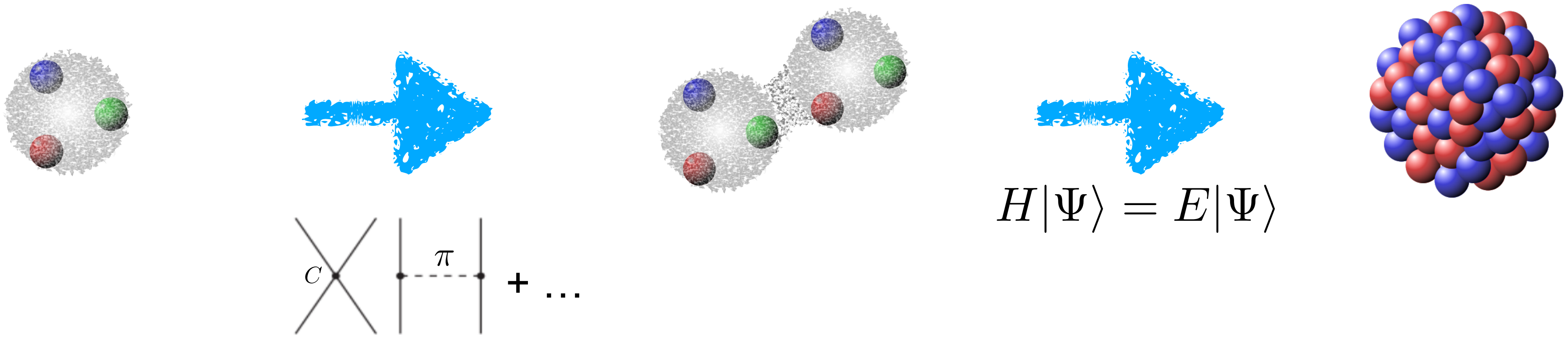
Impact of two-body current on magnetic dipole moments



Takayuki Miyagi

European conference on few-body problems in physics @ Mainz, Germany (July 31, 2023)

Collaborators

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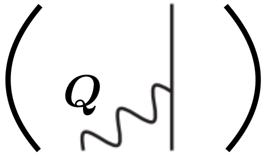
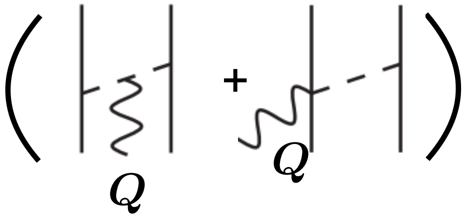
- TU Darmstadt: K. Hebeler, A. Schwenk, R. Seutin
- TRIUMF: J. D. Holt
- Johannes Gutenberg University of Mainz: S. Bacca
- University of Illinois: X. Cao
- Massachusetts Institute of Technology: R. F. Garcia-Ruiz

Motivation

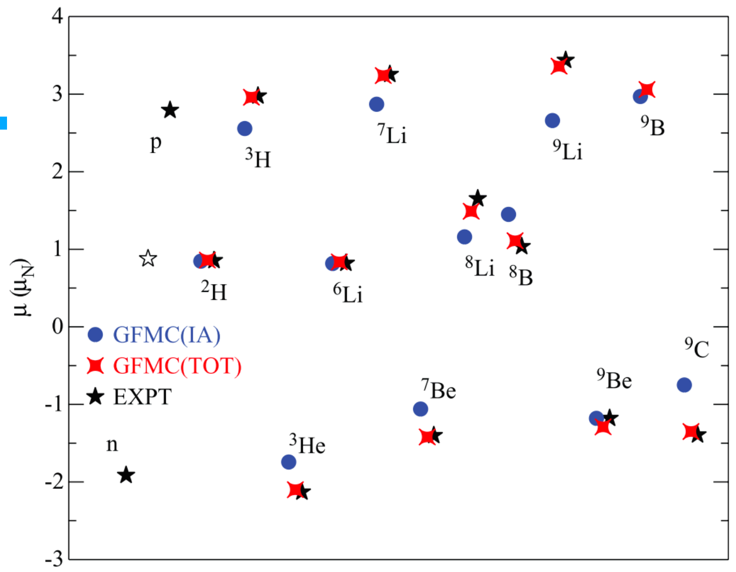
- Magnetic dipole observables can be used
  - to detect magic numbers
  - to test ab initio calculations.
- For more precise calculations, one needs to add 2BC effect.

$$\boldsymbol{\mu}_{1\mathrm{B}} = -\frac{i}{2}\nabla_{\boldsymbol{Q}}\times$$  $$(\boldsymbol{Q}\to\mathbf{0})$$ point-nucleon limit

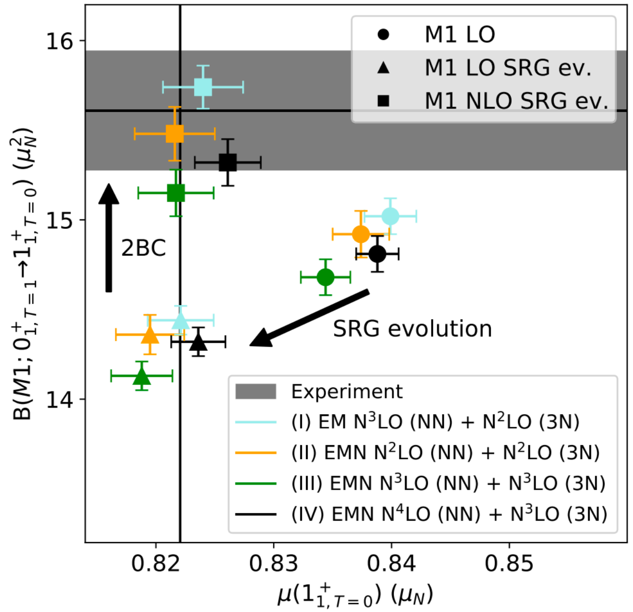
$$\boldsymbol{\mu}_{2\mathrm{B}} = -\frac{i}{2}\nabla_{\boldsymbol{Q}}\times$$  $$(\boldsymbol{Q}\to\mathbf{0})$$

- 2BC effect is well tested in light systems.
- What about heavier systems?

S. Pastore et al., Phys. Rev. C 87, 035503 (2013).



U. Friman-Gayer et al., Phys. Rev. Lett. 126, 102501 (2021).



Magnetic moment

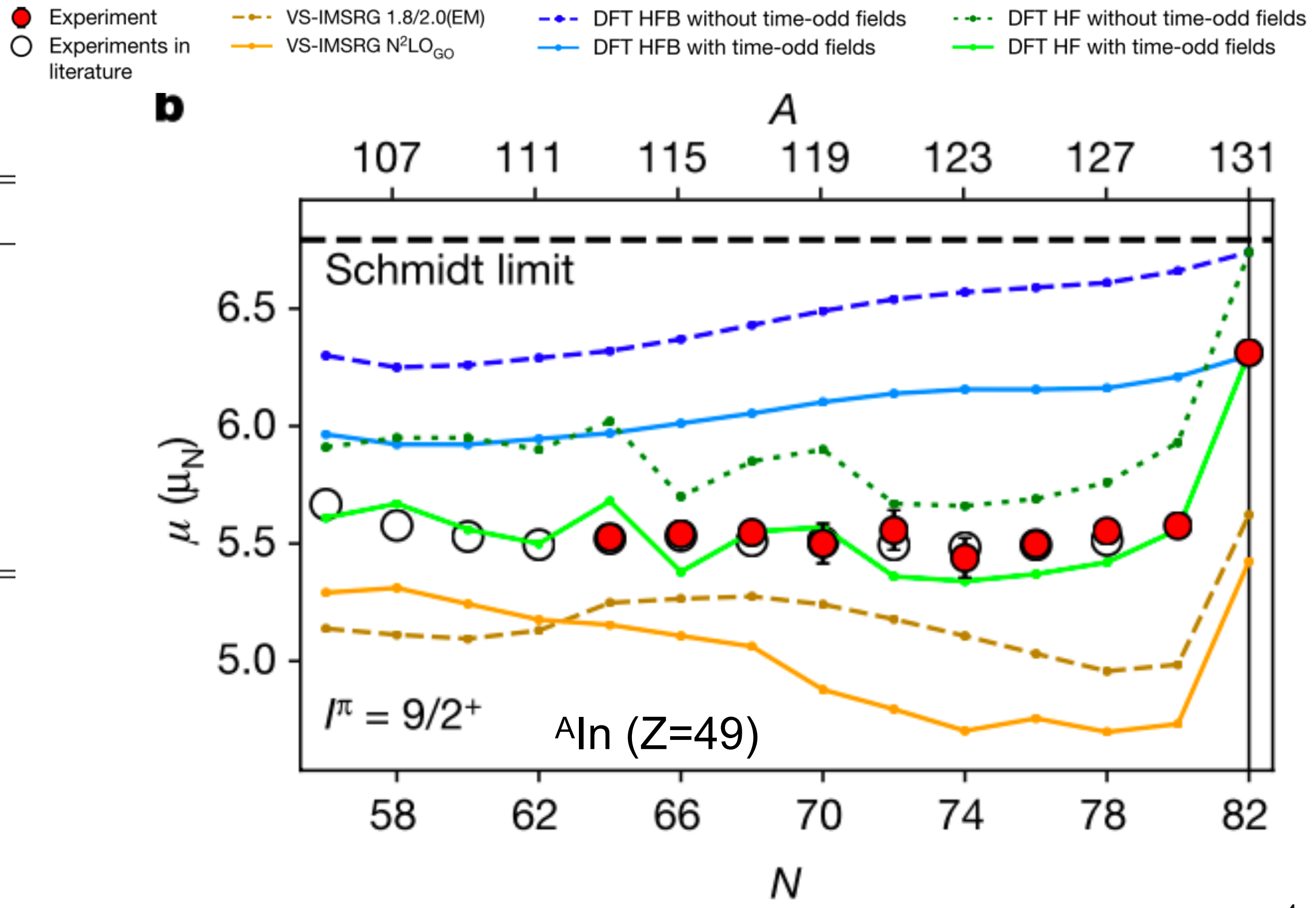
A. Klose et al., Phys. Rev. C 99, 061301 (2019).

A. R. Vernon et al., Nature 607, 260 (2022).

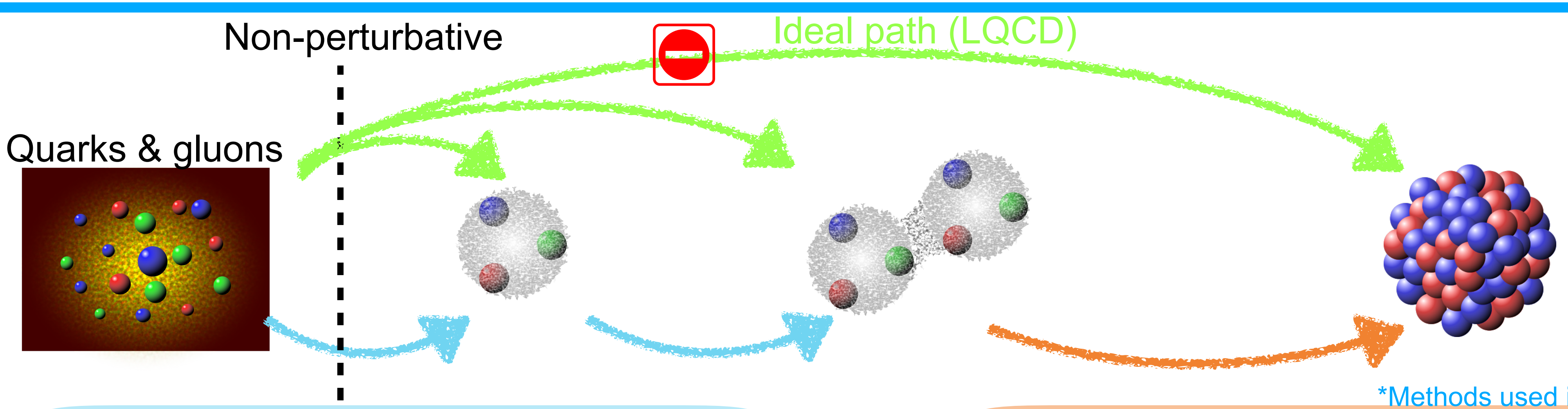
VS-IMSRG, 1.8/2.0 (EM)

A		$Z = 20$	$N = 20$
	sp g^{free}	+1.148	+0.124
39	Expt.	+1.0217(1) [23]	+0.3915073(1) [24]
	sp g^{eff}	+0.930	+0.469
	VS-IMSRG	+1.349	−0.035
37	Expt.	+0.7453(72)	+0.6841236(4) [25]
	USDA-EM1	+0.770	+0.677
	USDB-EM1	+0.754	+0.675
	VS-IMSRG	+1.055	+0.290

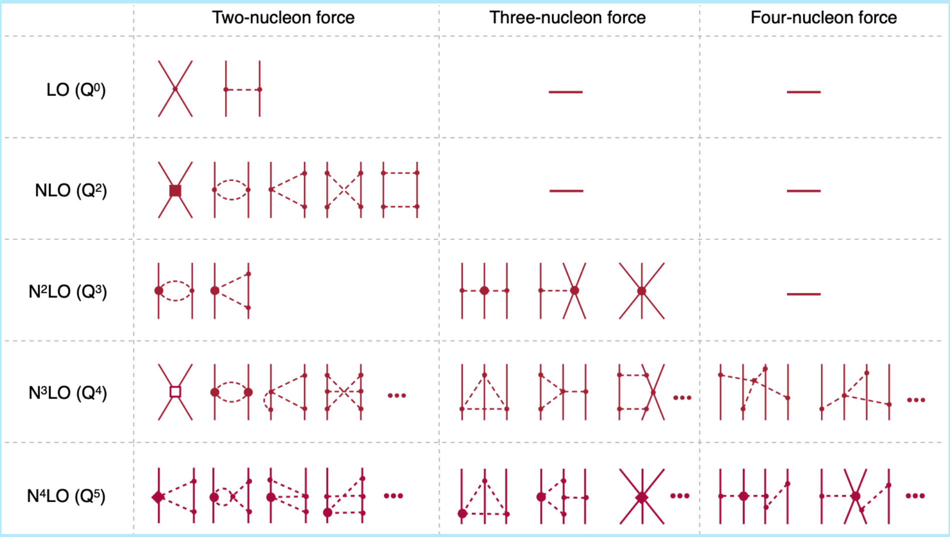
of ^{36}Ca. Compared to the USDA/B-EM1 calculations, the VS-IMSRG agrees with the dominance of the (620) partition for ^{36}Ca. However, the amount of the (522) partition that gives the core-polarization correction is a factor of 2 larger. The deviation is likely due to meson-exchange currents [39], which are not included in the present VS-IMSRG calculations, but are included indirectly through the effective g factors in the USDA/B-EM1 calculations.



Nuclear ab initio calculations



*Methods used in this work



Weinberg, van Kolck, Kaiser, Epelbaum, Glöckle, Meißner, Entem, Machleidt, Eskröm,…

Nuclear many-body problem

- Green's function Monte Carlo
- No-core shell model
- Nuclear lattice effective field theory
- Self-consistent Green's function
- Coupled-cluster
- In-medium similarity renormalization group*
- Many-body perturbation theory
- …

Nuclear interaction from chiral EFT

Weinberg, van Kolck, Kaiser, Epelbaum, Glöckle, Meißner, Entem, Machleidt, …

- Lagrangian construction
  - ✦ Chiral symmetry
  - ✦ Power counting
- Systematic expansion
  - ✦ Unknown LECs
  - ✦ Many-body interactions
  - ✦ Estimation of truncation error

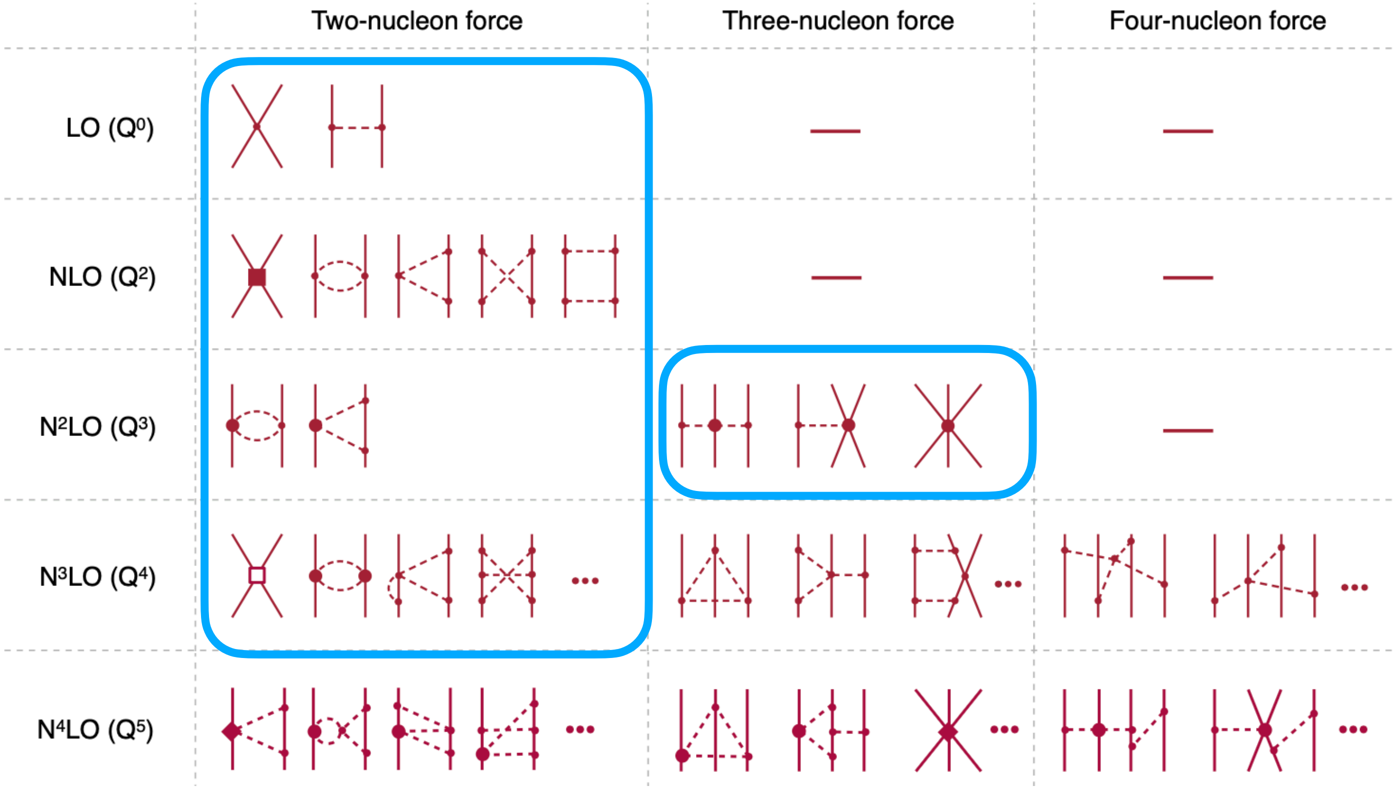
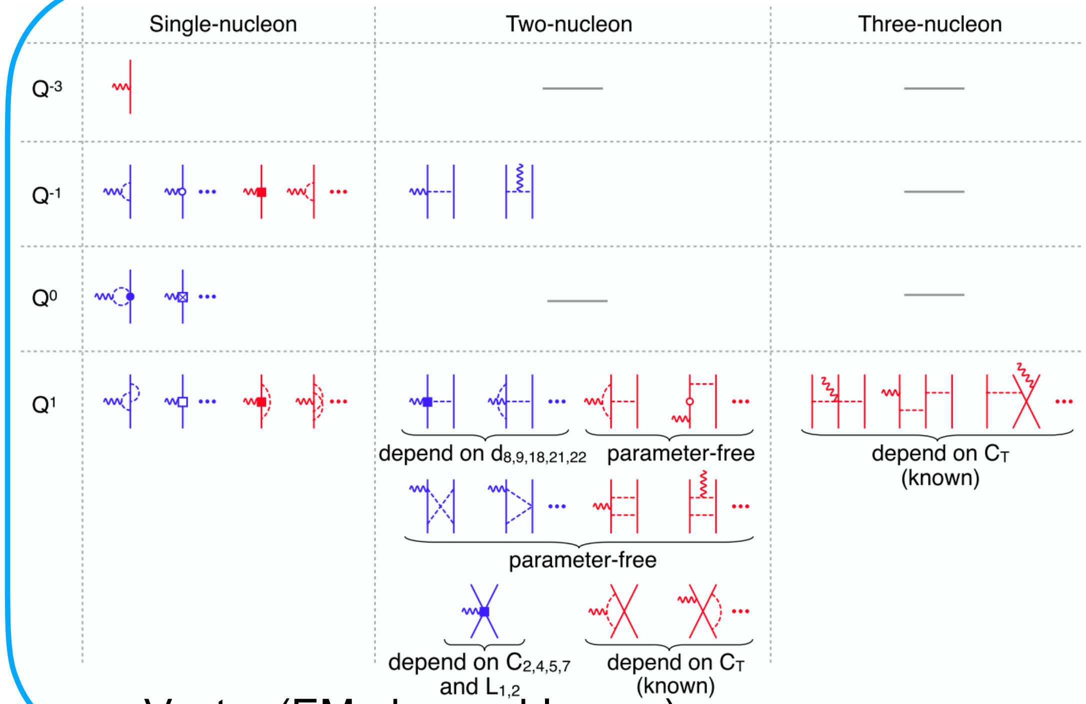


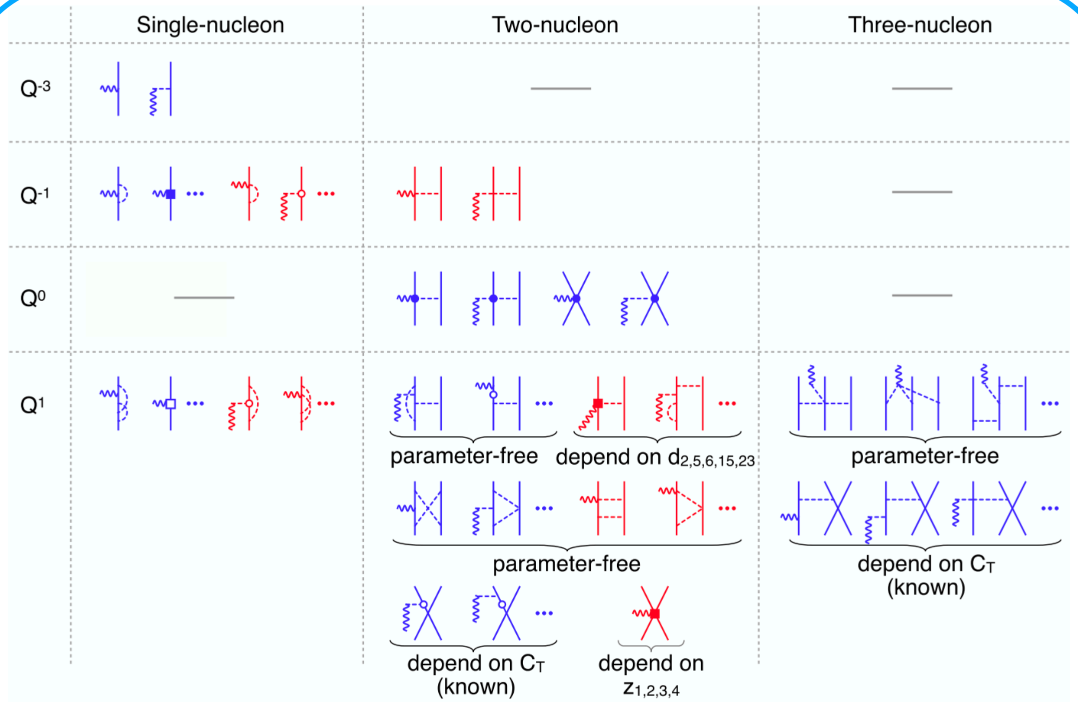
Figure is from E. Epelbaum, arXiv: 1510.07036

Nuclear currents from chiral EFT

- Nuclear observables (EM properties, beta decay, …) are measured through the interaction between a nucleus and external field.
- Chiral EFT allows us a systematic expansion for charge and current operators.



Vector (EM observables, …)



Axial vector (GT transition, …)

E. Epelbaum, arXiv:1908.09349.

Nuclear currents from chiral EFT

- Nuclear observables (EM properties, beta decay, …) are measured through the interaction between a nucleus and external field.
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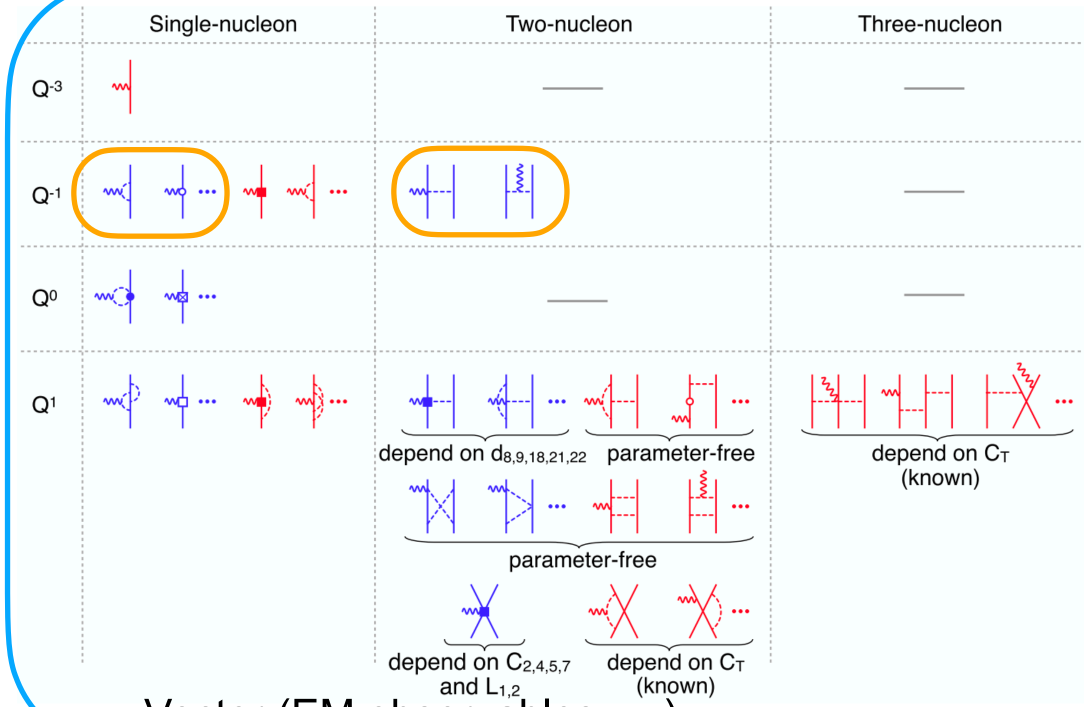

Vector (EM observables, …)

$$r_{ch}^2 = -\frac{6}{Z}\frac{1}{(4\pi)^{3/2}}\lim_{Q\to 0}\frac{d}{dQ^2}\int d\hat{\boldsymbol{Q}}\tilde{\rho}(\boldsymbol{Q})$$

$$Q_{20} = -\frac{15}{8\pi}\lim_{Q\to 0}\frac{d^2}{dQ^2}\int d\hat{\boldsymbol{Q}}Y_{20}(\hat{\boldsymbol{Q}})\tilde{\rho}(\boldsymbol{Q})$$

$$M_{10} = -i\frac{3}{8\pi}\lim_{Q\to 0}\frac{d}{dQ}\int d\hat{\boldsymbol{Q}}\left\{[\boldsymbol{Q}\times\nabla_{\boldsymbol{Q}}]Y_{10}(\hat{\boldsymbol{Q}})\right\}\cdot\tilde{\boldsymbol{j}}(\boldsymbol{Q})$$

Focus of this talk

Valence-space in-medium similarity renormalization group

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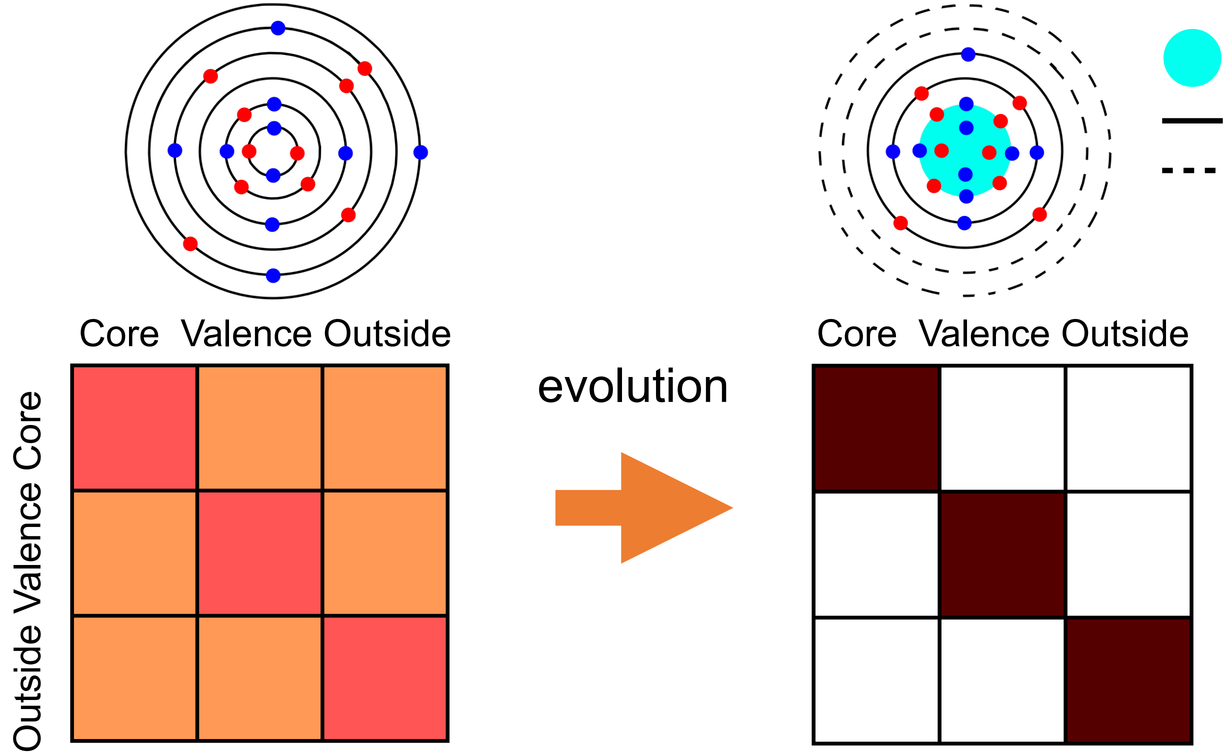


Similarity transformation

$$H \qquad H(s) = e^{\Omega(s)} H e^{-\Omega(s)}$$

$$H(s) \approx E(s) + \sum_{12} f_{12}(s)\{a_1^\dagger a_2\} + \frac{1}{4}\sum_{1234} \Gamma_{1234}(s)\{a_1^\dagger a_2^\dagger a_4 a_3\}$$

s: flow parameter

$$\frac{d\Omega}{ds} = \eta(s) - \frac{1}{2}[\Omega(s), \eta(s)] + \cdots$$

$$\eta(s) = \sum_{12} \eta_{12}(s)\{a_1^\dagger a_2\} + \sum_{1234} \eta_{1234}(s)\{a_1^\dagger a_2^\dagger a_4 a_3\}$$

$$\eta_{12} = \frac{1}{2}\arctan\left(\frac{2f_{12}}{f_{11} - f_{22} + \Gamma_{1212} + \Delta}\right)$$

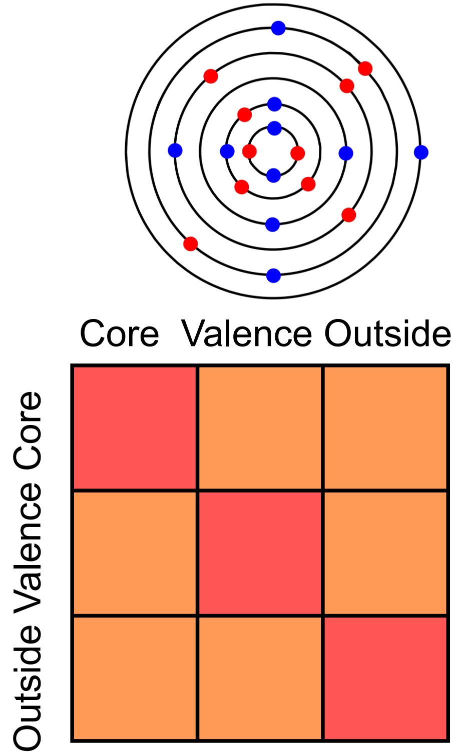
$$\eta_{1234} = \frac{1}{2}\arctan\left(\frac{2\Gamma_{1234}}{f_{11} + f_{22} - f_{33} - f_{44} + A_{1234} + \Delta}\right)$$

$$A_{1234} = \Gamma_{1212} + \Gamma_{3434} - \Gamma_{1313} - \Gamma_{2424} - \Gamma_{1414} - \Gamma_{2323}$$

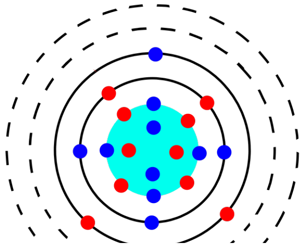
f_{12}, Γ_{1234} : matrix element we want to suppress

$$\mathcal{O}(s) = e^{\Omega(s)} \mathcal{O} e^{-\Omega(s)} \approx \mathcal{O}^{[0]}(s) + \sum_{12} \mathcal{O}^{[1]}_{12}(s)\{a_1^\dagger a_2\} + \frac{1}{4}\sum_{1234} \mathcal{O}^{[2]}_{1234}(s)\{a_1^\dagger a_2^\dagger a_4 a_3\}$$

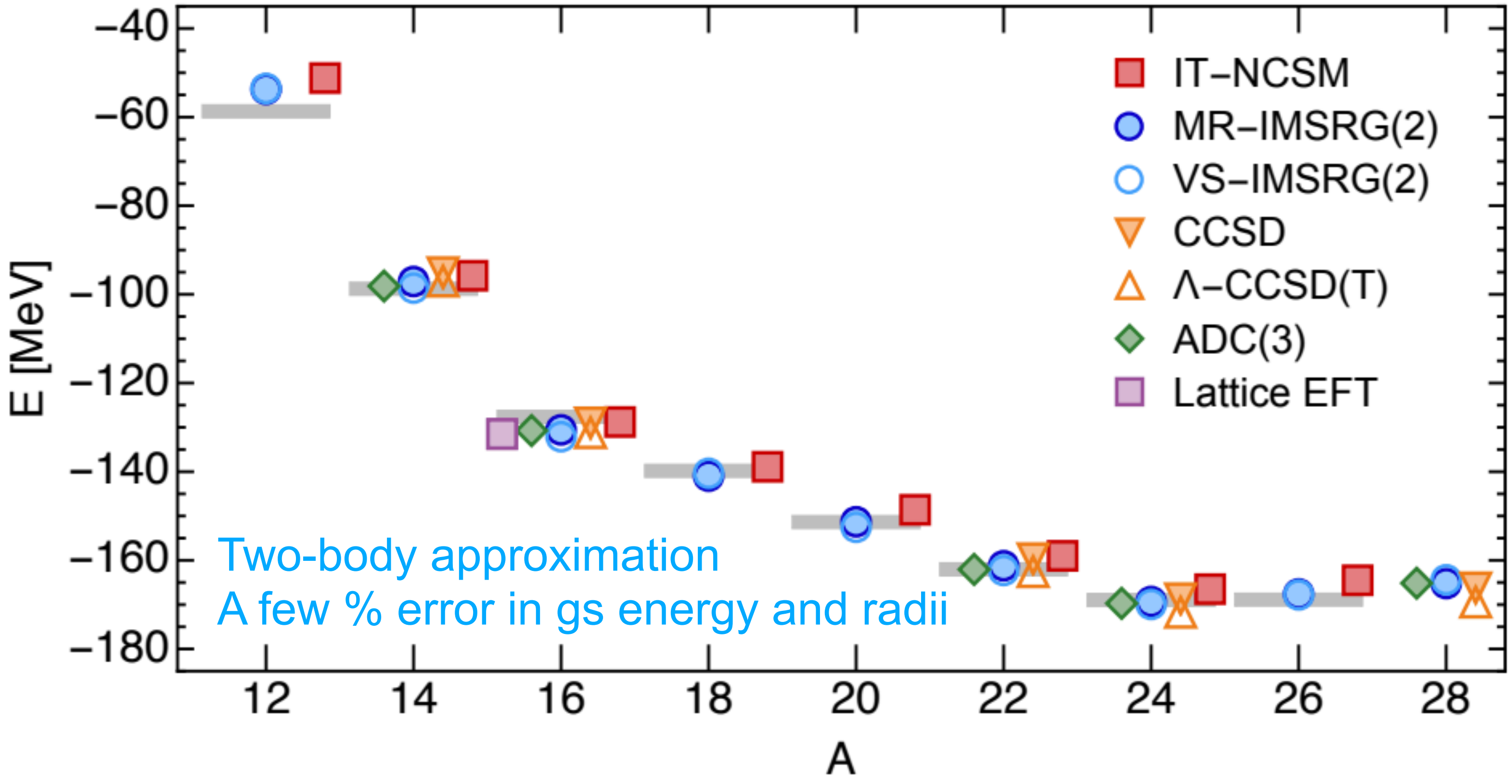
Valence-space in-medium similarity renormalization group



evolution



$$\frac{d\Omega}{ds} = \eta(s) - \frac{1}{2}[\Omega(s), \eta(s)] + \cdots$$



Similarity transform

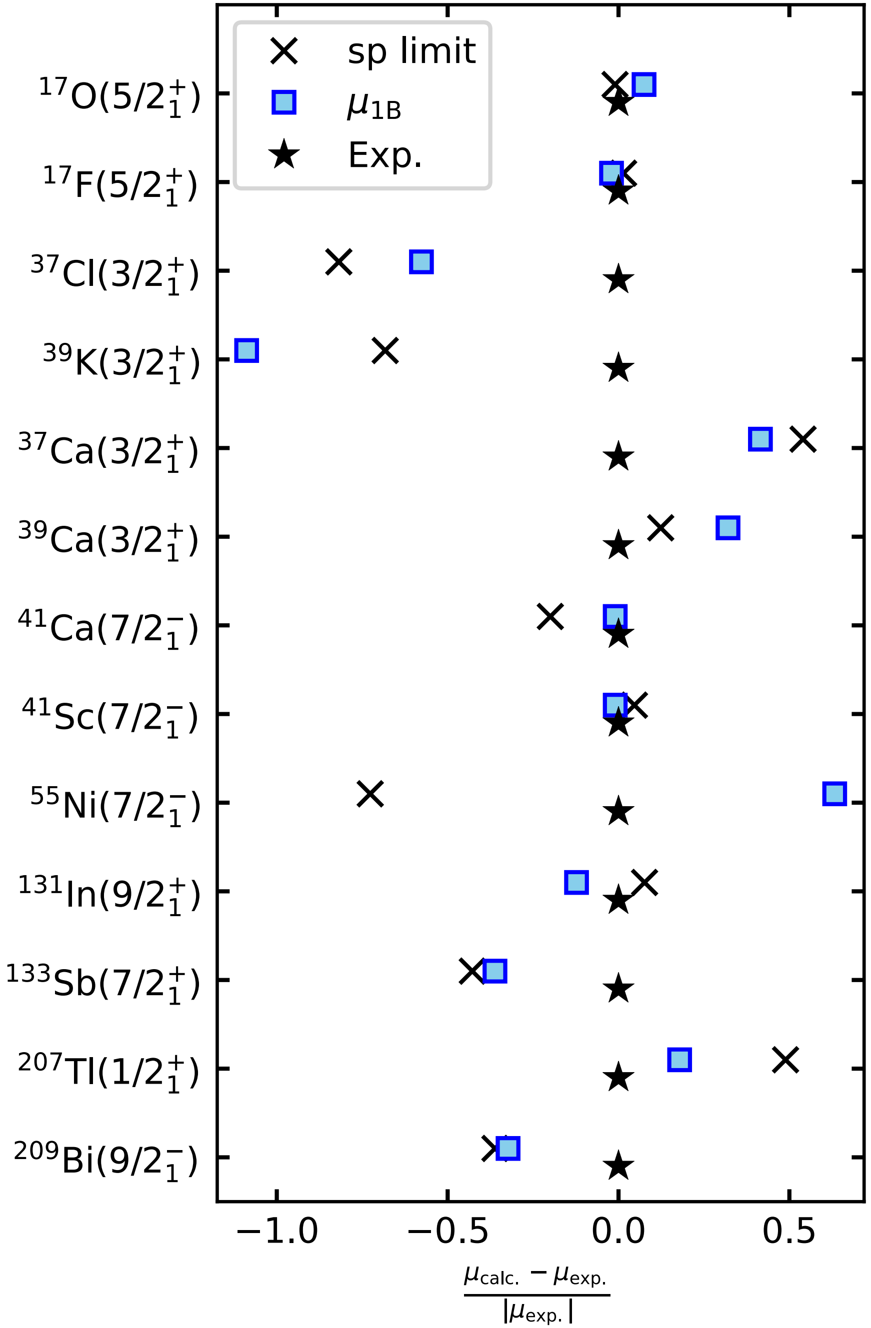
$$H$$

$$H(s) \approx E(s) + \sum_{12} f_{12}(s)\{a_1^\dagger a_2\} +$$

s: flow parameter

Magnetic dipole moments

- Magnetic moment from IMSRG.
- Single-particle analytical limits do not always explain the experimental data.
- A better agreements with IMSRG, but not perfect.



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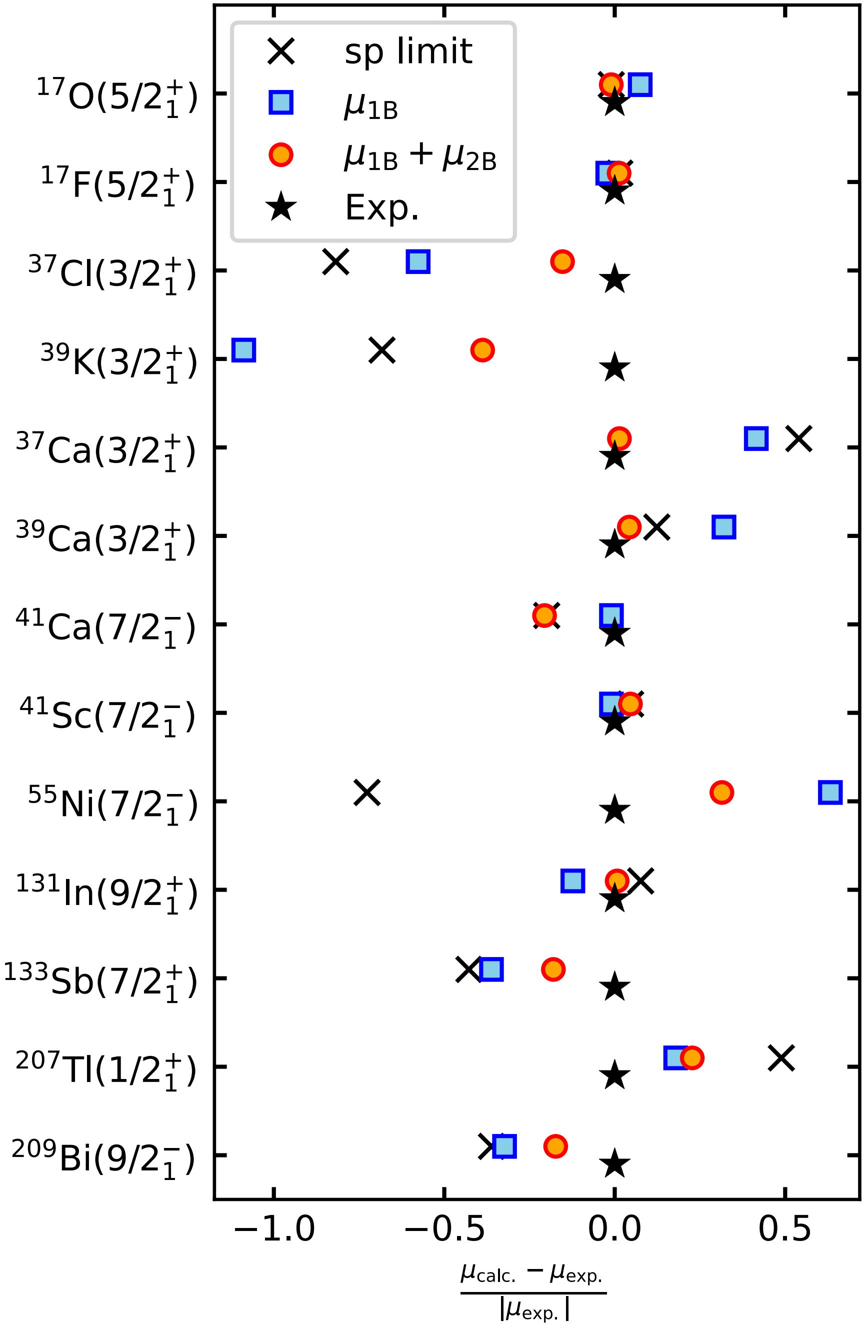
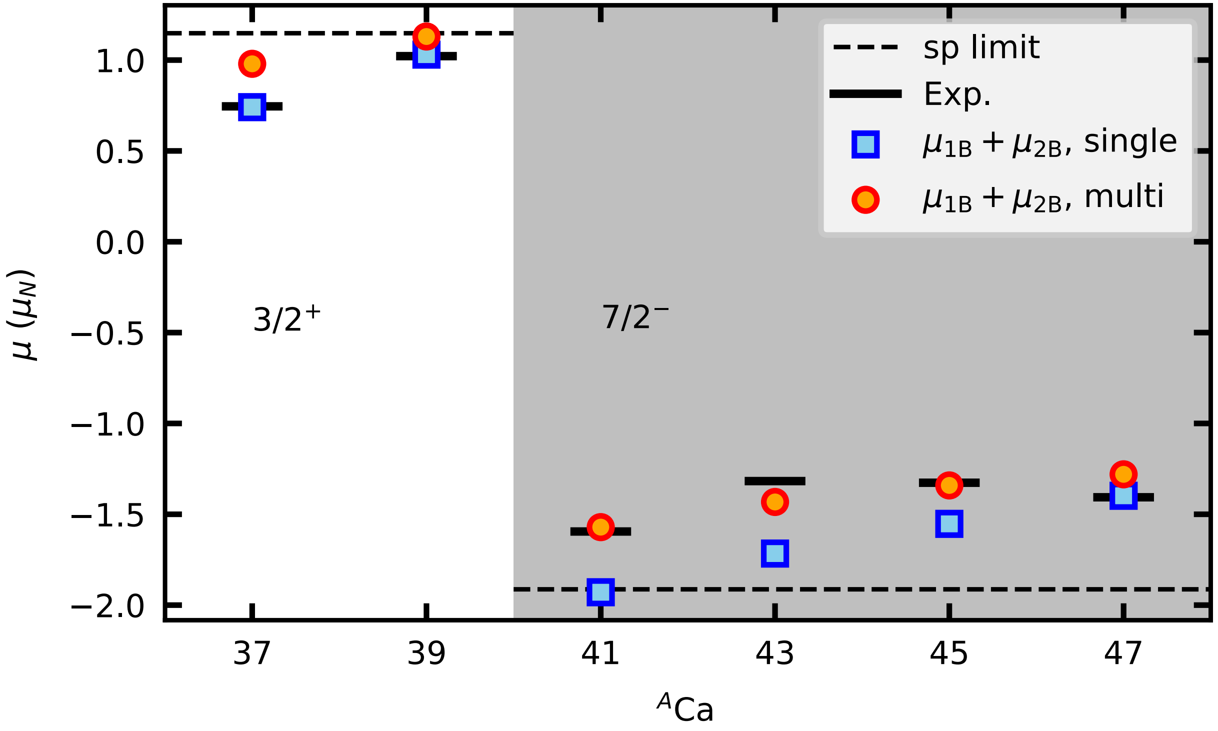
Magnetic dipole moments

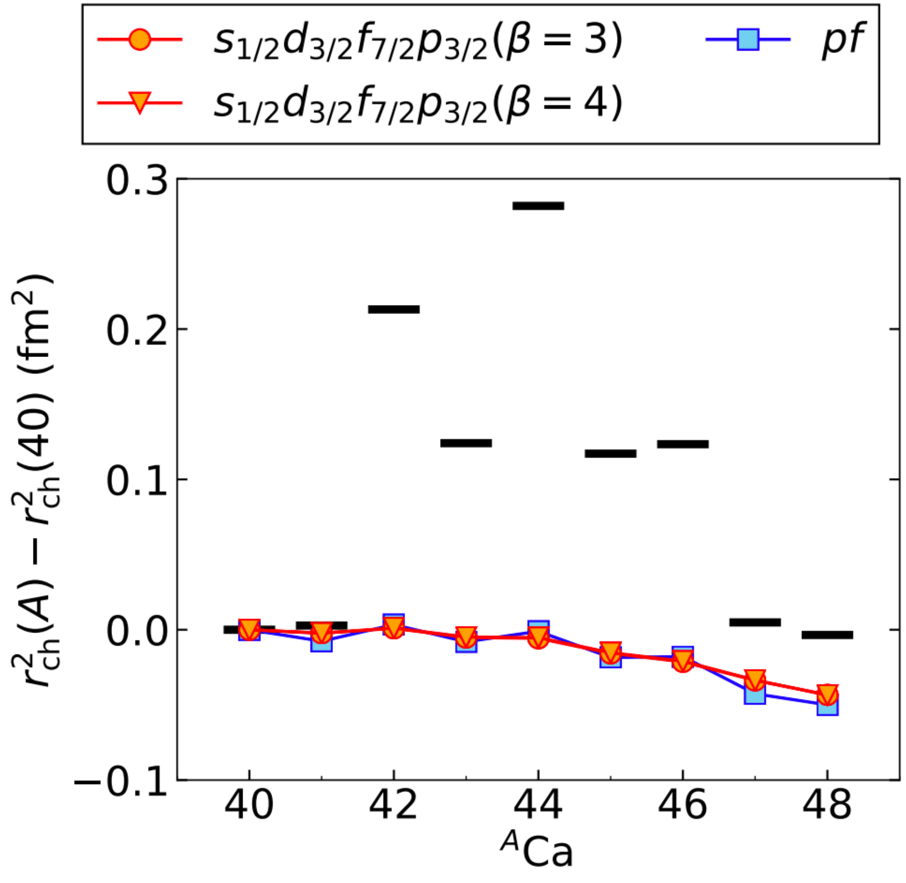
- Magnetic moment from IMSRG.
- Single-particle analytical limits do not always explain the experimental data.
- A better agreements with IMSRG, but not perfect.
- 2BC globally improves the magnetic moments.
- The magnetic transitions are next target.



Is ^{40}Ca magic?

- 2BC makes agreement worse.
- Activating ^{40}Ca core explains the magnetic moments better.
- The radii are not explained. Further investigations are needed!





TM et al., in prep.

Importance of Sachs contribution in heavier systems

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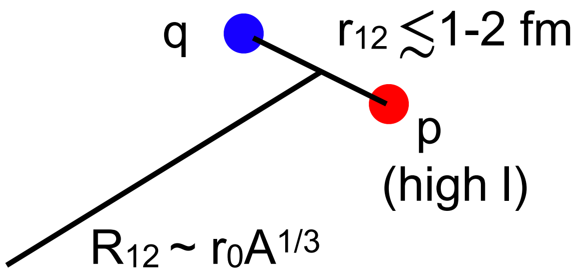
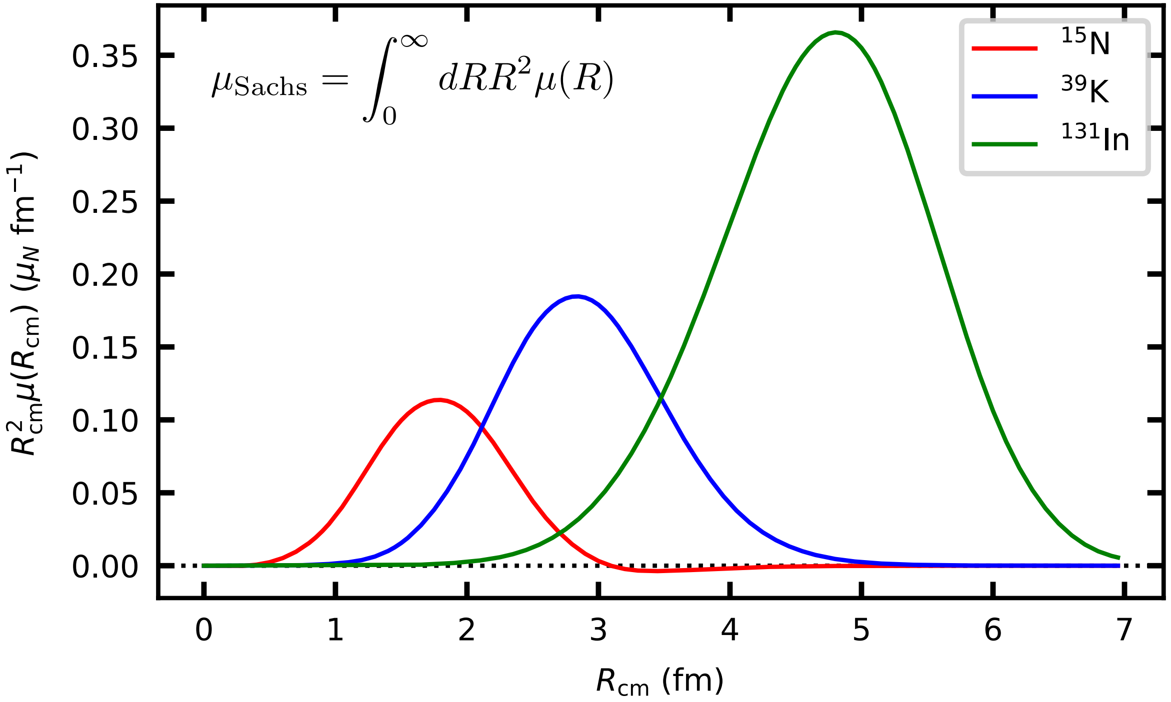


- The size of 2BC effect becomes larger in heavier systems.
- The simplest configuration limit is 0+ core + 1 particle (or hole)

$$\langle J||\mu||J\rangle \sim \sum_{q \in \mathrm{core}} \sum_{I} f(j_p, j_q, I) \langle pq : I||\mu||pq : I\rangle$$

- |r1 - r2| $\lesssim$ 1-2 fm because of pion-exchange potential $\boldsymbol{\mu}_{ij}^{\mathrm{Sachs}} \propto (\boldsymbol{R}_{ij} \times \boldsymbol{r}_{ij}) V^{\pi}(r_{ij})$



The peak position moves to larger R for heavier systems.

2BC effect on the magnetic moment becomes more important in heavier systems!

Summary

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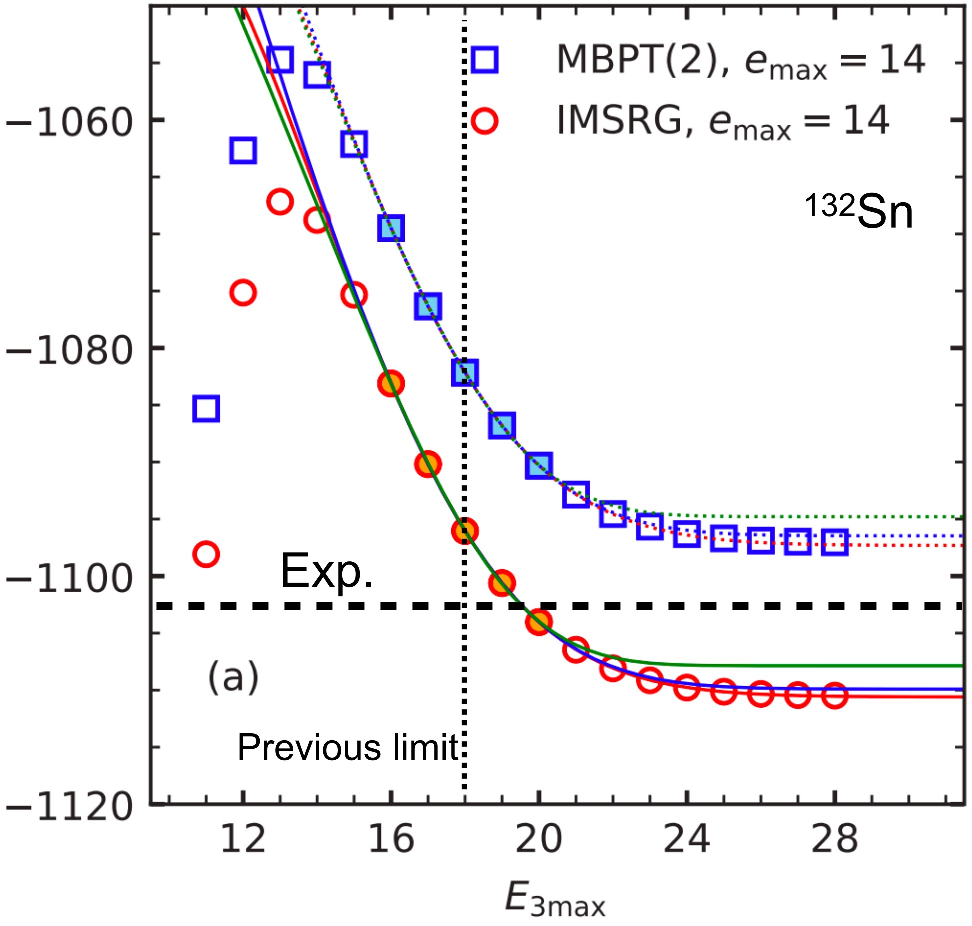
- The magnetic moments is a useful tool to investigate 2BC effect.
- The 2BC globally improves magnetic moments.
- The magnetic moments indicate weak magic in ^{40}Ca
- The 2BC effect tends to be important for heavier systems due to the two-body CM dependent Sachs contribution.

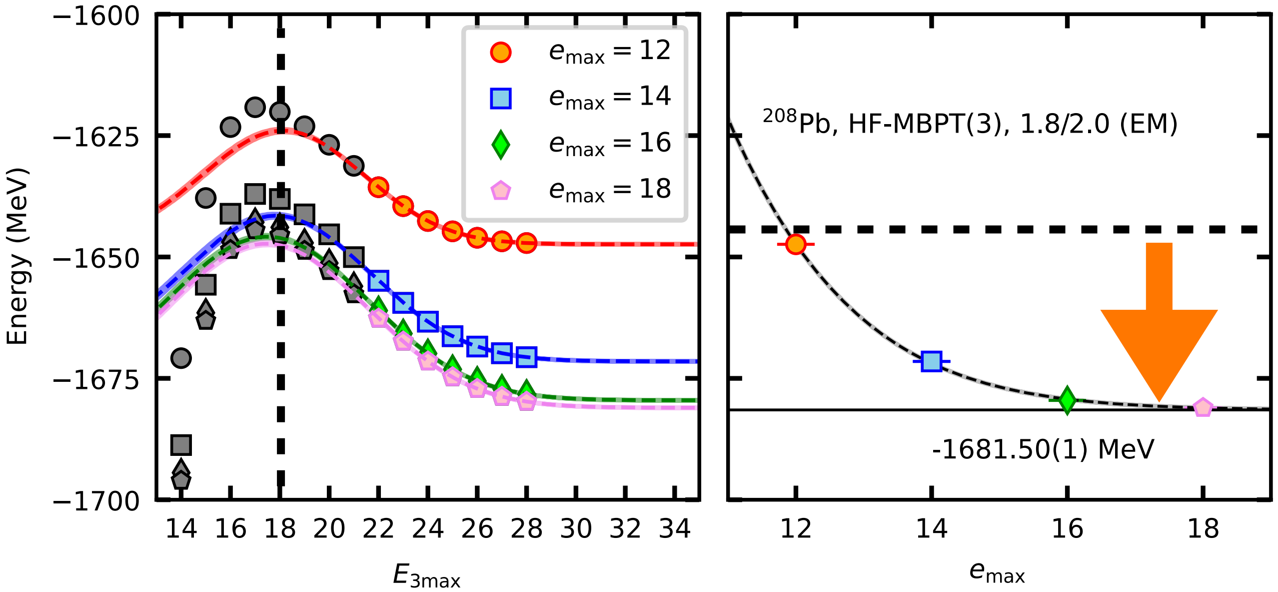
- Future works
  - Uncertainty quantification
  - M1 transition,
  - form factors
  - …

E_{3max} convergence in heavy nuclei

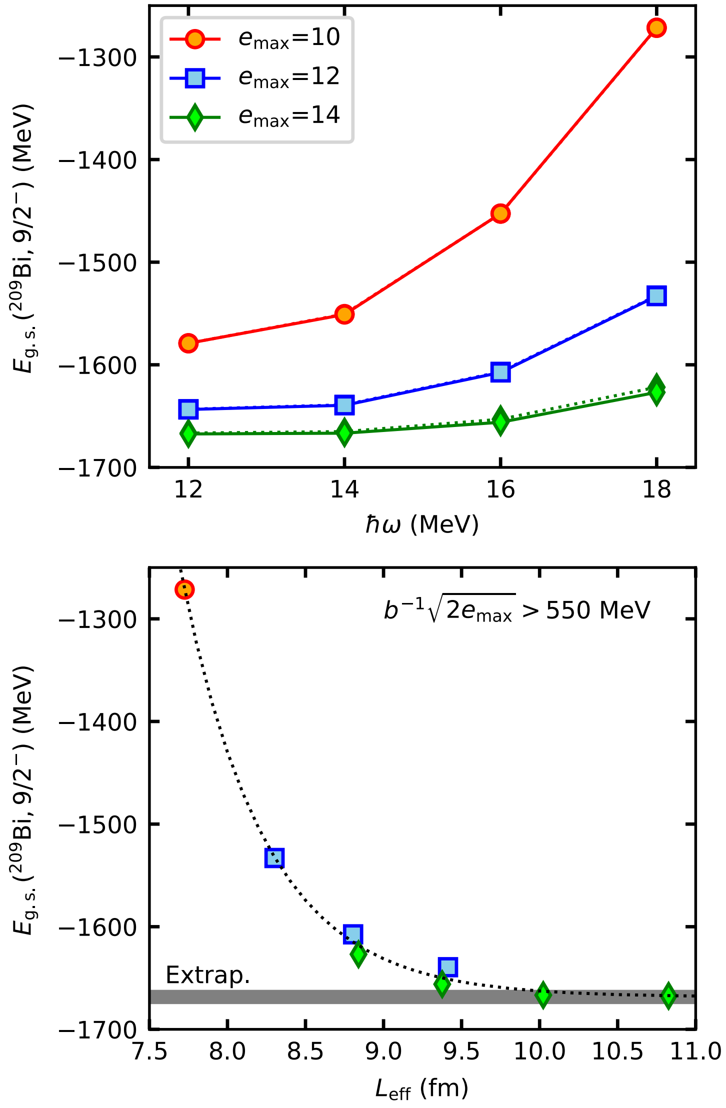
TM, S. R. Stroberg, P. Navrátil, K. Hebeler, and J. D. Holt, Phys. Rev. C 105, 014302 (2022).

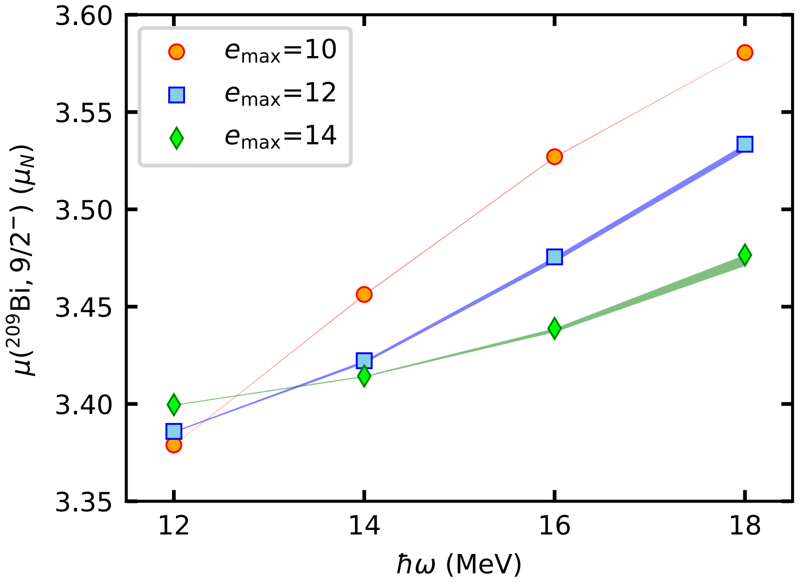


Asymptotic form: $E \approx A\gamma_{\frac{2}{n}}\left[\left(\frac{E_{3\max}-\mu}{\sigma}\right)^{n}\right] + E_{\infty}$



Convergence of ^{209}Bi





Dominance of Sachs term

- Expectation value: $\langle J||\mu_{\text{Sachs}}||J\rangle$
- The simplest limit: $|JM\rangle = [|j_i \dots j_{A-1} : 0^+\rangle|j_A m_A\rangle]\delta_{j_A J}\delta_{m_A M}$
- The expectation value depends a particle in the core and last unpaired particle.

$$
\begin{aligned}
\langle J||\mu||J\rangle &\approx \delta_{Jj_p} \sum_{q\in\text{core}} \langle p0 : j_p||\mu_{pq}||p0 : j_p\rangle \\
&= \delta_{Jj_p} \sum_{q\in\text{core}} \sum_{I} \frac{2I+1}{(2j_p+1)(2j_q+1)} \langle((pq)I, q : j_p||\mu_{pq}||(pq)I, q : j_p\rangle \\
&= \delta_{Jj_p} \sum_{q\in\text{core}} \sum_{I} \frac{2I+1}{2j_q+1} (-1)^{j_p+j_q+I+1} \begin{Bmatrix} j_p & I & j_q \\ I & j_p & 1 \end{Bmatrix} \langle pq : I||\mu||pq : I\rangle
\end{aligned}
$$

TM et al., in prep.