius relations of neutron stars





Mass and radius of a neutron star are sensitive to the stiffness of nuclear symmetry energy at high density

Applications of nuclear science

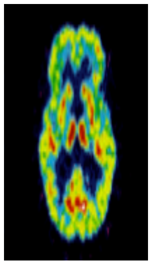


Radioactive dating

Use naturally occurring radioactive isotopes (^{14}C) for dating objects that were once living.

Smoke detectors

Use alpha emitter ^{241}Am to ionize the air.



Nuclear medicine: Use radioactive isotopes for diagnosing and treating disease (^{99m}Tc, ^{60}Co, ^{131}I) as well as for generating images of brain activity (^{18}F) via Positron Emission Tomography (PET).

Magnetic Resonance Imaging (MRI): Use nuclear magnetic transitions to produce 3-D images of the human body.

Space exploration

Use alpha particles for identifying chemical elements present in Martian rocks.

Nuclear reactors: Use fission of ^{235}U and ^{239}Pu nuclei to produce electric power.

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