SFB 1245
Project B03

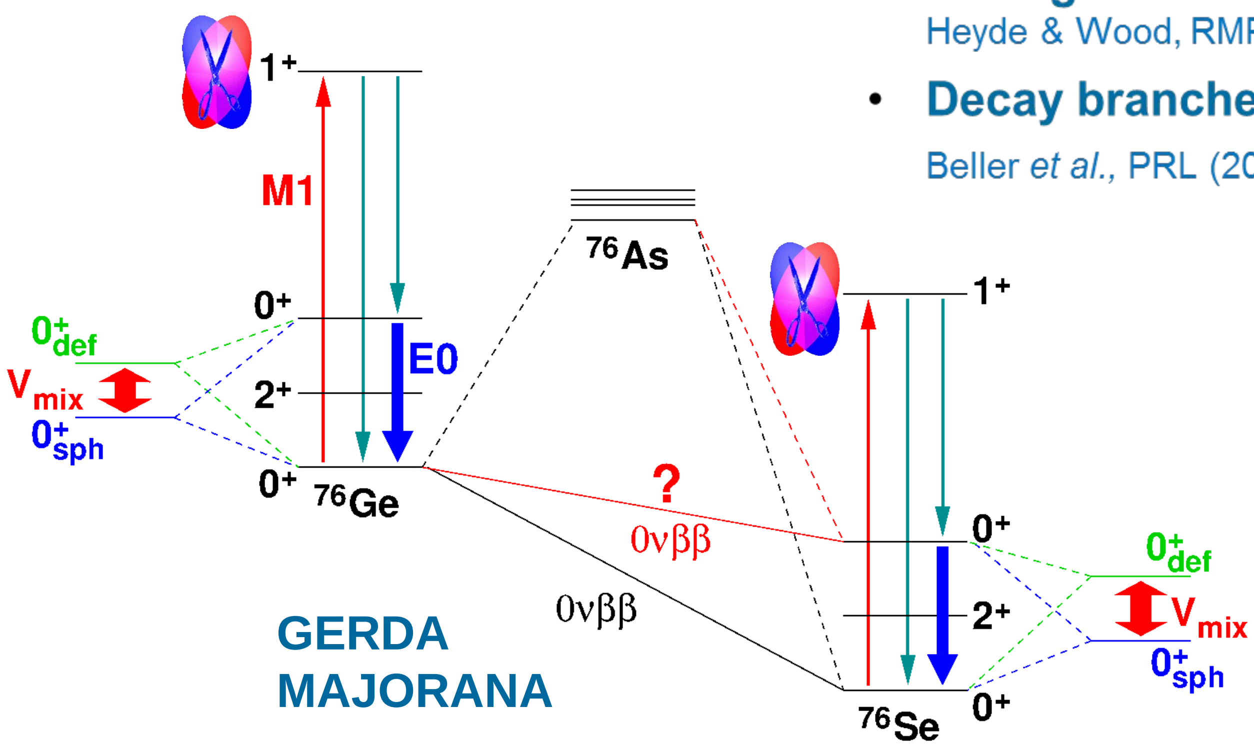
Summary and look to the B02 future

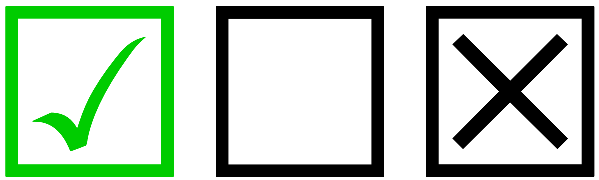
B03
Nuclear Structure in 0νββ Decay

$$\lambda = G \cdot \left| M^{(0\nu)} \right|^2 \cdot m_{\beta\beta}^2$$

Nuclear Structure Theory

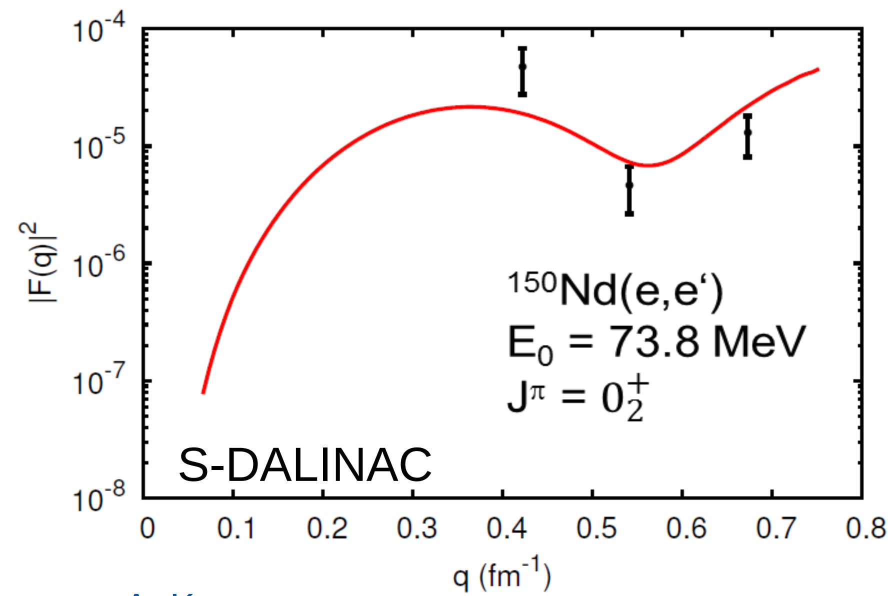
- **Mixing** of configurations
  Rodríguez & Martínez-Pinedo, PRL (2010), PPNP (2011)
  - modification of decay rate
  - 0νββ decay to excited states
- **Strong E0** between mixed states
  Heyde & Wood, RMP (2011)
- **Decay branches** to 0_1^+ and 0_2^+
  Beller *et al.*, PRL (2013)





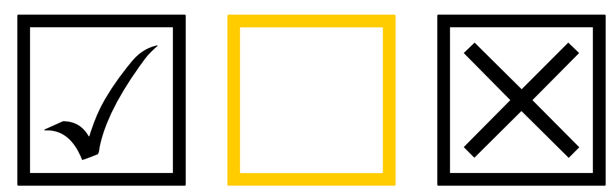
B03
0νββ Decay – Configuration Mixing

- Enhanced $0^+ \rightarrow 0^+$ E0 strength
  - known in ^{76}Se
  - unknown in ^{76}Ge
- **High-resolution electron scattering**



A. Krugmann,
Doctoral Dissertation, TU Darmstadt 2014

- **Decay branches**
  of the scissors mode in
  - ^{150}Sm/^{150}Nd **NEMO**
  - ^{82}Se/^{82}Kr **(Super-)NEMO**
  - ^{100}Mo/^{100}Ru **NEMO, MOON**



- DHIPS/S-DALINAC: **cross sections, spin assignments**
- HIγS/TUNL: **parities, decay branches**

B03
WIMP – Nucleus Scattering

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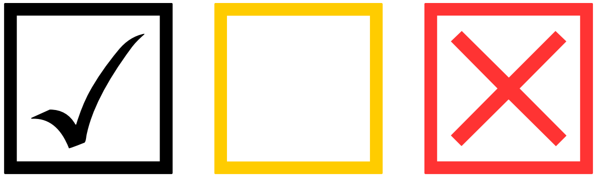
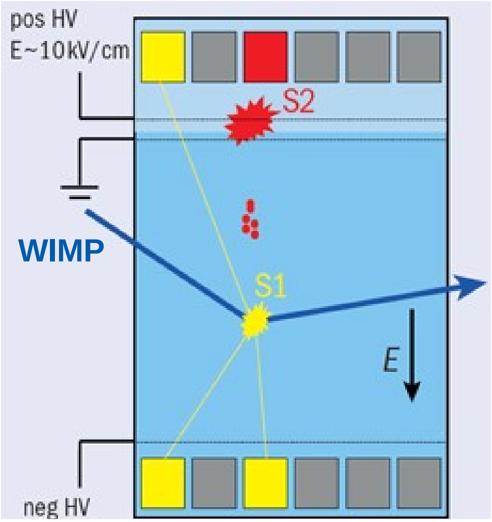
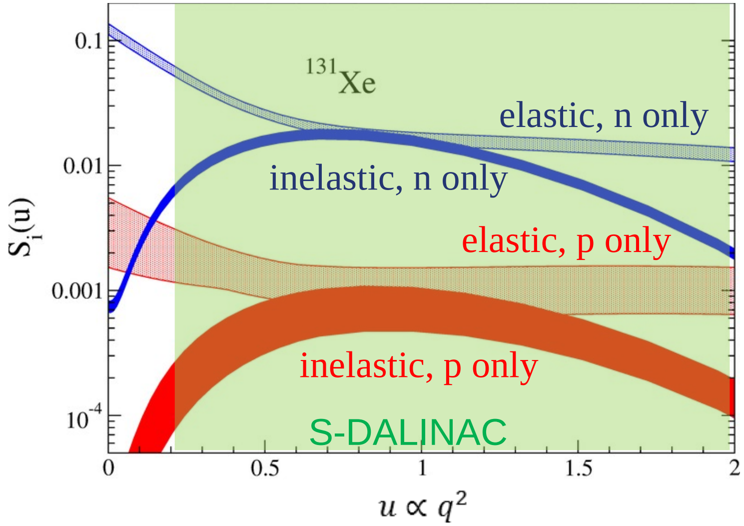
- WIMP-detection:
  XENON100/1T
  Aprile *et al.*, PRL (2012)



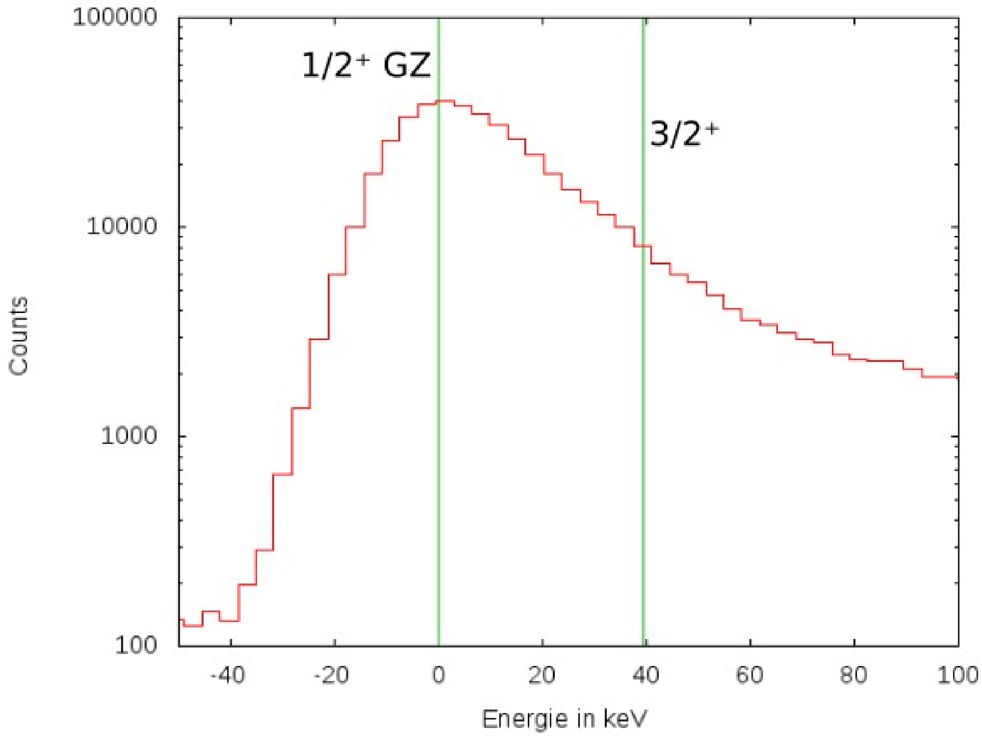


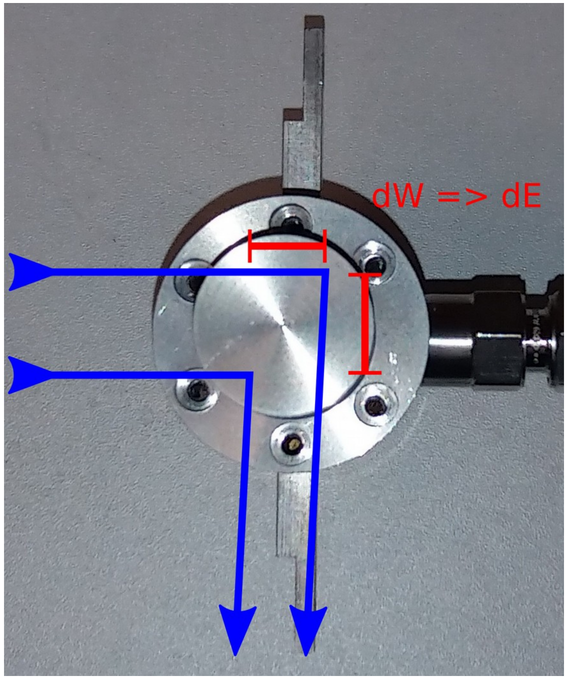
- chiral EFT/SM by TU Darmstadt theory:
  - WIMP-nucleus scattering
    relevant at low momentum transfer
    Klos *et al.*, PRD (2013)
  - Spin dependence:
    inelastic scattering relevant
    Baudis *et al.*, PRD (2013)



- Unknown: WIMP scattering form factors
  → **test nuclear structure calculations**

Xe deferred



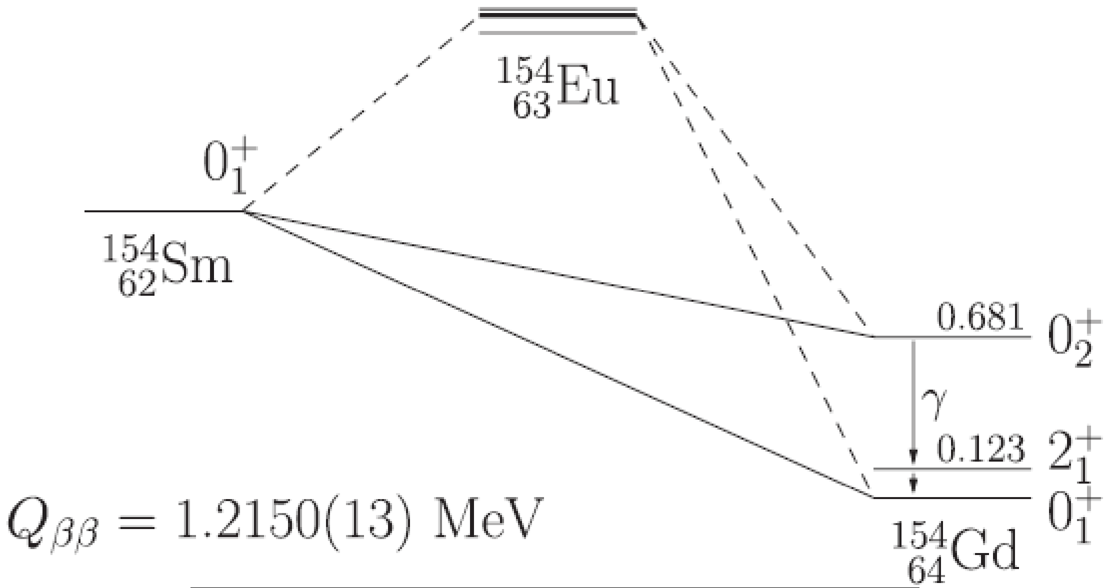


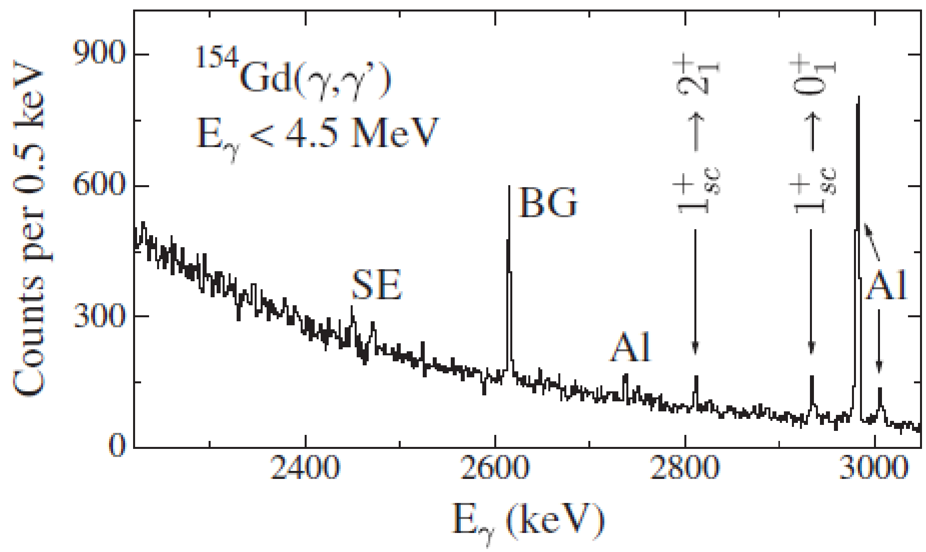
- Gas target constructed → cylinder
- Due to extended geometry necessary energy resolution not reached
- In addition: “sub-optimal” target chamber alignment for test shot
- Need: frozen target, or thin “sheet” gas target

Xe deferred

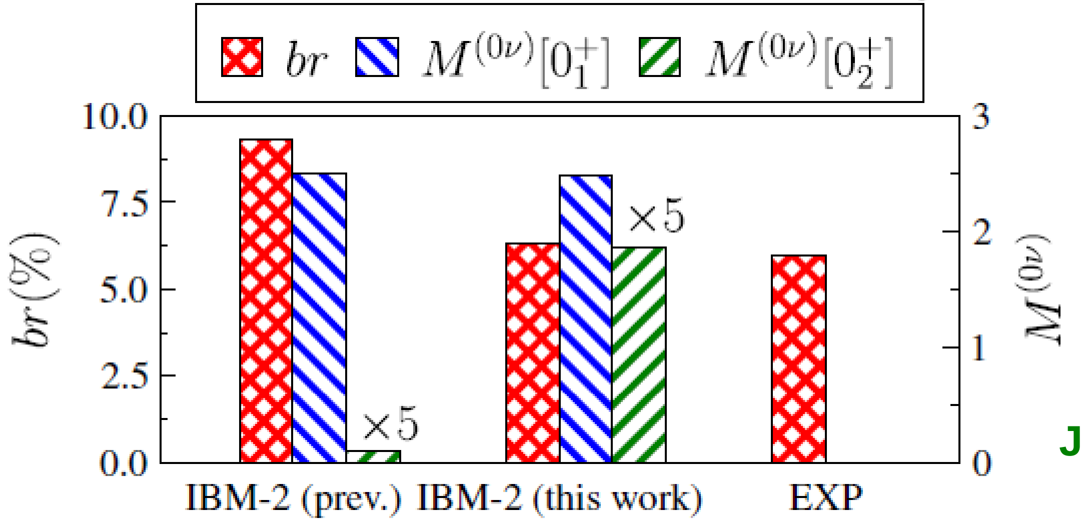
- New gas target ready – sheet, walls front/back 0.1 mm, LXe 1 mm @ 1 bar
- LINTOTT chamber aligned, waiting ...

^{154}Sm/Gd – first constraints from scissors mode decays



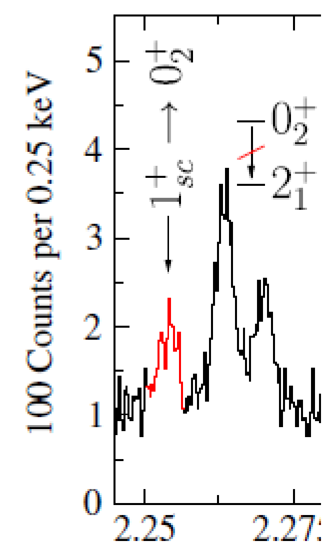


Photon scattering at Darmstadt



Branching to 0_2^+ observed in β-decay at Cologne Tandem

J. Beller, PRL 111, 172501 ('13)



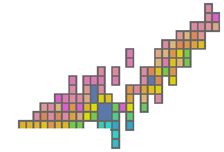
This new structure information leads to corrections of model parameters IBM-2 -> predicted 0ν2β matrix elements change

Location of 0νββ Candidates

^{150}Nd → ^{150}Sm

^{128}Te → ^{128}Xe

^{160}Gd → ^{160}Dy

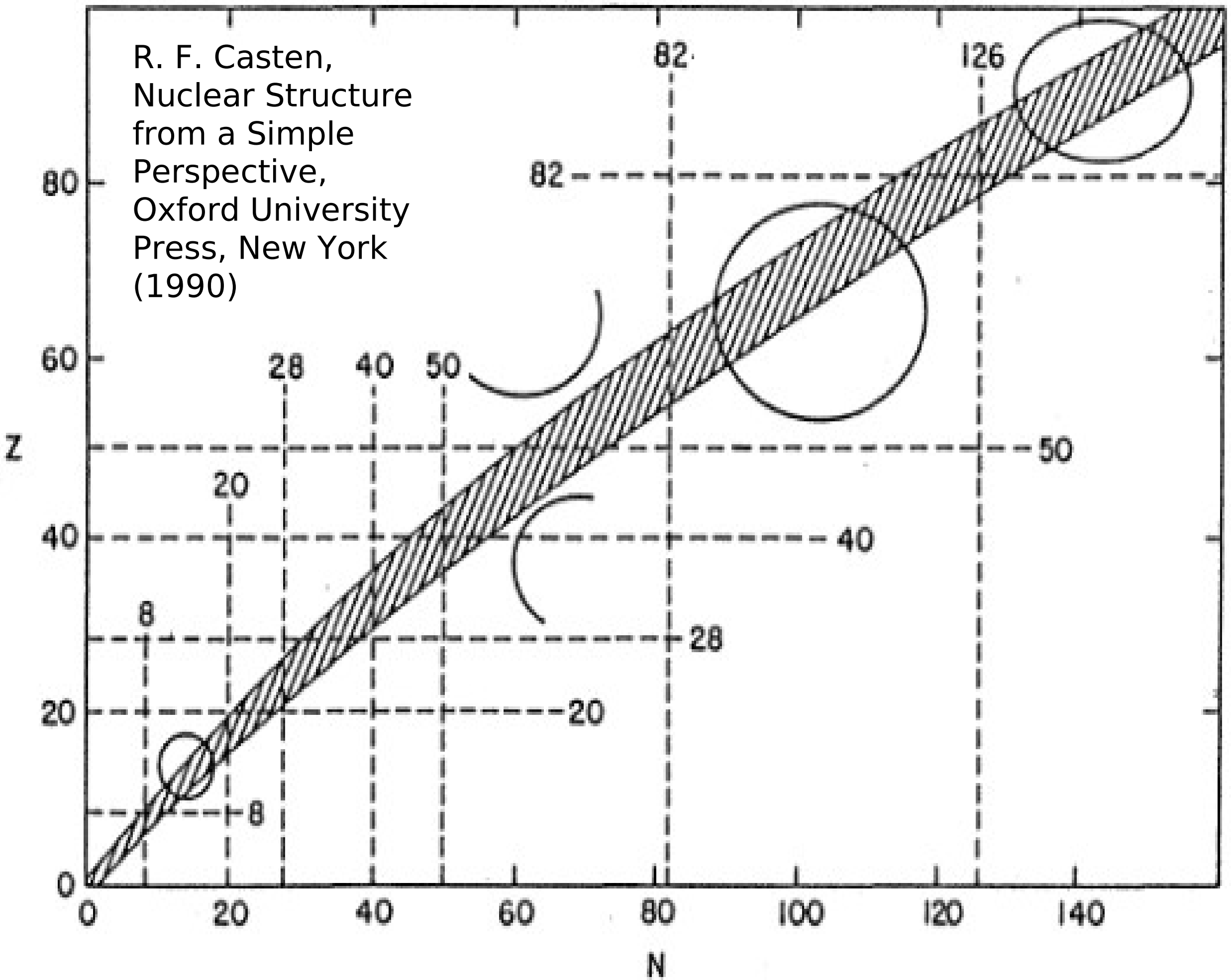


116

11

^{82}Se → ^{82}Kr

^{76}Ge → ^{76}Se



^{198}Pt → ^{198}Hg

^{154}Sm → ^{154}Gd

^{148}Nd → ^{148}Sm

→ ^{130}Xe

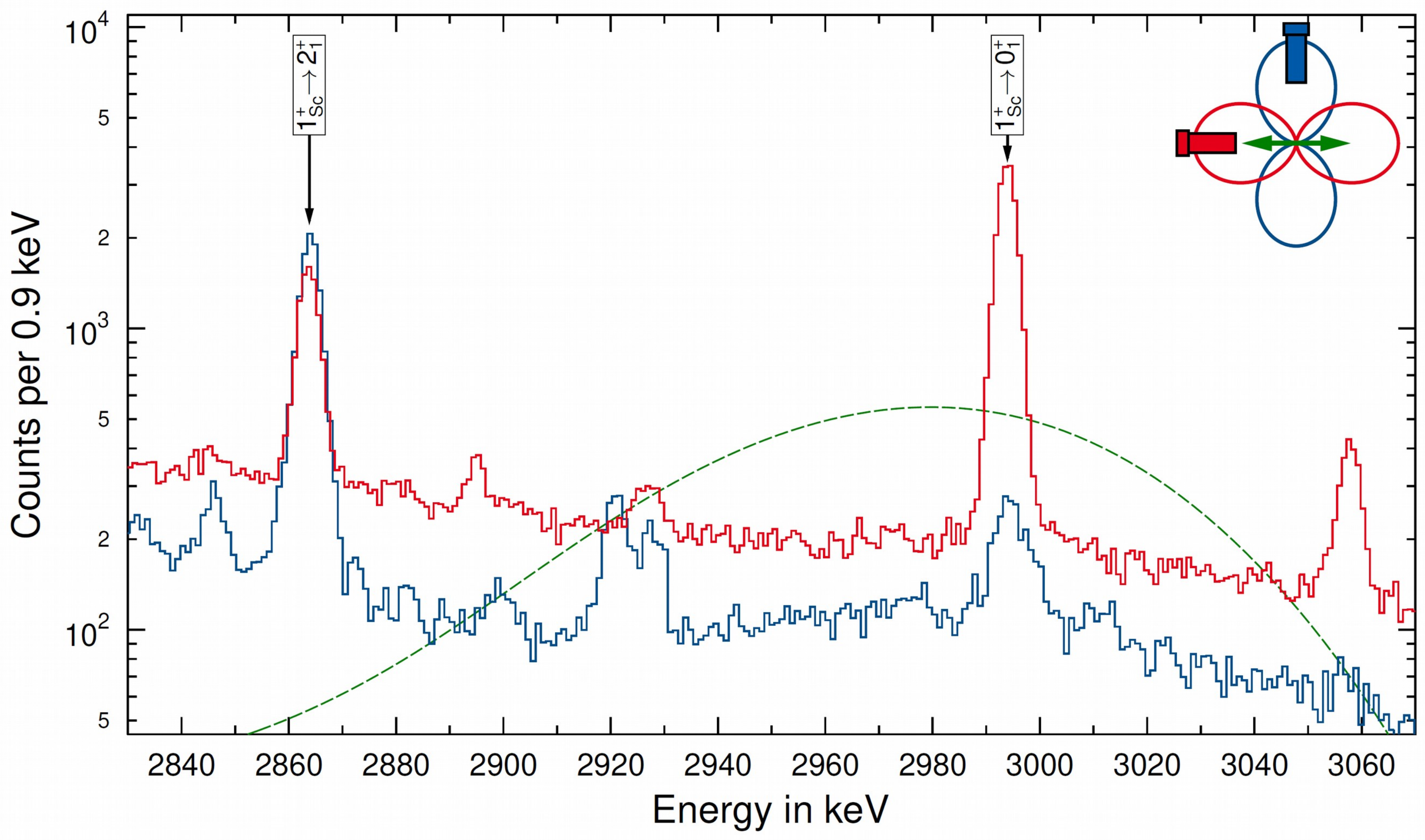
^{124}Sn → ^{124}Te

d/vcharthtml/VChartHTML.html

Phys. Rev. C 87 (2013)

014315

^{150}Nd @ ~3 MeV (scissors)



Scissors Mode Decays from HIGS

$0\nu\beta\beta$-decay mother ^{150}Nd:

$$\frac{\Gamma_{0_2^+}}{\Gamma_{0_1^+}} = 0.068(5)$$

$$B(M1\,;\,1^+_{Sc} \rightarrow 0^+_1) = 0.24(3)\,\mu_N{}^2$$

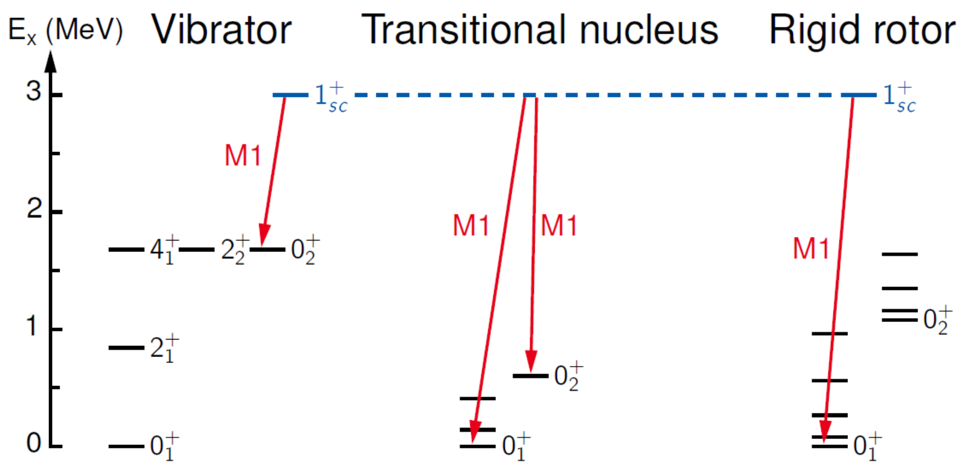
$$B(M1\,;\,1^+_{Sc} \rightarrow 0^+_2) = 0.035(5)\,\mu_N{}^2$$

$0\nu\beta\beta$-decay daughter ^{150}Sm:

$$\frac{\Gamma_{0_2^+}}{\Gamma_{0_1^+}} = 0.19(5)$$

$$B(M1\,;\,1^+_{Sc} \rightarrow 0^+_1) = 0.07(1)\,\mu_N{}^2$$

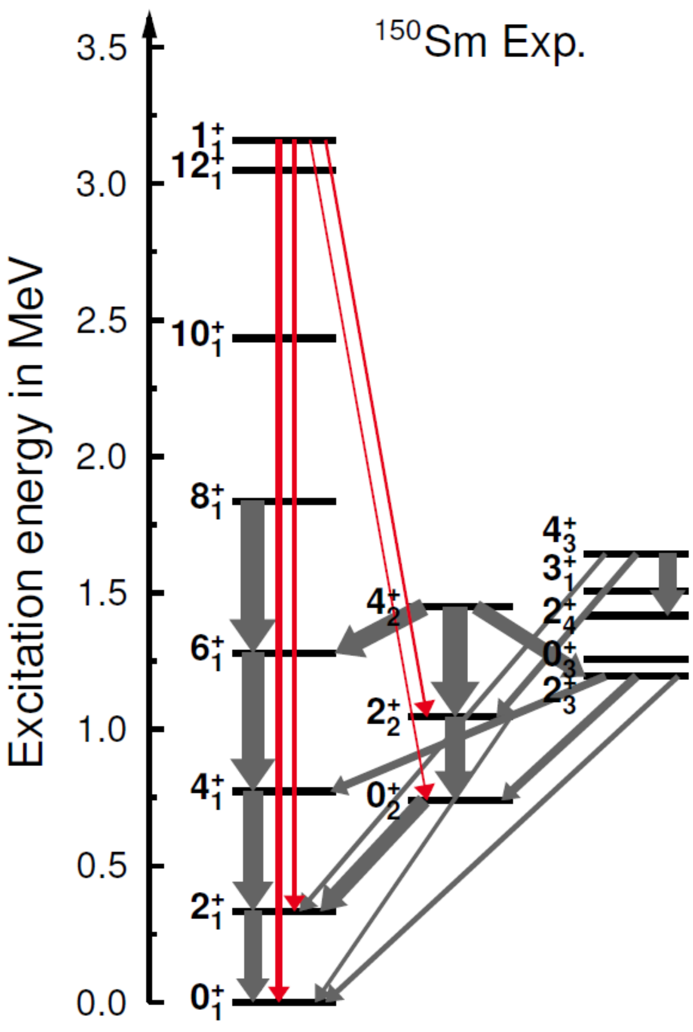
$$B(M1\,;\,1^+_{Sc} \rightarrow 0^+_2) = 0.030(9)\,\mu_N{}^2$$

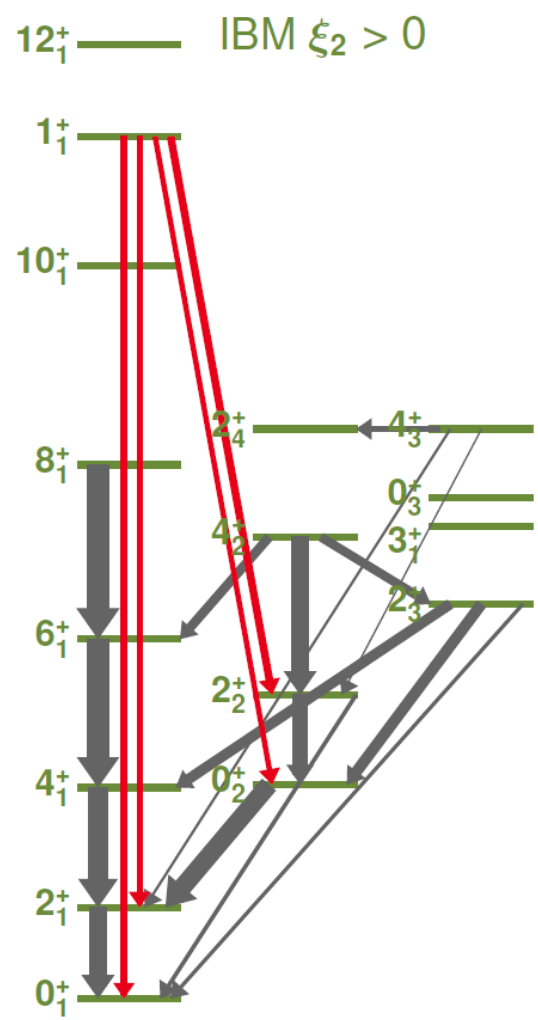


J. Beller, doctoral thesis, TU Darmstadt (2014)

J. Kleemann, BA/MA thesis

New IBM-2 Description





J. Kleemann, BA/MA thesis

Revised Matrix Elements

Novel data on decay characteristics of scissors mode in ^{150}Nd and ^{150}Sm

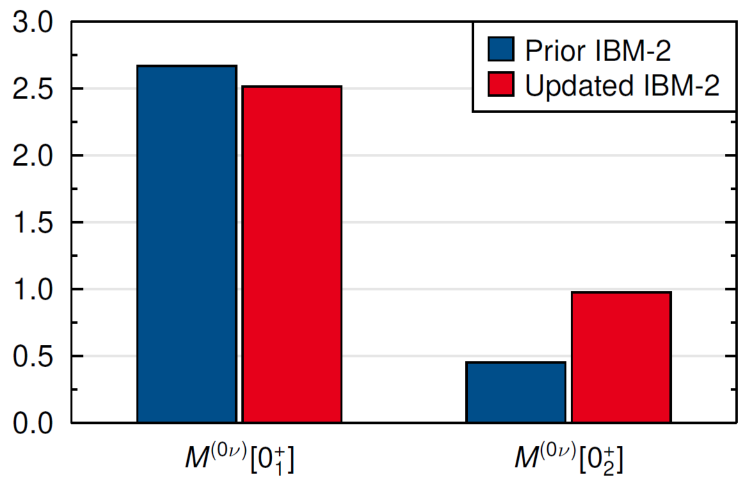
→ Constraints on IBM-2 Majorana parameters

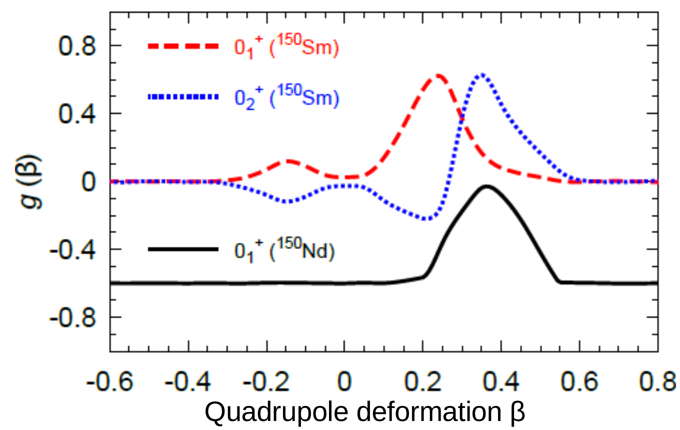
→ Updated IBM-2 0νββ-NME calculation

J. Kotila, private communication (2019)

→ Updated EDF NME calculation?

→ More reliable extraction of neutrino mass from 0νββ-decay rate

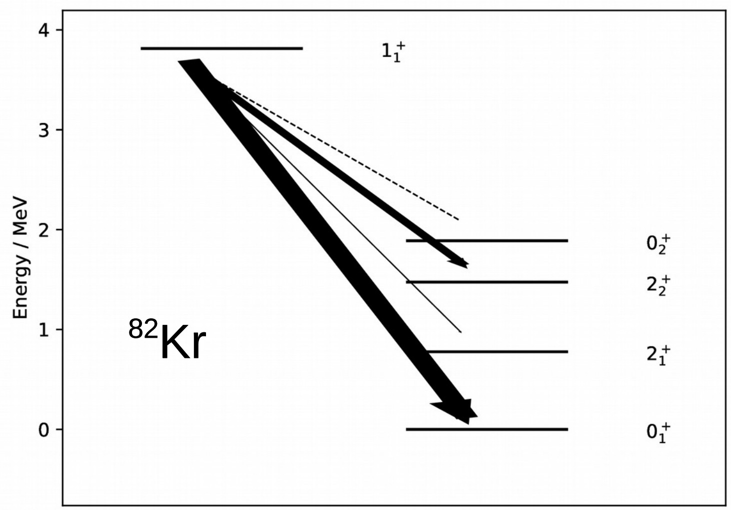


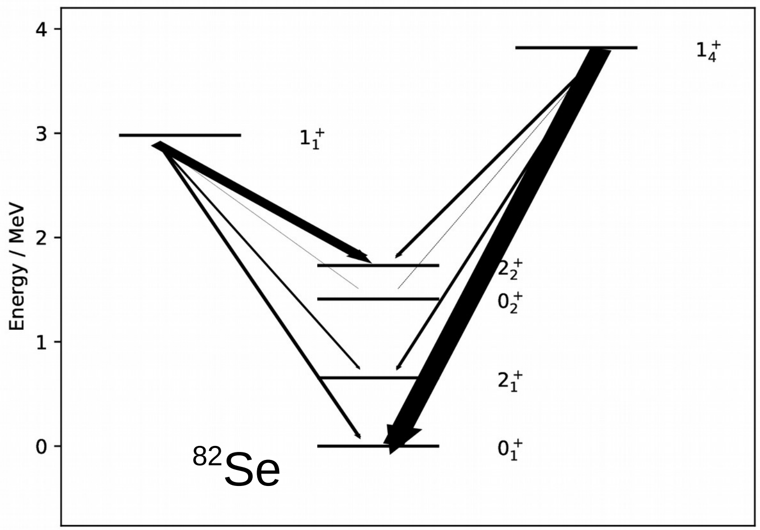


T. R. Rodríguez, private communication (2016)

^{82}Se / ^{82}Kr analysis finished

- High-precision data on decay of low-lying dipole strength in 0νββ partners ^{82}Kr and ^{82}Se
- Sensitive to el. cross sections of ~1 eVb and branchings of a few percent



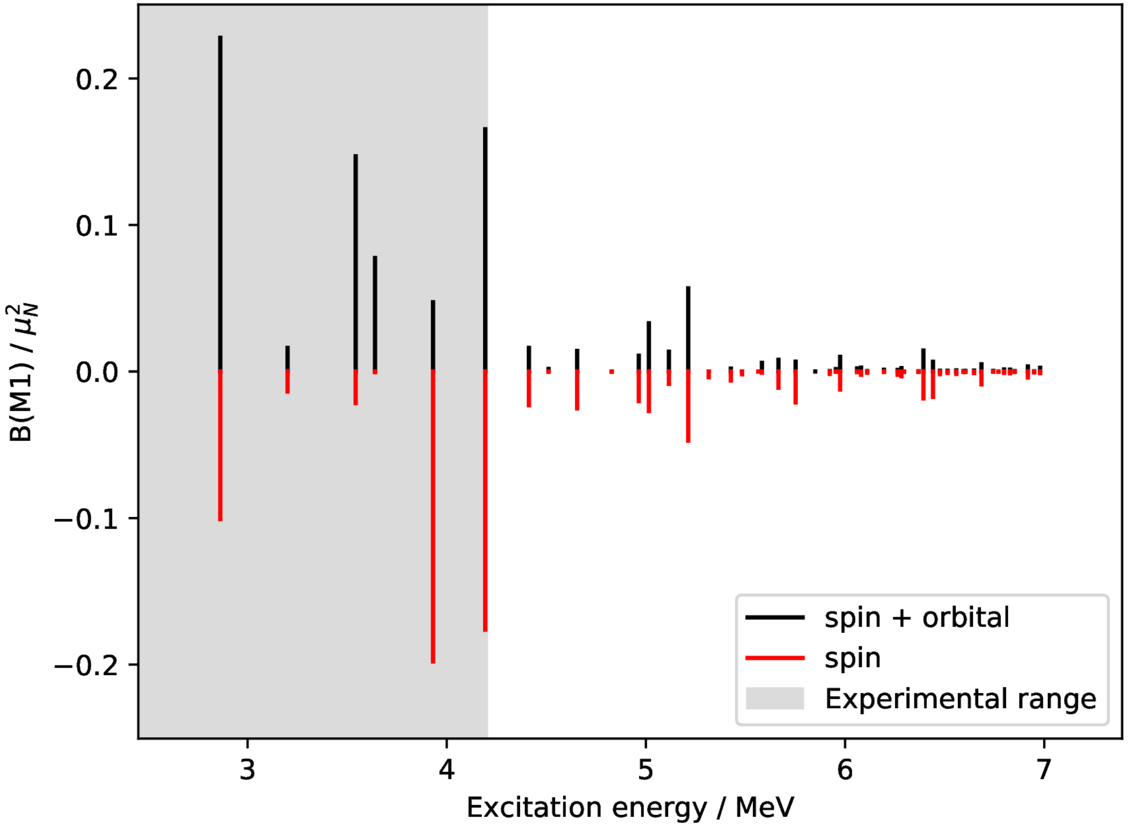


- Are we seeing true scissors mode?
- Is the model space able to describe the data?
- Implications for 0νββ decay?

U. Gayer

^{82}Se – spin-flip competing?

- Shell model calculations using the code **NuShellX**
- **jun45** interaction in **jj44** model space



U. Gayer

Problematic State at Q-Value ($^{82}Se \rightarrow ^{82}Kr$)

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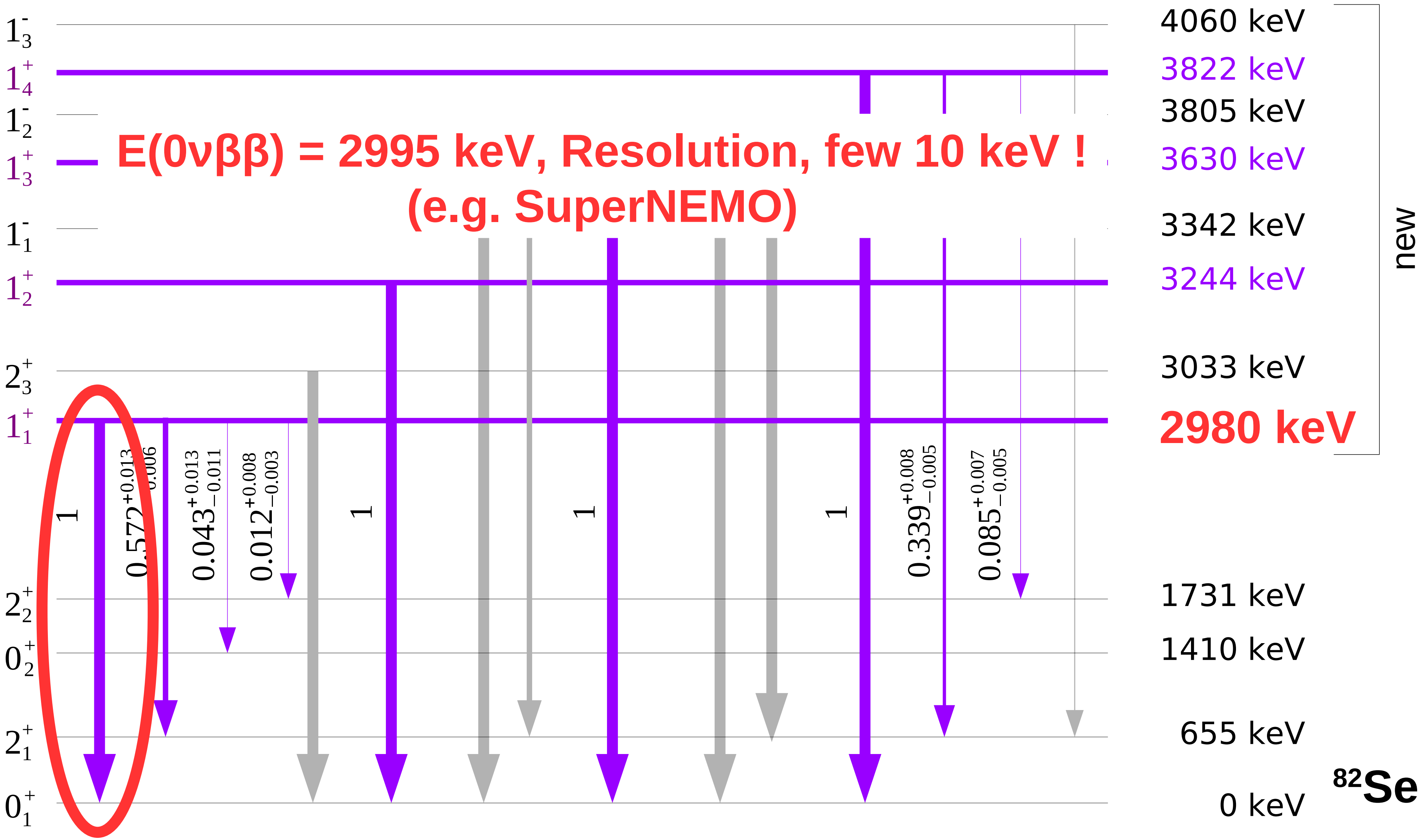

Asymmetries ^{152}Sm: revise scissors mode

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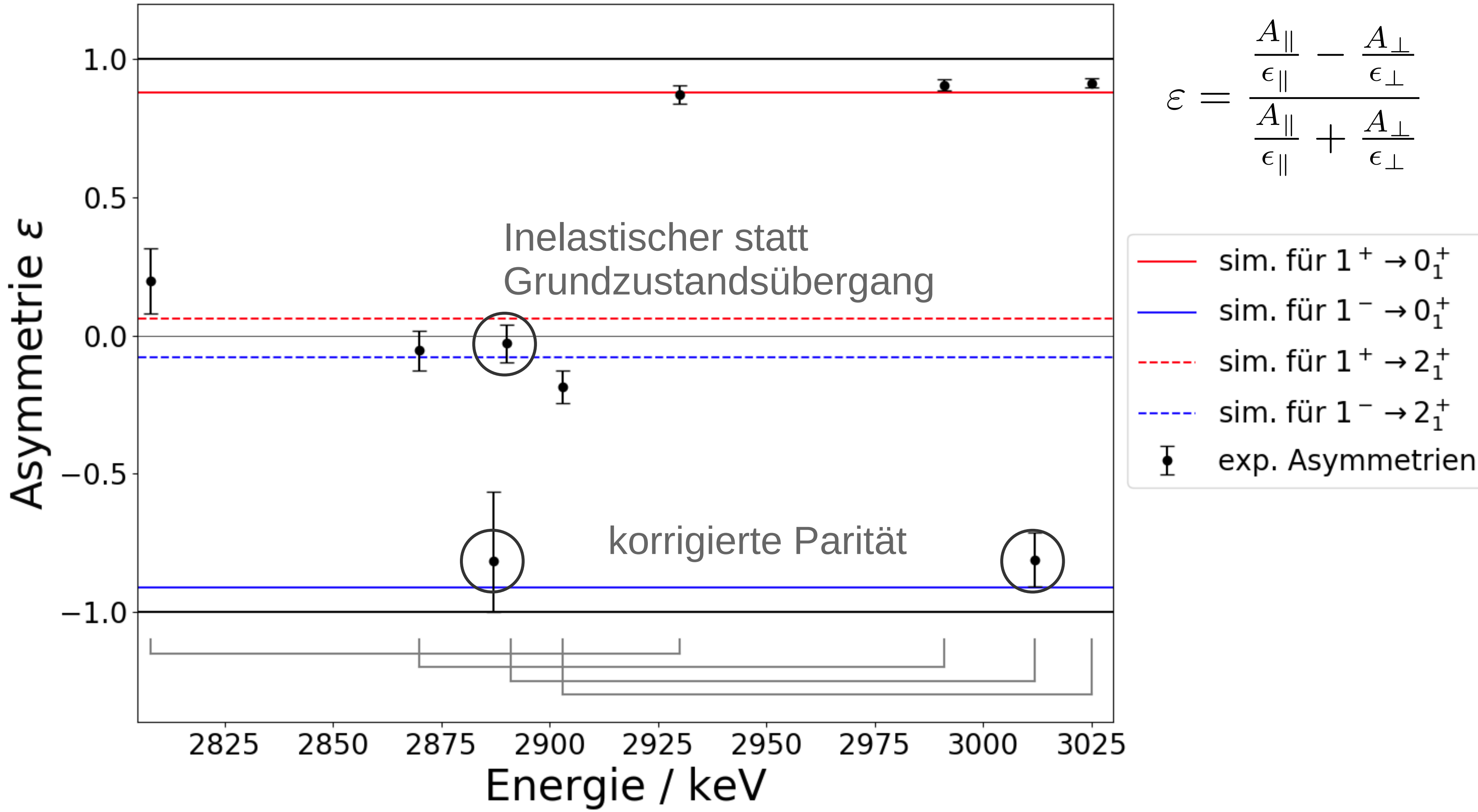
$$\varepsilon = \frac{\frac{A_{\parallel}}{\epsilon_{\parallel}} - \frac{A_{\perp}}{\epsilon_{\perp}}}{\frac{A_{\parallel}}{\epsilon_{\parallel}} + \frac{A_{\perp}}{\epsilon_{\perp}}}$$



Lokal effektive Boson Charges

F-skalar Transition

$$B(E2;2_1^+ \to 0_1^+) = 145(16)\,\mathrm{W.u.}$$

F-vector Transition

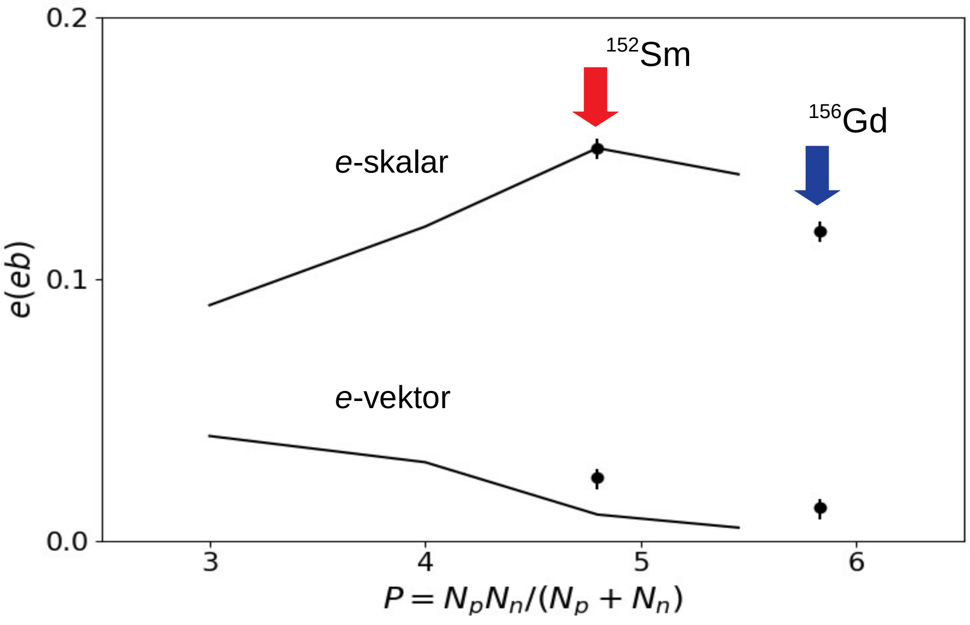
$$\Sigma B(E2;1_{sc}^+ \to 2_1^+) = 1.25^{+0.29}_{-0.50}\,\mathrm{W.u.}$$

$$e_\nu^B = 0.174\,e\mathrm{b}$$
$$e_\pi^B = 0.126\,e\mathrm{b}$$

$$e\text{-skalar}: \; e_s = \frac{1}{2}(e_\nu + e_\pi) = 0.15\;eb$$

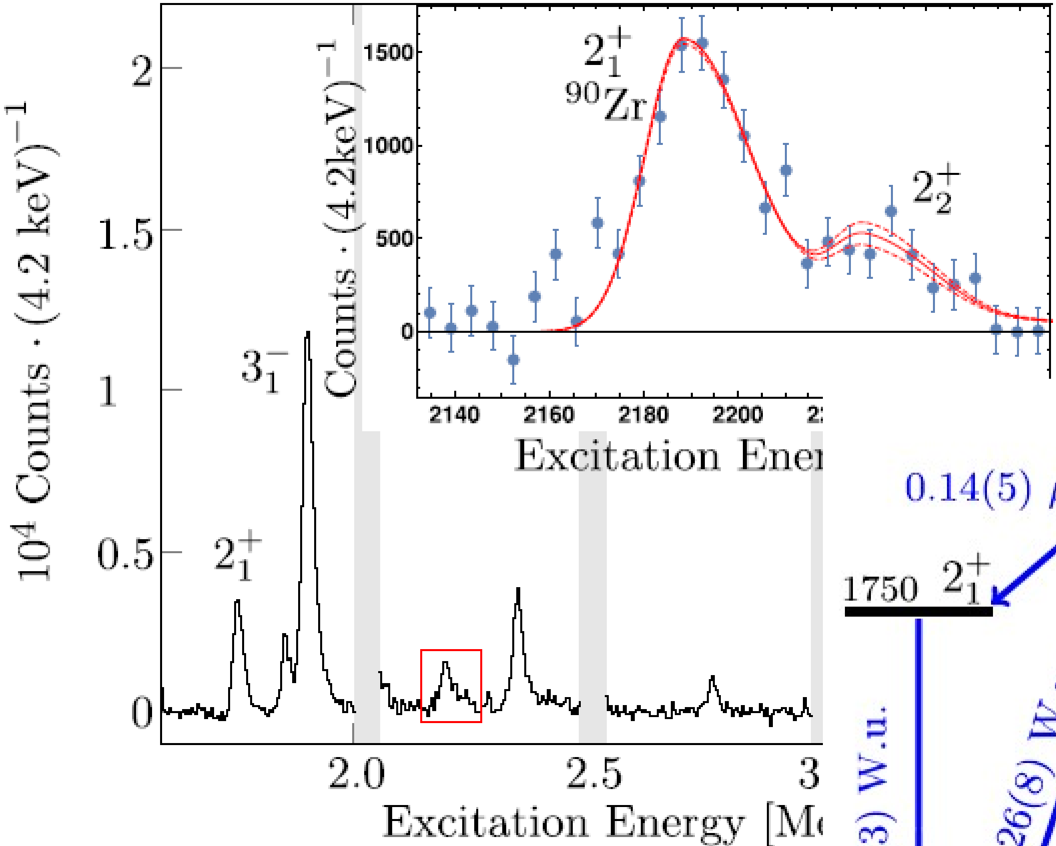
$$e\text{-vektor}: \; e_v = \frac{1}{2}|e_\nu - e_\pi| = 0.024\;eb$$

T. Otsuka und J.N. Ginocchio,
Phys. Rev. Lett. **54**, 777 (1985)



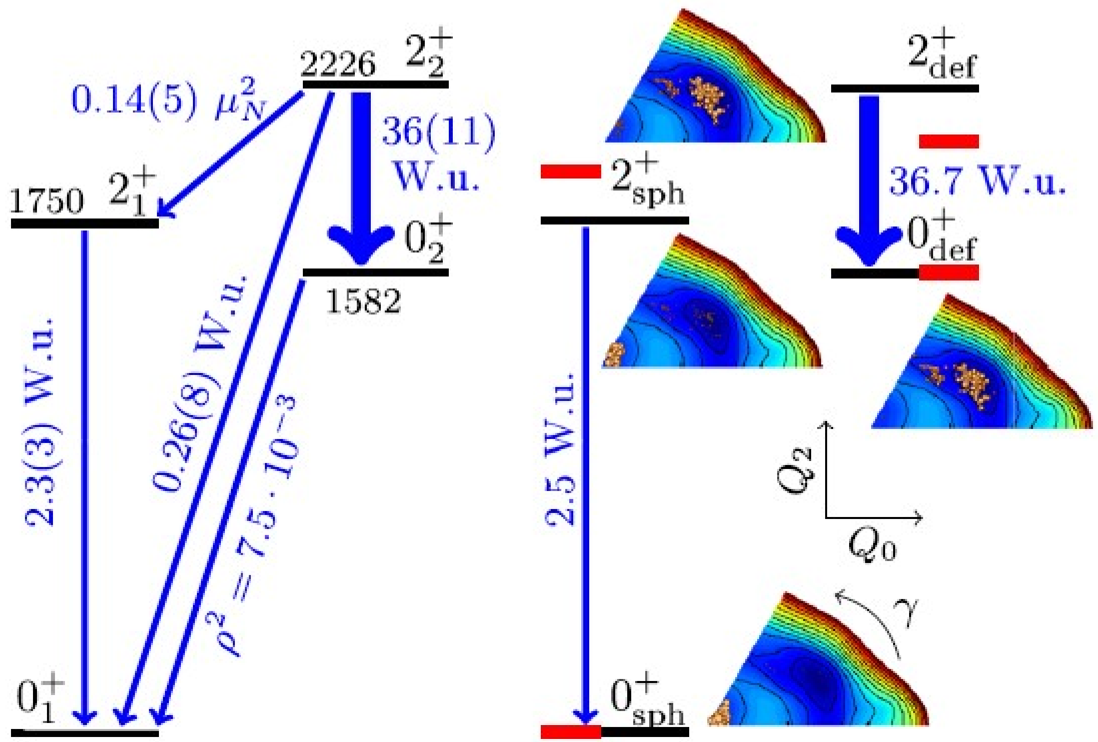
● T. Beck *et al.*,
Phys. Rev. Lett. **118**, 212502 (2017)

^{96}Zr – Type II Shell Evolution



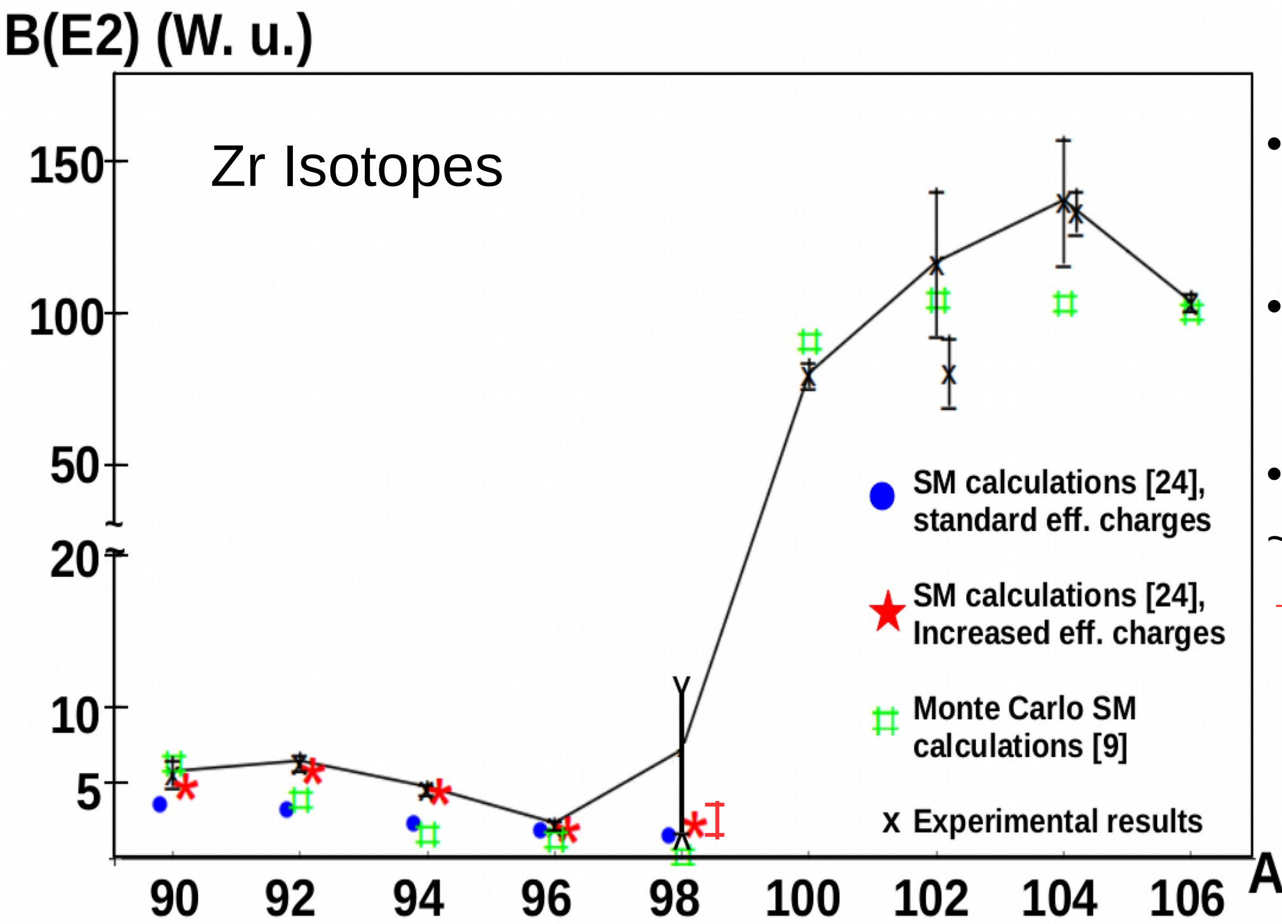
Electron Scattering at the S-DALINAC

C. Kremer, PRL 117, 172503 (2016)



Well-separated spherical and Deformed minima
=> weakly mixing structures

^{98}Zr ground state spherical



- Little collectivity in ground state (like in ^{94,96}Zr)
- Agreement with Togashi et al. (PRL 117, 2016)
- B(E2; $2_1^+ \rightarrow 0_2^+$)
~ magnitude higher
→ 2_1^+ coll. exc. on 0_2^+

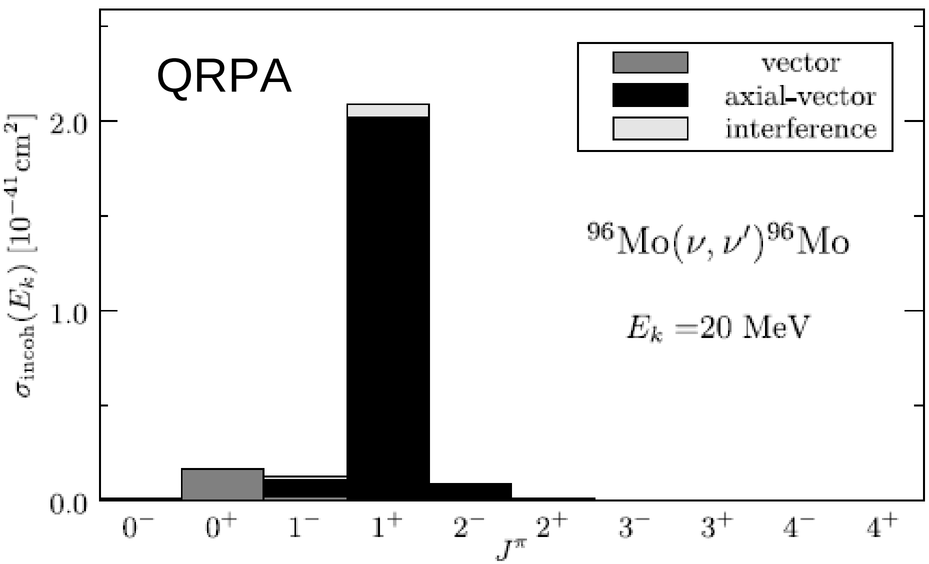
W. Witt, V.W. et al., PRC 98, 041302(R) (2018)
P. Singh et al., PRL 121, 192501 (2018)
W. Witt, V.W. et al., *in preparation*

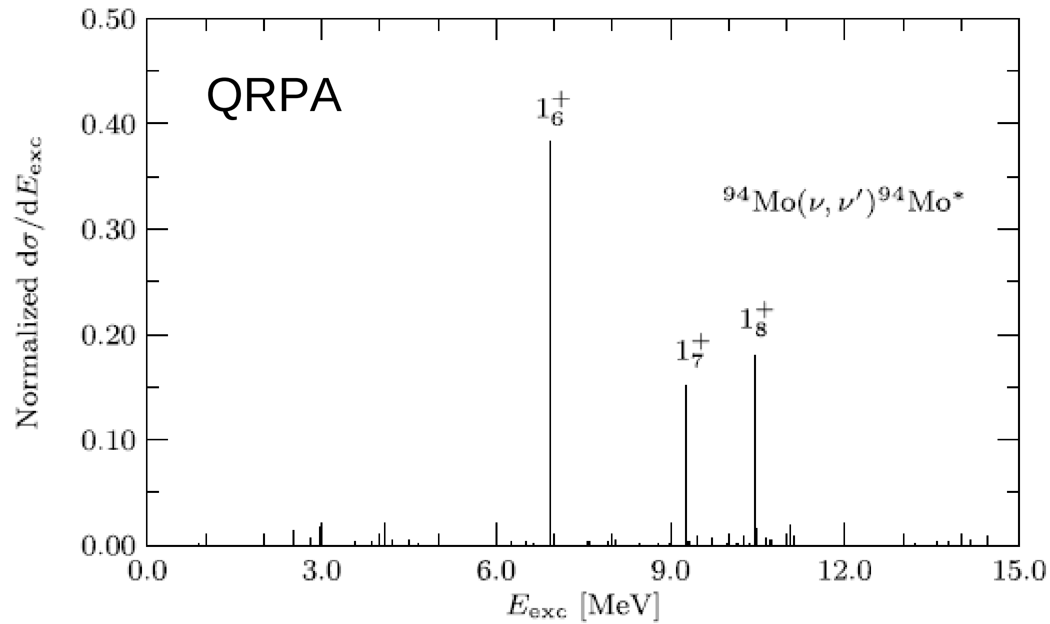
Next: M1's for (ν,ν')

Foreseen neutrino detectors (e.g., Mo-based MOON) work by

$n + \nu_e \rightarrow p + e^-$ and (ν,ν')

ν-scattering excites M1 excitation → Spin-Flip / GT excitations





E. Ydrefors *et al.*, NPA 896, 1 (2010)

We need to know where, and how much M1 strength there is.

Neutrino-detection Materials: ^{40}Ar

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https://solarsystem.nasa.gov/solar-system/sun/overview/

Solar neutrinos

Neutrino-nuclear reactions

Charged-current $^{40}Ar(\nu, e^{-})^{40}K^{*}$

Neutral current $^{40}Ar(\nu, \nu')^{40}Ar^{*}$

DUNE ν beam

Experimental constraints for these reactions?

Neutrino-Nuclear vs. E-M

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Charged-current $^{40}Ar(\nu, e^{-})^{40}K^{*}$

→ Study β^{+}-decay of mirror nucleus 40Ti

$$^{40}Ti \rightarrow \nu_e + e^{+} + {}^{40}Sc$$

M. Bhattacharya, C.D. Goodman, A. García, Phys. Rev. C 80 (2009) 055501

Neutral current $^{40}Ar(\nu, \nu')^{40}Ar^{*}$

Neutrino-nuclear cross section

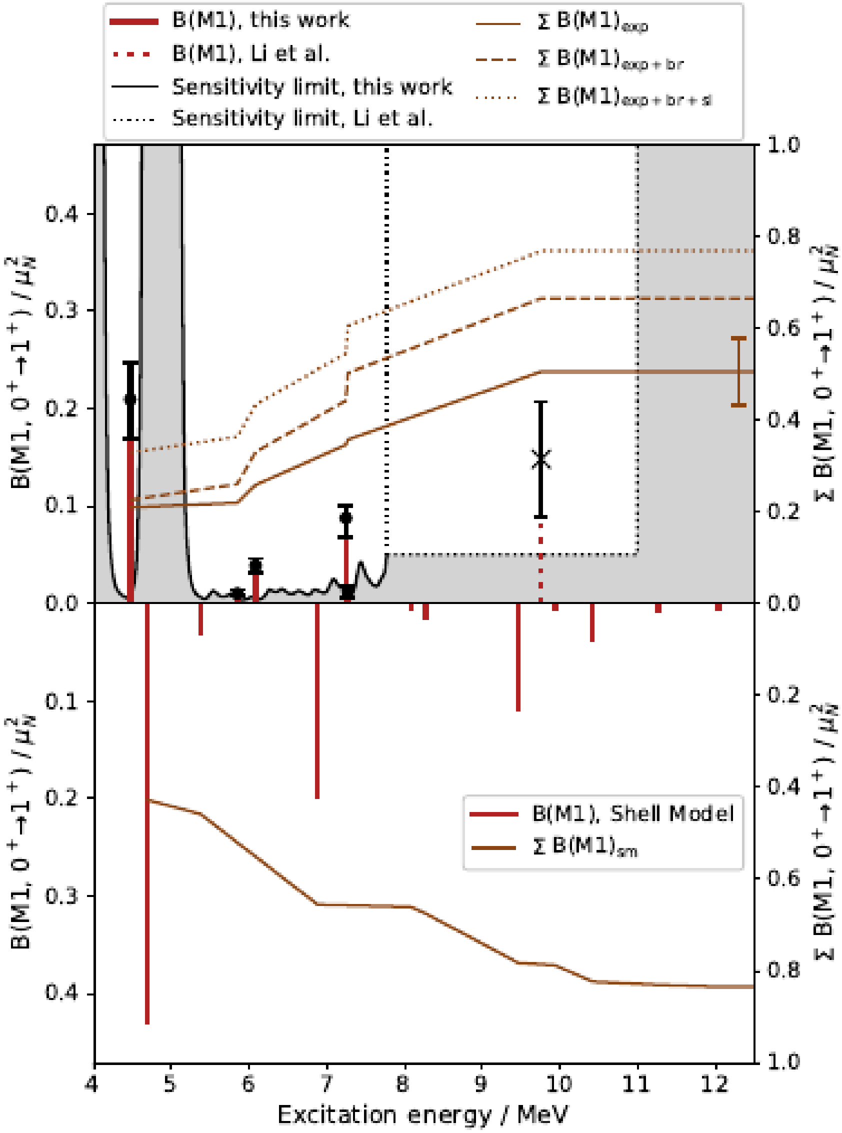
$$\sigma_{i,f}(E_\nu) = \frac{G_F^2 g_A^2}{\pi(2J_i+1)}(E_\nu - \omega)^2 |\langle f || \sum_k s(k)\tau(k) || i \rangle|^2$$

K. Langanke et al., Phys. Rev. Lett. 93 (2004) 202501

Electromagnetic M1 operator

$$O(M1) = \sqrt{\frac{3}{4\pi}} \sum_k [l(k)t(k) + (g_s^p - g_s^n) s(k)t(k)] \mu_N$$

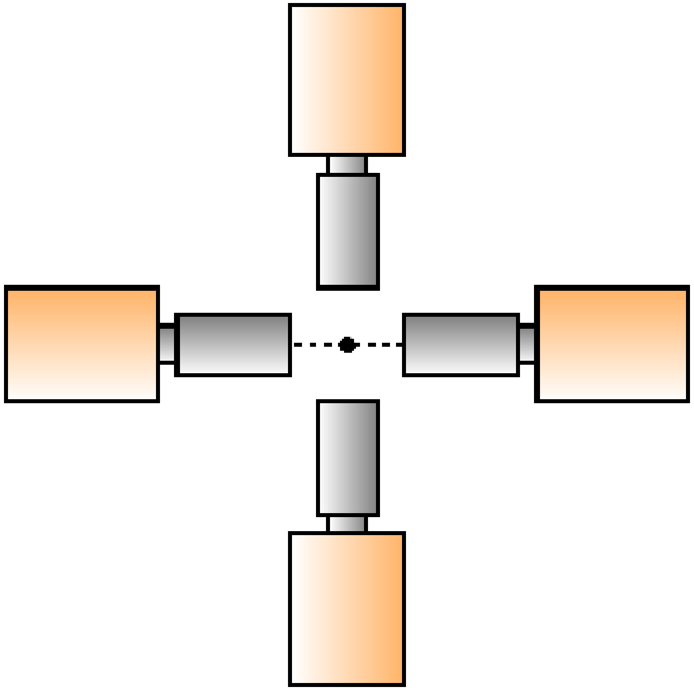
Less M1 Strength in Experiment



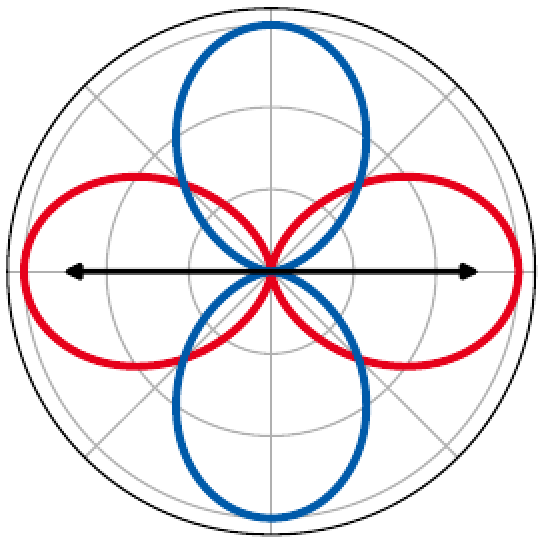
- **T.C. Li, N. Pietralla *et al.*, Phys. Rev. C 73 (2006) 054306**
  Energy range: 7.7 MeV – 11.0 MeV
  1 M1 excitation observed

- **New data**
  Energy range: 4.3 MeV – 7.7 MeV
  5 M1 excitations observed

Disentangle M1 vs E1

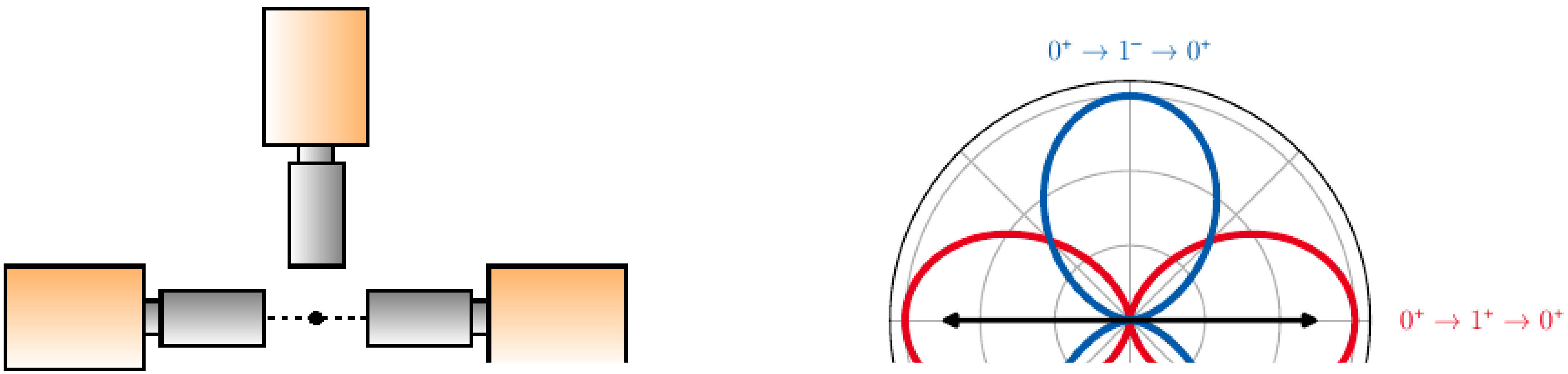


N. Pietralla et al., Phys. Rev. Lett. 88, 012502 (2001)

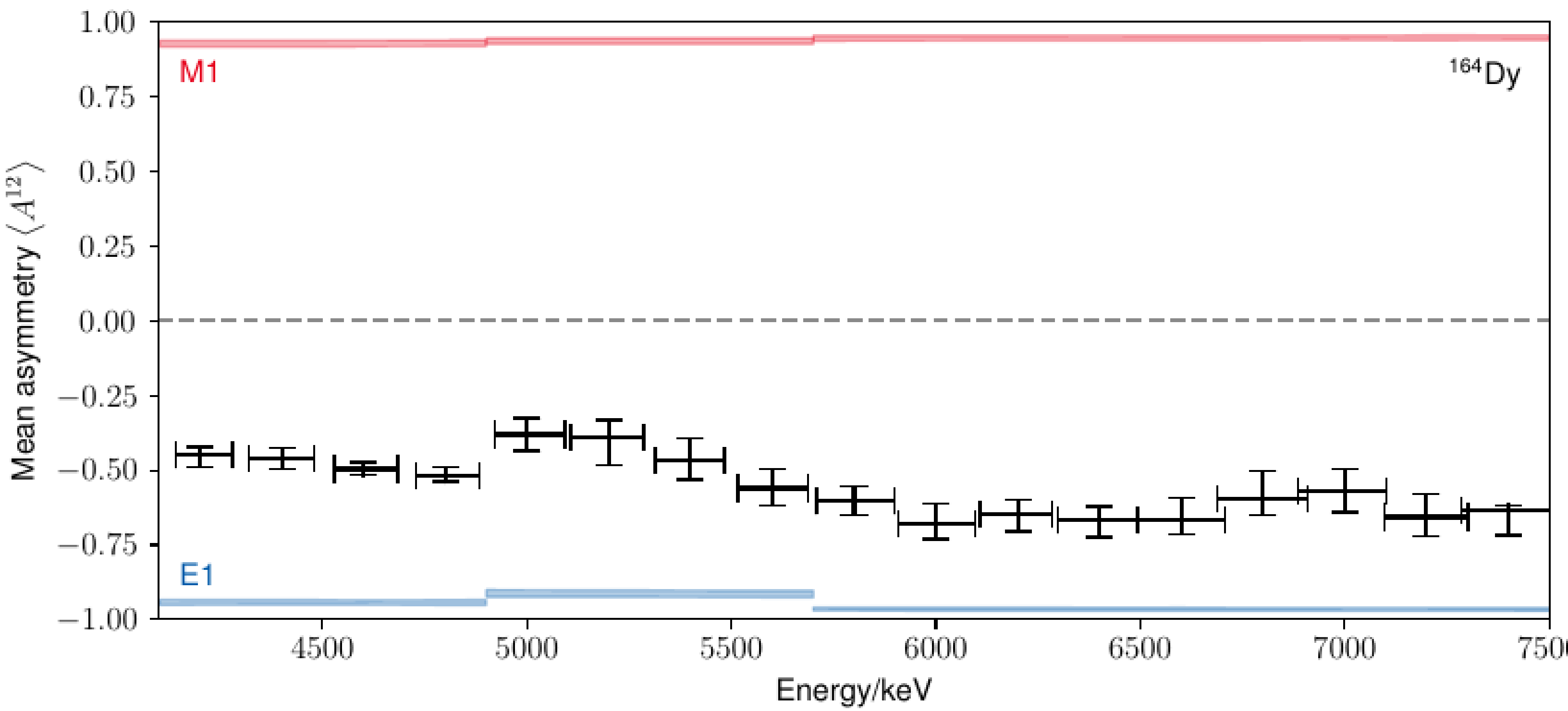


Polarimetry with polarized photon beams

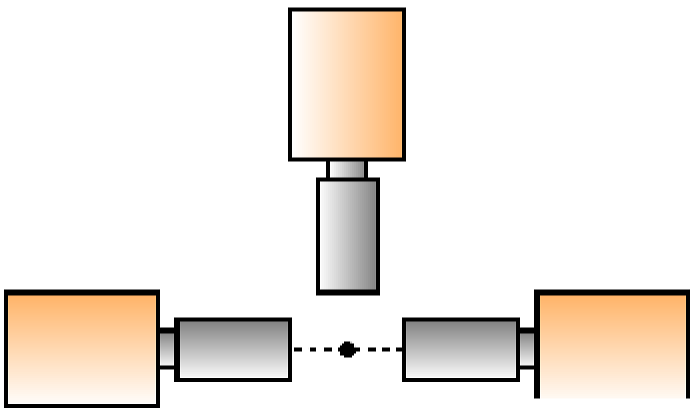
Disentangle M1 vs E1

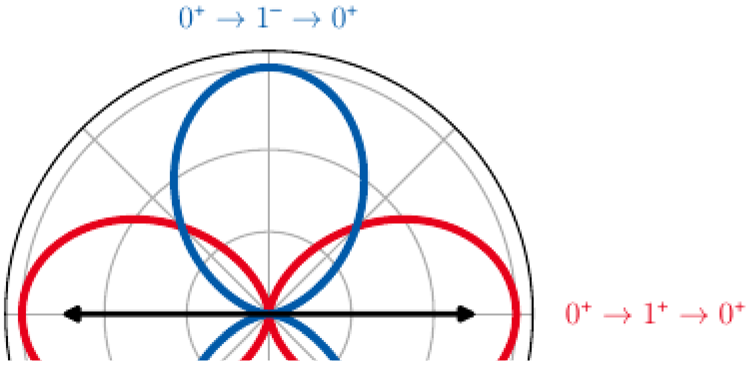


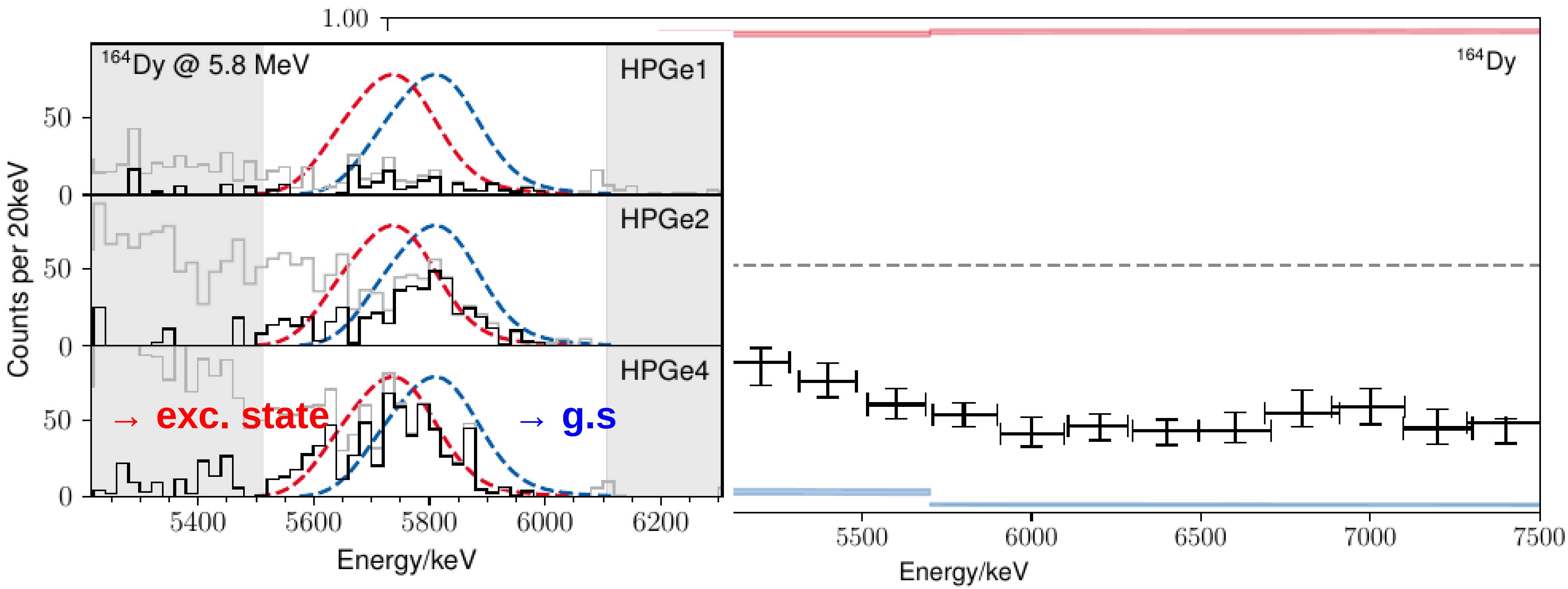
N. Pietralla et al.,



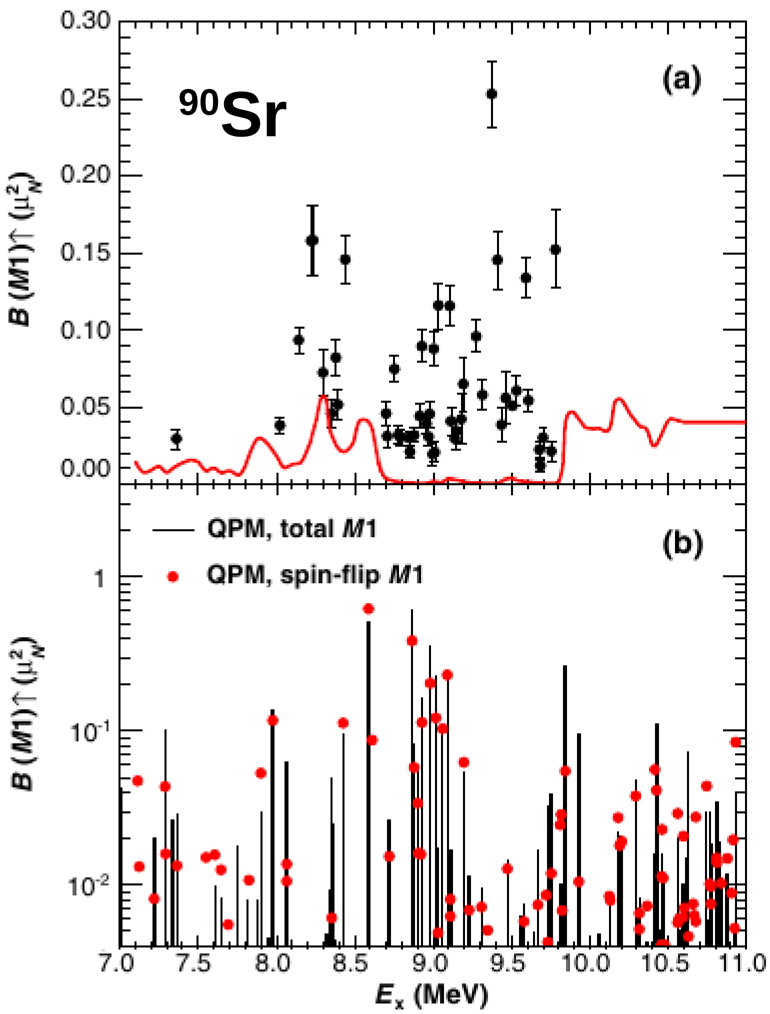
Disentangle M1 vs E1







First Check: ^{90}Sr (vs. ^{90}Mo)



Rusev et al., PRL 110, 022503 (2013)

- Many individual 1^+ states known
  - "giant-M1" resonance
  - close in energy
- Good test case for average method
- Measure side-by-side with ^{90}Mo
  - ^{90}Sr: closed pf-shell
  - ^{90}Mo: $\pi g_{9/2}$ open
  - $\pi g_{7/2}$ s-f partner above N=50
- Later go to "swiss army knife of neutrino-nuclear physics": ^{100}Mo

Publications

- Directly B03 (scissors mode, M1-related, shape coex.):
  - Published: 1 PRL, 1 PRC
  - Submitted: 1 PRC
  - In preparation: 4 (PRC, maybe 1 PRL)
- Very closely relevant for B03:
  - Published: 3 PRL, 3 PRC(Rapid), 1 PRC, 1 NPA, 1 EPJA
  - Submitted: 1 EPJA
  - In preparation: 1 PRL, 1 PRC
- General NRF, other than scissors mode or shape coex.:
  - Published: 2 PLB, 3 PRC, 1 Rom. Rep. Phys.
  - Submitted: 1 PRC(Rapid)
  - In preparation: 1 PRC(Rapid)
- Other relevant:
  - 1 Nature, 2 PRL, 2 PLB, 1 PRC(Rapid), 2 PRC, 2 EPJA
- Best of
  - ^{40}Ar M1 reponse, Gayer, PRC
  - ^{156}Gd scissors mode, Beck, PRL
  - ^{98}Zr shape coexistence, Witt, PRC(Rapid)

Theses

- Bachelor:
  - Köhler (^{76}Ge), Knösel (^{11}B), Kleemann (^{150}Sm), Papst (^{92,94}Zr), Ide (^{152}Sm)
- Master:
  - Gayer (^{48,50}Ti), Schilling (^{112}Sn), Beck (^{156}Gd), Kleemann (^{150}Nd/^{150}Sm), Papst (^{164}Dy)
- Doctoral:
  - Zweidinger ($^{92\text{-}96}$Zr)
- Related (e.g. shape coexistence, spectrometer enhancements):
  - Bachelor:
    - Ahmed (^{148,150}Ce)
    - Brandherm (LINTOTT trigger detector)
  - Master:
    - Ebert (scattering chamber)
  - Doctoral:
    - Witt (^{98}Zr), Koseoglou (^{148}Ce),

X-Links to other Projects

- A01:
  - Relative Self Absorption NRF
  - ^{12}C B(E2) measurement
  - Publication ^{7}Li RSA in preparation
- B01:
  - ^{40}Ar NRF, paper submitted
- B02:
  - Electro-weak interactions
- A07,B04:
  - Investigations into PDR, low-energy GDR tail at HIGS
- A04:
  - Medium-mass nuclei
  - Through NRF, but also complementary related studies

Workshops organized

- SEASTAR Workshop 2016 (in-beam spectroscopy at RIKEN), organizer
- High-resolution gamma-spectroscopy (in April), local committee
- AGATA with stable beams workshop, Legnaro March 2019, convener

Awards

- Haridas Pai (former NRF member)
  - Ramanujan fellow at SINP Kolkata
    (prestigious 5-year tenure-track path in India)

- Tobias Beck
  - Giersch Excellence Award
  - Msc-Forschungspreis Gerhard Herzberg Gesellschaft

Press / Media / PR

- Waldemar Witt, VW et al, ^{98}Zr, 2018
  - APS physics highlights
  - Welt der Physik

- Andreas Zilges et al, ELI-NP, 2018
  - Welt der Physik

- Knowledge transfer:
  - Became new member of NUMEN project (double-charge-exchange reactions)
  - Contributed to HIGS2 white paper (last HIGS umbrella proposal was used almost 1:1 for HIGS2 proposal)