HADRON STRUCTURE: THE UNSOLVED PUZZLE

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Fundamental Problem of Nuclear and Hadronic Physics

• Nearly all well-known (“visible”) mass in the universe is due to hadronic matter

• Fundamental theory of hadronic matter exists since the 1960’s: Quantum Chromo Dynamics
  • “Colored” quarks (u,d,c,s,t,b) and gluons; Lagrangian
  • BUT: knowing the ingredients doesn’t mean we know how to build hadrons and nuclei from them!
    • akin to the question: “Given bricks and mortar, how do you build a house?”

• Four related puzzles:
  • What is the “quark-gluon wave function” of known hadrons?
  • How are hadrons (nucleons) bound into nuclei? Does their quark-gluon wave function change inside a nucleus?
  • How do fast quarks and gluons propagate inside hadronic matter?
  • How do fast quarks and gluons turn back into observable hadrons?
Hadron Structure

- Simple-most (constituent quark) model of nucleons (protons and neutrons)

- ... becomes much more complicated once we consider the full relativistic quantum field theory called QCD

- Effective theories: Quark model, $\chi$PT, sum rules, ...

- and Lattice QCD!
Nuclear Structure

- Even more complicated!

- Effective degrees of freedom: nucleons, mesons, nucleon resonances... augmented by phenomenological NN potentials

- Effective theories: low-energy EFT, $\chi$PT, relativistic and non-relativistic potential models, shell model,...

- and Lattice QCD???
How Do We Study Hadron/Nuclear Structure?

- Energy levels: Nuclear and particle (baryon, meson) masses, excitation spectra, excited state decays -> Spectroscopy (*What exists?*)
- Elastic and inelastic scattering, particle production Reactions (*Relationships?*)
- Probing the internal structure directly Imaging (*Shape and Content?*)
- Particular way to encode this: Structure Functions
  - “Parton wave function”?  
    5(6)-dim. Wigner distribution → …
Overview

• Partonic Structure of the Nucleon
• Polarized and Unpolarized Structure Functions
• Recent Results
  • Spin-Averaged Structure Functions
  • Spin-Dependent Structure Functions
  • Nuclear Structure Functions
• Outlook
  • From 1D to 3D
  • Future Experiments

Duality

\[ d/u, \Delta q/q \]

\[ x \to 1 \]
Parton Distribution Functions

- The 1D world of nucleon/nuclear collinear structure:
  - Take a nucleon/nucleus
  - Move it real fast along $z$ → light cone momentum $P_+ = P_0 + P_z (\gg M)$
  - Select a “parton” (quark, gluon) inside
  - Measure its l.c. momentum $p_+ = p_0 + p_z (m \approx 0)$
  - ⇒ Momentum Fraction $x = p_+ / P_+ (*)$
  - In DIS **): $p_+ / P_+ \approx \xi = (q_z - \nu) / M$
  - $\approx \chi_{Bj} = Q^2 / 2M\nu$
  - Probability: $f_i^1(x), i = u, d, s, ..., G$

In the following, will often write “$q_i(x)$” for $f_1^i(x)$

*) Advantage: Boost-independent along $z$

**) DIS = “Deep Inelastic (Lepton) Scattering"
Introduce two more quantities of interest:
- Proton spin $S$
- Parton spin $s$
- Now we have 3 vectors: $\hat{z}, \vec{S}, \vec{s}$
- **But**: Every observable must be a scalar
- **And**: Spins are axial vectors!
- **Finally**: Must treat longitudinal and transverse directions differently (boost)
- 2 Pseudoscalars: $H = \vec{S} \cdot \hat{z}, \ h = \vec{s} \cdot \hat{z}$
- 2 transverse (2D) axial vectors: $\vec{S}_\perp, \vec{s}_\perp$
- $2^{\text{nd}}$ Structure function

\[ g_1^i(x) = \langle hH \rangle q_i(x) \text{ or } \langle hH \rangle G(x) = \Delta q_i(x) \text{ or } \Delta G(x) \]

\[ \Delta q_i = q \uparrow \uparrow(x) - q \uparrow \downarrow(x) \]

Can also form one more scalar: $T = \vec{S}_\perp \cdot \vec{s}_\perp$ (not measurable in DIS) $\rightarrow$ Transversity $h_1(x)$
Inclusive lepton scattering

Parton model: DIS can access

\[ F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x) \]  (and \( F_2(x) \approx 2 x F_1(x) \))

\[ g_1(x) = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x) \]  (and \( g_2(x) \approx -g_1(x) + \int_x^1 \frac{g_1(y)}{y} dy \))

At finite \( Q^2 \): pQCD evolution \( (q(x; Q^2), \Delta q(x; Q^2) \Rightarrow DGLAP \) equations), and gluon radiation

\[ g_1(x; Q^2)_{\text{pQCD}} = \frac{1}{2} \sum_q e_q^2 \left[ (\Delta q + \Delta q^-) \otimes \frac{\alpha_s(Q^2)}{2\pi} \delta C_q + \frac{\alpha_s(Q^2)}{2\pi} \Delta G \otimes \frac{\delta C_G}{N_f} \right] \]

\( \Rightarrow \) access to gluons. \( \delta C_q, \delta C_G - \text{Wilson coefficient functions} \)

SIDIS: Tag the flavor of the struck quark with the leading FS hadron \( \Rightarrow \) separate \( q_i(x; Q^2), \Delta q_i(x; Q^2) \)

Jefferson Lab kinematics: \( Q^2 \approx M^2 \Rightarrow \) target mass effects, higher twist contributions and resonance excitations

- Non-zero \( R = \frac{F_2}{2 x F_1} \left( \frac{4 M^2 x^2}{Q^2} + 1 \right)^{-1} \), \( g_2^{HT}(x) = g_2(x) - g_2^{WW}(x) \)
- Further \( Q^2 \)-dependence (power series in \( \frac{1}{Q^n} \))
Our 1D View of the Nucleon

(depends on $x$ and the resolution of the virtual photon $\sim 1/Q^2$)

$W = \text{final state invariant mass} = \sqrt{M^2 + \left(\frac{1}{x} - 1\right)Q^2}$

- Elastic scattering (Whole system recoils, $x = 1$, $W = M$)
- Resonances ($x < 1$, $W < 2$ GeV)
- Valence quarks ($x \geq 0.3$, $W > 2$ GeV)
- Sea quarks, gluons ($x < 0.3$)
- “Wee Partons” ($x \to 0$, Diffraction, Pomerons)

$E = \text{GeV}$

$Q^2 = \text{GeV}^2$
Valence PDFs

- Behavior of PDFs still unknown for $x \to 1$
  - SU(6): $d/u = 1/2$, $\Delta u/u = 2/3$, $\Delta d/d = -1/3$ for all $x$
  - Relativistic Quark model: $\Delta u$, $\Delta d$ reduced
  - Hyperfine effect (1-gluon-exchange): Spectator spin 1 suppressed, $d/u \to 0$, $\Delta u/u \to 1$, $\Delta d/d \to -1/3$
  - Helicity conservation: $d/u \to 1/5$, $\Delta u/u \to 1$, $\Delta d/d \to 1$
  - Orbital angular momentum: can explain slower convergence to $\Delta d/d \to 1$

- Plenty of data on proton $\to$ mostly constraints on $u$ and $\Delta u$

- Knowledge on $d$ limited by lack of free neutron target (nuclear binding effects in $d$, $^3$He)

- Large $x$ requires very high luminosity and resolution; binding effects become dominant uncertainty for the neutron
Related to matrix elements of local operators (OPE) - in principle accessible to lattice QCD calculations

Sum rules relate moments to the total spin carried by quarks in the nucleon (and β-decay matrix elements), sea quark asymmetries etc.

At low $Q^2$: Higher Twist, Parton-Hadron Duality, Chiral Perturbation Theory, GDH Sum Rule

Bjorken Sum Rule: $\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6} + \text{QCD corr.}$

GDH Sum Rule: $\Gamma_1(Q^2 \to 0) \to -\frac{Q^2}{2M^2} \frac{\kappa^2}{4}$

...and $\gamma_0, \delta_{LT}$

Gottfried Sum Rule:

$$\int_0^1 \left[ F_2^p(x,Q^2) - F_2^n(x,Q^2) \right] \frac{dx}{x} = \frac{1}{3} - \frac{2}{3} \int_0^1 [\bar{d}(x,Q^2) - \bar{u}(x,Q^2)] dx$$

$\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2) dx$
Experimental Facilities