proton : uud $Q = \frac{2}{3} + \frac{2}{3} + -\frac{1}{3} = +1$

"valence" $j = 1/2$

neutron : udd $Q = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$

$j = \frac{1}{2}$

But : $m_p c^2 = 938$ MeV

$2 m_u c^2 + m_d c^2 = 6 + 7 = 13$ MeV

This is the biggest surprise, peculiarity ...

Resolution : most of the proton/neutron rest mass is not from u/d quarks, but due to their interaction.

That ("chromodynamic") interaction is EXTREMELY STRONG. How do we know?

$$\underbrace{1\ \text{fm}}_{\text{nucleon size}} \simeq \frac{\overbrace{\hbar c}^{\simeq 200\ \text{MeV}\cdot\text{fm}}}{\underbrace{m_q c^2}_{\simeq 5\ \text{MeV}}} \cdot \underbrace{\text{"}\frac{1}{\alpha_s}\text{"}}_{\text{strong interaction}}$$

$$1\ \text{fm} = 40\ \text{fm}\ \frac{1}{\alpha_s}$$

$$\boxed{\alpha_s = 40 \, !} \quad \left(\frac{e^2}{\hbar c} = \alpha_{em} = \frac{1}{137} \right)$$

($\frac{e^2}{\hbar c}$: e+m)

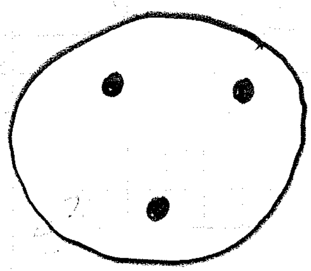
↓

boy, does this make things interesting

Structure of the nucleon ("old")

"valence" approximation

spin-$\frac{1}{2}$



~1 fm

3 quarks

uud or udd

uuu, ddd not allowed by Pauli

1. Quarks are relativistic.

(a) if they were confined just to their λ_c ...

$$\Delta x \, \Delta p \sim \tfrac{1}{2}\hbar \quad (\text{U.P.})$$

if $\Delta x = \frac{\hbar}{mc}$

then $\frac{\hbar}{mc} \cdot \Delta p \sim \frac{1}{2}\hbar$

$$\Delta p \sim \tfrac{1}{2} mc$$

... getting relativistic!

(b) 5 MeV quark ... in nucleus ...

$$\Delta x \sim \frac{1}{40} \lambda_c$$

$\Delta p \sim 40 \cdot \frac{1}{2} mc \sim 20 mc$

~ 100 MeV

very relativistic!

Strong force $\alpha_s = 40 \gg \alpha_{em} = \frac{1}{137}$

$\uparrow$ $\frac{e^2}{\hbar c}$

Hydrogen NOT Relativistic

Quarks Very Relativistic.

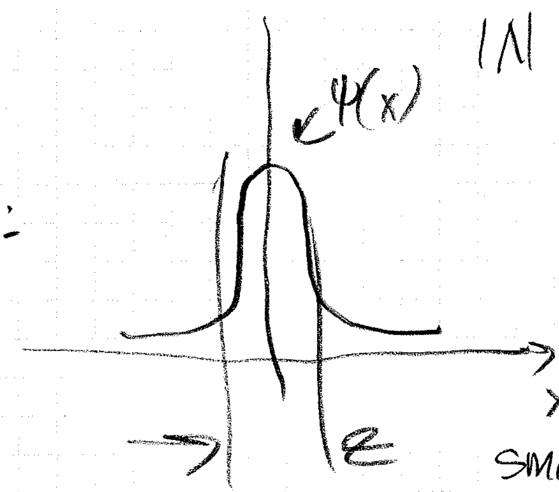
(c) **Zitterbewegung** (Trembling Motion)

Describing particle/waves that are confined to $< \lambda_c$

DEMANDS ANTIPARTICLES

(just particles...
NOT A COMPLETE SET
IN THE HILBERT
SPACE).

e^-:



small $\ll \frac{\hbar}{m_e c} = \frac{\hbar c}{m_e c^2} = \frac{200}{0.5}$

$= 400$ fm

$\psi(x) = \sum a_i \psi_i(\text{electron}) + \sum b_i \psi_i(\text{positron})$

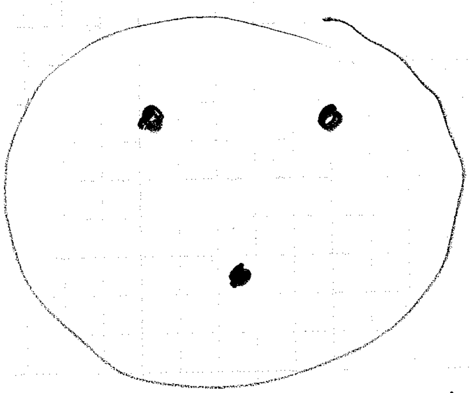
Antimatter: mass same as matter (CPT Theorem)

lifetime "

Additive quantum #'s **opposite**

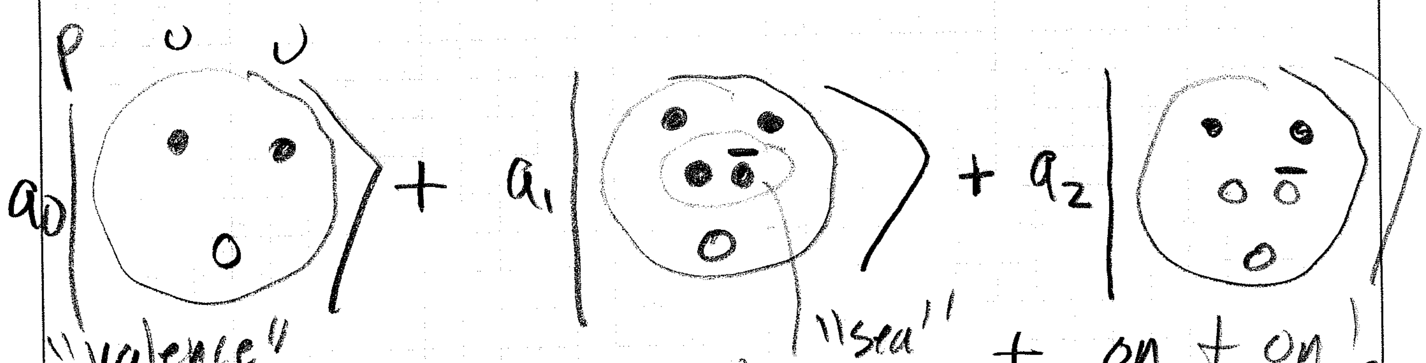
- electric charge.
- lepton number (?)

There are antiquarks in nucleons. (!!!!)



too simple.

"Ground State" Really superposition



+ on + on!

$\bar{o}$: $\bar{u}$ quark

electric charge $-2/3$

② LHC (Large Hadron Collider)

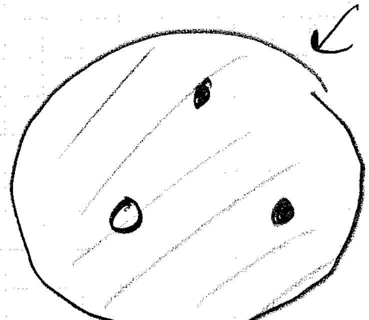
p $E \simeq cp \simeq$ 7 TeV (10^{12} eV) p 7 TeV

↑ ↑

a u quark $\bar{u}$ quark

Sometimes, matter + antimatter meet, even though to the casual observer, it's a matter/matter collider!

③ The GLUE



quarks like ball bearings in "gelatin"

↑ called ($\simeq$1970) the "glue" (what is it??)

How... imagine trying to pull a quark out of a nucleon.

Terminology :

Baryon : 3 quarks (valence)
(Antibaryon 3 antiquarks)

Meson : 1 quark, 1 antiquark } always unstable

1 Baryon (the Proton) is stable, the rest unstable.

Given a choice of quarks/antiquarks, still must specify total angular momentum (spin + orbital).

Proton/Neutron : L = 0 (no orbital)

Spin : ↑↑↓

3 spin-$\frac{1}{2}$ ...

which one? LATER.

u u u
↑ ↑ ↓ } gets into Pauli Principal Issues!