TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Nuclear Theory Efforts at TRIUMF

Francesco Raimondi | Theory Department | TRIUMF

On behalf of **Sonia Bacca, Jason Holt and Petr Navratil**

and

Angelo Calci, Michael Desrochers, Jeremy Dohet-Eraly,
Javier Hernandez, Chen Ji, Mirko Miorelli, Francesco Raimondi,
Ragnar Stroberg, Tianrui Xu

National Research Council Canada

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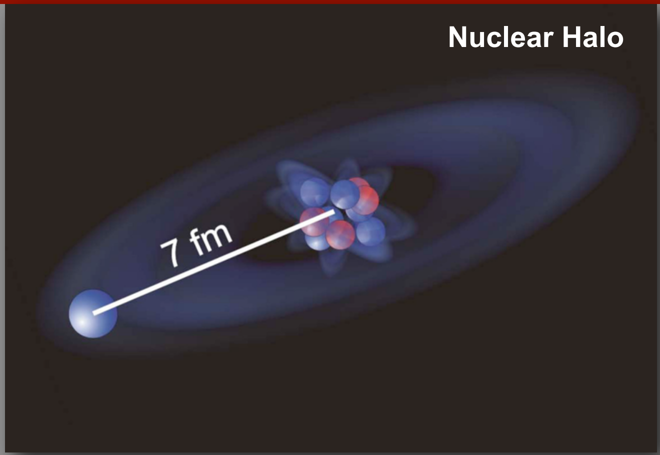

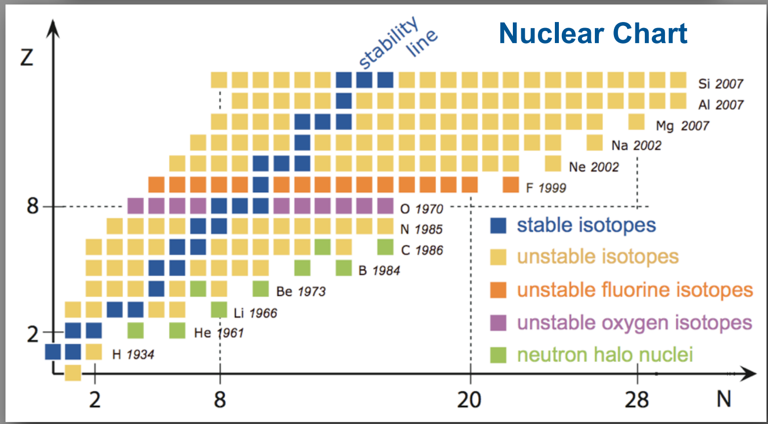

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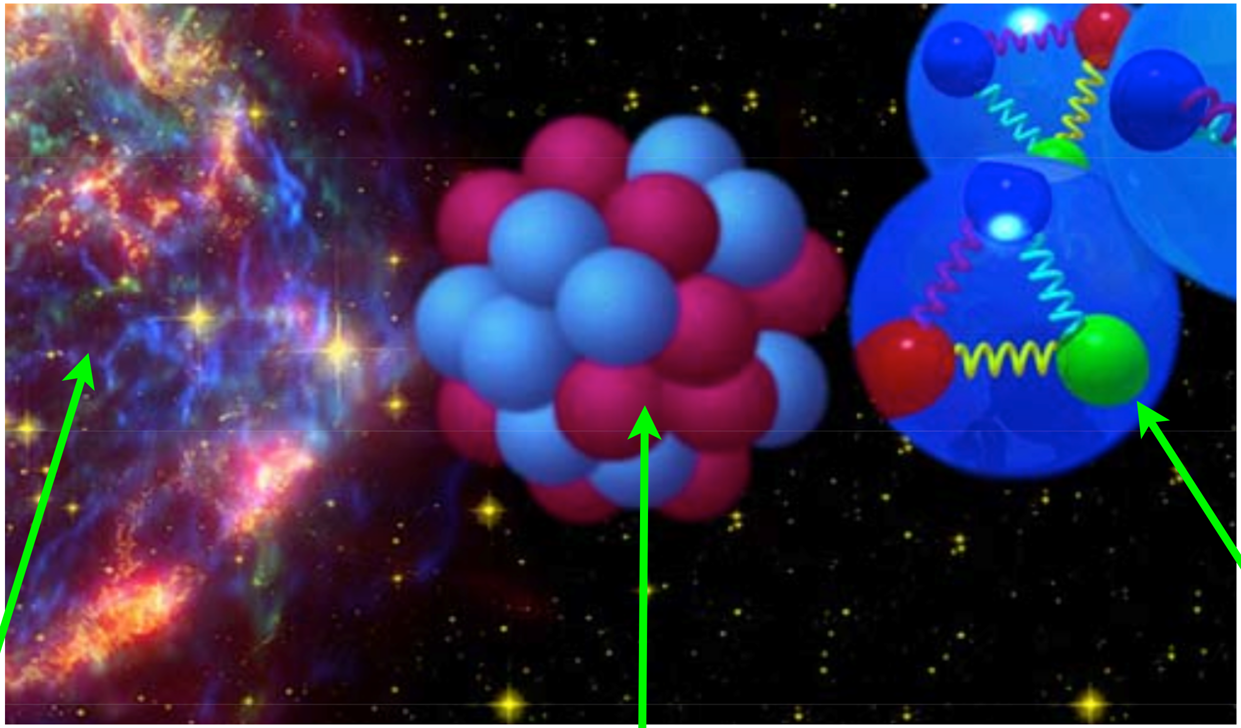
Nuclear Theory

Develop a unified theory of all nuclei in the nuclear chart

Connecting to Astrophysics



Connecting to QCD

- Astrophysics
  How does nuclear physics drive the nucleosynthesis of elements?

- Few and many-body methods
  How do nuclear forces give rise to structure of nuclei?
  How do we explain reactions?

- Interactions
  How can we connect nuclear forces to QCD?

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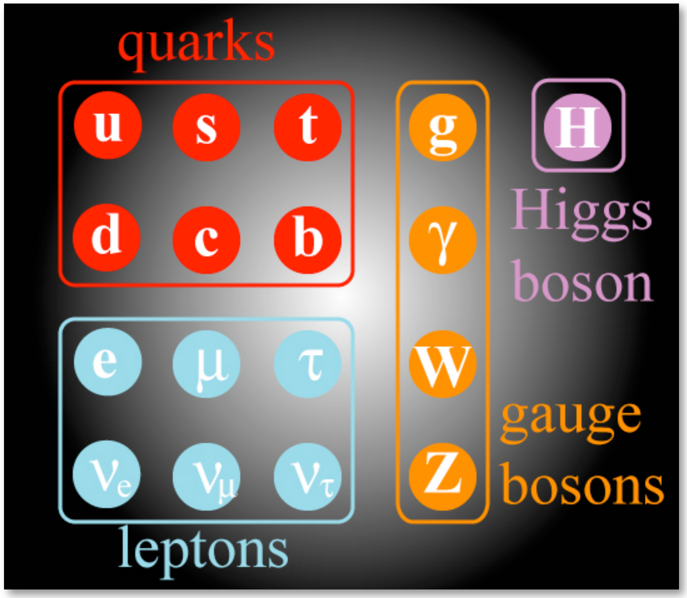
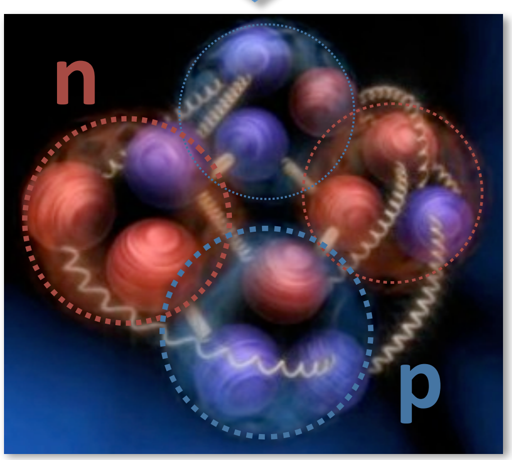
Chiral Effective Field Theory



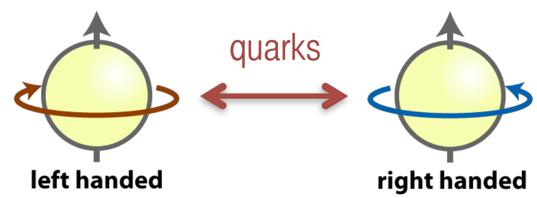


Quark/gluon (high energy) dynamics

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \bar{q}_L i \gamma_\mu D^\mu q_L + \bar{q}_R i \gamma_\mu D^\mu q_R - \bar{q} \mathcal{M} q$$

In the limit of vanishing quark masses
chiral symmetry (left- and right-handed quarks transform independently)

QCD chiral symmetry

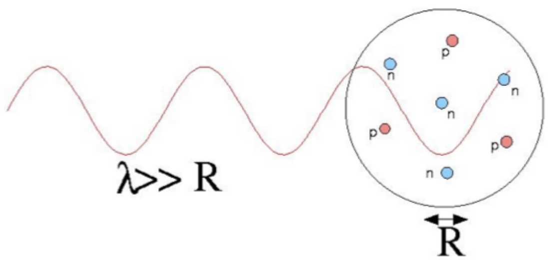


Nucleon/pion (low energy) dynamics

$$\mathcal{L}_{eff} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$$

Compatible with explicit and spontaneous
chiral symmetry breaking

Chiral Effective Field Theory



Limited resolution at low energy

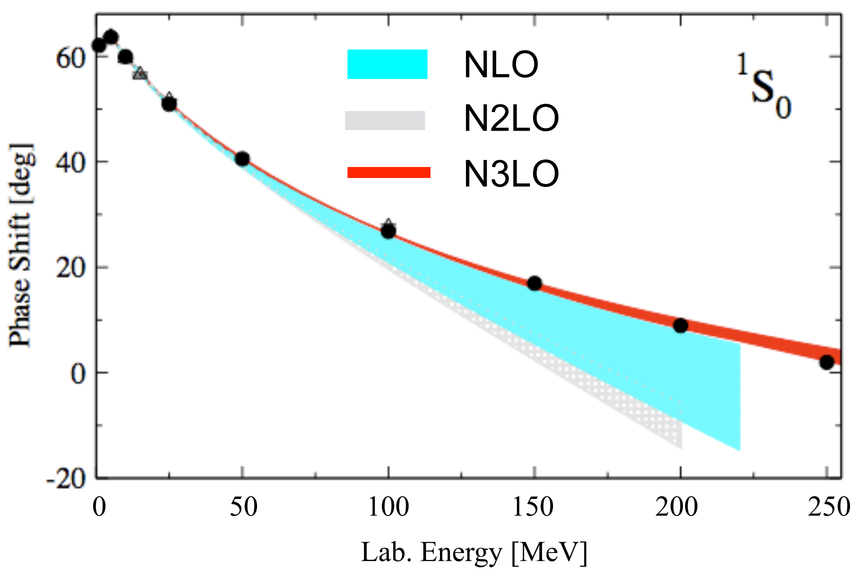
Separation of scales

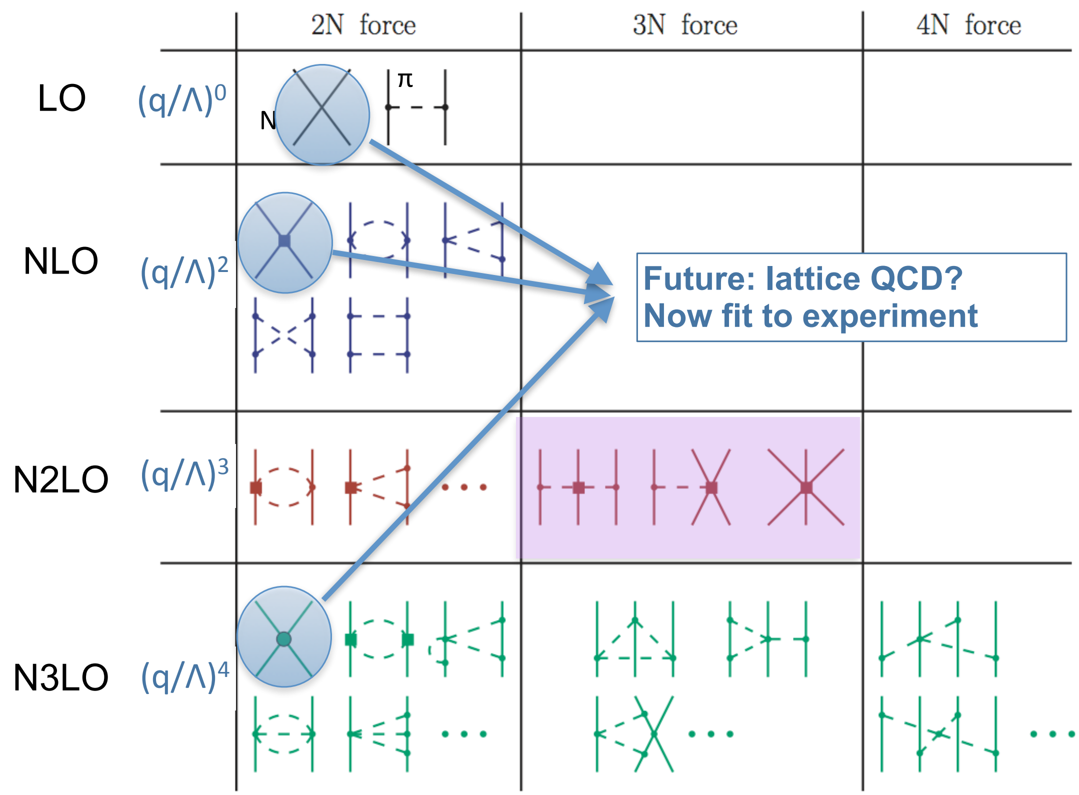
$$\frac{1}{\lambda} = Q \ll \Lambda_b = \frac{1}{R}$$

Systematic expansion

$$\mathcal{L} = \sum_k c_k \left(\frac{Q}{\Lambda_b}\right)^k$$

Details of short distance physics not resolved, but captured in low energy constants (LEC)

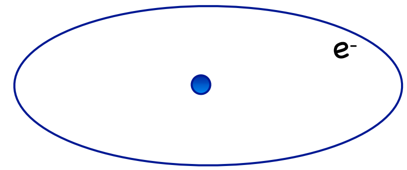




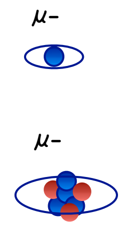
Goal: Predict observables in other nuclei

Few-body studies and the proton-radius puzzle

CODATA-2010: $r_p = 0.8775(51)$ fm
ordinary Hydrogen



Pohl *et al.*, Nature (2010) $r_p = 0.84184(67)$ fm (5σ)
μH Lamb shift



Is lepton universality violated?

Strong experimental program at PSI (Switzerland) to unravel this mystery by studying other μ-atoms?

$$\Delta E^{2S-2P} = \delta_{QED} + \delta_{nucl} + \frac{m_r^3 (Z\alpha)^4}{12} \langle r^2 \rangle$$

nuclear structure corrections

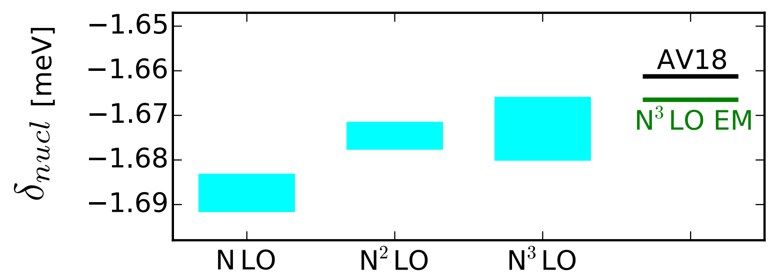
Calculation for μ^4He^+
With TRIUMF postdoc Chen Ji

PRL **111,** 143402 (2013) PHYSICAL REVIEW LETTERS week ending 4 OCTOBER 2013

Nuclear Polarization Corrections to the μ^4He^+ Lamb Shift

C. Ji,[1,*] N. Nevo Dinur,[2,†] S. Bacca,[1,‡] and N. Barnea[2,§]

Calculation for μD
With O.J.Hernandez, Msc Student at Manitoba
Phys. Lett. B **736**, 334 (2014)



1% error obtained averaging potentials and varying chiral EFT

Data on these nuclei currently being analyzed at PSI using our predictions

Coupled-cluster theory with continuum

New method to extend *ab-initio* calculations of break-up observables to medium mass nuclei

PRL **111,** 122502 (2013) PHYSICAL REVIEW LETTERS

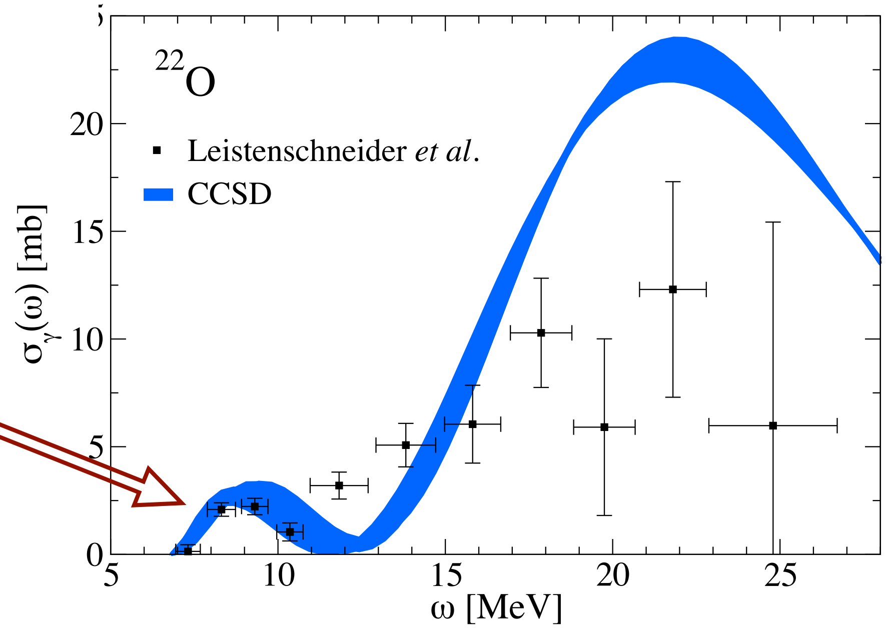
First Principles Description of the Giant Dipole Resonance in ^{16}O

S. Bacca,[1] N. Barnea,[2] G. Hagen,[3,4] G. Orlandini,[5] and T. Papenbrock[4,3]

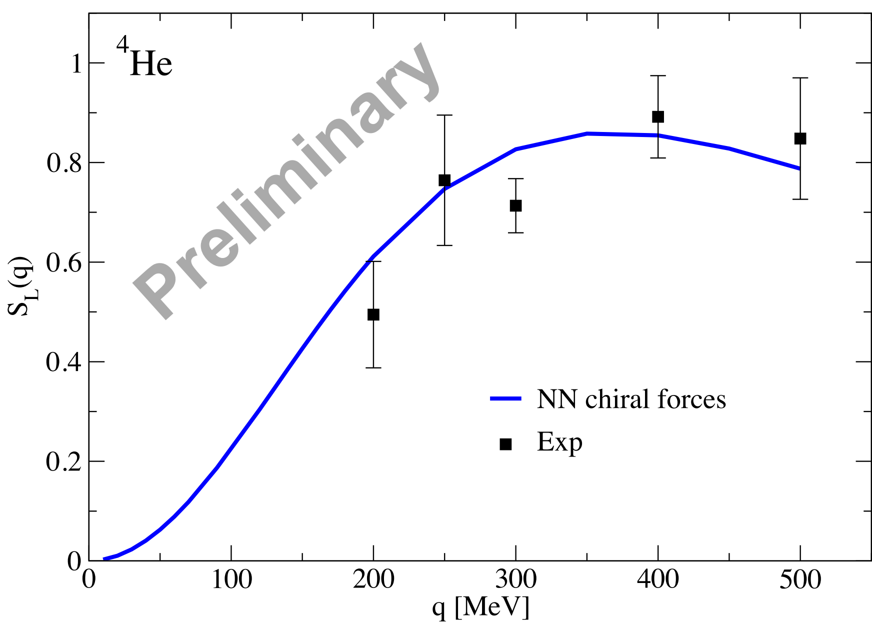
With M.Miorelli, PhD student at UBC
PRC **90**, 064619 (2014)
Soft dipole mode well described by theory

Future: Gamow-Teller strengths

Dipole response of neutron-rich nuclei



Coulomb sum rule (integral of charge response)



This method can be used to tackle quasi-elastic electron and neutrino scattering off nuclei

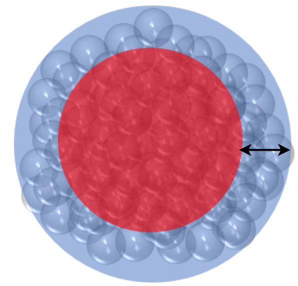
Ultimate Goal: neutrino scattering off ^{16}O (CCQE) needed for detector simulations

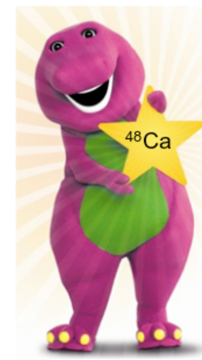
Present Goal:
test the theory on electron scattering off ^4He and ^{16}O

With Tianrui Xu, undergraduate at UBC

Coupled-cluster calculations on ^{48}Ca

In collaboration with the ORNL we are developing ab-initio calculations to predict observables for: $R_{\text{skin}}, \alpha_D$

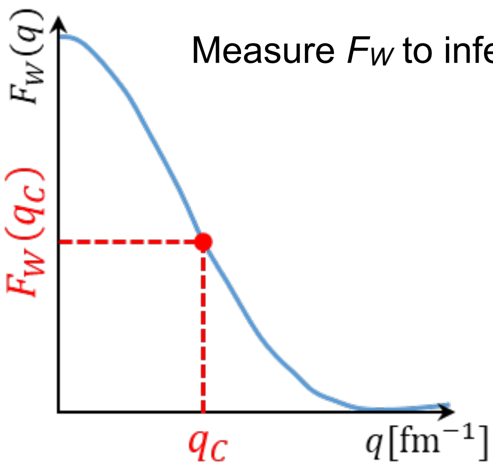




Spokesperson: J. Mammei, University of Manitoba

★ Parity violation electron scattering Calcium Radius Experiment (CREX) at JLab to measure R_{skin}

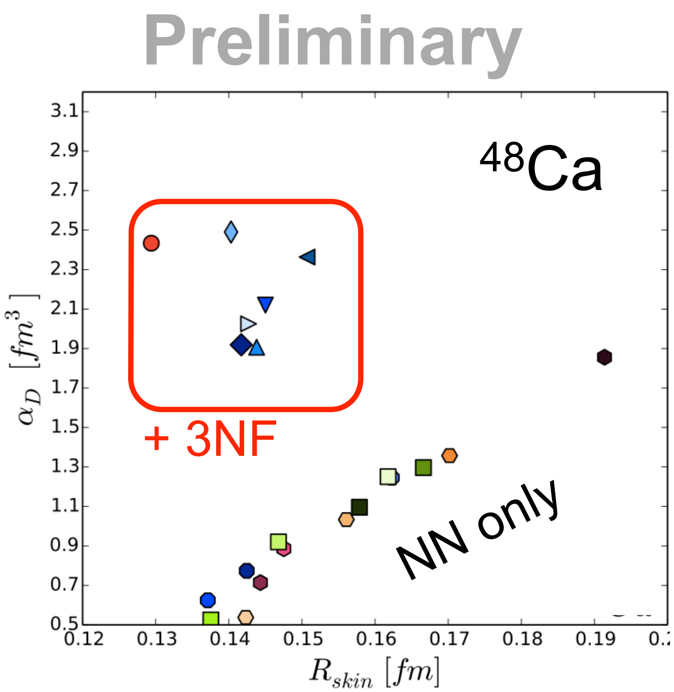
$$A_{pv} \equiv \frac{d\sigma/d\Omega_R - d\sigma/d\Omega_L}{d\sigma/d\Omega_R + d\sigma/d\Omega_L} \approx -\frac{G_F q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(q^2)}{Z F_{ch}(q^2)}$$



Measure F_W to infer distribution of neutrons

$$Q_W^n \approx -1$$

$$Q_W^p \approx 1 - 4\sin^2\theta_W \approx 0$$



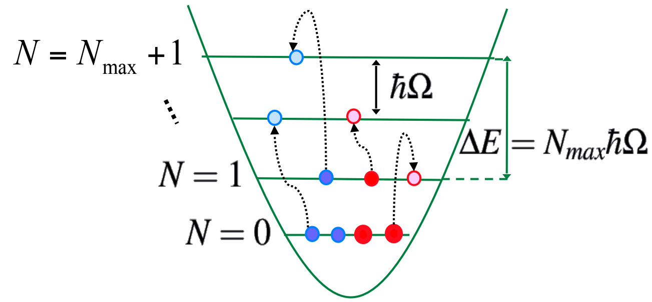
★ (p,p') scattering to extract the electric dipole polarizability at RCNP, Japan

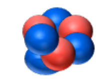
α_D is related to the symmetry energy in the EOS of nuclear matter

$$\alpha_D = 2\alpha \int_{\omega_{th}}^{\infty} d\omega \frac{R^D(\omega)}{\omega}$$ → electric dipole response function

Unified approach to bound & continuum states; to nuclear structure & reactions

- *Ab initio* no-core shell model
  - Short- and medium range correlations
  - Bound-states, narrow resonances
  - Harmonic-oscillator basis





NCSM

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)}, \lambda \right\rangle$$

Unknowns

Unified approach to bound & continuum states; to nuclear structure & reactions

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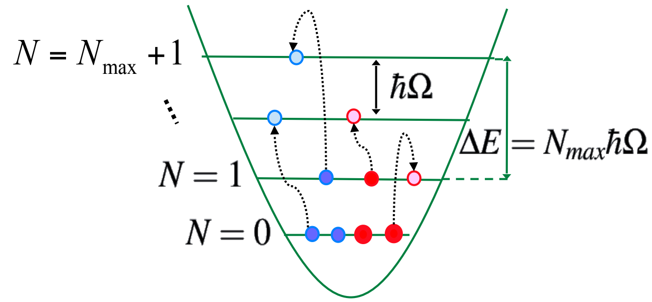
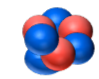
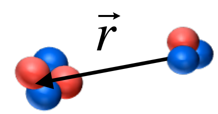




NCSM

- …with resonating group method
  - Bound & scattering states, reactions
  - Cluster dynamics, long-range correlations



NCSM/RGM

NCSM/RGM channel states

$$\Psi^{(A)} = \sum_{\nu} \int d\vec{r}\; \gamma_{\nu}(\vec{r})\; \hat{A}_{\nu} \left| (A-a) \;\; \vec{r} \;\; (a) \,, \nu \right\rangle$$

Unknowns

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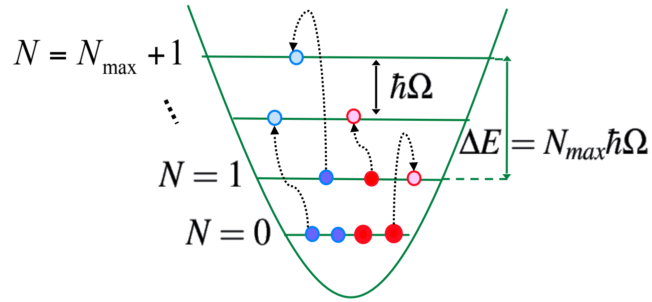
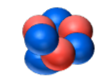
Unified approach to bound & continuum states; to nuclear structure & reactions

- *Ab initio* no-core shell model
  - Short- and medium range correlations
  - Bound-states, narrow resonances
  - Harmonic-oscillator basis





NCSM

- …with resonating group method
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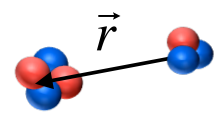

NCSM/RGM

TRIUMF postdoc

S. Baroni, P. Navratil, and S. Quaglioni, PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

- Most efficient: *ab initio* no-core shell model with continuum

NCSMC

NCSM eigenstates

NCSM/RGM channel states

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)} \, , \lambda \right\rangle + \sum_{\nu} \int d\vec{r} \; \gamma_{\nu}(\vec{r}\,) \; \hat{A}_{\nu} \left| \underset{(A-a)}{} \; \vec{r} \; (a) \, , \nu \right\rangle$$

Unknowns

General formalism applicable to *p*-shell and light *sd*-shell nuclei

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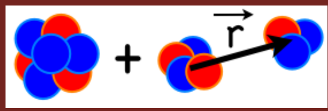
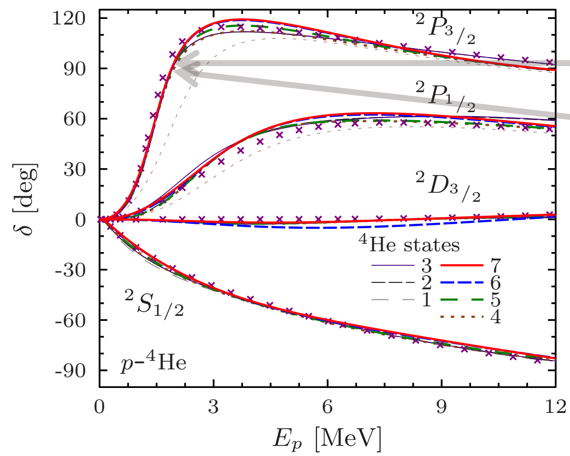
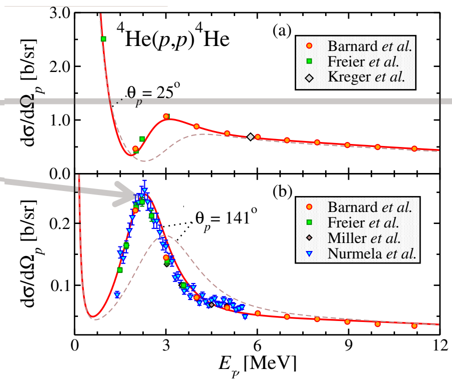
NCSMC



^{5}Li g.s. resonance & p-^{4}He scattering
^{6}Li states & d-^{4}He scattering

Predictive power in the ^{5}Li 3/2^{-} g.s. resonance region:
Applications to material science

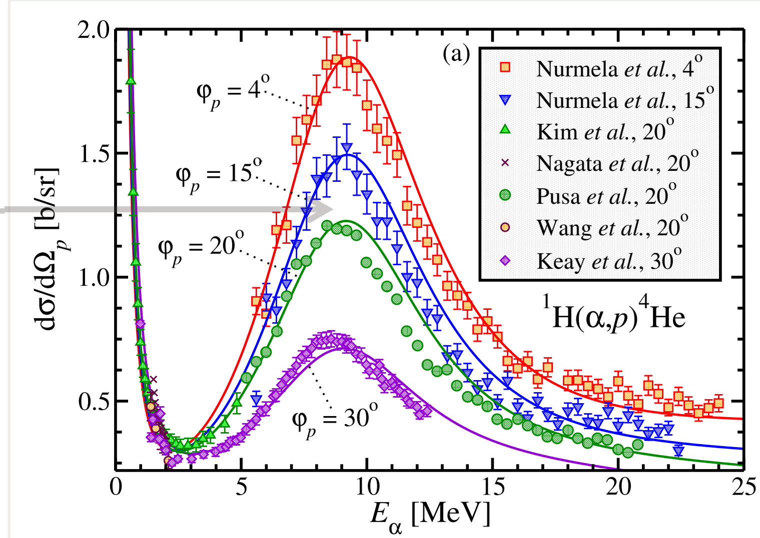




PHYSICAL REVIEW C **90**, 061601(R) (2014)

Predictive theory for elastic scattering and recoil of protons from ^{4}He

Guillaume Hupin,[1,*] Sofia Quaglioni,[1,†] and Petr Navrátil[2,‡]



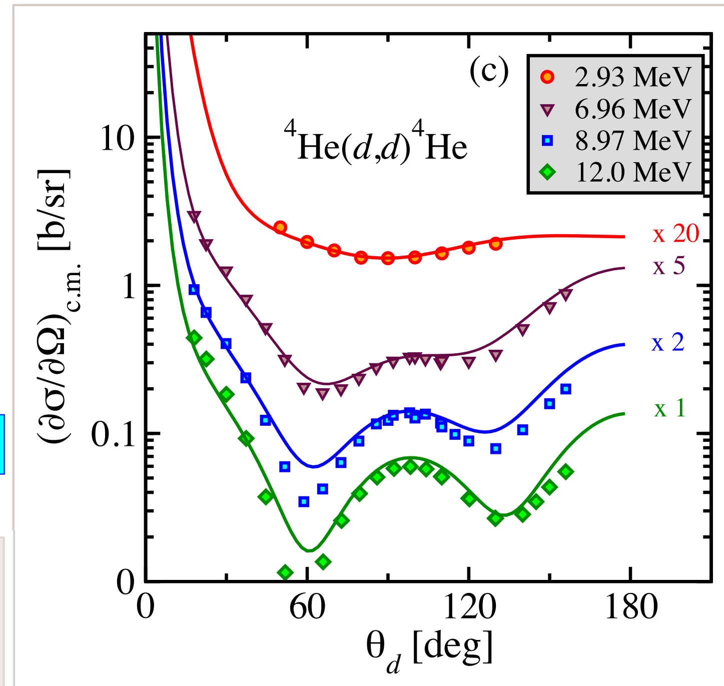
Unified description of ^{6}Li states and *d*-α scattering

Ab initio NCSMC with chiral *NN+3N* forces simultaneously calculates properties of ^{6}Li g.s., its resonances and the *d*-α cross sections.

The determined asymptotic *D*- to *S*-state ratio of the ^{6}Li g.s. wave function in the *d*-α configuration discriminates between two experiments.

Calculations of the capture reaction ^{2}H(α ,γ)^{6}Li important for astrophysics are under way.

^{6}Li(g.s.)	NCSMC	Experiment	
E [MeV]	-32.01	-31.994	
C_0 [fm$^{-1/2}$]	2.695	2.91(9)	2.93(15)
C_2 [fm$^{-1/2}$]	-0.074	-0.077(18)	
C_2/C_0	-0.027	-0.025(6)(10)	0.0003(9)



PRL **114**, 212502 (2015) PHYSICAL REVIEW LETTERS week ending 29 MAY 2015

Unified Description of ^{6}Li Structure and Deuterium-^{4}He Dynamics with Chiral Two- and Three-Nucleon Forces

Guillaume Hupin,[1,*] Sofia Quaglioni,[1,†] and Petr Navrátil[2,‡]

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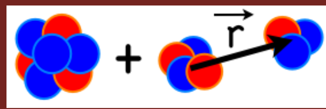
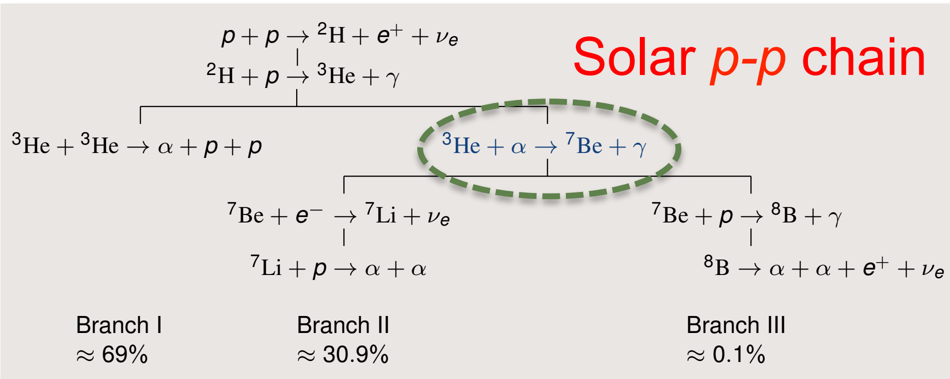
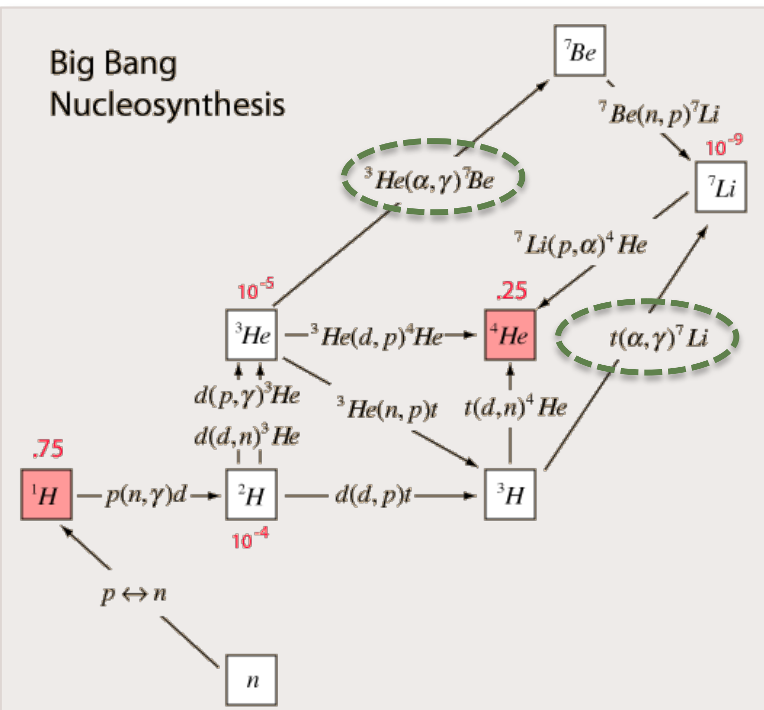
NCSMC

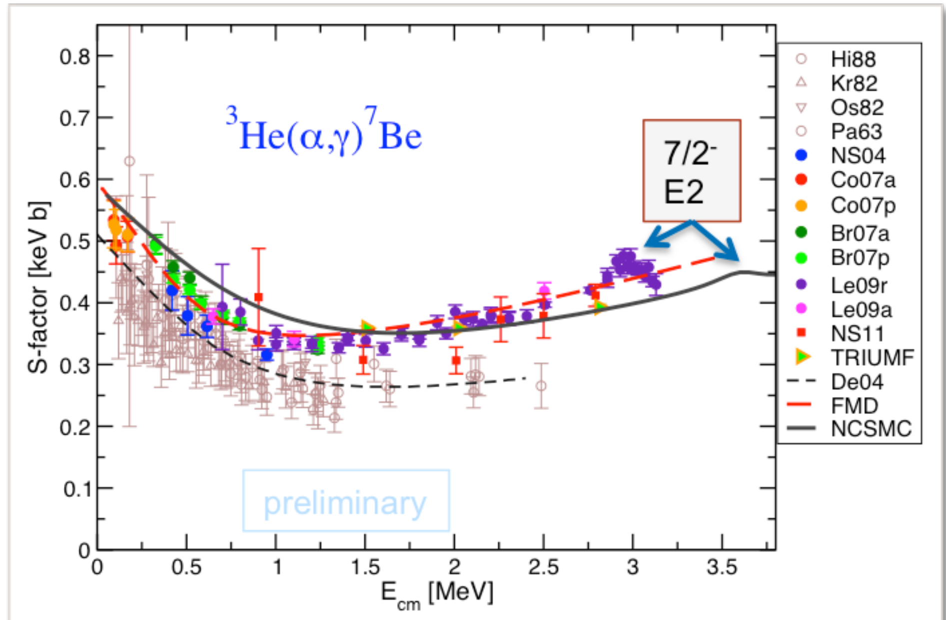


Reactions important for astrophysics

E1 radiative capture with small E2 contribution at 7/2[-] resonance







Ab initio calculations of $^3He(\alpha,\gamma)^7Be$ and $^3H(\alpha,\gamma)^7Li$

NCSMC with chiral *NN* forces is used to investigate $^3He(\alpha,\gamma)^7Be$ and $^3H(\alpha,\gamma)^7Li$ capture reactions important for astrophysics.

The $^3He(\alpha,\gamma)^7Be$ cross section results are directly compared to the recent TRIUMF DRAGON measurement.

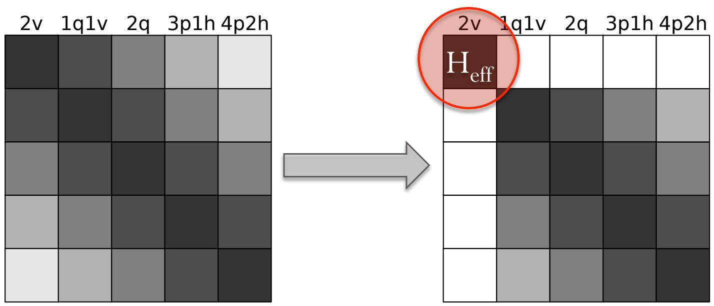
Work in progress by
J. Dohet-Eraly, P. Navratil, S. Quaglioni, W. Horiuchi, G.Hupin, F. Raimondi

TRIUMF postdocs

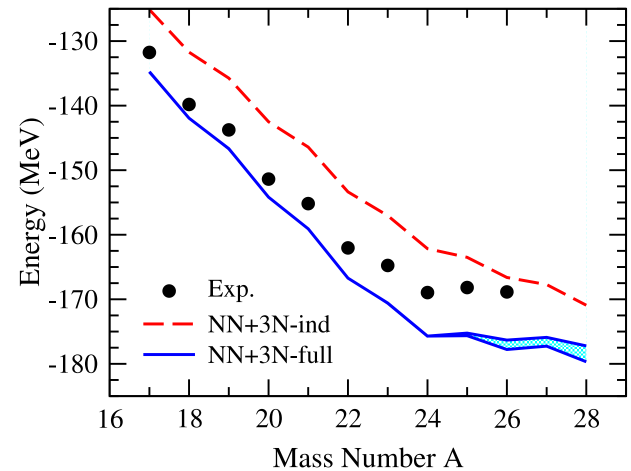
In-Medium SRG for Medium Mass Nuclei

Apply continuous unitary transformation:
decouples "off-diagonal" shell-model Hamiltonian

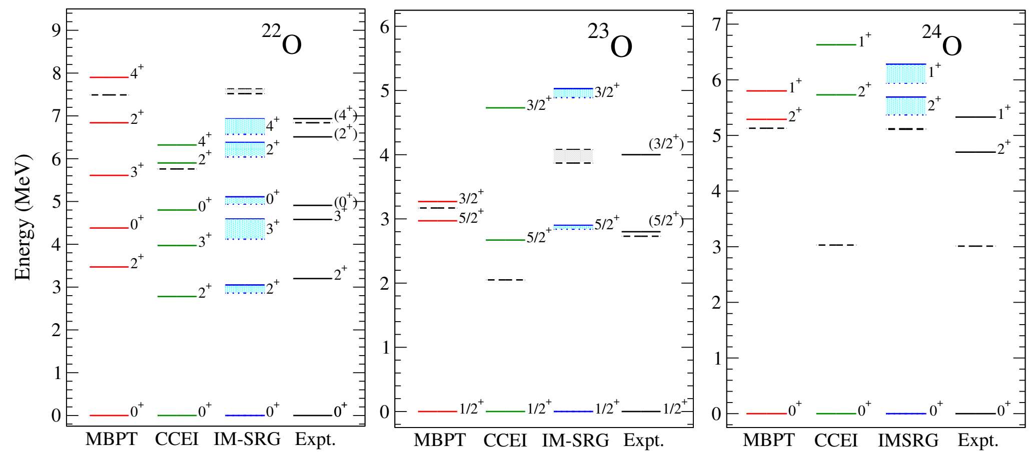
$$H(s) = U(s) H U^{\dagger}(s) \equiv H^{\mathrm{d}}(s) + H^{\mathrm{od}}(s) \rightarrow H^{\mathrm{d}}(\infty)$$



$$H(s=0) \rightarrow H(\infty)$$

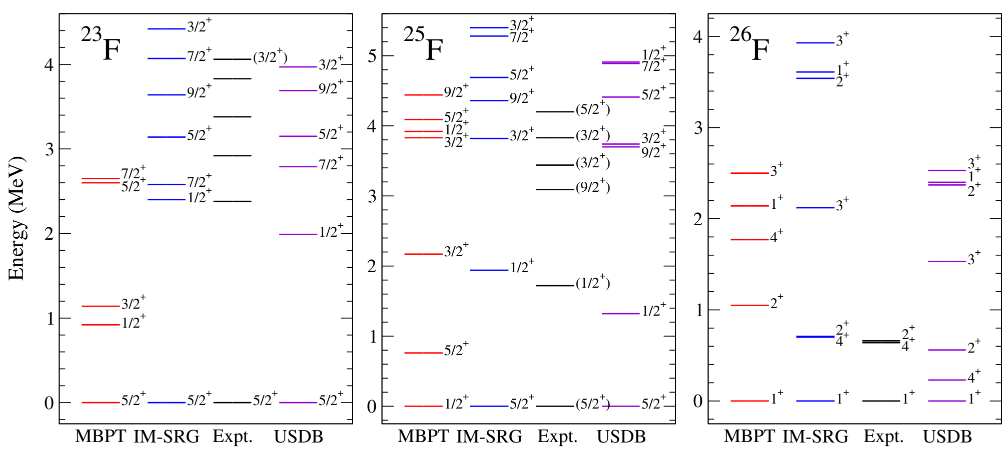


Reproduce oxygen dripline with NN+3N forces



Bogner, Hergert, JDH, Schwenk et al., PRL (2014)
Hebeler, JDH, Menéndez, Schwenk, ARNPS (2015)

Oxygen spectra: agree with CCEI to ~300keV



Bogner, Hergert, JDH, Schwenk, in prep.

Fluorine: competitive with phenomenology

IM-SRG for Medium Mass Nuclei: Operators

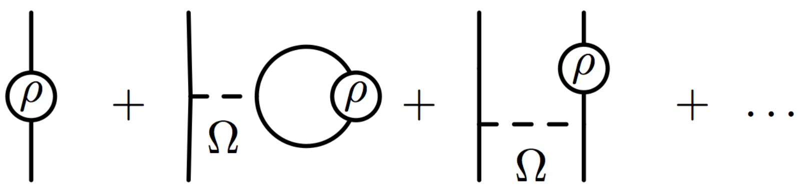
New approach: explicitly construct unitary transformation from operator $\Omega(s)$

$$U(s) = \exp \Omega(s)$$

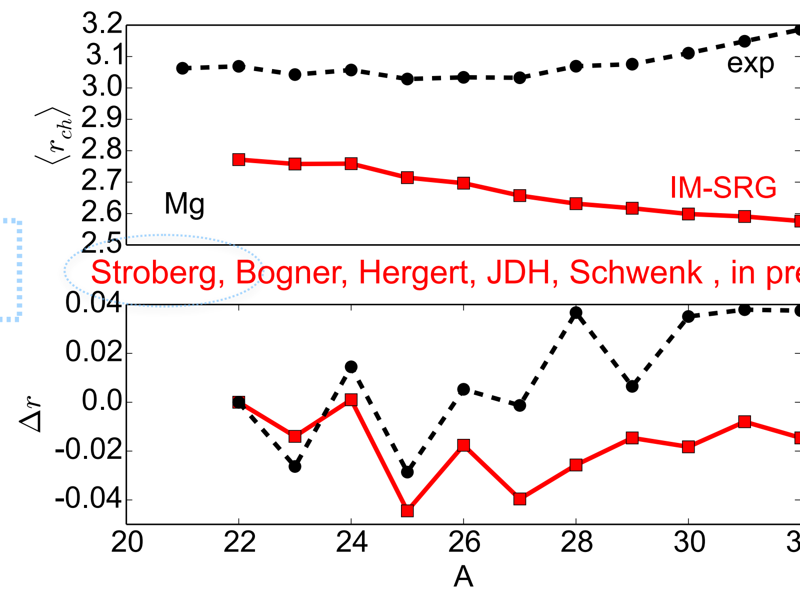
Apply to general operator

$$\mathcal{O}^{\Lambda}(s) = e^{\Omega(s)} \mathcal{O}^{\Lambda} e^{-\Omega(s)} = \mathcal{O}^{\Lambda} + \frac{1}{2}\left[\Omega(s), \mathcal{O}^{\Lambda}\right] + \frac{1}{12}\left[\Omega(s), \left[\Omega(s), \mathcal{O}^{\Lambda}\right]\right] + \cdots$$

Commutator relations induce higher-body parts



Absolute radii for entire sd shell with NN+3N



Deficiencies due to starting Hamiltonian

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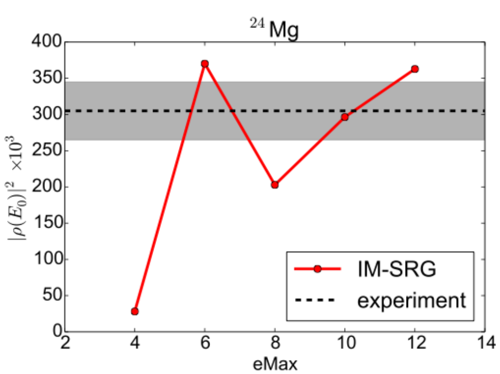
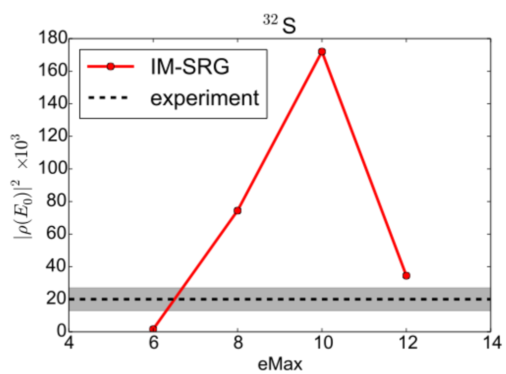
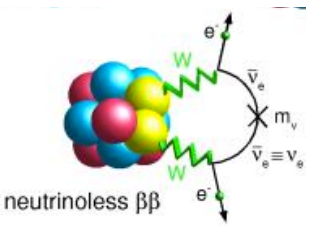
First apply to scalar operators: E0 transitions





Neutrinoless Double-Beta Decay

Broad impact for particle physics:
Nature of neutrino (Majorana or Dirac)
Lepton-number-violating process



Absolute mass scale of neutrino: must calculate nuclear matrix element

$$(T^{0\nu\beta\beta}_{1/2})^{-1} = G_{0\nu}|M_{0\nu}|^2|m_{\beta\beta}|^2$$

Uniform increase in value of nuclear matrix element

^{48}Ca	Bare	**0.77**
	Effective	**1.30**

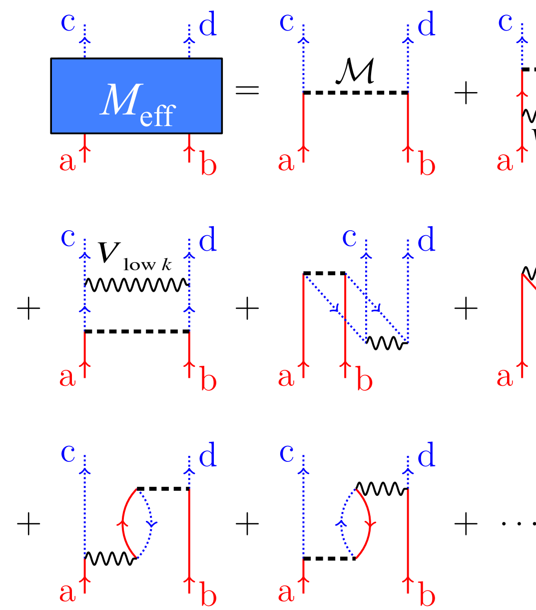
^{76}Ge	Bare	**3.12**
	Effective	**3.77**

^{82}Se	Bare	**2.73**
	Effective	**3.62**

Overall ~25-30% increase for ^{76}Ge, ^{82}Se; 75% for ^{48}Ca

Lincoln, JDH et al., PRL (2013)
JDH and Engel, PRC (2013)
Kwiatkowski, et al., PRC (2014)

Standard approaches use bare operator
Calculate shell-model **effective** operator

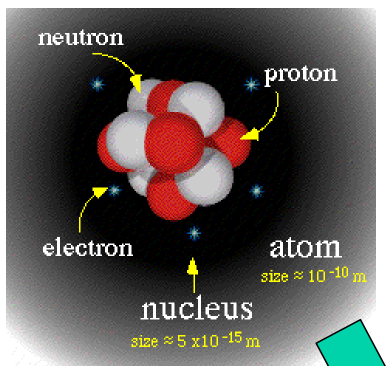


Next steps:
Include two-body electroweak currents
Calculate nonperturbatively with IM-SRG
Include uncertainty estimates
SRG-evolved beta-decay operator

Conclusions and Outlook

- The connection of forces to QCD and the use of advanced methods to solve the nuclear many-body problem are supporting and motivating new measurements at TRIUMF and abroad
- The experiments with stable nuclei and exotic beams provide, at the same time, critical tests for the theory
- Nuclear astrophysics benefits from this interplay

Nuclear Structure and Reactions



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Nuclear Theory

forces
methods
extrapolations

Nuclear Astrophysics