Nuclear Force

- Electrostatic and gravitational potential ▶ long range ($V \propto 1/r$).
- Near constancy of nuclear binding energy per nucleon B/A means that each nucleon feels only the effect of a few neighbors. This is called saturation. It implies also that the strong internucleon potential is short range.
- Range is of order of the 1.8 fm internucleon separation.
- Since volume $\propto A$, nuclei do not collapse, there is a very short range repulsive component.
- Exchange particles.
- Some particles are immune. Like what?
- Is nuclear physics just quark chemistry?
- Charge independence.
- Spin dependence. (Deuteron).
- Non-central (tensor) component ▶ conservation of orbital angular momentum….?

Nuclear Force (Compare to atomic)

Recall **Atomic** Binding Energies for **hydrogen like atoms**:

$$V(r) = \frac{-\alpha(\hbar c)Z}{r}, \quad (\hbar c = 1)$$

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \approx \frac{1}{137}$$

Dimensionless fine structure constant.

$$E_n = -\frac{1}{2}\alpha^2 \mu c^2 \frac{Z^2}{n^2}, \qquad \mu = \frac{m_e m_N}{m_e + m_N}$$

with Bohr radii: $$r_n = \frac{\hbar}{\mu c \alpha} n^2$$

Coulomb

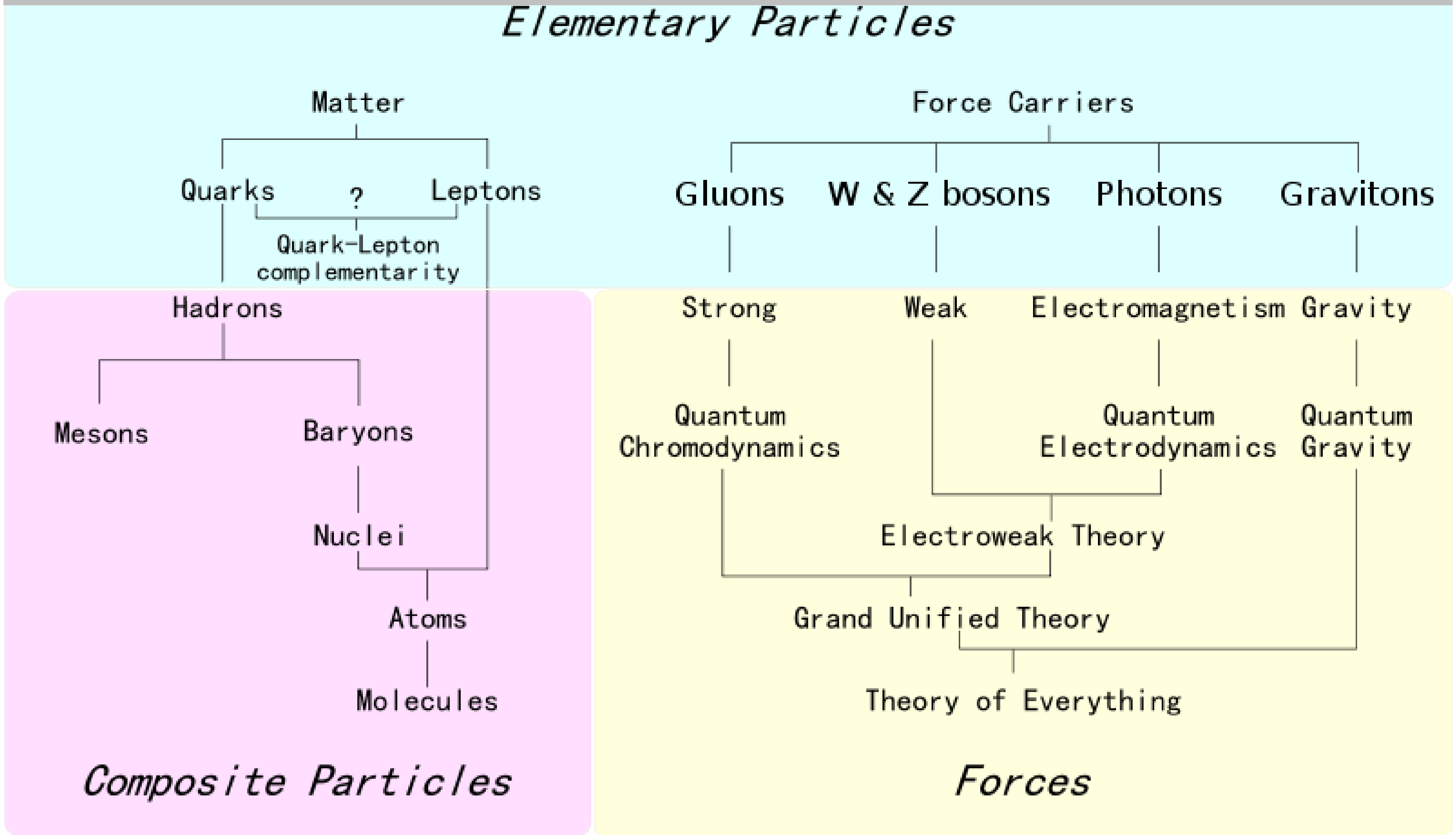
- Coupling constant ⇦⇨ Strength.
- Charge.
- Mediators (Bosons).

Other Forces !

Fundamental Forces

Force	Exchange Particle	Mass	Range
Electromagnetic	photon	0	infinite
Gravity	graviton	0	infinite
Weak	W boson	90 GeV/c^2	10^{-3} fm
Strong	gluon	> 140 MeV/c^2	< 1.4 fm

Fundamental Forces



Nuclear Force

The deuteron: proton-neutron bound state.

$$V(r) = \frac{-\alpha_S(\hbar c)}{r},$$

!!!!!!!!!!

$$\alpha_S = \frac{q_S{}^2}{4\pi\varepsilon_0 \hbar c} \approx 0.1$$

Color charge!

$$E_n = -\frac{1}{2}\alpha_S{}^2 \mu c^2 \frac{1}{n^2},$$

$$\mu = \frac{m_p m_n}{m_p + m_n}$$

!!!!!!!!!!

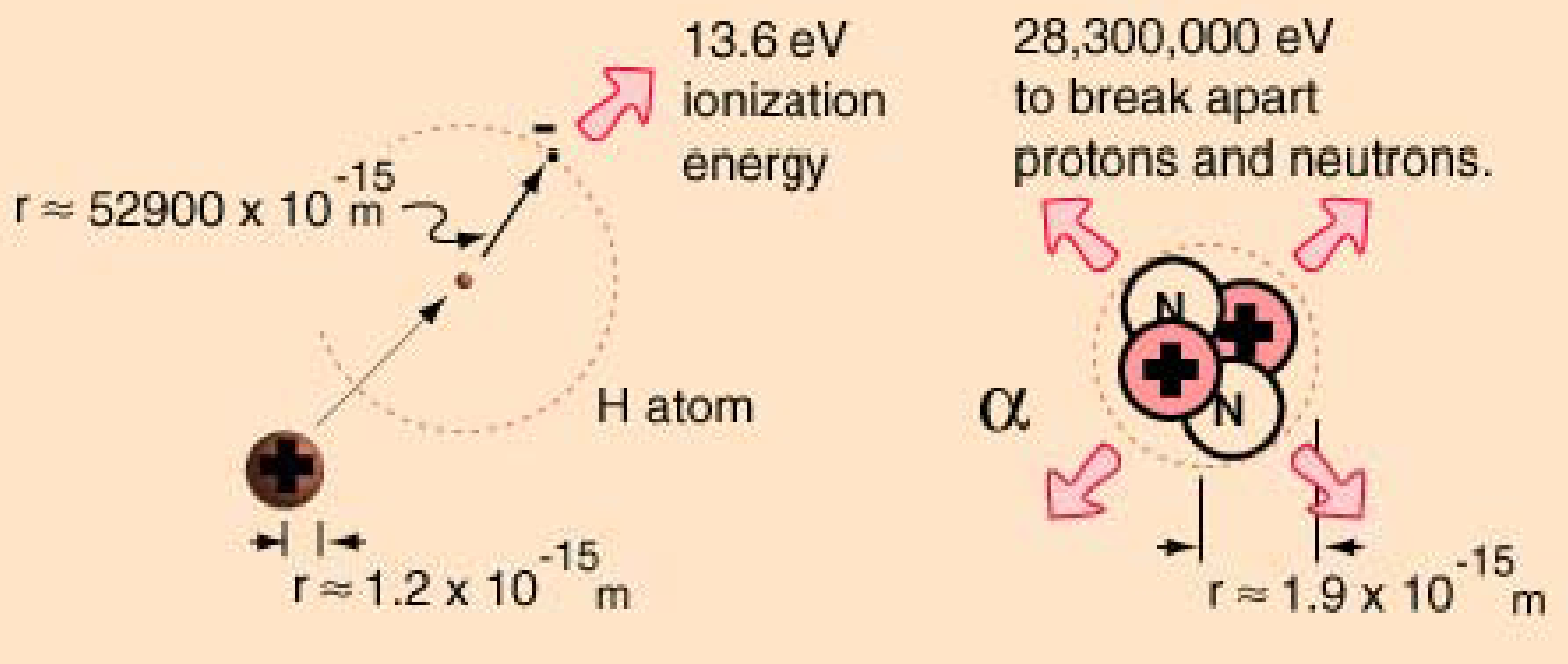
$$r_n = \frac{\hbar}{\mu c \alpha_S} n^2$$

Hydrogen: $E_1 = \ldots$ eV $r_1 = \ldots \times 10^{-10}$ m

Positronium: $E_1 = \ldots$ eV

Deuteron: $E_1 = \ldots$ MeV $r_1 = \ldots \times 10^{-15}$ m

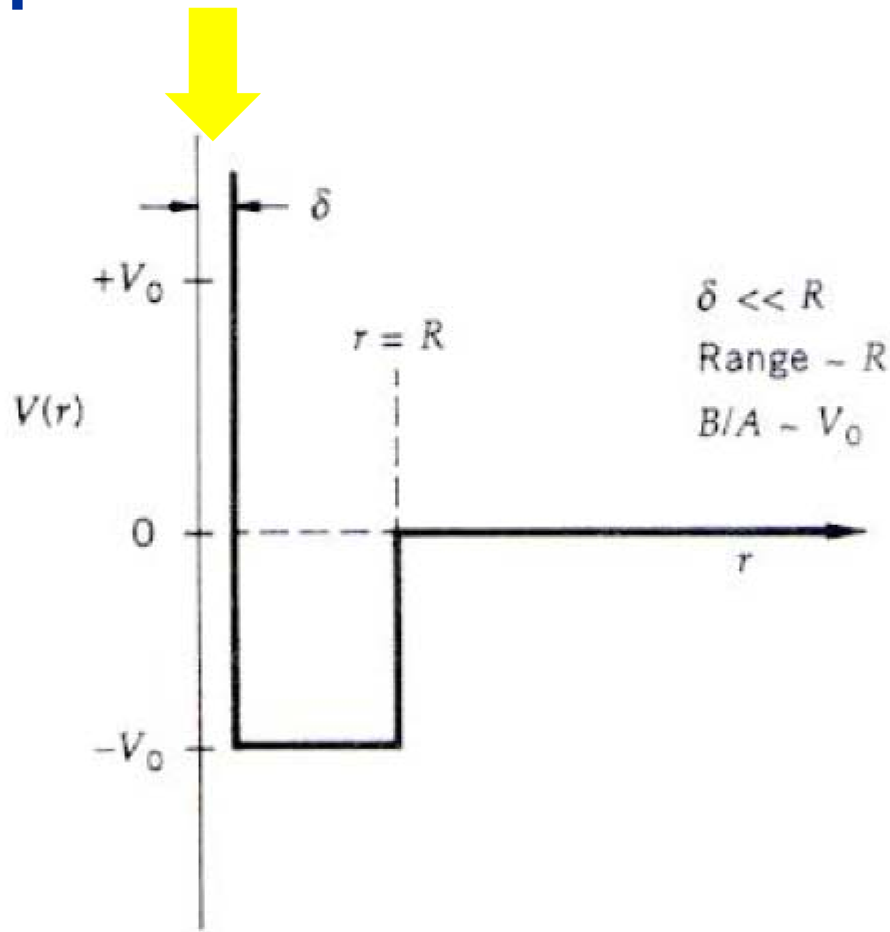
Nuclear Force



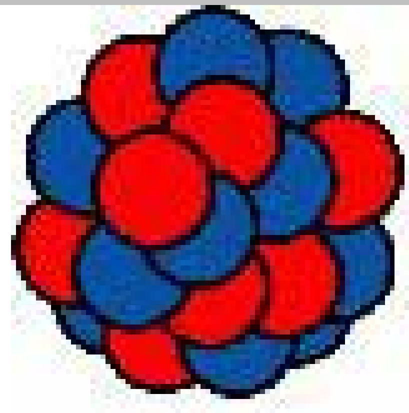
Comparison of atomic and nuclear scales and binding energy

Nuclear Force

Attractive but **repulsive core**. At what separation?



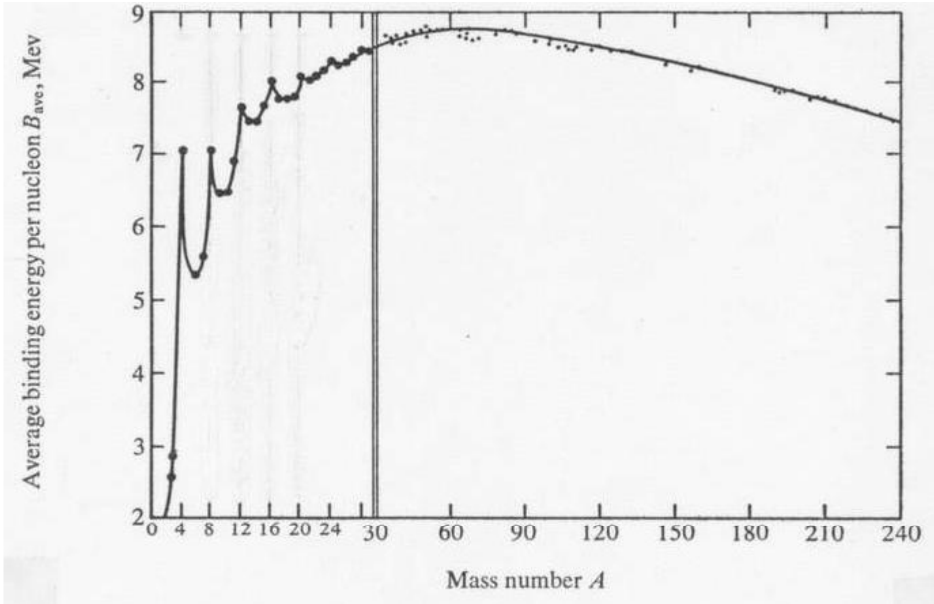
Nuclear Force



Is the nucleon bounded equally to **every** other nucleon?

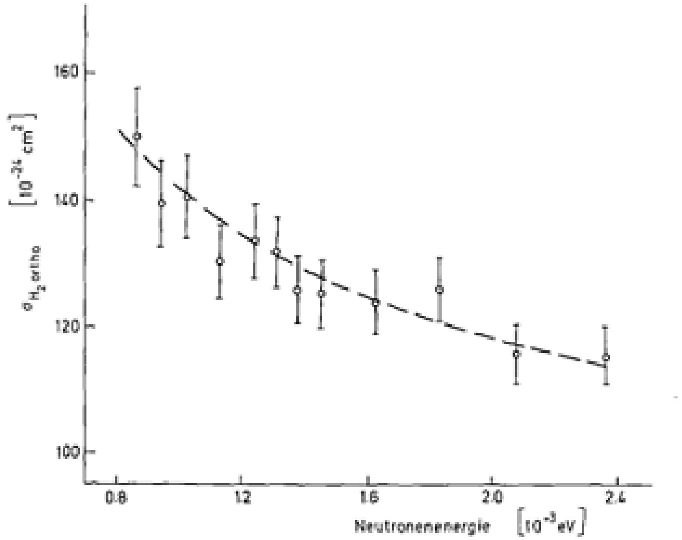
We discussed this earlier.

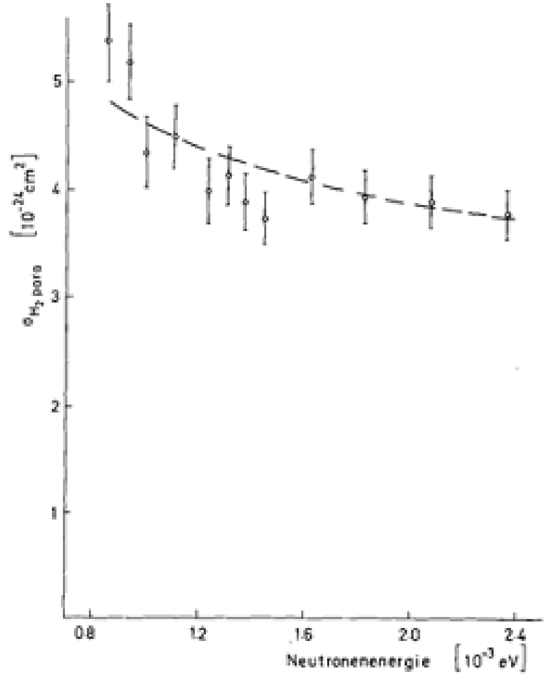
- **finite range** of strong force,
  and force saturation.

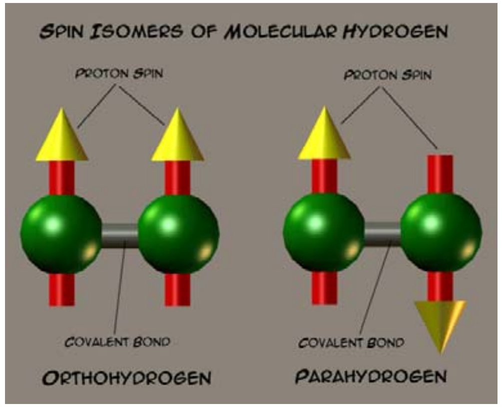


Nuclear Force

- Spin dependent ▶ difference in neutron scattering cross sections of ortho- and para-hydrogen.

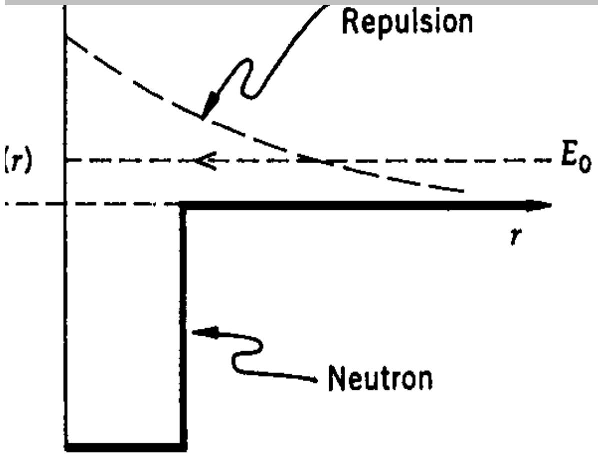


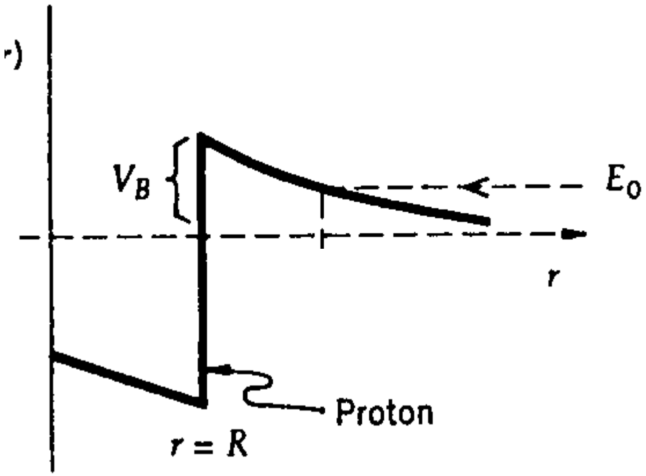


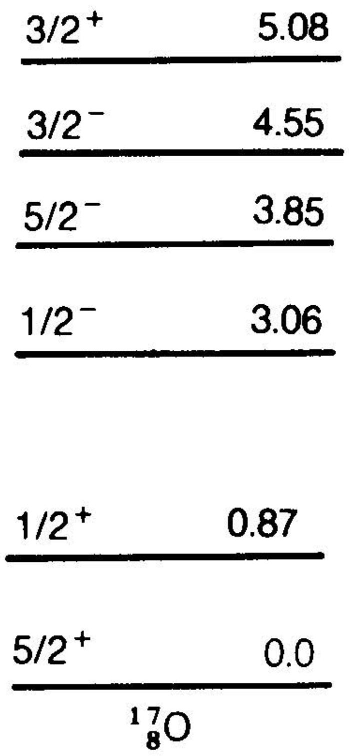


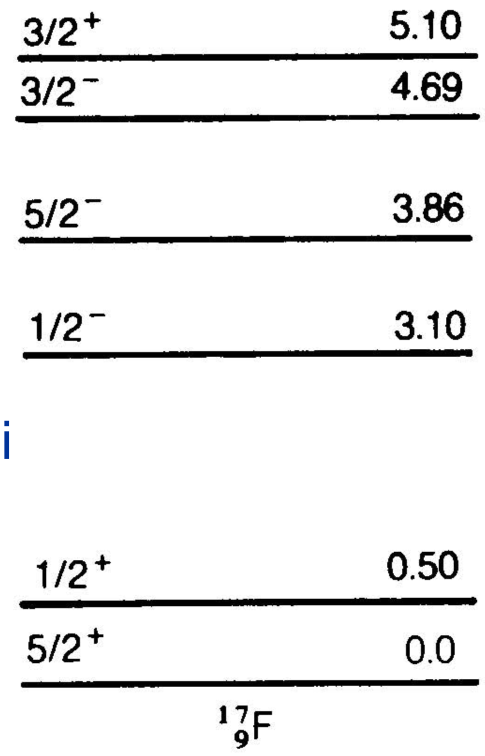
- Compare n-p to n-n and p-p ▶ Charge independence of nuclear force.

Nuclear Force



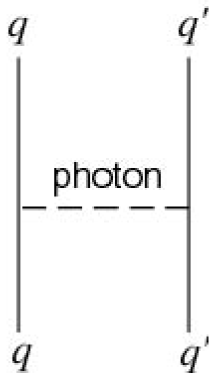






Mirror Nuclei

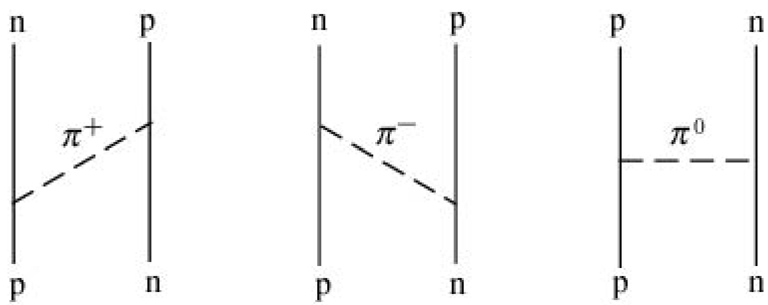
Nuclear Force

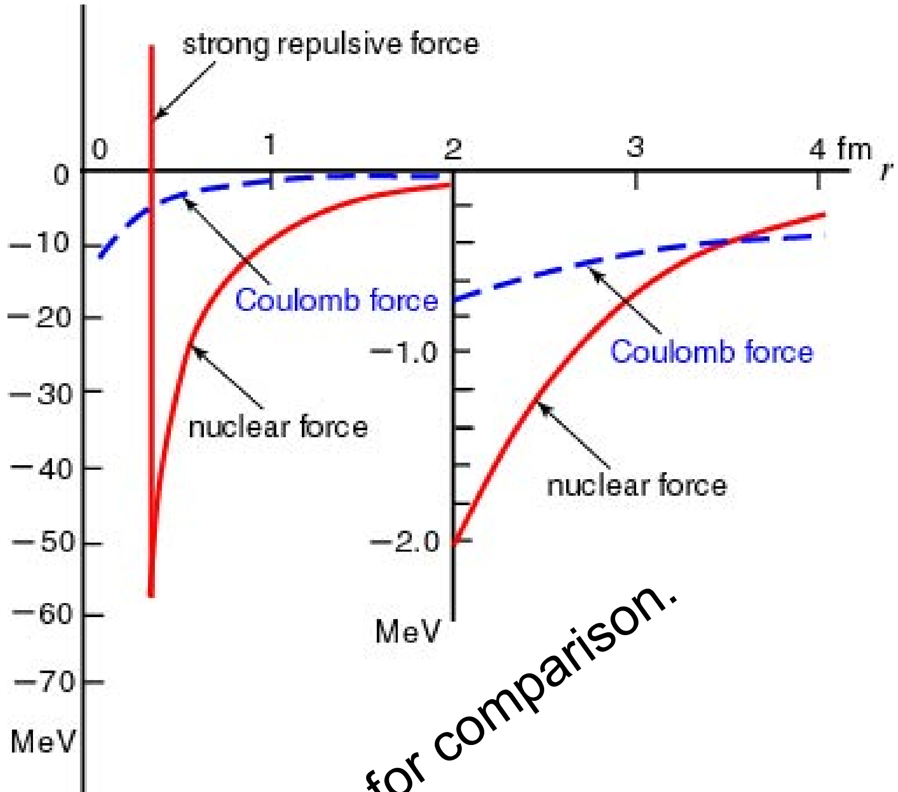


If two charges, q and q' exchange photons, the Coulomb force occurs between them.

Krane 4.5

What about forces between quarks? Color?





Just for comparison.

If pions are exchanged between two nucleons, the strong nuclear force occurs.

Remember the weak nuclear force…

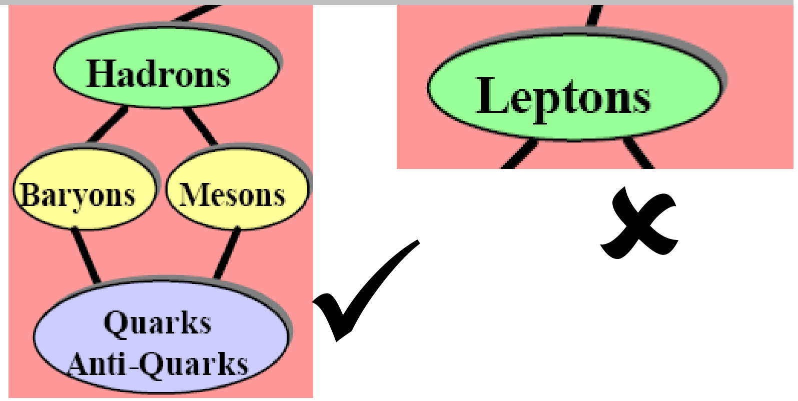
Boson?

$$n \to p + e + \bar{\nu}$$

Nuclear Force

Group	Composite system	Constituents	Interaction	Exchanged objects	Note
1	nucleon	quarks	strong	gluons	fundamental interactions
	atom	charged particles	electro-magnetic	photon	
2	nucleus	nucleons	nuclear	mesons	non-fundamental interactions
	molecule	atoms	molecular	photon electron	

Nuclear Force



- Only Hadrons.
- Typical time: 10^{-24} s.
- Exchange of light ~ 140 MeV pions.
- $\Delta t = \hbar/\Delta E = 4.7 \times 10^{-24}$ s.
- Range ~ $\Delta t\, c = \hbar/mc \sim 10^{-15}$ m.
- Range and time complicated by possibilities of heavier hadron exchange.
- Isospin dependence.
- Hadron multiplets: Doublet of nucleons and triplet of pions and …
- The members of a multiplet have the same strangeness, hypercharge, spin, *etc*… , but differ in charge and differ slightly in mass.
- Relationship between particle and nuclear physics.
- Accelerators and large accelerators.

Isospin

- **Isospin** Magnitude $\sqrt{T(T+1)}$
- T_3 can take *T, T-1, T-2, ….., -T.*
- 1,2,3 not x,y,z (Isospin space).
- Singlets ($T = 0$), Doublets ($T = ½$), Triplet ($T = 1$), Quartet (??).
- $-T_3$ for antiparticles.
- Isospin addition: for a collection of hadrons (e.g. in interaction)

$$T_{\max} = \sum_i T(i) \qquad T_3 = \sum_i T_3(i) \qquad T \geq |T_3|$$

- Example: π^+-p scattering, $T_{max} = {}^3/_2$, $T_3 = {}^3/_2$ ▶ T can only be ${}^3/_2$.

$$\text{For a nucleus } T_{\max} = \frac{A}{2}, \quad T_3 = \frac{1}{2}(Z - N)$$

Read Krane 11.3.

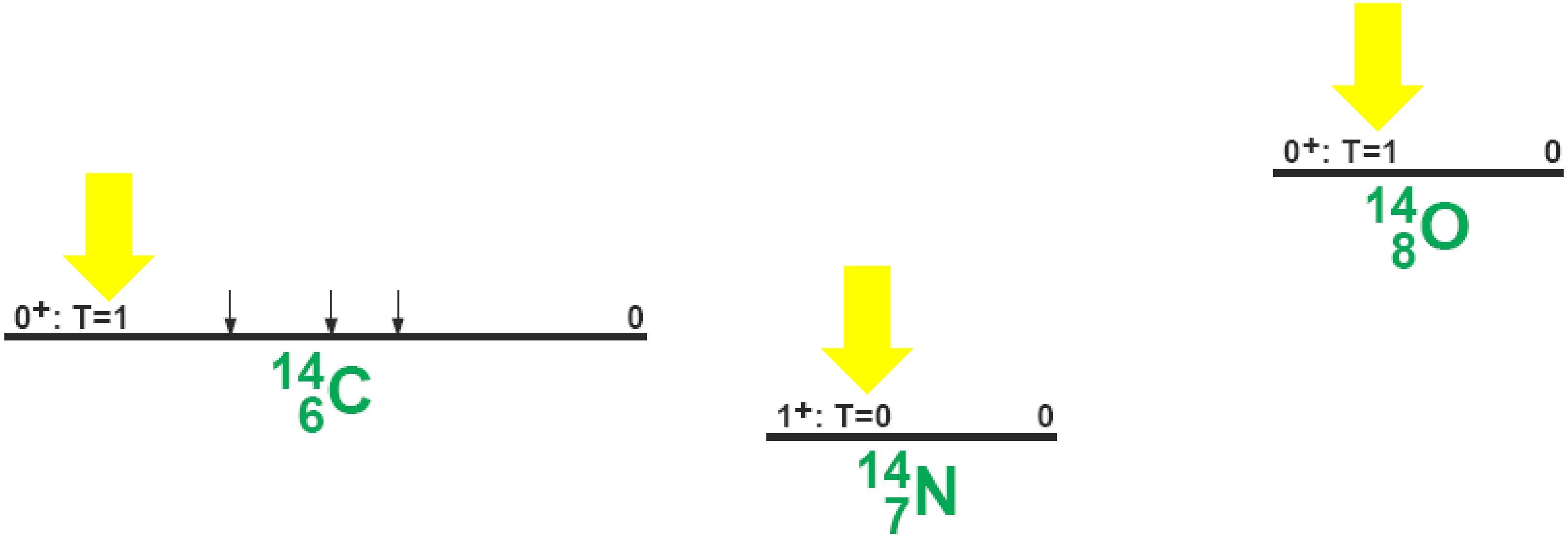
Isospin

$$T_3 = \sum_i T_3(i) = -1$$

$$T_3 = 0$$

$$T_3 = 1$$

$$0 \le T \le 7$$



$$T_{\max} = 7 \qquad T \ge |T_3|$$

The Deuteron

$^{2}_{1}\mathrm{H}$

%: 0.015 *1*

Δ: 13135.720 *10* **S$_n$:** 2224.57 **S$_p$:** 2224.57

σ_γ: 0.519 *7* mb

Levels:

0, 1^+, stable, μ=+0.857438230 *24*,
Q=+0.002860 *15*

$$T_{\max} = 1, \quad T_3 = 0$$

$$T = 0 \quad (1\,\text{excluded, no di-proton no di-neutron})$$

The Deuteron

- Deuterium (atom).
- The only bound state of two nucleons ▶ simplest bound state.
- Neither di-proton nor di-neutron are stable.

- Experimentally ~ 2.224 MeV (Recoil..!). $n + {}^{1}H \rightarrow {}^{2}H + \gamma$
- Also inverse (γ,n) reaction using Bremsstrahlung (Recoil…!).
- Mass spectroscopy ▶ mass of D (or deuterium atom).
- Δmc^2 = 2.224…??…MeV ▶ Very weakly bound.
- Mass doublet method ▶ all results are in agreement.
- Compare 2.224 MeV to 8 MeV (average B/A for nuclei).
- Only ground state. (There is an additional virtual state).

The Deuteron

$V(r) = -V_0 \quad r < R$

$\quad\quad = 0 \quad\quad r > R$

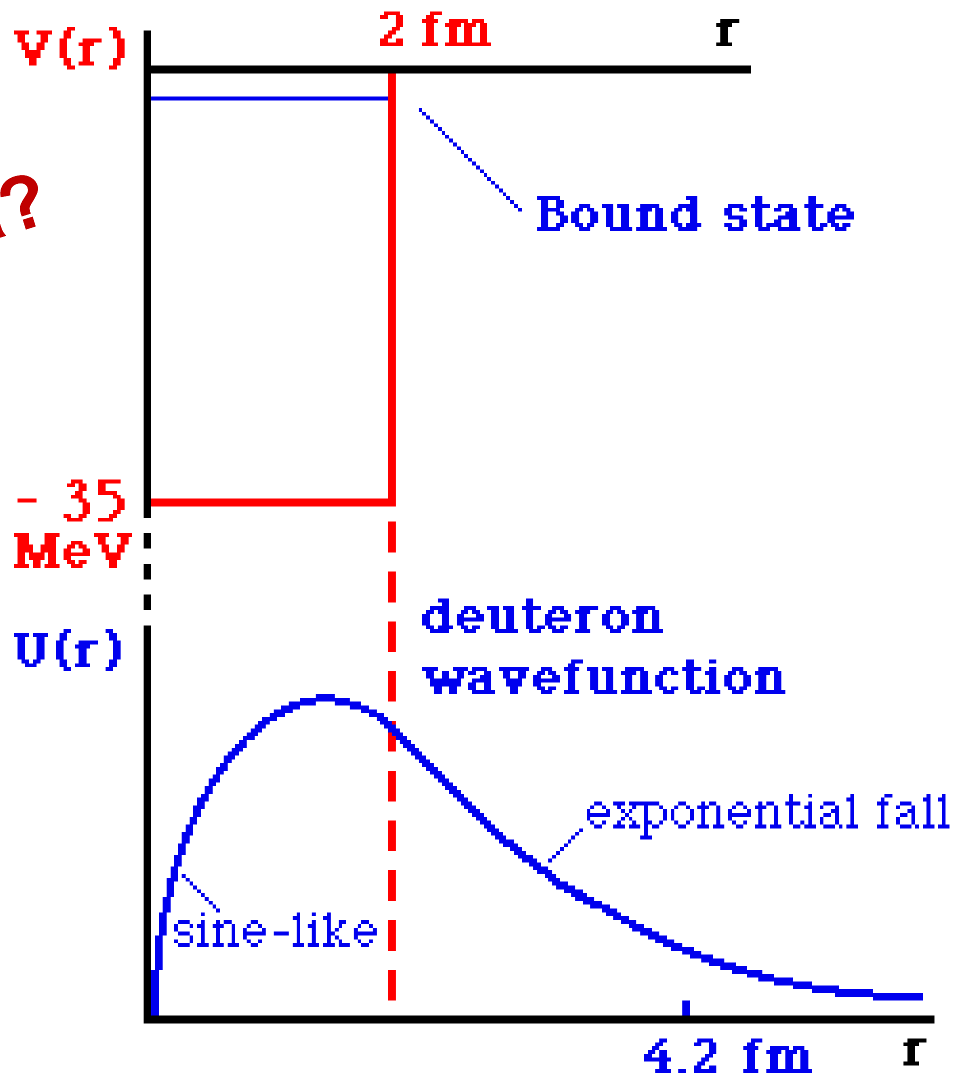
- Oversimplified.

Yukawa?

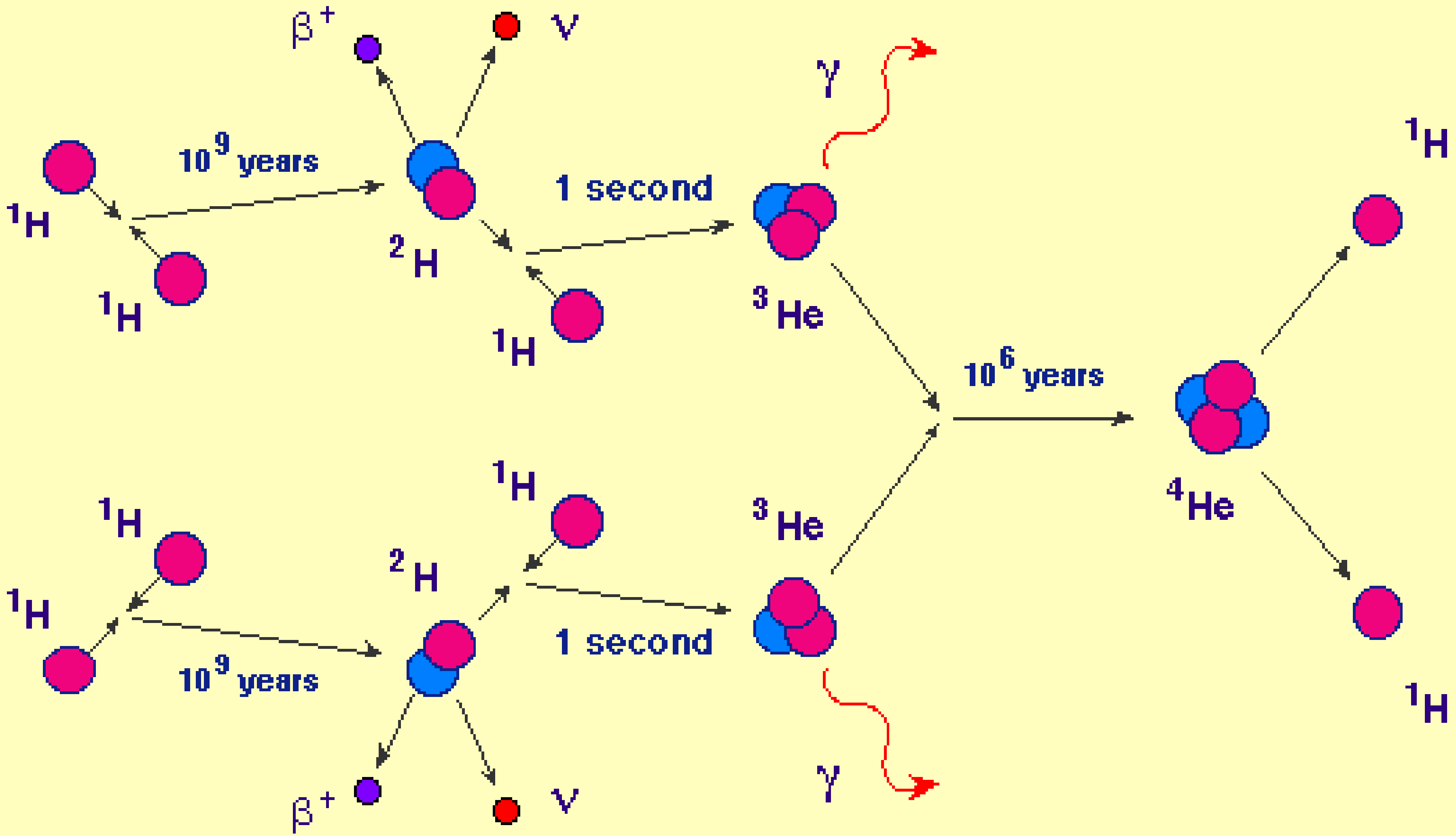
HW 13

Assuming $l = 0$, show that $V_0 \sim 35$ MeV. (Follow Krane Ch.4 and Problem 4.6), or similarly any other reference.

- Really weakly bound.
- What if the force were a bit weaker…?

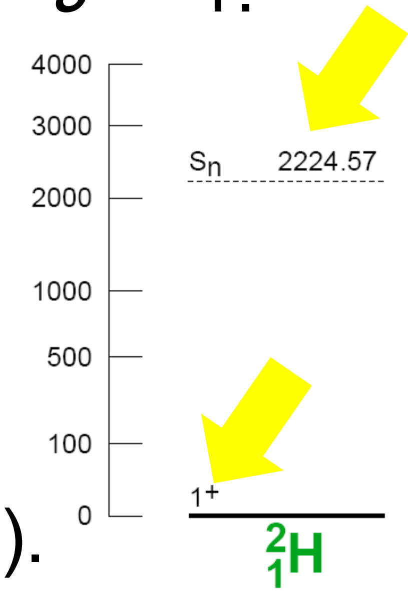


The Deuteron



The Deuteron

- Experiment ▶ deuteron is in triplet state ▶ J = 1.
- Experiment ▶ even parity.



- $J = l + s_n + s_p$ parity = $(-1)^l$
- Adding *spins* of proton and neutron gives:
  s = 0 (antiparallel) or s = 1 (parallel).
- For J = 1

parallel	*s*-state	even
parallel	*p*-state	odd
antiparallel	*p*-state	odd
parallel	*d*-state	even

The Deuteron

- Experiment ▶ $\mu = 0.8574376\ \mu_N$ ▶ spins are aligned…..But.?
- Direct addition ▶ $0.8798038\ \mu_N$.
- Direct addition of spin components assumes *s*-state (no orbital component).
- Discrepancy ▶ *d*-state admixture.

Non-central component

$$\psi = a_0\psi_0 + a_2\psi_2$$

$$\mu = a_0^2\mu_0 + a_2^2\mu_2$$

In solving HW 13 you assumed an *s*-state. How good was that assumption?

The Deuteron

- S-state ▶ No quadrupole moment.
- Experiment ▶ +0.002860 b.

- From μ and Q, is it really admixture?
- What about other effects?