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Quantum Monte Carlo calculations for next-generation electroweak physics experiments

Garrett King

Next-generation ab initio nuclear theory
ECT*, Trento, Italy
7/17/2025

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Exciting new experimental directions

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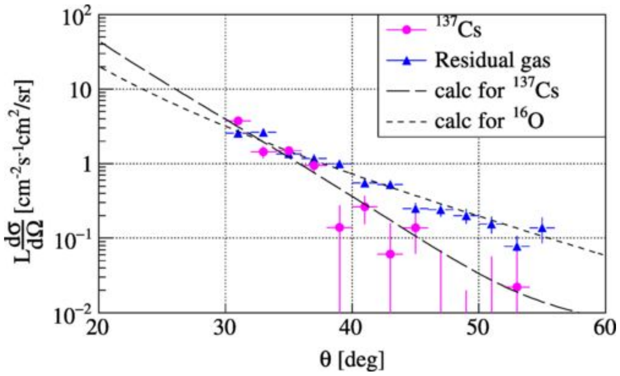
First Observation of Electron Scattering from Online-Produced Radioactive Target

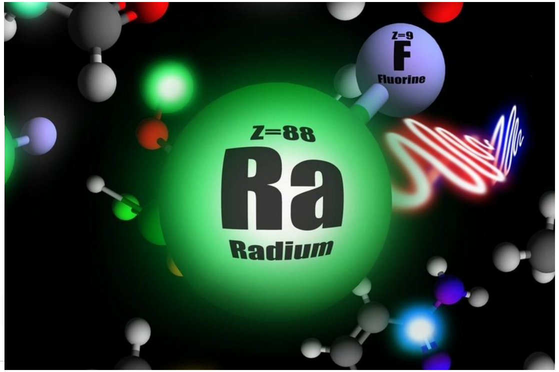
K. Tsukada[1,2], Y. Abe[2], A. Enokizono[2,3], T. Goke[4], M. Hara[2], Y. Honda[2,4], T. Hori[2], S. Ichikawa[2,*], Y. Ito[1] *et al.*

Show more

Phys. Rev. Lett. **131**, 092502 – **Published 30 August, 2023**

DOI: https://doi.org/10.1103/PhysRevLett.131.092502





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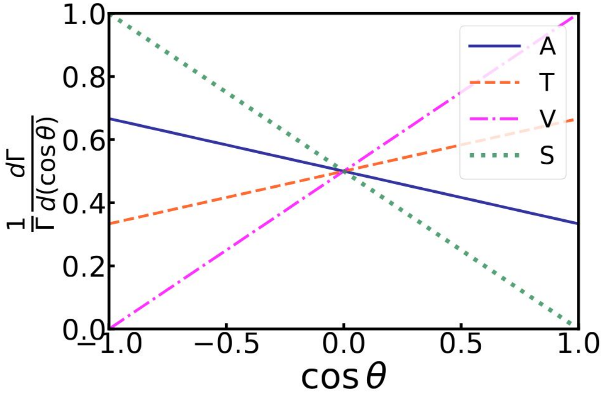
β-decays as a bridge to new physics

Weak currents with different transformation properties prefer different lepton angles

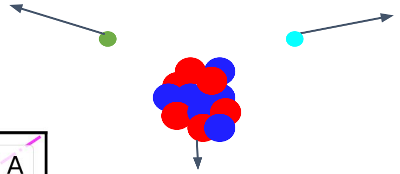
Standard Model is a vector minus axial theory

BSM tensor and scalar currents could interfere with standard current, changing kinematics

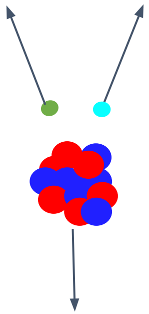
Neutrino mass would remove some phase space for the outgoing electron



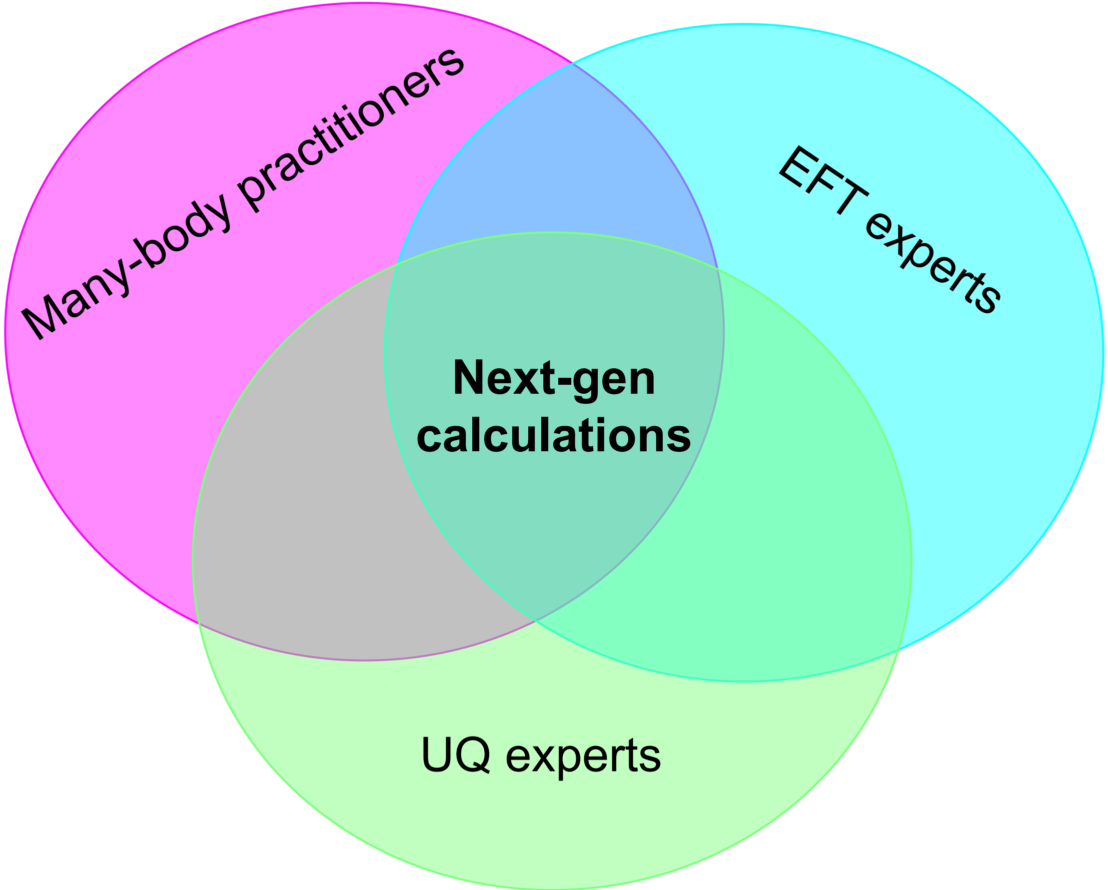
θ ~ 180°



θ ~ 0°



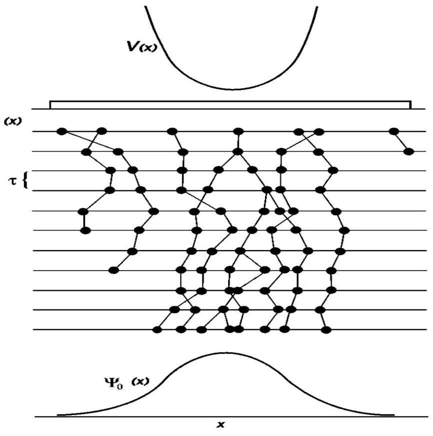
Heading into the next generation of theory



Quantum Monte Carlo

Solving the many-body problem using random sampling to compute integrals

Variational MC wave function $|\Psi_T\rangle = \mathcal{F}|\Phi\rangle$ contains model wave function and many-body correlations optimized by minimizing:



$$E_V = \min \left\{ \frac{\langle \Psi_T | H | \Psi_T \rangle}{\langle \Psi_T | \Psi_T \rangle} \right\} \geq E_0$$

Green's function MC improves by ***removing excited state contamination and gives the exact ground state***

$$\lim_{\tau \to \infty} e^{-(H-E_0)\tau} \Psi_V = \lim_{\tau \to \infty} e^{-(H-E_0)\tau} \left(c_0 \psi_0 + \sum_{i=1}^{N} c_i \psi_i \right) \to c_0 \psi_0$$

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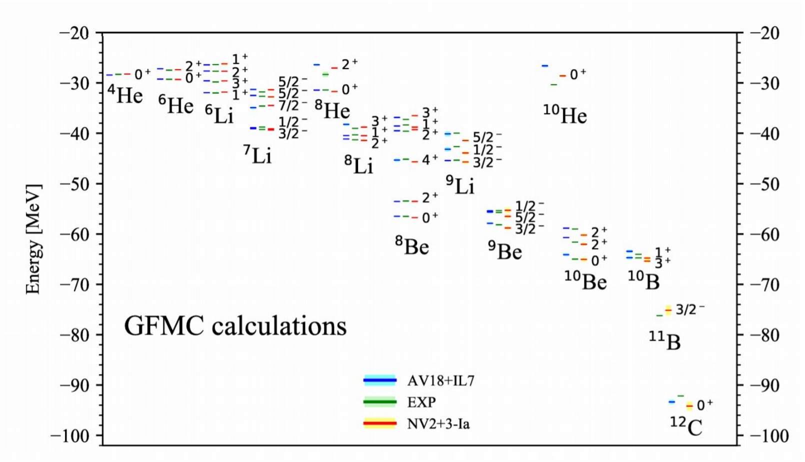
Foulkes et al. Rev. Mod. Phys. 73, 33 (2001)

The Norfolk (NV2+3) interaction

$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$



Model based on χEFT with pion, nucleon, and delta degrees of freedom by **Piarulli et al. [PRL 120, 052503 (2018)]**

NV2 contains 26 unknown LECs in contacts, two more from the NV3

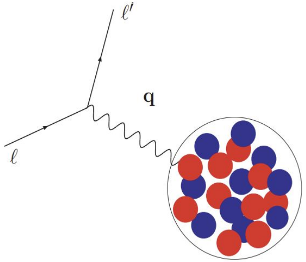
Eight model classes arrived at from different procedures to constrains the unknown LECs

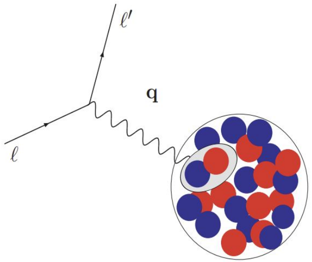
Electroweak charge and current operators

Need electromagnetic and weak current operators to study decays/transitions

Schematically:
$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots$$
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

External field interacts with single nucleons and correlated pairs of nucleons





Pastore et al. PRC 80, 034004 (2009), Pastore et al. PRC 84, 024001 (2011), Piarulli et al. PRC 87, 014006 (2013), Schiavilla et al. PRC 99, 034005 (2019)

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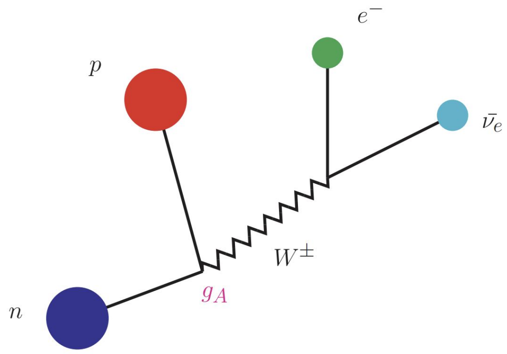
Beta decay

Composed of Fermi (S=0) and Gamow-Teller "GT" transition (S=1)

GT is mediated by purely axial vector transition operator

Connected to experiment via:

$$\Gamma_\beta \propto |M_\beta|^2 = |M_{\mathrm{F}}|^2 + \frac{g_A^2}{g_V^2}|M_{\mathrm{GT}}|^2$$

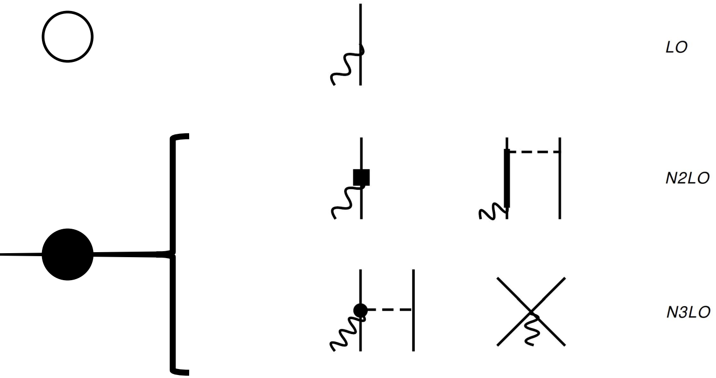


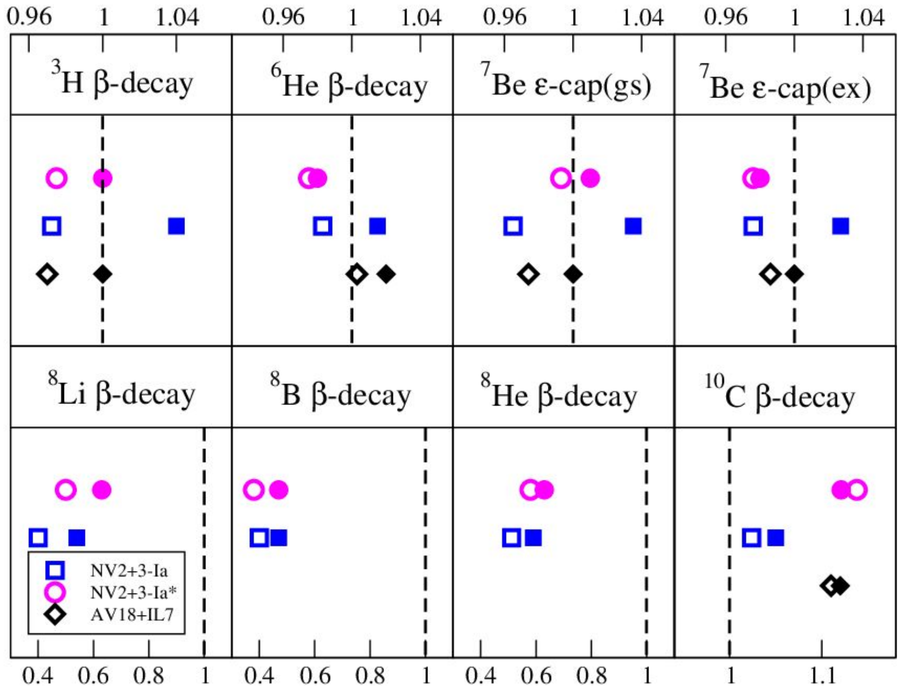
Gamow-Teller matrix elements

Calculations with NV2+3-Ia* and NV2+3-Ia compared to AV18+IL7 (◊) and exp (dashes)

Correlations quench strongly in light nuclei

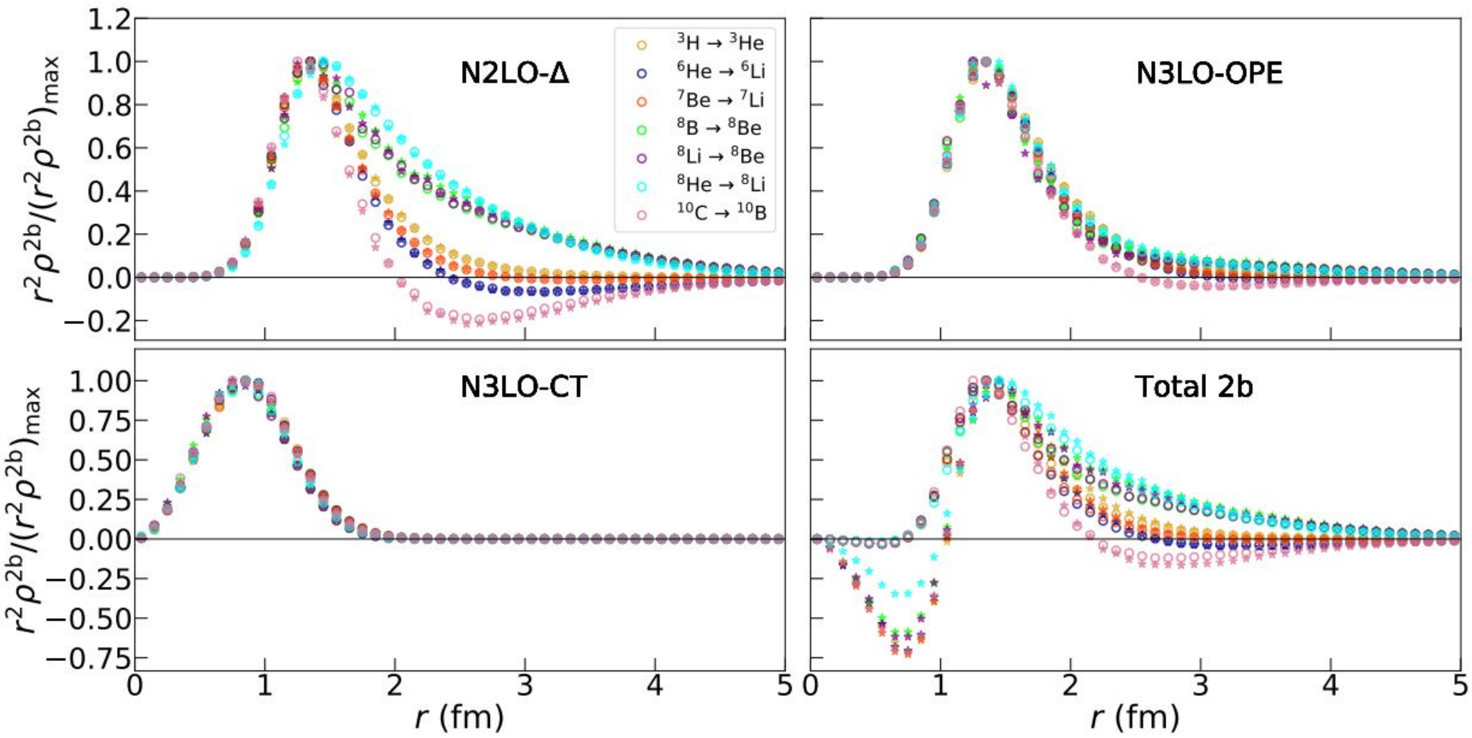
Two-body almost always enhances





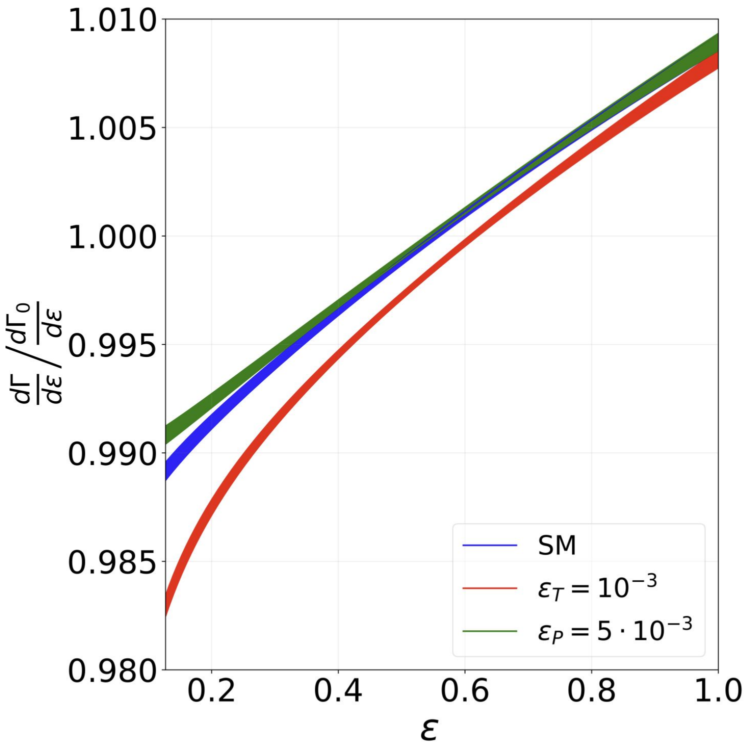
King et al. PRC 121, 025501 (2020)

Universal behavior in GT two-body densities



King et al. PRC 121, 025501 (2020)

^{6}He β-decay spectrum: BSM connections



Include new physics with strengths ϵ_i allowed from current analyses **[from Cirigliano, Mereghetti, …]**

Can see the effects of new physics on the SM curves

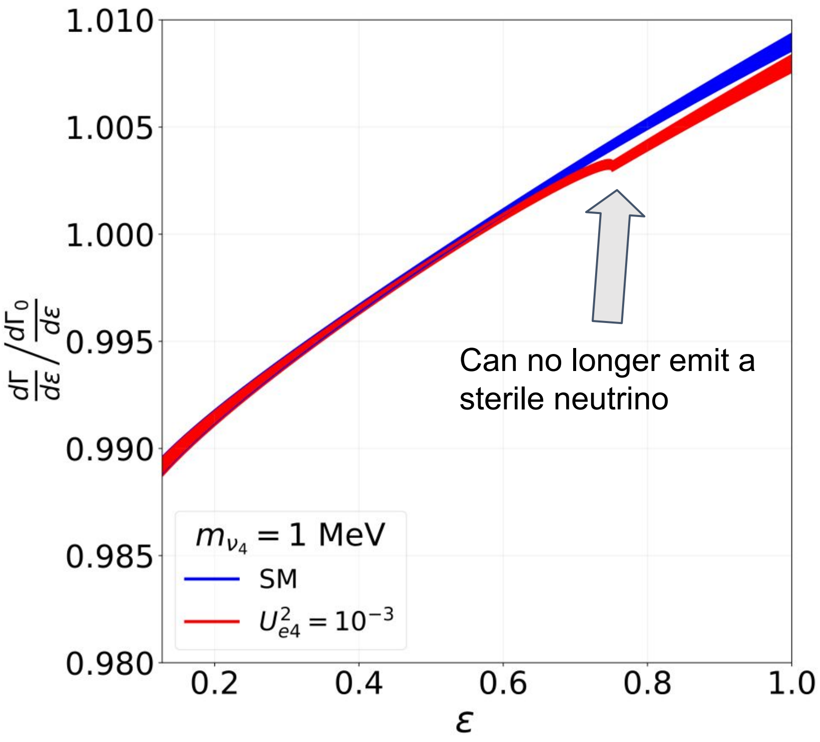
Uncertainty estimate is dominated by $O(Q_\beta^2/\Lambda_\chi^2 \sim 10^{-3})$ correction that is stable across NV2+3 models

King et al. PRC 107, 015503 (2023)

^{6}He β-decay spectrum: Probing neutrino physics

Can also investigate impacts from production of ~1 MeV sterile neutrinos

Can get a qualitative understanding of the effects new physics will generate



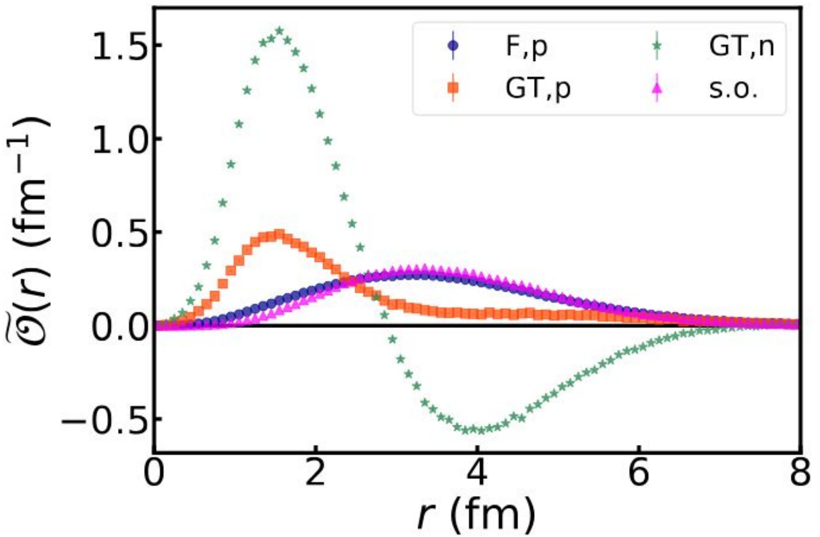
King et al. PRC 107, 015503 (2023)

$^{10}C(0+) \rightarrow {}^{10}B(0+)$ β-decay

In an effective field theory approach:

$$\delta_{\rm NS} = \sum_{m,n,i} \alpha^m E_0^n c_{m,n} M^i_{m,n}$$

Can also evaluate: $$M = \int dr C(r)$$



GFMC: $\delta_{\rm NS} = -4.05(38) \times 10^{-3} - \; -4.10(77) \times 10^{-3}$

Hardy and Towner: $\delta_{\rm NS} = -4.0(5) \times 10^{-3}$

Gennari et al PRL **134,** 012501: $\delta_{\rm NS} = -4.22(32) \times 10^{-3}$

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In collaboration with: **Mereghetti (LANL)**, Carlson (LANL), Flores (WUSTL), Gandolfi (LANL), Pastore (WUSTL), Piarulli (WUSTL)

Electron scattering cross section

$$\frac{d\sigma}{d\Omega} = 4\pi\sigma_M f_{\text{rec}}^{-1} \left[\frac{Q^4}{q^4} F_L^2(q) + \left(\frac{Q^2}{2q^2} + \tan^2\theta_e/2\right) F_T^2(q)\right]$$

Where:

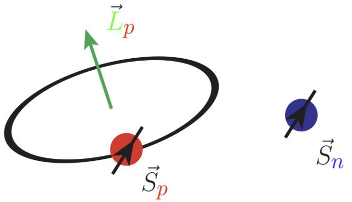
$$F_T^2(q) = F_M^2(q) = \frac{1}{2J_i+1}\sum_{L=1}^{\infty} |\langle J_f||M_L(q)||J_i\rangle|^2$$

$$F_L^2(q) = \frac{1}{2J_i+1}\sum_{L=0}^{\infty} |\langle J_f||C_L(q)||J_i\rangle|^2$$

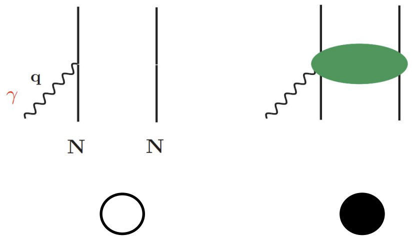
Magnetic moments

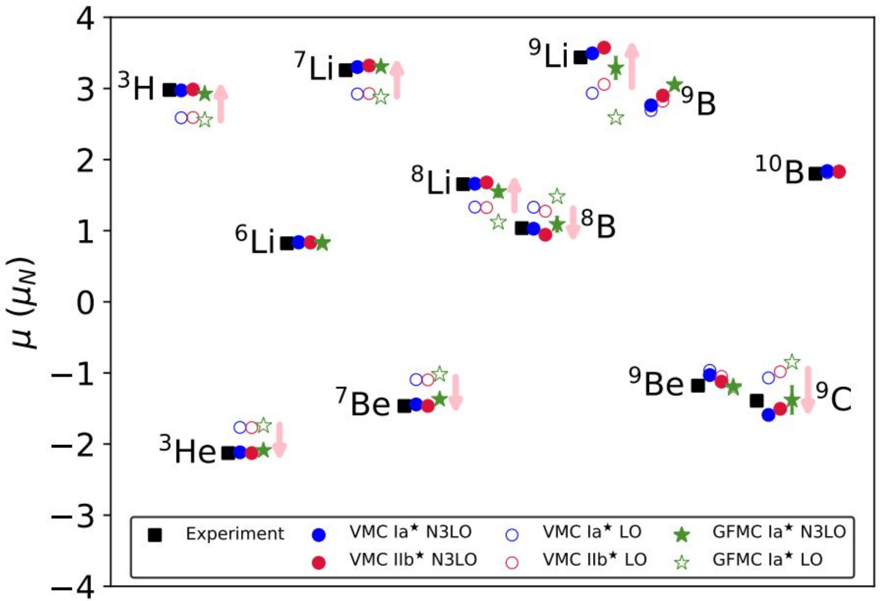
One-body picture:

$$\mu^{LO} = \sum_i \left(L_{i,z} + g_p S_{i,z}\right) \frac{1+\tau_{3,i}}{2} + g_n S_{i,z} \frac{1-\tau_{3,i}}{2}$$



Two-body currents can play a large role (up to ~33%) in describing magnetic dipole moments





Chambers-Wall, King, et al. PRL 133, 212501 (2024)
Chambers-Wall, King, et al. PRC 110, 054316 (2024)

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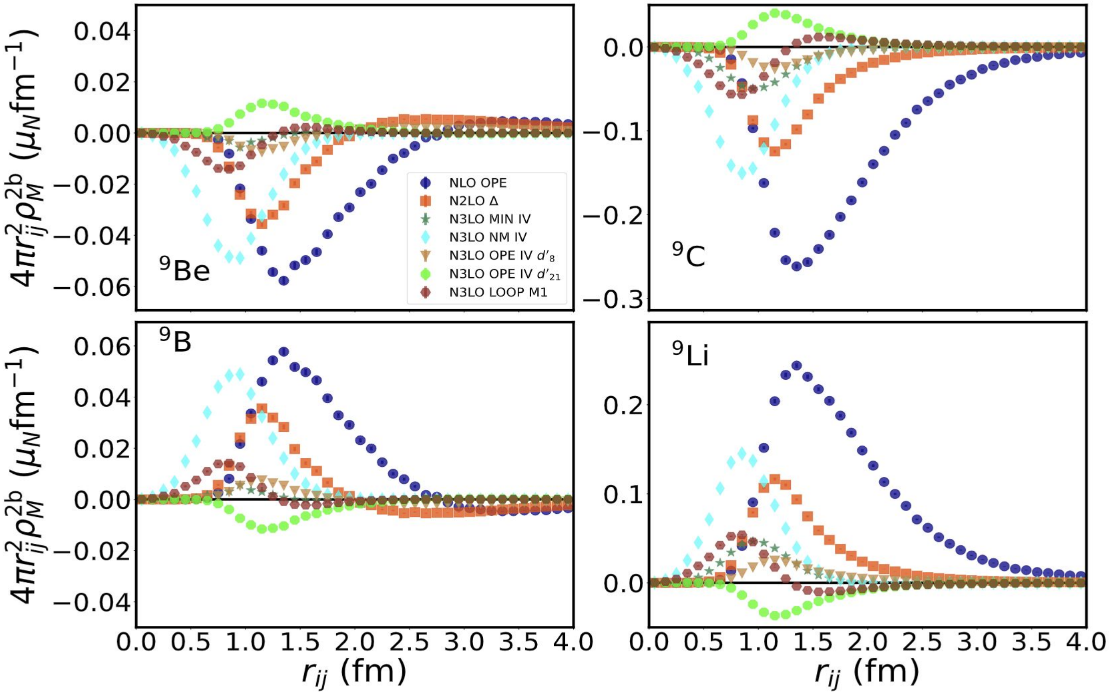
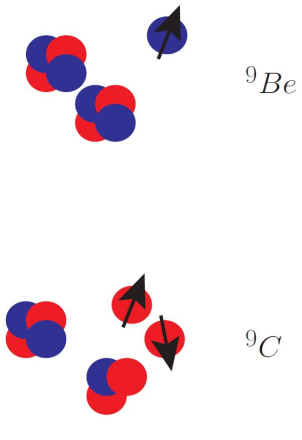
Structural effects in magnetic densities





$$\mu^{2b} = \int dr_{ij} 4\pi r_{ij}^2 \rho_M^{2b}(r_{ij})$$

Chambers-Wall et al. PRL 133, 212501 (2024)
Chambers-Wall et al. PRC 110, 054316 (2024)

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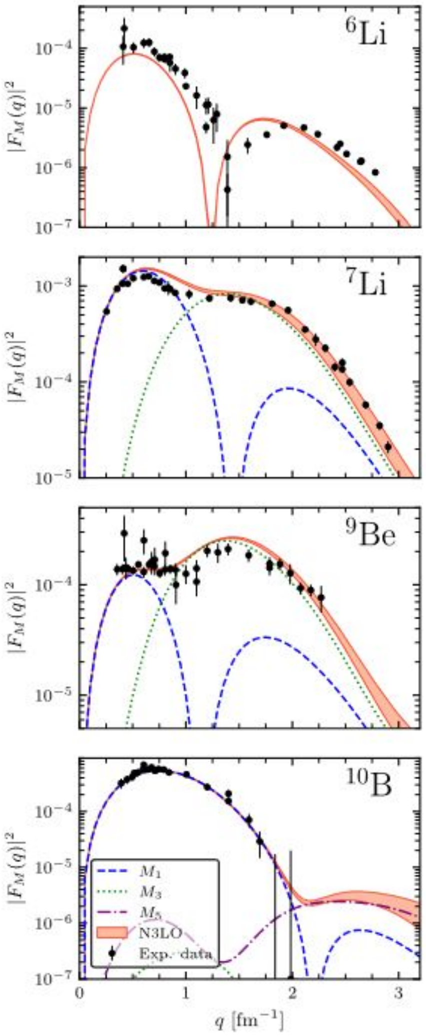
VMC magnetic form factors

NV2+3-IIb*

Form factors with naive truncation uncertainties up to N3LO in currents

Breakdown of contributions into different mulipolarities



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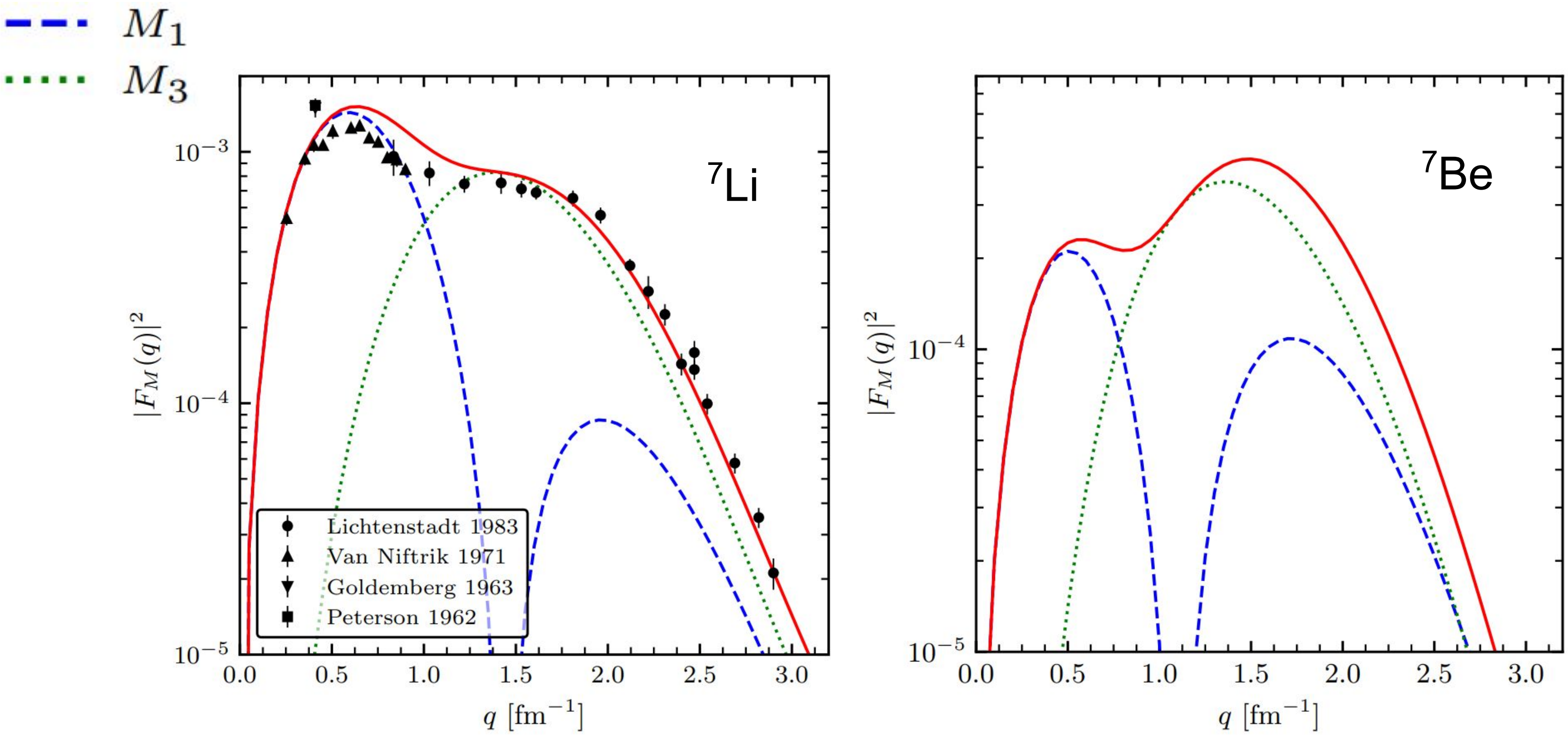
Magnetic form factors for mirror nuclei



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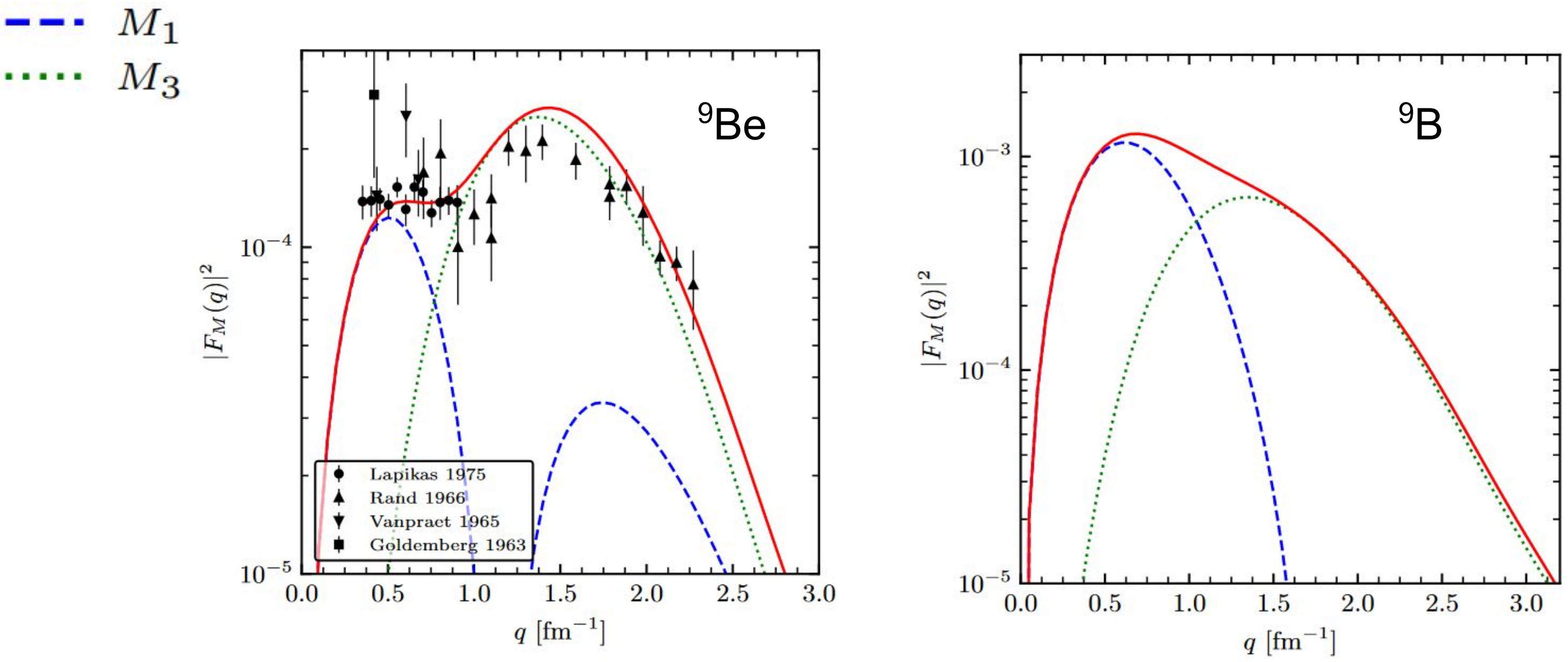
Magnetic form factors for mirror nuclei



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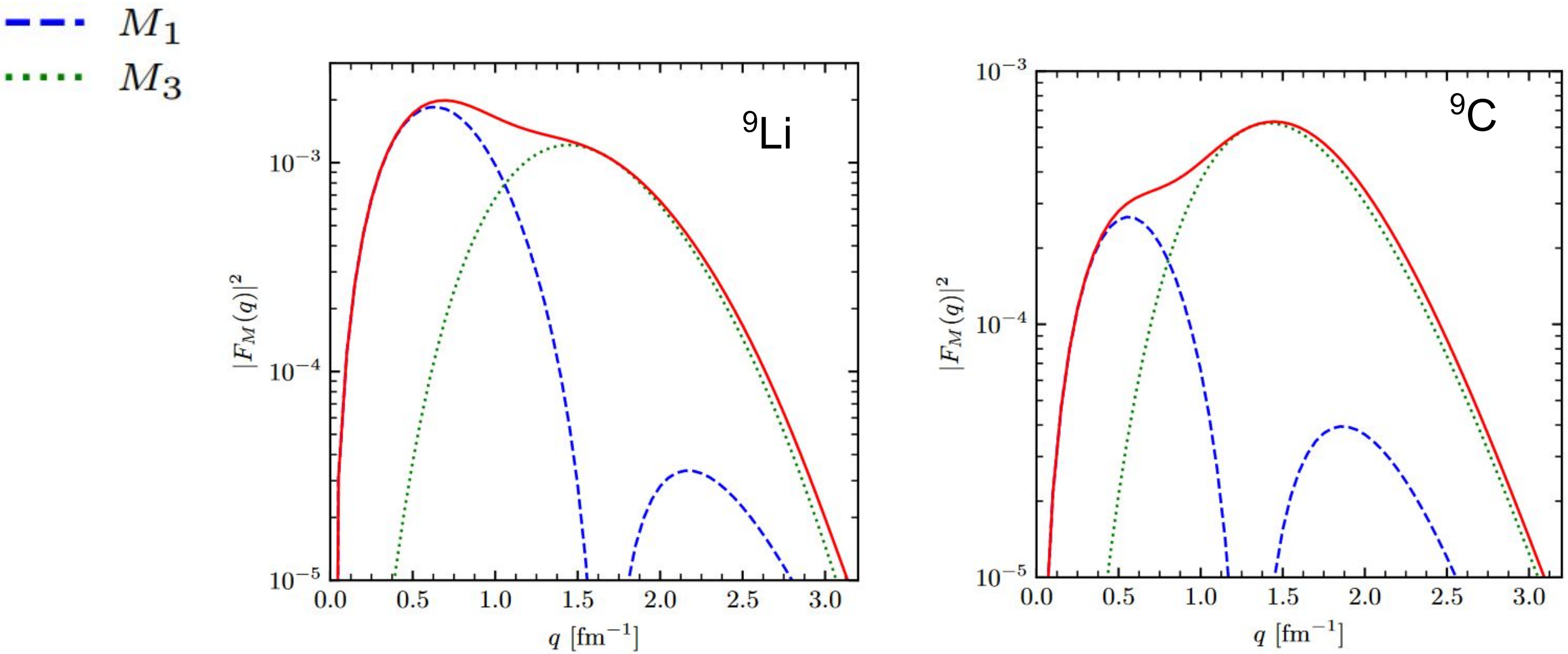
Magnetic form factors for mirror nuclei



Chambers-Wall et al. PRL 133, 212501 (2024)
Chambers-Wall et al. PRC 110, 054316 (2024)

Magnetic form factors for mirror nuclei

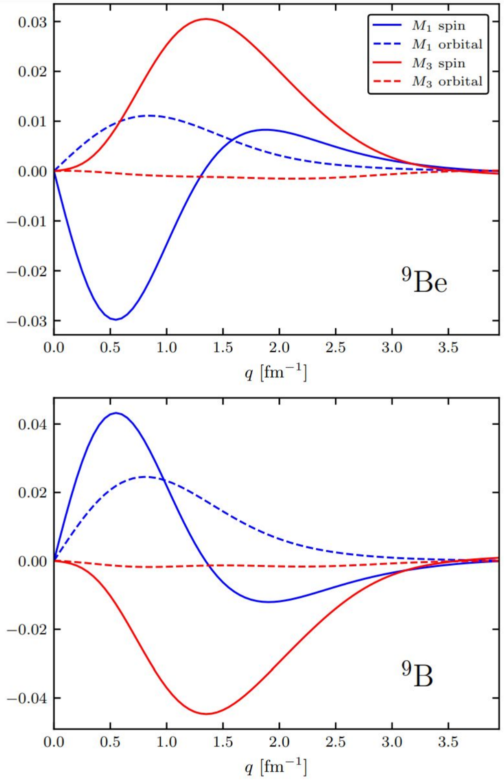
Pattern:

Unpaired proton nuclei have M1 peak > M3 peak

Unpaired neutron nuclei have M3 peak > M1 peak

Chambers-Wall et al. PRL 133, 212501 (2024)
Chambers-Wall et al. PRC 110, 054316 (2024)

Spin-orbit interference in M1



Orbital contribution generates positive contribution to M1

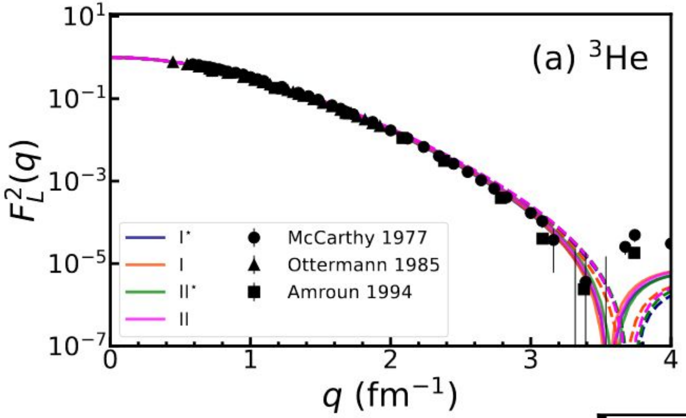
Spin is positive for an unpaired proton, negative for an unpaired neutron at small *q*

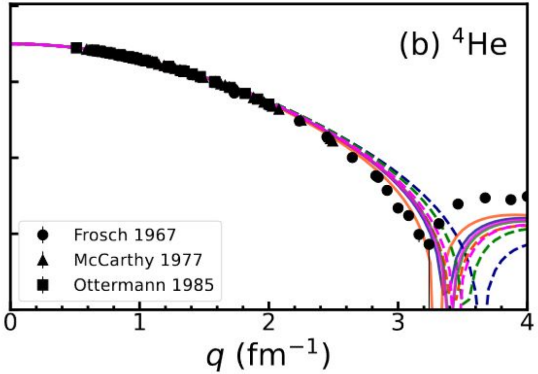
Minimal contribution orbital contribution to M3

Destructive interference between spin and orbit for unpaired neutron -> smaller M1 peak than M3

Chambers-Wall et al. PRL 133, 212501 (2024)
Chambers-Wall et al. PRC 110, 054316 (2024)

Charge form factors: model dependence





"Harder cutoff" = solid
"Softer cutoff" = dashed

Deviation roughly around the soft cutoff location in momentum space

Harder models tend to predict minimum inline with data

Low-energy physics consistent

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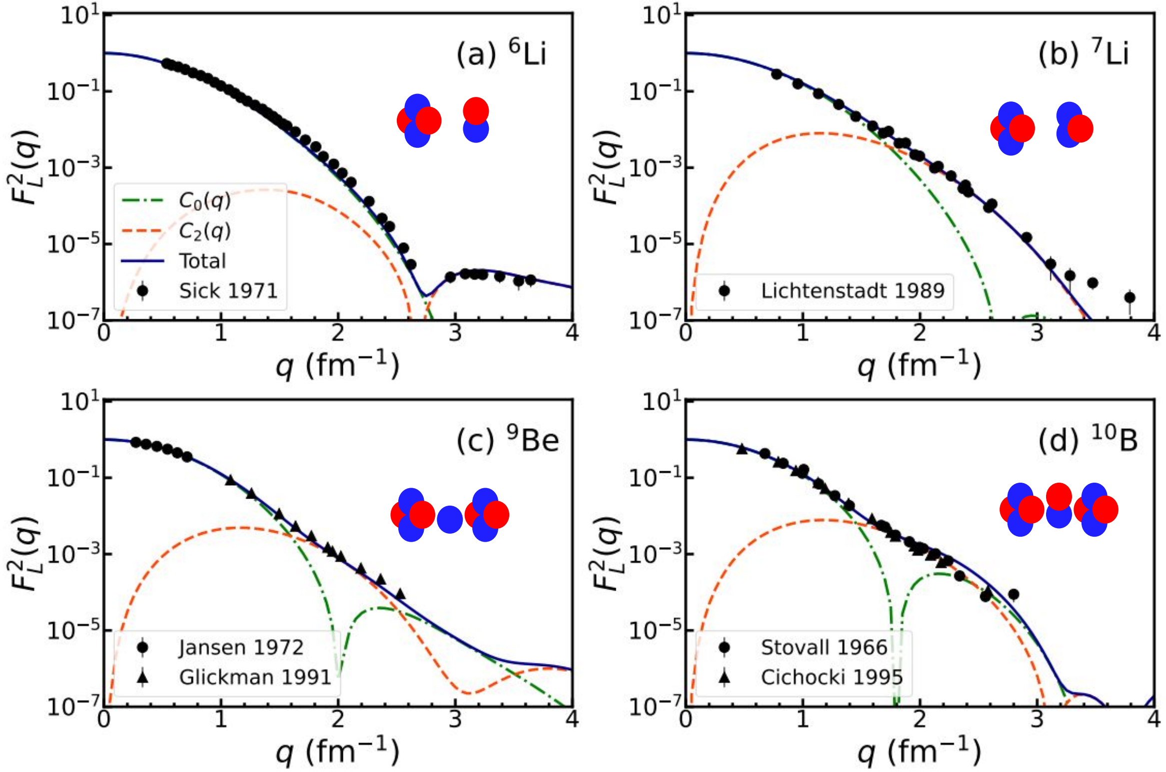
King et al. PRC 110, 054325 (2024)

Elastic electron scattering form factors



Charge form factor depends on sum of excited “multipolarities”

The l=0 term is related to spherically averaged charge density

l=2 is sensitive to quadrupole deformation of the nucleus

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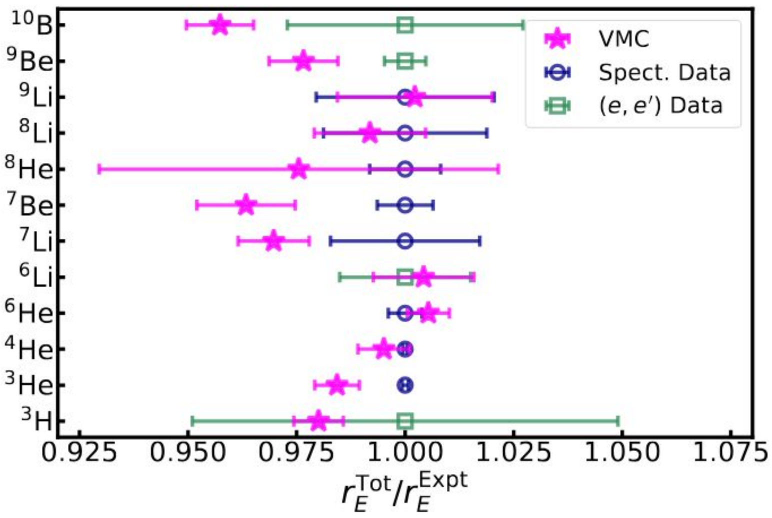
King et al. PRC 110, 054325 (2024)

Charge radii

NV2+3-IIb* nuclear interaction model

Agreement of ~5% or better across the board



Model successful for He and Li isotopes, less so for Be

Uncertainty is statistical, form factor dependence may also be important

$$\frac{1}{Z}\langle JJ|\rho(q\hat{\mathbf{z}})|JJ\rangle \approx 1 - \frac{1}{6}r_E^2 q^2 + \mathcal{O}(q^4)$$

King et al., arXiv:2504.04201

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What is missing?

Understanding convergence questions in currents (np→dɣ, pp fusion?)

More robust uncertainty quantification (emulators?)

What is missing?

Understanding convergence questions in currents (np→dɣ, pp fusion?)

More robust uncertainty quantification (emulators?)

Welcome ideas/collaboration to discuss to help improve QMC throughout the next-generation

Acknowledgements

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UW: Cirigliano

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Additional slides