HIyS and S-DALINAC experiments elucidating weak processes

Joachim Enders, **Volker Werner**, Udo Gayer, Philipp C. Ries

TECHNISCHE UNIVERSITÄT DARMSTADT

Supported by the
Deutsche Forschungsgemeinschaft
(German Research Foundation)
through
research grant **SFB 1245**

DFG
Deutsche Forschungsgemeinschaft

B03: Objective

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Neutrinoless double-beta decay

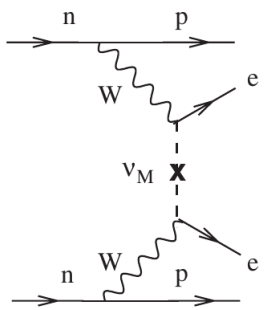

Fig. From: F. T. Avignone III, S. R. Elliott and J. Engel, Rev. Mod. Phys. **80** (2008)

WIMP – Matter interaction

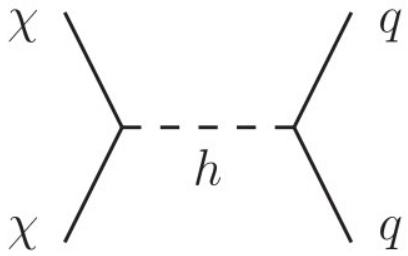

Fig. from: M. Hoferichter, P. Klos, J. Menéndez and A. Schwenk Phys. Rev. Lett. **119** (2017) 181803

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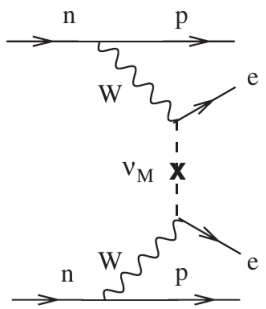

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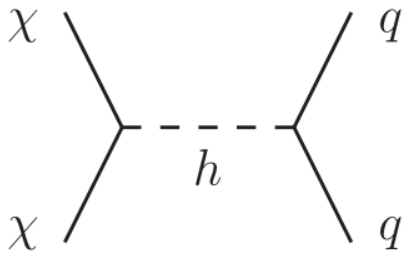

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Direct detection experiments

Decay rates
Cross sections

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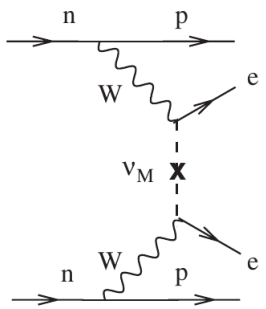
Neutrinoless double-beta decay



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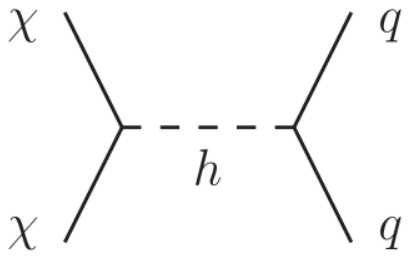

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Direct detection experiments

Decay rates
Cross sections

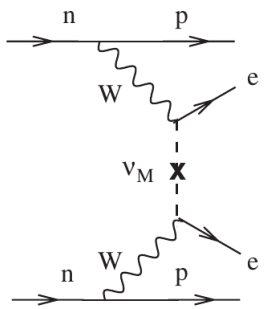
Fundamental physics information

Neutrino- and WIMP
Masses, couplings, …

B03: Objective

TECHNISCHE UNIVERSITÄT DARMSTADT

Neutrinoless double-beta decay



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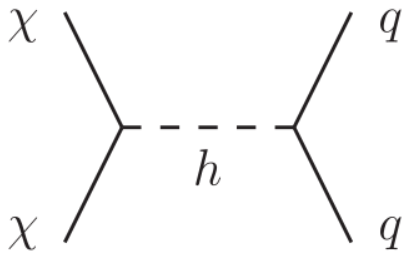

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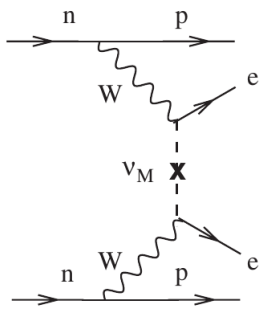
TECHNISCHE UNIVERSITÄT DARMSTADT

Neutrinoless double-beta decay



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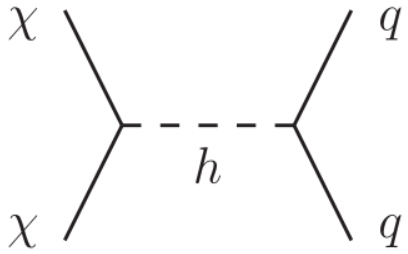

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Direct detection experiments

Decay rates
Cross sections

Nuclear theory

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B03: Objective

TECHNISCHE UNIVERSITÄT DARMSTADT

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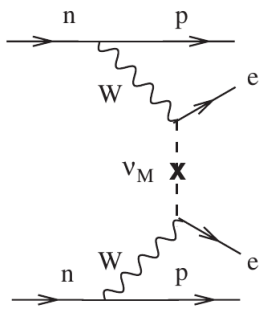

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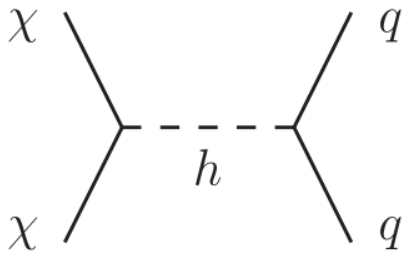

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Nuclear physics Experiments in B03

Direct detection experiments

Decay rates
Cross sections

Nuclear theory

Fundamental physics information

Neutrino- and WIMP
Masses, couplings, …

Neutrinoless double-beta (0νββ) decay

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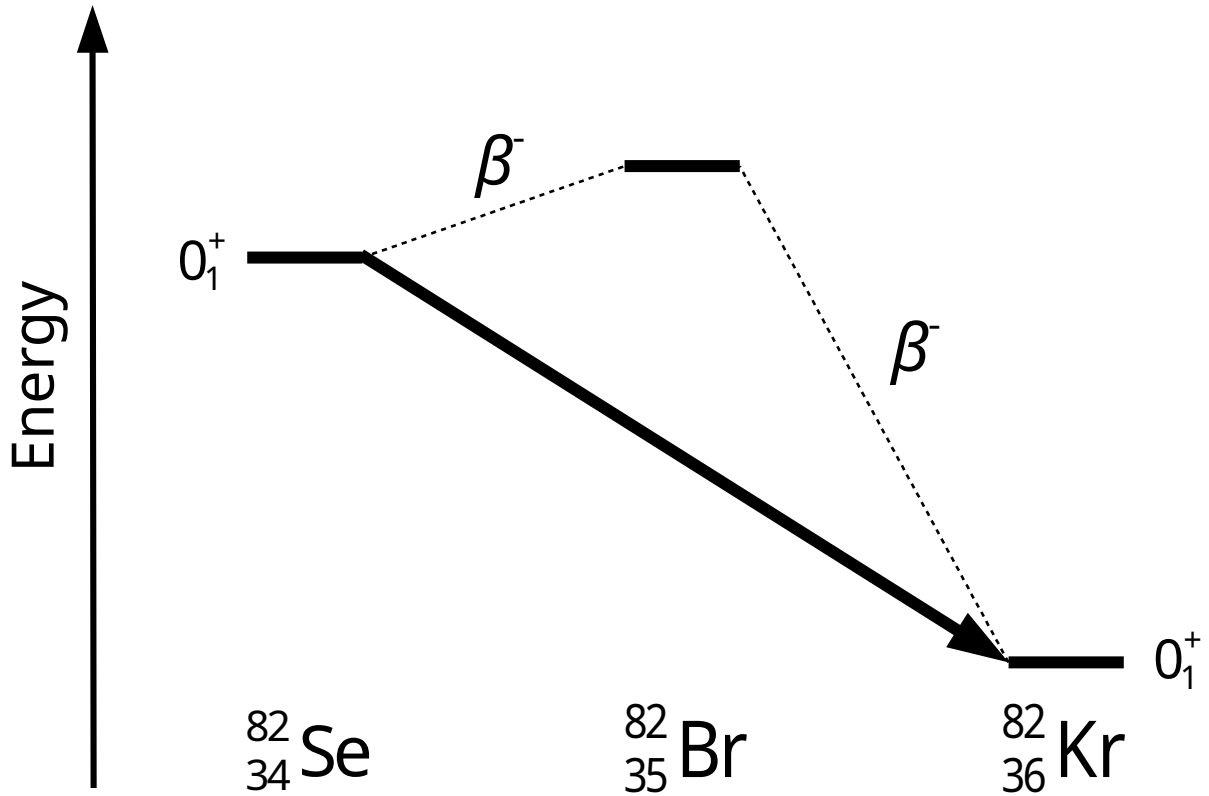
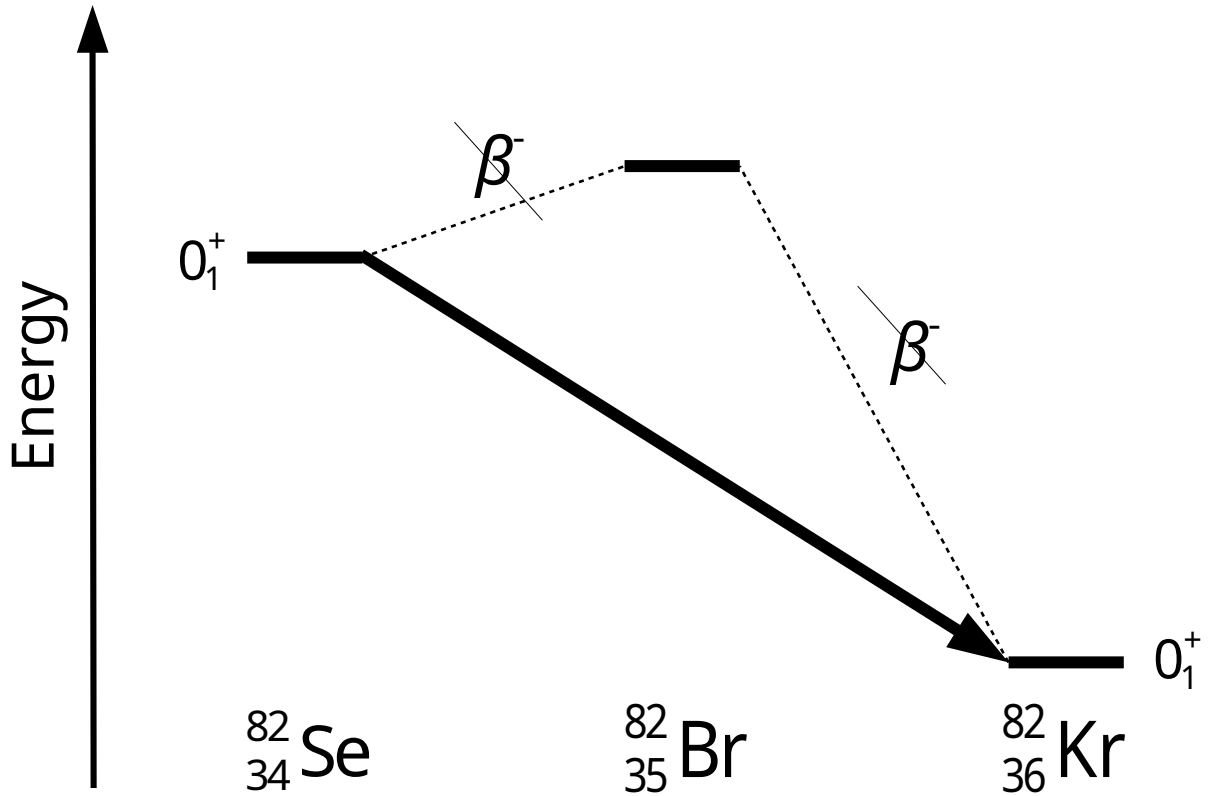
0νββ Decay

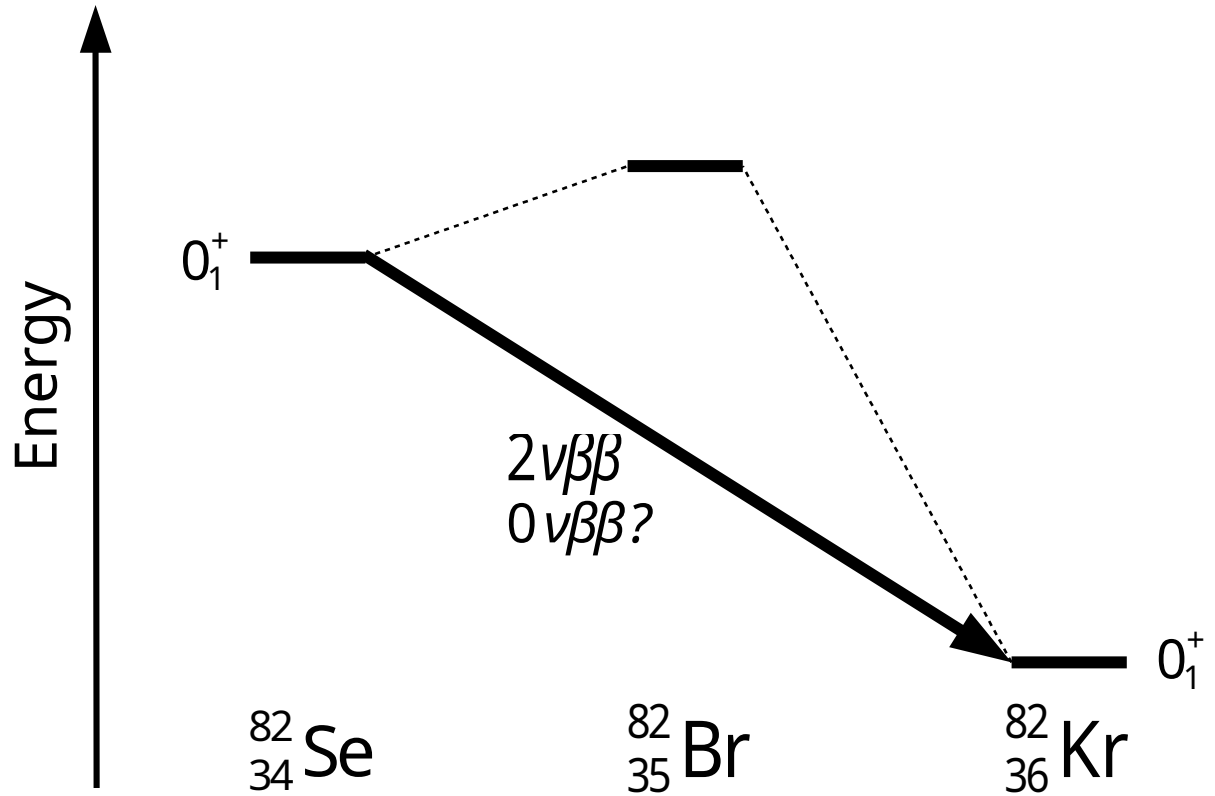


0νββ Decay

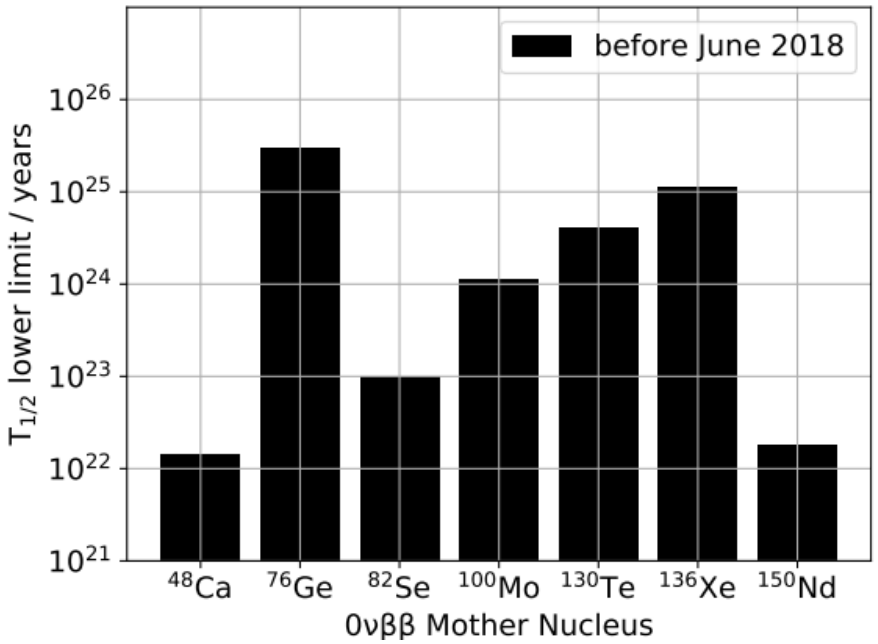


0νββ Decay

$$\lambda_{0\nu\beta\beta} \propto |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

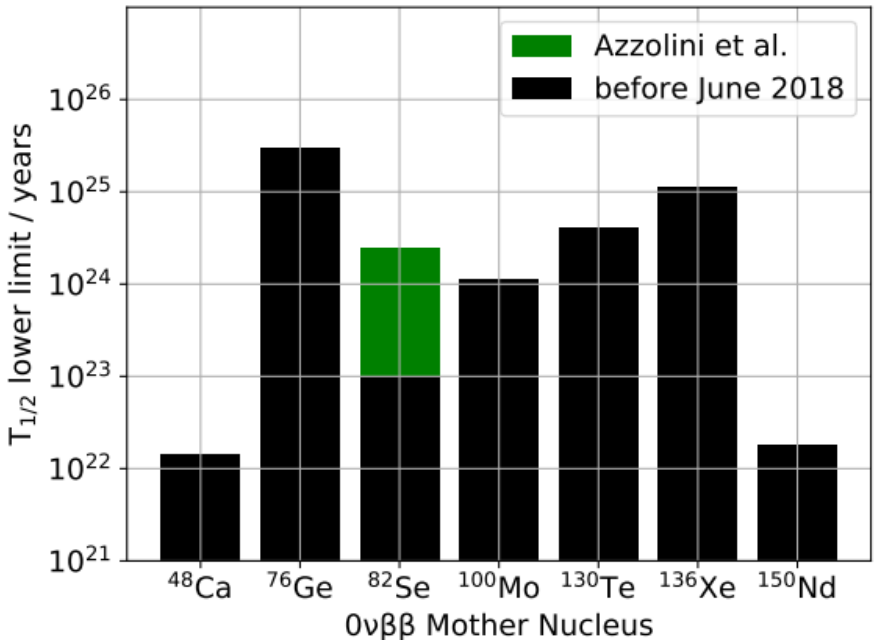


0νββ Decay



^{48}Ca: I. Ogawa et al., Nucl. Phys. A730 (2004) 215 (ELEGANT IV)
^{76}Ge: M. Agostini et al., Phys. Rev. Lett. **111** (2013) 122503 (GERDA)
^{82}Se: R. Arnold et al., Phys. Rev. Lett. **95** (2005) 182302 (NEMO-3)
^{100}Mo: R. Arnold et al., Phys. Rev. D **89** (2014) 111101(R) (NEMO-3)
^{136}Xe: J. Albert et al., Nature **510** (2014) 229 (EXO-200)
^{150}Nd: J. Argyriades et al., Phys. Rev. C **80** (2009) 032501 (NEMO-3)

0νββ Decay



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PHYSICAL REVIEW LETTERS **120,** 232502 (2018)

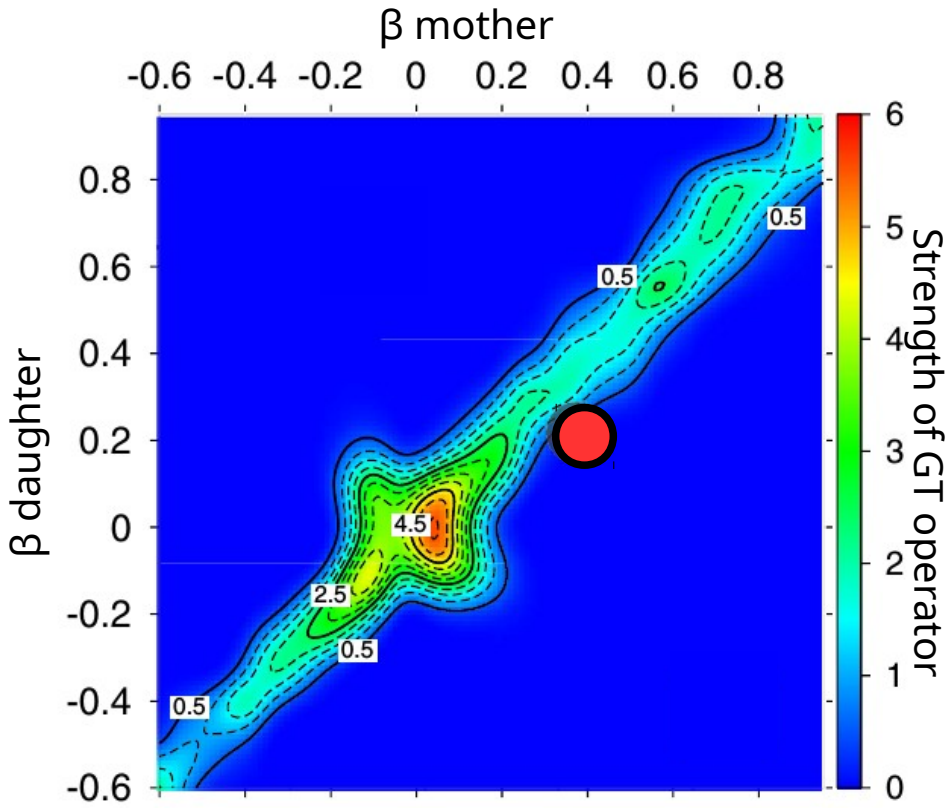
Editors' Suggestion

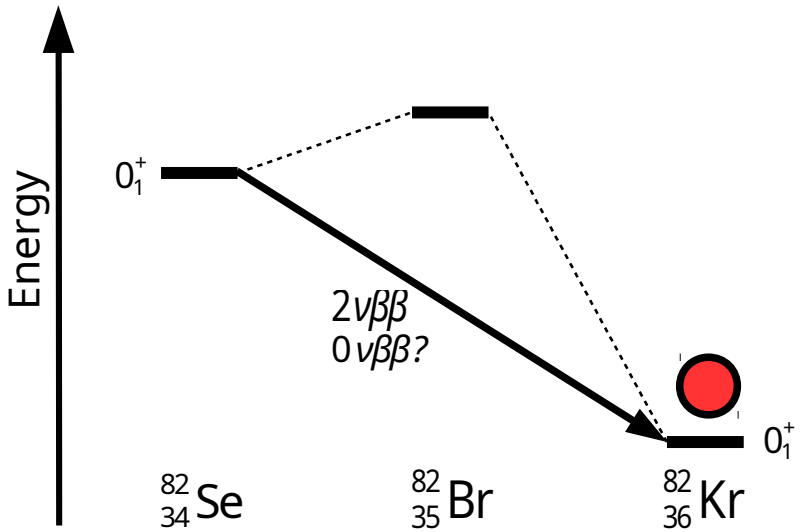
First Result on the Neutrinoless Double-β Decay of ^{82}Se with CUPID-0

O. Azzolini,[1] M. T. Barrera,[1] J. W. Beeman,[2] F. Bellini,[3,4,*] M. Beretta,[5,6] M. Biassoni,[6] C. Brofferio,[5,6] C. Bucci,[7]

0νββ Decay and Nuclear Structure

$$\lambda_{0\nu\beta\beta} \propto |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$





T. R. Rodríguez, G. Martínez-Pinedo, Phys. Rev. Lett. **105** (2010) 252503

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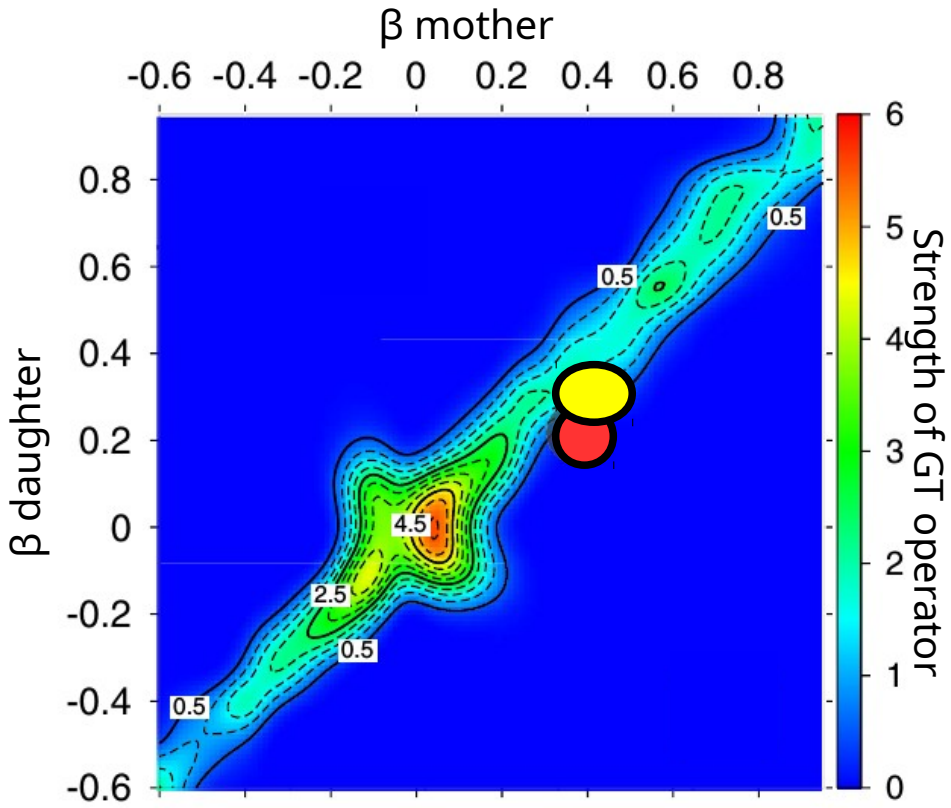

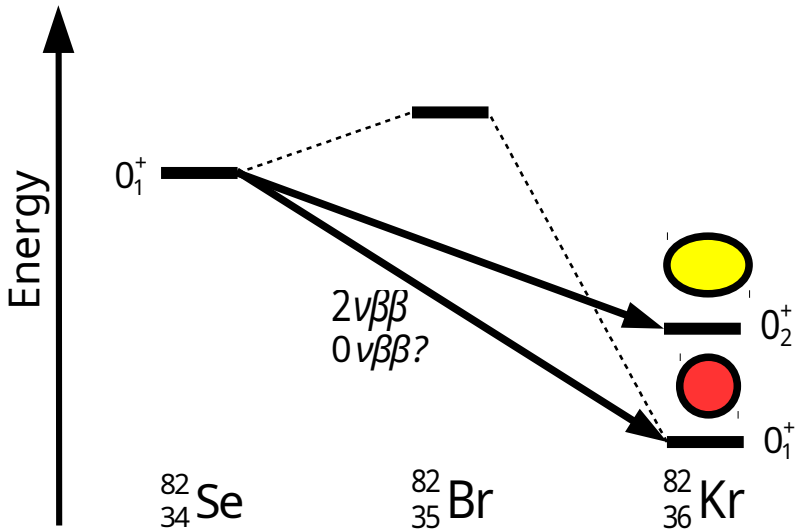

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0νββ Decay and Nuclear Structure

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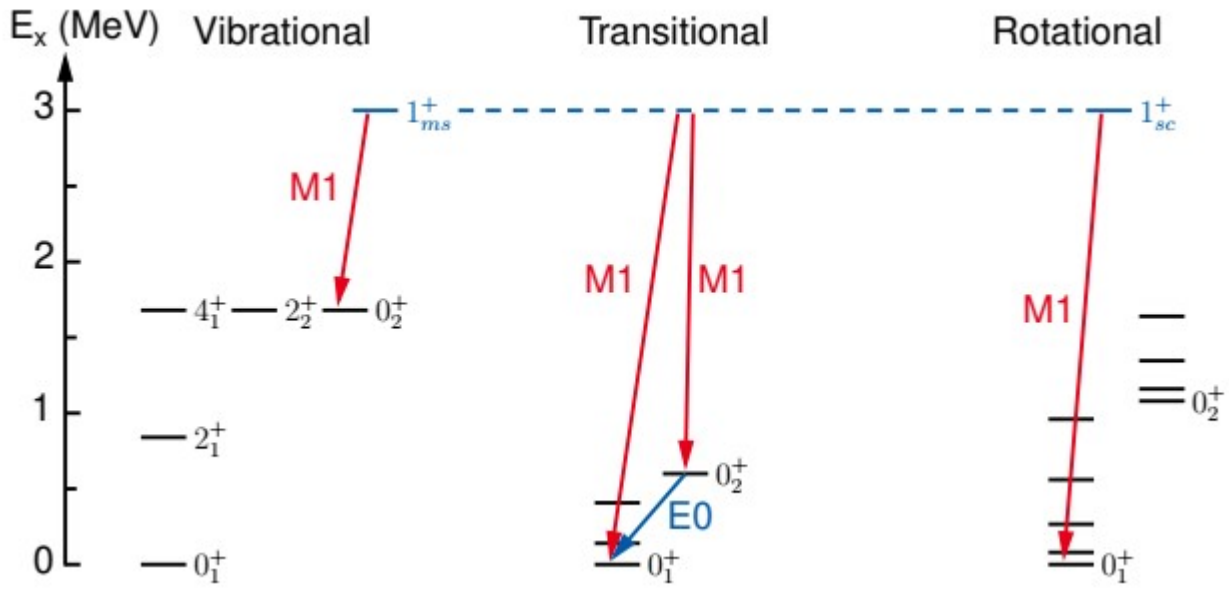
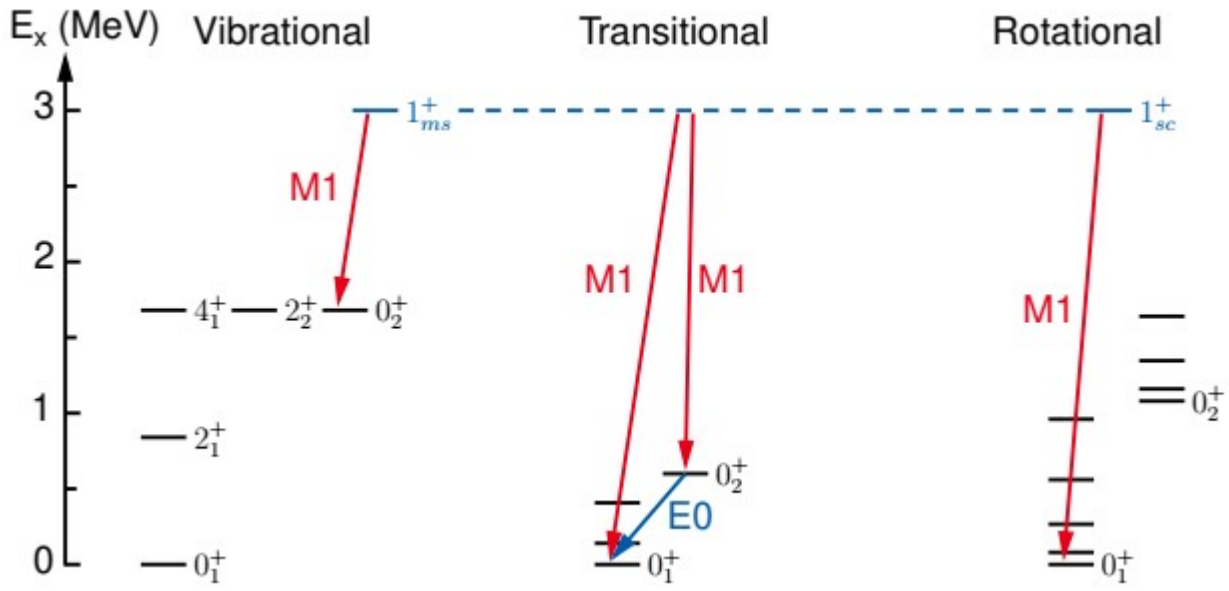
- Observables for shape coexistence?



0νββ Decay and Nuclear Structure

TECHNISCHE UNIVERSITÄT DARMSTADT

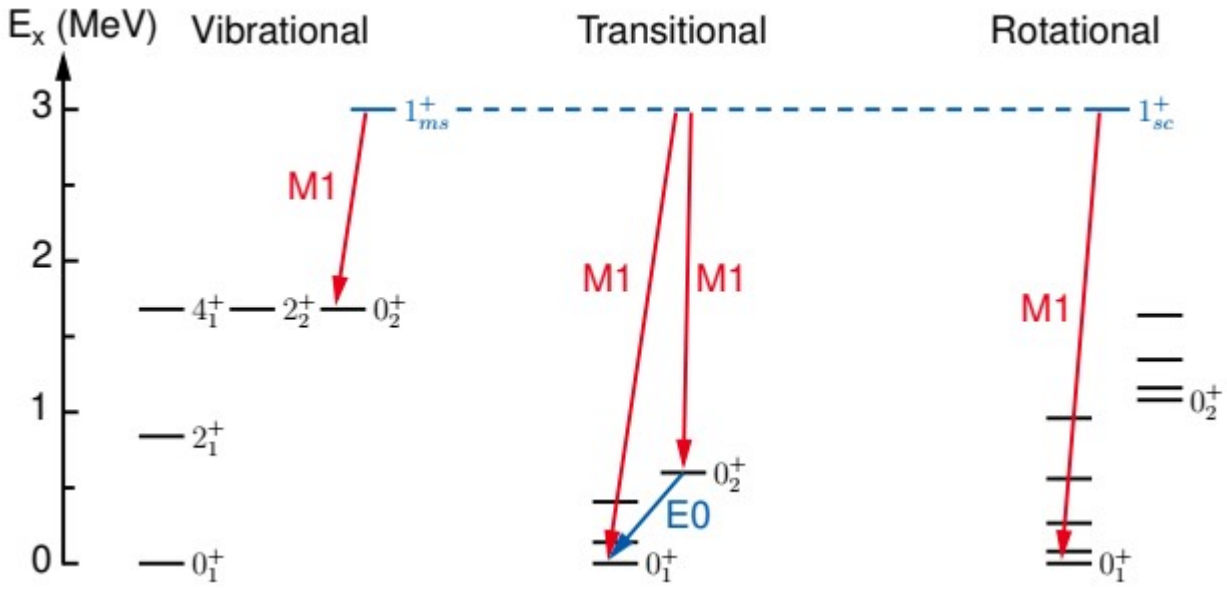
- Observables for shape coexistence?
  - Transitions between low-lying 0^+ states



0νββ Decay and Nuclear Structure

TECHNISCHE UNIVERSITÄT DARMSTADT

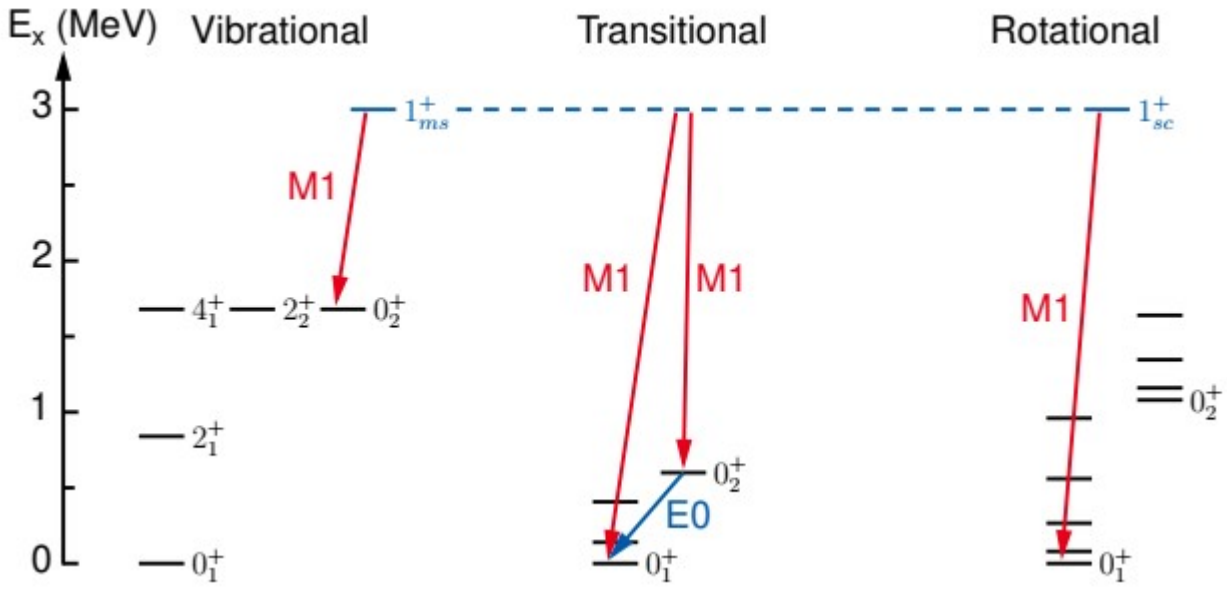
- Observables for shape coexistence?
  - Transitions between low-lying 0^+ states
  - Decay of 1^+ mixed-symmetry (MS) states („scissors mode“)



0νββ Decay and Nuclear Structure

TECHNISCHE UNIVERSITÄT DARMSTADT

- Observables for shape coexistence?
  - Transitions between low-lying 0^+ states → **(e,e')**
  - Decay of 1^+ mixed-symmetry (MS) states („scissors mode") → **(γ,γ')**



0νββ Decay and Nuclear Structure

TECHNISCHE UNIVERSITÄT DARMSTADT

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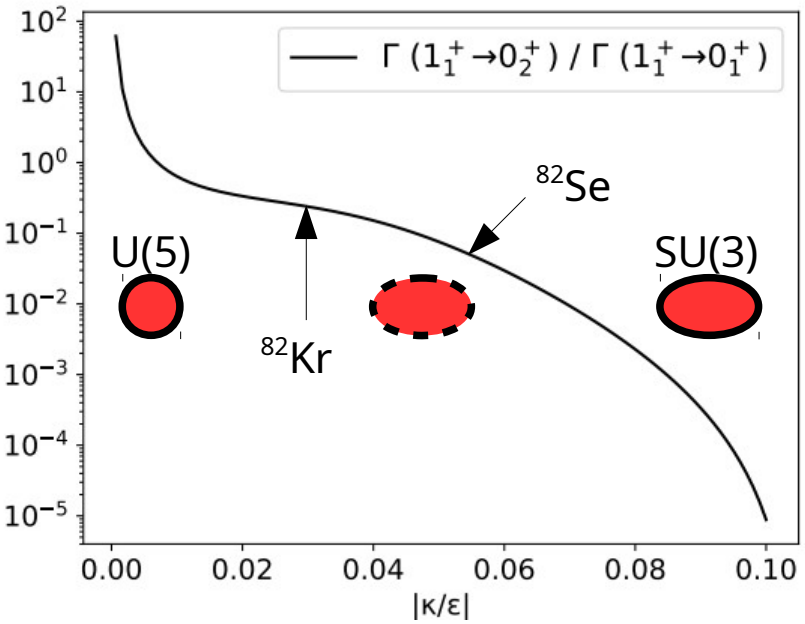
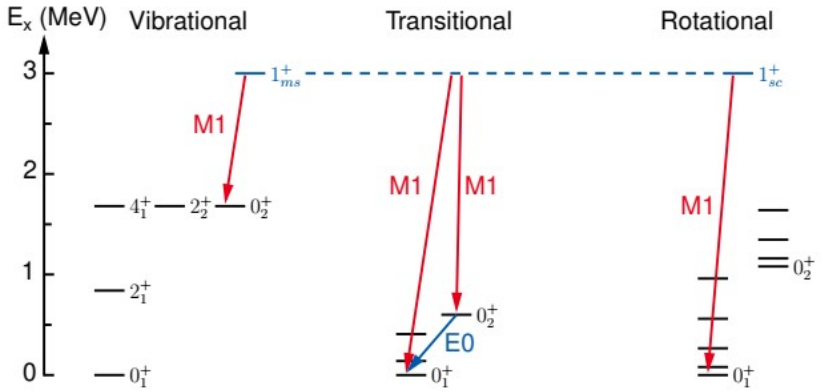
→ Schematic calculation in Interacting Boson Model (IBM)
F. Iachello and A. Arima, The interacting boson model, Cambridge University Press (1987)

$$\hat{H} = \varepsilon\left(\hat{n_{d,\pi}} + \hat{n_{d,\nu}}\right) + \kappa\left(\hat{Q_\pi^\chi} + \hat{Q_\nu^\chi}\right)\cdot\left(\hat{Q_\pi^\chi} + \hat{Q_\nu^\chi}\right) + \lambda\hat{M}_{\pi\nu}$$





Experimental Program for 0νββ Decay

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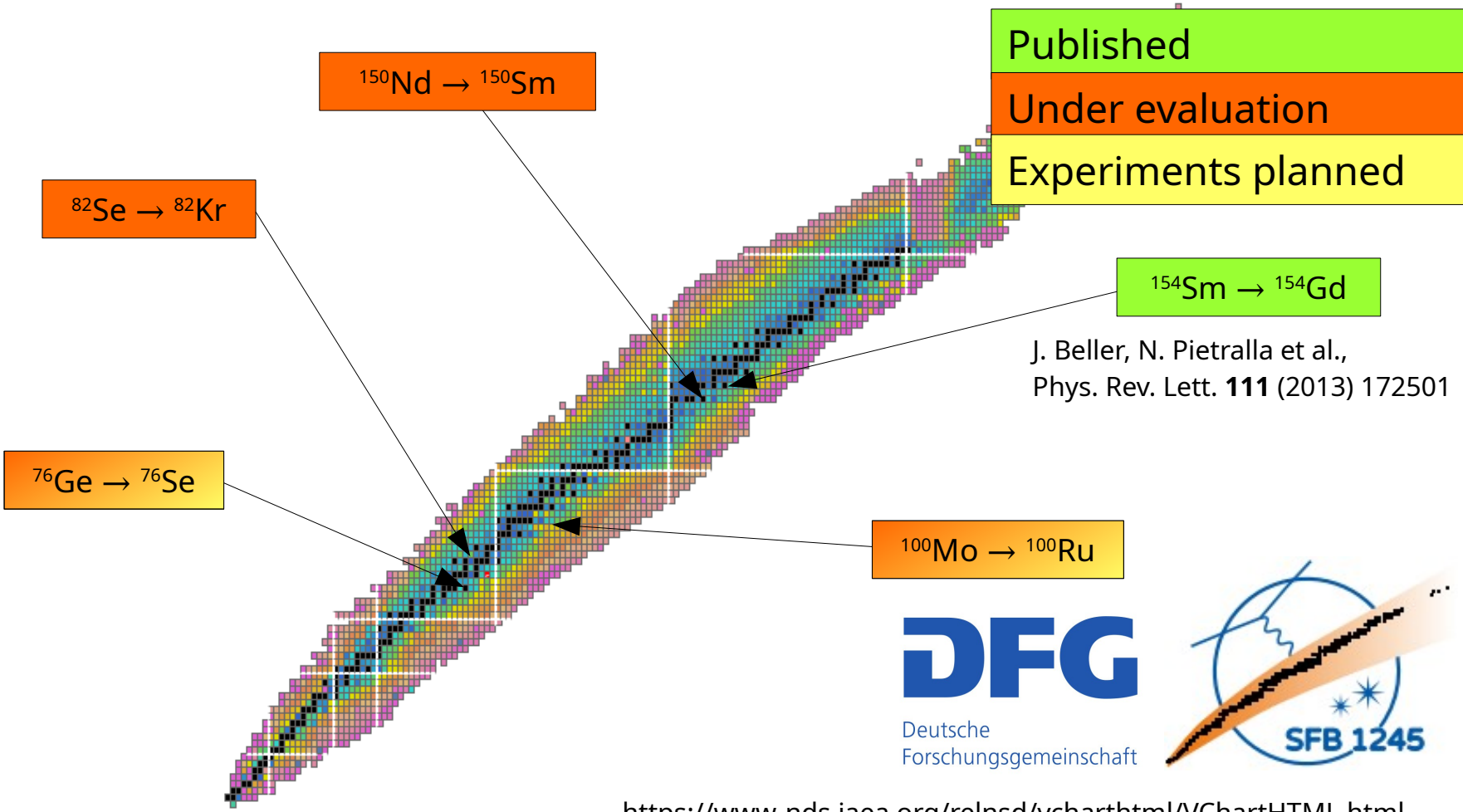


J. Beller, N. Pietralla et al.,
Phys. Rev. Lett. **111** (2013) 172501

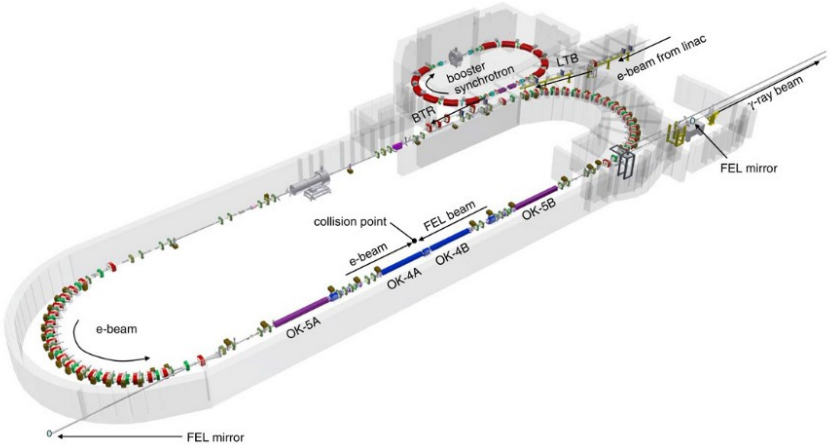
DFG Deutsche Forschungsgemeinschaft

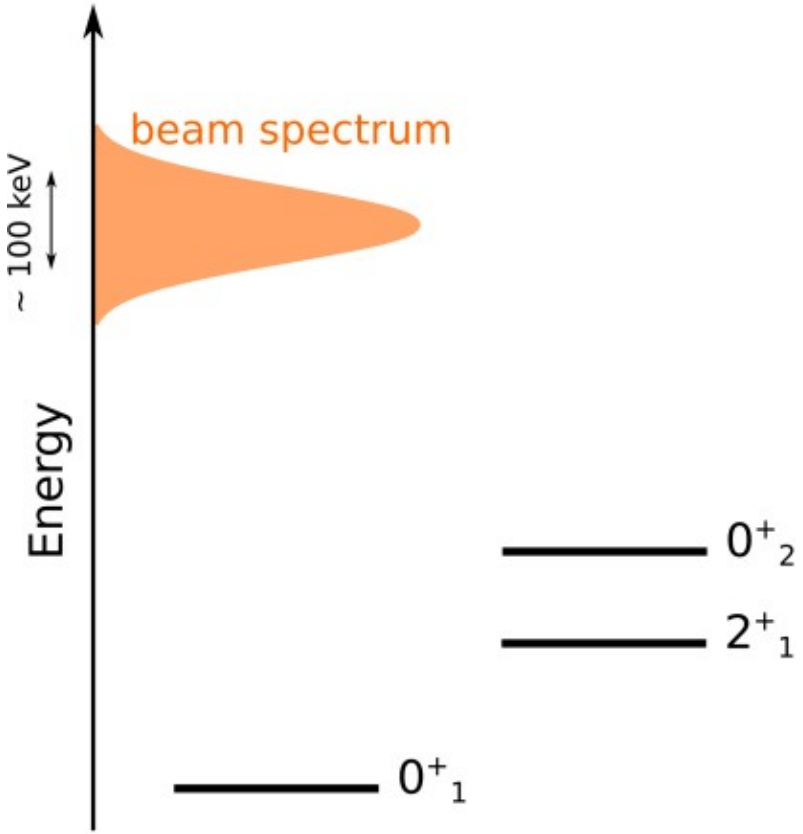
SFB 1245

https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

(γ,γ') Experiments - Facility

- High-Intensity Gamma-Ray Source (HIγS) @ Duke University
  → Quasi-monoenergetic, linearly polarized photon beam





HIγS:
H.R. Weller et al., Prog. Part. Nucl. Phys. **62** (2009) 257
NRF with polarized LCB beams:
N. Pietralla et al., Phys. Rev. Lett. **88** (2001) 012502

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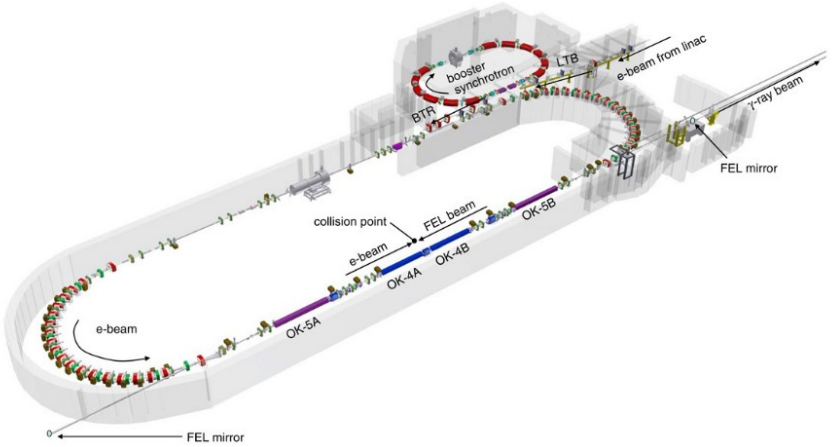

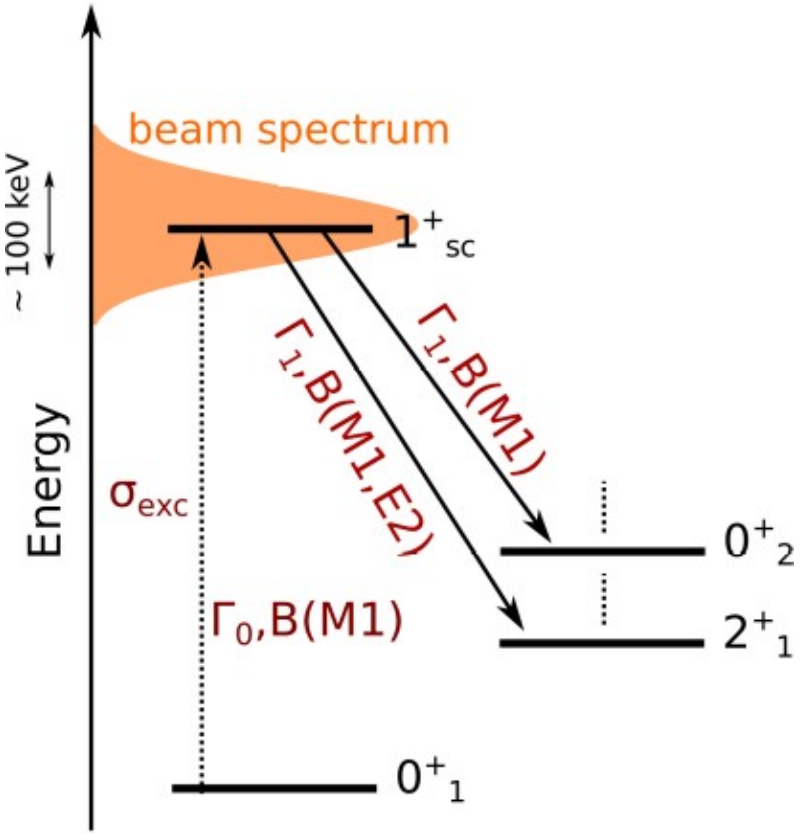

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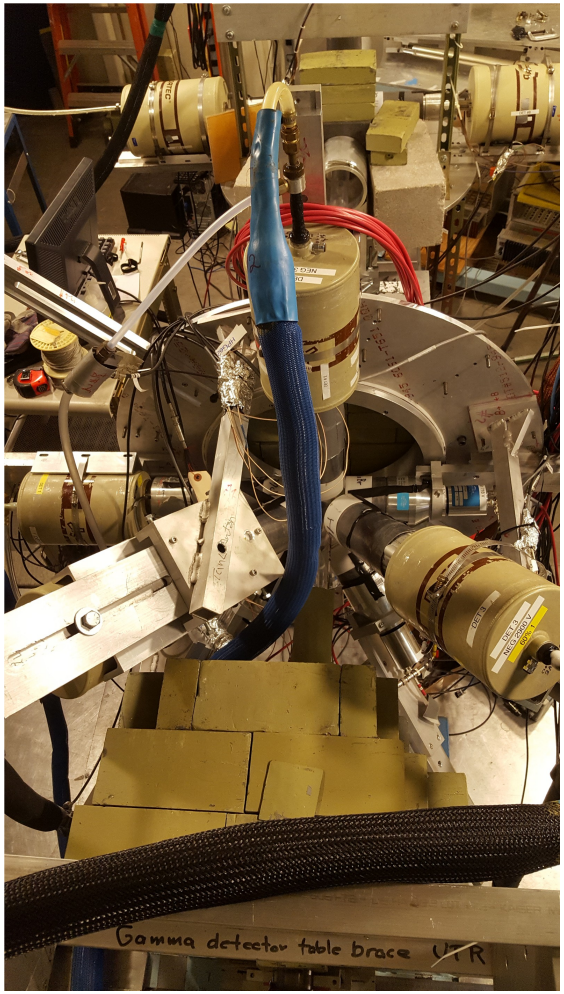
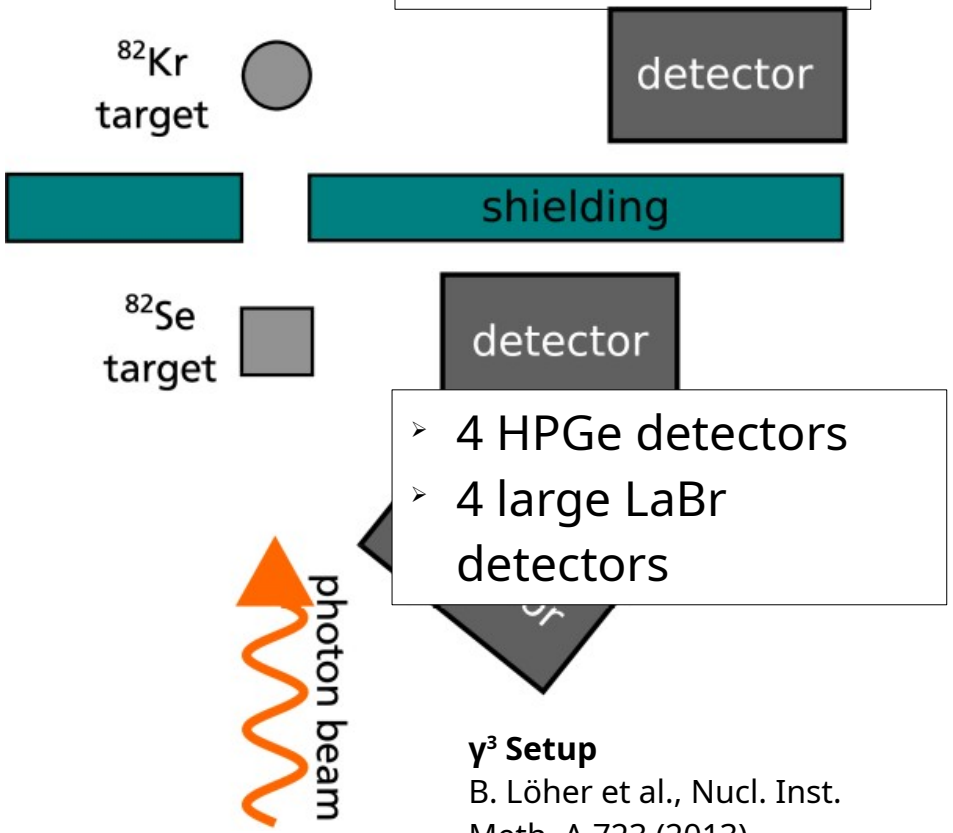
N. Pietralla et al., Phys. Rev. Lett. **88** (2001) 012502

(γ,γ') Experiments – Setups



- 4 HPGe detectors

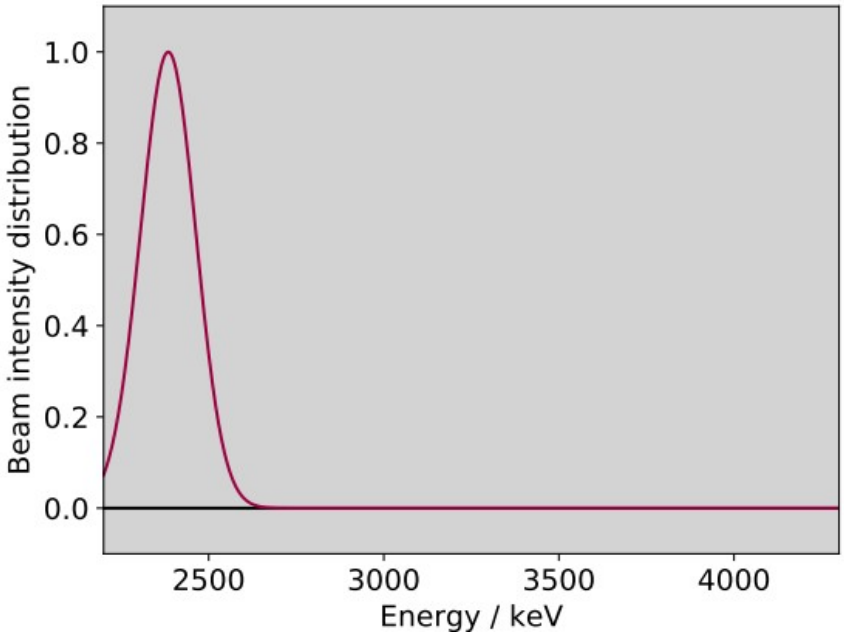


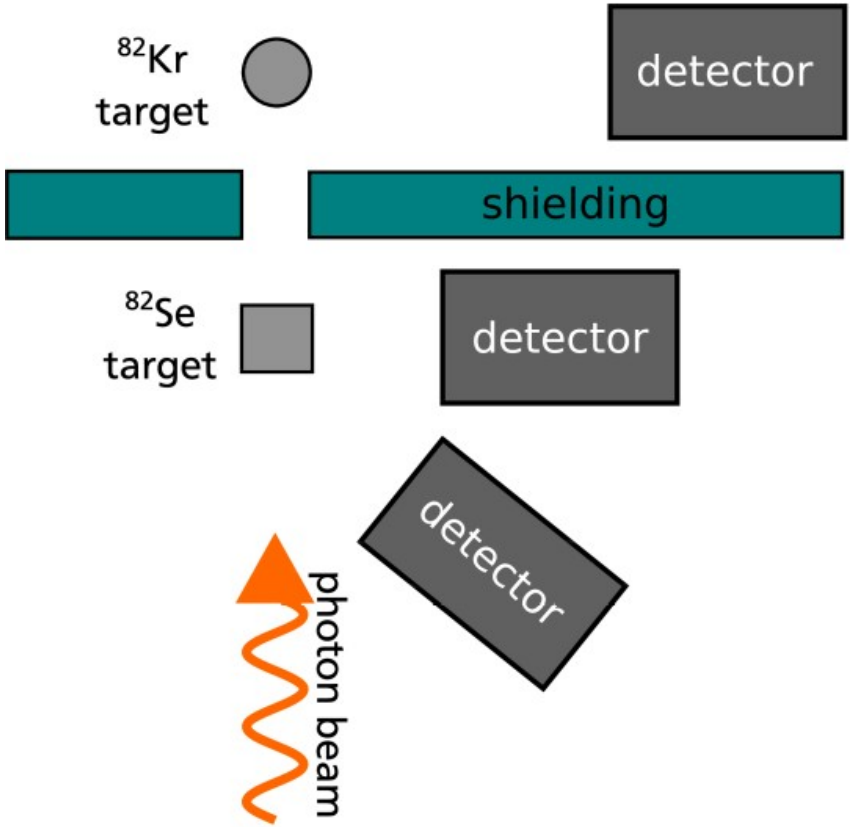
- 4 HPGe detectors
- 4 large LaBr detectors

γ³ Setup
B. Löher et al., Nucl. Inst. Meth. A 723 (2013) 136-142

(γ,γ') Experiments

- Systematic scan of dipole response





(γ,γ') Experiments

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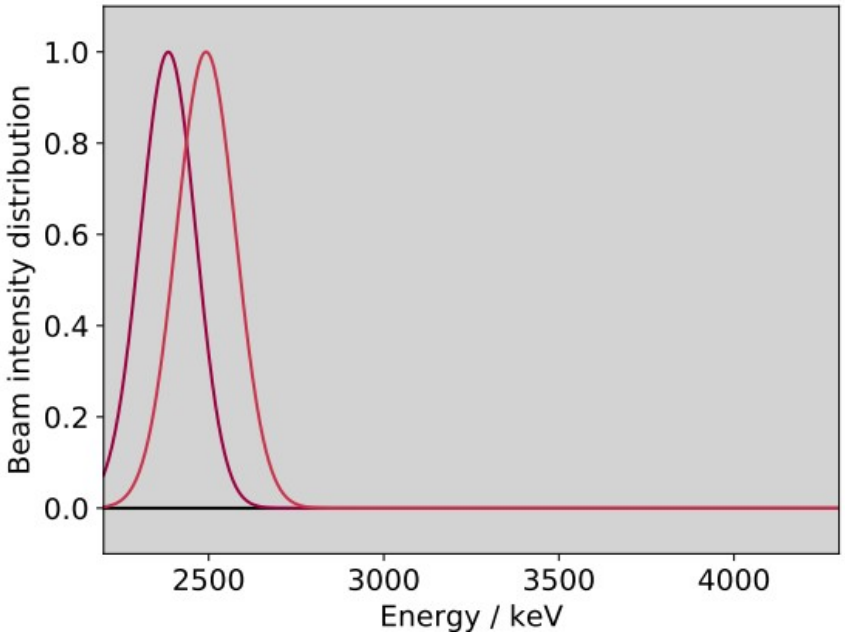

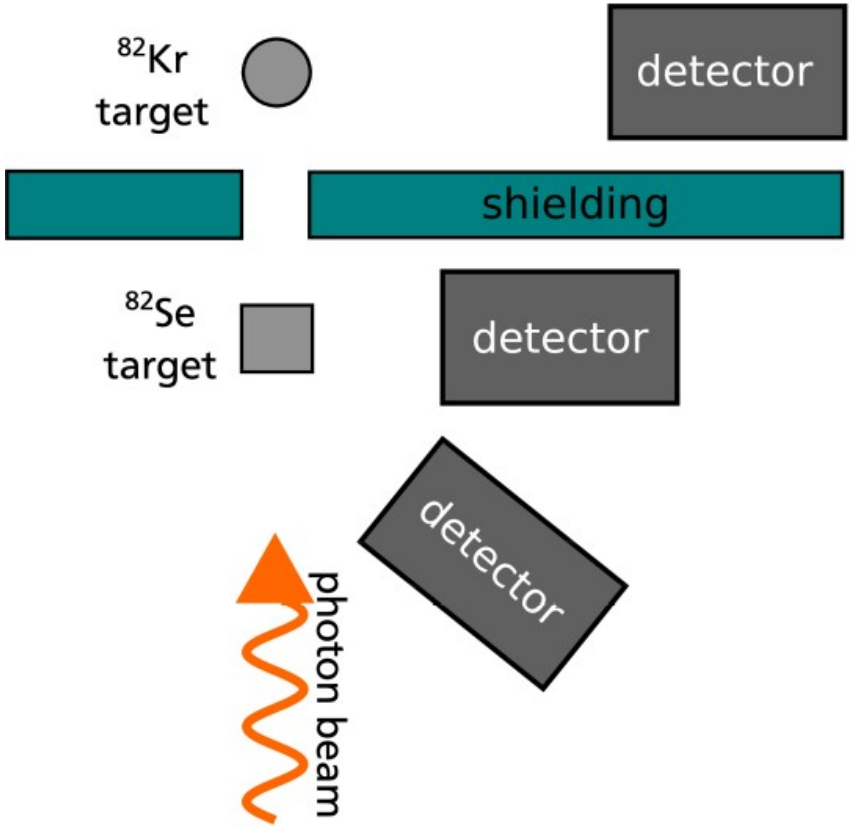

(γ,γ') Experiments

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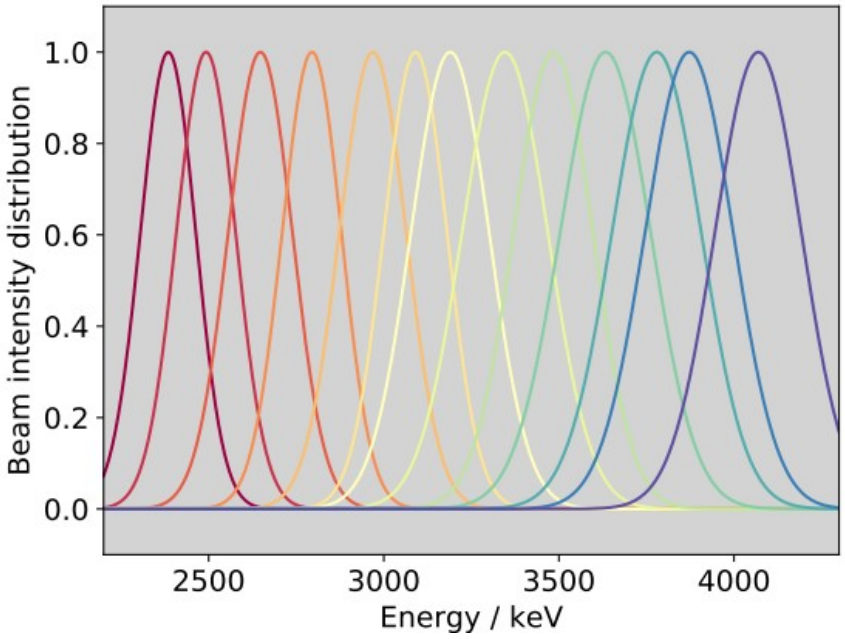
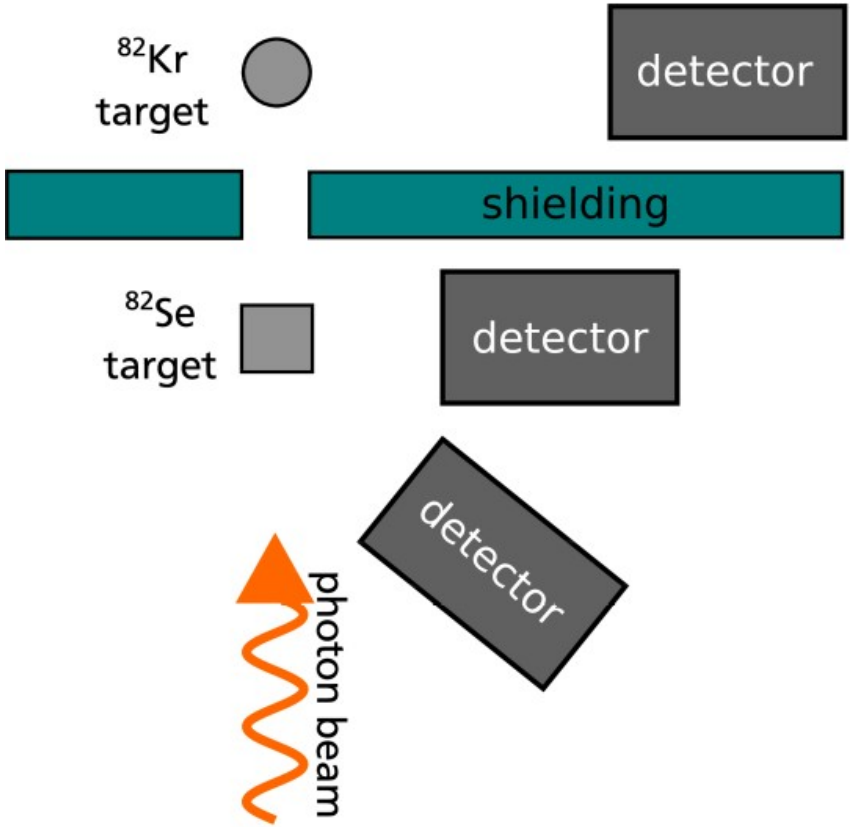
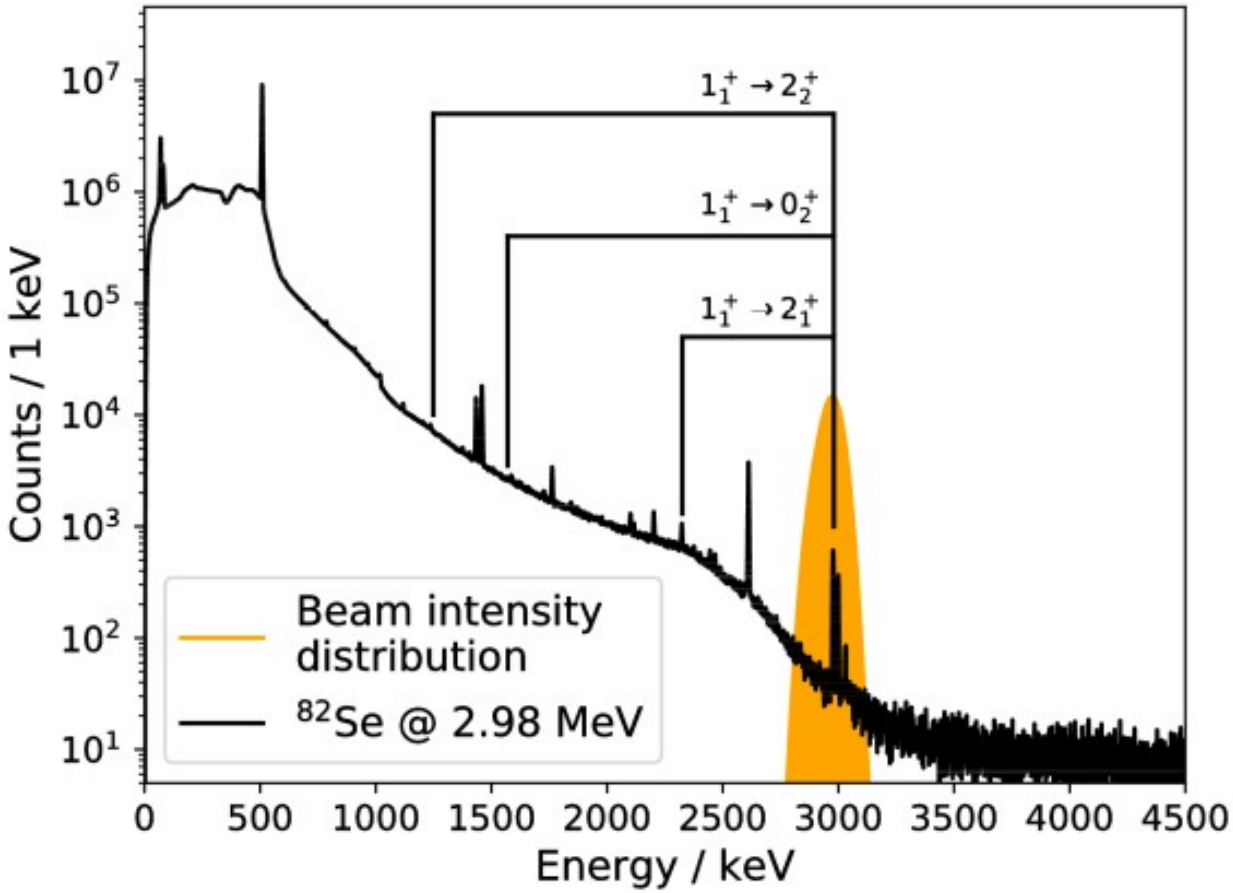
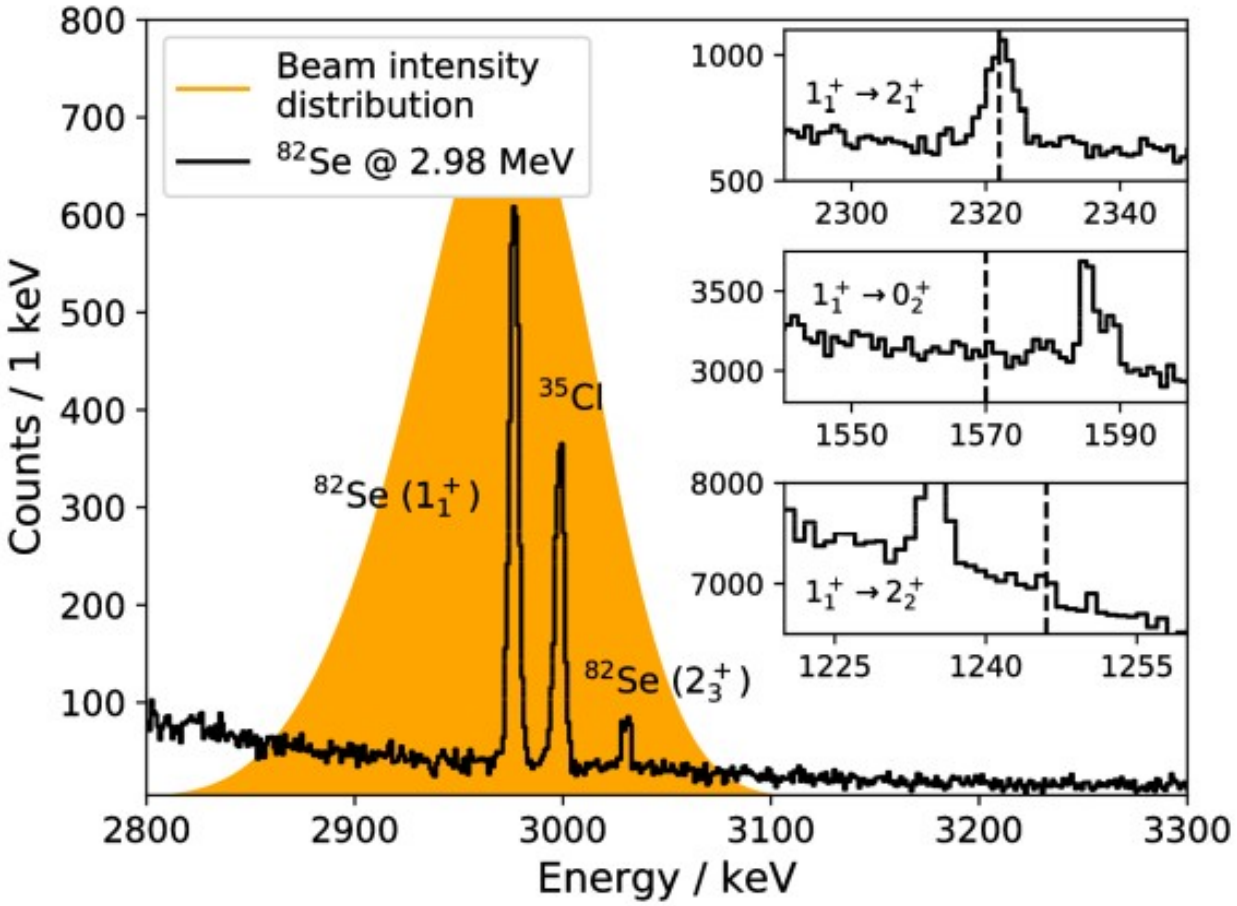




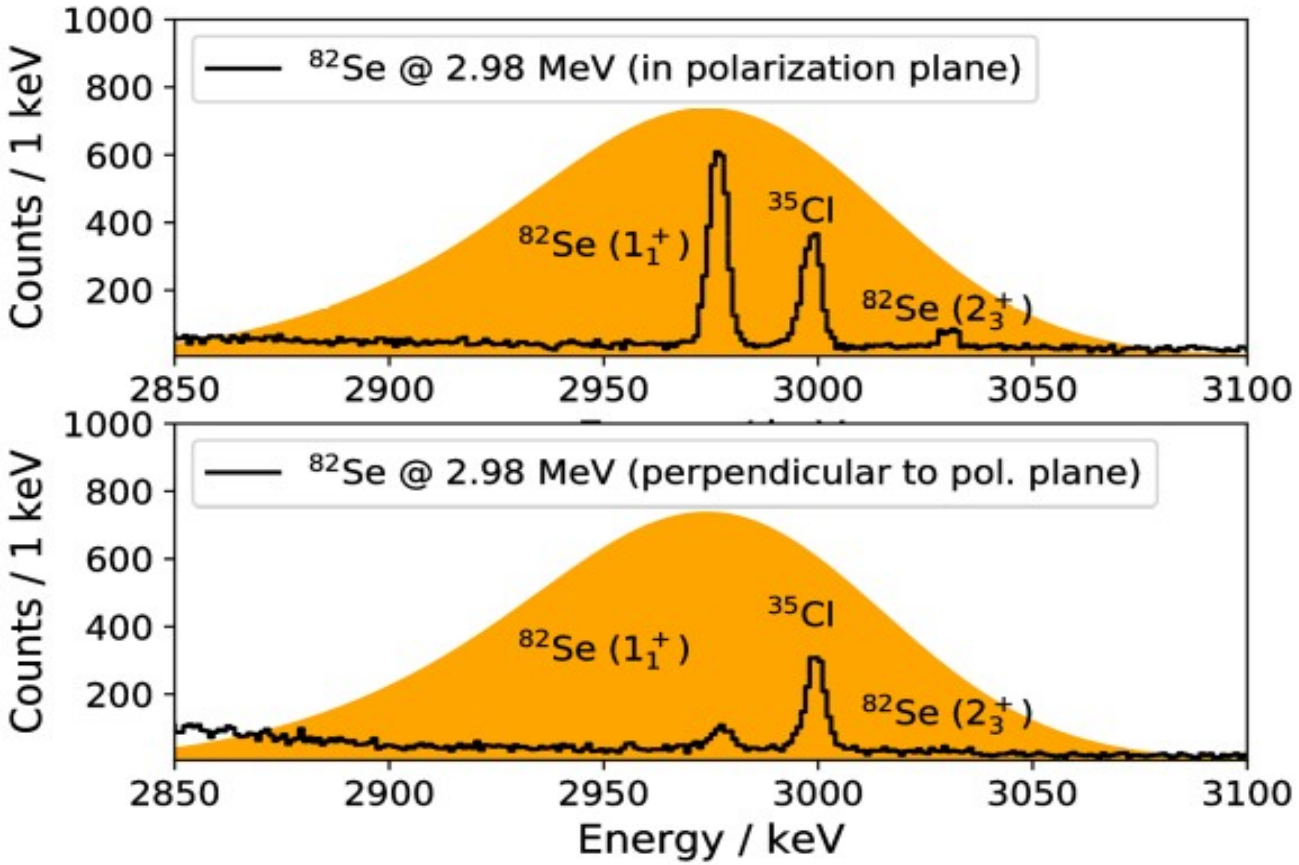
^{82}Se Experiment – Spectra



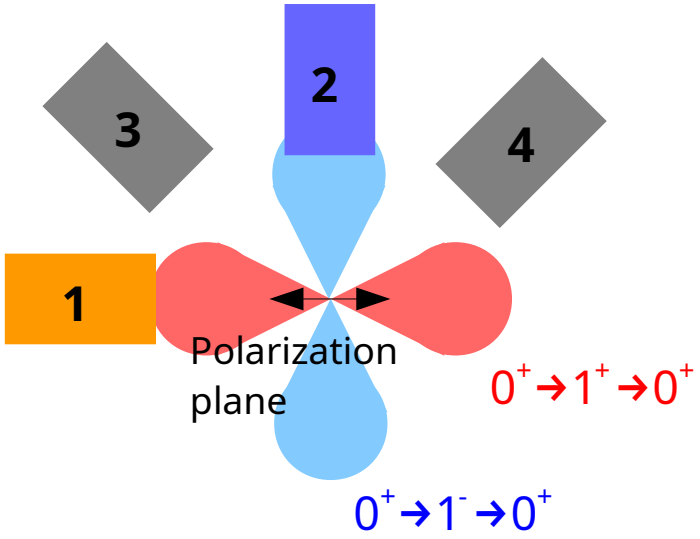
^{82}Se Experiment – Spectra



^{82}Se Experiment – Spectra

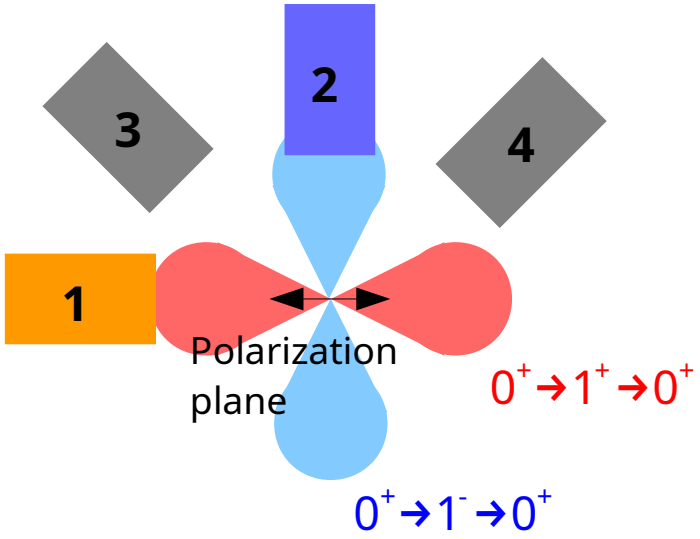


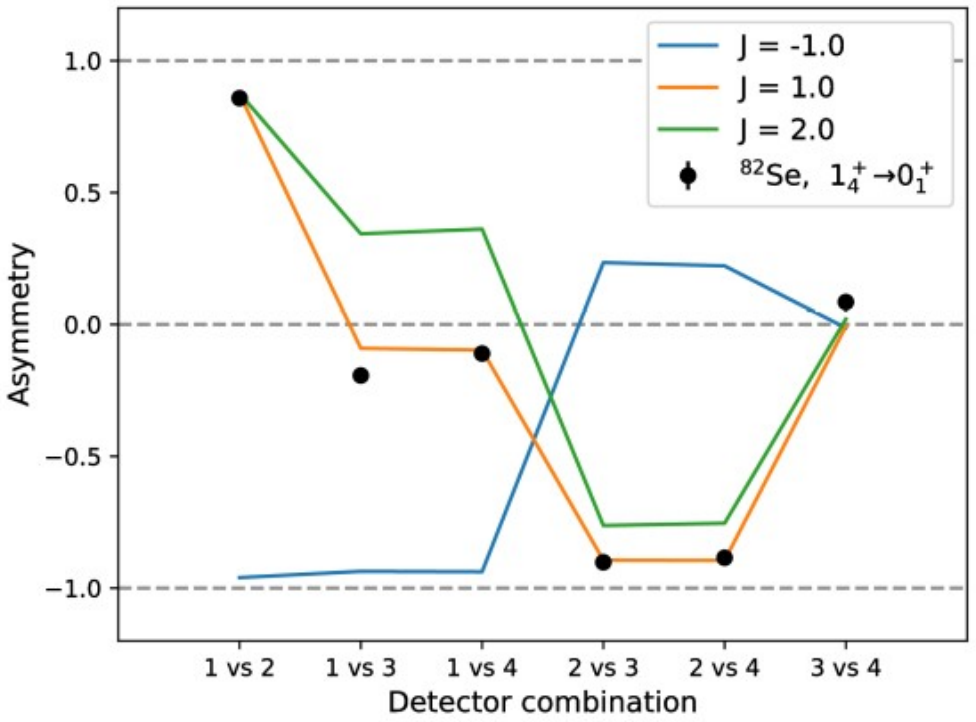
^{82}Se Experiment – Angular Distributions



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

^{82}Se Experiment – Angular Distributions



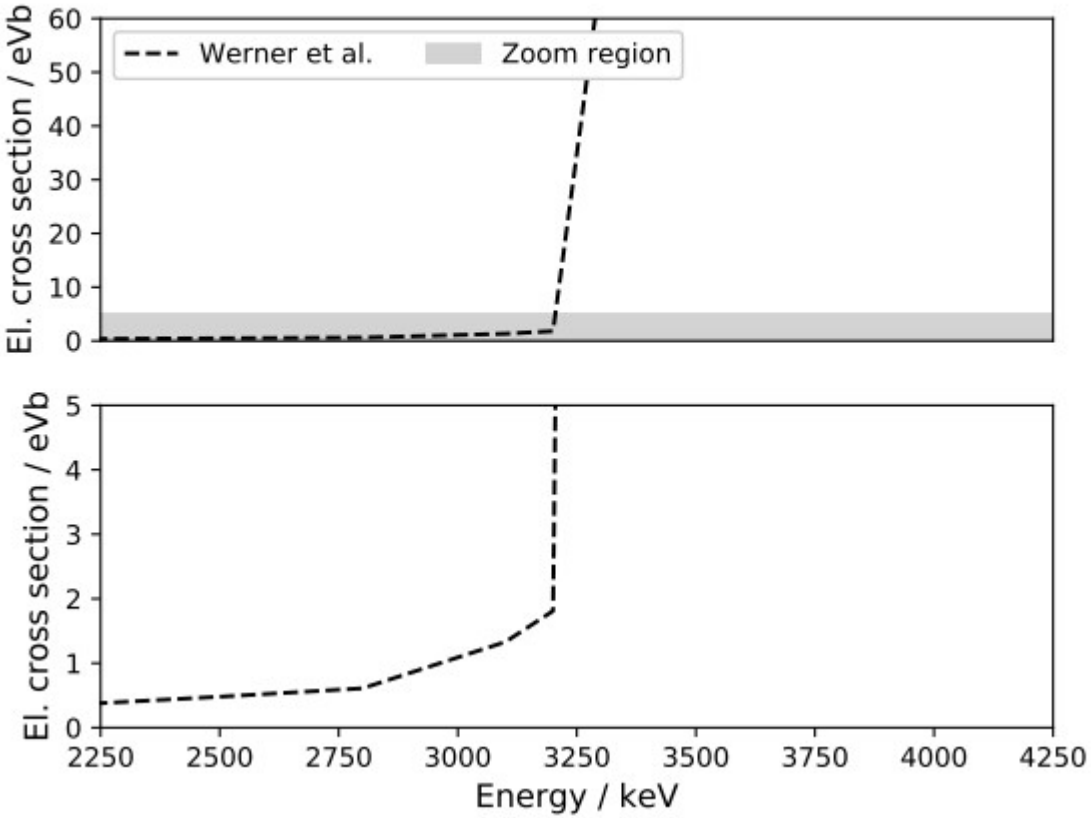


N. Pietralla et al., Phys. Rev. Lett. 88, 012502 (2001)

^{82}Se Experiment – Sensitivity

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Sensitivity to elastic transitions**



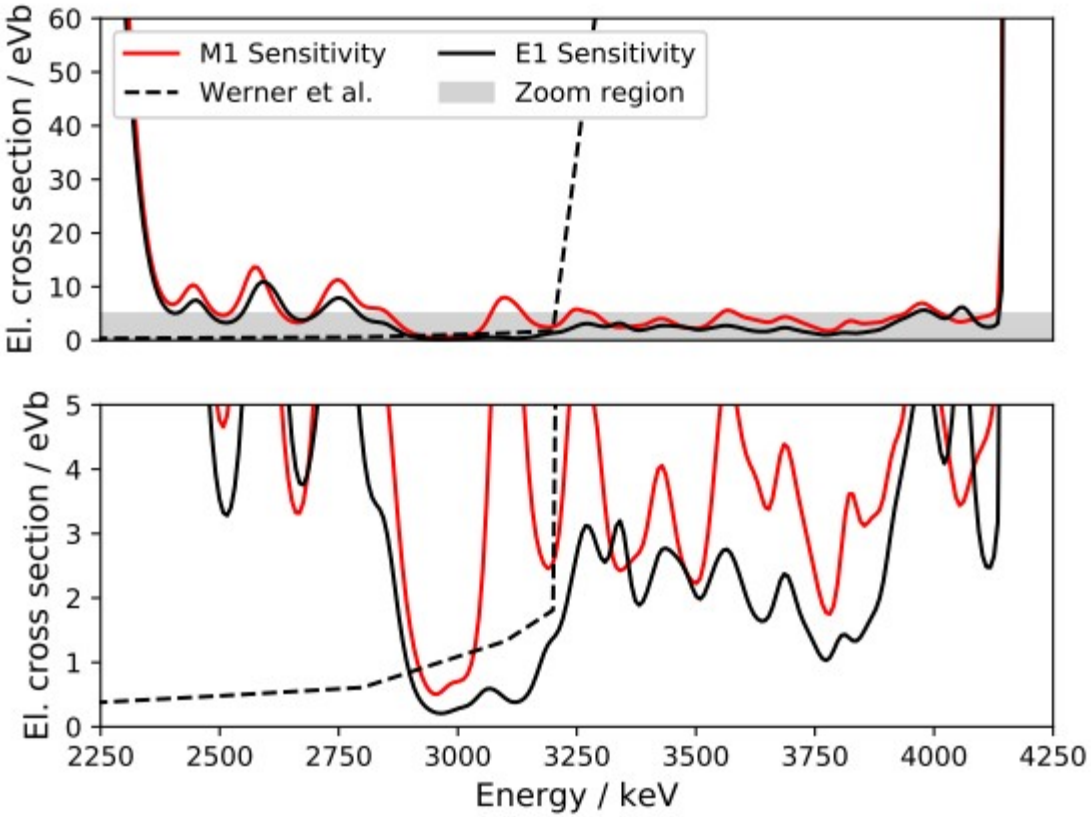
- Bremsstrahlung: ~36 h

  V. Werner, Diplomarbeit, Universität zu Köln (2002)

^{82}Se Experiment – Sensitivity

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Sensitivity to elastic transitions**



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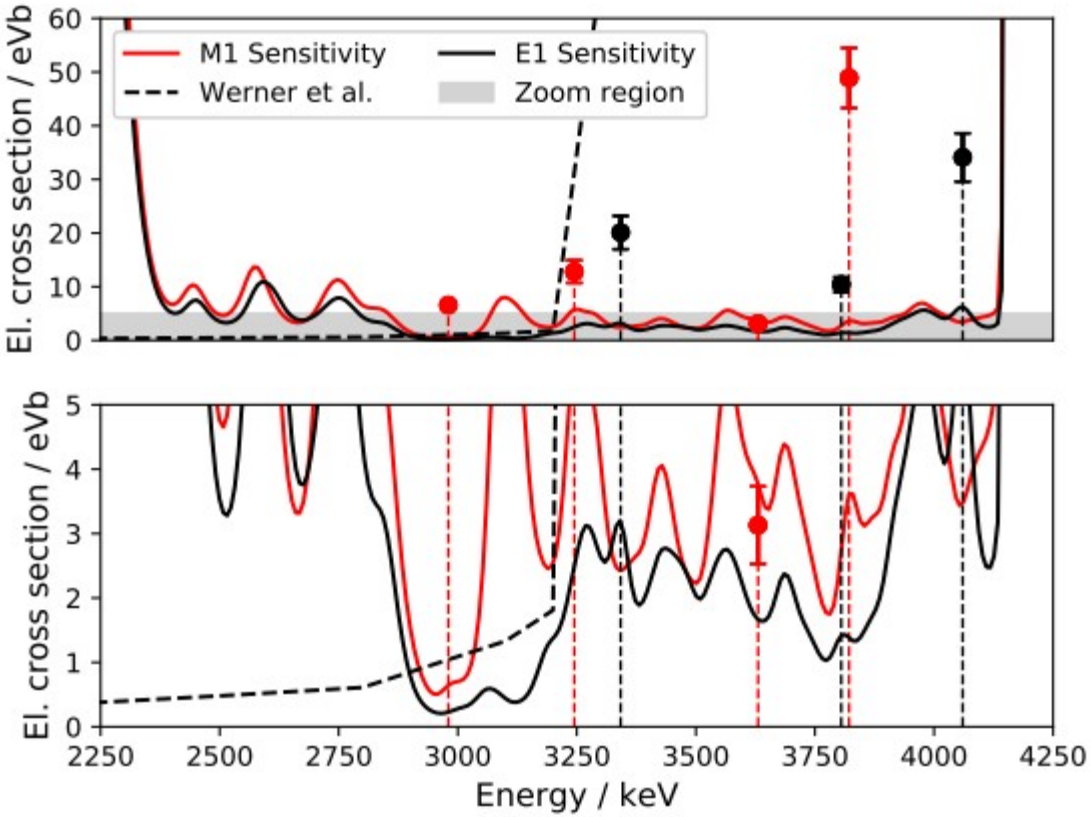
- LCB @ HIγS : ~76 h

^{82}Se Experiment – Sensitivity

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Sensitivity to elastic transitions**



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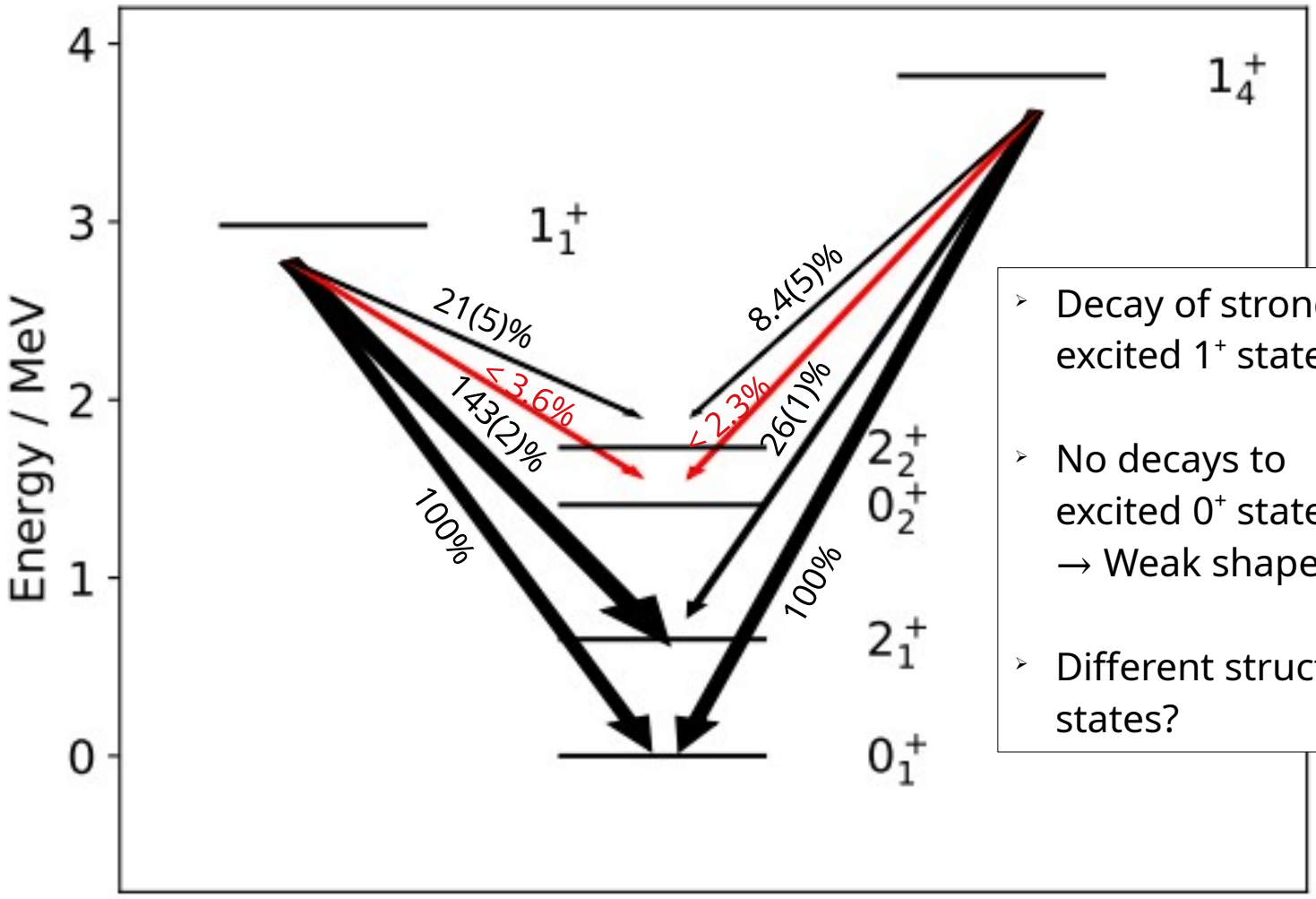
^{82}Se Experiment – Sensitivity



- Decay of strongly excited 1^+ states
- No decays to excited 0^+ state
  → Weak shape mixing?
- Different structure of 1^+ states?

^{82}Se - Discussion

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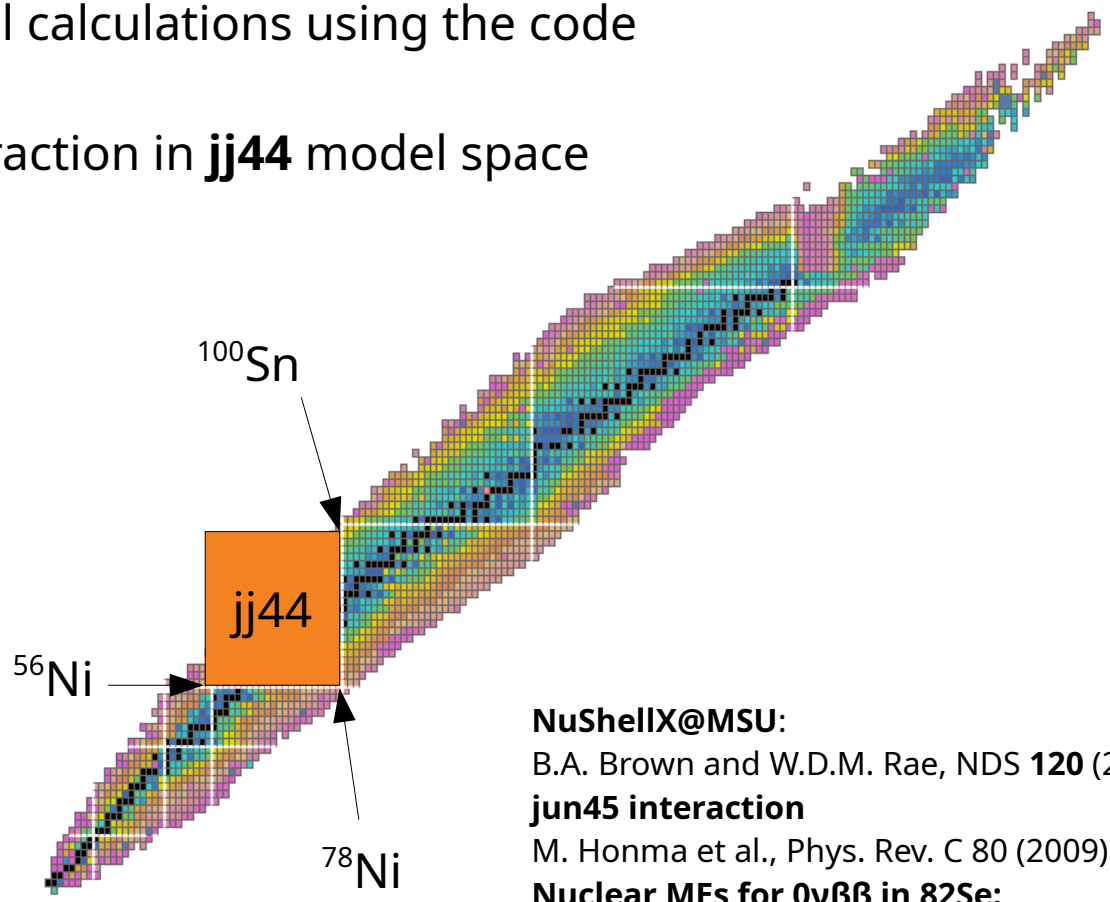
- Shell model calculations using the code **NuShellX**
- **jun45** interaction in **jj44** model space



NuShellX@MSU:
B.A. Brown and W.D.M. Rae, NDS **120** (2014) 115
jun45 interaction
M. Honma et al., Phys. Rev. C 80 (2009) 064323
Nuclear MEs for 0νββ in 82Se:
R.A. Senkov, M. Horoi, B.A. Brown, PRC 89 (2014) 054304

^{82}Se - Discussion

- Shell model calculations using the code **NuShellX**
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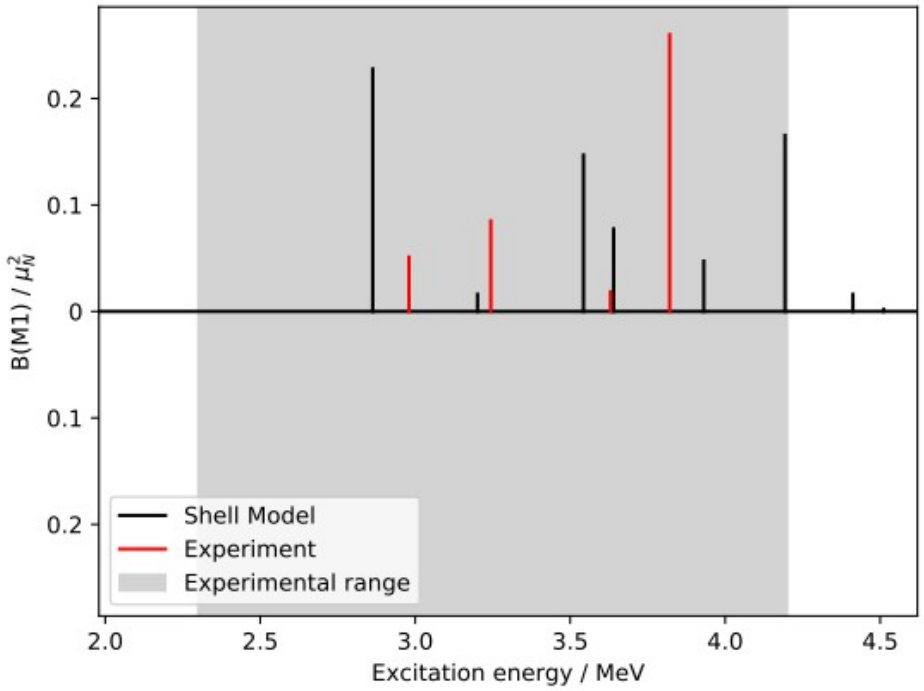

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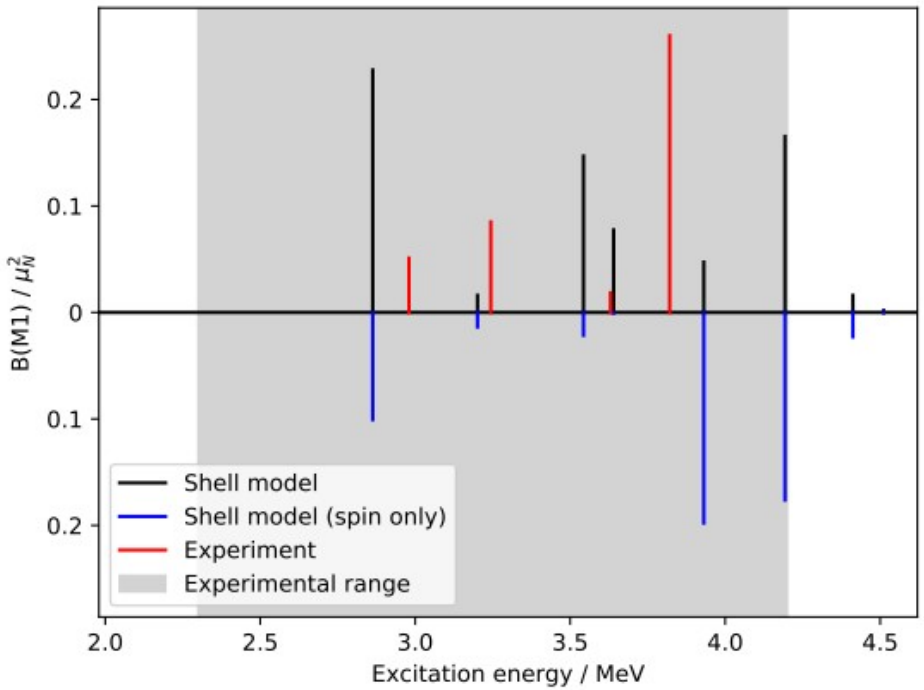
Nuclear MEs for 0νββ in 82Se:
R.A. Senkov, M. Horoi, B.A. Brown, PRC 89 (2014) 054304

^{82}Se – Spin vs. Orbital

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



$$\hat{O}(\mathrm{M1}) \sum_i g_l^{(i)} \hat{l}_i + g_s^{(i)} \hat{s}_i$$

NuShellX@MSU:
B.A. Brown and W.D.M. Rae, NDS **120** (2014) 115
jun45 interaction
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Nuclear MEs for 0νββ in 82Se:
R.A. Senkov, M. Horoi, B.A. Brown, PRC 89 (2014) 054304

150Nd – Spectra

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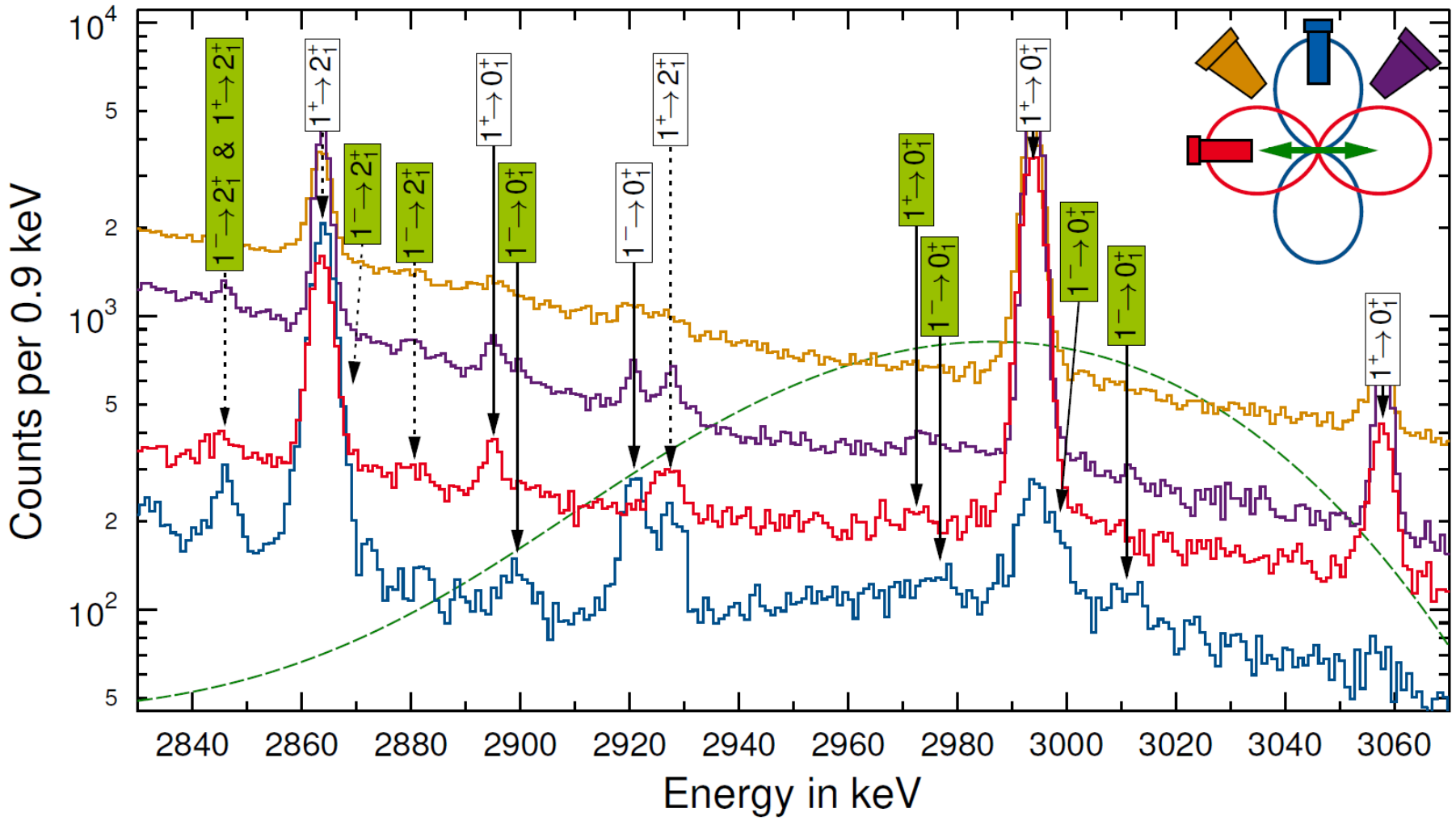
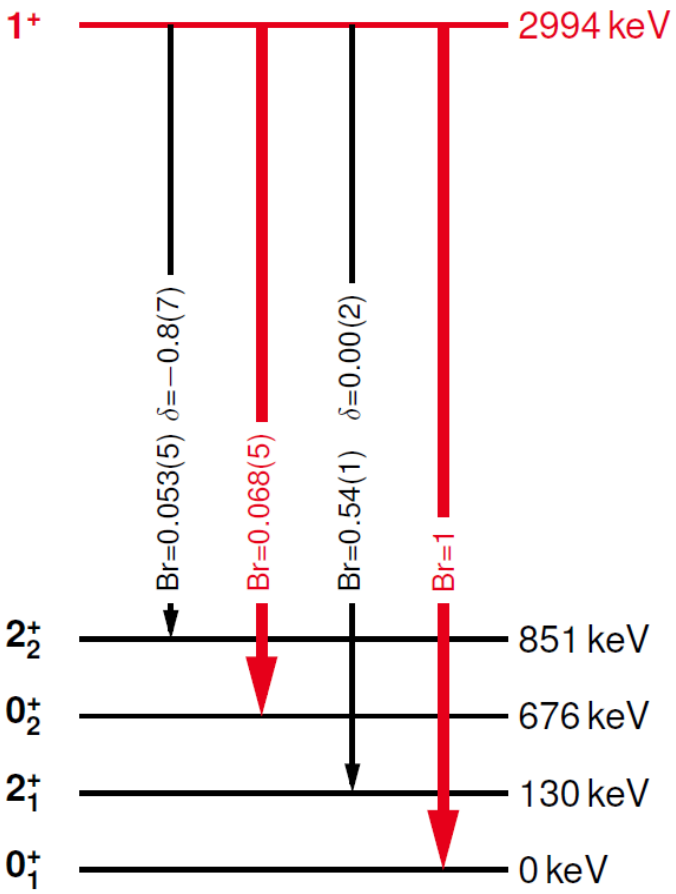
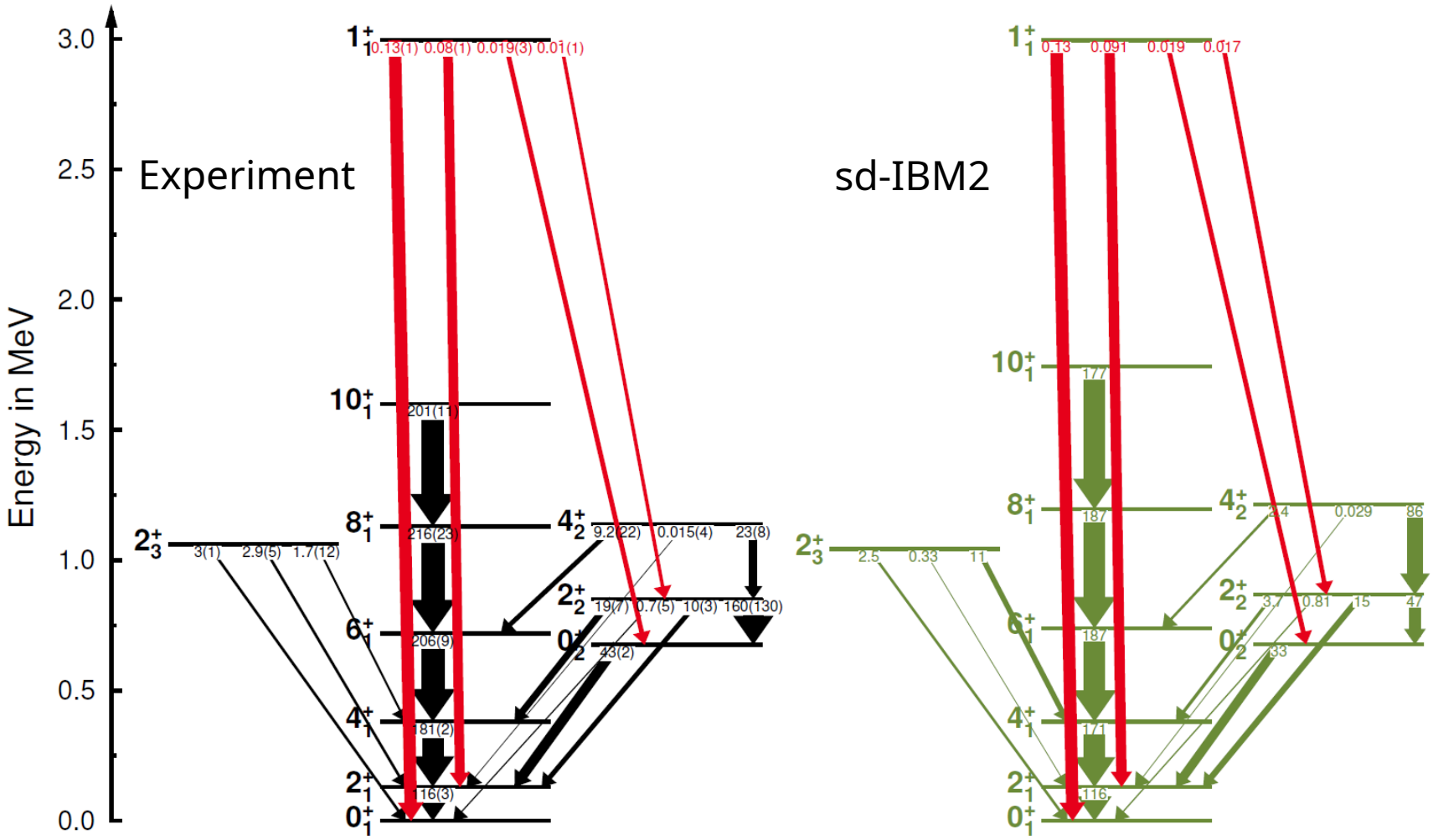


150Nd – Sensitivity

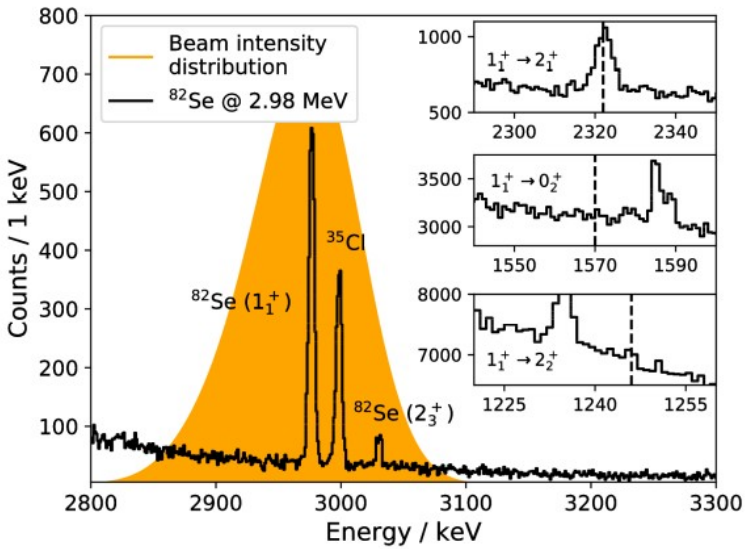


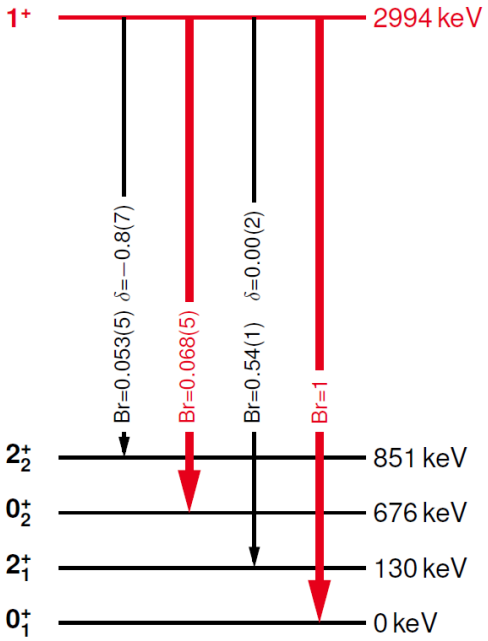
150Nd – Discussion



0νββ: Summary & Outlook

- High-precision data on decay of low-lying dipole strength in 0νββ candidates
- ^{76}Ge, ^{82}Se and ^{82}Kr, (^{100}Mo), ^{150}Nd and ^{150}Sm





- Interpretation of data and impact on 0νββ decay

Weakly interacting massive particles (WIMPs)

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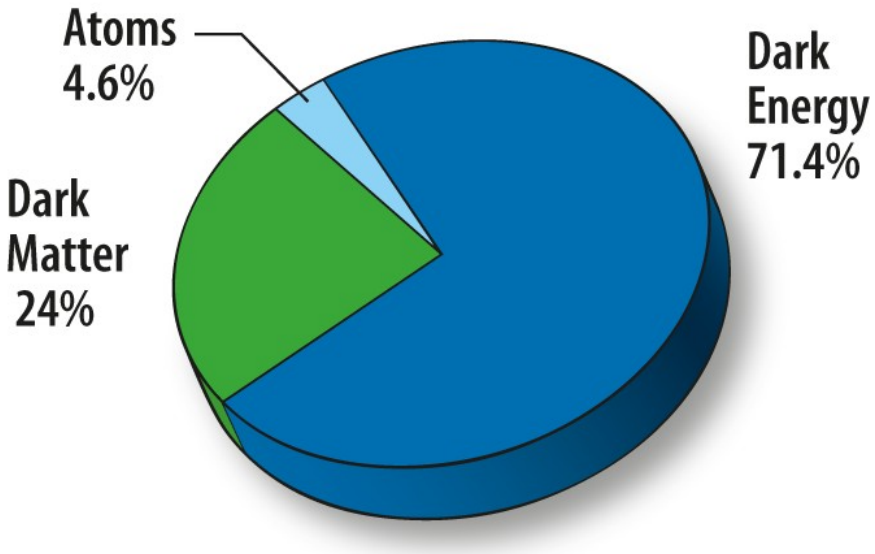
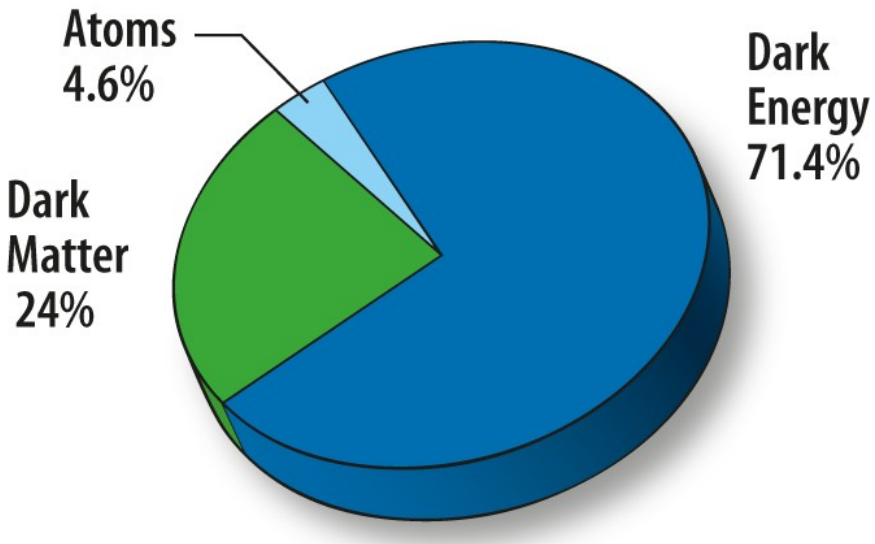
WIMPs



https://wmap.gsfc.nasa.gov/universe/uni_matter.html

WIMPs as candidates
for dark matter

WIMPs



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WIMPs as candidates
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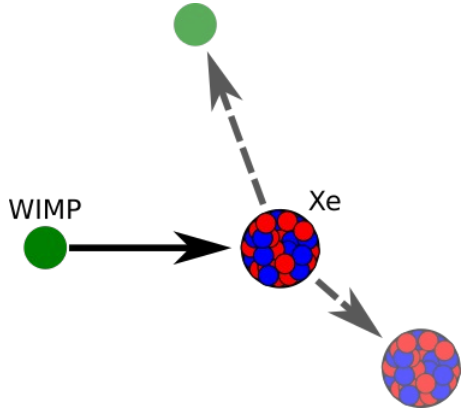
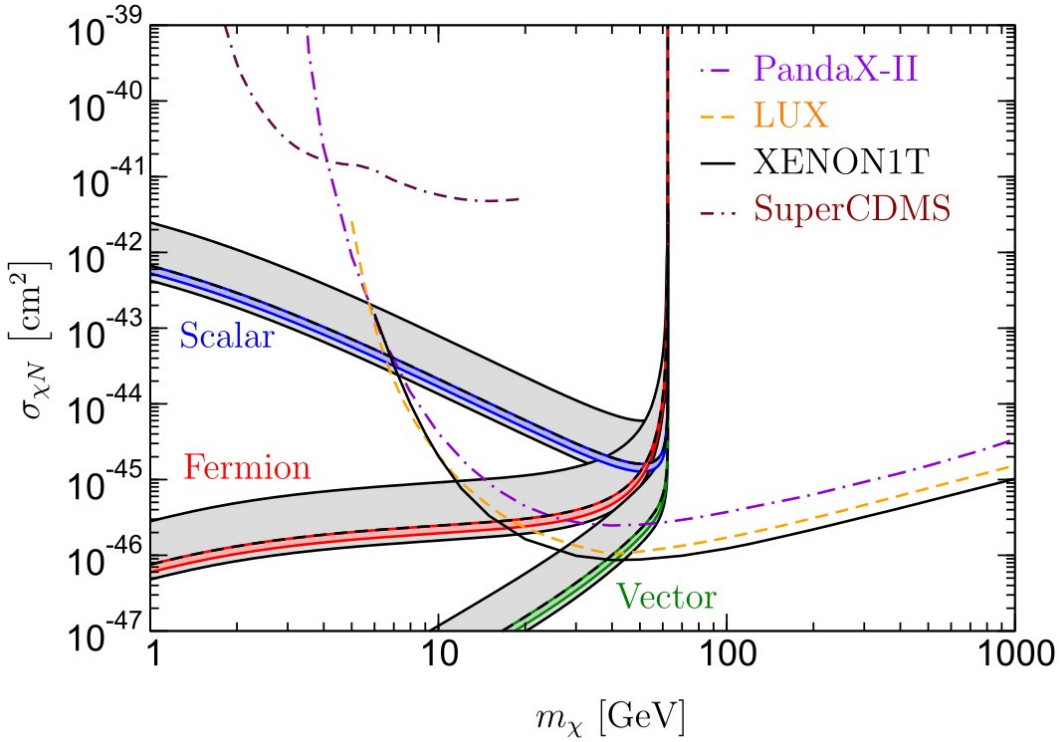


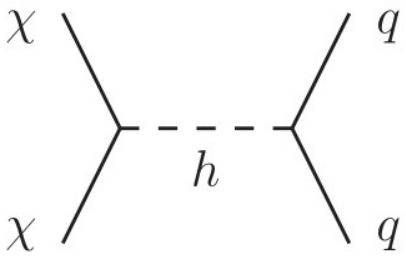
CDMS (Ge): R. Agnese et al., Phys. Rev. Lett. **116** (2016) 071301
PandaX-II (Xe): A. Tan et al., Phys. Rev. Lett. **117** (2016) 121303
LUX (Xe): D. S. Akerib et al., Phys. Rev. Lett. **118** (2017) 021303
XENON1T (Xe): E. Aprile et al., Phys. Rev. Lett. **119** (2017) 181301

Detection by
(in)elastic scattering
on atomic nuclei

WIMPs and Nuclear Structure



M. Hoferichter et al., Phys. Rev. Lett. **119** (2017) 181803



CDMS (Ge): R. Agnese et al., Phys. Rev. Lett. **116** (2016) 071301
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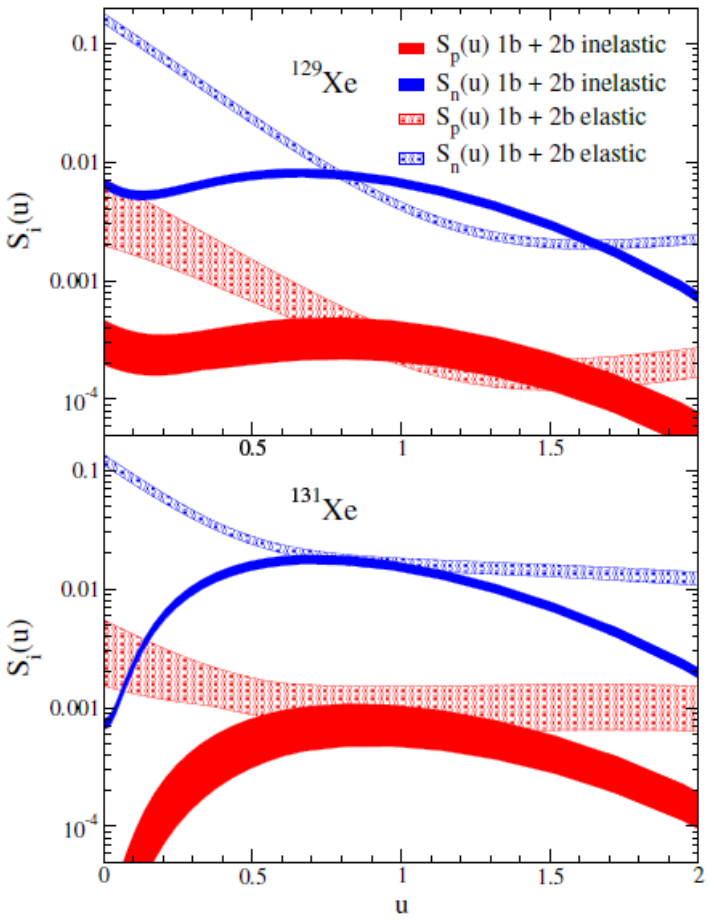
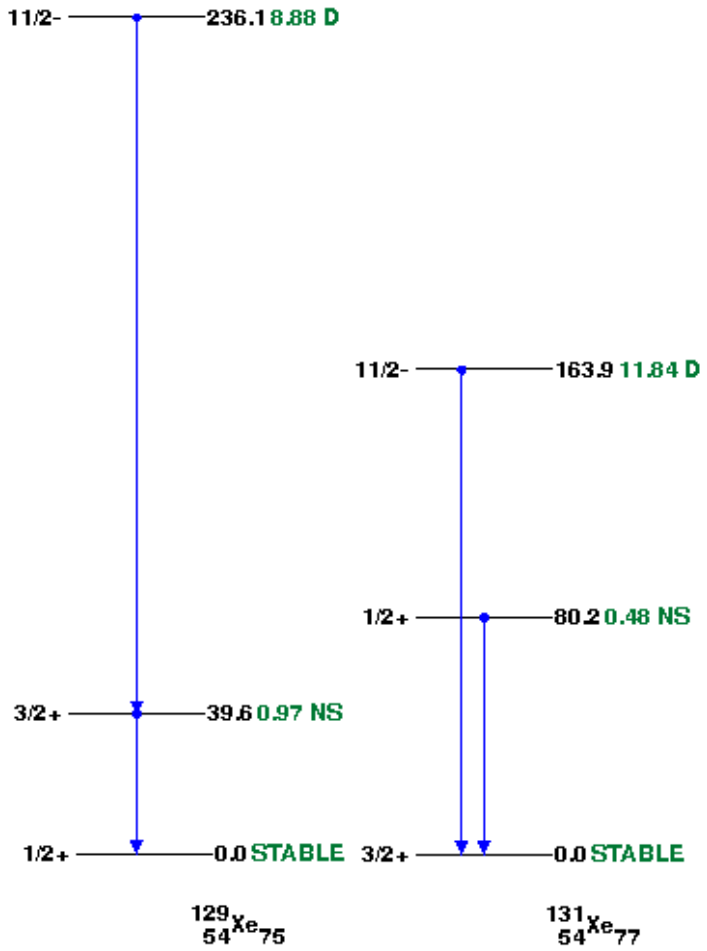
WIMPs and Nuclear Structure



L. Baudis et al., Phys. Rev. D **88** (2013) 115014



http://www.nndc.bnl.gov

Experimental Program for WIMPs

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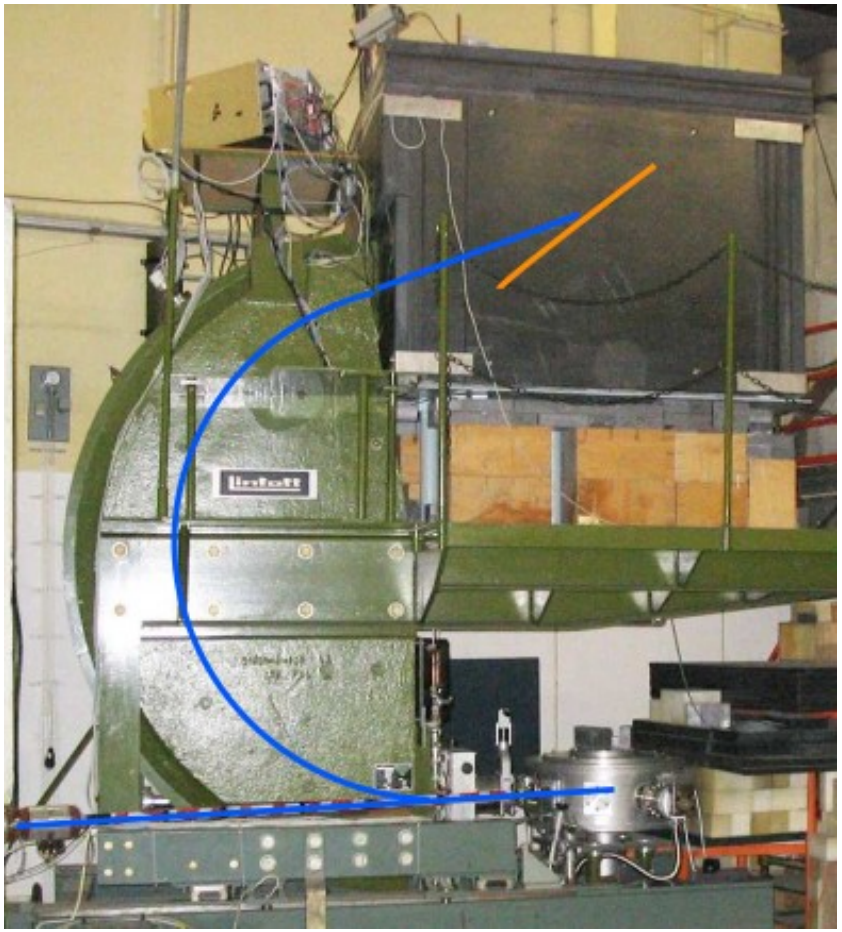
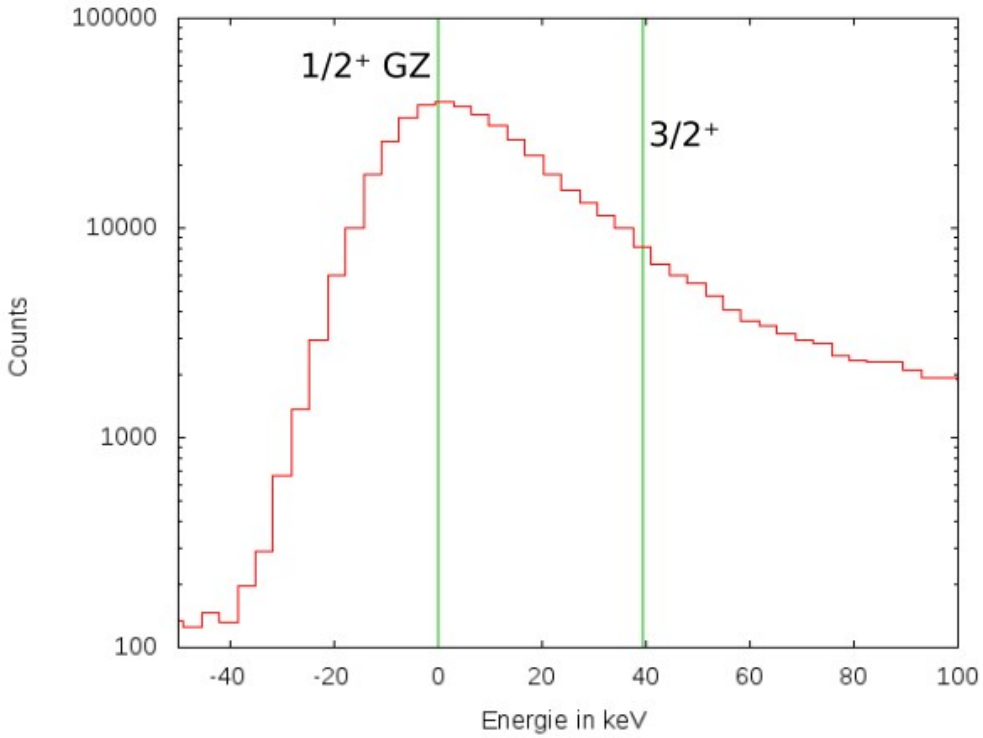
LINTOTT electron spectrometer @ IKP, TU Darmstadt

Measure electron scattering form factors of ground – and excited states with high energy resolution

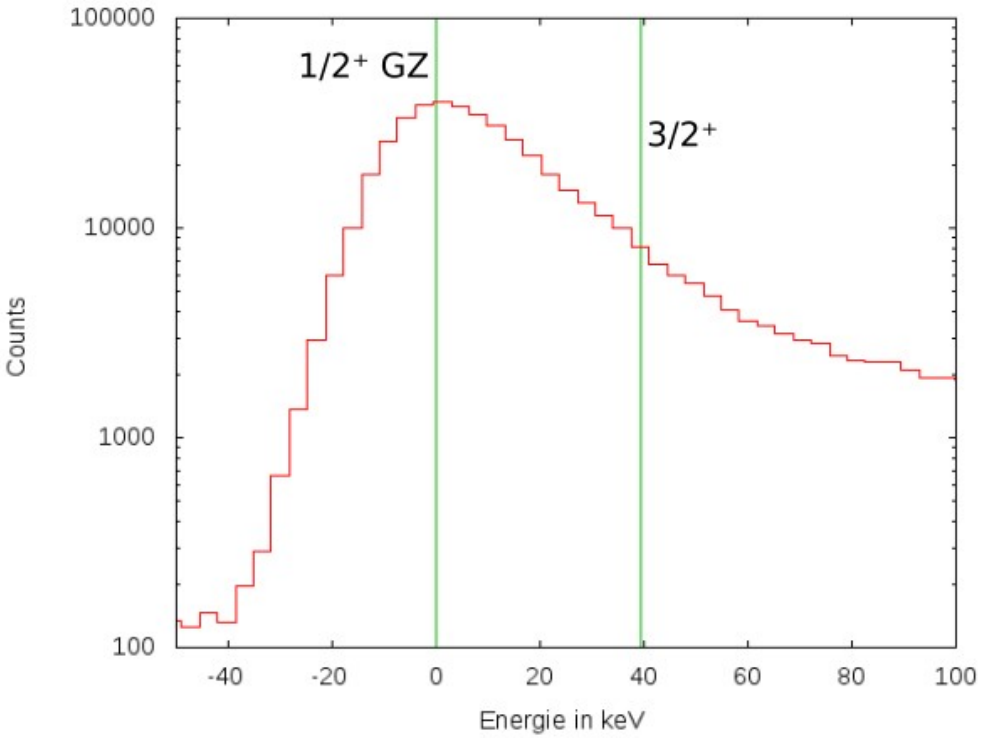


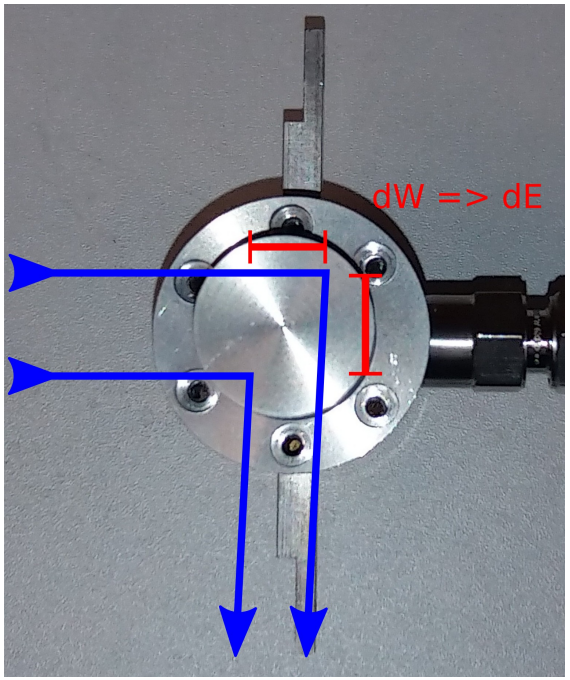
^{129}Xe Test Experiment



Test measurement at momentum transfer q = 0.32 fm^{-1} (93°, 43.5 MeV)

^{129}Xe Test Experiment





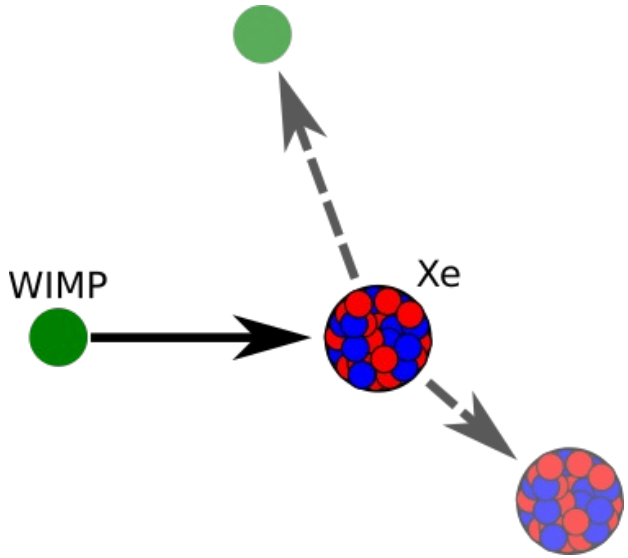
Test measurement at momentum transfer q = 0.32 fm^{-1} (93°, 43.5 MeV)

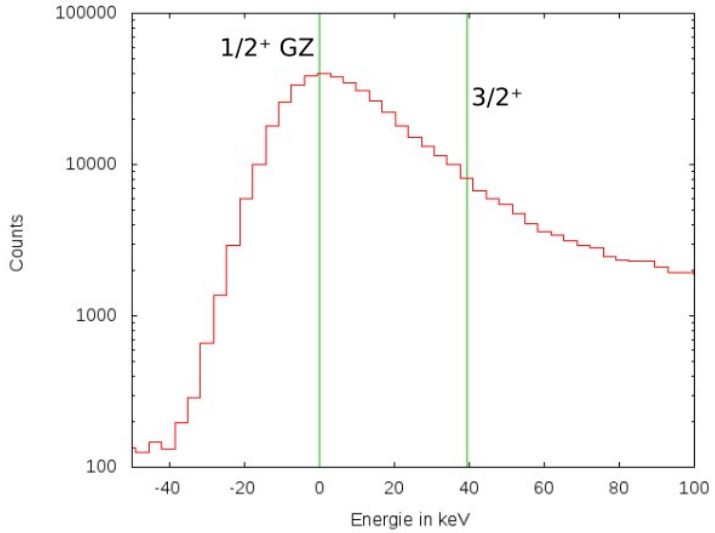
Energy resolution limited by size of Xenon target

WIMPs: Summary & Outlook

TECHNISCHE UNIVERSITÄT DARMSTADT

- First test experiment @ LINTOTT with ^{129}Xe target not successful





- Improve geometry of gas target
  OR
- Use Xe in solid chemical compound

- Measurement at different momentum transfers

HIyS and S-DALINAC experiments elucidating weak processes

Joachim Enders, **Volker Werner**, Udo Gayer, Philipp C. Ries

TECHNISCHE UNIVERSITÄT DARMSTADT

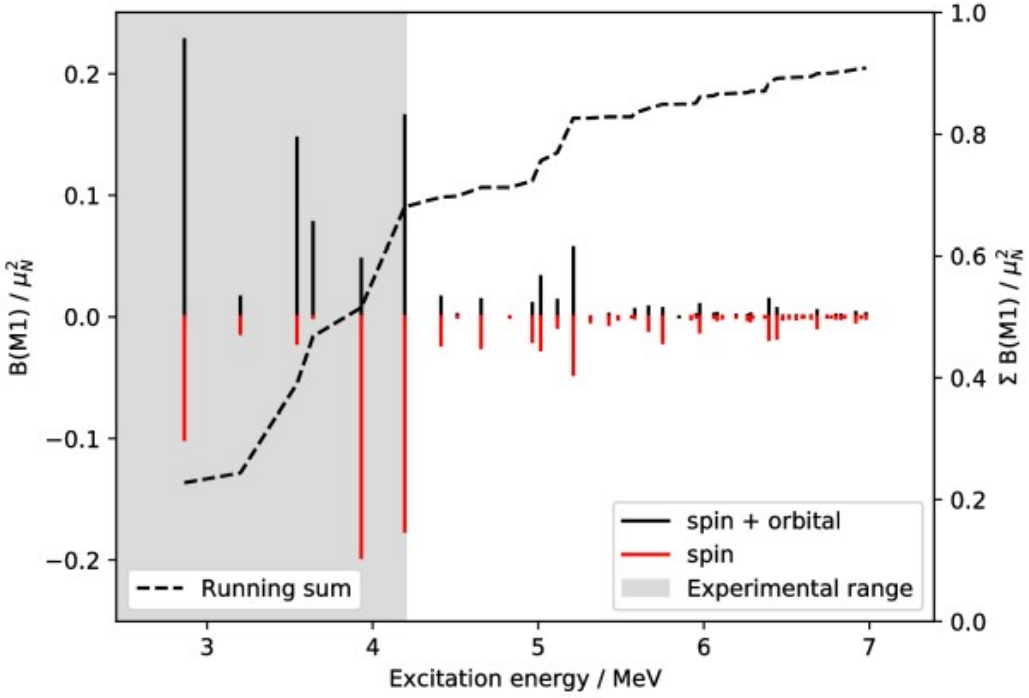
Supported by the
Deutsche Forschungsgemeinschaft
(German Research Foundation)
through
research grant **SFB 1245**

DFG
Deutsche Forschungsgemeinschaft

Backup

^{82}Se - Discussion

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



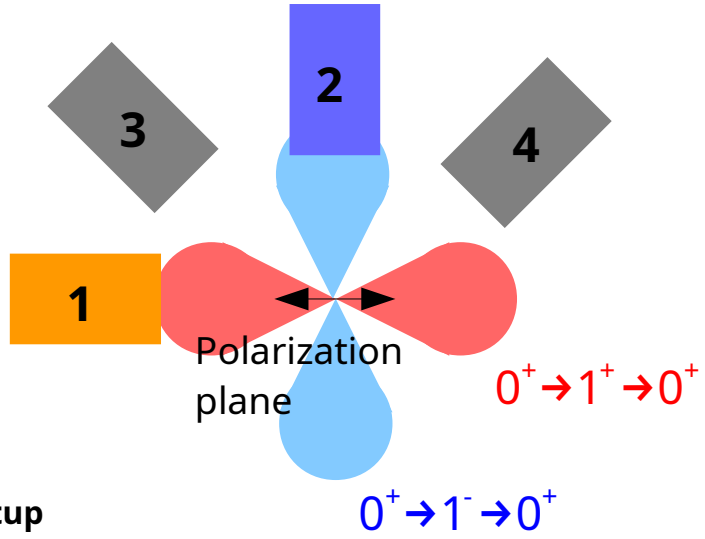
Orbital
„Scissors mode“

$$\hat{O}(\mathrm{M1}) \sum_i g_l^{(i)} \hat{l}_i + g_s^{(i)} \hat{s}_i$$

„Spin-flip“

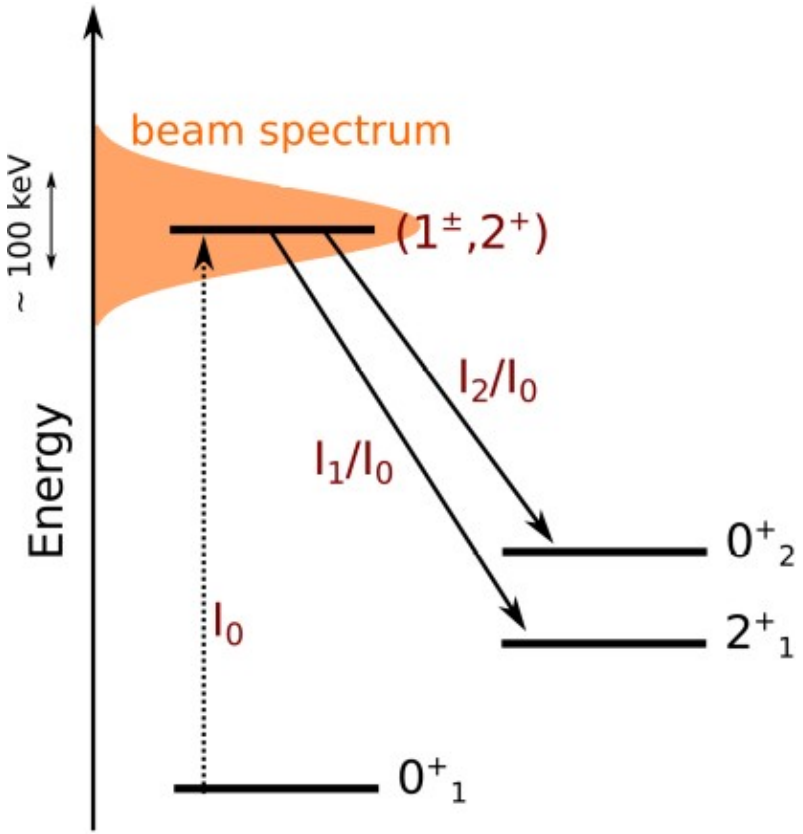
NuShellX@MSU:
B.A. Brown and W.D.M. Rae, NDS **120** (2014) 115
jun45 interaction
M. Honma et al., Phys. Rev. C 80 (2009) 064323
Nuclear MEs for 0νββ in 82Se:
R.A. Senkov, M. Horoi, B.A. Brown, PRC 89 (2014) 054304

Parity determination I

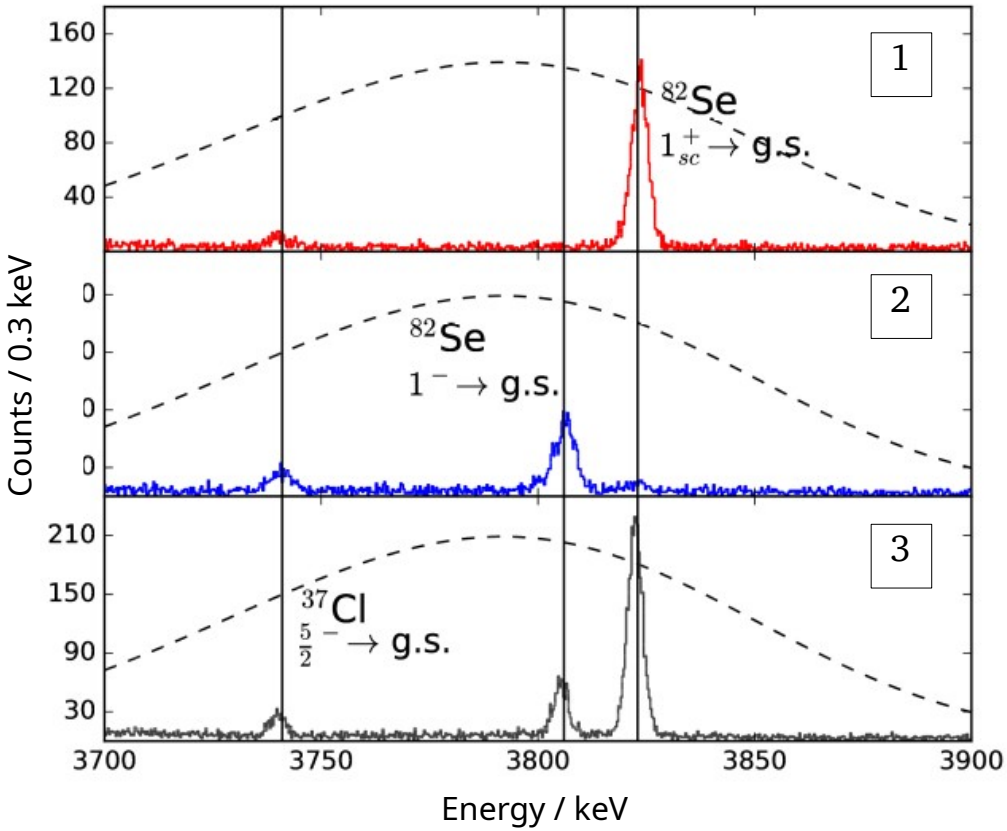


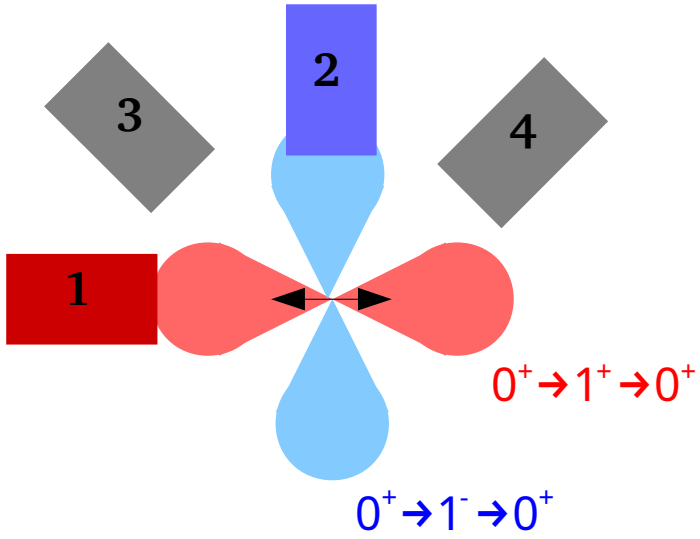
γ³ Setup
B. Löher et al., Nucl. Inst. Meth. A 723 (2013) 136-142

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

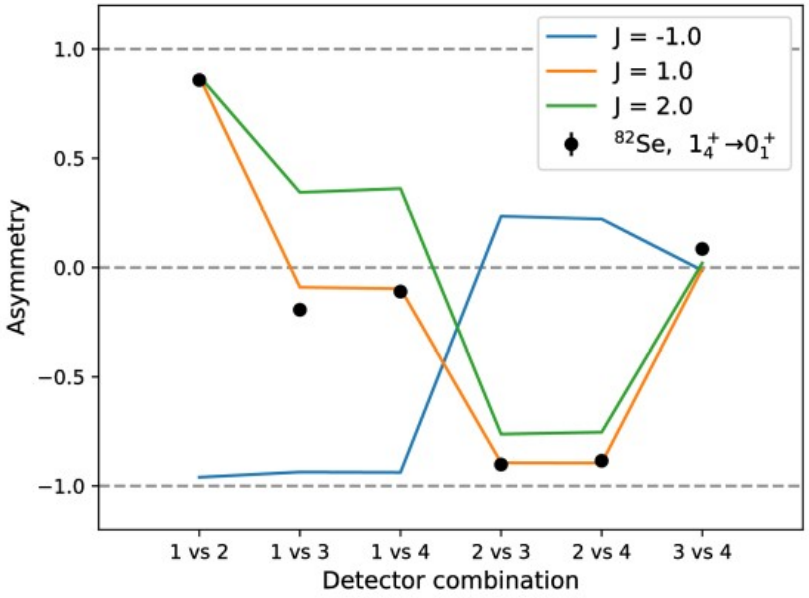


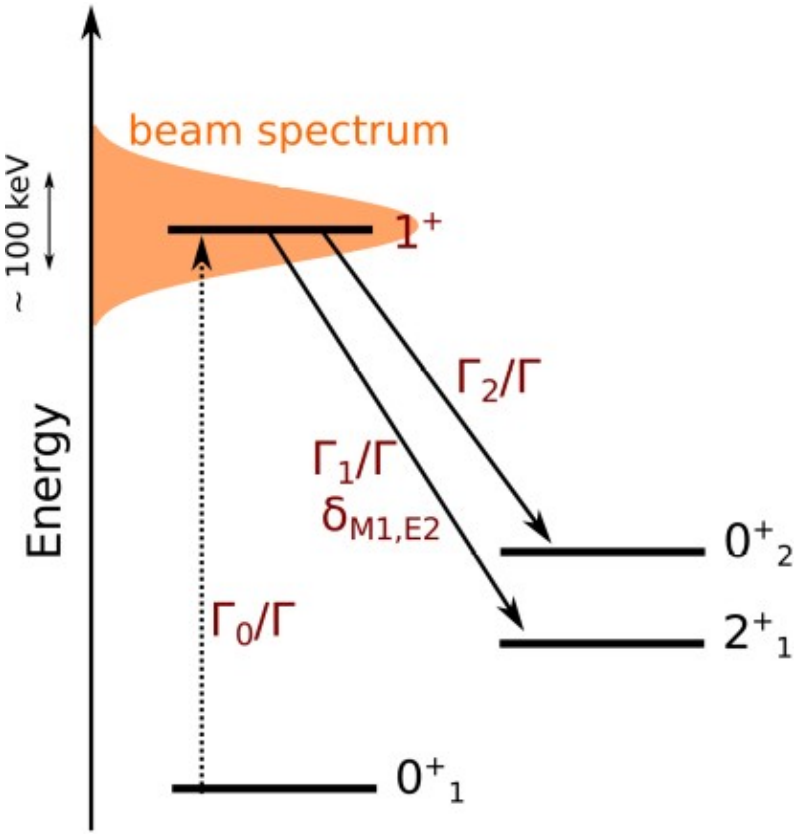
Parity determination II



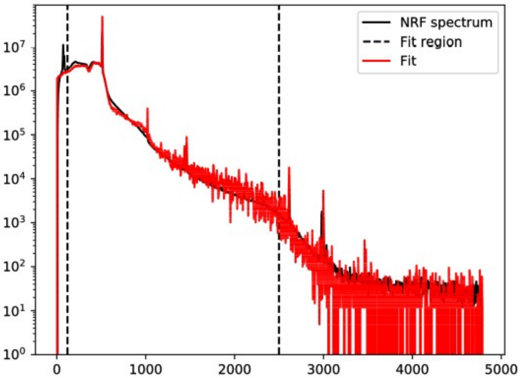


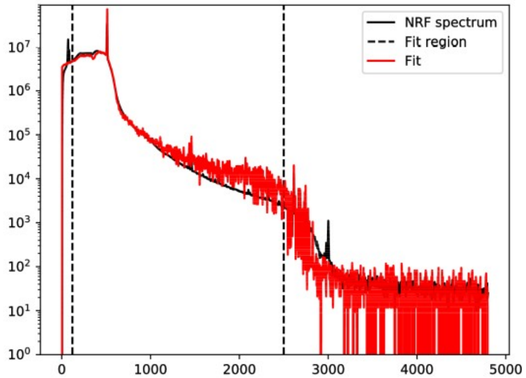
Spin determination

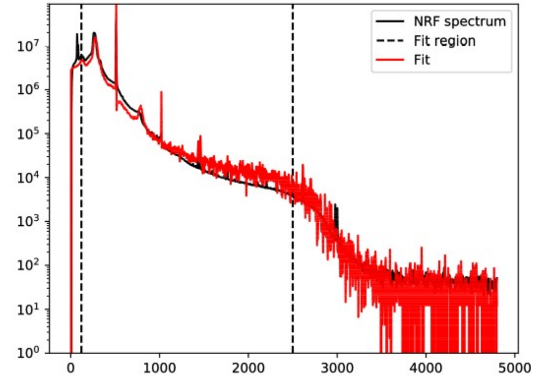


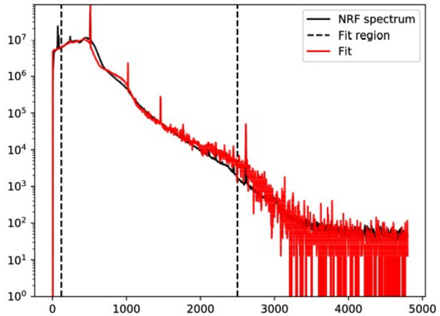


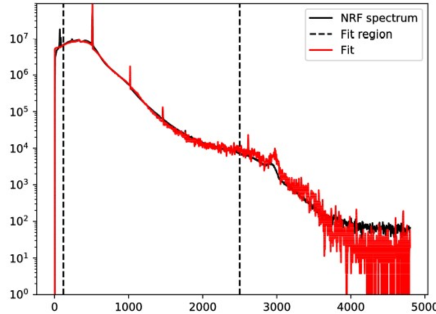
Background simulation

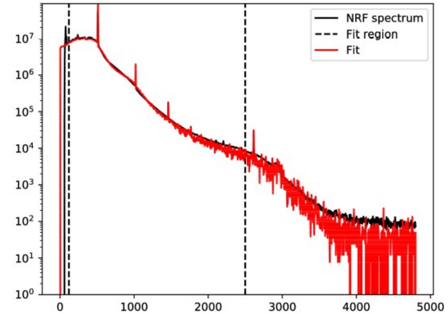


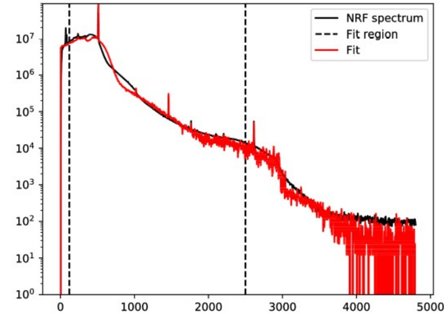




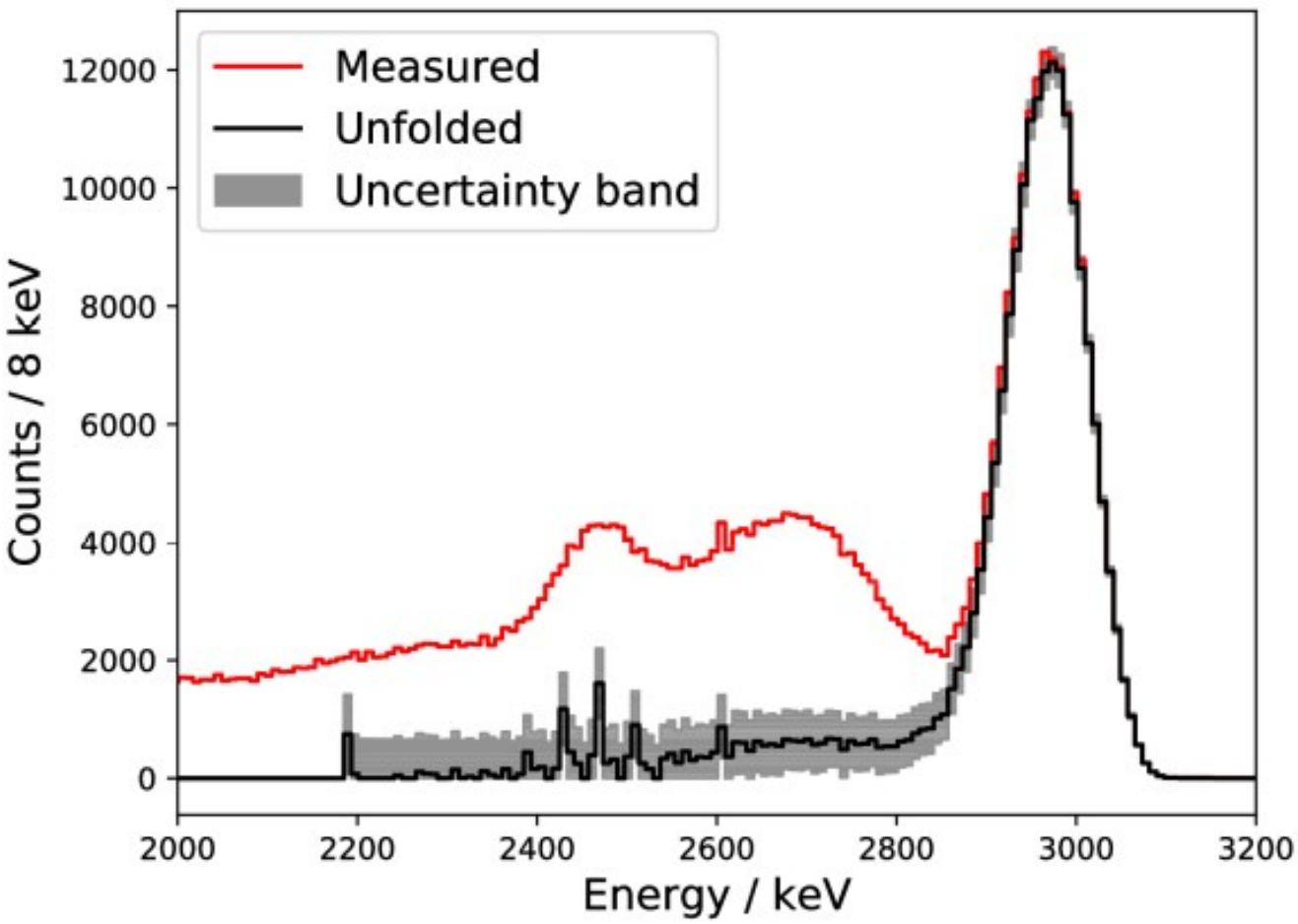








Beam spectrum



^{82}Kr + ^{82}Se Experiment – Experiment

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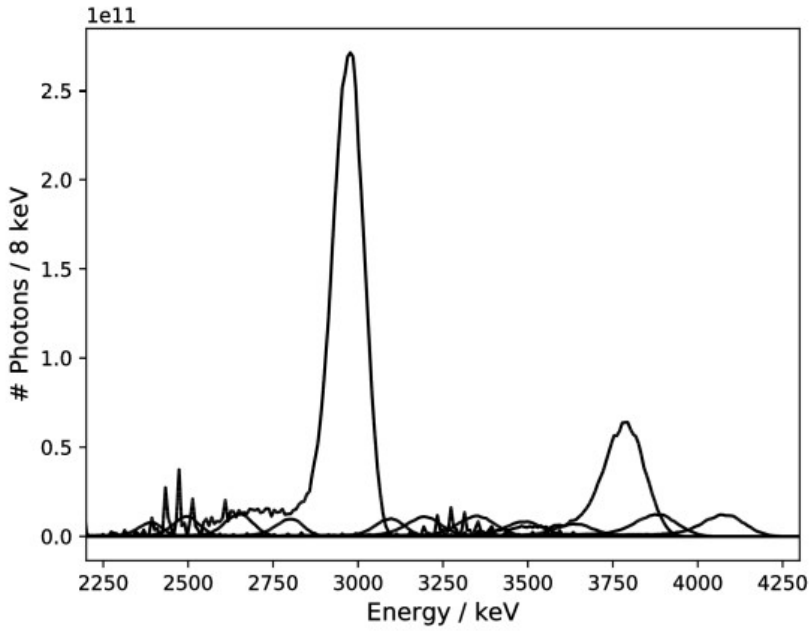
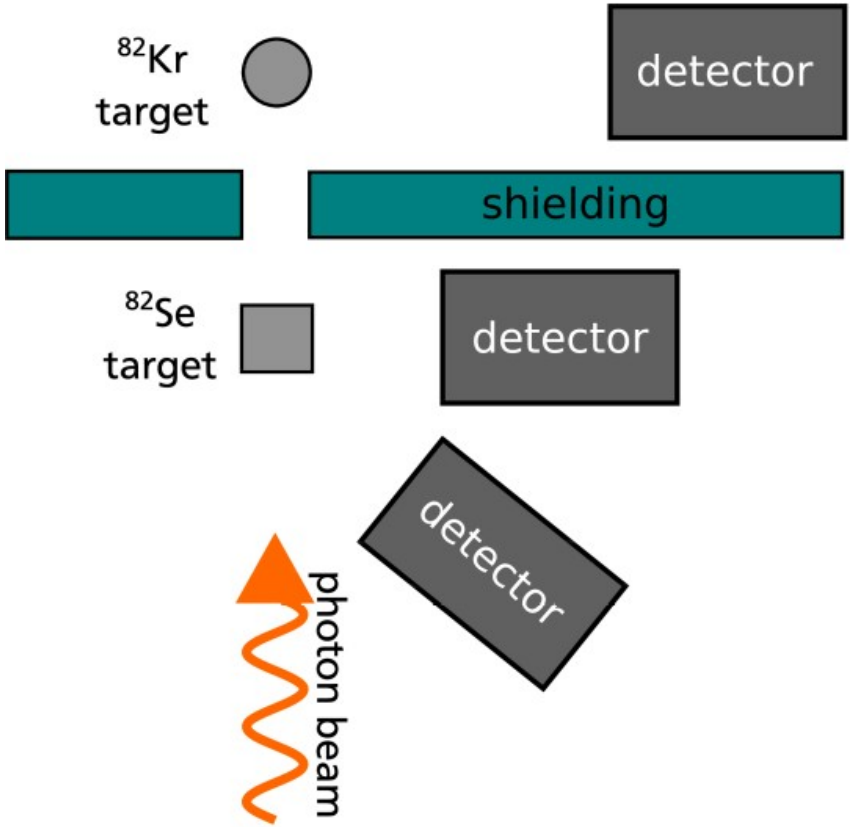
- 13 beam energy settings between 2.4 and 4.1 MeV





Krypton gas target

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^{154}Gd - ^{154}Sm

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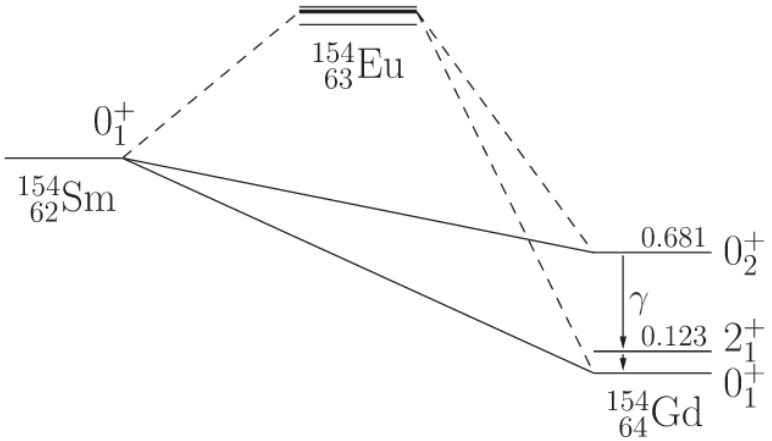
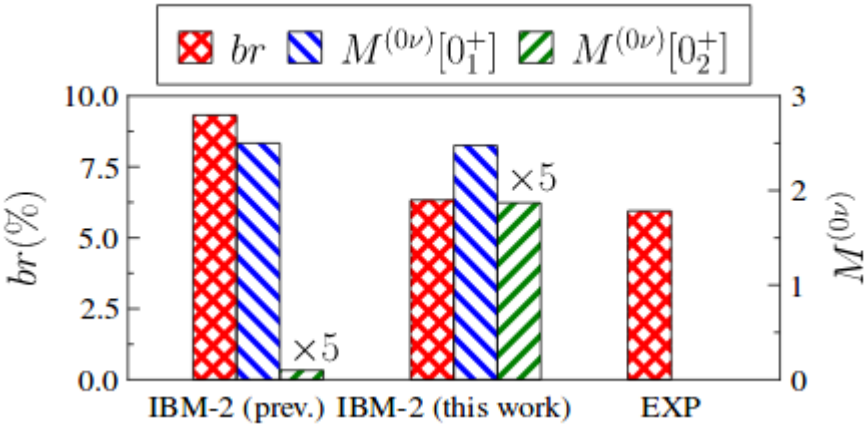
- J. Beller et al., Phy. Rev. Lett. **111** (2013) 172501
  - High-precision measurement of decay channels of the scissors mode
  - Sensitivity to proton-neutron interaction, nuclear shape
  - Improved predictions of 0νββ decay rates using new data





Motivation

Nuclear structure impact on 0νββ decay rates

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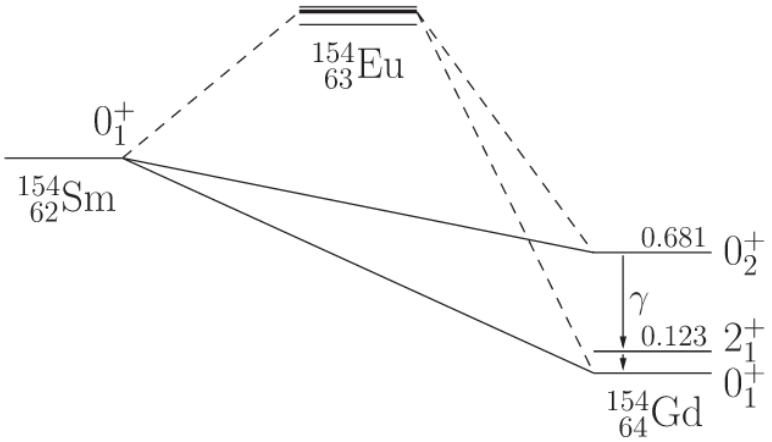

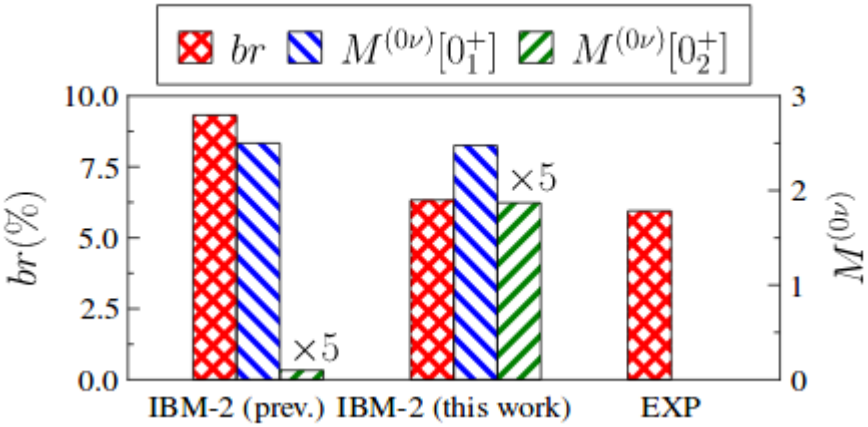

^{150}Nd results and IBM calculation

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