WILL DETMOLD
MIT

COMPUTING THE PROPERTIES OF NUCLEI FROM QCD

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FROM QCD TO NUCLEI

EMERGENCE OF NUCLEI

- QCD+EW encodes nuclear physics
- Computational challenge to see QCD produce nuclear physics
- Study emergence of layered complexity of nucleons and nuclei
- Input for intensity frontier experiments
  - Interactions of nuclei with external currents
  - Need lattice QCD calculations
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ELECTROWEAK PROCESSES

- Electroweak processes in nuclei
- Neutrino-nucleus interactions for long baseline neutrino program
  - Oscillation parameters require energy reconstruction from $\nu A$ scattering
- Double-$\beta$ decay: $nn \rightarrow pp$
  - Nuclear matrix element uncertainties
FROM QCD TO NUCLEI

BSM SEARCHES

- Non standard model currents in light nuclei
- Scalar currents
  - Dark matter direct detection
  - Lepton flavour violation: $\mu_2e$
- Precision spectroscopy
- Tensor currents
  - Quark contribution to EDMs of nuclei
How well do we know nuclear matrix elements?

Gamow-Teller transitions in nuclei
- Well measured for large range of nuclei (30<A<60)
- Many nuclear structure calculations (shell-model,...) describe spectrum well
- Matrix elements systematically off by 20-30%
- Correct using 2 body currents

Fundamental understanding from QCD

LATTICE QCD

- Strong coupling definition of QCD
- Numerical tool for nonperturbative QCD calculations
  - Discretise and compactify spacetime
  - Requires integration over $10^{12}$ degrees of freedom in current calculations!
- Major algorithmic and computational challenge
- Solve using importance sampling Monte Carlo
Case study LQCD with unphysical quark masses ($m_\pi \sim 800$ MeV, 450 MeV)

1. Spectrum and scattering of light nuclei ($A<5$) [PRD 87 (2013), 034506]


3. Nuclear reactions: $np \rightarrow dy$ [PRL 115, 132001 (2015)]

4. Gamow-Teller transitions: $pp \rightarrow de, g_A(3H)$ [PRL 119 062002 (2017)]

5. Double $\beta$ decay: $pp \rightarrow nn$ [PRL 119, 062003 (2017)]

6. Gluon structure ($A<4$) [PRD 96 094512 (2017)]

7. Scalar/tensor currents ($A<4$) [PRL 120 152002 (2018)]
TRITIUM BETA DECAY

- Tritium decay half life

\[
\frac{(1 + \delta_R) f_V}{K/G_V^2} t_{1/2} = \frac{1}{\langle F \rangle^2 + f_A/f_V g_A^2 \langle GT \rangle^2}
\]

known from theory or expt.

- Biggest uncertainty in

\[
g_A \langle GT \rangle = \langle ^3\text{He} | \bar{q} \gamma_k \gamma_5 \gamma^\tau q | ^3\text{H} \rangle
\]

- Form ratios of correlators to cancel leading time-dependence:

\[
\frac{R_{^3\text{H}}(t)}{R_{\pi}(t)} \xrightarrow{t \to \infty} g_A(3^\text{H})/g_A = \langle GT \rangle
\]
MASS DEPENDENCE OF TRITON AXIAL CHARGE

\[ \langle ^3\text{He} | A_z | ^3\text{H} > / g_A \]

\[ m_{\pi}^2 \text{ [GeV}^2\]
Axial Matrix Elements

PP Fusion

- Axial transition in two nucleon system: \( pp \rightarrow d\bar{e}^{+}\nu, \mu d \rightarrow n\bar{n}\nu, \nu d \rightarrow p\bar{p}\nu \)
- Important EFT contribution from two-body currents
  - First LQCD calculation of \( pp \rightarrow d\bar{e}^{+}\nu \) [NPLQCD PRL 119, 062002 (2017)]
  - Determines counter-term at similar precision to knowledge from pheno
  - Goal: precise prediction for current MuSun experiment
Complete flavour breakdown of nuclear effects on axial and tensor matrix elements

- Calculated forward limit MEs for $A=1,2,3$
-Disconnected contributions using hierarchical probing [Gambhir et al.]

Axial and tensor MEs show small nuclear effects

- Axial consistent with experiment

[NPLQCD, PRL 120, 152002 (2018)]
DM direct detection experiments search for recoil of nucleus from DM scattering

One popular class of DM interactions is through scalar exchange

\[ \mathcal{L} = \frac{G_F}{2} \sum_q \kappa_q (\bar{\chi}\chi)(\bar{q}q) \]

Direct detection depends on nuclear matrix element

\[ \overline{m} \langle Z, N | \bar{u}u + \bar{d}d | Z, N \rangle \]

At hadronic/nuclear level
NUCLEON SCALAR COUPLING

- Single nucleon contribution
- Calculated in LQCD
- Results from many groups

Summary from Shanahan 2016

- Fukugita et al. (95)
- Dong et al. (96)
- SESAM Collaboration (98)
- Leinweber et al. (04)
- Procura et al. (06)
- JLQCD Collaboration (08)
- Young & Thomas (10)
- BMW Collaboration (12)
- QCDSF Collaboration (12)
- QCDSF Collaboration (12)
- Semke et al. (12)
- Alvarez–Ruso et al. (13)
- Shanahan et al. (13)
- Lutz et al. (14)
- Ren et al. (15)
- χQCD Collaboration (15)
- χQCD Collaboration (15)
- BMW Collaboration (16)
- RQCD Collaboration (16)
- ETM Collaboration (16)

$\sigma_{NN}$ (MeV)
NUCLEAR EFFECTS CAN BE LARGE!

- LQCD study of scalar couplings for $A=1,2,3$
- Unexpectedly large (~10%) deviation from sum of nucleon matrix elements for $A=3$
- Naive extrapolation to $^{136}$Xe implies significant consequences for dark matter detection sensitivity

[Image: Diagram showing deviation from naive sum of nucleons]
FROM QCD TO NUCLEI

OUTLOOK

- Nuclei are under study directly from QCD
  - Comprehensive study of matrix elements at heavy quark masses
- Prospect of a quantitative connection to QCD makes this an exciting time for nuclear physics
  - Important role in current and upcoming intensity frontier experimental program
  - Learn many interesting things about the nature of hadrons and nuclei along the way
- Next steps: nuclear form factors
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