TRIUMF

Ab initio calculations of electric dipole and anapole moments in atomic nuclei

INT PROGRAM INT-24-1
Fundamental Physics with Radioactive Molecules

Institute for Nuclear Theory, UW, Seattle, March 18, 2024

Petr Navratil

TRIUMF

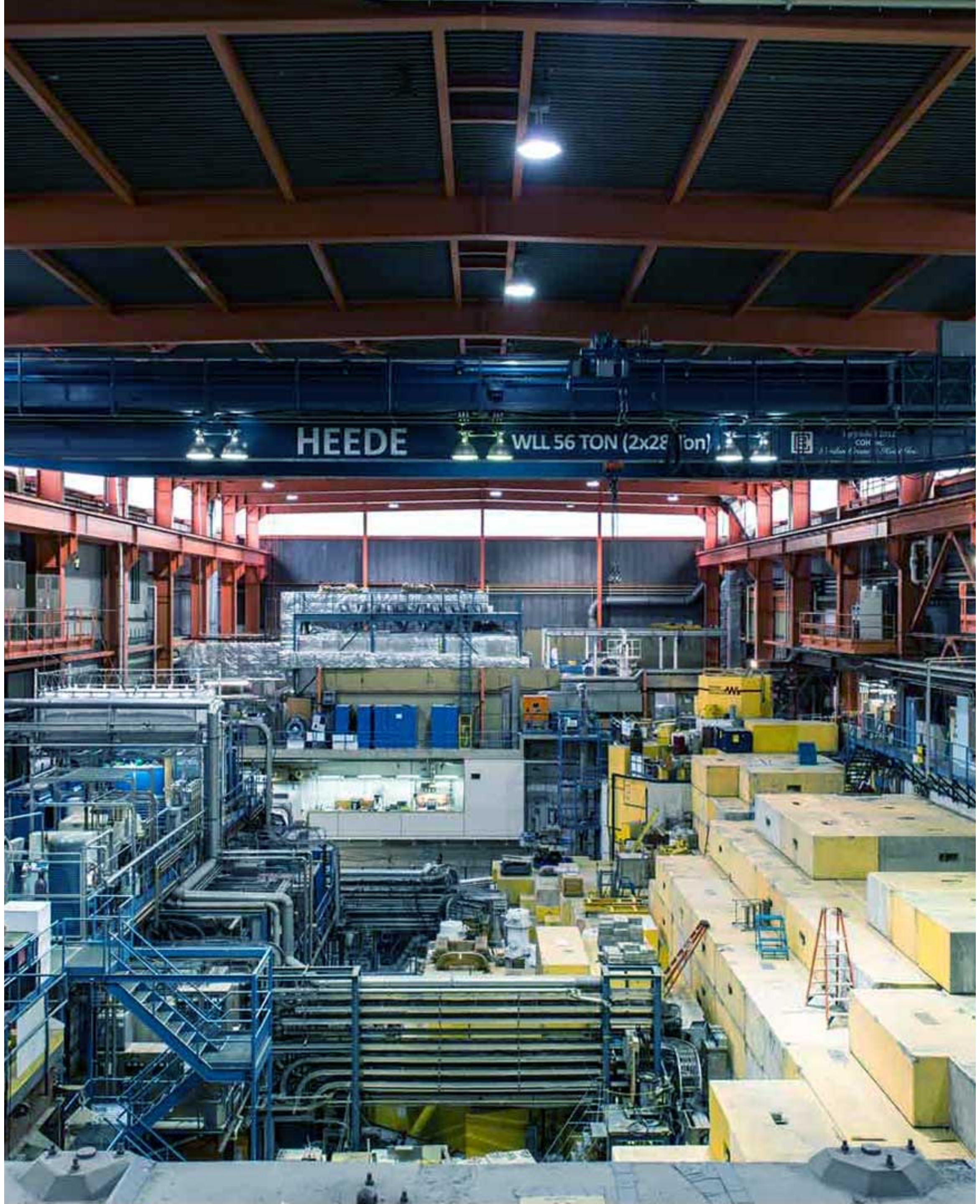
2024-03-18

Discovery, accelerated

Outline

- Motivation
- Radioactive molecule (RadMol) experimental program at TRIUMF
- *Ab initio* nuclear theory – no-core shell model (NCSM)
- Parity-violating and parity- plus time-reversal-violating nucleon-nucleon interactions
- NCSM calculations of anapole and electric dipole moments in light nuclei

Motivation



Why investigate the Electric Dipole Moment (EDM) and Schiff Moment?

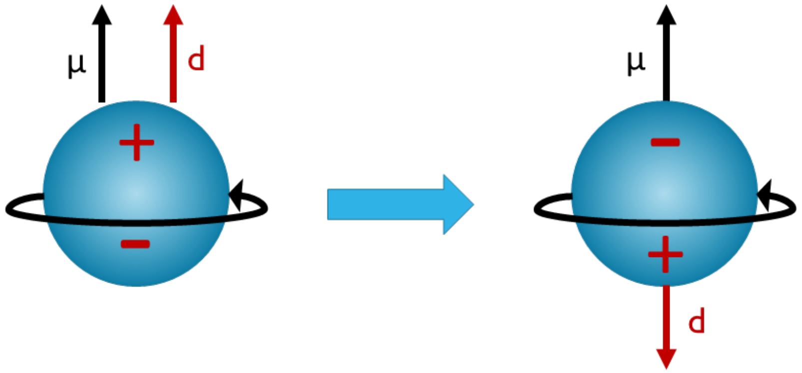
- Unsolved problem in physics: matter-antimatter asymmetry of the universe
- Standard model predicts some CP violation, not enough to explain this asymmetry
- The EDM and Schiff moment is a promising probe for CP violation beyond the standard model, as well as CP violating QCD $\bar{\theta}$ parameter

CP violation and the EDM

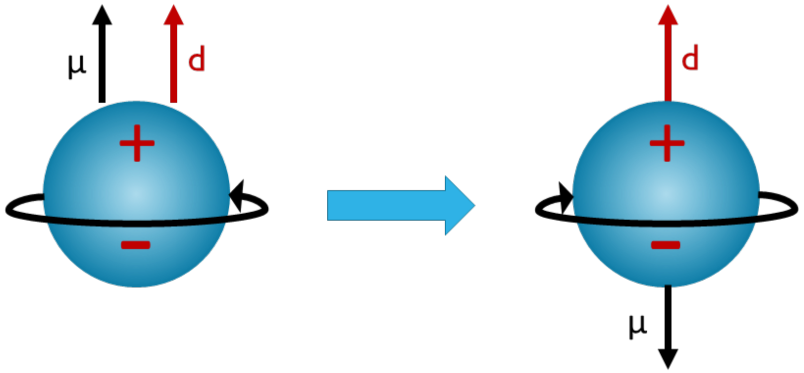
A non-zero EDM of any finite system requires P and T violation, which implies CP violation through the CPT theorem

Consider the neutron:

Under a Parity (P) Transformation:



Under a Time-reversal (T) Transformation:



Problem with neutron EDM: very small

Alternative: Nuclear EDM and nuclear Schiff moment

- Nuclear structure can enhance the EDM or the Schiff moment
- Nuclear EDMs can be measured in storage rings (CERN feasibility study: arXiv:1912.07881)
- Nuclear Schiff moments can be measured using (radioactive) molecules

To understand the nuclear EDM and Schiff moment, nuclear structure effects must be understood

Parity violation in atomic and molecular systems

- Important for tests of the
  - Standard Model
    - Information about parity violating nuclear forces
    - Test of nuclear theory and low-energy quantum chromodynamics
  - Physics beyond the standard model
    - Atomic PNC sensitive to a variety of “new physics”
      - measures a set of model-independent electron-quark electroweak coupling constants that are different from those that are probed by high-energy experiments
    - Low-mass Z' boson - the best limits on its parity violating interaction with electrons, protons, and neutrons from the data on atomic parity violation

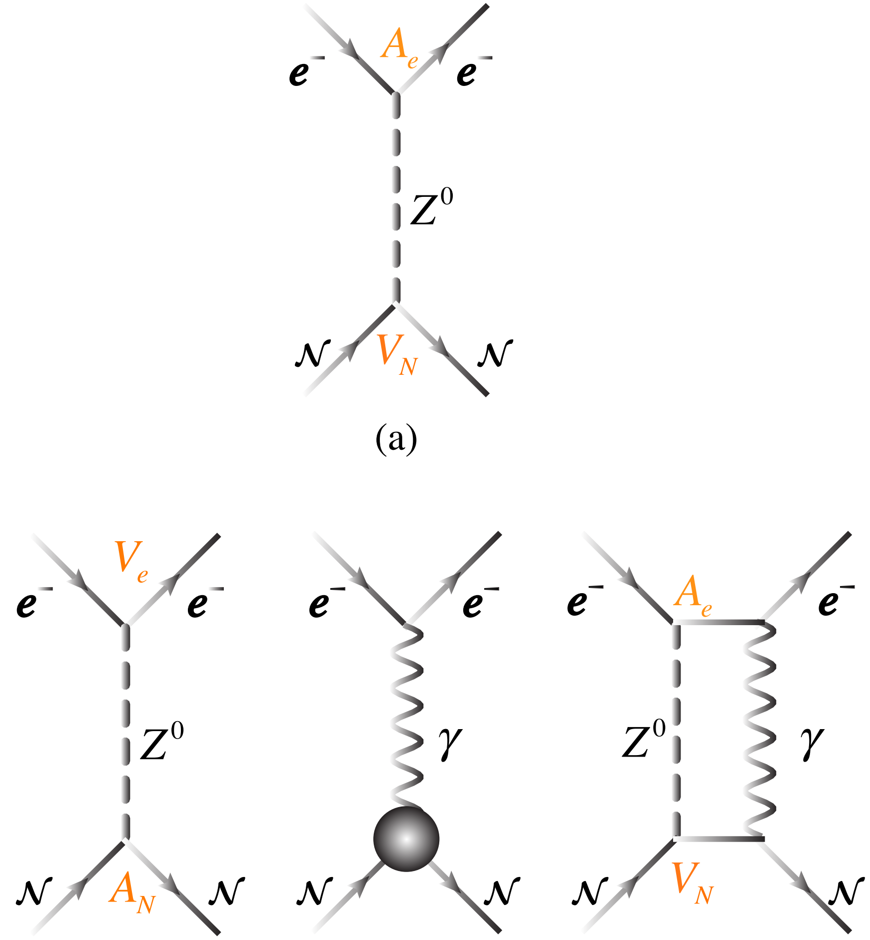
REVIEWS OF MODERN PHYSICS, VOLUME 90, APRIL–JUNE 2018

Search for new physics with atoms and molecules

M. S. Safronova

Parity violation in atomic and molecular systems

- Spin independent
  - Z-boson exchange between electron axial-vector and nucleon-vector currents
- Spin dependent
  - Z-boson exchange between nucleon axial-vector and electron-vector currents (b)
  - Electromagnetic interaction of atomic electrons with the nuclear anapole moment (c)
  - Combined effect of the A_eV_N and hyperfine interaction (d)



(a) (b) (c) (d)

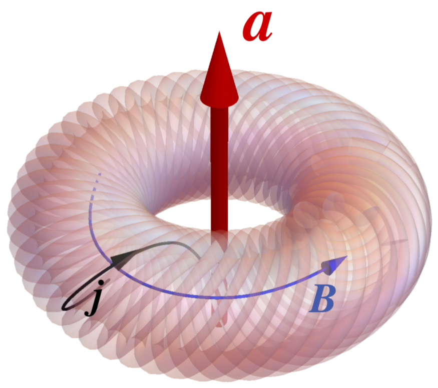
Parity violation in atomic and molecular systems

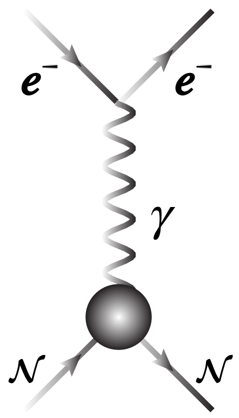
- Nuclear anapole moment
  - Weak interactions inside the nucleus lead to P-odd moments

$$\boldsymbol{a} = -\pi \int d^3r\, r^2\, \boldsymbol{j}(\boldsymbol{r})$$

  - Magnetic vector potential A = aδ(r)
    - Electromagnetic coupling to electrons
  - Nuclear anapole arises due to nucleon-nucleon interaction, mediated by meson exchange, where one of the nucleon-meson vertexes is strong and another is weak and P-violating
  - Determination of anapole moments from atomic parity violation provides a window into hadronic parity non-conservation (PNC)

$$\boldsymbol{a} = \frac{G_\mathrm{F}}{|e|\sqrt{2}}\, \eta_\mathrm{NAM}\mathbf{I}.$$





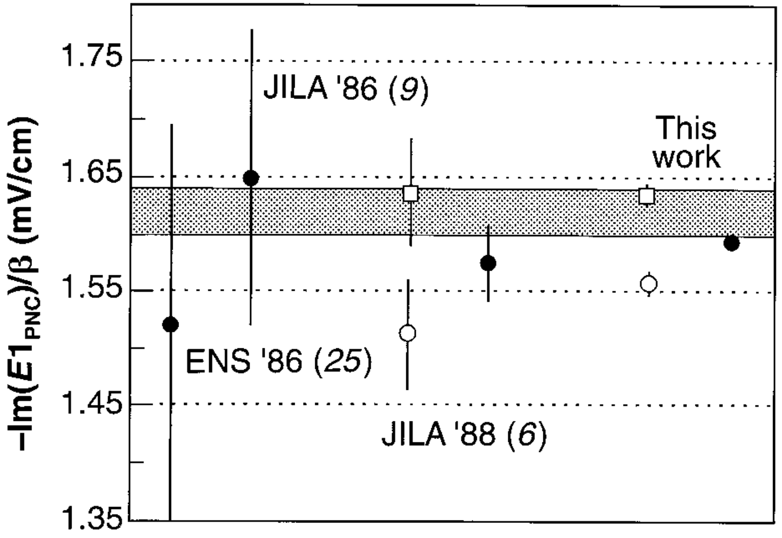
(c)

Nuclear anapole moment measured in ^{133}Cs

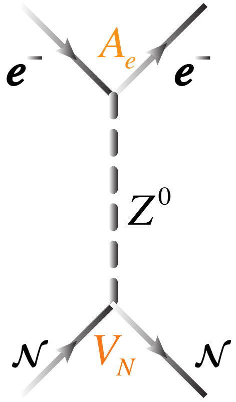
SCIENCE • VOL. 275 • 21 MARCH 1997 1759

Measurement of Parity Nonconservation and an Anapole Moment in Cesium

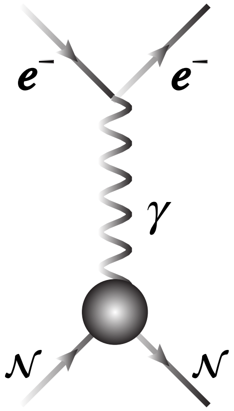
C. S. Wood, S. C. Bennett, D. Cho,* B. P. Masterson,†
J. L. Roberts, C. E. Tanner,‡ C. E. Wieman§



PNC results for the $6S_{F=3}$ to $7S_{F=4}$ and the $6S_{F=4}$ to $7S_{F=3}$ transitions



(a)



(c)

Anapole moment dominates the nuclear-spin-dependent parity violating effects in heavy atoms ~ $A^{2/3}$

Nuclear spin dependent parity violating effects in light polyatomic molecules

- Polyatomic molecules possess opposite-parity states that may be brought to near degeneracy using a magnetic field. This opens the possibility to measure nuclear spin dependent parity-violating effects in light nuclei where nuclear structure calculations are tractable
- Experiments proposed for ^{9}BeNC, ^{25}MgNC
- Expected to measure the spin-dependent parity-violating matrix elements with 70 times better sensitivity

COMMUNICATIONS PHYSICS

ARTICLE

https://doi.org/10.1038/s42005-019-0181-1 OPEN

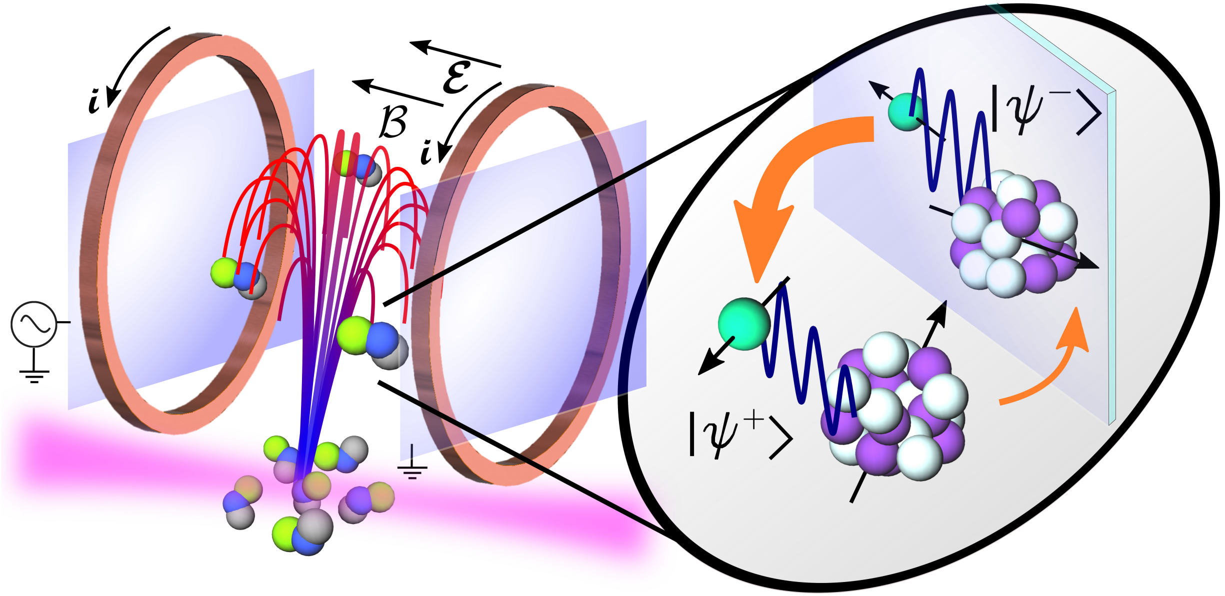
Nuclear-spin dependent parity violation in optically trapped polyatomic molecules

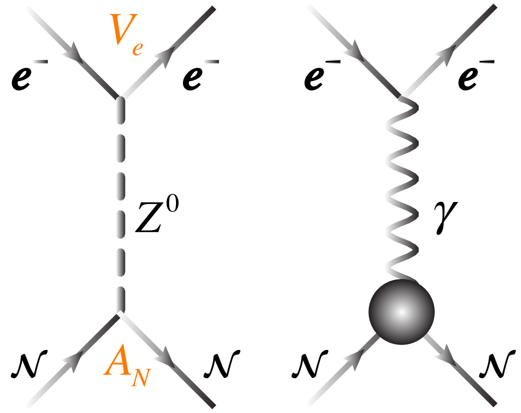
E.B. Norrgard [1], D.S. Barker[1], S. Eckel[1], J.A. Fedchak [1], N.N. Klimov[1] & J. Scherschligt [1]

COMMUNICATIONS PHYSICS | (2019)2:77

Nuclear spin dependent parity violating effects in light polyatomic molecules

- Experiments proposed for ^{9}BeNC, ^{25}MgNC
- In light atoms, the exchange of Standard Model Z bosons (or potential Z′ bosons) between an electron and individual nucleons can be as important as the anapole moment. It remains poorly characterized
  - $V_e\, A_N$: Z^0 exchange between *e* and quarks, couplings C_{2u}, C_{2d} known with uncertainties of 300% and 70%, respectively
- To extract the underlying physics, atomic, molecular, and **nuclear** structure effects must be understood
  - *Ab initio* calculations

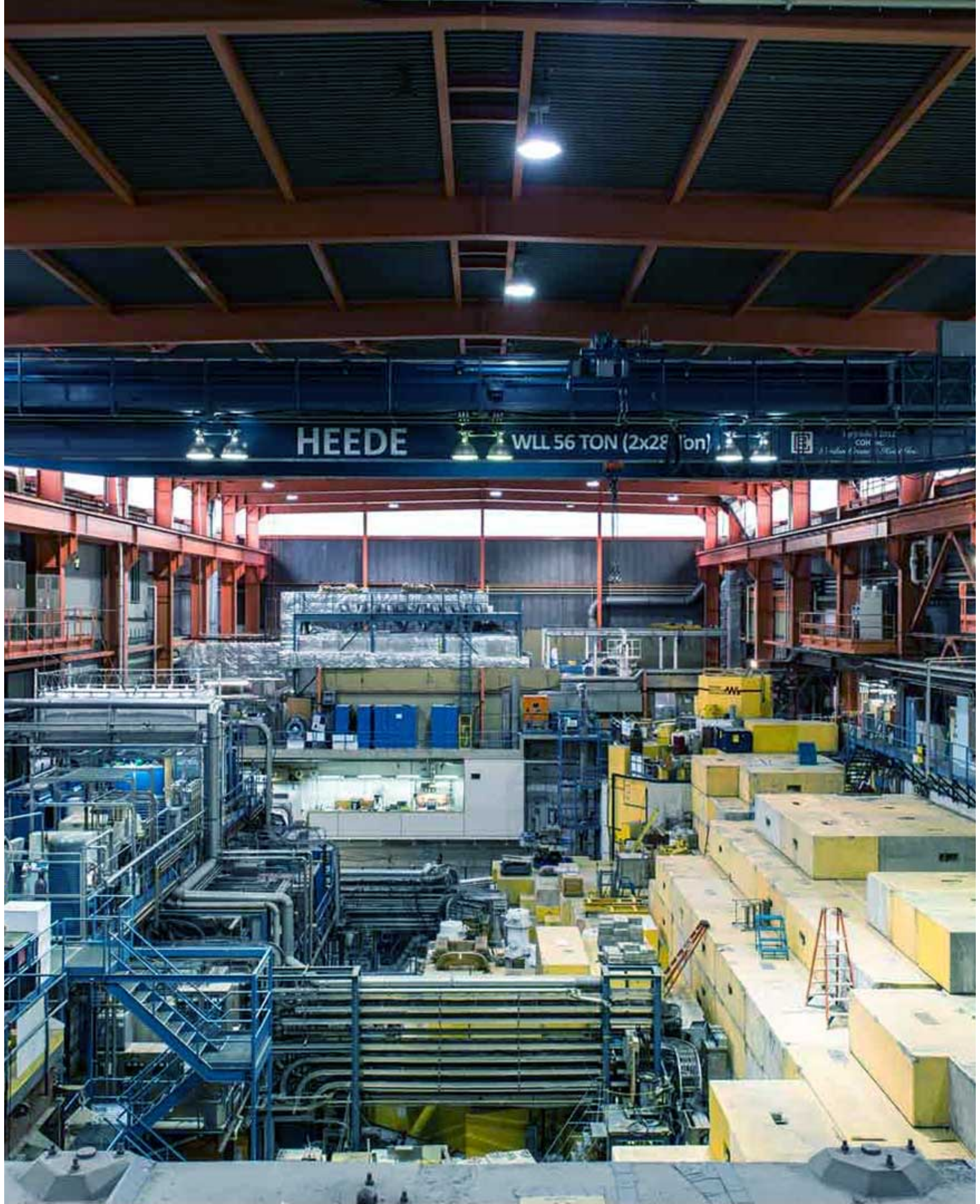




(b) (c)

TRIUMF

Radioactive Molecule (RadMol) experimental program at TRIUMF

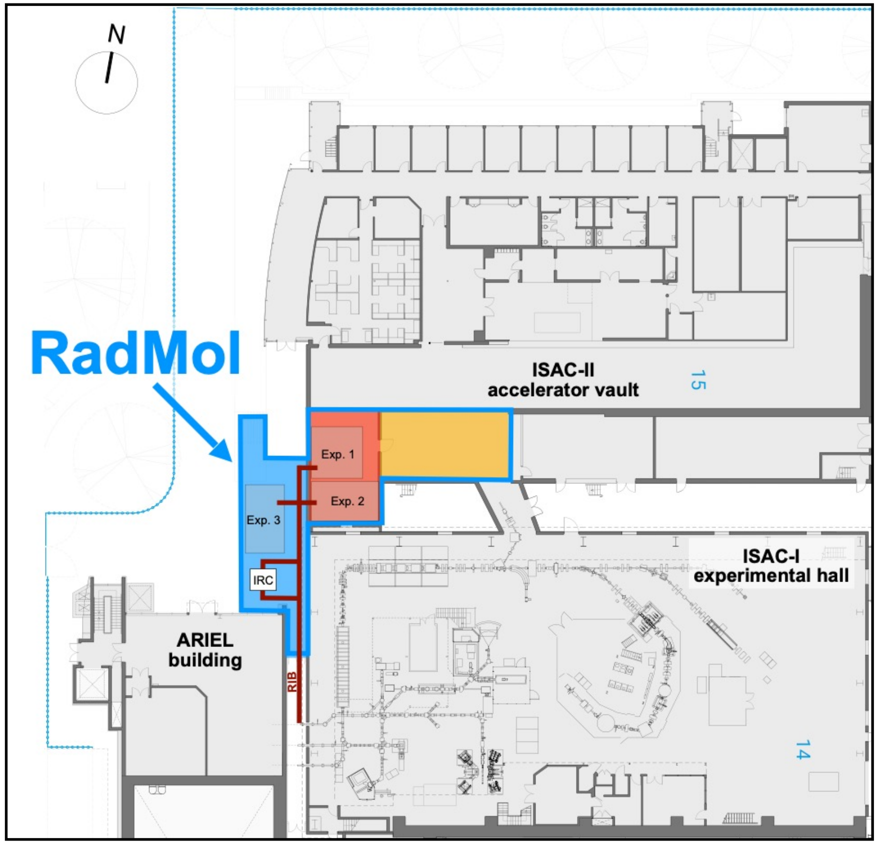


2024-03-18

Discovery, accelerated

RadMol

a radioactive molecule lab for fundamental physics



Goal:

dedicated laboratory to study of radioactive molecules

to host 3 experimental stations

precision studies for searches for new physics

Molecular EDM with unprecedented sensitivity to nuclear T-breaking Schiff moments

provision for expansions into other fields

TRIUMF advantages:

large variety in radioactive ion beams (RIB)

high beamtime availability (3 independent RIBs)

existing laboratory space for large, multi-station program

Current Canadian Team:

12 faculty and staff physicists

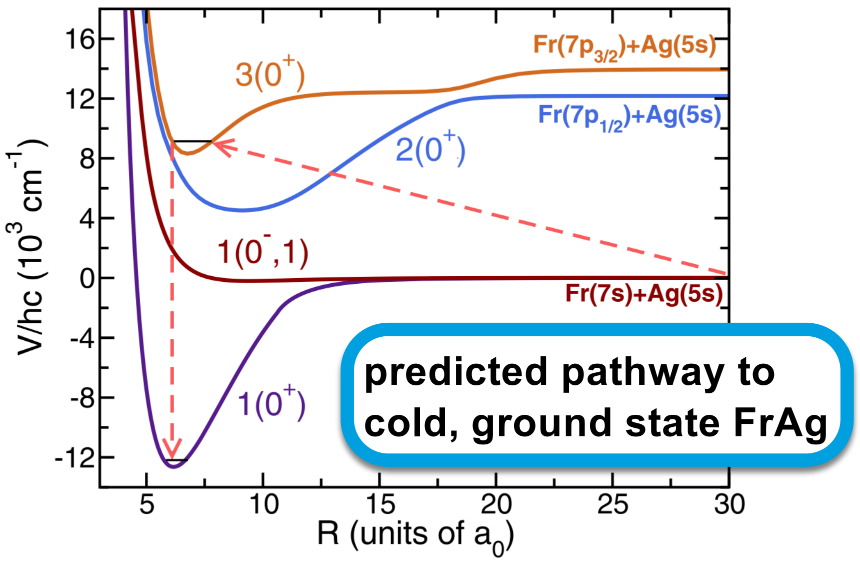
RadMol Collaboration:

TRIUMF, University of Toronto, UBC, University of Manitoba, uOttawa, University of Waterloo, McGill, The University of Chicago, University of Colorado Boulder, The University of Edinburgh, Philipps Universität Marburg, Massachusetts Institute of Technology

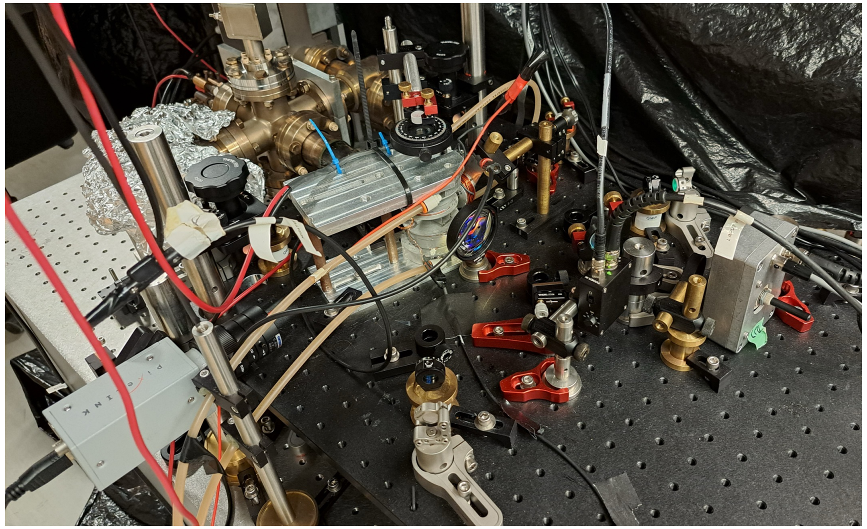
The Case of ^{223}FrAg

Awarded US$2.8 million grant by Gordon and Betty Moore Foundation (led by D. DeMille)

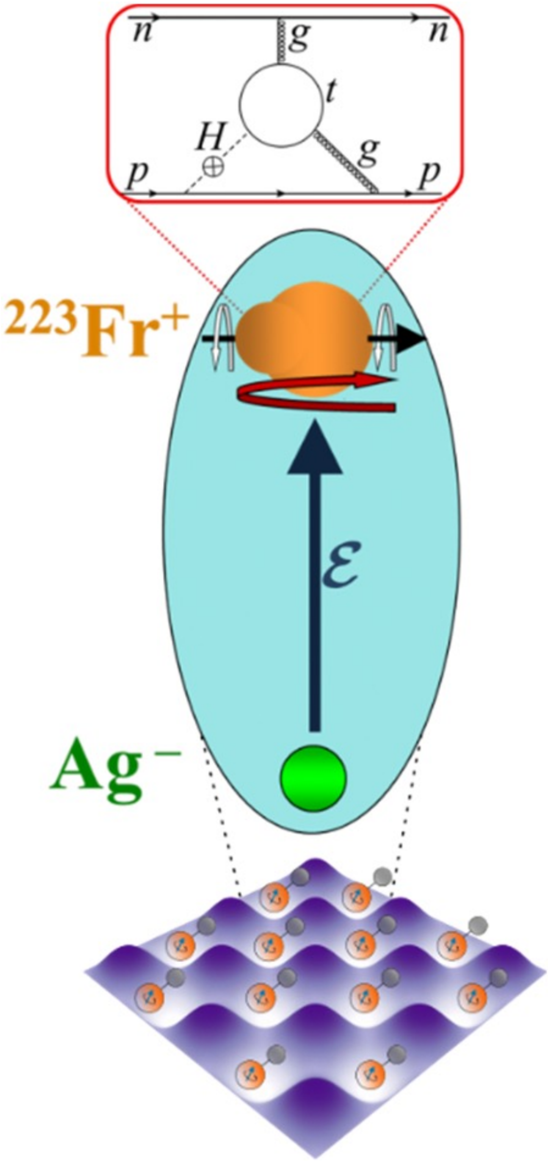
- **Schiff moment:**
  intrinsic enhancement of 10^7 compared to ^{199}Hg
  ➡️ **x1000 improvement on certain CPV-parameters with 'established' methods**
- ultracold molecule assembled from laser-cooled Fr and Ag atoms
- ^{223}Fr ($T_{1/2}$=22 min) at ISAC: $1.3 \cdot 10^7$ ions/sec
- infrastructure and expertise at TRIUMF's Fr trapping facility
- first exp. goal: measurement of Fr s-wave scattering length
  input to form ultracold Fr approaching Bose Einstein Condensate
  determined from two-colour photoassociation (2PA)



J Kłos et al., New J. Phys. 24, 025005 (2022)



Offline MOT setup at UBC to develop 2PA with low atom number

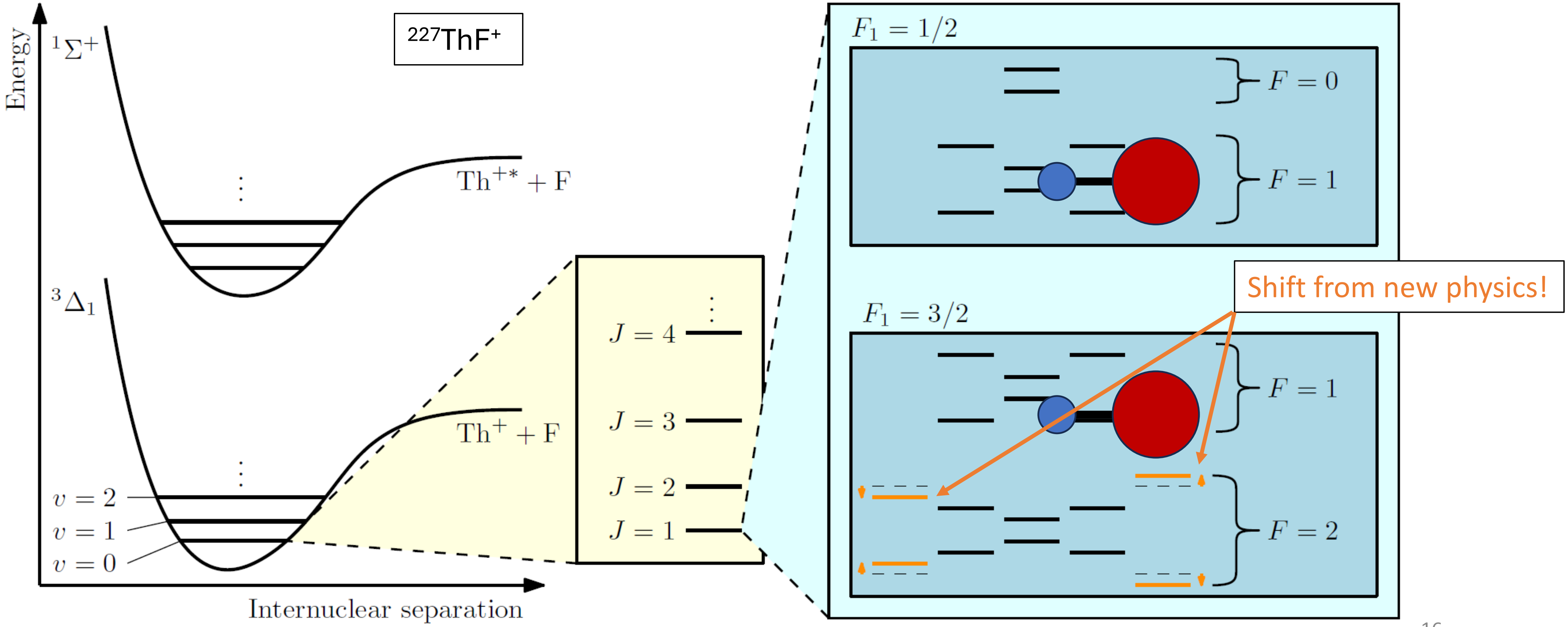


Slide by Stephan Malbrunot-Ettenauer

Charged-ion molecules – ThF^+, AcF^+, PaF^{3+}

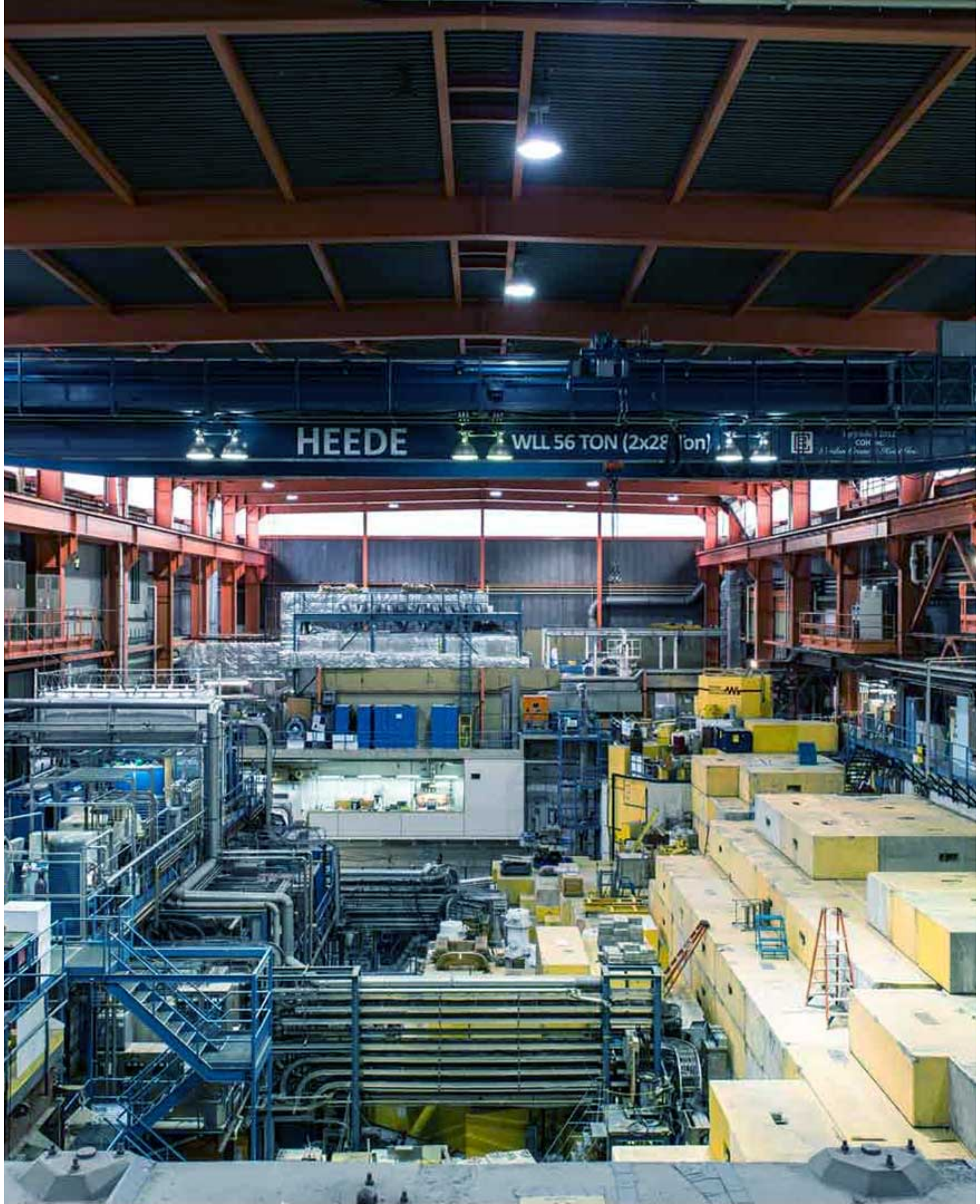
Developing first techniques in TRIUMF's TITAN ion trap facility

New physics ➔ very tiny shifts of quantum states in molecule.



Slide by Kia Boon Ng and Stephan Malbrunot-Ettenauer

Ab initio nuclear theory



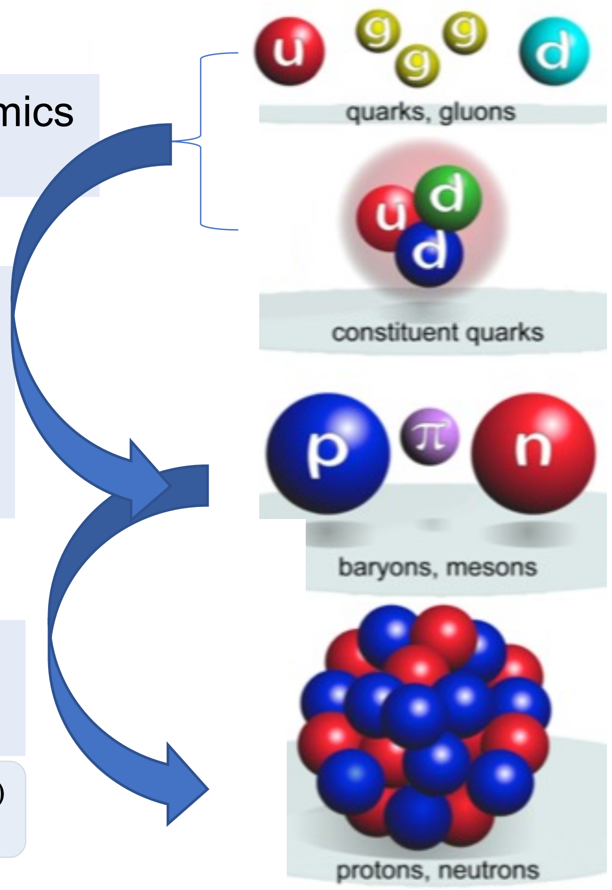
First principles or *ab initio* nuclear theory

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab anitio* nuclear theory

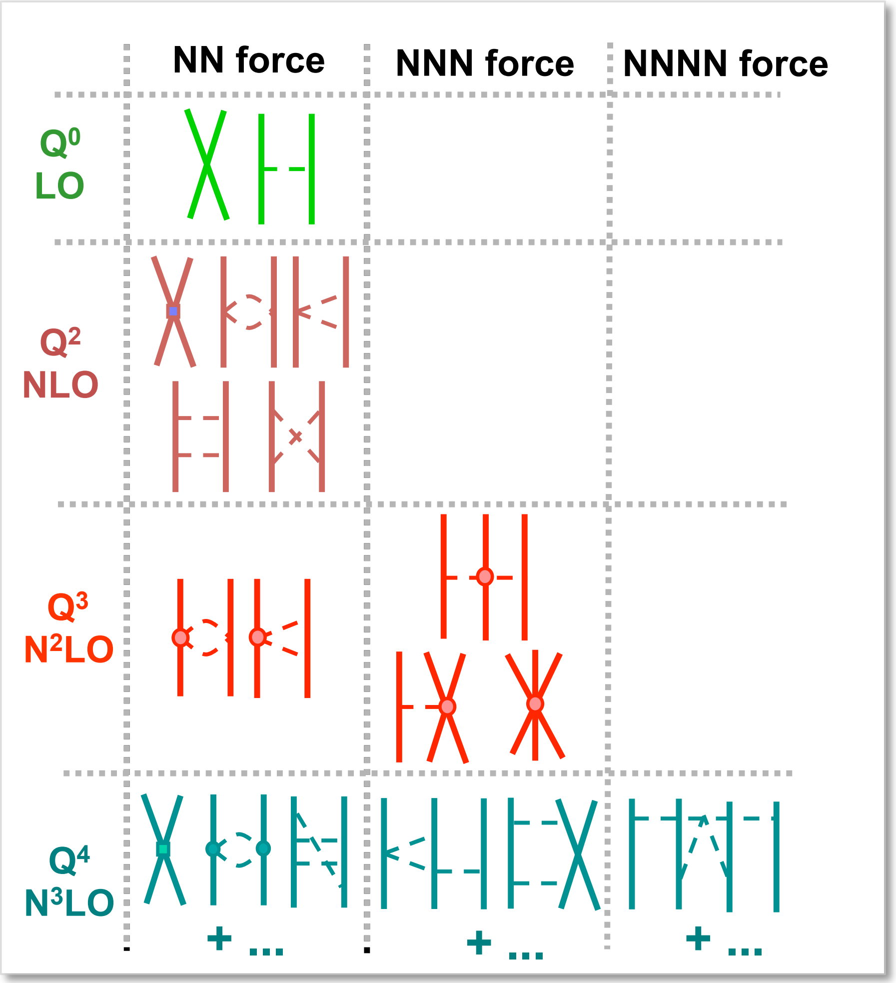
$$H\,\Psi^{(A)} = E\,\Psi^{(A)}$$



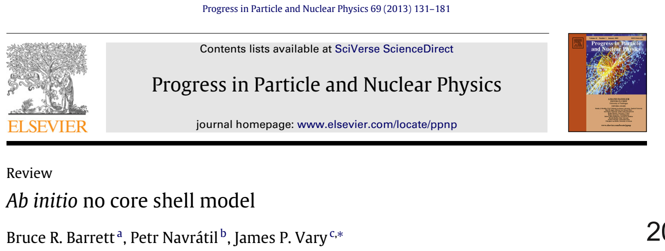
- *Ab initio*
- ✧ Degrees of freedom: Nucleons
- ✧ All nucleons are active
- ✧ Exact Pauli principle
- ✧ Realistic inter-nucleon interactions
  - ✧ Accurate description of NN (and 3N) data
- ✧ Controllable approximations

Chiral Effective Field Theory

- Inter-nucleon forces from chiral effective field theory
  - Based on the symmetries of QCD
    - Chiral symmetry of QCD ($m_u \approx m_d \approx 0$), spontaneously broken with pion as the Goldstone boson
    - Degrees of freedom: nucleons + pions
  - Systematic low-momentum expansion to a given order (Q/Λ_χ)
  - Hierarchy
  - Consistency
  - Low energy constants (LEC)
    - Fitted to data
    - Can be calculated by lattice QCD



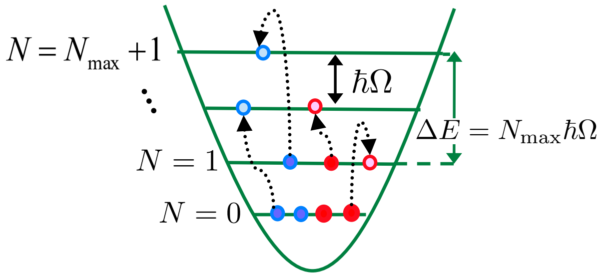
Λ_χ~1 GeV :
Chiral symmetry breaking scale


Progress in Particle and Nuclear Physics 69 (2013) 131–181
Contents lists available at SciVerse ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp
Review
Ab initio no core shell model
Bruce R. Barrett[a], Petr Navrátil[b], James P. Vary[c,*]

Conceptually simplest *ab initio* method: No-Core Shell Model (NCSM)

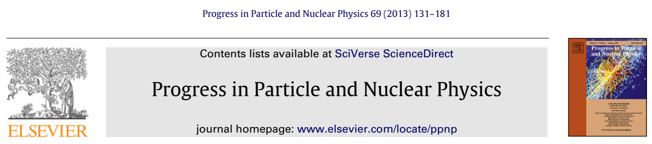
NCSM

- Basis expansion method
  - Harmonic oscillator (HO) basis truncated in a particular way ($N_{\max}$)
  - Why HO basis?
    - Lowest filled HO shells match magic numbers of light nuclei (2, 8, 20 – ^{4}He, ^{16}O, ^{40}Ca)
    - Equivalent description in relative(Jacobi)-coordinate and Slater determinant basis
- Short- and medium range correlations
- Bound-states, narrow resonances



$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni} \Phi_{Ni}^{HO}(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})$$

$$\Psi_{\mathrm{SD}}^A = \sum_{N=0}^{N_{\max}} \sum_j c_{Nj}^{\mathrm{SD}} \Phi_{\mathrm{SD}\,Nj}^{HO}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \Psi^A \, \varphi_{000}(\vec{R}_{CM})$$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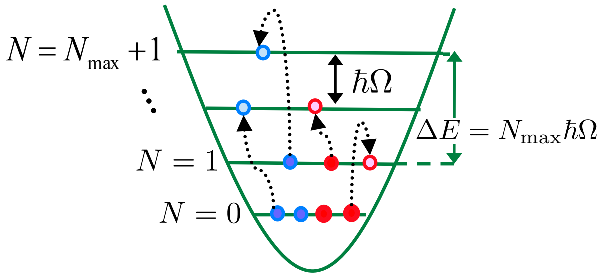
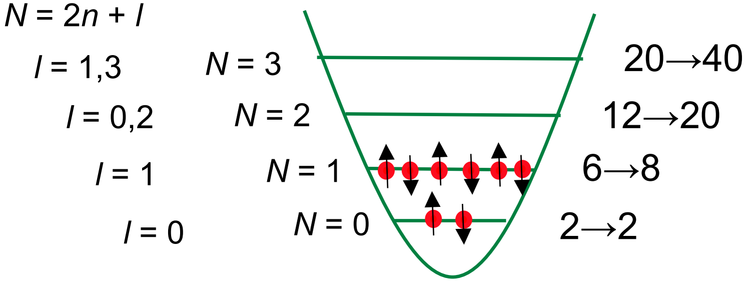




$$E = (2n + l + \tfrac{3}{2})\hbar\Omega$$

$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni} \Phi_{Ni}^{HO}(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})$$

$$\Psi_{\mathrm{SD}}^A = \sum_{N=0}^{N_{\max}} \sum_j c_{Nj}^{\mathrm{SD}} \Phi_{\mathrm{SD}\,Nj}^{HO}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A) = \Psi^A \, \varphi_{000}(\vec{R}_{CM})$$

PHYSICAL REVIEW C **101**, 014318 (2020)

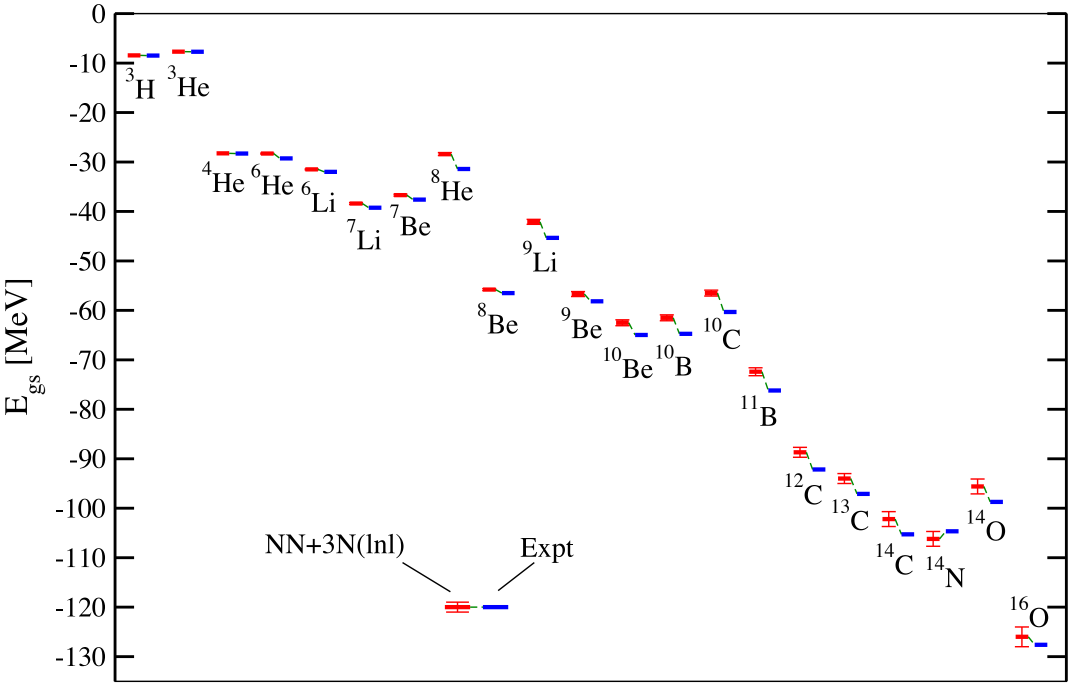
Novel chiral Hamiltonian and observables in light and medium-mass nuclei

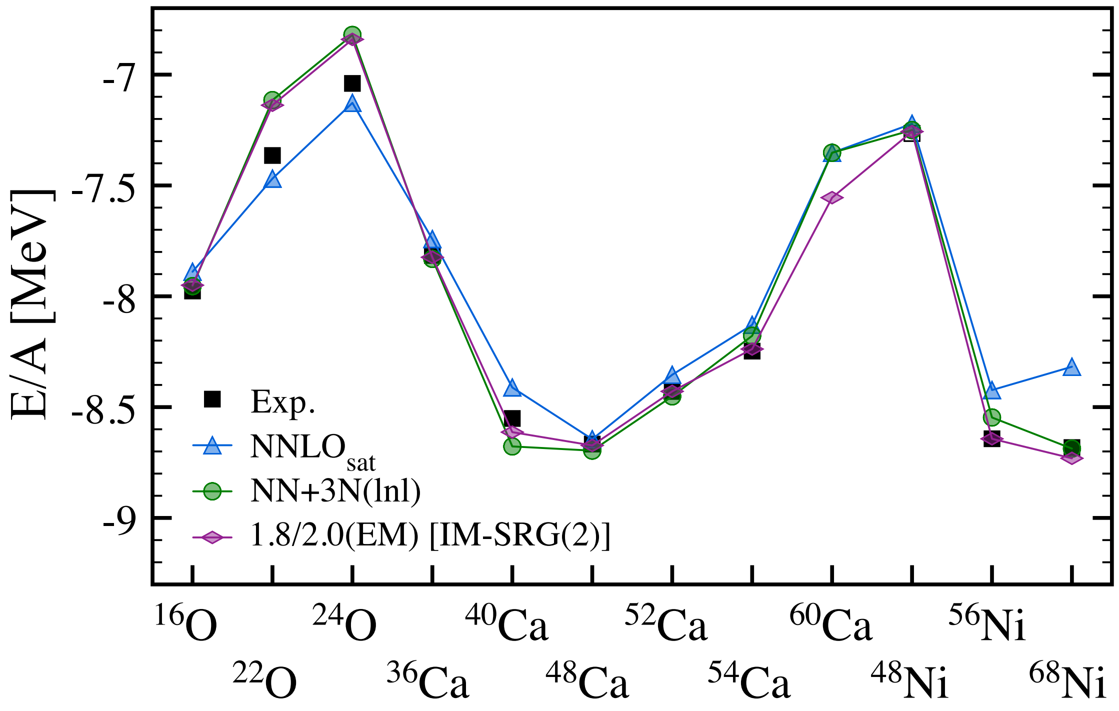
V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

PCTC Chiral NN+3N interaction used in this study

- Quite reasonable description of binding energies across the nuclear charts becomes feasible
  - **The Hamiltonian fully determined in *A*=2 and *A*=3,4 systems**
    - Nucleon–nucleon scattering, deuteron properties, ^{3}H and ^{4}He binding energy, ^{3}H half life
  - Light nuclei – NCSM
  - Medium mass nuclei – Self-Consistent Green's Function method

NN N^{3}LO (Entem-Machleidt 2003)
3N N^{2}LO w local/non-local regulator





1.8/2.0 (EM) results: J. Simonis, S. R. Stroberg, K. Hebeler, J. D. Holt, and A. Schwenk, Phys. Rev. C 96, 014303 (2017).

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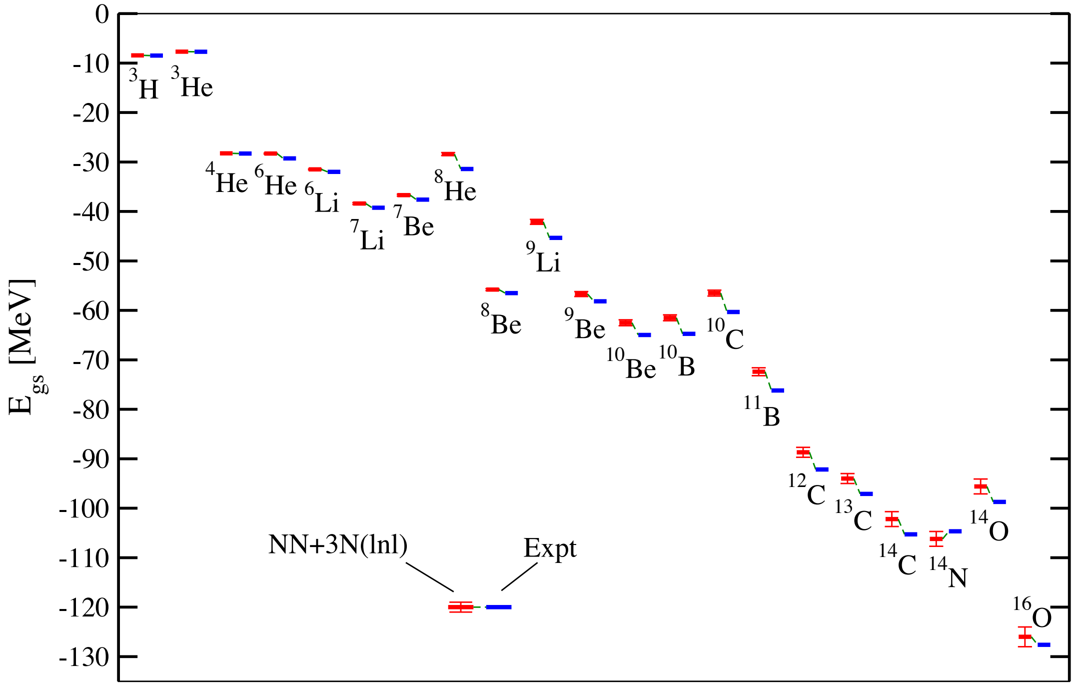
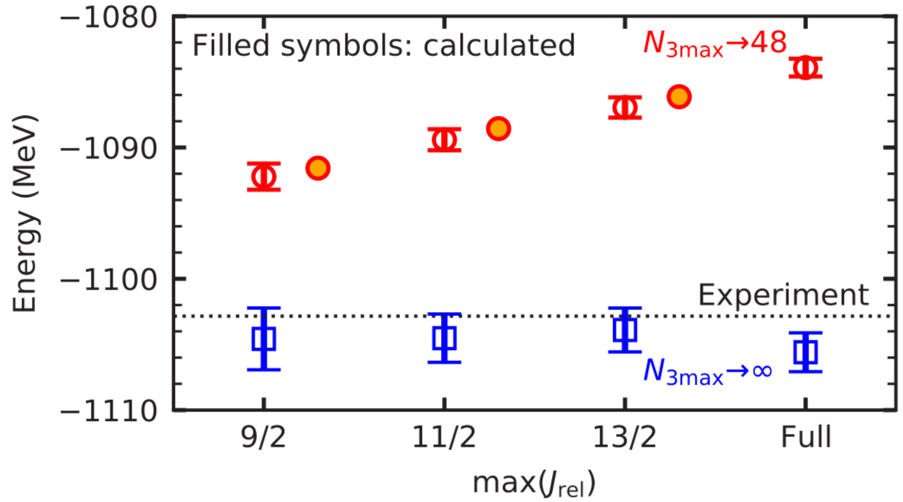




PHYSICAL REVIEW C **105**, 014302 (2022)

Converged *ab initio* calculations of heavy nuclei

T. Miyagi,[1,*] S. R. Stroberg,[2,†] P. Navrátil,[1,‡] K. Hebeler,[3,4,5,§] and J. D. Holt[1,6,‖]

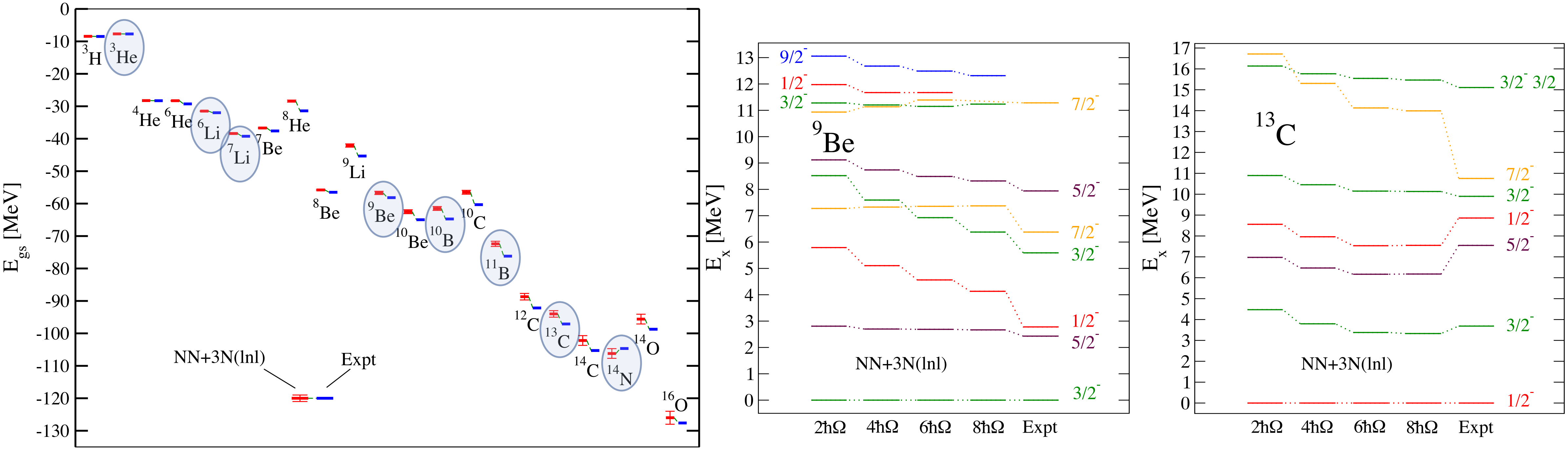
PHYSICAL REVIEW C **101**, 014318 (2020)

Novel chiral Hamiltonian and observables in light and medium-mass nuclei

V. Somà,[1,*] P. Navrátil,[2,†] F. Raimondi,[3,4,‡] C. Barbieri,[4,§] and T. Duguet[1,5,‖]

Nuclear structure calculations for light stable nuclei within NCSM

- Parity violation: ^{9}BeNC, ^{25}MgNC
  - ^{9}Be, ^{13}C, ^{14,15}N, ^{25}Mg
- Nuclear EDM
  - ^{3}He, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{13}C, ^{14,15}N, ^{19}F
- ORNL Summit – NCSD code with GPU acceleration



Calculations of parity-violating and parity- and time-reversal-violating terms

One-body contribution from nucleon EDMs easily evaluated

$$D^{(1)} = \langle\psi| \sum_{i=1}^{A} \frac{1}{2} \left[(d_p + d_n) - (d_p - d_n)\tau_i^z \right] \sigma_i^z |\psi\rangle$$

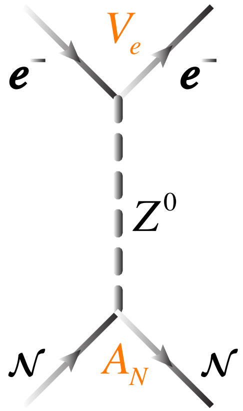
- d_p, d_n : intrinsic nucleon EDMs
- $|\psi\rangle$: Nuclear state with maximal magnetic quantum number
- Proportional to matrix elements of σ^z , not enhanced by nuclear structure

Similarly, the Z-boson exchange between nucleon axial-vector and electron-vector currents is easily calculated

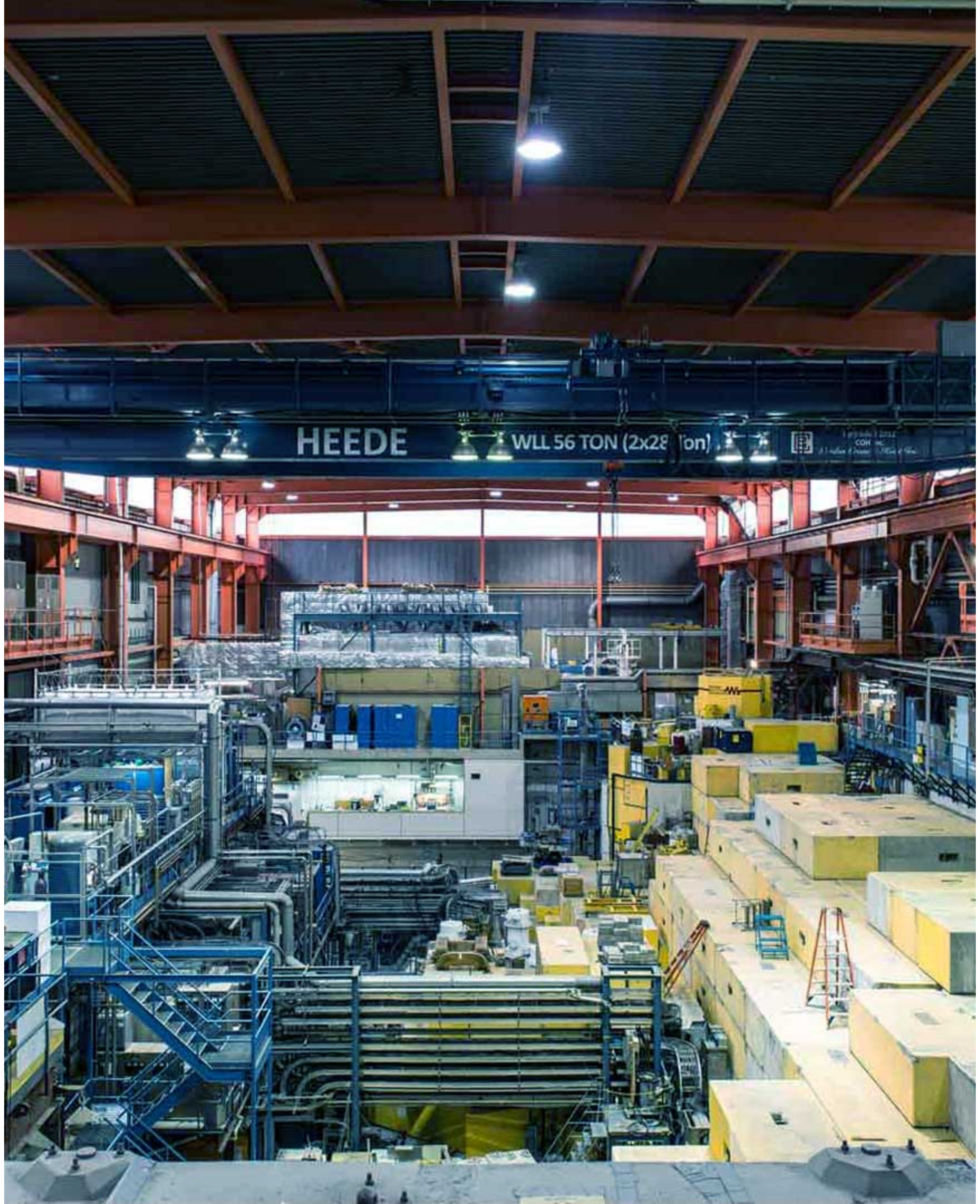
$$\kappa_{ax} \simeq -2C_{2p}\langle s_{p,z}\rangle - 2C_{2n}\langle s_{n,z}\rangle$$

$$\langle s_{\nu,z}\rangle \equiv \langle \psi_{\rm gs}\ I^\pi I_z{=}I | \hat{s}_{\nu,z} | \psi_{\rm gs}\ I^\pi I_z{=}I\rangle$$

$$C_{\rm 2p} = -C_{\rm 2n} = g_A(1 - 4\sin^2\theta_W)/2 \simeq 0.05$$



Parity-violating
and parity- plus time-reversal-violating
nucleon-nucleon interactions



Parity violating nucleon-nucleon interaction

- Meson exchange approach
- Chiral EFT
- Unknown parameters (LECs)
  - DDH (1980) – estimates based on the quark model
  - Experiments give conflicting limits on the weak couplings

ANNALS OF PHYSICS 124, 449–495 (1980)

Unified Treatment of the Parity Violating Nuclear Force

BERTRAND DESPLANQUES*

Institut de Physique Nucleaire, Division de Physique Théorique, 91406 Orsay Cedex—France

JOHN F. DONOGHUE†

Center for Theoretical Physics, Laboratory for Nuclear Science and Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

AND

BARRY R. HOLSTEIN

Physics Division, National Science Foundation, Washington, D. C. 20550

$$
\begin{aligned}
V_{12}^{\text{p.v.}} = {} & \frac{f_\pi g_{\pi NN}}{2^{1/2}}\, i \left(\frac{\vec\tau_1\times\vec\tau_2}{2}\right)^z (\vec\sigma_1+\vec\sigma_2)\cdot\left[\frac{\vec p_1-\vec p_2}{2M}, f_\pi(r)\right] \\
& - g_\rho\left(h_\rho^{\,0}\,\vec\tau_1\cdot\vec\tau_2 + h_\rho^{\,1}\left(\frac{\vec\tau_1+\vec\tau_2}{2}\right)^z + h_\rho^{\,2}\,\frac{(3\tau_1^z\tau_2^z-\vec\tau_1\cdot\vec\tau_2)}{2(6)^{1/2}}\right) \\
& \times\left((\vec\sigma_1-\vec\sigma_2)\cdot\left\{\frac{\vec p_1-\vec p_2}{2M}, f_\rho(r)\right\} + i(1+\chi_V)\,\vec\sigma_1\times\vec\sigma_2\cdot\left[\frac{\vec p_1-\vec p_2}{2M}, f_\rho(r)\right]\right) \\
& - g_\omega\left(h_\omega^{\,0} + h_\omega^{\,1}\left(\frac{\vec\tau_1+\vec\tau_2}{2}\right)^z\right) \\
& \times\left((\vec\sigma_1-\vec\sigma_2)\cdot\left\{\frac{\vec p_1-\vec p_2}{2M}, f_\omega(r)\right\} + i(1+\chi_S)\,\vec\sigma_1\times\vec\sigma_2\cdot\left[\frac{\vec p_1-\vec p_2}{2M}, f_\omega(r)\right]\right) \\
& - (g_\omega h_\omega^{\,1} - g_\rho h_\rho^{\,1})\left(\frac{\vec\tau_1-\vec\tau_2}{2}\right)^z (\vec\sigma_1+\vec\sigma_2)\cdot\left\{\frac{\vec p_1-\vec p_2}{2M}, f_\rho(r)\right\} \\
& - g_\rho h_\rho^{\prime 1}\, i\left(\frac{\vec\tau_1\times\vec\tau_2}{2}\right)^z (\vec\sigma_1+\vec\sigma_2)\cdot\left[\frac{\vec p_1-\vec p_2}{2M}, f_\rho(r)\right],
\end{aligned}
$$

$$f_\pi(r) = \frac{e^{-m_\pi r}}{4\pi r},$$

$$f_\rho(r) = f_\omega(r) = \frac{e^{-m_\rho r}}{4\pi r}.$$

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Parity- and Time-Reversal-Violating Nuclear Forces

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Parity violating nucleon-nucleon interaction

- Meson exchange approach
- Chiral EFT
- Unknown parameters (LECs)
  - DDH (1980) – estimates based on the quark model
  - Experiments give conflicting limits on the weak couplings

ANNALS OF PHYSICS 124, 449–495 (1980)

Unified Treatment of the Parity Violating Nuclear Force

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AND

BARRY R. HOLSTEIN

Physics Division, National Science Foundation, Washington, D. C. 20550

$$\mathscr{H}^{\mathrm{p.v.}}_{MNN} = (2)^{-1/2} f_\pi \bar{N} (\vec{\tau} \times \vec{\phi}^\pi)^3 N + \bar{N}\left[h_\rho^{\,0}\vec{\tau}\cdot\vec{\phi}_\mu^{\,\rho} + h_\rho^{\,1}\phi_\mu^{\rho 3} + h_\rho^{\,2}\frac{(3\tau^3\phi_\mu^{\rho 3} - \vec{\tau}\cdot\vec{\phi}_\mu^{\,\rho})}{2(6)^{1/2}}\right]\gamma^\mu\gamma_5 N + \bar{N}[h_\omega^{\,0}\phi_\mu^{\,\omega} + h_\omega^{1}\tau^3\phi_\mu^{\,\omega}]\gamma^\mu\gamma_5 N - h_\rho'^{1}\bar{N}(\vec{\tau}\times\vec{\phi}_\mu^{\,\rho})^3\frac{\sigma^{\mu\nu}k_\nu}{2M}\gamma_5 N.$$

$$\mathscr{H}^{\mathrm{p.c.}}_{MNN} = ig_{\pi NN}\bar{N}\gamma_5\vec{\tau}\cdot\vec{\phi}^\pi N + g_\rho\bar{N}\left(\gamma_\mu + \frac{i\chi_V}{2M}\sigma_{\mu\nu}k^\nu\right)\vec{\tau}\cdot\vec{\phi}^{\mu\rho}N + g_\omega\bar{N}\left(\gamma^\mu + \frac{i\chi_S}{2M}\sigma^{\mu\nu}k_\nu\right)\phi_\mu^{\,\omega}N$$

$$\begin{aligned}
V_{12}^{\mathrm{p.v.}} = {} & \frac{f_\pi g_{\pi NN}}{2^{1/2}}\, i\left(\frac{\vec{\tau}_1\times\vec{\tau}_2}{2}\right)^z(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2M}, f_\pi(r)\right] \\
& - g_\rho\left(h_\rho^{\,0}\vec{\tau}_1\cdot\vec{\tau}_2 + h_\rho^{\,1}\left(\frac{\vec{\tau}_1+\vec{\tau}_2}{2}\right)^z + h_\rho^{\,2}\frac{(3\tau_1^{\,z}\tau_2^{\,z}-\vec{\tau}_1\cdot\vec{\tau}_2)}{2(6)^{1/2}}\right) \\
& \times\left((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2M}, f_\rho(r)\right\} + i(1+\chi_v)\,\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2M}, f_\rho(r)\right]\right) \\
& - g_\omega\left(h_\omega^{\,0} + h_\omega^{\,1}\left(\frac{\vec{\tau}_1+\vec{\tau}_2}{2}\right)^z\right) \\
& \times\left((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2M}, f_\omega(r)\right\} + i(1+\chi_S)\,\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2M}, f_\omega(r)\right]\right) \\
& - (g_\omega h_\omega^{\,1} - g_\rho h_\rho^{\,1})\left(\frac{\vec{\tau}_1-\vec{\tau}_2}{2}\right)^z(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2M}, f_\rho(r)\right\} \\
& - g_\rho h_\rho'^{1} i\left(\frac{\vec{\tau}_1\times\vec{\tau}_2}{2}\right)^z(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2M}, f_\rho(r)\right],
\end{aligned}$$

$$f_\pi(r) = \frac{e^{-m_\pi r}}{4\pi r},$$

$$f_\rho(r) = f_\omega(r) = \frac{e^{-m_\rho r}}{4\pi r}.$$

Parity violating nucleon-nucleon interaction

PHYSICAL REVIEW LETTERS **125,** 131803 (2020)

Featured in Physics

First Precision Measurement of the Parity Violating Asymmetry in Cold Neutron Capture on ^{3}He

M. T. Gericke,[1,*] S. Baeßler,[2,3] L. Barrón-Palos,[4] N. Birge,[5] J. D. Bowman,[3] J. Calarco,[6] V. Cianciolo,[3] C. E. Coppola,[5] C. B. Crawford,[7] N. Fomin,[5] I. Garishvili,[5] G. L. Greene,[5,3] G. M. Hale,[8] J. Hamblen,[9] C. Hayes,[5] E. Iverson,[3] M. L. Kabir,[7] M. McCrea,[1,10] E. Plemons,[5] A. Ramírez-Morales,[4] P. E. Mueller,[3] I. Novikov,[11] S. Penttila,[3] E. M. Scott,[5] J. Watts,[9] and C. Wickersham[9]

PHYSICAL REVIEW LETTERS **121,** 242002 (2018)

Editors' Suggestion

First Observation of *P*-odd γ Asymmetry in Polarized Neutron Capture on Hydrogen

D. Blyth,[1,2] J. Fry,[3,4] N. Fomin,[5,6] R. Alarcon,[1] L. Alonzi,[3] E. Askanazi,[3] S. Baeßler,[3,7] S. Balascuta,[8,1] L. Barrón-Palos,[9] A. Barzilov,[10] J. D. Bowman,[7] N. Birge,[5] J. R. Calarco,[11] T. E. Chupp,[12] V. Cianciolo,[7] C. E. Coppola,[5] C. B. Crawford,[13] K. Craycraft,[5,13] D. Evans,[3,4] C. Fieseler,[13] E. Frlež,[3] I. Garishvili,[7,5] M. T. W. Gericke,[14] R. C. Gillis,[7,4] K. B. Grammer,[7,5] G. L. Greene,[5,7] J. Hall,[3] J. Hamblen,[15] C. Hayes,[16,5] E. B. Iverson,[7] M. L. Kabir,[17,13] S. Kucuker,[18,5] B. Lauss,[19] R. Mahurin,[20] M. McCrea,[13,14] M. Maldonado-Velázquez,[9] Y. Masuda,[21] J. Mei,[4] R. Milburn,[13] P. E. Mueller,[7] M. Musgrave,[22,5] H. Nann,[4] I. Novikov,[23] D. Parsons,[15] S. I. Penttilä,[7] D. Počanić,[3] A. Ramirez-Morales,[9] M. Root,[3] A. Salas-Bacci,[3] S. Santra,[24] S. Schröder,[3,25] E. Scott,[5] P.-N. Seo,[3,26] E. I. Sharapov,[27] F. Simmons,[13] W. M. Snow,[4] A. Sprow,[13] J. Stewart,[15] E. Tang,[13,6] Z. Tang,[4,6] X. Tong,[7] D. J. Turkoglu,[28] R. Whitehead,[5] and W. S. Wilburn[6]

(NPDGamma Collaboration)

- Meson exchange approach
- Chiral EFT
- Unknown parameters (LECs)
  - DDH (1980) – estimates based on the quark model
  - Two recent precision experiments constraining the parameters

$$
\begin{aligned}
V_{12}^{\text{p.v.}} = {} & \frac{f_\pi g_{\pi NN}}{2^{1/2}}\, i\left(\frac{\vec\tau_1 \times \vec\tau_2}{2}\right)^z (\vec\sigma_1 + \vec\sigma_2)\cdot\left[\frac{\vec p_1 - \vec p_2}{2M}, f_\pi(r)\right] \\
& - g_\rho\left(h_\rho^{\,0}\vec\tau_1\cdot\vec\tau_2 + h_\rho^{\,1}\left(\frac{\vec\tau_1 + \vec\tau_2}{2}\right)^z + h_\rho^{\,2}\,\frac{(3\tau_1^{\,z}\tau_2^{\,z} - \vec\tau_1\cdot\vec\tau_2)}{2(6)^{1/2}}\right) \\
& \times\left((\vec\sigma_1 - \vec\sigma_2)\cdot\left\{\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\right\} + i(1+\chi_v)\,\vec\sigma_1\times\vec\sigma_2\cdot\left[\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\right]\right) \\
& - g_\omega\left(h_\omega^{\,0} + h_\omega^{\,1}\left(\frac{\vec\tau_1 + \vec\tau_2}{2}\right)^z\right) \\
& \times\left((\vec\sigma_1 - \vec\sigma_2)\cdot\left\{\frac{\vec p_1 - \vec p_2}{2M}, f_\omega(r)\right\} + i(1+\chi_S)\,\vec\sigma_1\times\vec\sigma_2\cdot\left[\frac{\vec p_1 - \vec p_2}{2M}, f_\omega(r)\right]\right) \\
& - (g_\omega h_\omega^{\,1} - g_\rho h_\rho^{\,1})\left(\frac{\vec\tau_1 - \vec\tau_2}{2}\right)^z (\vec\sigma_1 + \vec\sigma_2)\cdot\left\{\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\right\} \\
& - g_\rho h_\rho'^{\,1} i\left(\frac{\vec\tau_1 \times \vec\tau_2}{2}\right)^z (\vec\sigma_1 + \vec\sigma_2)\cdot\left[\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\right],
\end{aligned}
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$$f_\pi(r) = \frac{e^{-m_\pi r}}{4\pi r},$$

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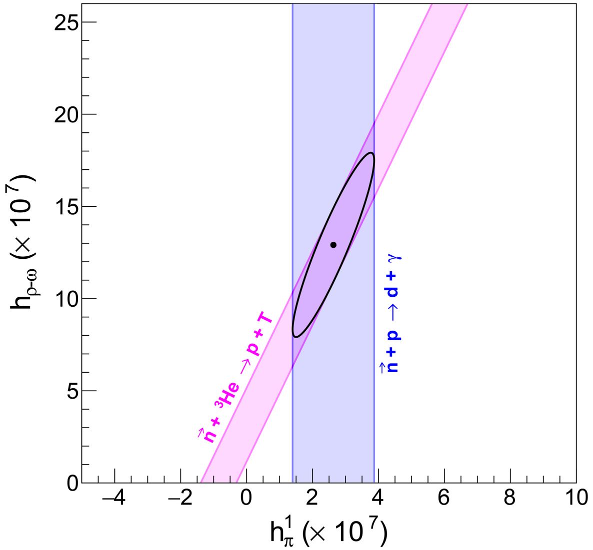

$$f_\pi \equiv h_\pi^1$$

$$h_{\rho-\omega} \equiv h_\omega^1 + 0.46h_\rho^1 - 0.46h_\omega^0 - 0.76h_\rho^0 - 0.02h_\rho^2$$

Parity and time-reversal violating nucleon-nucleon interaction

PHYSICAL REVIEW C **70**, 055501 (2004)

***P*- and *T*-odd two-nucleon interaction and the deuteron electric dipole moment**

C.-P. Liu* and R. G. E. Timmermans†

Introduced through Hamiltonian H_{PVTV} :

$$H_{PVTV}(\boldsymbol{r}) = \frac{1}{2m_n} \boldsymbol{\sigma}_- \cdot \nabla \left(-\bar{G}_\omega^0 y_\omega(r)\right)$$
$$+\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \, \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}_\pi^0 y_\pi(r) - \bar{G}_\rho^0 y_\rho(r)\right)$$
$$+\frac{\tau_+^z}{2} \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}_\pi^1 y_\pi(r) - \bar{G}_\rho^1 y_\rho(r) - \bar{G}_\omega^1 y_\omega(r)\right)$$
$$+\frac{\tau_-^z}{2} \boldsymbol{\sigma}_+ \cdot \nabla \left(\bar{G}_\pi^1 y_\pi(r) + \bar{G}_\rho^1 y_\rho(r) - \bar{G}_\omega^1 y_\omega(r)\right)$$
$$+(3\tau_1^z \tau_2^z - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)\boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}_\pi^2 y_\pi(r) - \bar{G}_\rho^2 y_\rho(r)\right)$$

- Based on one meson exchange model
- $y_x(r) = e^{-m_x r}/(4\pi r)$

$$\sigma_\pm = \sigma_1 \pm \sigma_2$$
$$\tau_\pm^z = \tau_1^z \pm \tau_2^z$$

Parity and time-reversal violating nucleon-nucleon interaction

PHYSICAL REVIEW C **70**, 055501 (2004)

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$$+\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\, \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}^0_\pi y_\pi(r) - \bar{G}^0_\rho y_\rho(r)\right)$$

$$+\frac{\tau^z_+}{2} \boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}^1_\pi y_\pi(r) - \bar{G}^1_\rho y_\rho(r) - \bar{G}^1_\omega y_\omega(r)\right)$$

$$+\frac{\tau^z_-}{2} \boldsymbol{\sigma}_+ \cdot \nabla \left(\bar{G}^1_\pi y_\pi(r) + \bar{G}^1_\rho y_\rho(r) - \bar{G}^1_\omega y_\omega(r)\right)$$

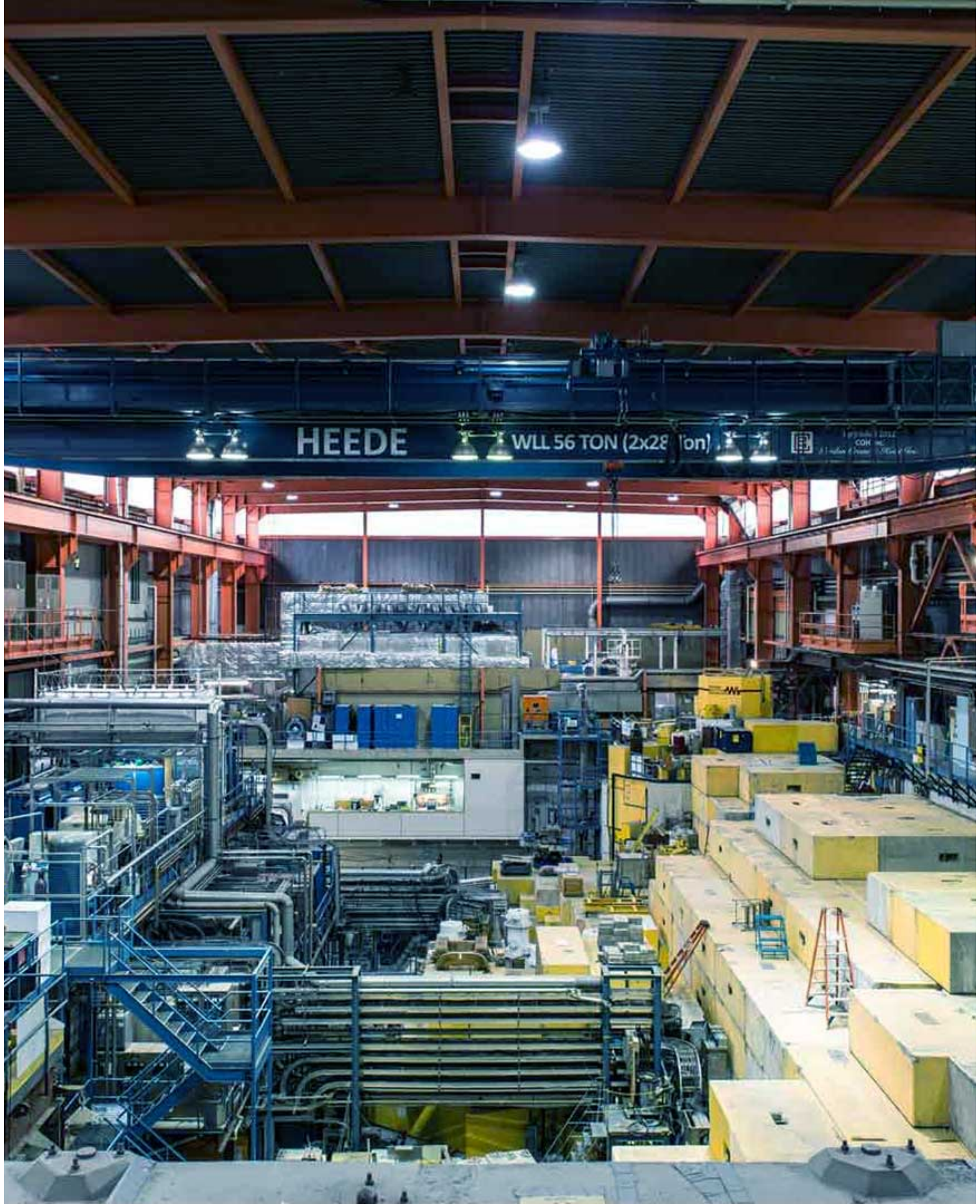
$$+(3\tau^z_1\tau^z_2 - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)\boldsymbol{\sigma}_- \cdot \nabla \left(\bar{G}^2_\pi y_\pi(r) - \bar{G}^2_\rho y_\rho(r)\right)$$

- Based on one meson exchange model
- $y_x(r) = e^{-m_x r}/(4\pi r)$
- Coupling constants

$$\sigma_\pm = \sigma_1 \pm \sigma_2$$

$$\tau^z_\pm = \tau^z_1 \pm \tau^z_2$$

NCSM calculations of anapole and electric dipole moments in light nuclei



Discovery, accelerated

Parity and time-reversal violating nucleon-nucleon interaction and nuclear EDM or Schiff moment

H_{PVTV} introduces parity admixture in the ground state (perturbation theory):

$$|0\rangle \longrightarrow |0\rangle + |\tilde{0}\rangle$$

$$|\tilde{0}\rangle = \sum_{n \neq 0} \frac{1}{E_0 - E_n} |n\rangle\langle n| H_{PVTV} |0\rangle$$

Nuclear EDM is dominated by polarization contribution:

$$\boldsymbol{S} = \frac{e}{10} \sum_{i=1}^{Z} \left(r_i^2 \boldsymbol{r}_i - \frac{5}{3} \langle r^2 \rangle_{\mathrm{ch}} \boldsymbol{r}_i \right)$$

$$D^{(pol)} = \langle 0 | \widehat{D}_z | \tilde{0} \rangle + c.c.$$

$$\widehat{D}_z = \frac{e}{2} \sum_{i=1}^{A} (1 + \tau_i^z)\, z_i$$

Parity and time-reversal violating nucleon-nucleon interaction and nuclear EDM or Schiff moment

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Low lying states of opposite parity can lead to enhancement!

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Parity violating nucleon-nucleon interaction and the nuclear anapole moment

- Parity violating (non-conserving) V_{NN}^{PNC} interaction
  - Conserves total angular momentum *I*
  - Mixes opposite parities
  - Has isoscalar, isovector and isotensor components
  - Admixes unnatural parity states in the ground state

$$|\psi_{\rm gs}\; I\rangle = |\psi_{\rm gs}\; I^{\pi}\rangle + \sum_j |\psi_j\; I^{-\pi}\rangle \times \frac{1}{E_{\rm gs} - E_j} \langle \psi_j\; I^{-\pi}|V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\; I^{\pi}\rangle$$

$$\begin{aligned}
V_{12}^{\text{p.v.}} = {} & \frac{f_\pi g_{\pi NN}}{2^{1/2}}\, i \left(\frac{\vec\tau_1 \times \vec\tau_2}{2}\right)^z (\vec\sigma_1 + \vec\sigma_2) \cdot \left[\frac{\vec p_1 - \vec p_2}{2M}, f_\pi(r)\right] \\
& - g_\rho \left(h_\rho^{\,0} \vec\tau_1 \cdot \vec\tau_2 + h_\rho^{\,1} \left(\frac{\vec\tau_1 + \vec\tau_2}{2}\right)^z + h_\rho^{\,2} \frac{(3\tau_1^{\,z}\tau_2^{\,z} - \vec\tau_1 \cdot \vec\tau_2)}{2(6)^{1/2}}\right) \\
& \times \left((\vec\sigma_1 - \vec\sigma_2) \cdot \left\{\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\right\} + i(1 + \chi_v)\, \vec\sigma_1 \times \vec\sigma_2 \cdot \left[\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\right]\right) \\
& - g_\omega \left(h_\omega^{\,0} + h_\omega^{\,1} \left(\frac{\vec\tau_1 + \vec\tau_2}{2}\right)^z\right) \\
& \times \left((\vec\sigma_1 - \vec\sigma_2) \cdot \left\{\frac{\vec p_1 - \vec p_2}{2M}, f_\omega(r)\right\} + i(1 + \chi_S)\, \vec\sigma_1 \times \vec\sigma_2 \cdot \left[\frac{\vec p_1 - \vec p_2}{2M}, f_\omega(r)\right]\right) \\
& - (g_\omega h_\omega^{\,1} - g_\rho h_\rho^{\,1}) \left(\frac{\vec\tau_1 - \vec\tau_2}{2}\right)^z (\vec\sigma_1 + \vec\sigma_2) \cdot \left\{\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\right\} \\
& - g_\rho h_\rho'^{\,1} i \left(\frac{\vec\tau_1 \times \vec\tau_2}{2}\right)^z (\vec\sigma_1 + \vec\sigma_2) \cdot \left[\frac{\vec p_1 - \vec p_2}{2M}, f_\rho(r)\right],
\end{aligned}$$

$$f_\pi(r) = \frac{e^{-m_\pi r}}{4\pi r},$$

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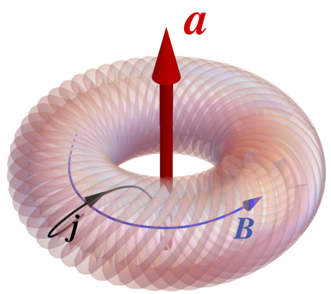
$$|\psi_{\rm gs}\ I\rangle = |\psi_{\rm gs}\ I^{\pi}\rangle + \sum_j |\psi_j\ I^{-\pi}\rangle \times \frac{1}{E_{\rm gs}-E_j}\langle\psi_j\ I^{-\pi}|V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\ I^{\pi}\rangle$$

- Anapole moment operator dominated by spin contribution



$$\boldsymbol{a} = -\pi \int d^3r\, r^2\, \boldsymbol{j}(\boldsymbol{r})$$

$$\hat{\boldsymbol{a}}_s = \frac{\pi e}{m}\sum_{i=1}^{A}\mu_i(\boldsymbol{r}_i \times \boldsymbol{\sigma}_i)$$

$$\mu_i = \mu_p(1/2+t_{z,i}) + \mu_n(1/2-t_{z,i})$$

$$a_s = \langle\psi_{\rm gs}\ I\ I_z{=}I|\hat{a}^{(1)}_{s,0}|\psi_{\rm gs}\ I\ I_z{=}I\rangle$$

- Here is what we want to calculate:

$$\kappa_A = \frac{\sqrt{2}e}{G_F}a_s$$

$$\kappa_A = -i4\pi\frac{e^2}{G_F}\frac{\hbar}{mc}\frac{(II10|II)}{\sqrt{2I+1}}\sum_j\langle\psi_{\rm gs}\ I^{\pi}||\sqrt{4\pi/3}\sum_{i=1}^{A}\mu_i r_i[Y_1(\hat{r}_i)\sigma_i]^{(1)}||\psi_j\ I^{-\pi}\rangle\frac{1}{E_{\rm gs}-E_j}\langle\psi_j\ I^{-\pi}|V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\ I^{\pi}\rangle$$

How to calculate the sum of intermediate unnatural parity states?

$$|\psi_{\rm gs}\ I\rangle = |\psi_{\rm gs}\ I^{\pi}\rangle + \sum_j |\psi_j\ I^{-\pi}\rangle \frac{1}{E_{\rm gs} - E_j} \langle \psi_j\ I^{-\pi} | V_{\rm NN}^{\rm PNC} | \psi_{\rm gs}\ I^{\pi}\rangle$$

- Solving Schroedinger equation with inhomogeneous term

$$(E_{\rm gs} - H)|\psi_{\rm gs}\ I\rangle = V_{\rm NN}^{\rm PNC} |\psi_{\rm gs}\ I^{\pi}\rangle$$

- To invert this equation, we apply the Lanczos algorithm

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$$|\psi_{\rm gs}\ I\rangle = |\psi_{\rm gs}\ I^{\pi}\rangle + \sum_j |\psi_j\ I^{-\pi}\rangle \frac{1}{E_{\rm gs} - E_j} \langle \psi_j\ I^{-\pi}| V_{\rm NN}^{\rm PNC} |\psi_{\rm gs}\ I^{\pi}\rangle$$

- Solving Schroedinger equation with inhomogeneous term

$$(E_{\rm gs} - H)|\psi_{\rm gs}\ I\rangle = V_{\rm NN}^{\rm PNC} |\psi_{\rm gs}\ I^{\pi}\rangle$$

- To invert this equation, we apply the Lanczos algorithm
  - — Bring matrix to tri-diagonal form ($\mathbf{v}_1$, $\mathbf{v}_2$ … orthonormal, H Hermitian)

$$\begin{aligned}
H\mathbf{v}_1 &= \alpha_1\mathbf{v}_1 + \beta_1\mathbf{v}_2 \\
H\mathbf{v}_2 &= \beta_1\mathbf{v}_1 + \alpha_2\mathbf{v}_2 + \beta_2\mathbf{v}_3 \\
H\mathbf{v}_3 &= \beta_2\mathbf{v}_2 + \alpha_3\mathbf{v}_3 + \beta_3\mathbf{v}_4 \\
H\mathbf{v}_4 &= \beta_3\mathbf{v}_3 + \alpha_4\mathbf{v}_4 + \beta_4\mathbf{v}_5
\end{aligned}$$

  - — n^{th} iteration computes $2n^{th}$ moment
  - — Eigenvalues converge to extreme (largest in magnitude) values
  - — ~ 150-200 iterations needed for 10 eigenvalues (even for 10^9 states)

How to calculate the sum of intermediate unnatural parity states?

$$|\psi_{\rm gs}\ I\rangle = |\psi_{\rm gs}\ I^{\pi}\rangle + \sum_j |\psi_j\ I^{-\pi}\rangle \frac{1}{E_{\rm gs}-E_j} \langle \psi_j\ I^{-\pi}|V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\ I^{\pi}\rangle$$

- Solving Schroedinger equation with inhomogeneous term

$$(E_{\rm gs}-H)|\psi_{\rm gs}\ I\rangle = V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\ I^{\pi}\rangle$$

- To invert this equation, we apply the Lanczos algorithm

$$|\mathbf{v}_1\rangle = V_{\rm NN}^{\rm PNC}|\psi_{\rm gs}\ I^{\pi}\rangle$$

$$|\psi_{\rm gs}\ I\rangle \approx \sum_k g_k(E_0)|\mathbf{v}_k\rangle$$

$$\hat{g}_1(\omega) = \cfrac{1}{\omega-\alpha_1-\cfrac{\beta_1^2}{\omega-\alpha_2-\cfrac{\beta_2^2}{\omega-\alpha_3-\beta_3^2 \ddots}}}$$

Few-Body Systems 33, 259–276 (2003)
DOI 10.1007/s00601-003-0017-z

Few-Body Systems
Printed in Austria

Efficient Method for Lorentz Integral Transforms of Reaction Cross Sections

M. A. Marchisio[1], N. Barnea[2], W. Leidemann[1], and G. Orlandini[1]

Lanczos continued fraction method

PHYSICAL REVIEW C **104**, 025502 (2021)

Ab initio **calculations of electric dipole moments of light nuclei**

Paul Froese*
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada
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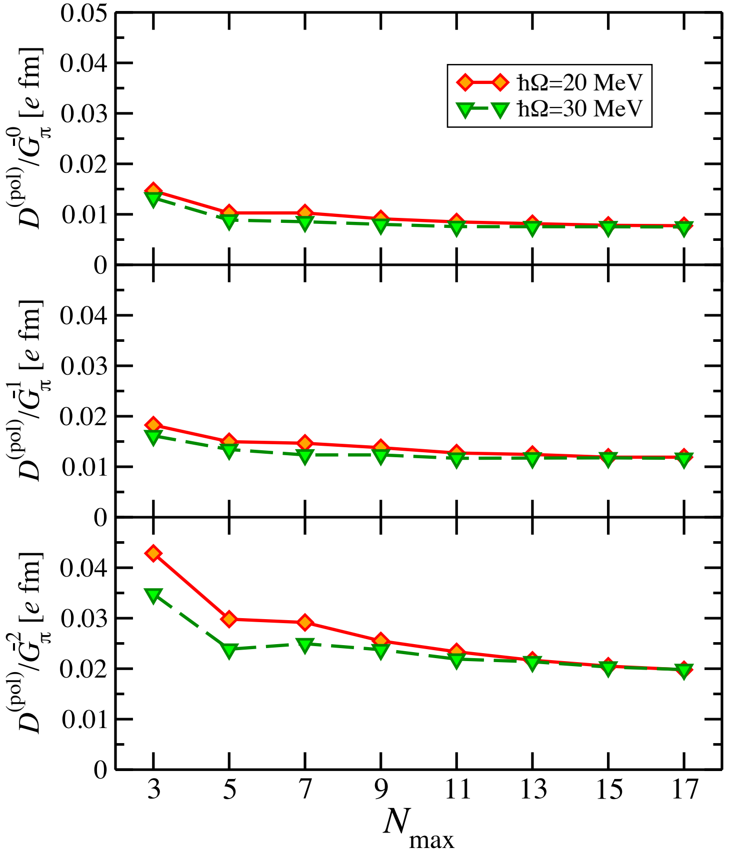
^{3}He EDM Benchmark Calculation

Discrepancy between calculations?

	PLB 665:165-172 (2008) (NN EFT)	PRC 87:015501 (2013)	PRC 91:054005 (2015)	Our calculation (NN EFT)
$\bar{G}_\pi^0$	0.015	(x 1/2)	(x 1/2)	0.0073 (x 1/2)
$\bar{G}_\pi^1$	0.023	(x 1/2)	(x 1/2)	0.011 (x 1/2)
$\bar{G}_\pi^2$	0.037	(x 1/5)	(x 1/2)	0.019 (x 1/2)
$\bar{G}_\rho^0$	-0.0012	(x 1/2)	(x 1/2)	-0.00062 (x 1/2)
$\bar{G}_\rho^1$	0.0013	(x 1/2)	(x 1/2)	0.00063 (x 1/2)
$\bar{G}_\rho^2$	-0.0028	(x 1/5)	(x 1/2)	-0.0014 (x 1/2)
$\bar{G}_\omega^0$	0.0009	(x 1/2)	(x 1/2)	0.00042 (x 1/2)
$\bar{G}_\omega^1$	-0.0017	(x 1/2)	(x 1/2)	-0.00086 (x 1/2)

N_{max} convergence for ^{3}He

N^{3}LO NN



Our results confirm those of Yamanaka and Hiyama, PRC 91:054005 (2015)

PHYSICAL REVIEW A **102**, 052828 (2020)

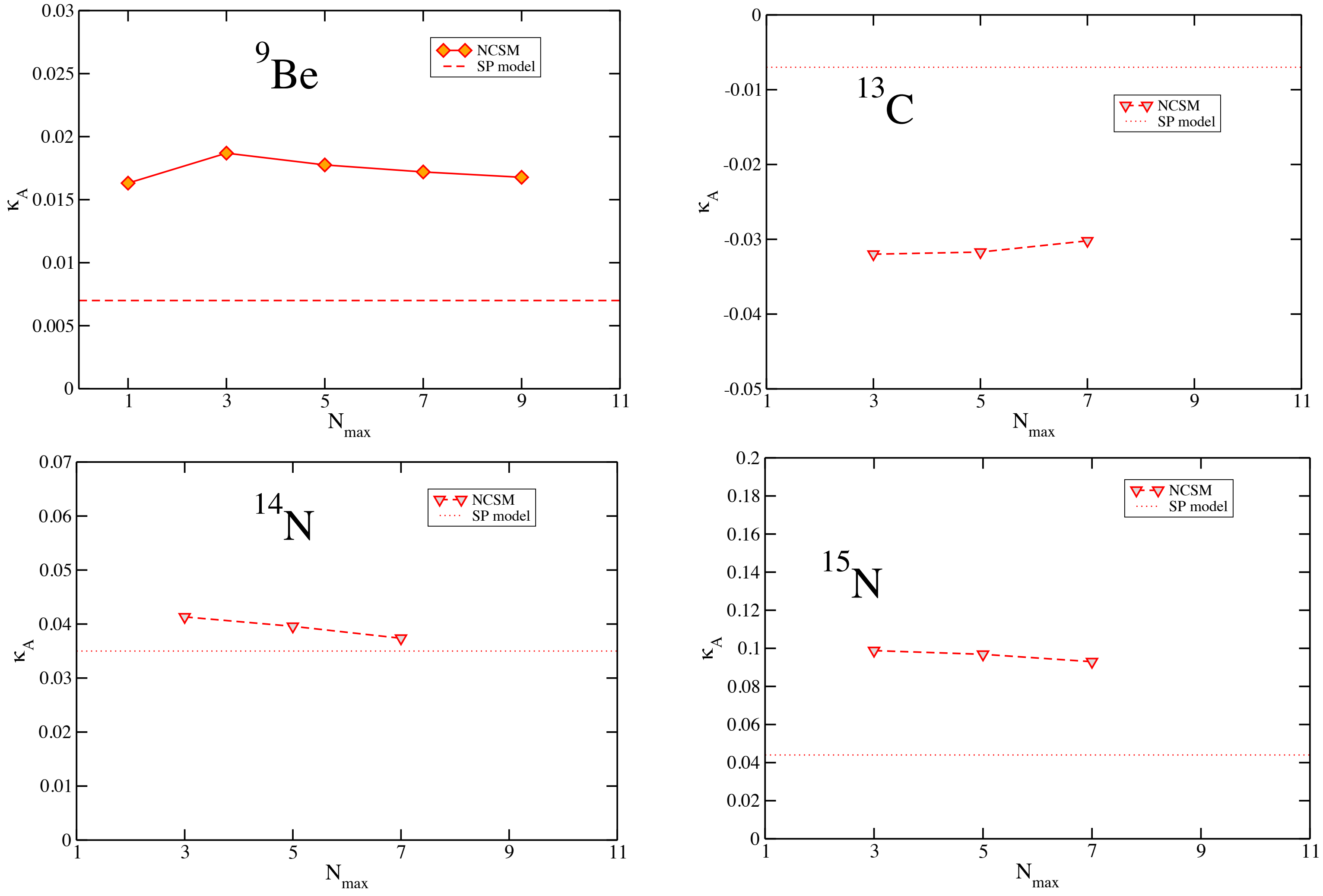
Editors' Suggestion

Nuclear spin-dependent parity-violating effects in light polyatomic molecules

Yongliang Hao,[1] Petr Navrátil,[2] Eric B. Norrgard,[3] Miroslav Iliaš,[4] Ephraim Eliav,[5] Rob G. E. Timmermans,[1] Victor V. Flambaum,[6] and Anastasia Borschevsky[1,*]

Anapole moment calculations: Basis size convergence

- Overall, convergence very good, comparable to that of the magnetic moment



Comparison to valence nucleon model (dotted lines)

$$\kappa_A = \frac{9}{10}\frac{\alpha\mu_i}{m_p r_0} g_i A^{2/3}\frac{K}{I+1}$$
$$\simeq 1.15\times 10^{-3} g_i \mu_i A^{2/3}\frac{K}{I+1},$$

$$K = (I+1/2)(-1)^{I-\ell_i+1/2}$$

Anapole moments from *ab initio* calculations larger in absolute value

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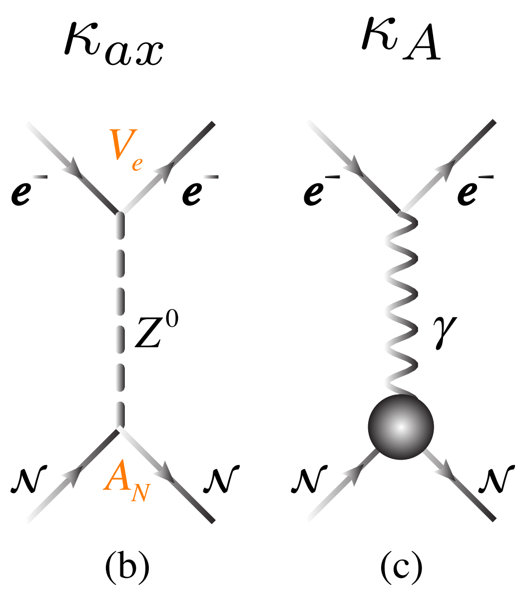
Nuclear spin-dependent parity-violating effects from NCSM

- Contributions from nucleon axial-vector and the anapole moment

	^{9}Be	^{13}C	^{14}N	^{15}N	^{25}Mg
I^π	$3/2^-$	$1/2^-$	1^+	$1/2^-$	$5/2^+$
$\mu^{\text{exp.}}$	-1.177[a]	0.702[b]	0.404[c]	-0.283[d]	-0.855[e]
			NCSM calculations		
μ	-1.05	0.44	0.37	-0.25	-0.50
κ_A	0.016	-0.028	0.036	0.088	0.035
$\langle s_{p,z}\rangle$	0.009	-0.049	-0.183	-0.148	0.06
$\langle s_{n,z}\rangle$	0.360	-0.141	-0.1815	0.004	0.30
κ_{ax}	0.035	-0.009	0.0002	0.015	0.024
κ	0.050	-0.037	0.037	0.103	0.057



$$\kappa_{ax} \simeq -2C_{2p}\langle s_{p,z}\rangle - 2C_{2n}\langle s_{n,z}\rangle \simeq -0.1\langle s_{p,z}\rangle + 0.1\langle s_{n,z}\rangle$$

$$\langle s_{\nu,z}\rangle \equiv \langle \psi_{\rm gs}\ I^\pi I_z{=}I | \hat{s}_{\nu,z} | \psi_{\rm gs}\ I^\pi I_z{=}I\rangle$$

$$C_{2\rm p} = -C_{2\rm n} = g_A(1 - 4\sin^2\theta_W)/2 \simeq 0.05$$

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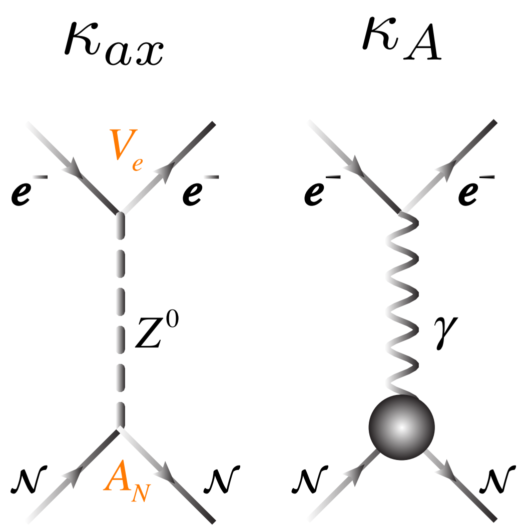
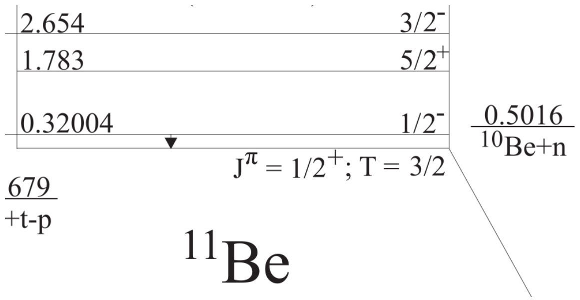


(b) (c)

Expecting a significant enhancement of the anapole moment for ^{11}Be

^{11}Be anapole moment calculations in progress –
NCSM with continuum (NCSMC) applied



PHYSICAL REVIEW C **104**, 025502 (2021)

Calculated EDMs of selected stable nuclei

Ab initio **calculations of electric dipole moments of light nuclei**

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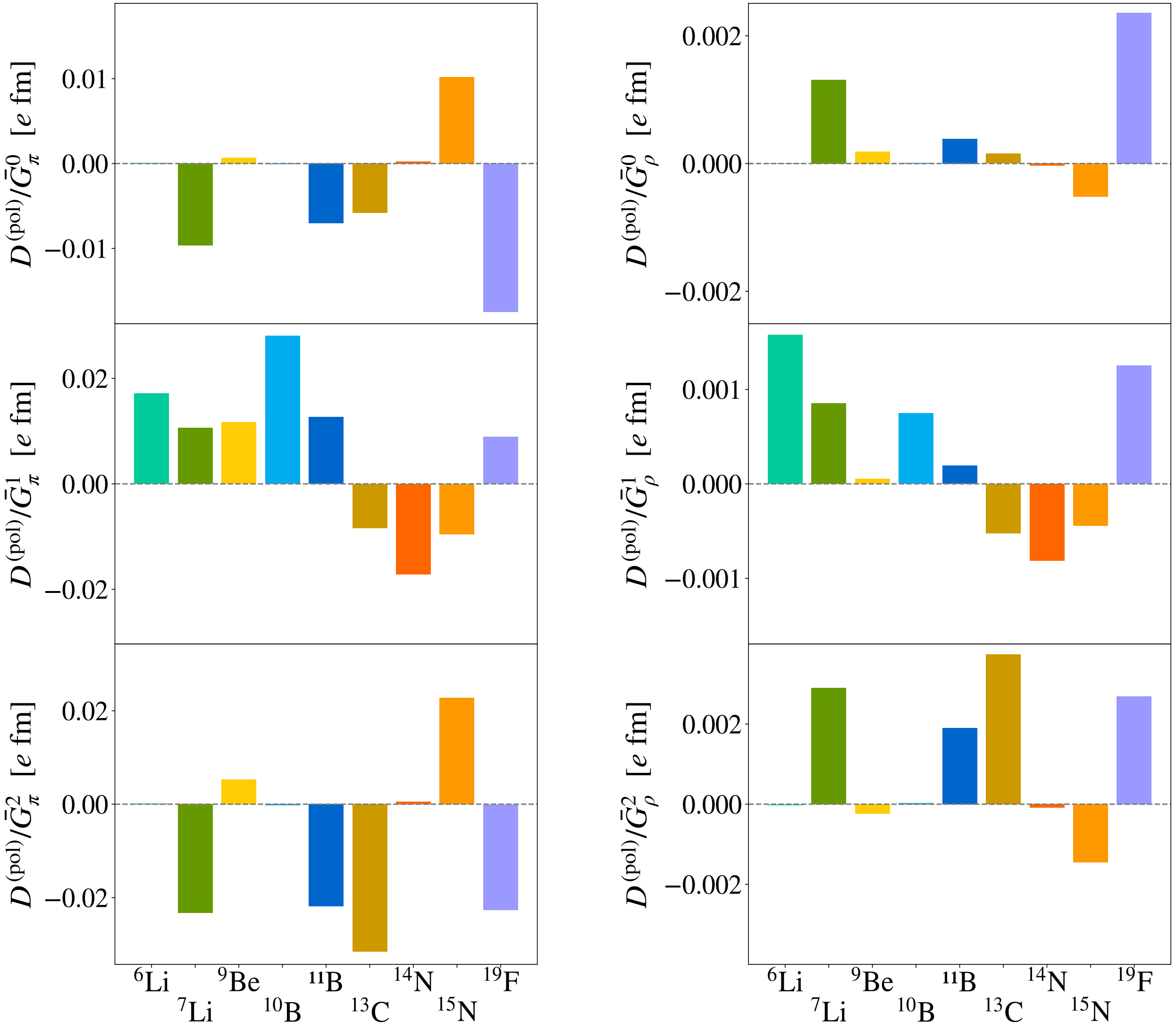
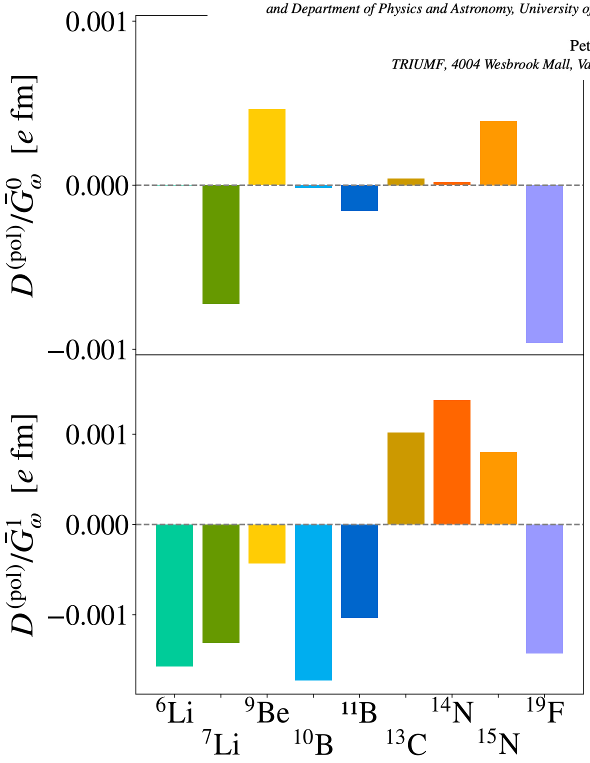
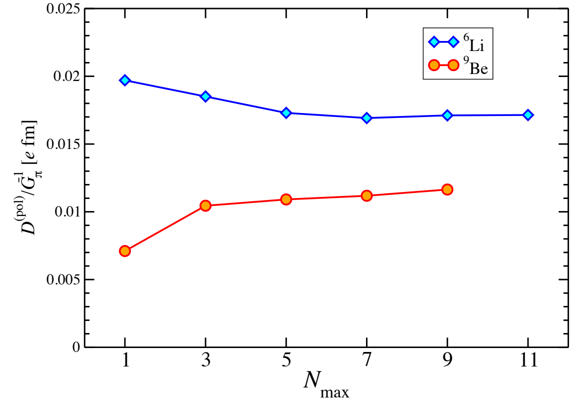




Examples of N_{max} convergence



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	d_p	d_n	$\bar{G}^0_\pi$	$\bar{G}^1_\pi$	$\bar{G}^2_\pi$	$\bar{G}^0_\rho$	$\bar{G}^1_\rho$	$\bar{G}^2_\rho$	$\bar{G}^0_\omega$	$\bar{G}^1_\omega$	μ	$\mu^{\text{exp.}}$
^{3}He	-0.031	0.905	0.0073	0.011	0.019	-0.00062	0.000063	-0.0014	0.00042	-0.00086	-1.79	-2.127
^{6}Li	0.892	0.890	0.00006	0.0171	0.0002	-0.000003	0.00158	-0.00002	-0.000002	-0.0016	+0.84	+0.822
^{7}Li	0.930	0.018	-0.0096	0.0106	-0.0233	0.00131	0.00085	0.0029	-0.00072	-0.0013	+2.99	+3.256
^{9}Be	0.018	0.720	0.0007	0.0116	0.0053	0.00019	0.00005	-0.0002	0.00046	-0.0004	-1.05	-1.177
^{10}B	0.852	0.848	-0.0001	0.0281	-0.0002	0.00001	0.00075	0.00002	-0.00002	-0.0017	+1.83	+1.801
^{11}B	0.444	0.050	-0.0070	0.0127	-0.0219	0.00039	0.00019	0.0019	-0.00016	-0.0010	+2.09	+2.689
^{13}C	-0.098	-0.282	-0.0058	-0.0084	-0.0316	0.00016	-0.00052	0.0037	0.00004	0.0010	+0.44	+0.702
^{14}N	-0.366	-0.363	0.0003	-0.0172	0.0006	-0.00003	-0.00081	-0.0001	0.00002	0.0014	+0.37	+0.404
^{15}N	-0.296	0.008	0.0102	-0.0095	0.0228	-0.00052	-0.00044	-0.0015	0.00039	0.0008	-0.25	-0.283
^{19}F	0.818	-0.052	-0.0175	0.0089	-0.0226	0.00236	0.00125	0.0027	-0.00096	-0.0014	+2.85	+2.629

Table I. The nucleonic and polarization contributions to EDMs of ^{3}He, stable p-shell nuclei, and ^{19}F (in e fm) decomposed as coefficients of d_p, d_n, and $\bar{G}^T_\chi$, where χ stands for π, ρ, or ω exchanges. In the last two columns, calculated and experimental (from Ref. [49]) nuclear magnetic dipole moments (in $\mu_{\rm N}$) are compared. SRG-evolved chiral NN+3N(lnl) PTC interaction from Ref. [34] was used except for ^{3}He where the chiral N^{3}LO PTC NN [35] was utilized.

Conclusions

- *Ab initio* no-core shell model capable to calculate accurately nuclear structure effects needed for analysis of parity-violation and time-reversal violation experiments in atoms and molecules
  - First results available
  - 10% precision within the reach
- Different nuclei can be used to probe different terms of the parity & time-reversal violating interaction
- Theoretical calculations of EDMs allow us to suggest promising candidates for planned experiments in storage rings
- Improvements include
  - SRG renormalization of the parity- & time-reversal violating interactions and the anapole & E1 operators
  - Higher-order terms of the anapole operator
  - Chiral EFT based parity- & time-reversal violating interaction with sub-leading terms
- Outlook
  - Calculation of the ^{11}Be EDM and the anapole moment that are expected to be strongly enhanced
    - ^{11}Be has low lying states of opposite parity, but ground state is an extended halo state, NCSM with continuum (NCSMC) must be applied
  - NCSM calculations of Schiff moments for light nuclei (also useful for benchmarking with other *ab initio* methods)
  - PV and PVTV NN interaction matrix elements made available to the SDSU and ORNL groups for applications in LSM and CCM, respectively

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Thank you!
Merci!

Discovery, accelerated