Magnetic hexadecapole gamma transitions in the Microscopic Quasiparticle-Phonon Model (MQPM)

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Motivation

- With the help of reduced matrix elements one can study the probability of transitions
- Earlier studies have revealed that the experimental reduced matrix elements of GT(1+) and SD(2-) β-transitions are reduced much in comparison with the theoretical ones
  - Why?
  - How about the transitions with higher multipolarities?

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Introduction

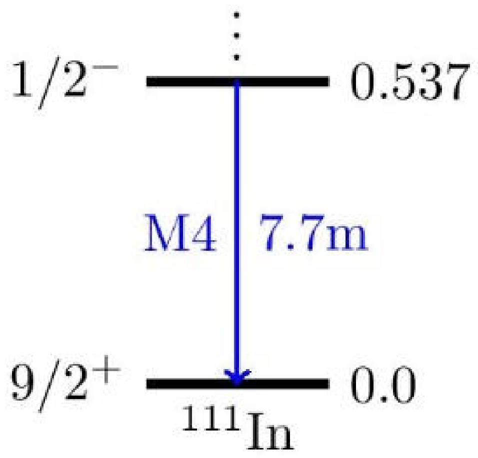
- L. Jokiniemi, J. Suhonen and H. Ejiri. *Magnetic hexadecapole γ transitions and neutrino-nuclear responses in medium-heavy nuclei.* Adv. High Energy Phys. 2016 (2016) 8417598.
- Highly forbidden (λ=4) β-transitions are rare
  - Not enough data
  - Instead the M4 transitions of the isomeric states were studied
- Transitions examined were stretched M4 transitions in the mass regions of DBD, A=85-115 and A=135-143
- Transitions either $0g_{9/2} \leftrightarrow 1p_{1/2}$ or $0h_{11/2} \leftrightarrow 1d_{3/2}$

Introduction

- Example nuclei either proton or neutron odd
- Reduced matrix elements calculated using BCS and MQPM theories
  - Comparison with experimental values

$$\left|M_{4,exp.}\right| = \sqrt{\frac{(2J_i + 1)\ln 2}{1.899 \times 10^{-6} E^9 t_{1/2} (1 + \alpha)}}$$

- Effect of gyromagnetic ratios?



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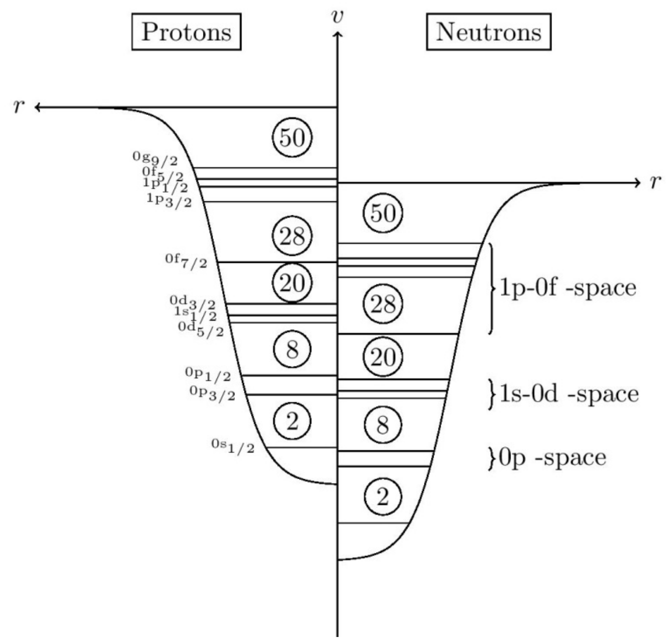
Theories used in the work

- BCS
- QRPA
- MQPM

Bardeen-Cooper-Schrieffer theory (BCS)

- Is used to describe the quasiparticle energies of the nuclei
  - H.O. single-particle energies with Woods-Saxon potential
  - No spin-isospin correlation



BCS

- Bogoliubov-Valatin transformation

$$\begin{cases} a_\alpha^\dagger = u_a c_\alpha^\dagger + v_a \tilde{c}_\alpha \\ \tilde{a}_\alpha = u_a \tilde{c}_\alpha - v_a c_\alpha^\dagger \end{cases}$$

- Quasiparticle matrix element

$$M_{QP}(M4) = M_{sp}(M4) P_{ij},$$

where $P_{ij} = u_i u_j + v_i v_j$.

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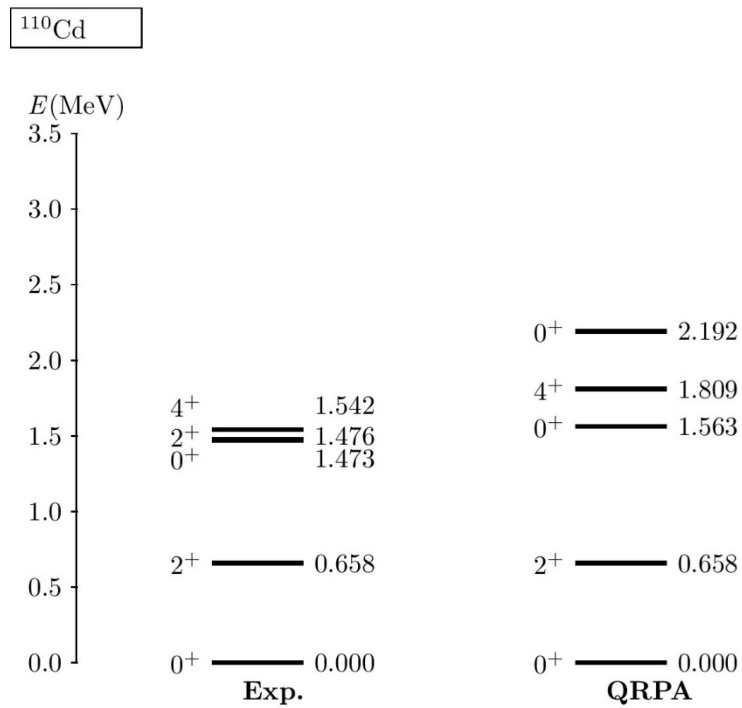
Quasiparticle Random Phase Approximation (QRPA)

- Describes the excited states of spherical, even-even, open-shell nuclei as two-quasiparticle configurations, QRPA phonons
- Takes into account the spin-isospin correlation



Natural parity phonon: Phonon with parity $\pi = (-1)^J$ $(2^+, 3^-, ...)$
Unnatural parity phonon: Phonon with parity $\pi = (-1)^{J+1}$ $(2^-, 3^+, ...)$

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Microscopic Quasiparticle-Phonon Model (MQPM)

- Couples the QRPA phonons with the BCS quasiparticles
- Solves the three different parts of the microscopic Hamiltonian: The particle, The phonon, and the particle-phonon parts
- Schematically the MQPM matrix element can be written as

$$M_{MQPM} = g_s^{(p)} M_{sp} + g_l^{(p)} M_{lp} + g_s^{(n)} M_{sn} + g_l^{(n)} M_{ln}$$

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Methods

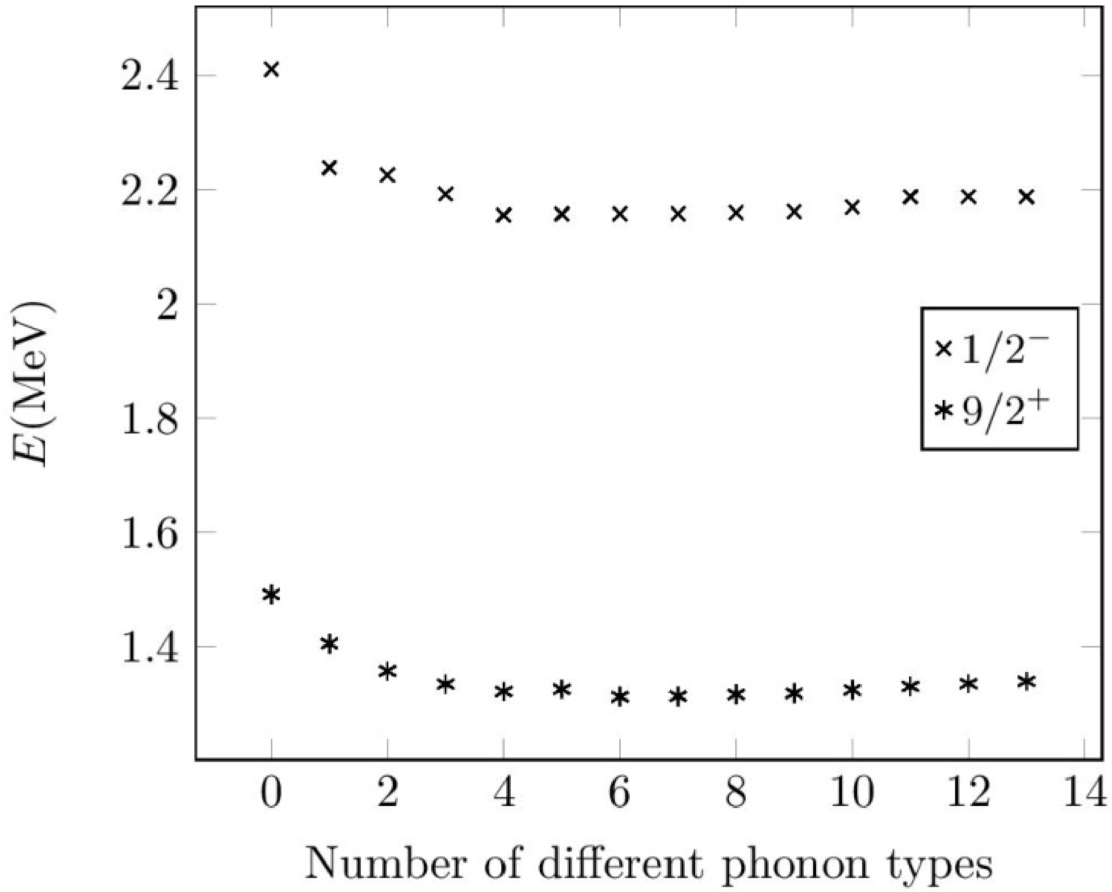
- Woods-Saxon single-particle basis
- BCS quasiparticles
  - Pairing factors of protons and neutrons were adjusted to the experimental pairing gaps
- QRPA phonons
  - Particle-hole factor was adjusted to the experimental energies if possible
  - Particle-particle factor was kept as $g_{pp} = 1.0$

Methods

- MQPM couples the quasiparticles and phonons
  - Odd-state = even-even –state + p/n quasiparticle
    (For example: ${}^{111}_{49}\mathrm{In} = {}^{110}_{48}\mathrm{Cd} \otimes \mathrm{p}$)
  - First the natural and then the unnatural parity phonons were added
  - Phonons were added until the convergence was reached

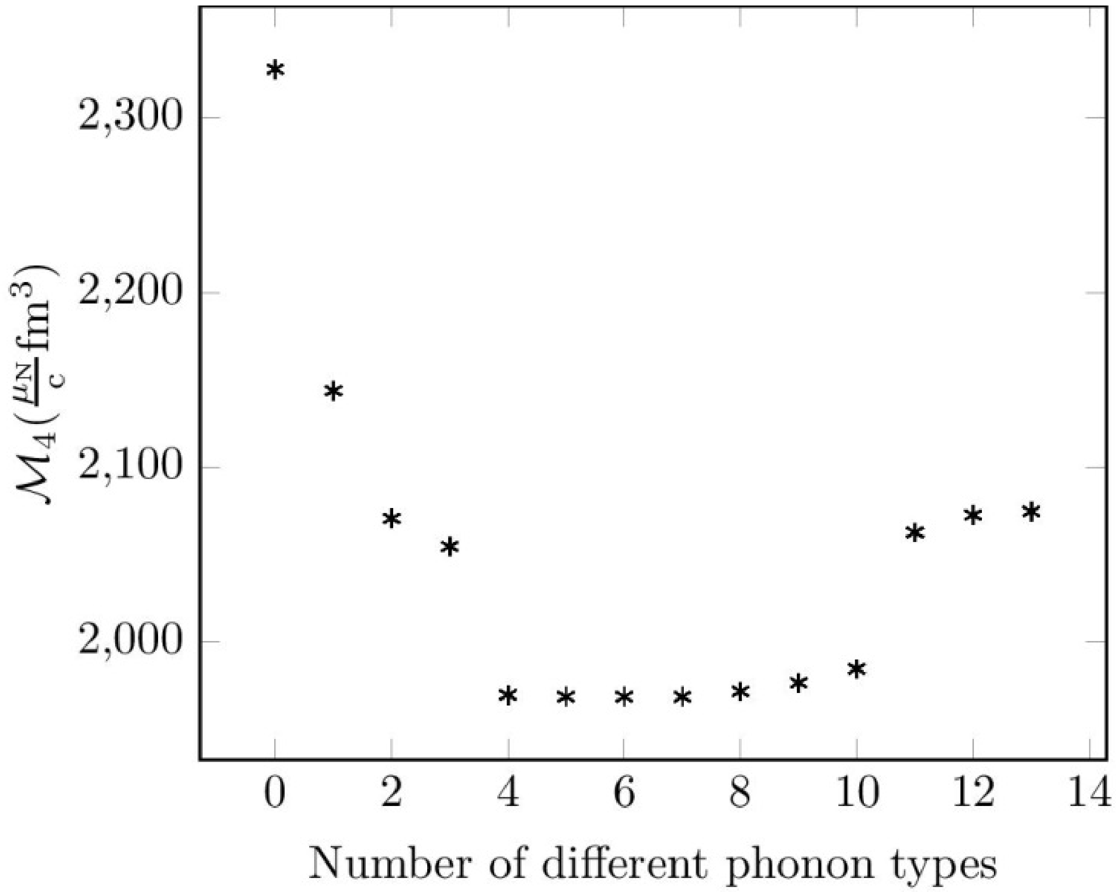
Convergence of the MQPM energies

The MQPM energies for 111In as a function of the added phonon types. The phonons were added in the order 2+, 3-, 4+, 5-, 6+, 7-, 0+,1+, 2-, 3+, 4-, 5+ and 6-. The cut-off energy was 15 MeV.



Convergence of the MQPM NMEs

The MQPM NME for $^{111}\mathrm{In}$ as a function of the added phonon types. The phonons were added in the order 2+, 3-, 4+, 5-, 6+, 7-, 0+, 1+, 2-, 3+, 4-, 5+ and 6-. The cut-off energy was 15 MeV.



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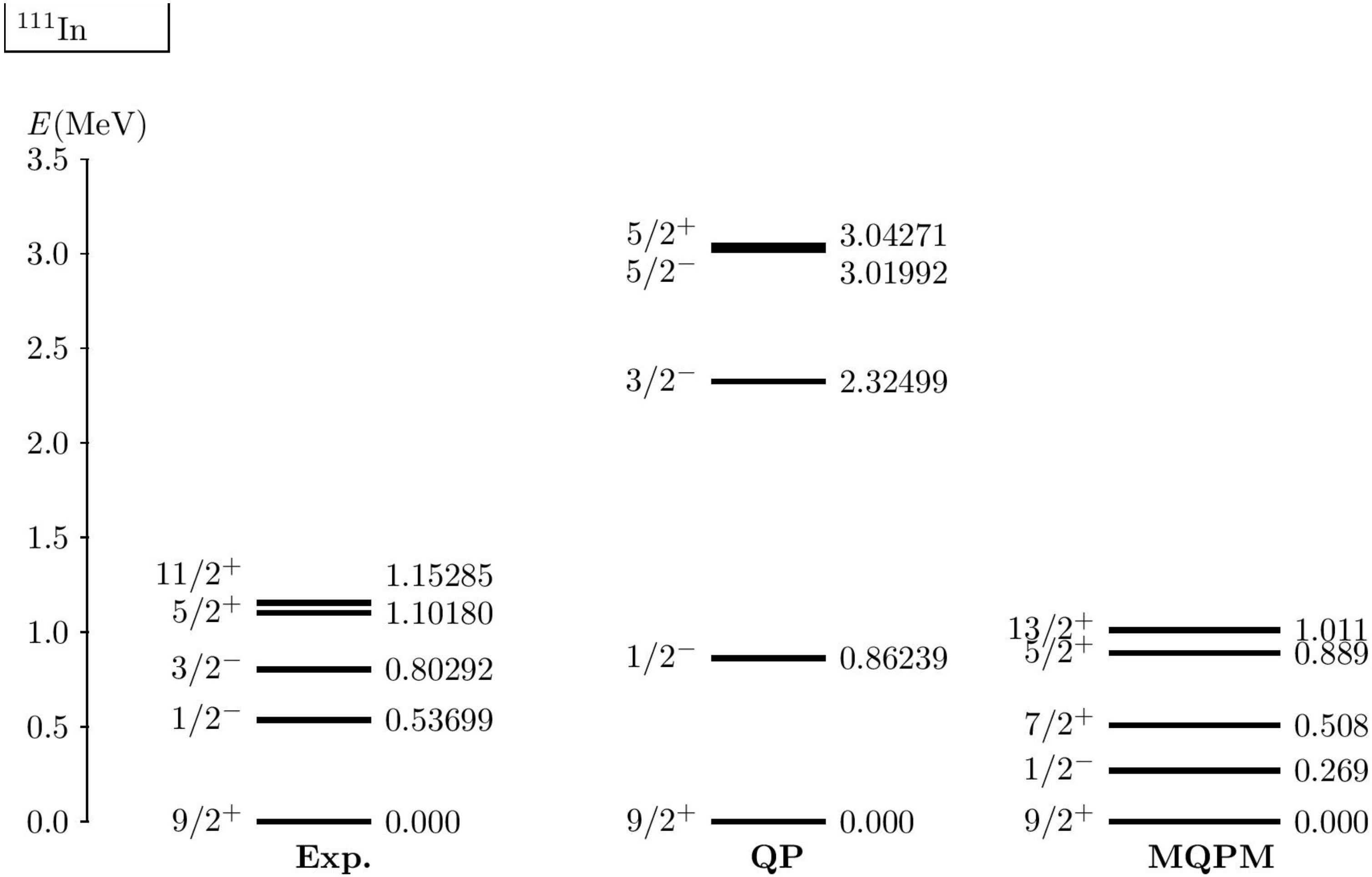
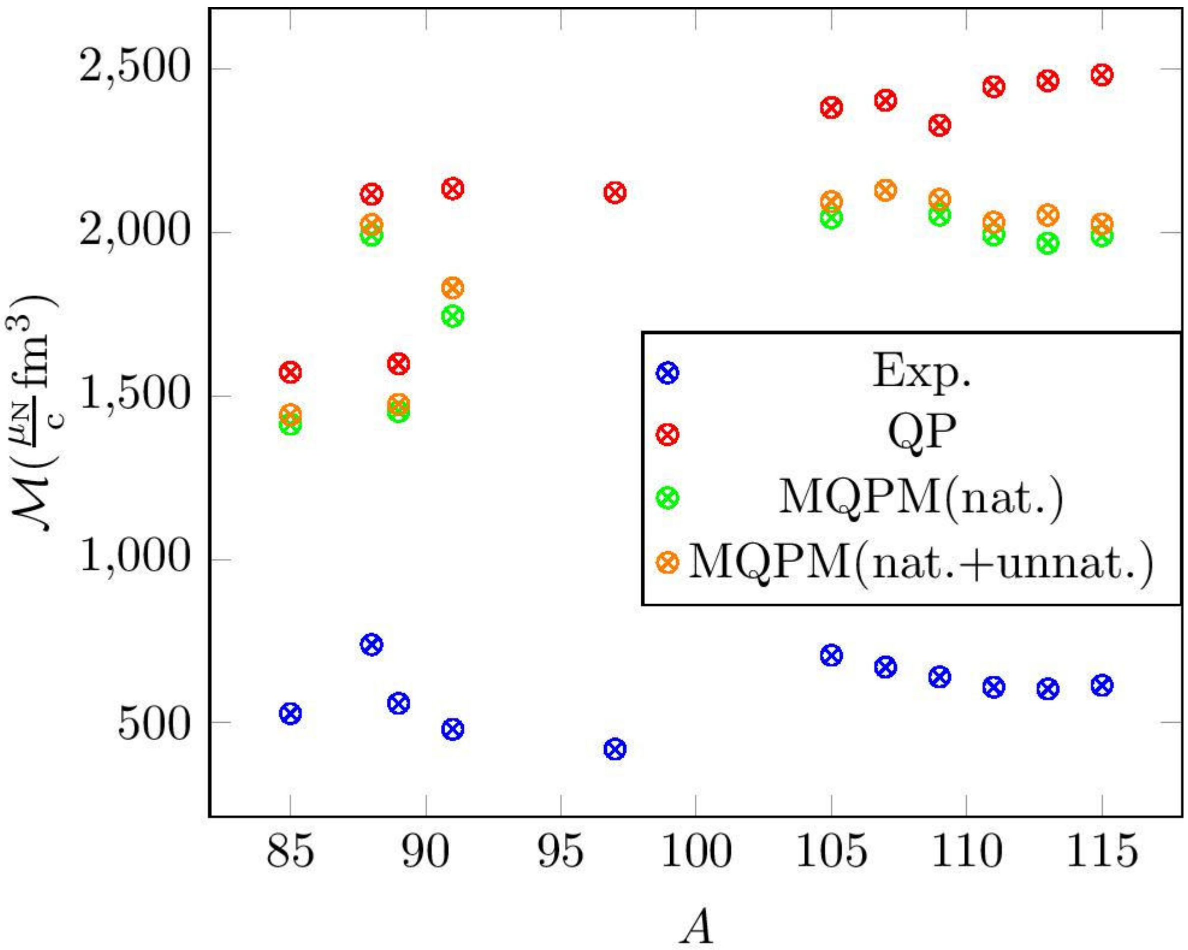


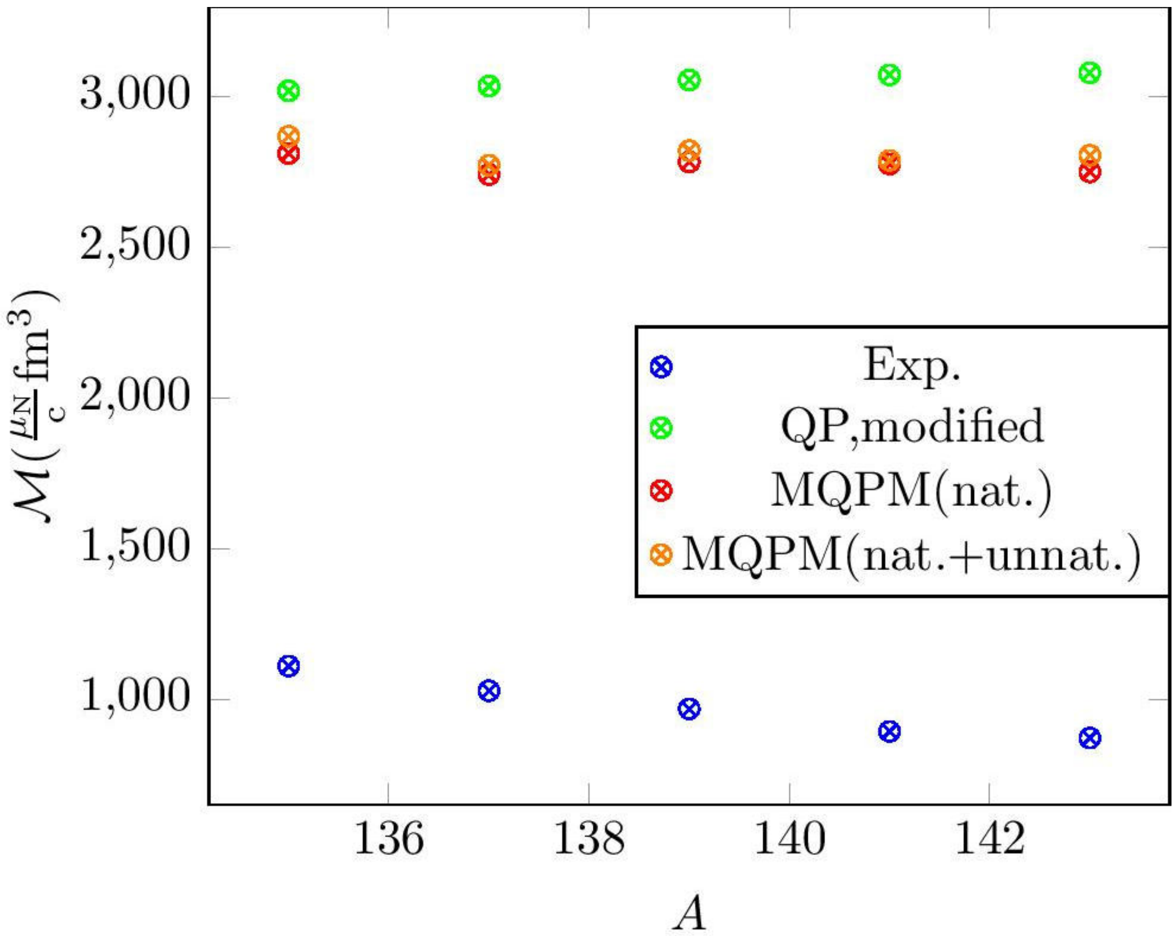
Spectra of ^{111}In

The experimental, quasiparticle, and MQPM spectra of ^{111}In.



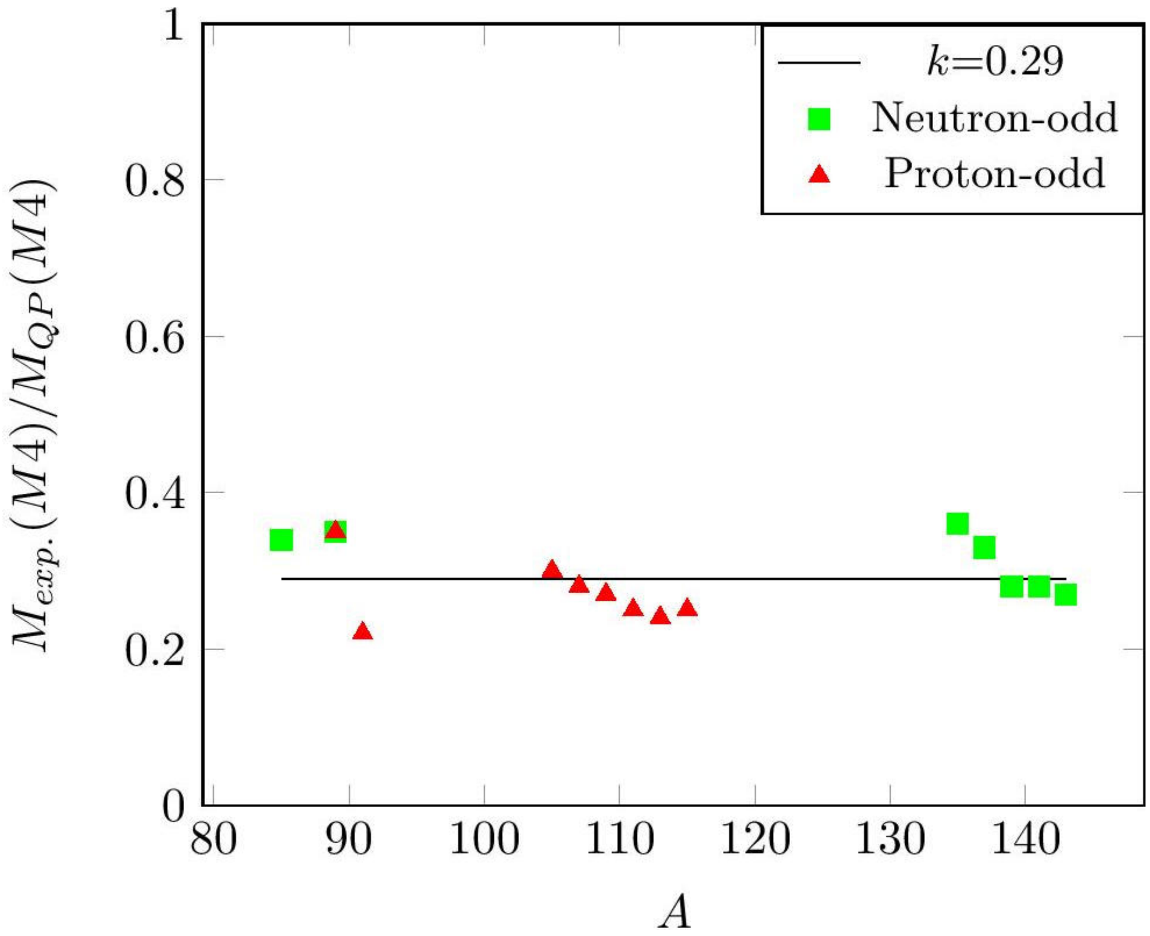
Results for the region A=85-115

The experimental, quasiparticle and MQPM NMEs of the nuclei in the region A=85-115. The MQPM NMEs with only natural parity and both natural and unnatural parity phonons are presented separately.



Results for the region A=135-143

The experimental, quasiparticle and MQPM NMEs of the nuclei in the region A=135-43. The quasiparticle NMEs are calculated with the modified single-particle bases. The MQPM NMEs with only natural parity and both natural and unnatural parity phonons are presented separately.



Reduction coefficient for the QP NMEs

The reduction coefficients defined by $k = M_{exp.}(M4)/M_{QP}(M4)$ for the nuclei in the regions A=85-115 and A=135-143. The green squares refer to the neutron-odd and red triangles to the proton-odd nuclei. The average reduction coefficient $k = 0.29$ is presented as a solid line.

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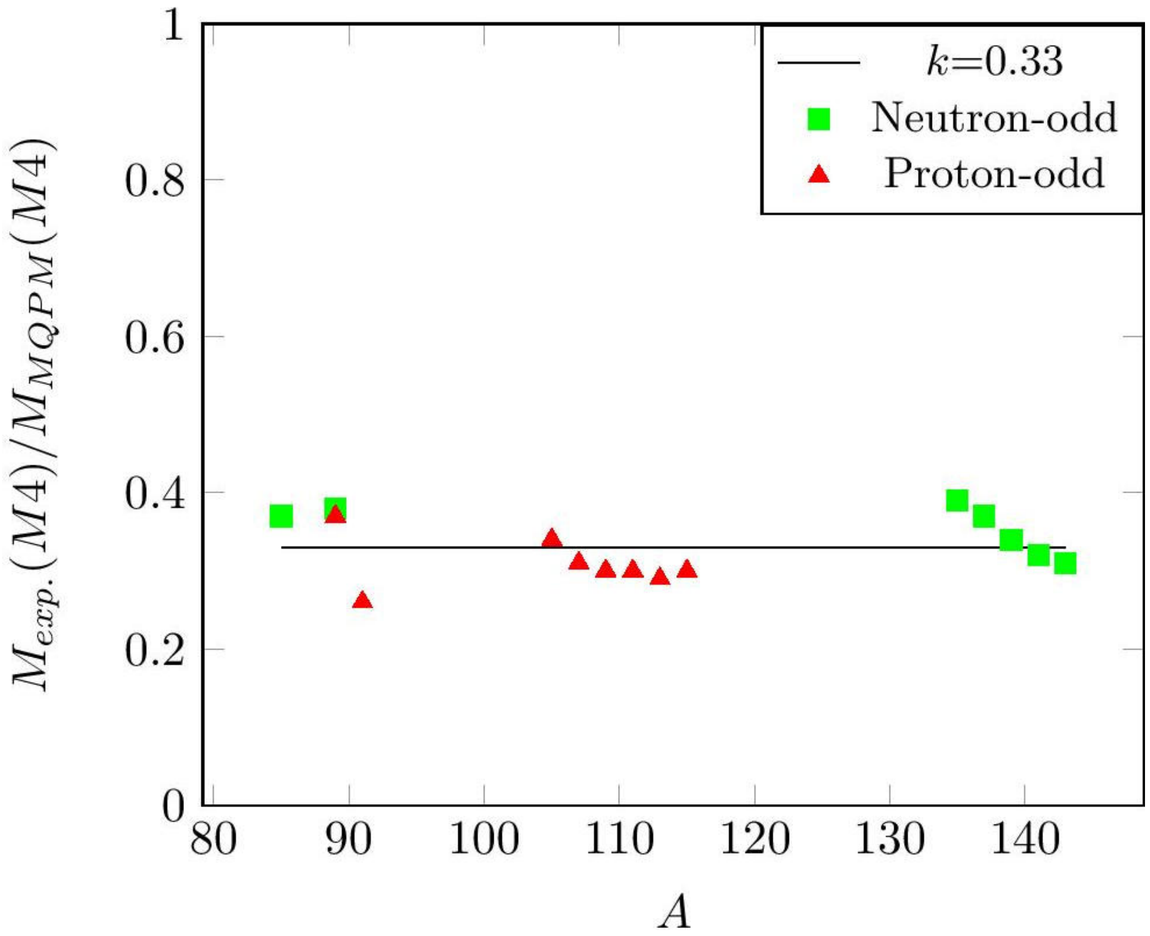

Reduction coefficient for the MQPM NMEs

The reduction coefficients defined by $k = M_{exp.}(M4)/M_{MQPM}(M4)$ for the nuclei in the regions A=85-115 and A=135-143. The green squares refer to the neutron-odd and red triangles to the proton-odd nuclei. The average reduction coefficient $k = 0.33$ is presented as a solid line.

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Results

- $$\begin{cases} M_{exp.}(M4)/M_{QP}(M4) = 0.29 \\ M_{exp.}(M4)/M_{MQPM}(M4) = 0.33 \end{cases}$$
- In earlier studies
  - $$\begin{cases} M_{exp.}(SD2)/M_{QP}(SD2) = 0.2 \\ M_{exp.}(SD2)/M_{pnQRPA}(SD2) = 0.5 \end{cases}$$ [1]
  - $$\begin{cases} M_{exp.}(GT1)/M_{QP}(GT1) = 0.23 \\ M_{exp.}(GT1)/M_{pnQRPA}(GT1) = 0.6 \end{cases}$$ [2]
- How about the effect of the gyromagnetic ratios?

[1] H. Ejiri, N. Soukouti and J.Suhonen. *Phys.Lett.B.* 729:27-32, 2014
[2] H. Ejiri and J. Suhonen. *J. Phys. G, Nucl. Part. Physics.* 42:055201, 2015

Effect of gyromagnetic ratios

$$M_{MQPM} = g_s^{(p)} M_{sp} + g_l^{(p)} M_{lp} + g_s^{(n)} M_{sn} + g_l^{(n)} M_{ln}$$

	$M_{MQPM}(M4)(^{89}\mathrm{Zr})$	$M_{MQPM}(M4)(^{109}\mathrm{In})$
Bare g factors	1474	2101
$g_l^{(p)} = 1.5,\ g_l^{(n)} = -0.5$	1388	2007
$g_s^{(p)} = 4.586$	1473	1690
$g_s^{(p)} = 6.586$	1475	2512
$g_s^{(n)} = -4.826$	1857	2098
$g_s^{(n)} = -2.826$	1091	2104
Experimental values	559	640

Bare *g* factors:

$g_l^{(p)} = 1, \quad g_s^{(p)} = 5.586,$

$g_l^{(n)} = 0, \quad g_s^{(n)} = -3.826$

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Discussion

- Experimental NMEs reduced a lot in comparison with the theoretical ones
- Quasiparticle NMEs reduction coefficient of the same order that in the earlier studies
- MQPM NMEs not as close to the experimental ones as pnQRPA NMEs in the earlier studies

Discussion

- Reduction of the experimental NMEs partly due to the spin-isospin correlations but also other nuclear-medium effects
- Changing the spin *g* factor affected the NMEs a little
  - Effective spin *g* factor?

What's next?

- Analysis of the strength and energy of isovector spin-dipole and spin-quadrupole resonances of DBD nuclei
  - Study of the key multipoles
    $J^{\pi} = 0^{-}, 1^{+}, 1^{-}, 2^{+}, 2^{-}$ and 3^{+} in the intermediate odd-odd nuclei for $0\nu\beta\beta$-decay triplets
  - In the earlier work [3], the states were studied for closed-shell nuclei by the pnRPA model
  - In the ongoing work, the states are studied for open-shell nuclei by the pnQRPA model

[3] N. Auerbach and A. Klein, Structure of isovector spin excitations in nuclei. Phys. Rev. C 30 (1984) 1032.

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Thank you!