TECHNISCHE UNIVERSITÄT DARMSTADT

Three-nucleon Forces and Two-body Currents in Nuclear Structure

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EMMI Program
“The extreme matter physics of nuclei:
from universal properties to neutron-rich extremes”

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Outline

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Microscopic calculation of medium-mass nuclei

Microscopic calculation of medium-mass nuclei including 3N forces

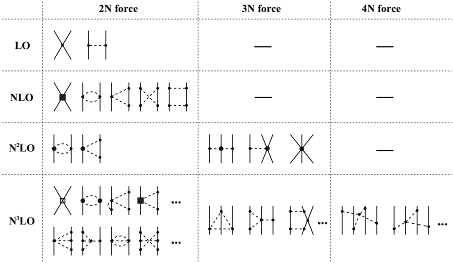
- Use Chiral Effective Field Theory (chiral EFT) interactions, includes naturally NN and 3N forces.
- Perform a renormalization group evolution to V_{lowk} interaction to enhance convergence of the MBPT calculation
- Apply Many-Body Perturbation Theory (MBPT) to obtain interactions to be used in Shell Model (SM) calculations

$\Rightarrow$ 3N forces are naturally included
Shown necessary to reproduce light nuclei spectra

$\Rightarrow$ All the parameters that appear in the SM hamiltonian calculated from the input of the microscopic interaction (no fits!)
Test nuclear forces for stable and exotic nuclei

NN+3N Forces in Chiral EFT

Systematic expansion: nuclear forces



NN force couplings fitted to NN data

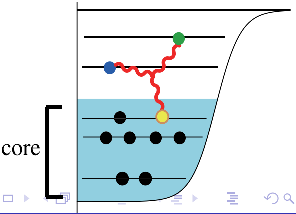
3N force couplings fitted to few body data

Chiral EFT potentials for NN at N^3LO and 3N at N^2LO

normal-ordered 2B: 2 valence, 1 core particle
⇒ (effective) Two-body Matrix Elements (TBME)

normal-ordered 1B: 1 valence, 2 core particles
⇒ (effective) Single particle energies (SPE)

residual 3B:
⇒ Estimated to be suppressed by $N_{valence}/N_{core}$



Shell Model calculations

- Shell Model interactions
  Ca isotopes: *pf* shell and $pfg_{9/2}$ valence space
    - *pf* shell, empirical SPEs
    - $pfg_{9/2}$ valence space, empirical and MBPT SPEs
- Test perturbative character of $g_{9/2}$ orbit
    - *pf* shell, treated perturbatively
    - $pfg_{9/2}$ valence space treated non-perturbatively
- Full diagonalizations using codes ANTOINE and NATHAN
  Caurier et al. RMP77 427(2005)
- Results with 3N forces included to 3rd order in MBPT

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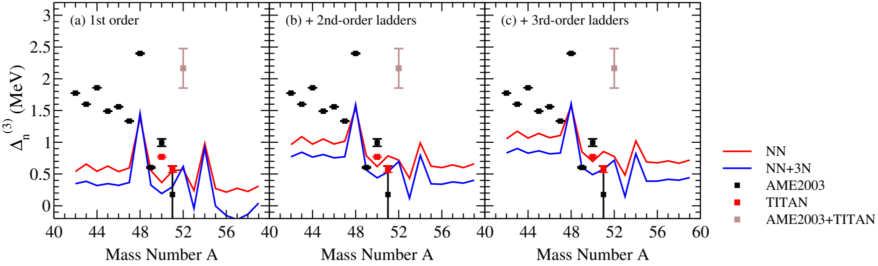
Pairing Gaps of Neutron rich Ca isotopes

- Nuclear mass and spectrum measurements explore nuclear shell evolution
- Ca isotopes: $N = 20, 28, 32, 34?$ closed shells, extremely interesting region
- Reliable predictions for neutron rich isotopes

Theoretical pairing gaps compared to experiment via the three point mass formula:

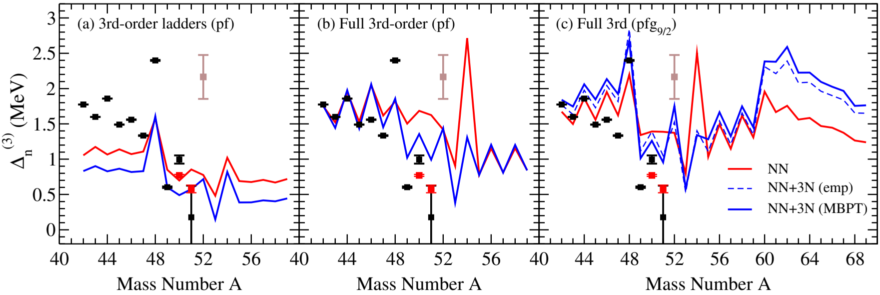
$$\Delta_N^3 = (-1)^N \frac{BE\,(N-1) + BE\,(N+1) - 2BE\,(N)}{2}$$

Convergence of MBPT



- Succesive orders *pp*, *hh* ladder diagrams build up pairing gaps
- At third order *pp*, *hh* ladders results seem to be converged
- 3N forces reduce the pairing gaps
  $\Rightarrow$ agree with EDF: Lesinski et al. JPhysG39 015108 (2012)

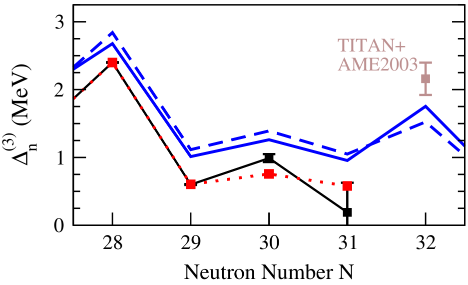
Full 3rd order MBPT calculation



- Full third order MBPT improves agreement with experiment
  Core-polarization effects significantly enhance pairing gaps
- Very good agreement with experimental trends

Pairing Gaps in the $A = 48 - 52$ region

$pfg_{9/2}$ space necessary to reproduce $N = 28$ closure,
and also to describe pairing gaps in the region $A = 48 - 52$



A. T. Gallant et al. arXiv 1204.1987

New precision measurements in ^{51,52}Ca change previous slope from AME 2003

The experimental trend is very well reproduced by theory

Theoretical results systematically 0.5 MeV higher than experiment

Two sets of spe's, empirical and calculated

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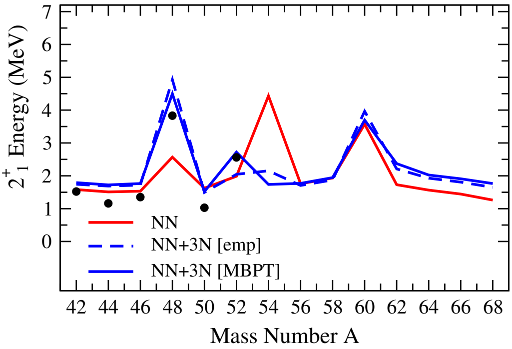
Shell closures in calcium isotopes

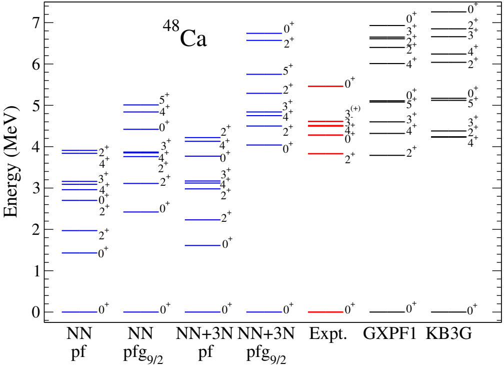
2_1^+ energies characterise shell closures of the neutron rich calcium isotopes



- Correct closure at $N = 28$ when 3N forces are included ($pfg_{9/2}$)
- 3N forces enhance closure at $N = 32$
- 3N forces vanish closure at $N = 34$
- Predicted shell closure at $N = 60$

^{48}Ca spectra

Results in *pf*–*pfg*$_{9/2}$ spaces and based on NN–NN+3N interactions compared to standard phenomenological interactions



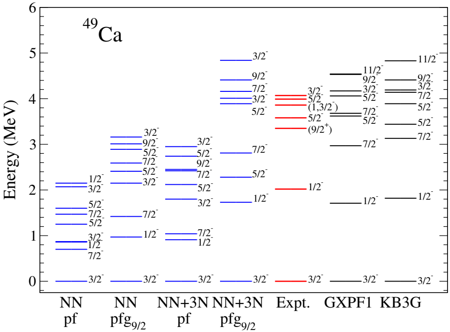
Spectra too compressed

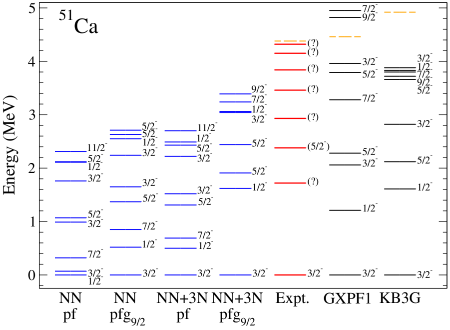
2_1^+ state only ∼appropriate energy in *pfg*$_{9/2}$ NN+3N calculation

Importance of 3N forces

Importance of including $g_{9/2}$ orbit

^{49}Ca, ^{51}Ca neutron rich spectra



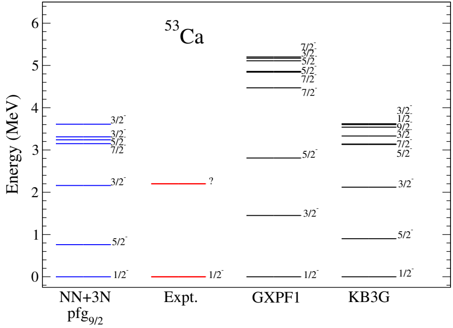


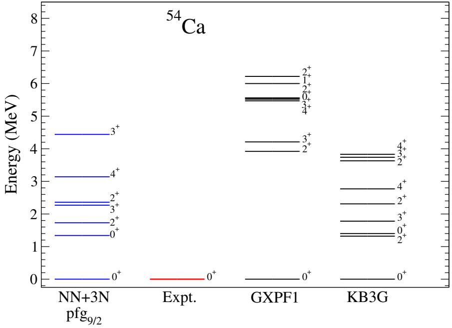
Spectrum compressed unless $pfg_{9/2}$ NN+3N

Correct $(1/2)^-$ energy, (too low $(5/2)^-$), possibility to assign experimental spins

Similar quality as phenomenological interactions

^{53}Ca, ^{54}Ca neutron rich spectra





Phenomenological interactions different results in neutron rich nuclei

MBPT: prediction

Explore sensitivity to theoretical uncertainties

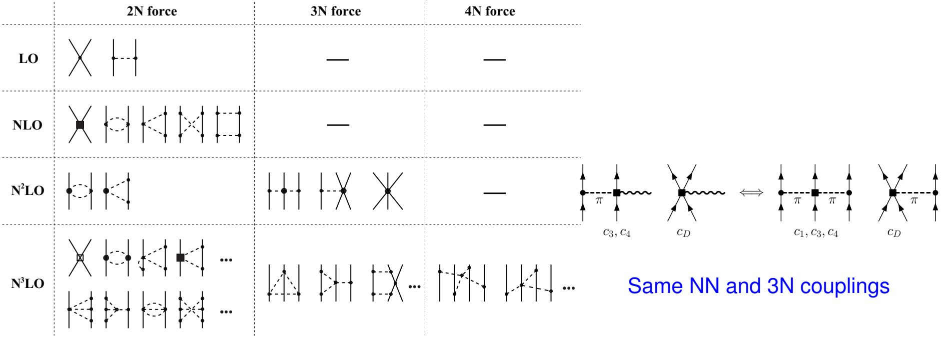
More experimental information greatly appreciated!

Outline

1. Introduction
2. 3N forces in neutron rich Ca isotopes
   - Pairing gaps
   - Spectra
3. 2B currents in electroweak transitions
4. Summary and Outlook

Forces and Currents in Chiral EFT

- Systematic expansion: nuclear forces and electroweak currents

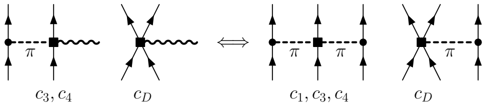


Same NN and 3N couplings

Chiral weak currents

Chiral EFT currents Park et al. PRC67 055206(2003)

- Systematically obtain the currents at Q^0, $Q^2 \dots$ order
- Order Q^0:
  - Fermi term: $J_n^0(p^2) = g_V(0)\,\tau_n^-$
  - Gamow-Teller term: $\mathbf{J}_{n,1B}(p^2) = g_A(0)\,\sigma_n\tau_n^-$
- Order Q^2:
  - $\frac{1}{m_N}$ terms
  - Loop corrections, pion propagator $\propto \mathbf{p}^2 \sim$ form factors
- Order Q^3, two-body currents: $\mathbf{J}_{2B}\,(\text{Axial})$



Two-body currents in light nuclei

Two-body currents needed to reproduce data in light nuclei:

^{3}H β decay

Gazit et al. PRL103 102502(2009) $\Longrightarrow$

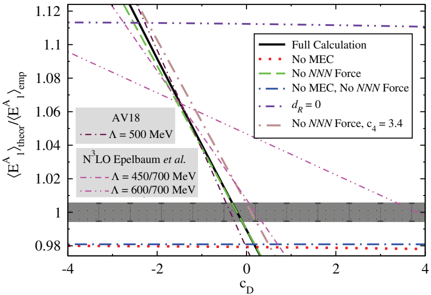
^{6}He β decay

Vaintraub et al. PRC79 065501(2009)

^{3}H μ capture

Gazit PLB666 472(2008)

Marcucci et al. PRC83 014002(2011)

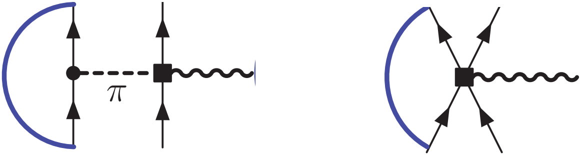


Two-body currents give contributions $\sim$ few % for these nuclei

Two-body currents order Q^3 $\Rightarrow$ larger effect in medium-mass nuclei

Normal-ordered one-body current

- In order to estimate their effect on medium-mass nuclei take normal-ordered 1-body approximation with respect to Fermi gas,
- Sum over one nucleon, direct and the exchange terms



c_3, c_4 c_D

- $\Rightarrow \mathbf{J}^{\mathrm{eff}}_{n,2B}$, normal-ordered (effective) one-body current
- Corrections are $o\left(n_{\mathrm{valence}}/n_{\mathrm{core}}\right)$ in Fermi systems

One- plus two-body currents

- The one- plus two-body currents are

$$J^0_{n,1B}(p^2) = \tau_n^- \left[g_V(p^2) \right] ,$$

$$\mathbf{J}_{n,1B}(p^2) = \tau_n^- \left[g_A(p^2)\sigma_n - g_P(p^2) \frac{\mathbf{p}\,(\mathbf{p}\cdot\sigma_n)}{2m_N} + i\,(g_M + g_V)\,\frac{\sigma_n \times \mathbf{p}}{2m_N} \right] ,$$

$$\mathbf{J}^{\rm eff}_{n,2B} = -\frac{g_A \rho}{m_N f_\pi^2} \tau_n^- \sigma_n \left[F\left(\rho, c_3, c_4, c_D, p\right) \right] ,$$

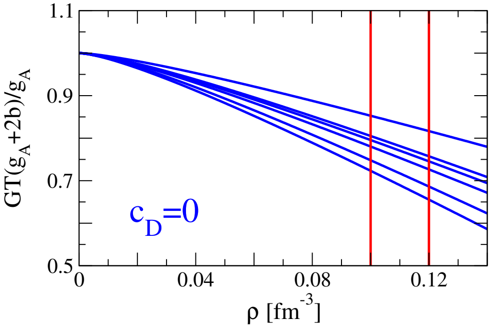
$$F\left(\rho, c_3, c_4, c_D, p\right) = \frac{c_D}{g_A \Lambda_\chi} + \frac{2}{3}\, c_3\, \frac{\mathbf{p}^2}{4m_\pi^2 + \mathbf{p}^2} + I(\rho, P) \left(\frac{1}{3}\,(2c_4 - c_3) + \frac{1}{6m_N} \right)$$

short-range $\quad$ p dependent $\quad$ long-range

- $J^0_{n,1B}$, $\mathbf{J}_{n,1B}$ agree with phenomenologically derived 1B currents
- $\mathbf{J}^{\rm eff}_{n,2B}$ only modifies the Gamow-Teller one-body current, general for spin/isospin symmetric core

Long-range 2B currents and quenching

At $p = 0$ and $c_D = 0$ (long-range part of the currents only)
2B currents suppress 1B currents by $q = 0.85 \ldots 0.66$



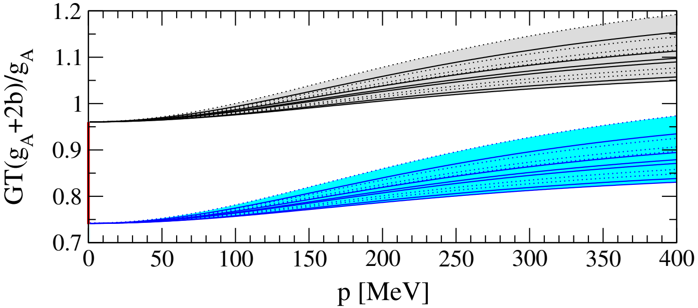
Long-range 2B currents predict g_A quenching

Taking into account c_D uncertainty and short-range 2B currents:

- 2B currents responsible for large quenching ($q \sim 0.75$) found in theoretical calculations
- 2B currents responsible only for small part of this quenching (main part due to the nuclear many-body method)

1b+2b Gamow-Teller p dependence

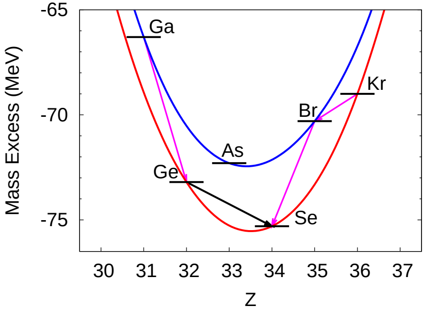
The $\sigma\tau^-$ term, when two-body currents are included, depends on transferred momentum p through the $\frac{2}{3}\,c_3\,\frac{\mathbf{p}^2}{4m_\pi^2+\mathbf{p}^2}$ term



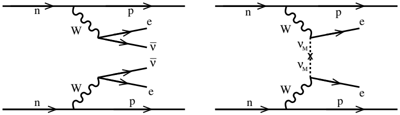
Quenching gets weaker at $p \neq 0$
Typically $p \sim 100$ MeV values for $0\nu\beta\beta$ decay

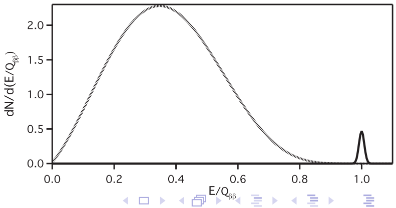
Double beta decay

- Double beta decay only appears when single-β decay is energetically forbidden or hindered by large J difference



$T_{1/2}^{2\nu\beta\beta} \gtrsim 10^{19}$ y $T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y

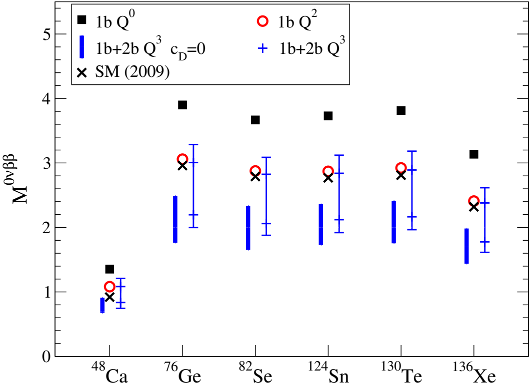




$$\left(T_{1/2}^{0\nu\beta\beta}\left(0^+ \to 0^+\right)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Neutrinoless $\beta\beta$ decay Nuclear Matrix Elements

Neutrinoless $\beta\beta$ decay key for neutrino nature (Majorana) and mass



JM, Gazit, Schwenk PRL107 062501(2011)

g_A uncertainty in the Nuclear Matrix Element

Order Q^2 similar to phenomenological currents

Long-range Q^3 predicts NME $\sim$ 35% reduction

Effect of 2B currents Q^3 ranges from +10% to -35% of the NME

Outline

Summary and Outlook

Microscopic calculation based on chiral EFT (NN+3N forces) and MBPT gives good agreement with experimental information for Calcium isotopes: neutron pairing gaps and excitation spectra

Consistent weak chiral 1B+2B currents have been studied, the long-range 2B currents predict g_A quenching.
Applied to neutrinoless $\beta\beta$ decay, NMEs modified $-35 \ldots 10\%$

Outlook:

Explore heavier isotope and isotone chains: include T=0

Study electromagnetic 2B currents: contributions to M1 transitions