# Proton structure—historical view

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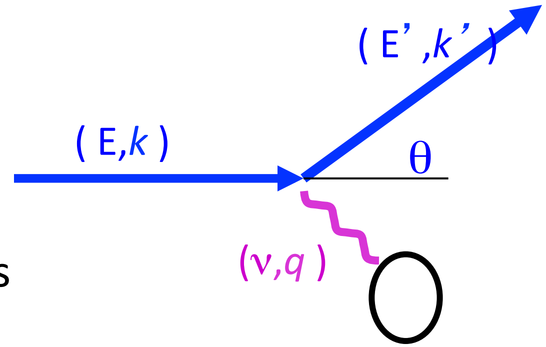
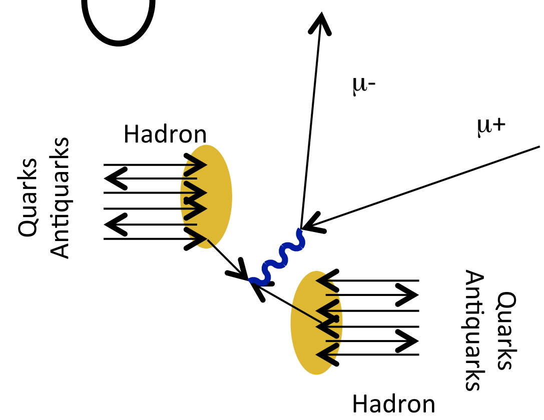
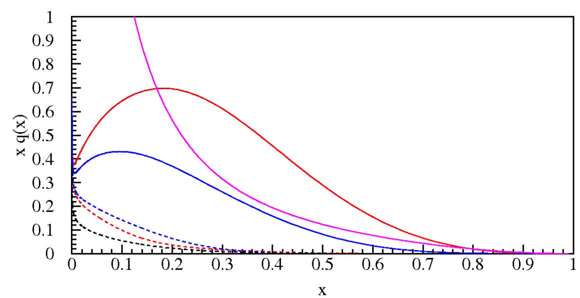



Really—two separate topics unified by my interests

I. Flavor Structure of the Proton
   A. Proton structure—historical view
      1. Historical overview: Nuclei to nucleons to quarks
      2. "Traditional" picture of nuclear physics (hadrons)
      3. QCD picture of nuclear physics (quarks & gluons)
      4. How is the flavor structure determined?
   B. Sea quarks in the proton & the Drell-Yan reaction
   C. Proton structure in nuclei



# Pre-history of Nuclear Physics


Ancient Tradition: Basic Elements (see, *e.g.* ParticleAdventure.org):

- ca. 450 BC, Greece (**Empedocles**) Earth, Air, Fire and Water
- ca. 200-300 AD, India (**Samkhya-karikas** by Ishvarakrsna) Space, Air, Fire, Water, and Earth.
- Chinese (in Pinyin, *Wu Xing*) Earth, Wood, Metal, Fire, and Water

Indivisible Unit: The Atom

- BC 600's in India the concept of smallest piece of mater developed
- BC 450 Democritus used the term ατομοσ or atom for this

Empty Space: Rutherford scattering

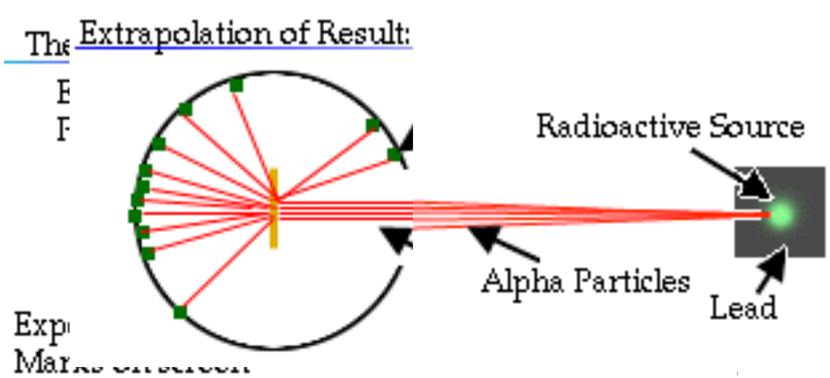
- 1909: Small hard core surrounded by empty space
- Expected small scattering through diffuse material but saw occasional large angle scattering

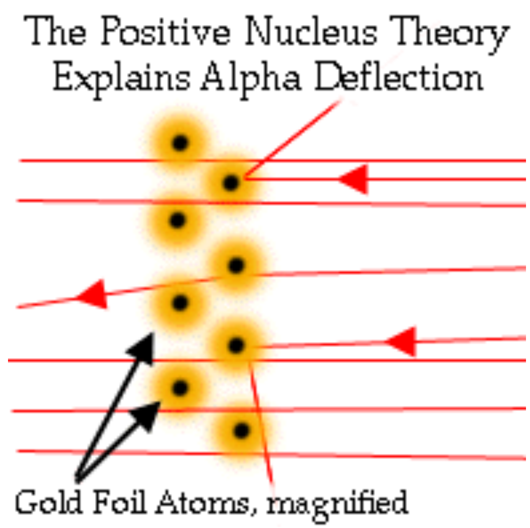
- Actual measurements may by **Hans Geiger** and **Ernest Marsden**—under Rutherford's supervision

# Rutherford's Atom


LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* *By* Professor E. RUTHERFORD, *F.R.S., University of Manchester* *.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle.

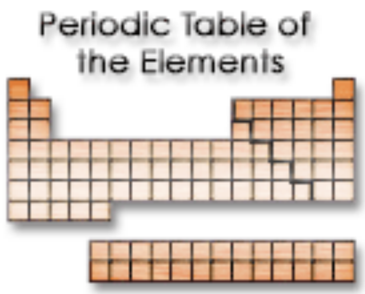



Graphics: ParticleAdventure.org

Interpreted data as a positively charged core with negatively charged electron cloud, partially based on the low mass of the electron

# Other Particles




Neutron

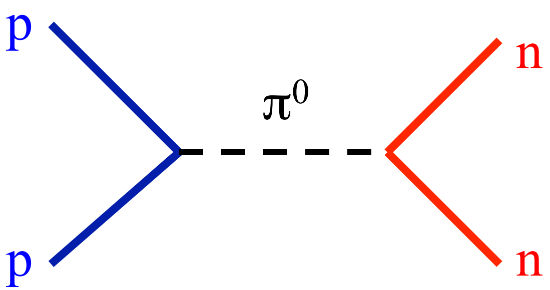
- 1920 existence speculated on by Rutherford
- 1932 discovered by Chadwick

Now we could explain the periodic table

except that something had to hold the positively charged core together

First attempt:

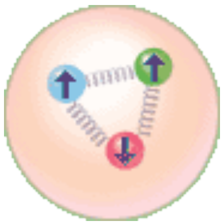
- Yukawa's original idea—nucleons interact by exchanging massive particles (mesons)


- Range ≅ $c\Delta t$ ≅ $h/2mc$ ≅ 1fm or m ≅100 MeV for the lightest meson (the pion)
- The pion was discovered in 1947 by Cecil Powell, confirming Yukawa's prediction

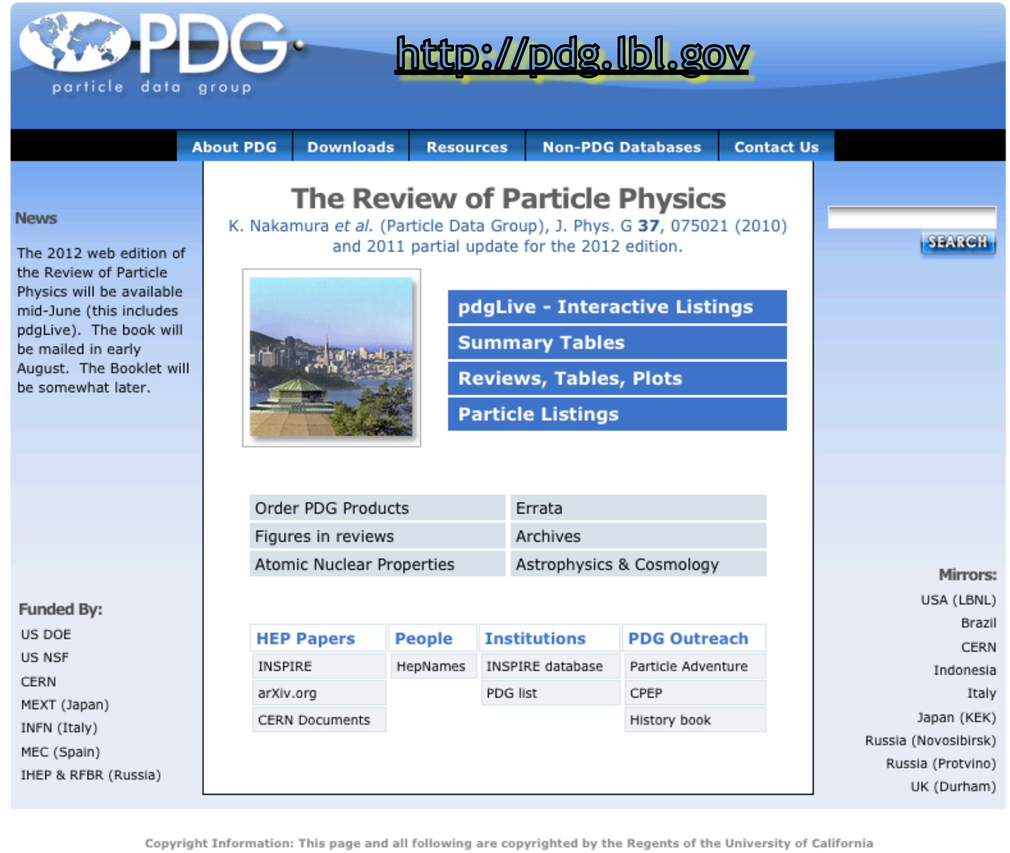
The discovery of the pion was followed by an explosion of particle discoveries (1947-1960s)

This Led Gell-Mann and Zweig introduce quarks to organize the spectrum (particle zoo).



$\Delta^{++}$ (u,u,u) ⇨ additional quantum number (color)

Provides classification scheme for observed particles, properties and decays. (See for example, Halzen and Martin.)

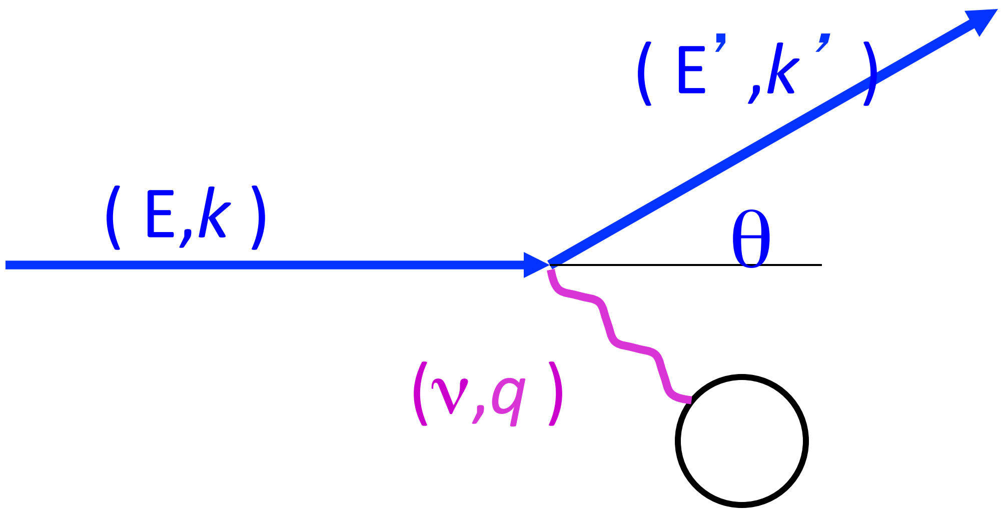



But, how do we know* that there is substructure to the proton?

*As an experimentalist, I claim we don't "know" something until we measure** it

**Measurements are subject to mistakes and data is subject to interpretation.

# Inclusive Scattering: Kinematics




Measure:

E, E', $\theta$

Reconstruct virtual photon:

$\nu = E - E'$ (energy transfer)

$q = k - k'$ (momentum transfer)

$Q^2 = q^2 - \nu^2 = 4EE' \sin^2(\theta/2)$

$x = Q^2 / 2M\nu$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm point} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott}$$

$$= \frac{(Z\alpha)^2 E^2}{2k^4 \sin^4 \frac{\theta}{2}} \left(1 - \frac{k}{E} \sin^2 \frac{\theta}{2}\right)$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm point} |F(q)|^2$$

Non-pointlike behavior kept in structure function

See Perkins and/or Halzen & Martin

# The Standard Model

**BOSONS** force carriers spin = 0, 1, 2, …

| Unified Electroweak spin = 1 | | |
|---|---|---|
| Name | Mass GeV/c$^2$ | Electric charge |
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.4 | –1 |
| $W^+$ | 80.4 | +1 |
| $Z^0$ | 91.187 | 0 |

| Strong (color) spin = 1 | | |
|---|---|---|
| Name | Mass GeV/c$^2$ | Electric charge |
| g gluon | 0 | 0 |

Problem:

- Quarks and gluons make up the bulk of the matter, but do not appear as relevant can never be "seen"!

**FERMIONS** matter constituents spin = 1/2, 3/2, 5/2, …

| Leptons spin = 1/2 | | |
|---|---|---|
| Flavor | Mass GeV/c$^2$ | Electric charge |
| $\nu_e$ electron neutrino | $<1\times10^{-8}$ | 0 |
| e electron | 0.000511 | –1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | –1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |
| $\tau$ tau | 1.7771 | –1 |

| Quarks spin = 1/2 | | |
|---|---|---|
| Flavor | Approx. Mass GeV/c$^2$ | Electric charge |
| u up | 0.003 | 2/3 |
| d down | 0.006 | –1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | –1/3 |
| t top | 175 | 2/3 |
| b bottom | 4.3 | –1/3 |

Graphics: ParticleAdventure.org

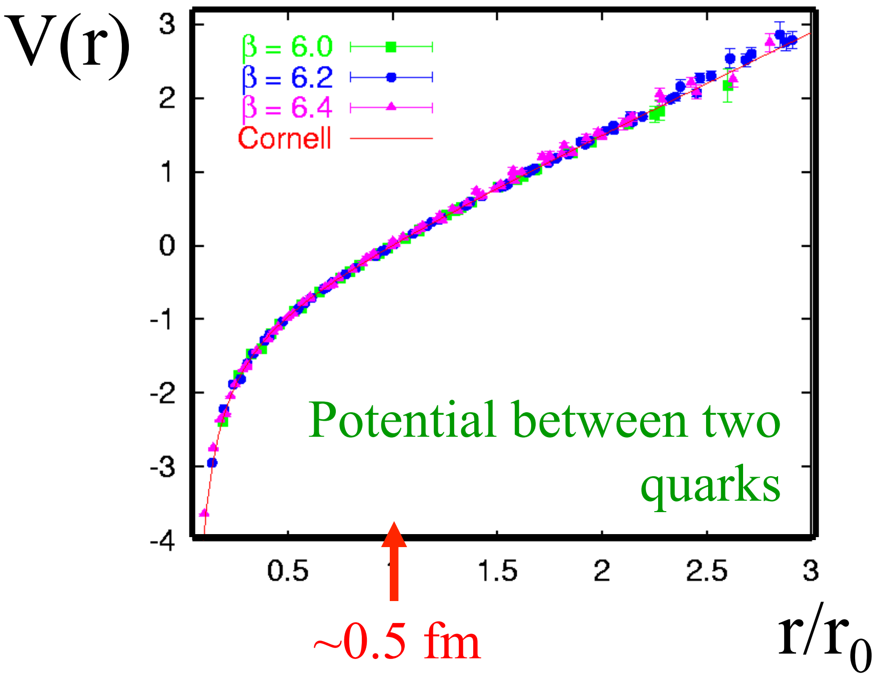
# Aside: Do Quarks really exist?
# Two "Realms" of Nuclear Physics

Quantum Chromo Dynamics (QCD): The fundamental theory describing the strong force in terms of quarks and gluons carrying color charges.

Strongly attractive at all distances.

1 GeV/cm → *18 tons*

$>10^{12}$ times the Coulomb attraction in hydrogen




Slide from John Arrinton

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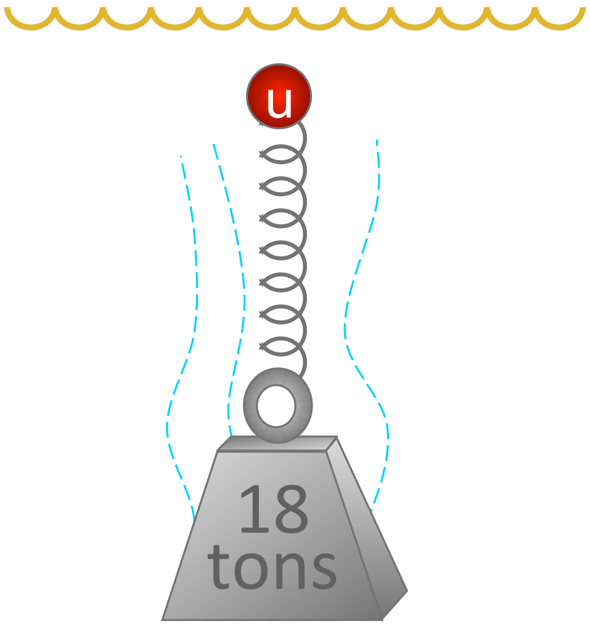
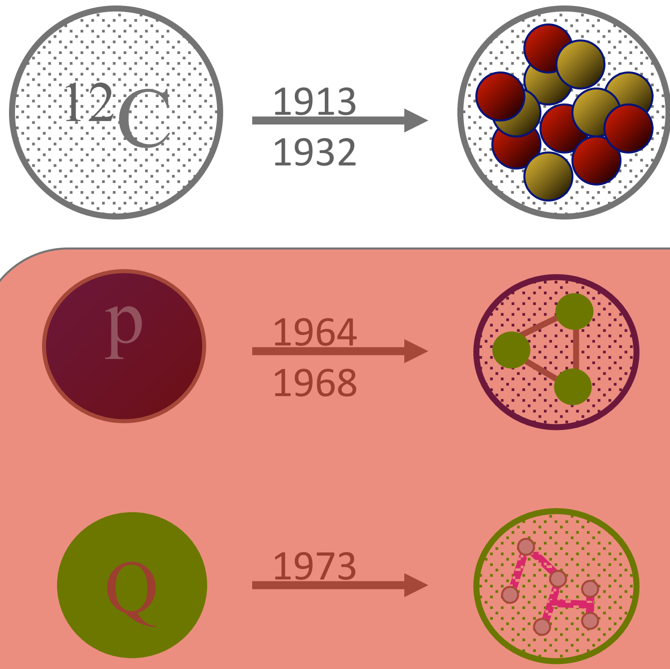



Slide from John Arrinton

# Summary (last 100 years)



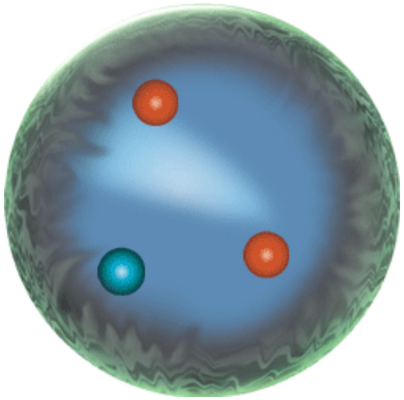

Nucleus = protons + neutrons + strong interaction of hadrons

proton = Constituent Quarks + strong interaction of Quarks

Constituent Quark = quarks + gluons + strong interaction of QCD

Nearly a century of nuclear physics has shown that a ***NUCLEUS*** can be well described in terms of protons, neutrons, the strong force, ***and nothing else***

# Review



- Protons, neutrons, pions, *etc* are composed of quarks bound together by gluons.
  - Hadrons are categorized by their quark content. For example the proton is uud, neutron is udd, $\pi^+$ is u anti-d
- Quark distributions are discussed in terms of $x_{Bj}$—representing the fraction of the hadron's momentum carried by that particular quark.
- It is possible to study (if we are arrogant, we say "measure") the quark probability distributions.