Elementary Particles ~ 1932:

proton	$m \cong 1.7 \times 10^{-27}$ kg.	$Q = +e$	${}^1_1p_1$
neutron	$m \cong 1.7 \times 10^{-27}$ kg	$Q = 0$	${}^1_0n_9$
electron	$m = 9.1 \times 10^{-31}$ kg	$Q = -e$	${}^0_{-1}e$

Convention:

unified mass unit, u or "Atomic Mass Unit"

$\exists$ ${}^{12}C$ is exactly 12 u

so $1u = 1.660559 \times 10^{-27}$ kg. $= 931.5\ MeV/c^2$

$m_p = 1.007276\ u$

$m_n = 1.008665\ u$) bigger

$m_e = 0.000549\ u$

and, as you know:

$m_p c^2 = 938.28$ MeV

$m_n c^2 = 939.57$ MeV

$m_e c^2 = 0.511$ MeV

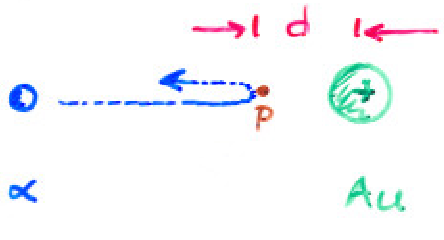
So, neutrons and protons... how many?

element	A	Z	N
$^{1}_{1}H$	1	1	0
$^{4}_{2}He$	4	2	2
$^{7}_{3}Li$	7	3	4
$^{9}_{4}Be$	9	4	5
$^{12}_{6}C$	12	6	6
$^{16}_{8}O$	16	8	8
$^{23}_{11}Na$	23	11	12
$^{27}_{13}Al$	27	13	14
$^{35}_{17}Cl$	35	17	18
$^{56}_{26}Fe$	56	26	30
$^{63}_{29}Cu$	63	29	34
$^{108}_{47}Ag$	108	47	61
$^{197}_{79}Au$	197	79	118
$^{208}_{82}Pb$	208	82	126
$^{238}_{92}U$	238	92	146

Sizes and shapes of Nuclei

Hard to not think of them as little spheres -- or bundles of spheres --

Remember, Rutherford's scattering early on estimated the "size" ⇒ appreciable extent of + charge repulsion of Gold.



at the turning point P, the kinetic energy of the α would be instantaneously all electrostatic repulsive potential

$$\frac{1}{2}mv^2 = \frac{1}{4\pi\epsilon_0}\frac{Q_\alpha Q_{Au}}{r}$$

$$= \frac{1}{4\pi\epsilon_0}\frac{(2e)(Ze)}{d}$$

$$d = \frac{4}{4\pi\epsilon_0}\frac{Ze^2}{mv^2} \sim 3.2\times10^{-14}\,\mathrm{m}$$

⇒ Au nucleus is smaller than that

For Ag... he found 2×10^{-14} m.

Concluded that the "nucleus" was $\sim 10^{-14}$ m

New Unit:

femtometer (fm)

$1\text{ fm} = 10^{-15}$ m

also called the "Fermi"

Many experiments since show roughly:

$$R = r_0 A^{1/3}$$

where $r_0 = 1.2\times10^{-15}$ m.

Density...

Assume nucleus is spherical, what's the density of nuclear "matter"?

$V = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi r_0^3 A$ $\qquad V \propto A$ ✓

$\rho = \frac{M}{V} = \frac{Am}{\frac{4}{3}\pi r_0^3 A} = \frac{3m}{4\pi r_0^3}$ $\qquad m \doteq m_p \doteq m_n \sim 1.67\times10^{-27}$ kg

$\rho = 2.3\times10^{17}$ kg/m^3 $\sim 2\times10^{14}$ more dense than water.

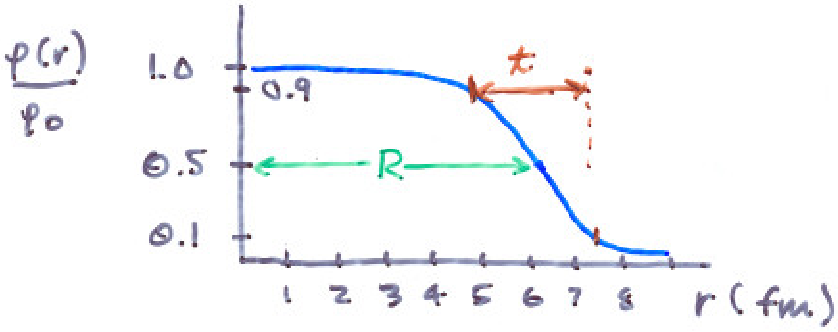
$\sim$ the density of a neutron star

Prob 9.35: $\sim10^{18}$ kg/m^3

Refinements in beam projectiles led to a long program of <u>electron</u> scattering at the Stanford Linear Accelerator Center .. SLAC

The charge distribution ..

for a representative nucleus, $Z \sim 50$



ρ_0 : central charge density

t : a definition of the "surface"

$$\rho(r) = \frac{\rho_0}{1 + e^{(r-R)/a}}$$

$t = 4.4a$

reasonable for $Z \gtrsim 10$

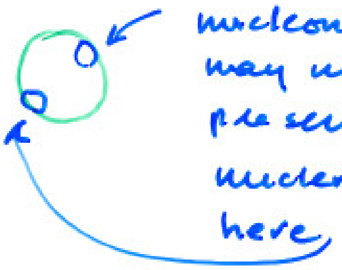
looks like F_{FD} and is indeed called the "Fermi Distribution"

Did you notice ...

$$R \propto A^{1/3} \quad \Rightarrow \quad \rho \text{ is independent of } A.$$

This suggests that as A goes up, the density does not.

And this suggests that the "nuclear force" is of very short range



nucleons over here may not feel the presence of nucleons over here

$\Rightarrow$ the forces of attraction between

n-p

n-n

p-p

are all about the same ...

Keeps nuclei very compact, but still growing with A.

Implies the force to remove a p or n is very strong.

Nuclear spin

Nuclei have a quantum mechanical spin: "I"

can be half-integer or integer.

recall that ^{4}He acts like a boson

and condenses...

^{3}He in fact is a fermion...

and does <u>not</u> condense.

As usual:

$$|\vec{I}| = \hbar\sqrt{I(I+1)}$$

So... nuclei have magnetic moments

new unit: "nuclear magneton"

$$\mu_N \equiv \frac{e\hbar}{2m_p} = 5.05\times10^{-27}\,J/T$$

$$\ll \mu_B$$

$\mu_p = 2.7928\,\mu_N$

BUT:

$\mu_n = -1.9135\,\mu_N$!

neutron is neutral...
but has a magnetic
moment ⇒ structure.

So, apply a field to a nucleus...

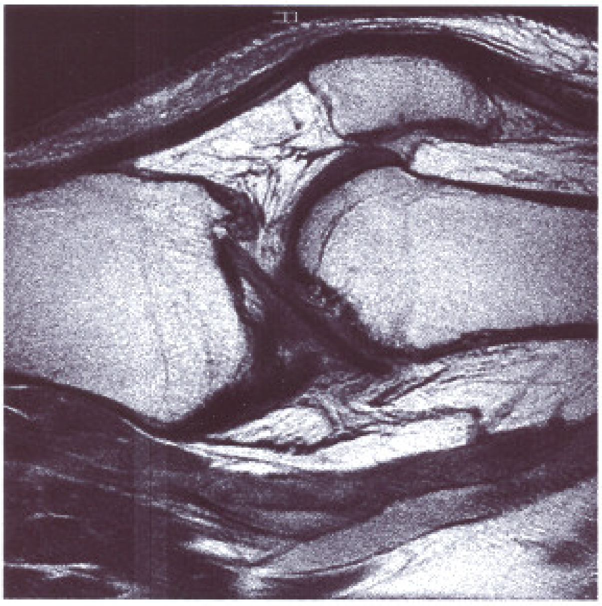
get a level splitting and μ precession

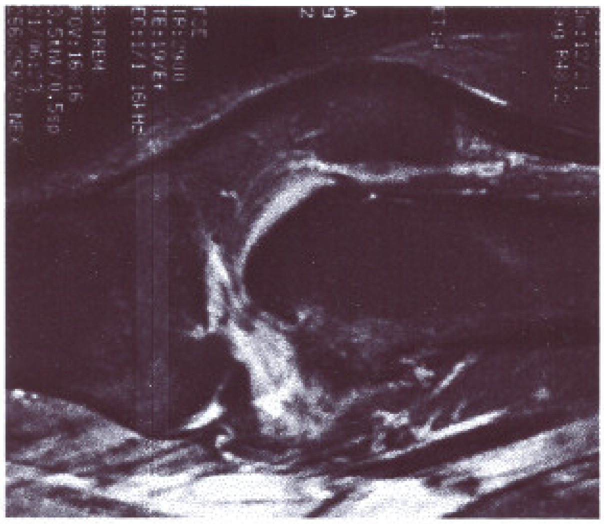
for $I = 1/2$
nucleus.

Boltzmann tells us:

$$\frac{N_{up}}{N_{dn}} = e^{-(E_{up} - E_{dn})/kT}$$

so this population difference can be exploited.





"Nuclear Magnetic Resonance", NMR

... became softened to "Magnetic Resonance Imaging",
MRI

Nuclear Forces and Binding

Referred to this many times...

That 2 protons can come together and bind, overcoming their electrostatic repulsion suggest a STRONG force... called:

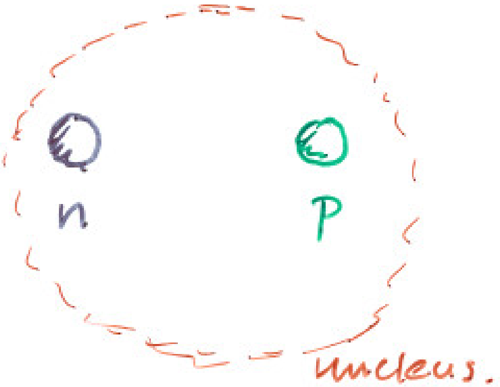
the strong force.

(or historically, the nuclear force)

In fact, nuclei are not just protons

neutrons are also contributors to the total attractive force of the nucleus.

A quantum "explanation" .. or at least "picture"



Suppose the neutron, of rest energy $m_n c^2$

emits another quantum of ΔE

How & still be a neutron & conserve energy?

Uncertainty

$$\Delta E \, \Delta t \sim \hbar$$

too short to be observed.

Energy violations over such a time scale? OK.

Consistent with our quantum mechanical worldview...

&

this game of catch is attractive - "Exchange Force"

Interpret $\Delta E = m_? c^2$

$$\Delta E \, \Delta t = \hbar$$

$$\Delta t = \frac{\hbar}{m_? c^2}$$ = ⇒ "shortest" time

how short? ... furthest it could travel is for $v_? \sim c$

$$x = c \Delta t$$

$$x = \frac{\hbar c}{m_? c^2}$$

So: $$m_? c^2 = \frac{\hbar c}{x}$$

what's a good x? ... confine it to be inside the nucleus before it disappears into an adjacent p (or n).

$$x \sim 1 \text{ fm} = 10^{-15} \text{ m}$$

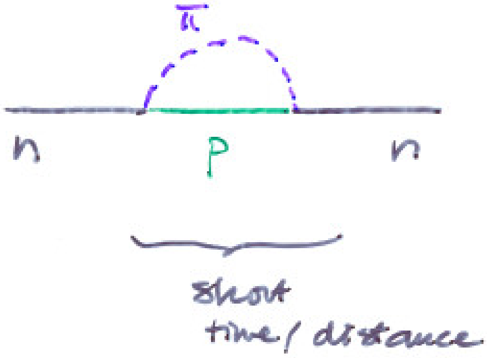
$$m_? c^2 = \frac{\hbar c}{10^{-15} \text{ m}} = \frac{197.3 \text{ eV}\cdot\text{nm}}{10^{-6} \text{ nm}} \simeq 200 \text{ MeV}$$

Predicted in 1935 by Hideki Yukawa

"Yukawa particle", "Y" ... now pion, π

Hideki Yukawa

1949



called "virtual particles"

more on this later...

Simplest nucleus ... ${}^{1}_{1}H$

Next simplest ... ${}^{2}_{1}H$ Deutrium

Remember the "$E=mc^2$ discussion" of H ?

$$m_e c^2 + m_p c^2 = m_H c^2 + \underset{\substack{\uparrow \\ \text{a mass deficit}}}{13.6 \text{ eV}}$$

$$m_e c^2 + m_p c^2 - m_H c^2 = B$$

called by chemists :-)

"Binding Energy"

to liberate e & p to freedom... must supply B.

Same for nuclear binding... but much bigger deal.