THE INTERNAL STRUCTURE OF PARTICLES

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LIP Summer Internship Lecture









SMALLEST STRUCTURE OF MATTER — QUESTIONS

- What is meant with internal structure of particles?
- What levels of structure exist?
- What kind of experiments probe structure?
- How can structure be described theoretically?

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STRONLGY-INTERACTING MATTER MATTERS!







STRUCTURE OF THE ATOM

• Geiger and Marsden 1909 observed in Rutherford scattering: 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

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- explains data through famous $\sin^{-4}\phi/2$ law
- Question: Is the nucleus pointlike?

STRUCTURE OF THE NUCLEUS

 Hofstadter et al. 1950's: Electron-gold elastic Coulomb scattering ⇒ deviations from Rutherford formula for pointlike nucleus



Spatial extension of nuclear charge density described by form factor
 ⇔ nucleus has finite size with radius ≥ 1 fm = 10⁻¹⁵ m
 (for comparison: atomic radius ~ 100 pm = 10⁻¹⁰ m)

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• Question: Is the nucleus made out of constituents?

ENERGY LEVELS



• Inelastic electron-nucleus scattering

Fregeau; Hofstadter 1955

Nucleus excited into quantized energy states

NUCLEONS AND THE STRONG FORCE

- Energy spectra from internal quantized motion of A **nucleons**: *Z* protons and *N* neutrons (ordinary matter in Universe)
- Question: What is the nature of the strong nuclear force between them?



- Nuclear force
 - almost charge-independent
 - stronger than electromagnetic force

DISTRIBUTION OF NUCLEAR CHARGE





• Skin thickness pprox 2.3 fm orall nuclei

DISTRIBUTION OF NUCLEAR MATTER



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PREX, CREX at Jefferson Lab 2012, 2021

- Polarized electron scattering: interaction of electrons with neutrons via weak nuclear force ⇒ neutron distribution
- Large nucleus is like a chocolate truffle: filling of protons and neutrons with pure **neutron shell** $R_n R_p \approx 0.28$ fm
- 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.









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NUCLEON-NUCLEON INTERACTION

- Deviations from Rutherford formula at high energies
 ⇒ NN-interaction is short-range
 ~ 2 fm; more n's than p's in stable heavy nuclei
- Similar densities in all nuclei
 ⇒ repulsive core at short
 distance keeps nucleons separated



STRUCTURE OF THE NUCLEON

Question: Is the nucleon pointlike?

- Hofstadter et al. 1963: Elastic electron scattering from nucleons
 - proton has form factor and charge distribution with rms $\sim 0.8~\text{fm}$
 - proton and neutron have magnetic moment distributions
 - \Rightarrow nucleon is **not structureless**
- Inelastic electron scattering: Nucleon spectroscopy



- excitations of nucleon \Rightarrow internal motion of **constituents**
- first inelastic peak: Δ resonance

ENERGY SPECTRA OF HADRONS



Baryons:

- doublet: n and p as ground states
- quartet: $\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$ ground states
- Mesons: triplet with π^-, π^0, π^+ as ground states

QUARK MODEL

 Inelastic electron-proton scattering at large scattering angles ⇒ ∃ 'hard constituents': Quarks!



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- Gell-Mann, Zweig 1964:
 - u- and d-quarks with spin- $\frac{1}{2}$ and charges $Q_{\rm u} = \frac{2}{3}$ e, $Q_{\rm d} = -\frac{1}{3}$ e
 - Baryons: **3 quarks**, e.g. p = uud, n = udd, $\Delta^{++} = uuu$
 - Mesons: quark-antiquark, e.g. $\pi^+ = u\bar{d}$

COLOR CHARGE AND QCD

- Δ^{++} : 3-quark wave function ($\ell = 0$) would be $\frac{1}{\sqrt{4\pi}} \otimes |uuu\rangle \otimes |\uparrow\uparrow\uparrow\rangle$ not antisymmetric under exchange of 2 quarks!
- Need additional **color charge** to respect Pauli principle: **Red**, **Green**, **Blue** $\rightarrow \psi_{\Delta^{++}} = \frac{1}{\sqrt{4\pi}} \otimes |uuu\rangle \otimes |\uparrow\uparrow\uparrow\rangle \otimes \varepsilon_{\text{RGB}}$
- Hadrons only observed as ('white') color singlets **R+G+B=**White



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



HADRONS AND MULTIQUARKS

Mesons (qq)

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Tetraquarks (qqq̄q̄) 2016 discovered by LHCb





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Pentaquarks (qqqqq̄) 2015 discovered by LHCb





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HADRON STRUCTURE – OPEN QUESTIONS

- Clusterization properties inside hadrons and multiquarks?
- Are there more multiquarks like glueballs or hybrids?
- Do quarks, leptons, Higgs and gauge bosons have substructure?
 Current understanding: Not composed of smaller constituents





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NUCLEAR STRUCTURE – OPEN PROBLEMS

- NN-interaction from QCD
- Properties of hypernuclei
- Hyperon-nucleon and hyperon-hyperon interactions





LITERATURE FOR FURTHER INFORMATION



