

THE INTERNAL STRUCTURE OF PARTICLES

FROM THE ATOM TO QUARKS

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July 7, 2026

LIP Summer Internship Lecture

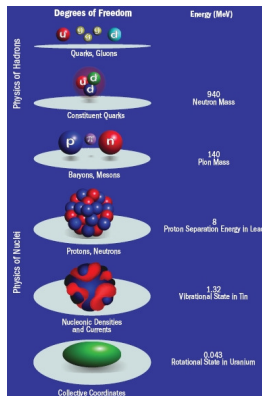


QUESTIONS

- How do we know whether a particle has internal structure?
- How did we discover nuclei, nucleons, and quarks?
- What do scattering experiments tell us about size, constituents, and their distribution?
- What exotic forms of matter exist?
- What remains unknown?

STRONGLY-INTERACTING MATTER MATTERS!

- Understanding the structure of matter connects
 - particle physics
 - hadronic physics
 - nuclear physics
 - astrophysics
- The **strong force** plays central role



Idea: Scattering as a microscope

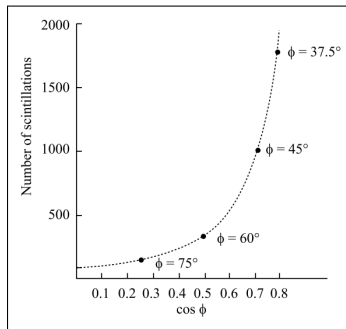
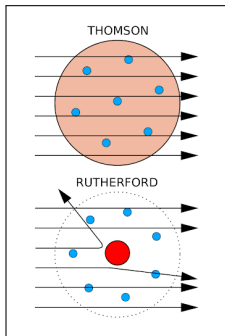
- To resolve a structure of a size distance, we need a probe with comparable or smaller de Broglie wavelength

$$\lambda = \frac{\hbar}{p}$$

- Larger momentum (energy) transfer means better spatial resolution.

STRUCTURE OF THE ATOM

- **Coulomb scattering** experiments by [Geiger and Marsden 1909](#):
 α particles reflected by thin gold foil also under **large** scattering angles ϕ



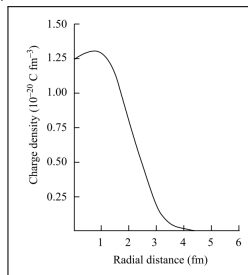
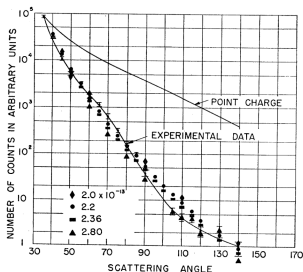
- [Rutherford 1911](#):
 - $\exists$ a 'hard constituent' – a small, massive, positively-charged **nucleus**
 - explains data through famous law for differential cross section:

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\sin^4 \phi/2}$$

- **Question**: Is the nucleus pointlike?
- **Experiment**: Scatter something from it!

STRUCTURE OF THE NUCLEUS

- Hofstadter et al. 1950's: Electron-gold elastic Coulomb scattering
- For pointlike charge expect Rutherford/Mott cross section



Carbon-12 nucleus

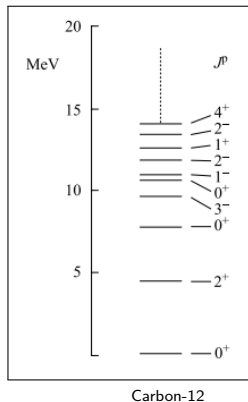
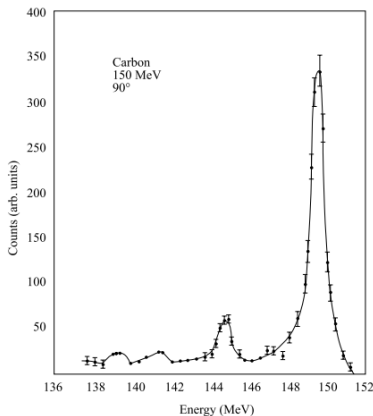
- **Observed:** **deviation** from pointlike expectation
For extended charge distribution: cross section modified by **form factor**

$$\left(\frac{d\sigma}{d\Omega} \right)_{\text{measured}} = \left(\frac{d\sigma}{d\Omega} \right)_{\text{pointlike}} |F(q^2)|^2$$

- $F(q^2)$ contains information about the spatial charge distribution
 $\Leftrightarrow$ nucleus has **finite size** with radius $\gtrsim 1 \text{ fm} = 10^{-15} \text{ m}$
- **Question:** Is the nucleus made out of constituents?
- **Experiment:** Scatter something **inelastically** from it!

ENERGY LEVELS

- Elastic scattering: nucleus remains in ground state
- **Inelastic** electron-nucleus scattering: nucleus is excited
- **Peaks** only at certain energies

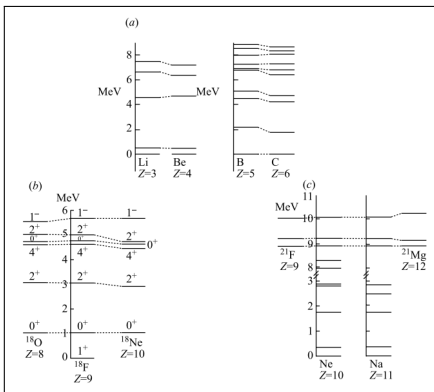


Fregeau; Hofstadter 1955

- Nuclei have discrete or **quantized** energy states

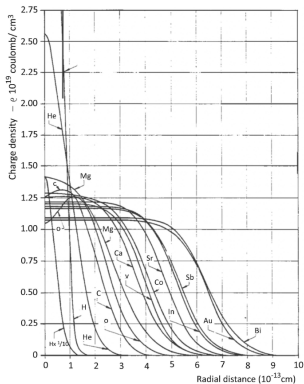
NUCLEONS AND THE STRONG FORCE

- Energy spectra from internal quantized motion of A nucleons:
 Z **protons** + N **neutrons**
- **Question:** What is the nature of the strong nuclear force between them?



- Nuclear force must be
 - almost **charge-independent**
 - **much stronger** than electromagnetic force to overcome proton repulsion
- **Question:** How are the protons and neutrons distributed inside nuclei?

DISTRIBUTION OF NUCLEAR CHARGE

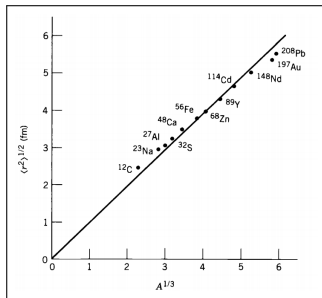


Original figure Hofstadter et al. 1955

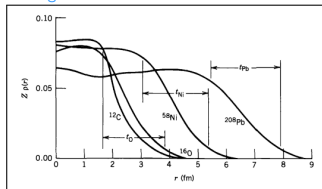
Central nuclear **charge densities**
similar for many nuclei

$$\rho_0 \sim \frac{A}{\frac{4}{3}\pi R^3} \approx \text{const.}$$

$$\Rightarrow R = R_0 A^{\frac{1}{3}} \text{ with } R_0 \approx 1.25 \text{ fm}$$



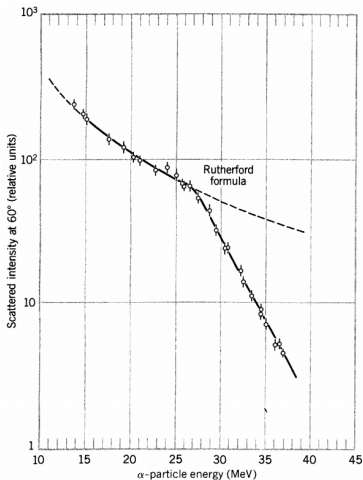
De Jager et al. 1974



Barrett, Jackson 1977

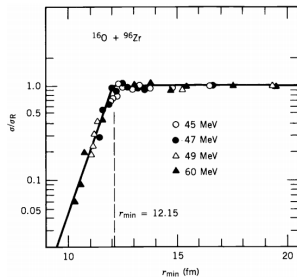
Skin thickness roughly **similar** for
many nuclei ($\approx 2.3 \text{ fm}$)

DISTRIBUTION OF NUCLEAR MATTER



Eisberg, Porter, 1961

- Electron scattering mostly probes charge (protons)
- α scattering also sensitive to nuclear matter distribution: with increasing energy α 's get closer to nucleus and interact also through **nuclear force** $\Rightarrow$ **short range**
- Get size of **nuclear matter distribution**



Christensen et al. 1973

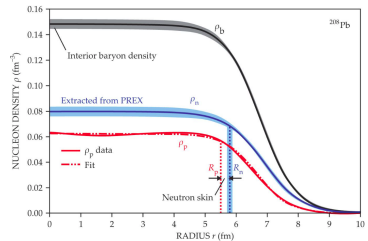
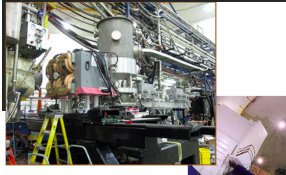
Question: How are the neutrons distributed inside nuclei?

Experiment: Polarized electron scattering!

Physicists Measure the Skin of a Nucleus

If improved, study could have major implications for physics of neutron stars

2 MAR 2012 - BY SCIENCE 100

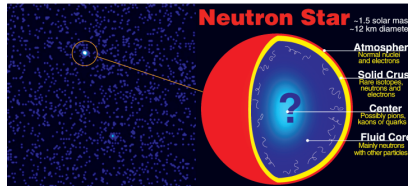


PREXII, CREX at Jefferson Lab 2021, 2022

- Polarized electron scattering: electrons interact with neutrons via weak nuclear force $\Rightarrow$ get **neutron distribution**
- **Simple picture:** Large neutron-rich nucleus is like a chocolate truffle, filling of protons and neutrons with **neutron shell**

$$\Delta R_{np} = R_n - R_p \approx 0.28 \text{ fm} \quad (\text{for } ^{208}\text{Pb})$$

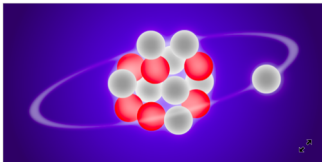
- **Astrophysical implications:**
 - **r-process:** production of heavy elements inside exploding stars
 - **neutron stars**



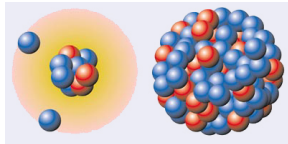
Targeting a Nuclear Halo

January 4, 2023 • Physics 16, s2

New modeling explains the relatively high fusion reaction probabilities of halo nuclei, which are composed of a dense core surrounded by a "satellite" of one or two nucleons.

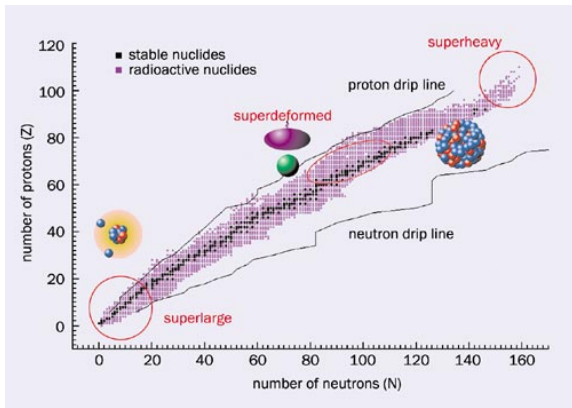


APS/Alan Stonebraker



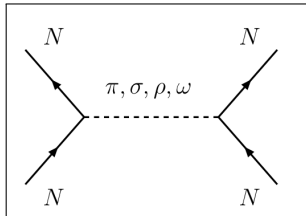
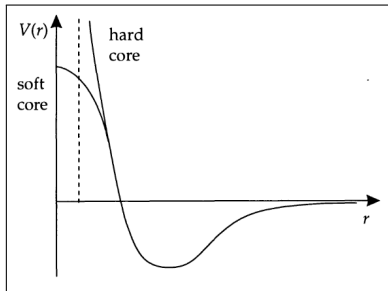
^{11}Li

^{208}Pb



NUCLEON-NUCLEON INTERACTION

- **Short range:** Deviations from Rutherford formula at high energies shows that nuclear force is short-range ~ 2 fm
- **Attraction:** Nuclear binding requires attraction at distances around 1-2 fm.
- **Repulsive core:** Saturation of nuclear density suggests a repulsive core at short distances that keeps nucleons separated
- **Meson exchange:** Interaction between 2 nucleons described by exchange of mesons $\pi, \sigma, \rho, \omega, \dots$

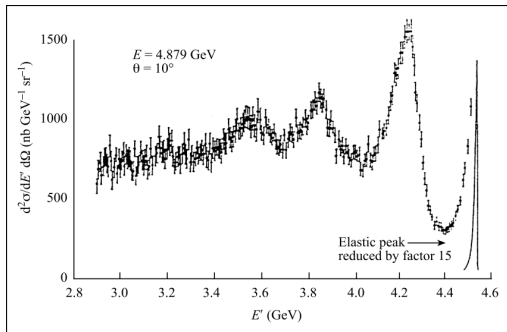


Question: Is the nucleon pointlike?

Experiment: Scatter electrons elastically from it!

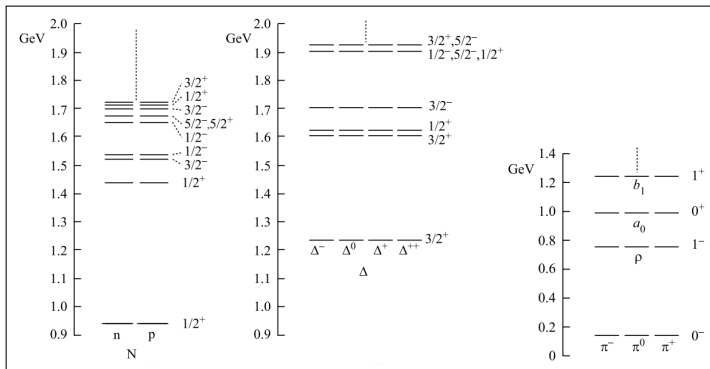
STRUCTURE OF THE NUCLEON

- **Elastic electron-nucleon scattering** (Hofstadter et al. 1963)
 - proton has form factor and charge distribution with radius ~ 0.8 fm
 - proton and neutron have magnetic moment distributions
 - $\Rightarrow$ nucleon is **not structureless**
- **Inelastic electron scattering:** Nucleon spectroscopy



- nucleon can be excited, first inelastic peak: **Delta resonance**
- resonances reveal internal motion of **constituents**

ENERGY SPECTRA OF HADRONS



Hadrons appear in families:

- The 2 nucleons form a **doublet**
- The 4 Delta resonances form a **quartet**
- The 3 pions form a **triplet**

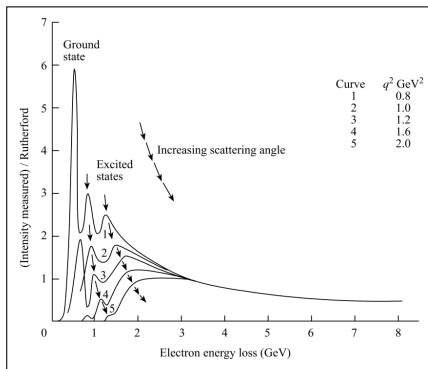
This regularity suggested an underlying '**quark structure**'

Question: What is the nature of this structure?

Experiment: Inelastic electron-proton scattering at large scattering angles!

QUARK MODEL

- Deep inelastic electron-proton scattering at **SLAC in 1968** showed **pointlike constituents** inside the proton
- Quark model:** **Gell-Mann, Zweig 1964**
 - Baryons (like N , Δ) contain three valence quarks
 - Mesons (like π) contain a quark and an antiquark
 - Up** and **down** quarks explain charges of proton and neutron



$$Q_u = \frac{2}{3}e, \quad Q_d = -\frac{1}{3}e, \quad Q_{\bar{u}} = -\frac{2}{3}e, \quad Q_{\bar{d}} = \frac{1}{3}e$$

$$p = uud, \quad n = udd, \quad \Delta^{++} = uuu, \quad \pi^+ = u\bar{d}$$

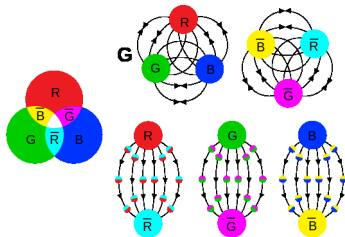
Flavour	up	down	charm	strange	top	bottom
Charge (e)	2/3	-1/3	2/3	-1/3	2/3	-1/3
Mass (MeV/c ²)	2	5	1273	93	172600	4186

COLOR CHARGE AND QCD

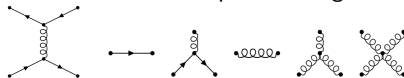
- The Δ^{++} contains 3 up quarks with spins aligned
- If quarks only had position, spin, and flavour, the Δ^{++} wave function would violate the Pauli principle
- Introduce a new quantum number: **color charges** Red, Green, Blue

$$\psi_{\Delta^{++}} = \frac{1}{\sqrt{4\pi}} \otimes |uuu\rangle \otimes |\uparrow\uparrow\uparrow\rangle \otimes \varepsilon_{\text{RGB}}$$

- Hadrons only observed as ('white') color singlets



Quantum Chromodynamics (QCD):
Fundamental theory of strong interaction between quarks and gluons



HADRONS AND MULTIQUARKS

Particle Data Group (PDG) 2026

~ 180 **Baryons:** qqq and $qqqq\bar{q}$

Proton Neutron

[illegible]

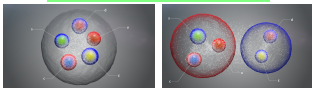
~ 230 **Mesons:** $q\bar{q}$ and non- $q\bar{q}$

Pions



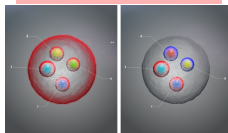
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(DST)		152DST (DST)		153DST (DST)		154DST (DST)		155DST (DST)		156DST (DST)		157DST (DST)		158DST (DST)		159DST (DST)		160DST (DST)		161DST (DST)		162DST (DST)		163DST (DST)		164DST (DST)		165DST (DST)		166DST (DST)		167DST (DST)		168DST (DST)		169DST (DST)		170DST (DST)		171DST (DST)		172DST (DST)		173DST (DST)		174DST (DST)		175DST (DST)		176DST (DST)		177DST (DST)		178DST (DST)		179DST (DST)		180DST (DST)		181DST (DST)		182DST (DST)		183DST (DST)		184DST (DST)		185DST (DST)		186DST (DST)		187DST (DST)		188DST (DST)		189DST (DST)		190DST (DST)		191DST (DST)		192DST (DST)		193DST (DST)		194DST (DST)		195DST (DST)		196DST (DST)		197DST (DST)		198DST (DST)		199DST (DST)		200DST (DST)		201DST (DST)		202DST (DST)		203DST (DST)		204DST (DST)		205DST (DST)		206DST (DST)		207DST (DST)		208DST (DST)		209DST (DST)		210DST (DST)		211DST (DST)		212DST (DST)		213DST (DST)		214DST (DST)		215DST (DST)		216DST (DST)		217DST (DST)		218DST (DST)		219DST (DST)		220DST (DST)		221DST (DST)		222DST 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(DST)		294DST (DST)		295DST (DST)		296DST (DST)		297DST (DST)		298DST (DST)		299DST (DST)		300DST (DST)		301DST (DST)		302DST (DST)		303DST (DST)		304DST (DST)		305DST (DST)		306DST (DST)		307DST (DST)		308DST (DST)		309DST (DST)		310DST (DST)		311DST (DST)		312DST (DST)		313DST (DST)		314DST (DST)		315DST (DST)		316DST (DST)		317DST (DST)		318DST (DST)		319DST (DST)		320DST (DST)		321DST (DST)		322DST (DST)		323DST (DST)		324DST (DST)		325DST (DST)		326DST (DST)		327DST (DST)		328DST (DST)		329DST (DST)		330DST (DST)		331DST (DST)		332DST (DST)		333DST (DST)		334DST (DST)		335DST (DST)		336DST (DST)		337DST (DST)		338DST (DST)		339DST (DST)		340DST (DST)		341DST (DST)		342DST (DST)		343DST (DST)		344DST (DST)		345DST (DST)		346DST (DST)		347DST (DST)		348DST (DST)		349DST (DST)		350DST (DST)		351DST (DST)		352DST (DST)		353DST (DST)		354DST (DST)		355DST (DST)		356DST (DST)		357DST (DST)		358DST (DST)		359DST (DST)		360DST (DST)		361DST (DST)		362DST (DST)		363DST (DST)		364DST 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Pentaquarks: $qqqq\bar{q}$



Observed by LHCb 2015

Tetraquarks: $qq\bar{q}\bar{q}$

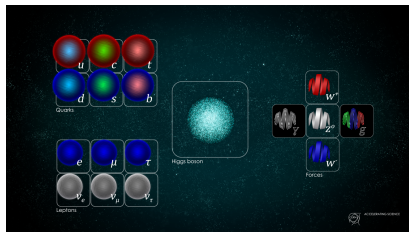
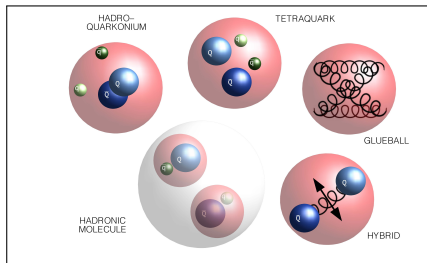


Observed by LHCb 2016

HADRON STRUCTURE – OPEN QUESTIONS

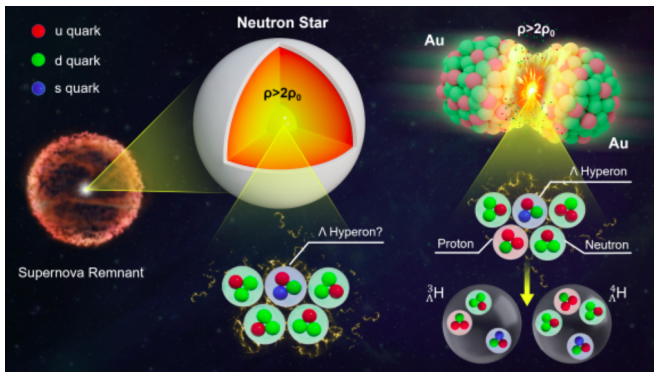
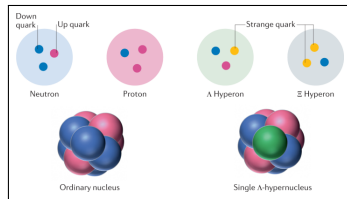
- Do quarks cluster inside an exotic hadron or is it a compact multiquark state?
- Do glueballs and hybrid mesons exist as identifiable states?
- Are quarks and leptons elementary?

Current experiments find **no evidence** that quarks, leptons, gauge bosons, or the Higgs boson are composite.

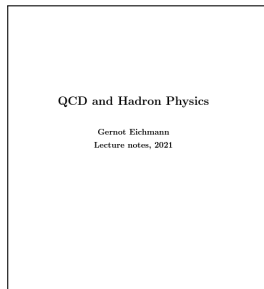
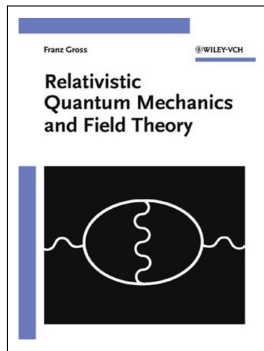
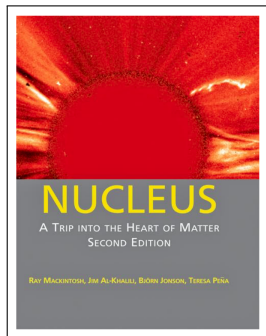


NUCLEAR STRUCTURE – OPEN PROBLEMS

- Can we derive NN-interaction directly from QCD?
- What are the properties of hypernuclei?
- How do hyperons interact with nucleons?
- Do hyperons appear inside neutron stars?



LITERATURE FOR FURTHER INFORMATION



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<https://doi.org/10.1140/epjc/s10052-023-11949-2>

**THE EUROPEAN
PHYSICAL JOURNAL C**



Review

50 Years of quantum chromodynamics

Introduction and Review