
From αϐγ
to udscbt
Contemporary ideas on the structure of things
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NUSTRAP

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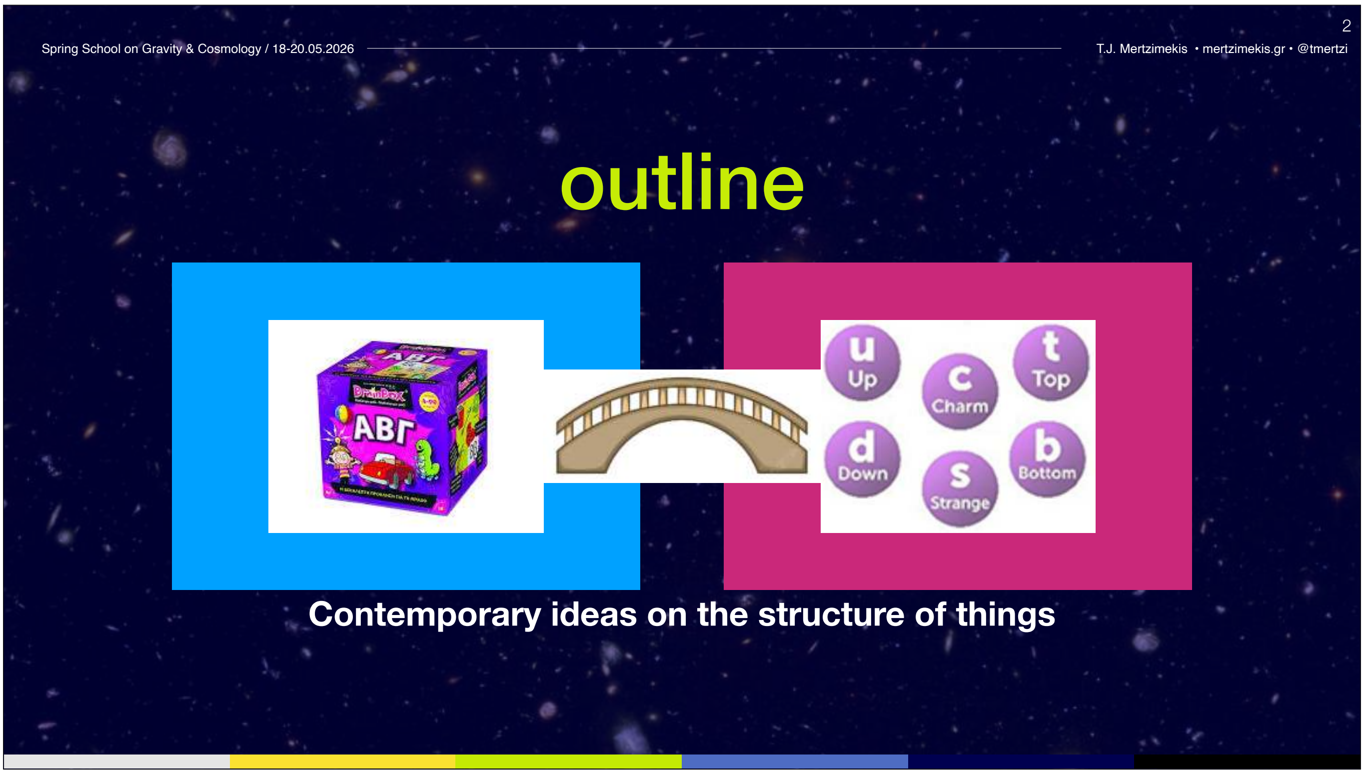
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outline
ABΓ
u Up
c Charm
t Top
d Down
s Strange
b Bottom
Contemporary ideas on the structure of things

part I

we can start with some history…

Starting point: the Atom

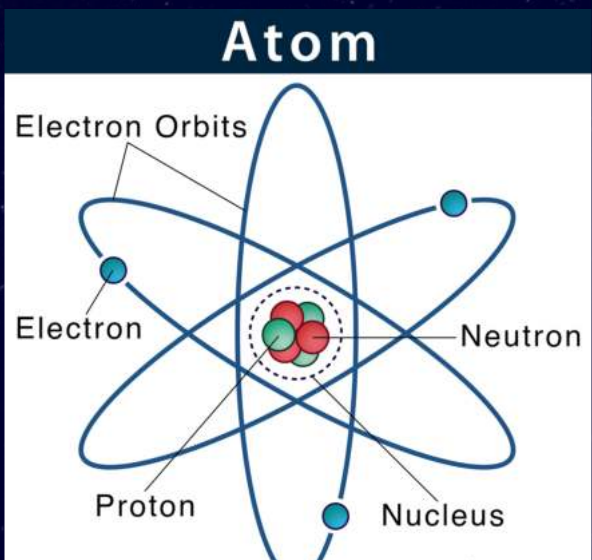


image: sciencefacts.net

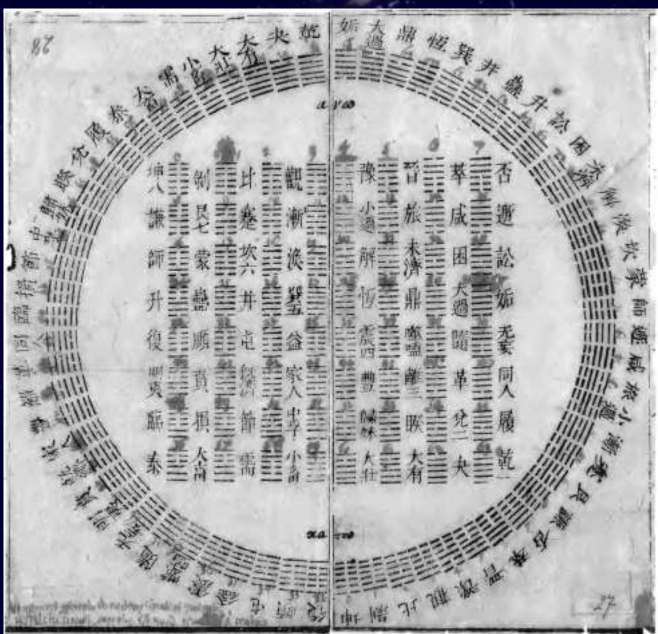
ancient Mayans (10th BC)

source: Duke U.

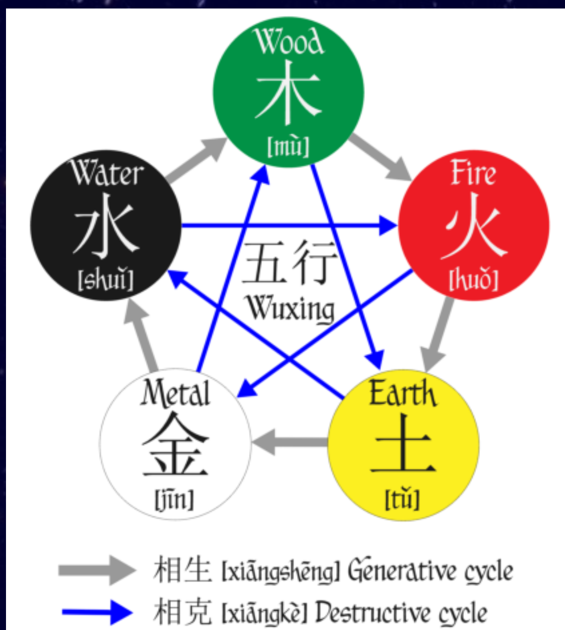
The Four Elements and Duality

- ✳ Elemental Forces: Earth, Water, Fire, and Air, governed by the sacred center, often associated with the Fifth Element or the cosmos.
- ✳ Duality: All matter was thought to exist in a state of dynamic balance hot and cold, light and dark, life and death. Matter and spirit were not separate

ancient Chinese (5th BC)



source: wikipedia

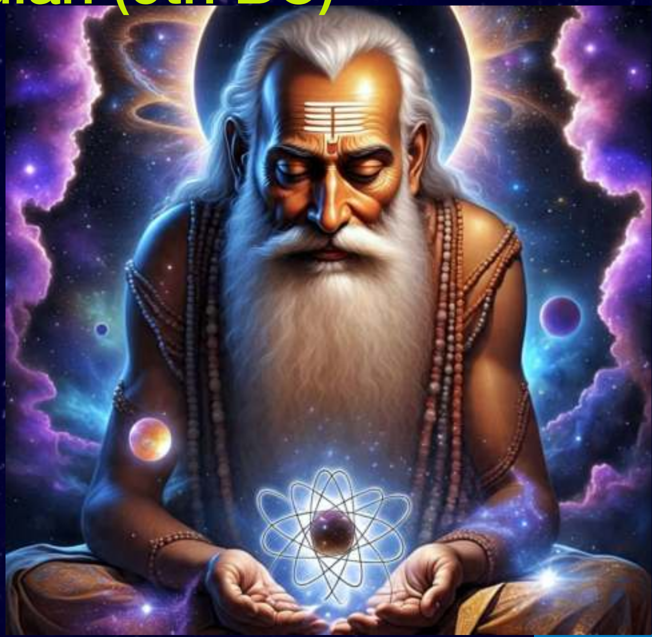


ancient Indian (6th BC)

The (Atomic) Theory of Anu and Parmanu

Acharya Kanad's Vaisheshika Sutra, a Sanskrit text, outlines his atomic theory. According to his theory:

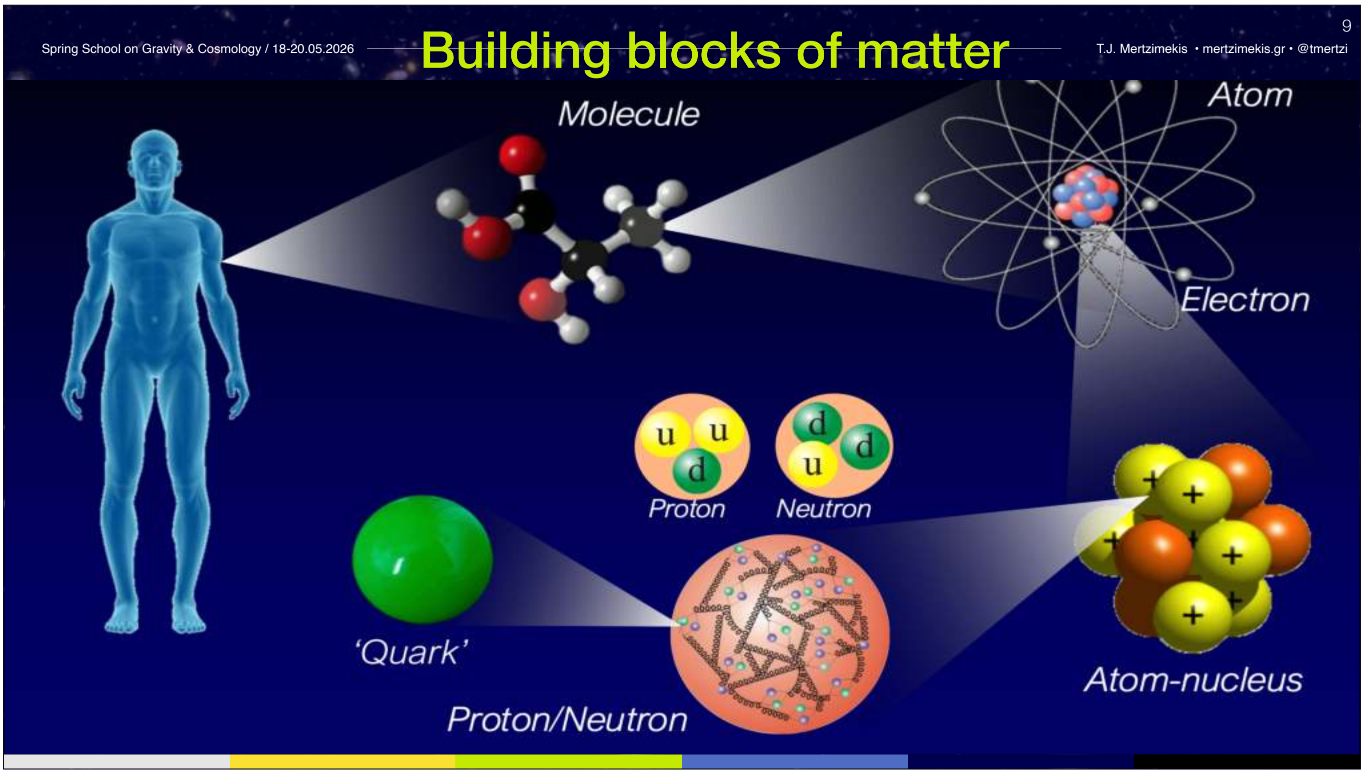
- ✳All matter is made of indivisible, indestructible particles called Parmanu (subtle atoms).
- ✳These Parmanu combine to form Anu (visible atoms), which then create more complex matter.
- ✳The combination of these atoms occurs due to an unseen force, driven by motion and time.
- ✳Atoms differ based on the properties of the matter they create (such as taste, smell, texture).



source: facebook

ancient Greeks

images: private collection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Building blocks of matter
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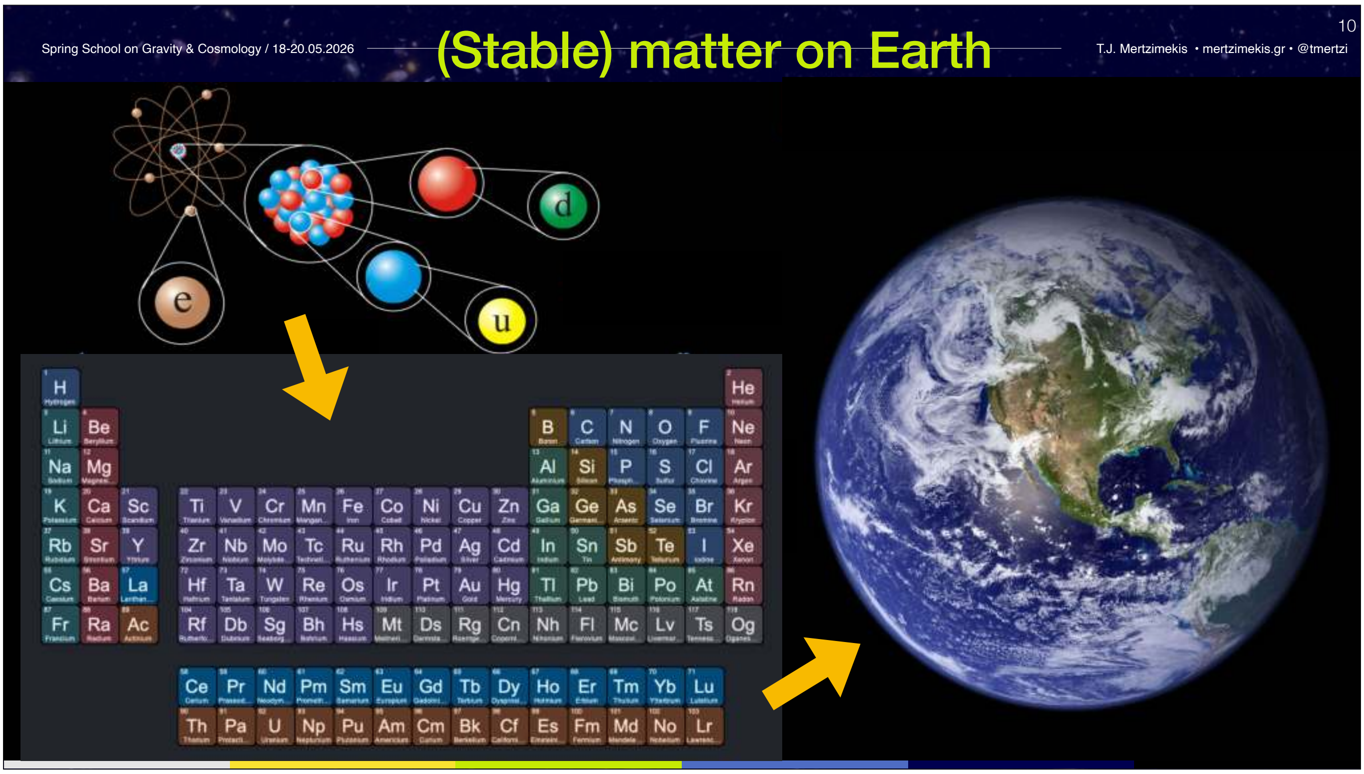
9
Molecule
Atom
Electron
u u d
Proton
d d u
Neutron
'Quark'
Proton/Neutron
Atom-nucleus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(Stable) matter on Earth
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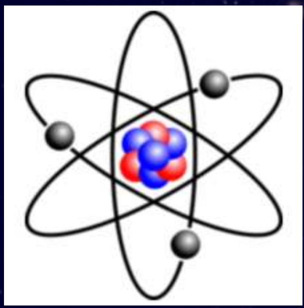
10
e
d
u
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac Rf Db Sg Bh Hs Mt Ds Rg Cn Nh Fl Mc Lv Ts Og
Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

Atom selfie?



- Does something “move”?
- Is it “empty”?
- How does an electron exist?

Also

- Quantum Mechanics!

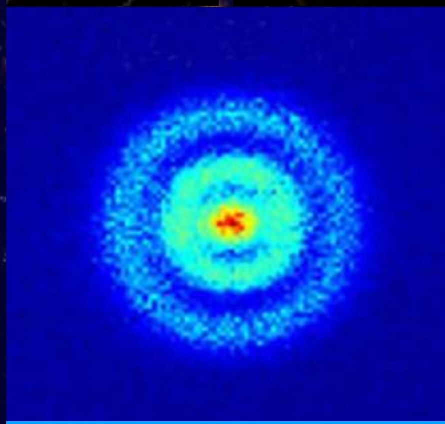


image: Phys. Rev. Lett.

Orbitals

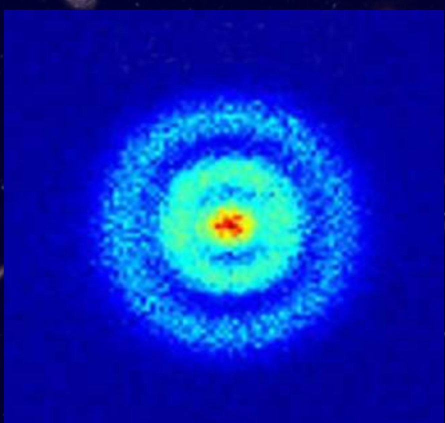
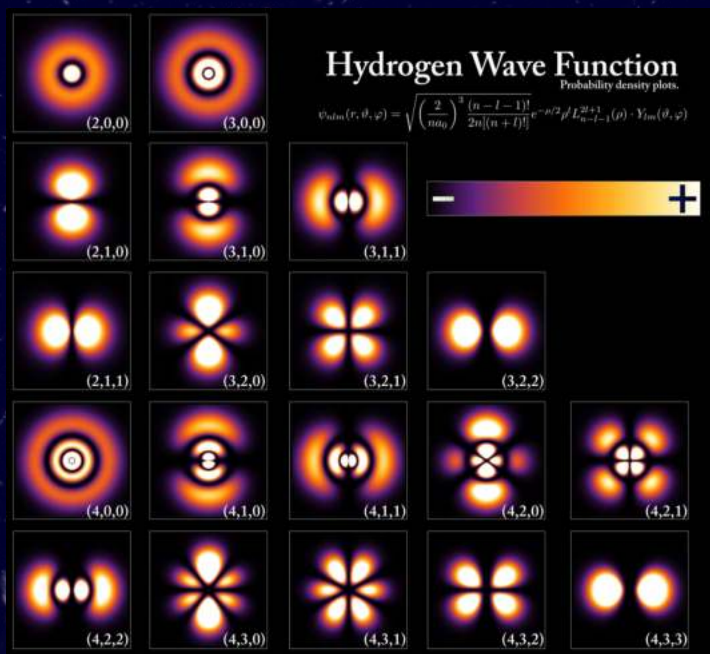
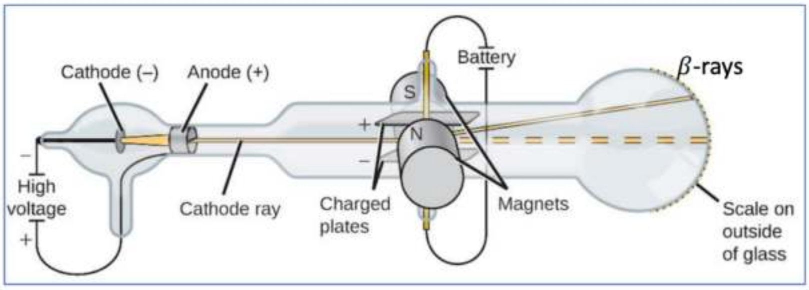


image: Phys. Rev. Lett.



Discovery of the electron

- JJ Thomson (1897): Cathode rays are bent by electric and magnetic field
  - Charged particles



1. Compensate Electric and Magnetic deflection:

$F_E = F_B$

$qE = qvB\,;\, v = {}^{E}/_{B}$

2. Only B-field, cycle orbit:

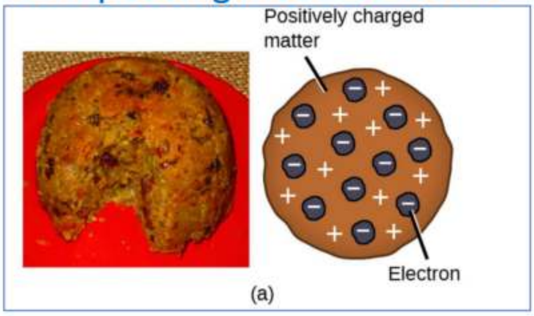
$F_c = F_B$

$\frac{mv^2}{r} = qvB$

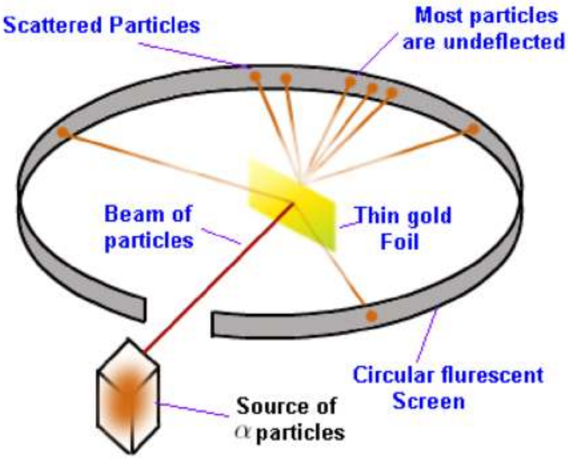
$$\frac{q}{m} = \frac{E}{rB^2}$$

Electrons are much lighter than ions of same charge!

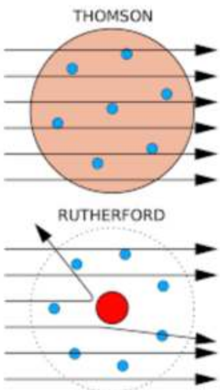
- Plum-pudding model of atoms:

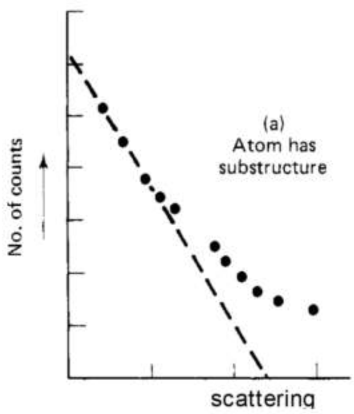


Rutherford and the nucleus



- Rutherford (1911)
  - α-particles at gold target
  - Most particle pass undisturbed, few have a "hard" collision
  - Atom has substructure: small heavy nucleus

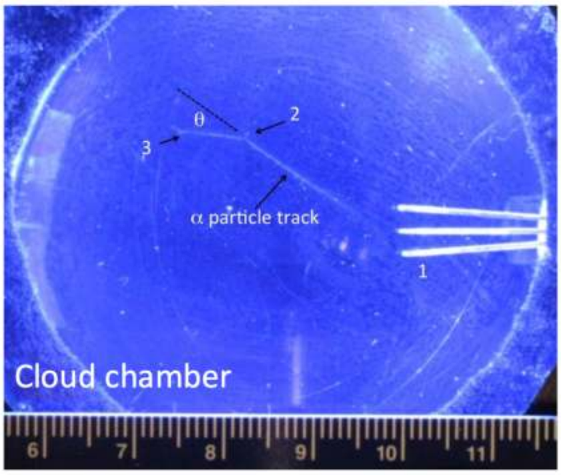


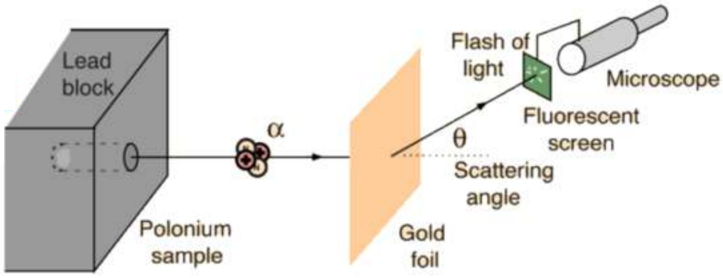


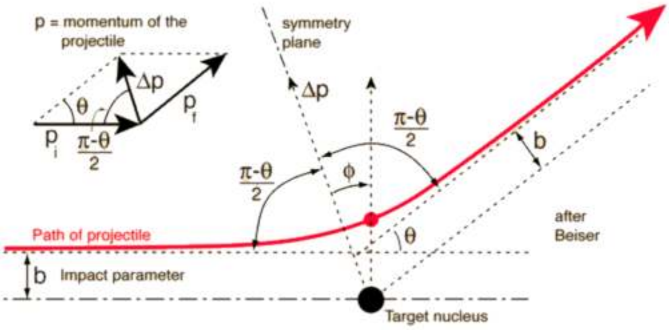
- Atom is basically just vacuum:
  - Atom size: ~ $10^{-10}\ m$
  - Nucleus size: ~ $10^{-15}\ m$

Rutherford scattering

α





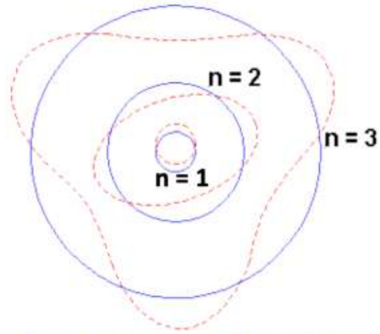


part II

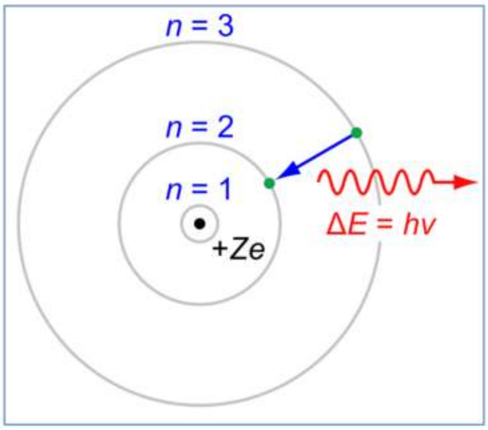
atomic nuclei

The Bohr atom

- Niels Bohr, 1914:
  - Calculate atomic energy levels using semi classical method



$$L = rp = r\frac{h}{\lambda}$$
$$= rn\frac{h}{2\pi r} = n\frac{h}{2\pi} = n\hbar$$



Protons and neutrons

- Nuclei include protons, p
  - Masses of nuclei studied in chemistry (Avogadro)
    - Hydrogen = 1 proton: $M_H = 1\,GeV/c^2 = 200\,M_e$
- Study q/m of nuclei:
  - Masses of nuclei do not scale with charge, but with $\boldsymbol{A} \approx 2 \times \boldsymbol{Z}$
    - $\boldsymbol{A}$= mass number, $\boldsymbol{Z}$=atomic number = nucleus charge
  - What keeps heavy nuclei together?
- Chadwick 1932: Discovery of neutron, n
  - Neutron has almost same mass as proton
  - Neutrons act as a glue to nucleons in the nucleus
    - Later we will see it is due to the gluon color force
- Notation: ${}^{A}_{Z}\mathrm{MyAtom}$, with $Z = \#p$, $A = \#(p+n)$
  - Isotopes: same $\#p$, different $\#n$

James Chadwick

1926

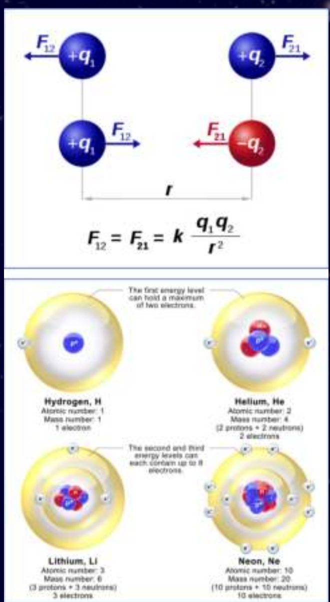
"…ο πυρήν του υδρογόνου φέρει τη μονάδα του θετικού ηλεκτρισμού, το όλον δε άτομον του υδρογόνου αποτελείται εκ του πυρήνος τούτου και ενός αρνητικού ηλεκτρονίου, περί τον πυρήνα αυτόν κινουμένου…"

"…ο πυρήν του ηλίου αποτελείται από τέσσαρας πυρήνας υδρογόνου και δύο αρνητικά ηλεκτρόνια…"

"…the nucleus of hydrogen carries one unit of positive charge, while the atom of hydrogen consists of the nucleus and one negative electron in orbit around it (the nucleus)…"

"…the nucleus of helium consists of four nuclei of hydrogen and two negative electrons…"

E/M vs nuclear force

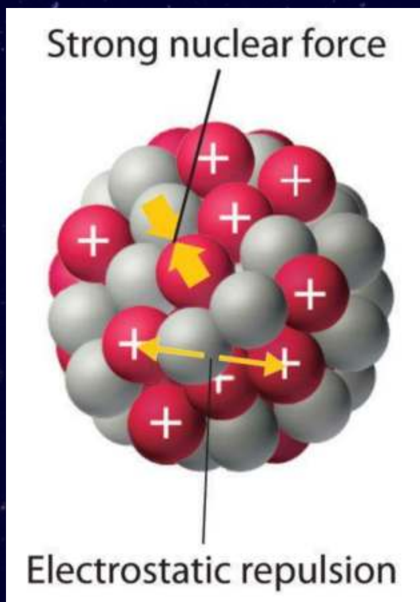


Electromagnetic force:

generated by exchanged massless photons

Strong nuclear force:

must be stronger then E/M inside the nucleus
must be weaker than E/M outside the nucleus

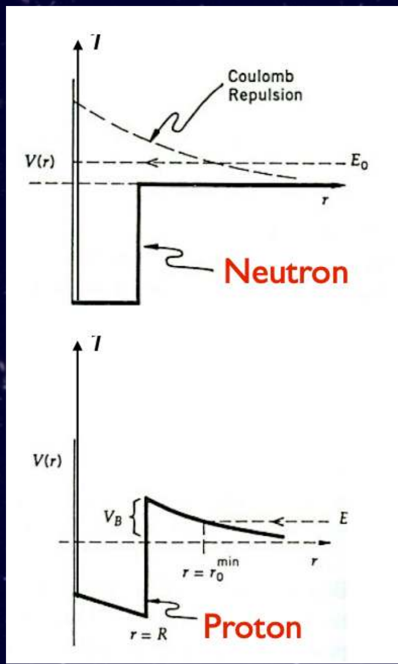


E/M vs nuclear force + QM

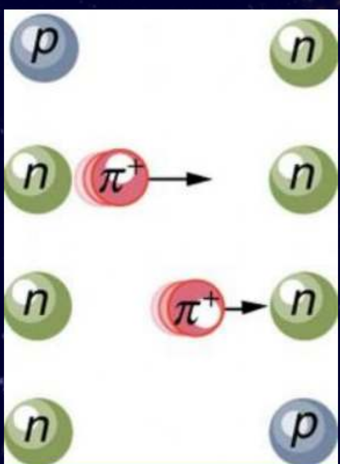
- Pauli exclusion principle:
Two fermions (p,n) cannot be at the same position (strong repulsion at r—>0)

- Square well potential:
For p, a Coulomb barrier V_B exists
Can be neglected for r >>R
R can be determined by scattering (RBS)

- But what is the mediator?
Yukawa postulates the “pion”



Yukawa and the pion



- Yukawa:
a π meson generates the attraction between nucleons

- π meson mass:
Estimated via the Heisenberg uncertainty principle

$$\Delta E \cdot \Delta t \leq \frac{\hbar}{2}$$

- What does it mean?
Energy conservation can be violated if the uncertainty principle is valid

$$E = mc^2 \quad \Delta t \sim \frac{h}{mc^2} \rightarrow R \sim c\Delta t = \frac{h}{2mc}$$

Photons: m=0 —> infinite range
Pions: m≠0 —> discrete range

The NN interaction

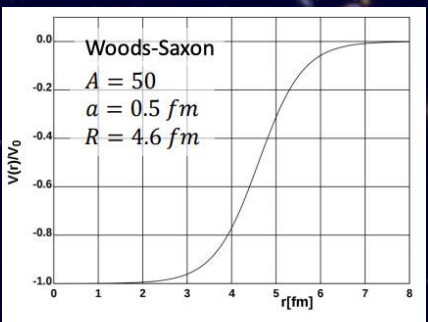
A traditional goal of nuclear physics has been the understanding of the properties of atomic nuclei in terms of the "bare" interaction between pairs of nucleons. However, the underlying theory of strong interactions, QCD, shows that the NN interaction is not fundamental.

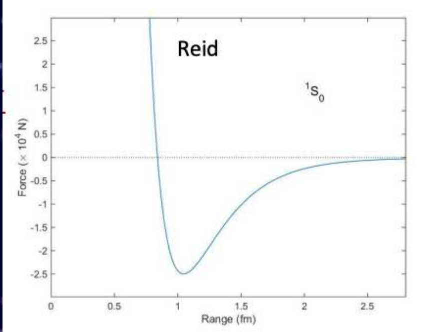
The nucleon-nucleon interaction is still unknown nowadays!

The NN interaction:

✳ has short range (~ 1 fm = 10^{-15} m) <— particle scattering, size of nucleus
✳ is (very) attractive for distances 1-2.5 fm
✳ is repulsive for short distances, <0.7 fm —> solid, repulsive core; shapes the size of the nucleus
✳ saturates; nucleons interact with their closest neighbors. Binding energy: 8 MeV/A
✳ is charge independent; Vpn=Vnn=Vpp <— deuteron
✳ depends on relative spin orientation of nucleons
✳ has a tensor character —> departs from spherical symmetry

The NN interaction





- Woods Saxon Potential, 1954
  - $V(r) = -\frac{V_0}{1+\exp\left(\frac{r-R}{a}\right)}$
  - Nuclear Radius: $R = 1.25$ fm $\times A^{1/3}$
    A is mass number, $V_0 \approx 50$ MeV , $a \approx 0.5\, fm$

- Reid Potential, 1968, (semi-empirical) implements repulsive core:
  - $V_{Reid}(R) = -10.463\frac{e^{-\mu r}}{\mu r} - 1650.6\frac{e^{-4\mu r}}{\mu r} + 6482.2\frac{e^{-7\mu r}}{\mu r}$
    in MeV with $\mu = 0.7\, fm^{-1}$

Nijmegen potential:

- De Swart, Rijken et al., 1980 - 1990
- https://arxiv.org/pdf/nucl-th/9509024.pdf

The NN interaction

Microscopic approach: The degrees of freedom are the nucleons (position, spin, isospin)

$$\vec{r_i},\ \vec{p_i},\ \vec{s_i},\ \vec{t_i} \quad (i = 1, \ldots, A) \qquad \Psi_{NN} = \psi(\vec{r})\chi_S^{m_s}\phi_T^{T_z}$$

$$H = \sum_{i=1}^{A} T_i + \frac{1}{2}\sum_{i,j} V(i,j)$$

Parameterizations of the NN potential rely on NN scattering and the deuteron properties.

There are two classes: local and non-local

V(i,j) is not known; symmetry arguments help.

NNN terms are often neglected. In (very recent) years, this has been revised!

Symmetry

General form: $V(1,2) = V(\vec{r_1}, \vec{p_1}, \vec{\sigma_1}, \vec{\tau_1}, \vec{r_2}, \vec{p_2}, \vec{\sigma_2}, \vec{\tau_2})$

Nucleon exchange invariance: $V(1,2) = V(2,1)$

Translational invariance: $V(1,2) = V(\vec{r}, \vec{p_1}, \vec{\sigma_1}, \vec{\tau_1}, \vec{p_2}, \vec{\sigma_2}, \vec{\tau_2})$

Galilean invariance: $V(1,2) = V(\vec{r}, \vec{p}, \vec{\sigma_1}, \vec{\tau_1}, \vec{\sigma_2}, \vec{\tau_2})$

Rotation invariance: $V(1,2) = \text{scalar}$

Parity invariance: $V(\vec{r}, \vec{p}, \vec{\sigma_1}, \vec{\tau_1}, \vec{\sigma_2}, \vec{\tau_2}) = V(-\vec{r}, -\vec{p}, \vec{\sigma_1}, \vec{\tau_1}, \vec{\sigma_2}, \vec{\tau_2})$

Time-reversal invariance: $V(\vec{r}, \vec{p}, \vec{\sigma_1}, \vec{\tau_1}, \vec{\sigma_2}, \vec{\tau_2}) = V(\vec{r}, -\vec{p}, -\vec{\sigma}_1, \vec{\tau_1}, -\vec{\sigma}_2, \vec{\tau_2})$

Symmetry

Under the symmetry considerations:

$$V(1,2) = V_C + V_S(\vec{\sigma_1}\cdot\vec{\sigma_2}) + V_T S_{12}(\vec{r}) + V_{T'} S_{12}(\vec{p}) + V_L(\vec{L}\cdot\vec{S}) + V_Q(\vec{L}\cdot\vec{S})^2$$

spin-orbit interaction: $$\vec{L}\cdot\vec{S} = \frac{1}{2}(\vec{r}\times\vec{p})\cdot(\vec{\sigma_1}+\vec{\sigma_2})$$

tensor operator: $$S_{12} = 3\left(\vec{\sigma_1}\cdot\frac{\vec{r}}{r}\right)\left(\vec{\sigma_2}\cdot\frac{\vec{r}}{r}\right) - (\vec{\sigma_1}\cdot\vec{\sigma_2})$$

scalar terms: $$V_\alpha = V_\alpha(r^2, p^2, L^2) \quad \alpha = \{C, S, T, T', LS, Q\}$$

Back to Yukawa

Klein-Gordon for the pion field: $$\left(\nabla^2 - \frac{m_\pi^2 c^2}{\hbar^2}\right)\phi = -g\delta(\vec{r})$$

solution: $$\phi = g\frac{e^{-\mu r}}{r} \qquad \mu = \frac{m_\pi c}{\hbar}$$

Yukawa potential: $$V = g^2\frac{e^{-\mu r}}{r}$$

Back to Yukawa

The Yukawa potential function,

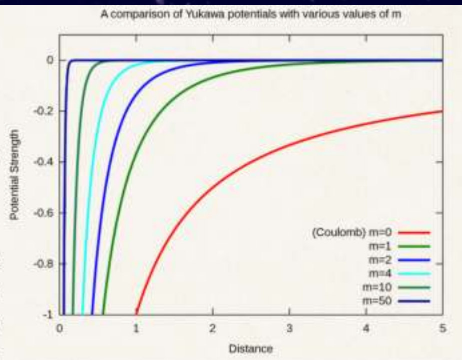
$$V_{\text{Yukawa}}(r) = -g^2 \frac{e^{-kmr}}{r},$$

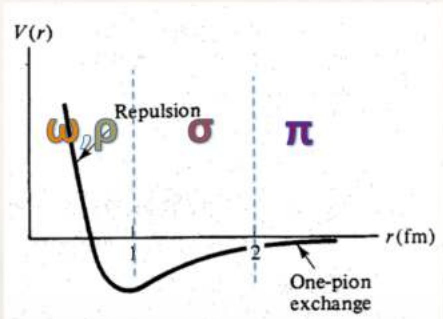
$V_{\text{Yukawa}}(r) \rightarrow -\infty$ as $r \rightarrow 0$ (same as the Coulomb potential).

This "unnatural" behavior of the infinitely attractive force is corrected by the addition of a potential of an impenetrable hard sphere (i.e. an infinitely repulsive force), the existence of which has been ascertained by scattering experiments p - p and p - n.

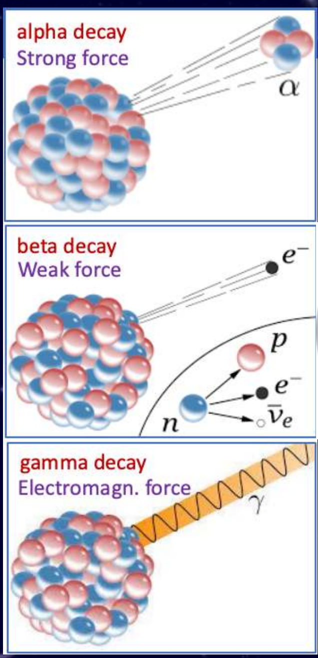
Thus, the N-N potential takes the form:

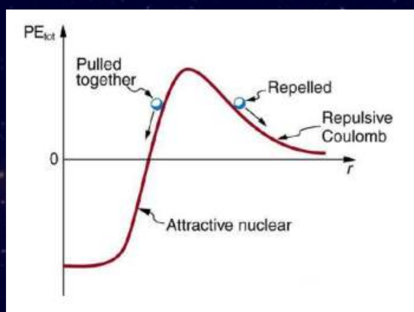
$$V(r) = +\infty, \ \gamma\iota\alpha\ r < r_C$$
$$V(r) = V_{\text{Yukawa}}(r), \ \gamma\iota\alpha\ r > r_C$$





The αβγ of unstable nuclei



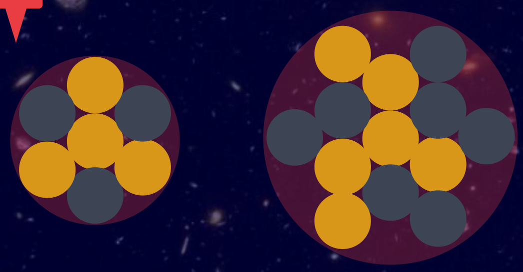


- Unstable nucleus
- Quantum tunneling process

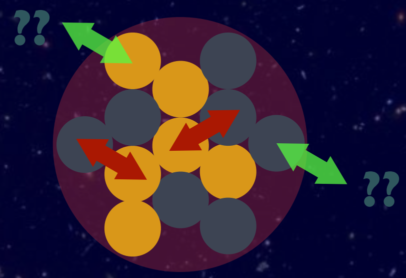
$$N = N(0)e^{-\lambda t} = N(0)e^{-t/\tau} = N(0)e^{-t\ln 2/t_{1/2}}$$

Liquid-drop model

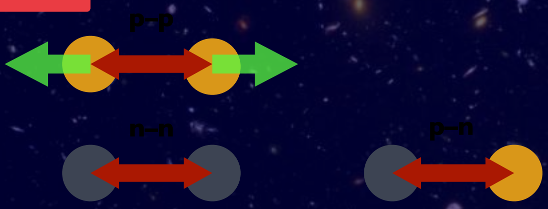
$BE \sim A$ εξαρτάται από τον όγκο



$BE \sim -A^{2/3}$ εξαρτάται αρνητικά από την επιφάνεια



$BE \sim -Z^2 / A^{1/3}$ εξαρτάται αρνητικά από τη δύναμη Coulomb



$BE \sim -(N-Z)^2 / A = -(A-2Z)^2 / A$

εξαρτάται από την ασυμμετρία Z-N

$BE \sim \delta$, δ=+1,0,-1 για e-e, e-o, o-o

εξαρτάται από το ζεύγος

Liquid-drop model

$BE(Z,A) = a_V A$ Όγκος

$- a_S A^{2/3}$ Επιφάνεια

$- a_C Z^2 / A^{1/3}$ Coulomb

$- a_{sym} (A-2Z)^2 / A$ Συμμετρία

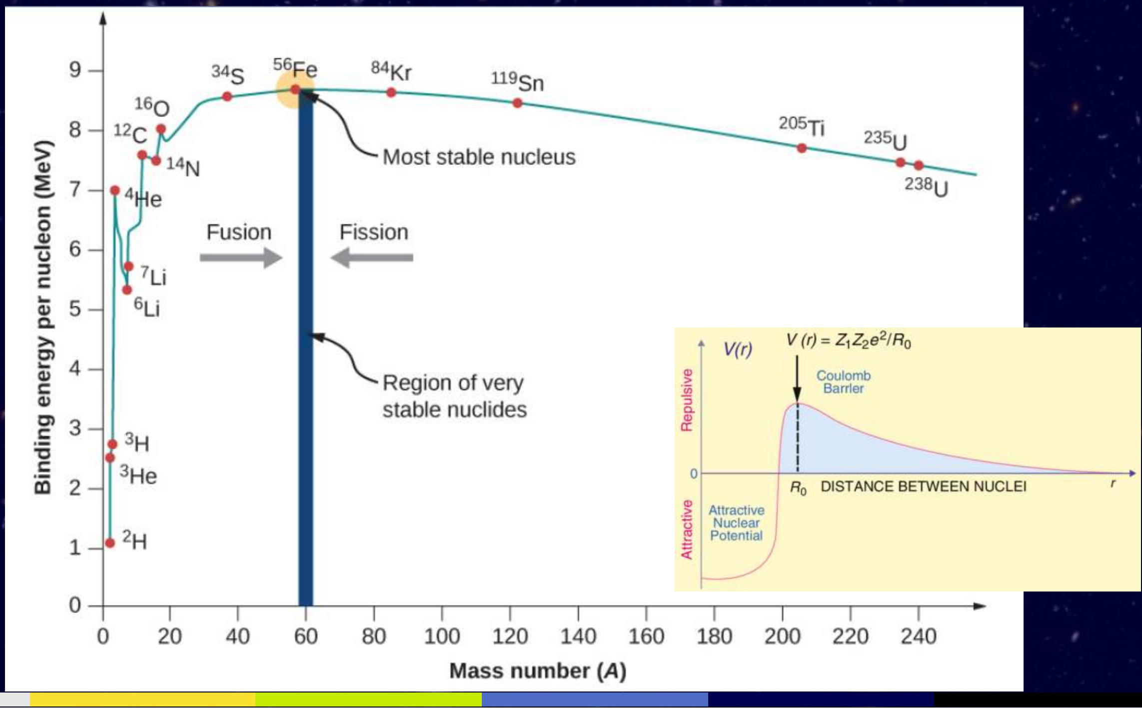
$- \delta a_P / A^{1/2}$ Ζεύγος

Carl Friedrich von Weizsäcker

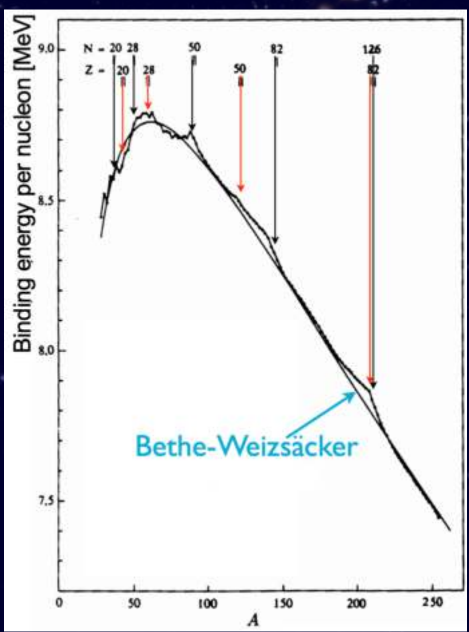
Atomic Mass Evaluation 2022

a_V	15.247 MeV
a_S	16.325 MeV
a_C	0.685 MeV
a_{sym}	22.098 MeV
a_P	10.608 MeV

Binding Energy, B(A,Z)



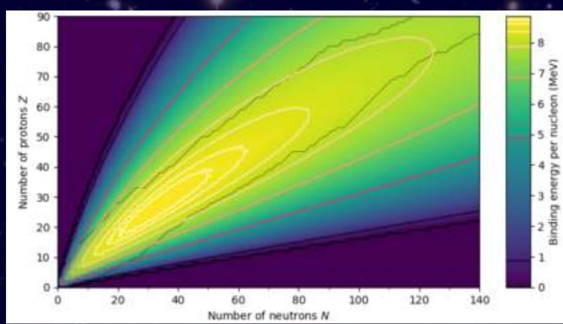
“magic” numbers



- B(A,Z)/A fits the data quite well
- It cannot explain ‘peaks’ that occur at ‘magic numbers’, where those nuclei are strongly bound
- N or Z = 2, 8, 20, 28, 50, 82, 126

Double magic nuclei (both N and Z are magic):

- ^{4}He, ^{16}O, ^{40}Ca , ^{48}Ca , ^{48}Ni , ^{208}Pb



Microscopic description

There are many «***structure effects***» in nuclei, that **can not be reproduced by macroscopic approaches** like the liquid drop model.

Need for **microscopic approaches**, for which the fundamental ingredients are the nucleons and the interaction between them

Nucleus = A nucleons in strong interaction

The many-body problem
Can be solved exactly for A < 4
For A >> 10 : approximations

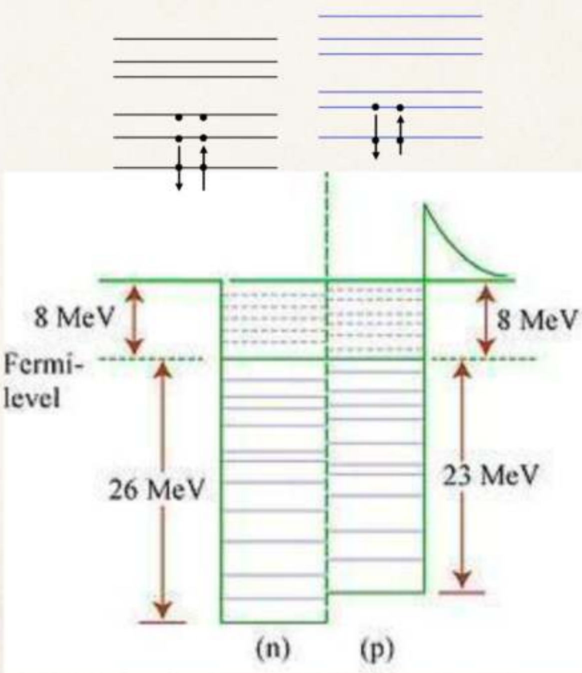
Nucleon-Nucleon force unknown
Different effective forces used depending on the method chosen to solve the many-body problem

Shell Model
only a small number of particles are active

Mean Field models
- no inert core
- not all the correlations between particles are taken into account

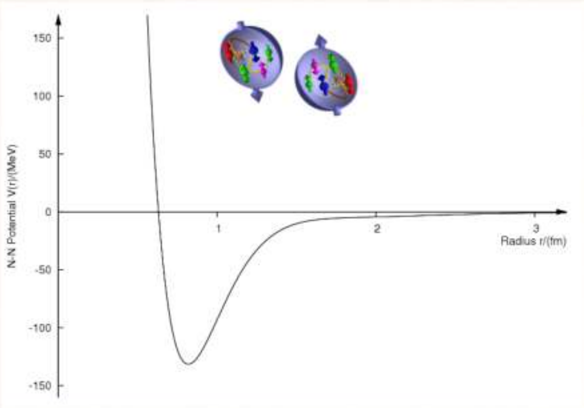
Nuclear Shell Model

- **Nucleons are quantum objects**: only some values of the energy are available, a **discrete number of states**
- **Nucleons are fermions**: two nucleons can not occupy the same quantum state: the Pauli principle. **The energy levels of the nucleons are filled from the lowest to the highest** as nucleons are added to the nucleus.
- There are **separate energy levels for protons and neutrons.**
- Nucleons **fill every energy level in orbitals with a definite angular momentum.**
- As in atoms, **many nuclear properties** (angular momentum, magnetic moment, shape, etc.) **are determined by the last occupied or unoccupied level.**



Nuclear Shell Model

The basic assumption of the nuclear shell model is, to first order, the independent motion of each nucleon (proton or neutron) in an average nuclear potential.



… model Hamiltonian for A independent nucleons:

$$H_0 = \sum_{i=1}^{A}(T_i + U_i(r)) \equiv \sum_{i=1}^{A} h_0(i)$$

eigenfunctions: $\Psi_{a_1,a_2,\dots a_A}(\vec{r}_1,\vec{r}_2,\dots\vec{r}_A) = \prod_{i=1}^{A}\phi_{a_i}(\vec{r}_i)$

eigenvalues: $E_0 = \sum_{i=1}^{A}\epsilon_{a_i}$

… antisymmetrization:

$$\Psi_{a_1,a_2}(\vec{r}_1,\vec{r}_2) = \frac{1}{\sqrt{2}}\left[\phi_{a_1}(\vec{r}_1)\phi_{a_2}(\vec{r}_2) - \phi_{a_1}(\vec{r}_2)\phi_{a_2}(\vec{r}_1)\right]$$

The average potential U(r) is not given explicitly. If one starts from a one- plus two-body Hamiltonian:

$$H = \sum_{i=1}^{A} T_i + \frac{1}{2}\sum_{i,j=1}^{A} V_{i,j}$$

Nuclear Shell Model

The smaller the effect of H_{RES}, the better the assumption of an average, independent field for each nucleon.

$$H = \sum_{i=1}^{A}[T_i + U_i(r_i)] + \left(\frac{1}{2}\sum_{i,j=1}^{A} V_{i,j} - \sum_{i=1}^{A} U_i(r_i)\right) \equiv \sum_{i=1}^{A} h_0(i) + H_{RES}$$

Nuclear potential deduced from data:

Wood Saxon potential: $V(r) = -\frac{V_0}{1+\exp[(r-R)/a]}$

Square well: $V(r) = -V_0\,(r \leqslant R)$ and $V(r) = 0\,(r > R)$

harmonic oscillator: $V(r) = \frac{1}{2}m\omega^2 r^2$

… solutions for the HO potential: $U(r) = \frac{1}{2}m\omega^2 r^2$

$$u_{kl}(r) = N_{kl}\, r^{l+1} e^{-\nu r^2} L_k^{l+1/2}(2\nu r^2) \qquad (\nu = m\omega/2\hbar)$$

Laguerre polynomials

$$E = \hbar\omega(2k + l + \frac{3}{2}) = \hbar\omega(N + \frac{3}{2})$$

N = 0,1,2 ... major oscillator quantum number
l = N,N-2, ... ,1 or 0 orbital quantum number
k = (N-l) /2 radial quantum number

n = k+1 = (N-l+2)/2 number of nodes of the radial wave function in the interval [0,∞).

$$D_N = 2\sum_{l=0\text{or}1}^{N}(2l+1) = (N+1)(N+2)$$

spin projections

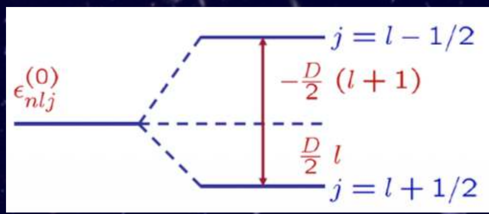
The spin-orbit coupling

Mayer (1949,1950) and Haxel, Jensen, Suess (1949, 1950) – the average single-nucleon potential should contain a spin-orbit term

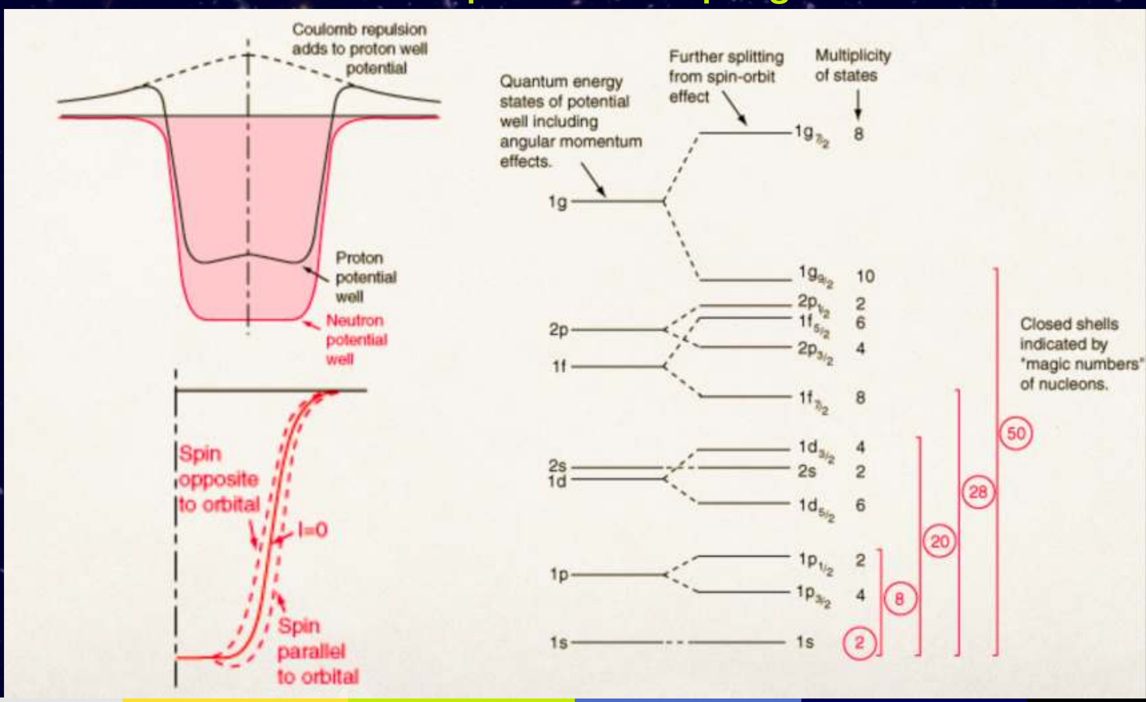
$$h = h_0 + \zeta(r)\vec{l}\cdot\vec{s}$$

... an intrinsically relativistic effect. It is automatically included in the effective potential when the single – nucleon dynamics is described by the Dirac equation. When the nucleons are described as non-relativistic particles, the spin-orbit term must be added to the Schrödinger equation.

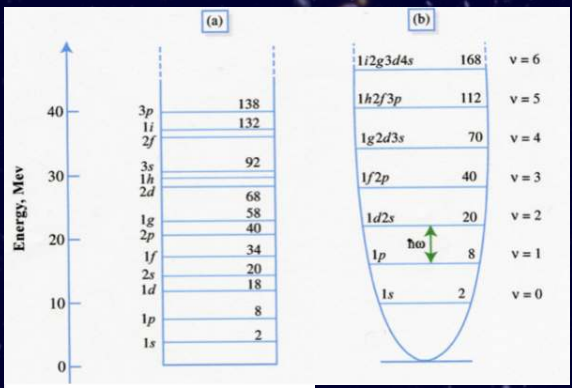
$$\Delta\varepsilon_{nlj=l+1/2} = \frac{D}{2}l$$
$$\Delta\varepsilon_{nlj=l-1/2} = -\frac{D}{2}(l+1)$$



Spin-orbit coupling

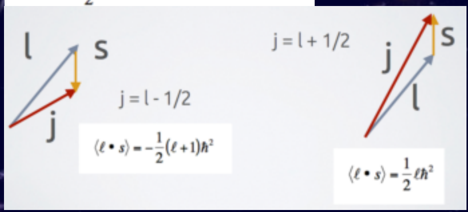


Nuclear Shell Model



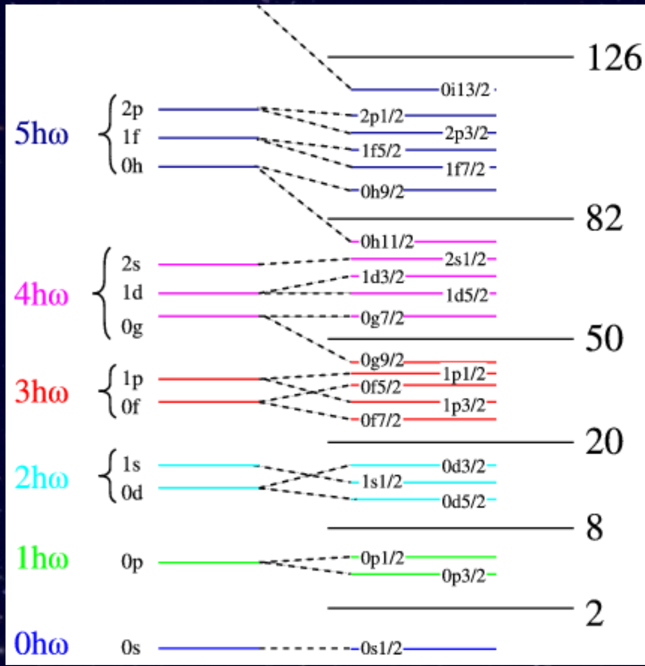
$$j^2 = (l+s)^2 = l^2 + s^2 + 2l \bullet s$$

$$\langle l \bullet s \rangle = \frac{1}{2}\left[j(j+1) - \ell(\ell+1) - s(s+1)\right]\hbar^2$$



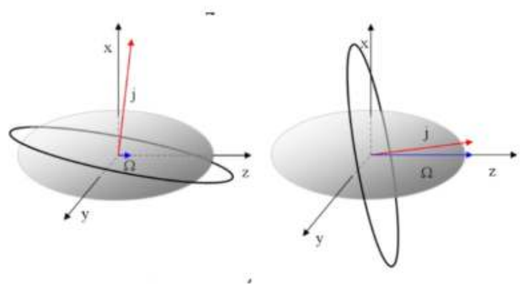
$$\langle \ell \bullet s \rangle = -\frac{1}{2}(\ell+1)\hbar^2$$

$$\langle \ell \bullet s \rangle = \frac{1}{2}\ell\hbar^2$$

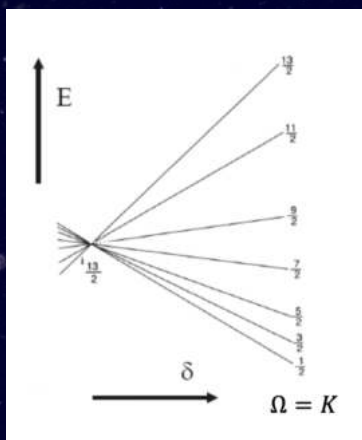


Deformed Shell Model

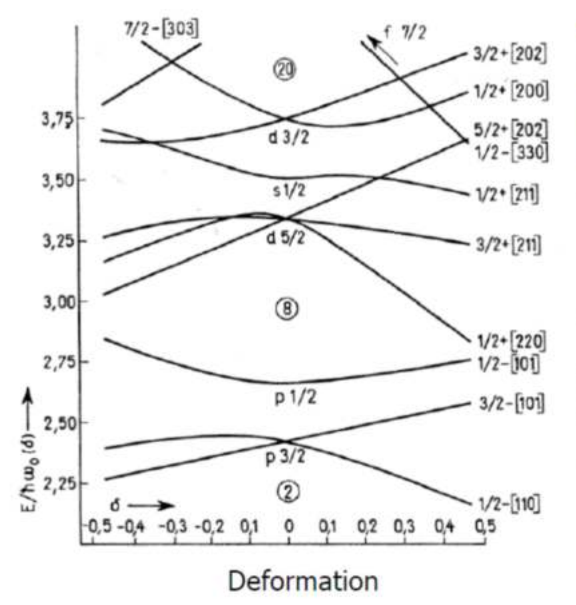
- spherical nucleus: $R = R_0$
- deformed nucleus: $R = R_0 \cdot \left[1 + \sum_{\lambda=2,\mu} \alpha_{2\mu} \cdot Y_{2\mu}\right]$
  → can rotate



- Separation of laboratory system and body-fixed (intrinsic) system
- Ω = K projection of the single-particle angular momentum onto the symmetry axis
- Rotation perpendicular to the symmetry axis will not change the Ω-quantum number



Nilsson model



Nilsson Model is a single-particle model for deformed nuclei.

$$H = \frac{p^2}{2m} + \frac{m\cdot\left[\omega_x^2\left(x^2+y^2\right)+\omega_z^2\cdot z^2\right]}{2} + C\cdot l\cdot s + D\cdot l^2$$

with $\omega_x^2 = \omega_0^2\cdot\left(1+\frac{2}{3}\cdot\delta\right)$ $\omega_z^2 = \omega_0^2\cdot\left(1-\frac{4}{3}\cdot\delta\right)$

The labelling of the Eigen-states is: $\Omega^{\pi}[Nn_z\Lambda]$

Ω projection of the total particle angular momentum on the symmetry axis

π parity of the wave function $\pi = (-1)^N$

N the principal quantum number of the major oscillator shells

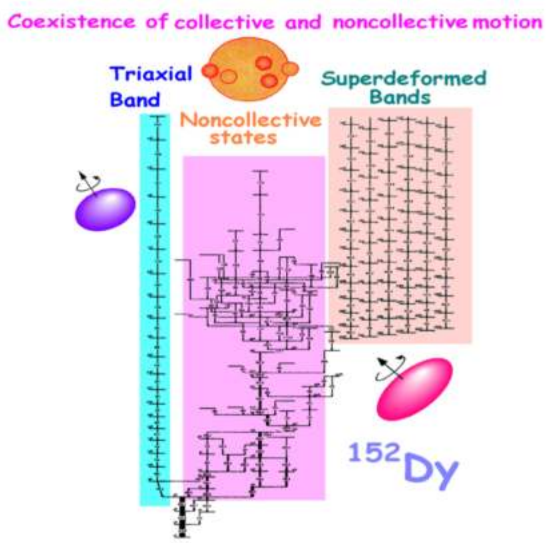
n_z the number of quanta associated with the wave function moving along the z-direction

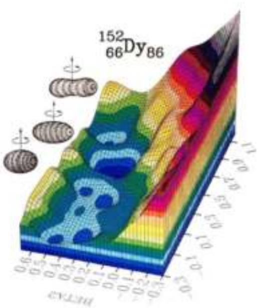
$\Lambda = m_\ell$ projection of the orbital angular momentum onto the z-axis

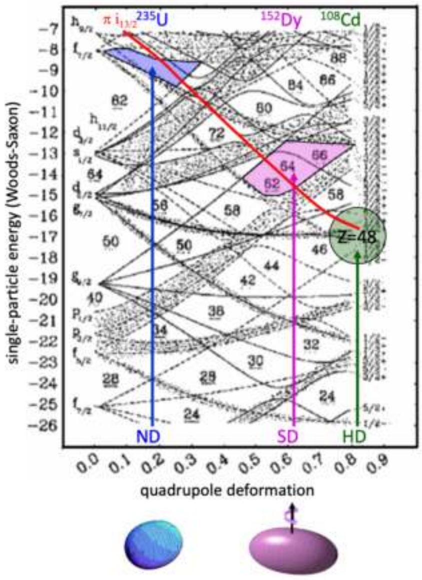
Sven Göata Nilsson

$$H = \underbrace{-\frac{\hbar^2}{2m}\Delta + \frac{m}{2}\omega_0^2 r^2 + C\cdot\vec{L}\bullet\vec{S} + D\cdot\vec{L}^2}_{\text{shell model with H.O. potential}} \underbrace{- m\omega_0^2 r^2 \delta \frac{4}{3}\sqrt{\frac{4\pi}{5}}Y_{20}(\theta,\Phi)}_{H_{def}}$$

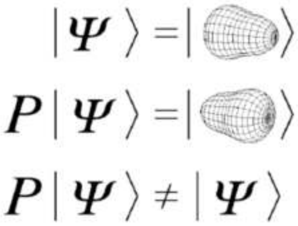
Super/Hyper/Ultra - Deformation

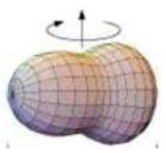


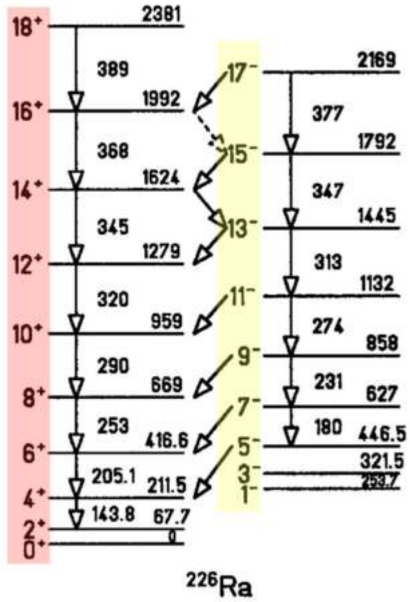


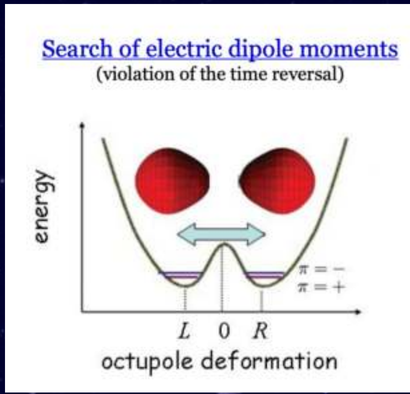


Octupole deformation

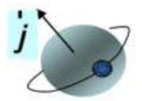



Rotation

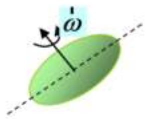




Symmetries in nuclear physics

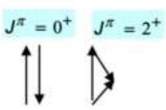


Spherical Symmetry: 1949 Mayer

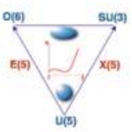


Deformed nuclear field (spontaneous symmetry breaking)
symmetry restoration → rotational spektra:
1952 Bohr-Mottelson

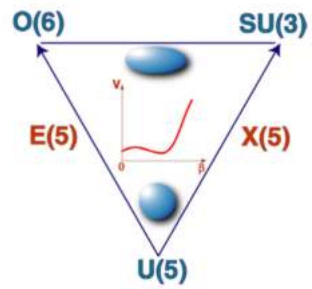
SU(3) dynamical Symmetry: 1958 Elliott



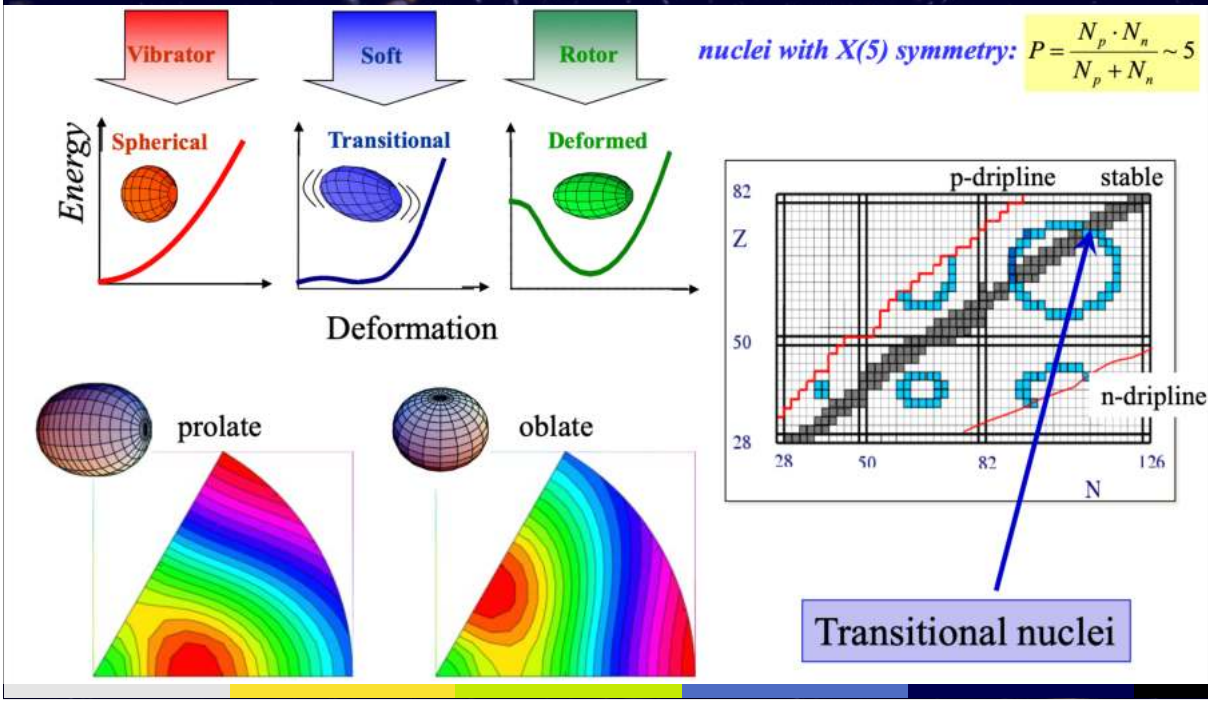
Interacting Boson Model (IBM dynamical symmetry):
1974 Arima and Iachello



Critical point symmetry E(5), X(5) ….
2000… F. Iachello



Nuclear shapes and symmetries



part III

particles

From nucleons to quarks and leptons

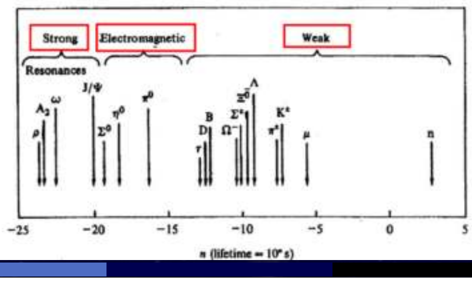
Evidence for quarks

- The magnetic moments of proton and neutron are not $\mu_N = e\hbar/2m_p$ and 0 respectively $\Rightarrow$ not point-like
- Electron-proton scattering at high q^2 deviates from Rutherford scattering $\Rightarrow$ proton has substructure
- Hadron jets are observed in e^+e^- and pp collisions
- Symmetries (patterns) in masses and properties of hadron states, "quarky" periodic table $\Rightarrow$ sub-structure
- Steps in $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$
- Observation of $c\bar{c}$ and $b\bar{b}$ bound states

The weak interaction accounts for many decays in particle physics, e.g.

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \qquad \tau^- \to e^- \bar{\nu}_e \nu_\tau$$
$$\pi^+ \to \mu^- \bar{\nu}_\mu \qquad n \to pe^- \bar{\nu}_e$$

Characterised by long lifetimes and small interaction cross-sections



Two types of weak interaction

Charged current (CC): $W^\pm$ bosons

Neutral current (NC): Z bosons

Particle overview

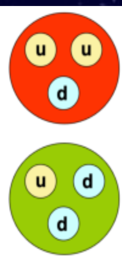
matter and antimatter

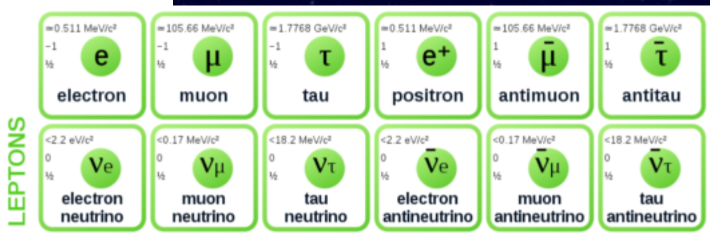
- hadrons
  - baryons
  - mesons
- leptons

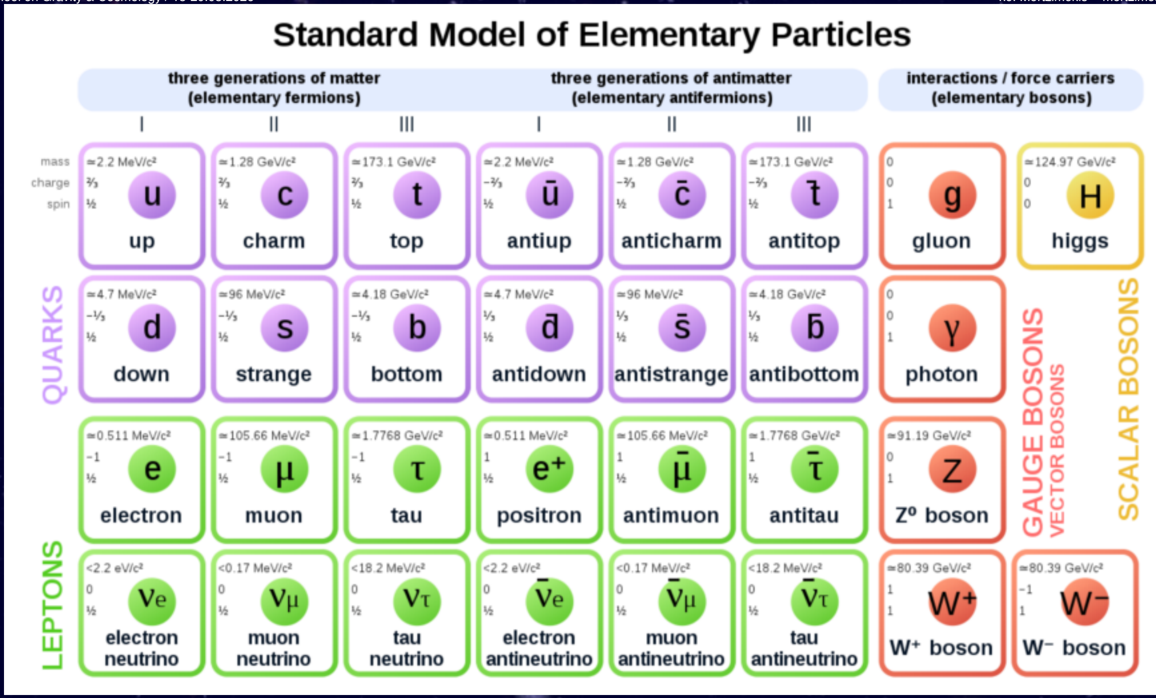
BARYONS
Consist of three quarks: q q q

ANTIBARYONS
Consist of three antiquarks: $\bar{q}\,\bar{q}\,\bar{q}$

MESONS
Consist of a quark-antiquark pair: q $\bar{q}$

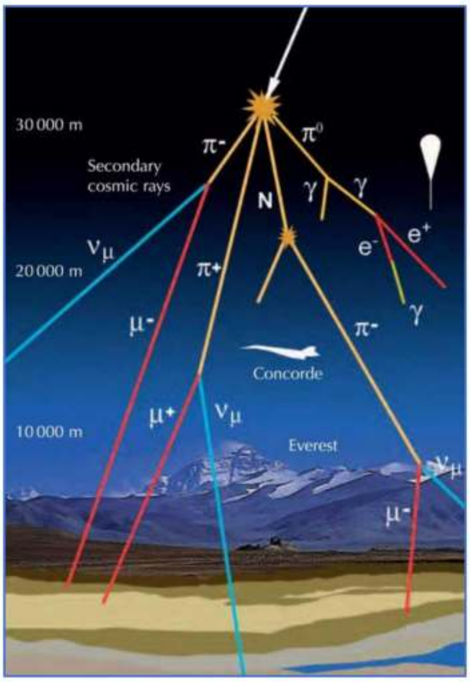


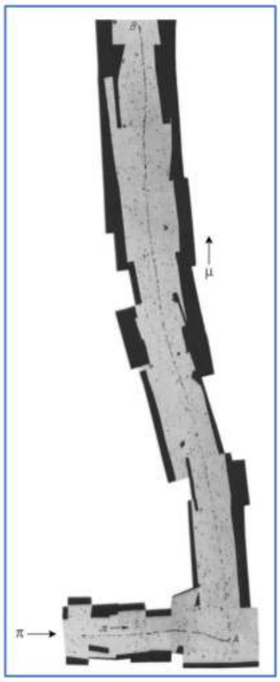




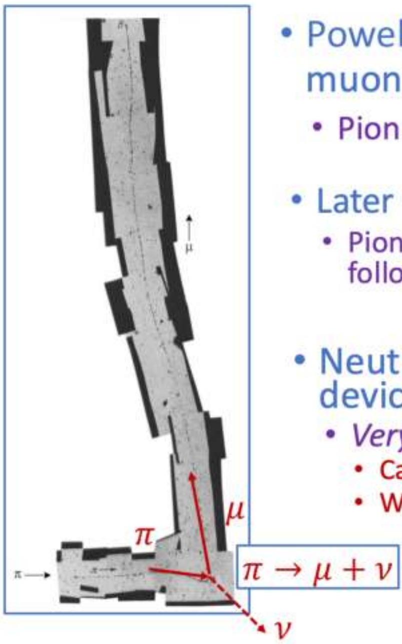
Discovery of the pion

- Powell, 1947
  - Go to mountain top
  - Photographic emulsion
- Observes that cosmic rays include muons and pions
  - $m_\pi = 140\ MeV/c^2$
  - $m_\mu = 105\ MeV/c^2$
- A pion can decay into a muon, which again decays into an electron
- The pion was Yukawa's meson

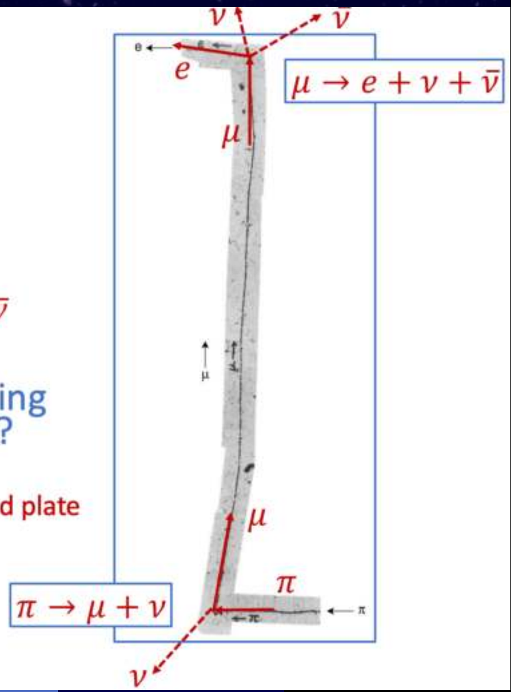




Neutrinos

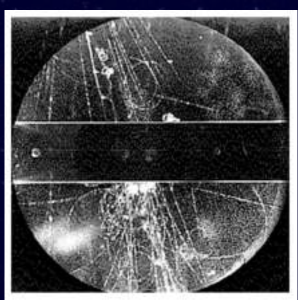


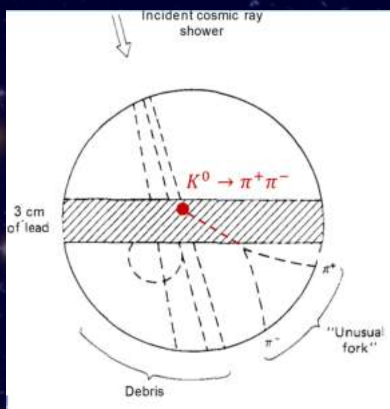
- Powell's discovery of muon and pion
  - Pion decay: $\pi \rightarrow \mu + \nu$
- Later discovery of Powell
  - Pion *and* muon decays: $\pi \rightarrow \mu + \nu$
    followed by: $\mu \rightarrow e + \nu + \bar{\nu}$
- Neutrinos: are they a bookkeeping device or are they real particles?
  - *Very weak* interaction
    - Can penetrate 1000 lightyears thick lead plate
    - What is their mass? $m_\nu \neq 0$?



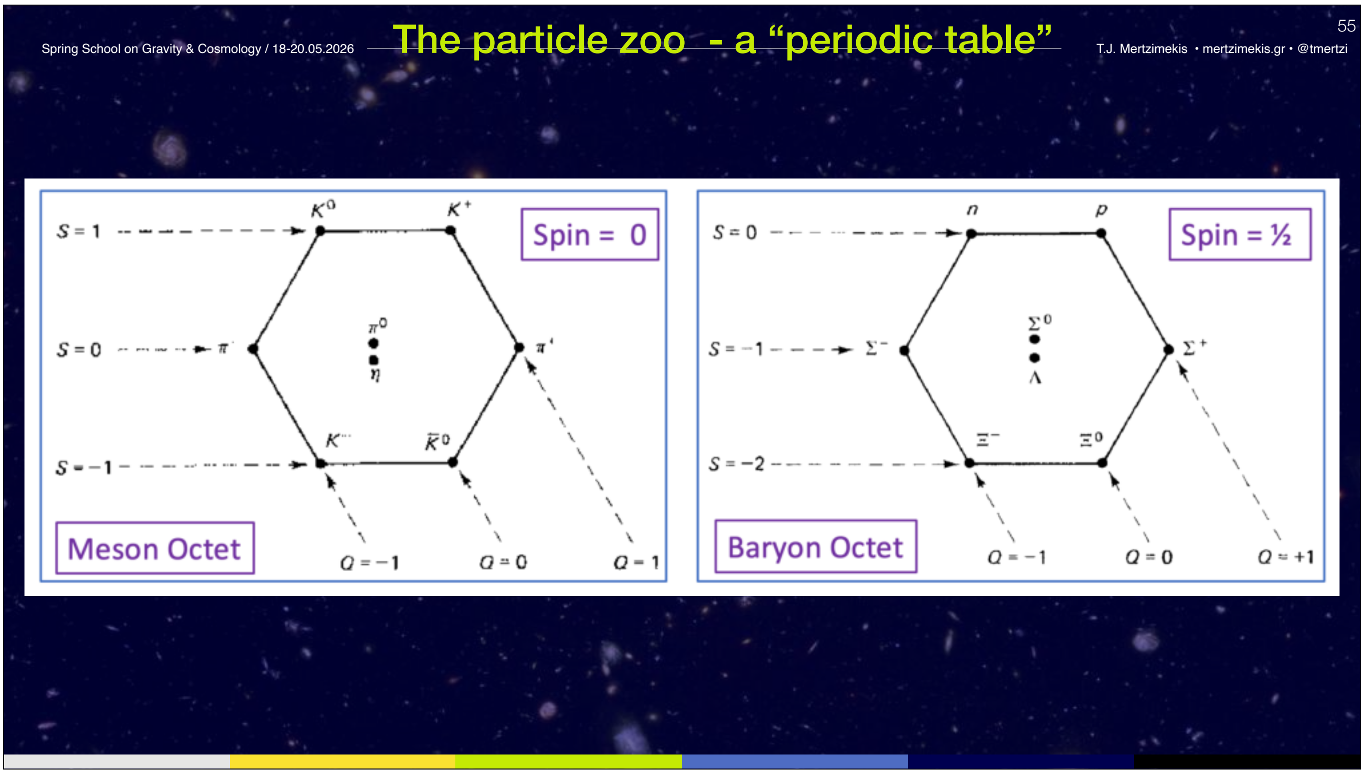
Strangeness

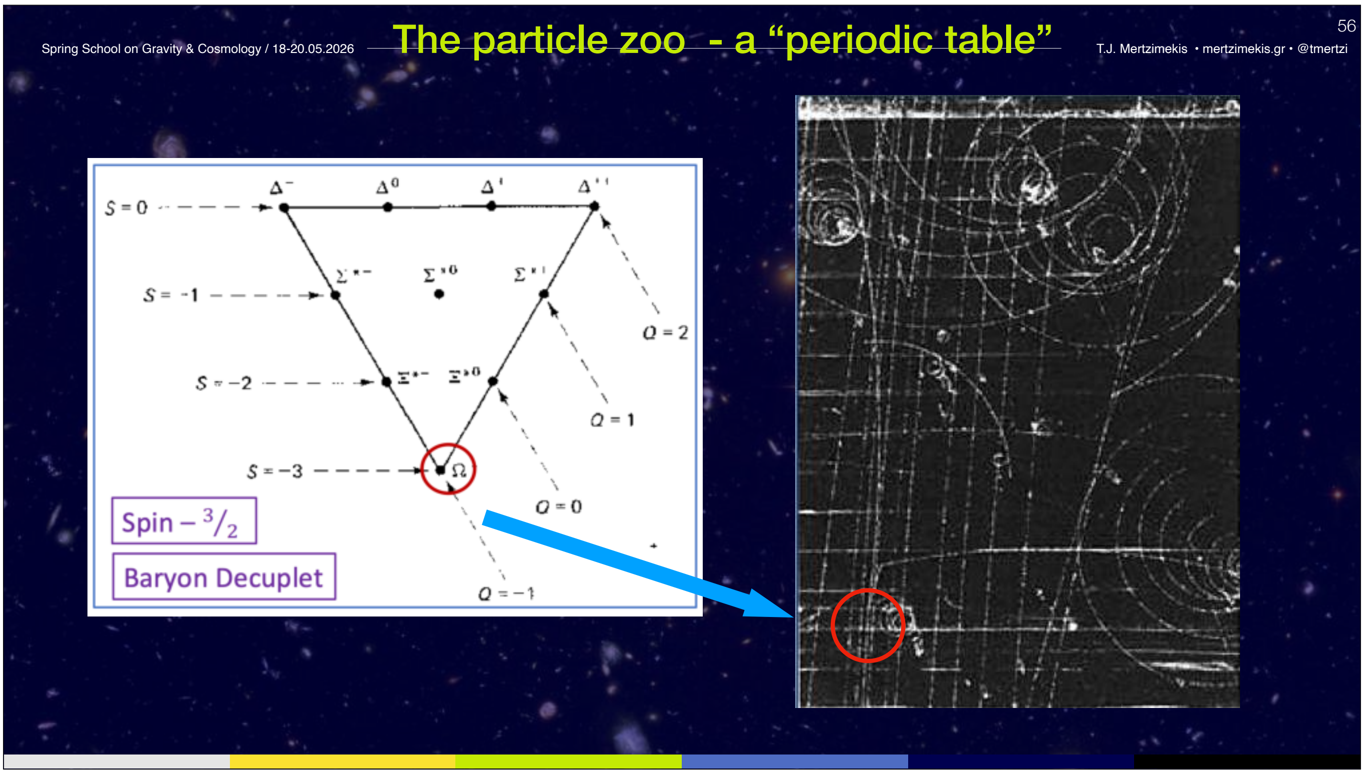
- Strange: produced copiously, but decay slowly!
  - Abraham Pais: They are produced with the strong force, but they decay with the weak force.





- Also observed: $K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$ ➔M_K~500 MeV ; it's a meson
- 1952, Brookhaven cosmotron: new strange *baryons*: Σ (~1.2 GeV), Ξ (~1.3 GeV)


Spring School on Gravity & Cosmology / 18-20.05.2026
The particle zoo - a “periodic table”
T.J. Mertzimekis • mertzimekis.gr • @tmertzi
55
Spin = 0
S = 1
S = 0
S = −1
Q = −1
Q = 0
Q = 1
Meson Octet
Spin = ½
S = 0
S = −1
S = −2
Q = −1
Q = 0
Q = +1
Baryon Octet


Spring School on Gravity & Cosmology / 18-20.05.2026
The particle zoo - a “periodic table”
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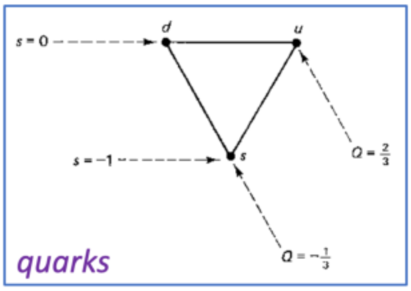
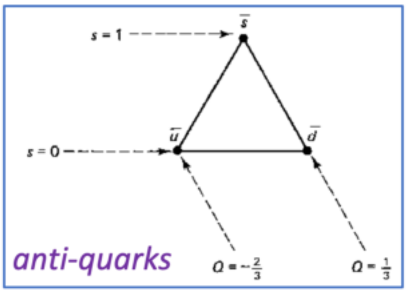
56
S = 0
S = −1
S = −2
S = −3
Q = 2
Q = 1
Q = 0
Q = −1
Spin – 3/2
Baryon Decuplet

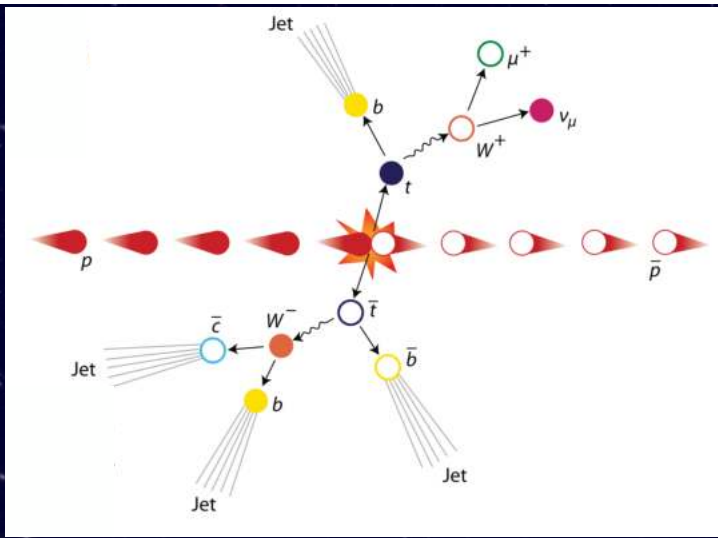
The quark model





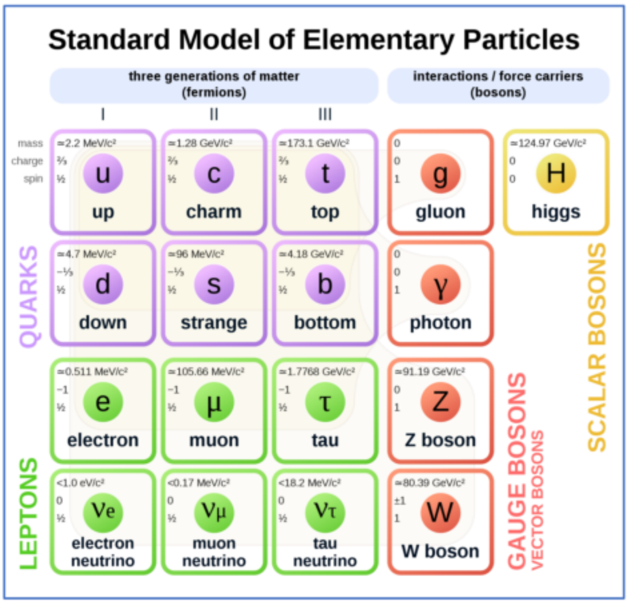
Terminology: upness, downness, strangeness, charm, beauty = ***"Flavour"***

- Quarks have *charge*, *flavor* and *color* quantum numbers

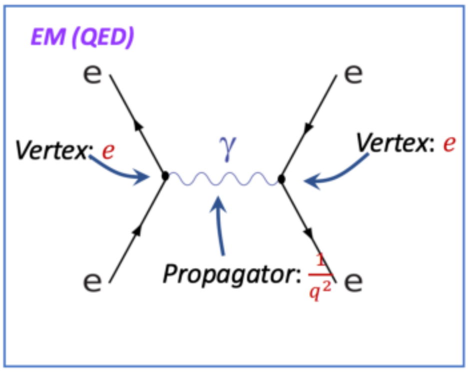


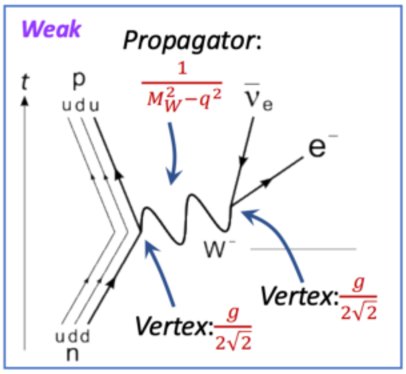
Classification of particles

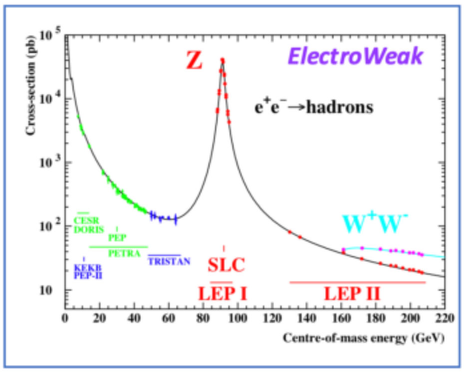
- Lepton: fundamental particle
- Hadron: consist of quarks
  - Meson: 1 quark + 1 antiquark (π^+,B_s^0, …)
  - Baryon: 3 quarks (p ,n , Λ, …)
    - Anti-baryon: 3 anti-quarks
- ***Fermion***: particle with half-integer spin.
  - Antisymmetric wave function: obeys Pauli-exclusion principle and Pauli-Dirac statistics
  - All fundamental quarks and leptons are spin-½
  - Baryons (S=$^1/_2$, $^3/_2$)
- ***Boson***: particle with integer spin
  - Symmetric wave function: Bose-Einstein statistics
  - Mesons: (S=0, 1), Higgs (S=0)
  - Force carriers: γ, W, Z, g (S=1); graviton(S=2)

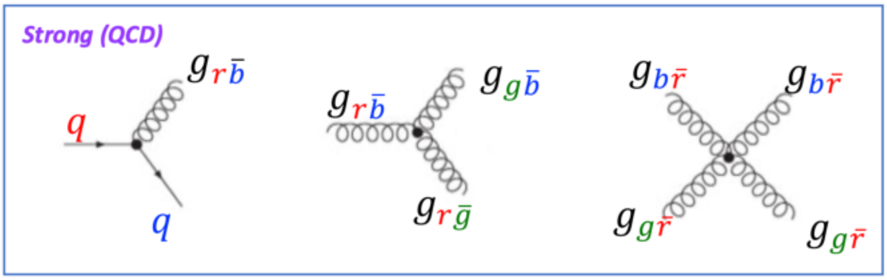


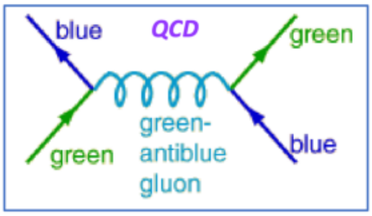
The 3 forces of the SM











- The Lagrangian of the Standard Model includes electromagnetic, weak and strong interactions according to the gauge field principle
- Construction of the Lagrangian: $\mathcal{L} = \mathcal{L}_{\text{free}} - \mathcal{L}_{\text{interaction}} = \mathcal{L}_{\text{Dirac}} - gJ^\mu A_\mu$
  - With g a coupling constant, J^μ a *current* $(\bar{\psi}O_i\psi)$ and A_μ a *force field*

A. Local $U(1)$ gauge invariance: symmetry under complex phase rotations
  - Conserved quantum number: (hyper-) charge
  - Lagrangian: $\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi - q\,\underbrace{\bar{\psi}\gamma^\mu\psi}_{J^\mu_{EM}}\,A_\mu$
    $(\partial_\mu \to D_\mu \equiv \partial_\mu + iqA_\mu)$

Note Spinor: $\psi = \begin{pmatrix}\psi_1\\ \psi_2\\ \psi_3\\ \psi_4\end{pmatrix}$

B. Local $SU(2)$ gauge invariance: symmetry under transformations in isospin doublet space.
  - Conserved quantum number: weak isospin
  - Lagrangian: $\mathcal{L} = \bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi - \frac{g}{2}\underbrace{\bar{\Psi}\gamma^\mu\vec{\tau}\Psi}_{J^\mu_{Weak}}\vec{b}_\mu$

$(I\partial_\mu \to D_\mu = I\partial_\mu + igB_\mu)$; $B_\mu = \frac{1}{2}\vec{\tau}\cdot\vec{b}_\mu = \frac{1}{2}\tau^a b^a_\mu = \frac{1}{2}\begin{pmatrix} b_3 & b_1 - ib_2\\ b_1 + ib_2 & -b_3\end{pmatrix}$

Note doublet spinors: $\Psi = \begin{pmatrix}\psi_u\\ \psi_d\end{pmatrix}$ with ψ_u, ψ_d spinors

C. Local $SU(3)$ gauge invariance: symmetry under transformations in colour triplet space
  - Conserved quantum number: color
  - Lagrangian: $\mathcal{L} = \bar{\Phi}(i\gamma^\mu D_\mu - m)\Phi = \bar{\Phi}(i\gamma^\mu \partial_\mu - m)\Phi - \frac{g_s}{2}\underbrace{\bar{\Phi}\gamma^\mu\vec{\lambda}\Phi}_{J^\mu_{QCD}}\vec{c}_\mu$
    $(I\partial_\mu \to D_\mu = I\partial_\mu + ig_sC_\mu)$ C_μ are 3x3 matrices →gluon fields

Note triplet spinors: $\Phi = \begin{pmatrix}\psi_r\\ \psi_g\\ \psi_b\end{pmatrix}$ ψ_r, ψ_g, ψ_b spinors

- The Lagrangian of the Standard Model includes electromagnetic, weak and strong interactions according to the gauge field principle
- Construction of the Lagrangian: $\mathcal{L} = \mathcal{L}_{\text{free}} - \mathcal{L}_{\text{interaction}} = \mathcal{L}_{\text{Dirac}} - gJ^{\mu}A_{\mu}$
  - With g a coupling constant, J^{μ} a *current* ($\bar{\psi}O_i\psi$) and A_{μ} a *force field*

Standard Model Lagrangian:

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi - qJ^{\mu}_{EM}A_{\mu} - \frac{g}{2}\overrightarrow{J^{\mu}}_{\text{Weak}} \cdot \vec{b}_{\mu} - \frac{g_s}{2}\overrightarrow{J^{\mu}}_{\text{QCD}} \cdot \vec{c}_{\mu}$$

Implements U(1), SU(2) and SU(3) symmetries simultaneous:

$$SU(3)_{\text{color}} \times SU(2)_L \times U(1)_Y$$

Requiring the Lagrangian to be invariant (symmetry) implies that the EM, Weak and Strong force fields must exist and the interactions respectively conserve charge, weak isospin, and color.

Symmetry breaking

- Massive particles are forbidden in the SM Lagrangian
  - A hypothetical mass term in the Lagrangian for the photon is not gauge invariant under $A^{\mu} \to A^{\mu\prime}$:

$$m^2 A_{\mu}A^{\mu} \to m^2\left(A_{\mu} + \frac{1}{e}\partial_{\mu}\alpha\right)\left(A^{\mu} + \frac{1}{e}\partial^{\mu}\alpha\right) \neq m^2 A_{\mu}A^{\mu}$$

- The same holds (harder to show) for the weak mediators W, Z
  - However they **are** massive
  - ➔ SU(2)xU(1) symmetry is *broken*

The Higgs mechanism breaks the symmetry of the (electro-)weak interaction

- Works along the lines as described in previous slides; introduce a complex SU(2) doublet

The Higgs mechanism

- Electroweak Lagrangian: $\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi + (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi)$
  - Where the covariant derivatives:

    U(1): $\psi(x) \to \psi'(x) = e^{i\alpha(x)}\psi(x)$

    $A^\mu(x) \to A'^\mu(x) = A^\mu(x) - \frac{1}{q}\partial^\mu\alpha(x)$

    $\Rightarrow \quad D^\mu = \partial^\mu + iqA^\mu$

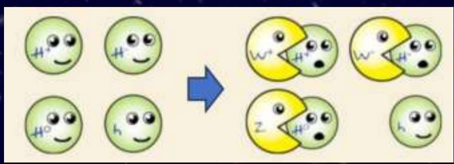
    and SU(2): $\psi(x) \to \psi'(x) = G(x)\psi(x)$

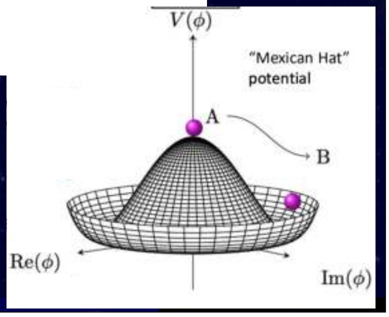
    with $G(x) = \exp\left(\frac{i}{2}\vec{\tau}\cdot\vec{\alpha}(x)\right)$

    $B'_\mu = GB_\mu G^{-1} + \frac{i}{g}(\partial_\mu G)G^{-1}$

    $\Rightarrow \quad D_\mu = I\partial_\mu + igB_\mu$

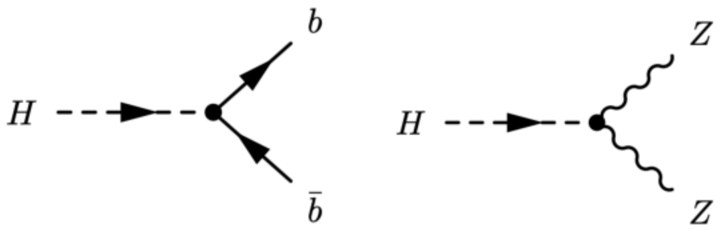
- Higgs field is weak isospin doublet: $\phi = \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2\\ \phi_3 + i\phi_4\end{pmatrix}$; $\phi_0 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$
  - With the potential: $V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$ where: $\mu^2 < 0$



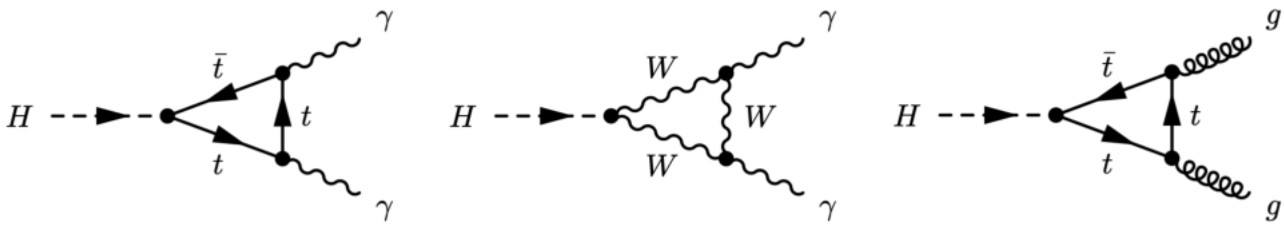


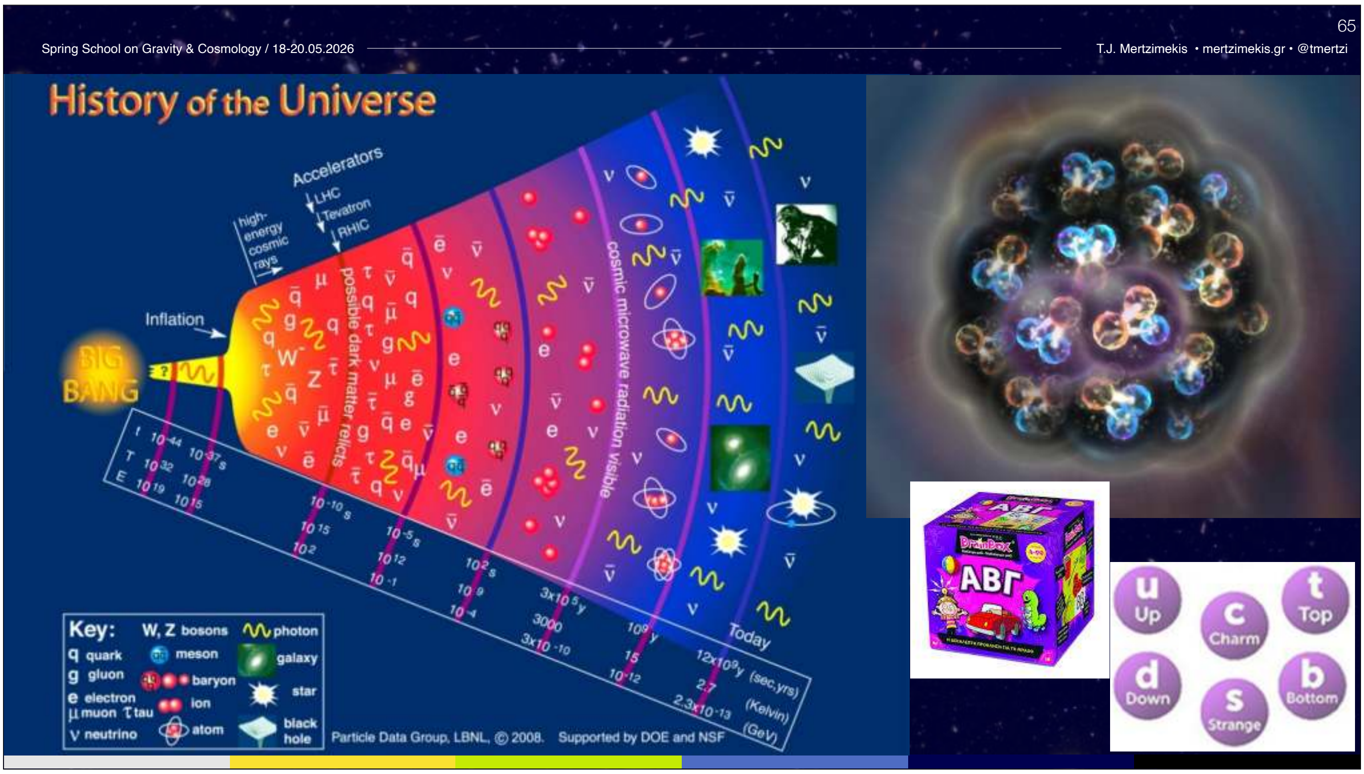
The Higgs decay mechanism

Directly to two fundamental fermions or bosons, coupling to mass, e.g.



Indirectly to massless particles (photons or gluons) via massive loops

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RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
Today
Key:
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g gluon
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