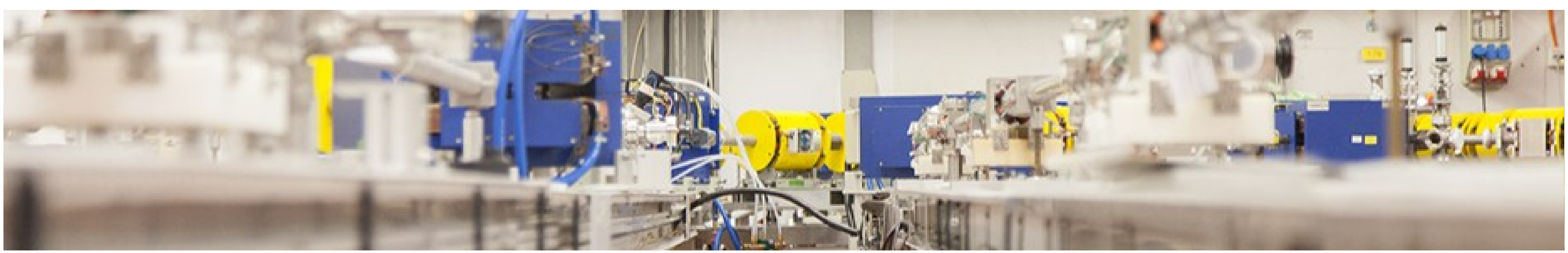
Shape Mixing in $0\nu\beta\beta$ Candidates

Volker Werner

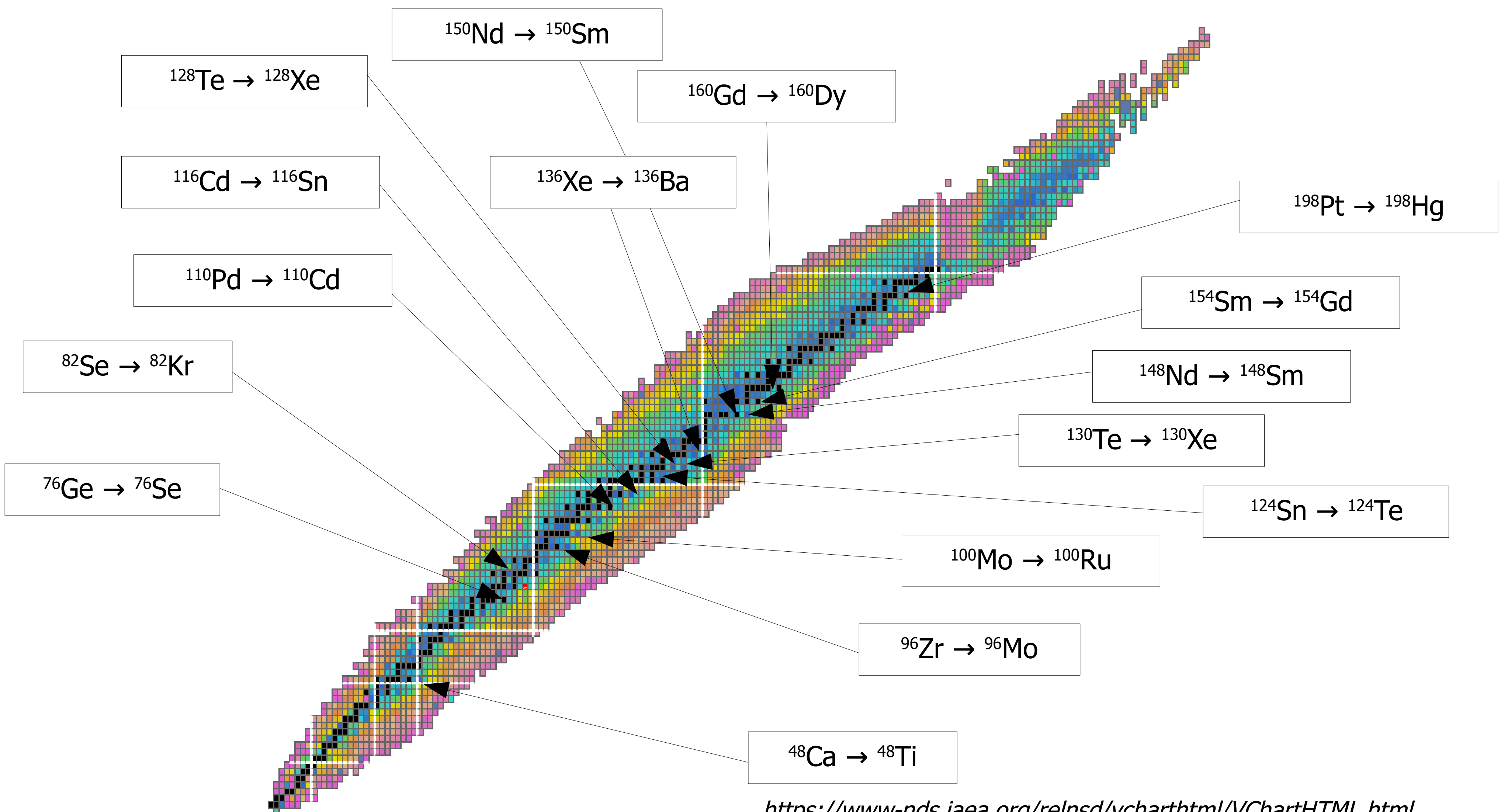
Institut für Kernphysik, TU Darmstadt



Outline

- The scissors mode and $0\nu\beta\beta$
  - Test of wave functions: shape coexistence / mixing
  - Isovector → complementary information
  - Decay behavior of the scissors mode
  - Photon-scattering experiments
  - First results
- Outlook
  - Next step: E0 measurements
  - WIMP – nucleus scattering
    - First electron-scattering experiments prepared
  - Survey of M1 response for ν-nucleus scattering

Location of 0νββ Candidates



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

Set of Nuclei from: J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 87 (2013) 014315

Location of 0νββ Candidates

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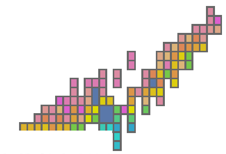
^{150}Nd → ^{150}Sm

^{128}Te → ^{128}Xe

^{160}Gd → ^{160}Dy

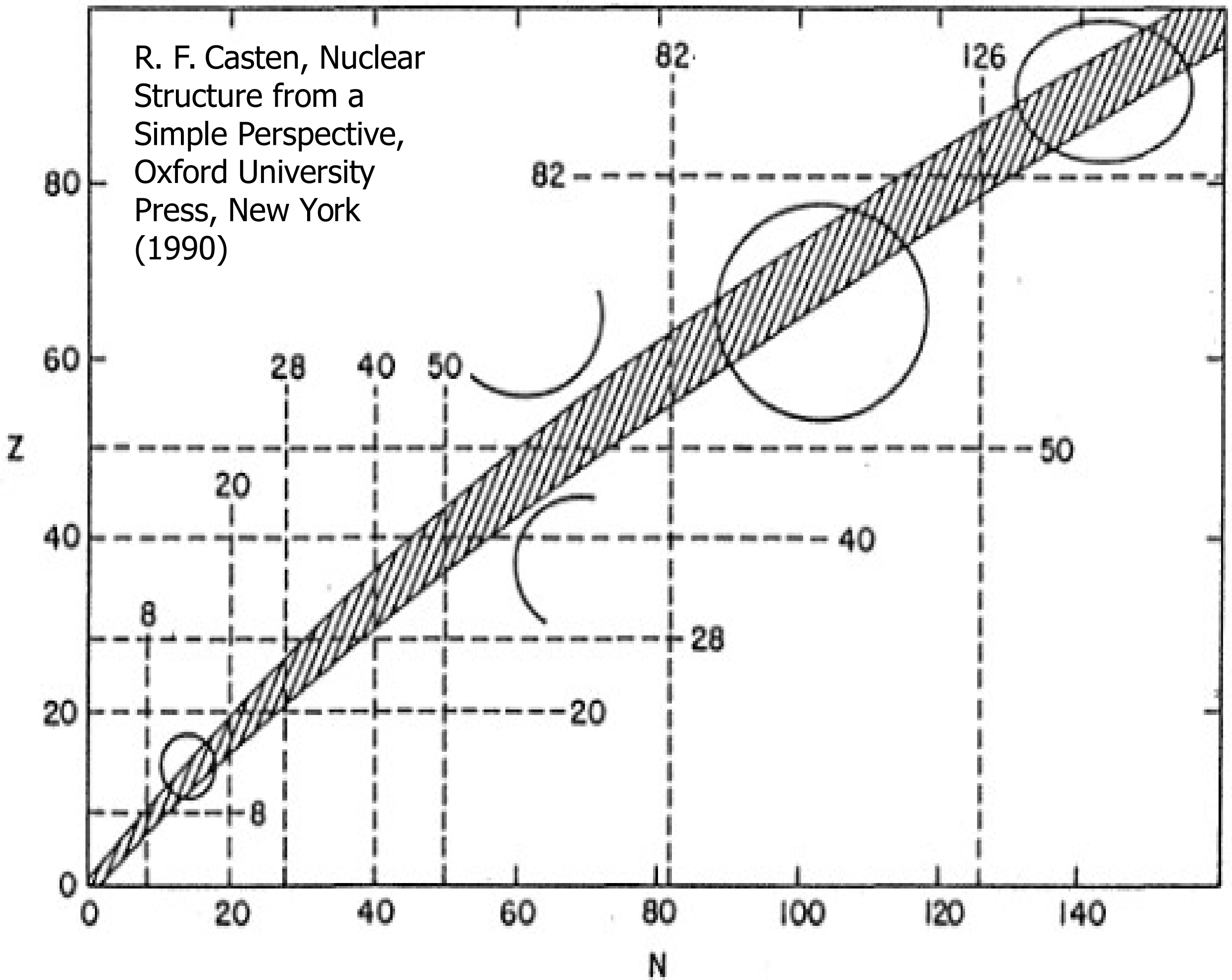


116

1

^{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

:harthtml/VChartHTML.html

Rev. C 87 (2013) 014315

Location of 0νββ Candidates

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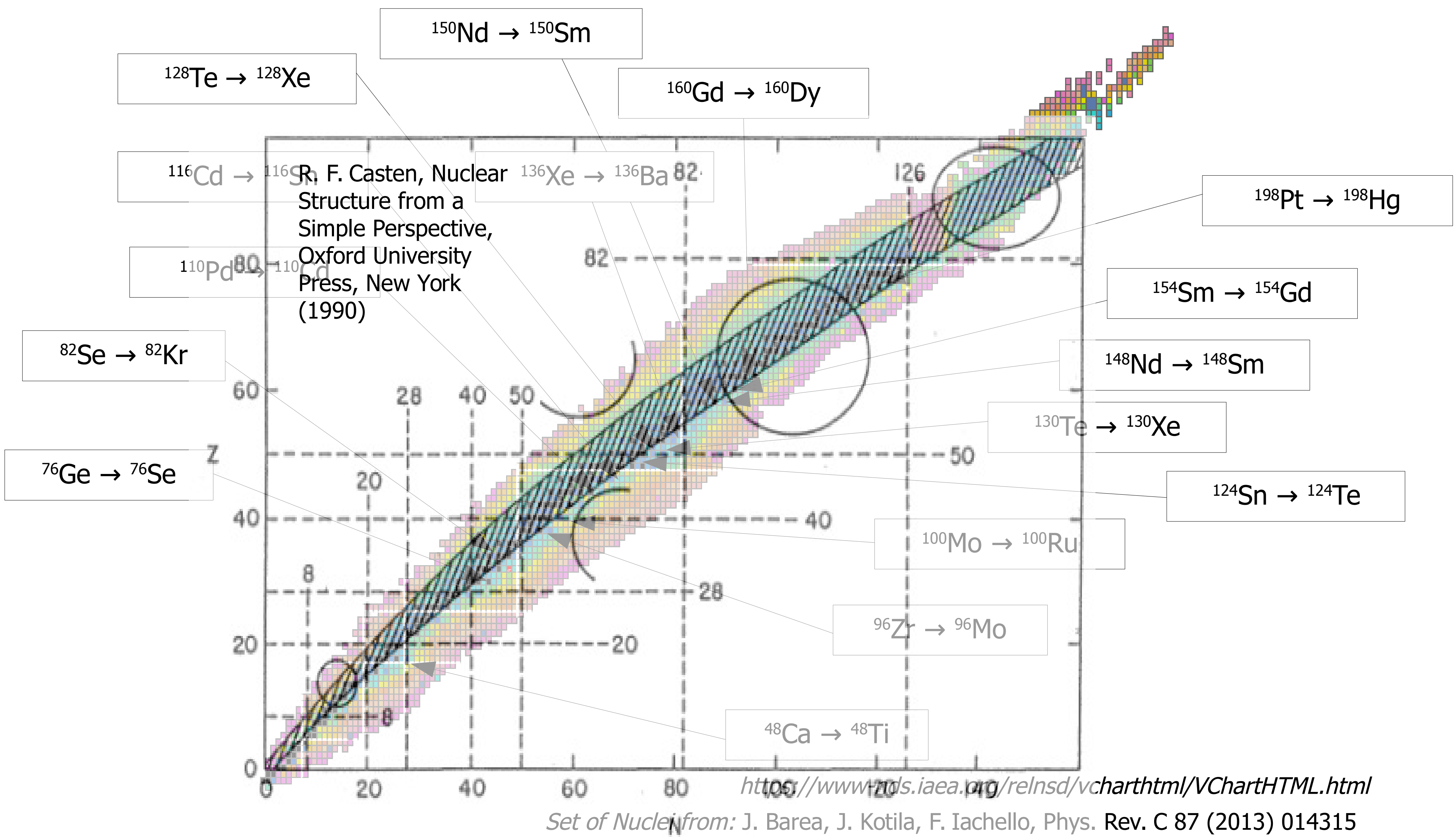

R. F. Casten, Nuclear Structure from a Simple Perspective, Oxford University Press, New York (1990)

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Location of 0νββ Candidates

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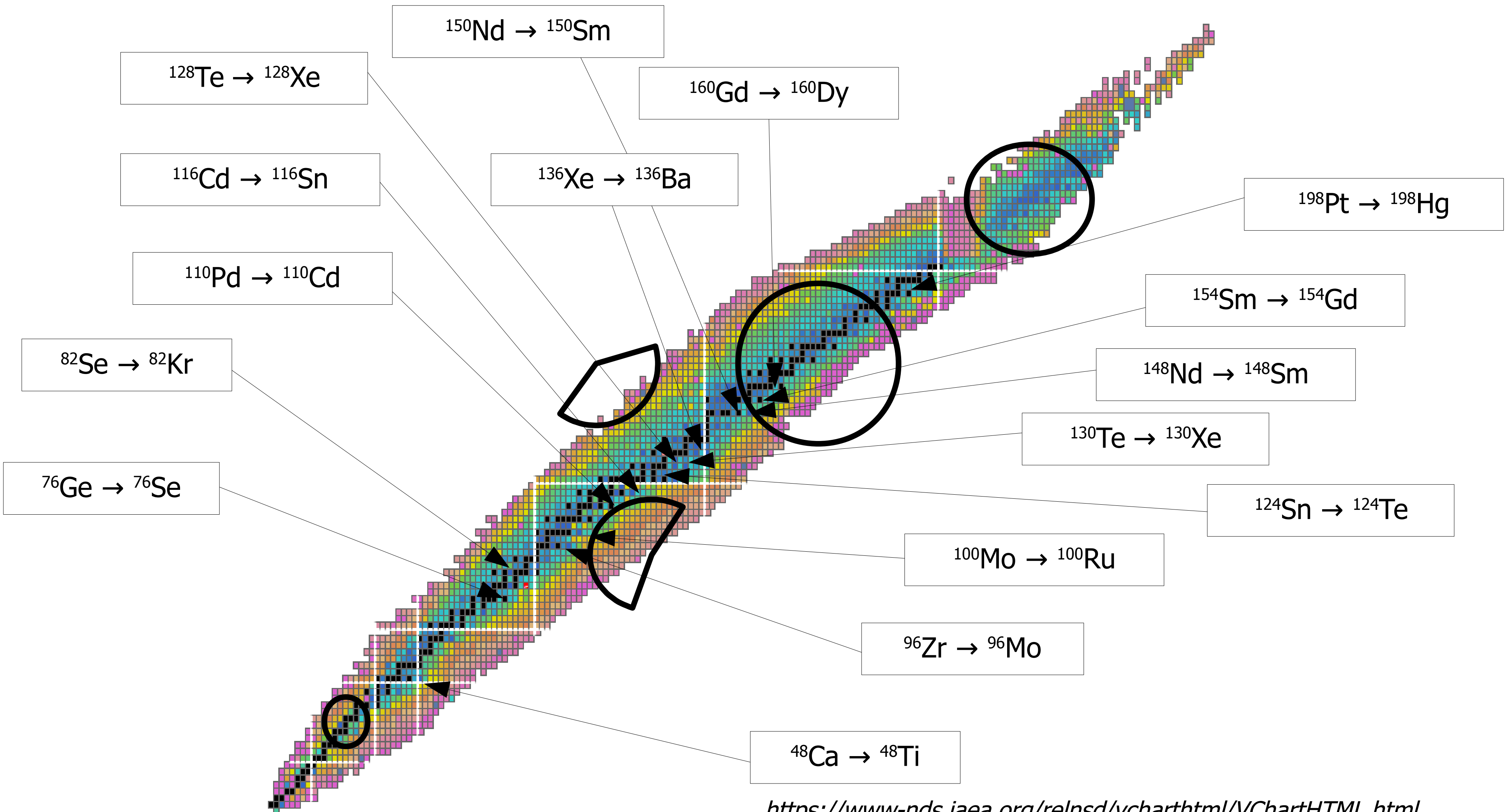

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Set of Nuclei from: J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 87 (2013) 014315

Quadrupole Collectivity

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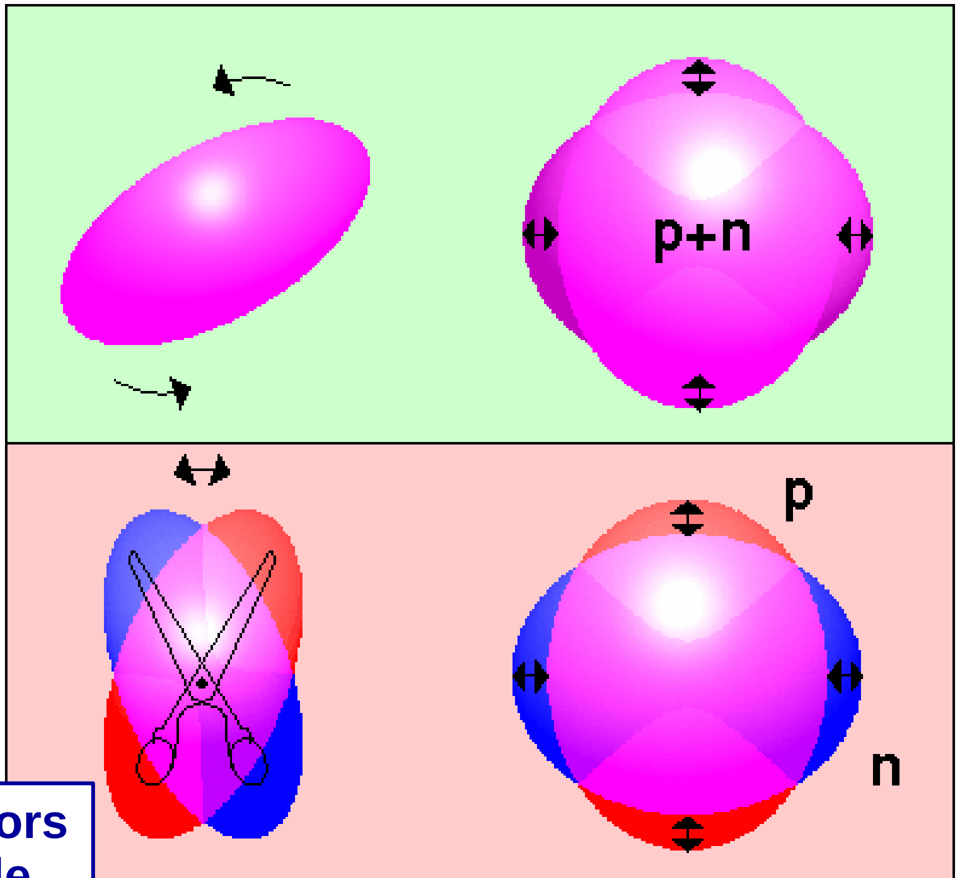
Proton-Neutron symmetric



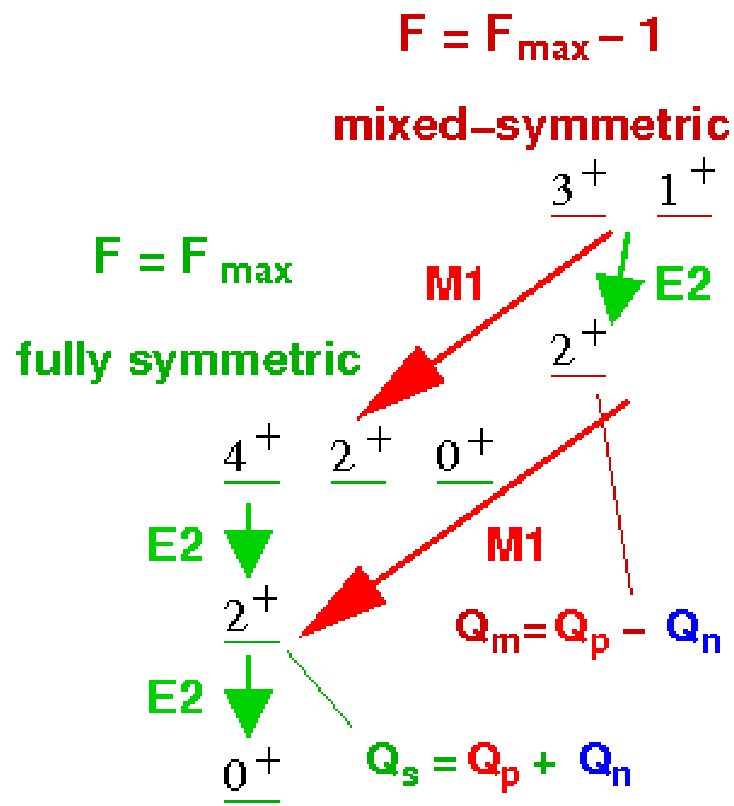
Scissors Mode

Rotors

Vibrators

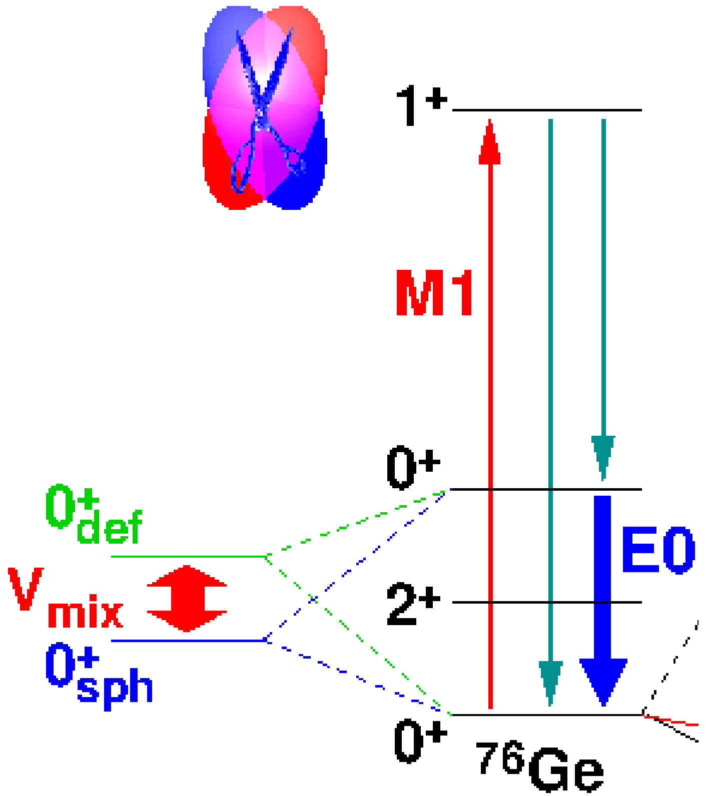
Proton-Neutron mixed-symmetric

F-Spin is the bosonic analog to isospin



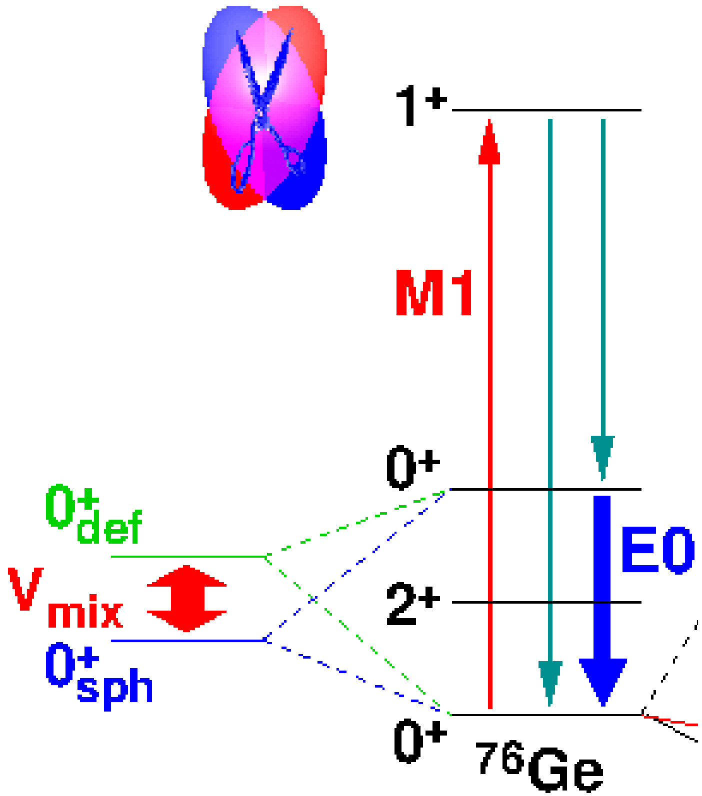
Excitation by the quadrupole operator

Shape Coexistence has Influence on Decay Behavior of S.M.

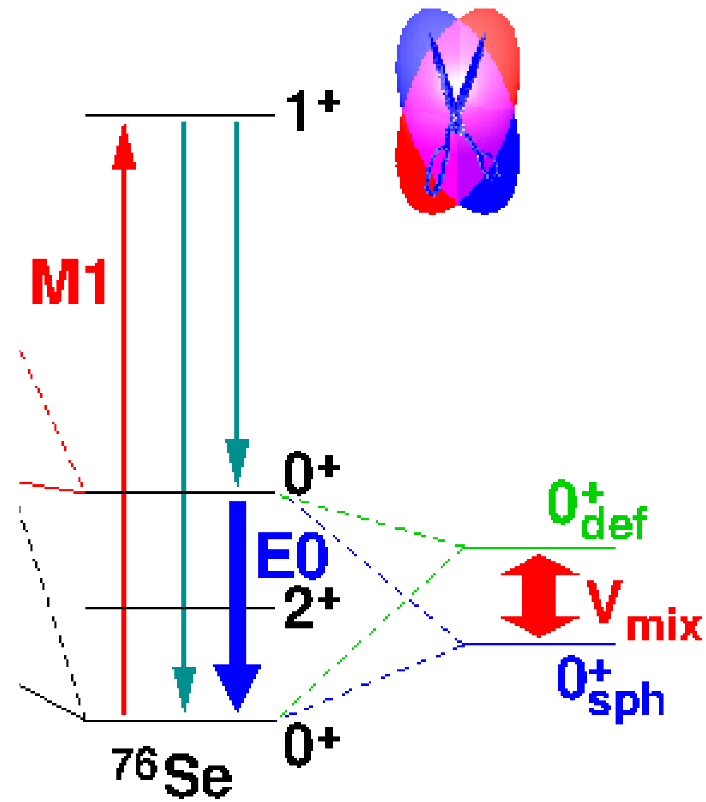


- Scissors Mode excited from sph/def mixed state
- Will decay to both 0^+ states, same configurations in both !
- Search for Scissors Mode Branching to excited 0^+ state
- Complementary observable for shape/configuration mixing: E0-strength

Shape Coexistence has Influence on Decay Behavior of S.M.



Same can (and does) happen for mother and daughter isotopes



Decay Behavior of S.M. connected to Double-Beta Rates

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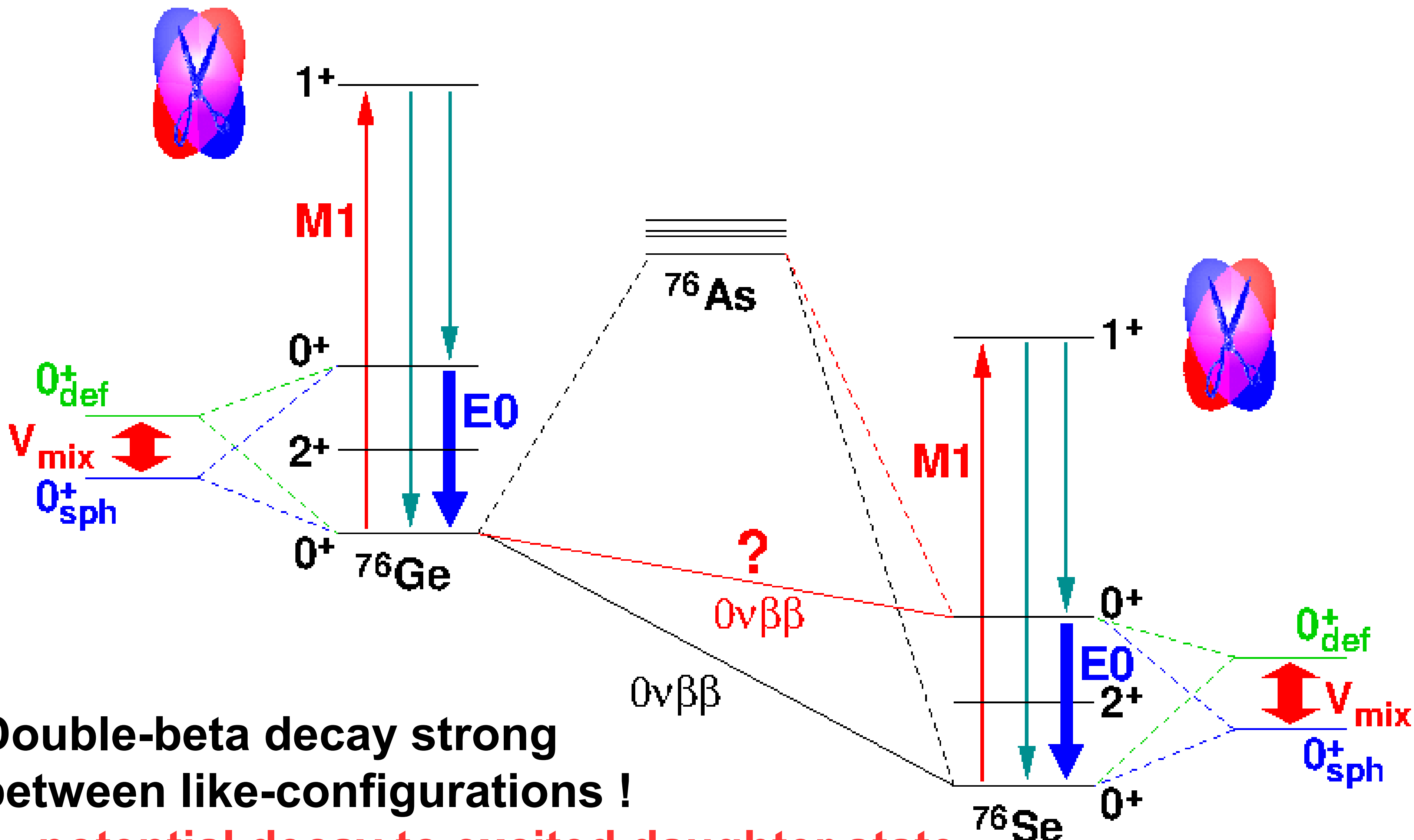

Double-beta decay strong between like-configurations !

→ potential decay to excited daughter state

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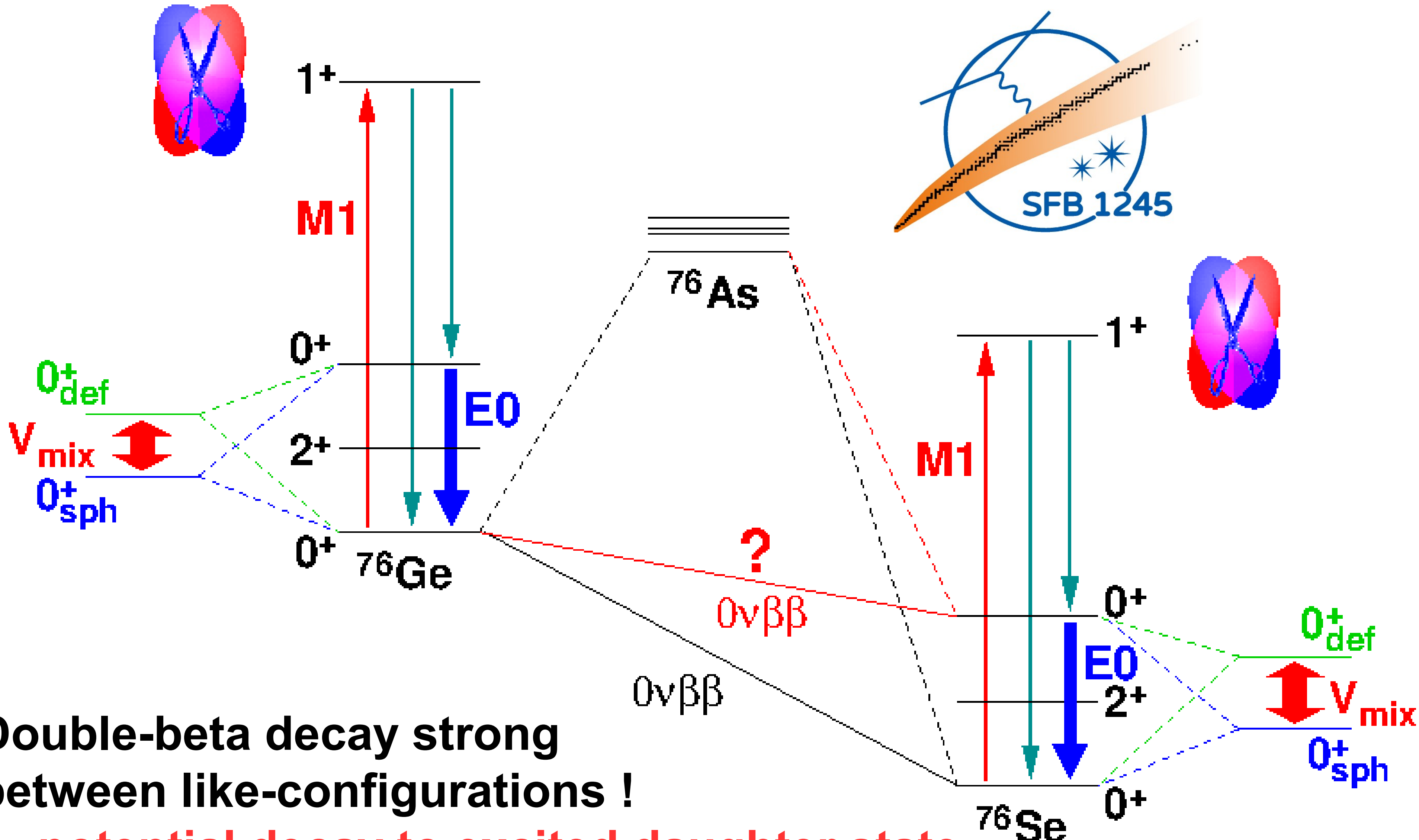

Double-beta decay strong between like-configurations !

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

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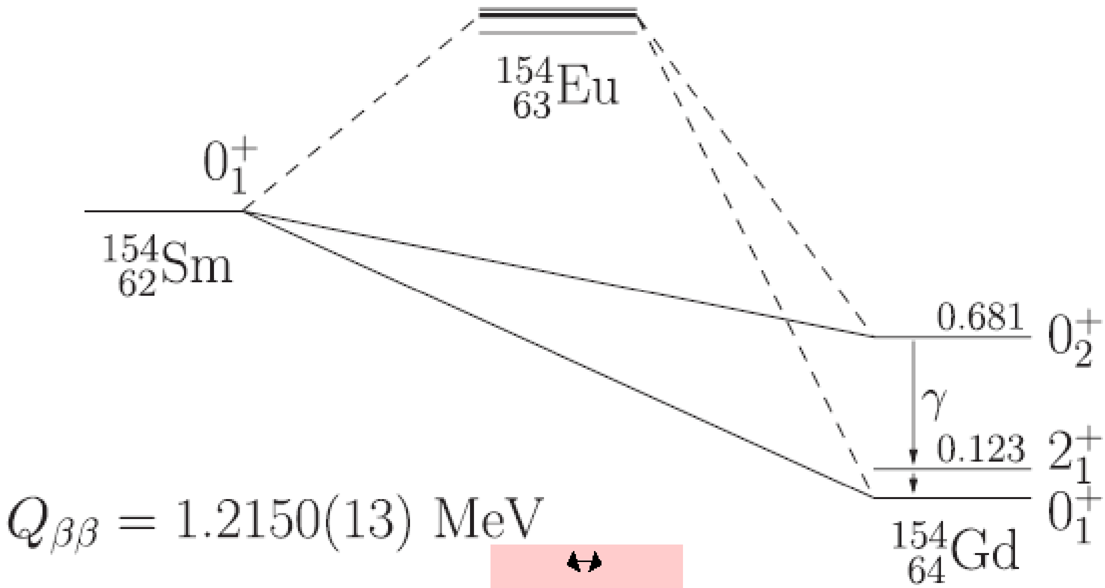
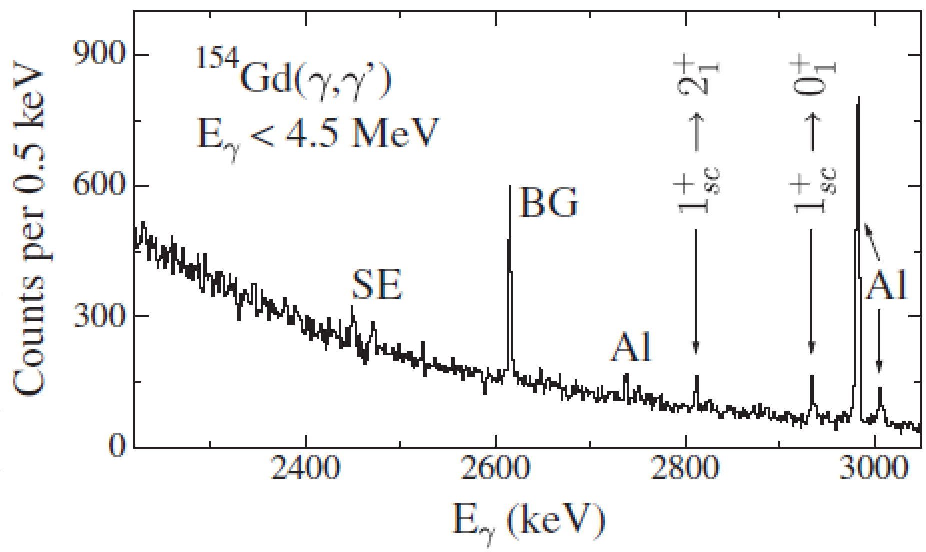
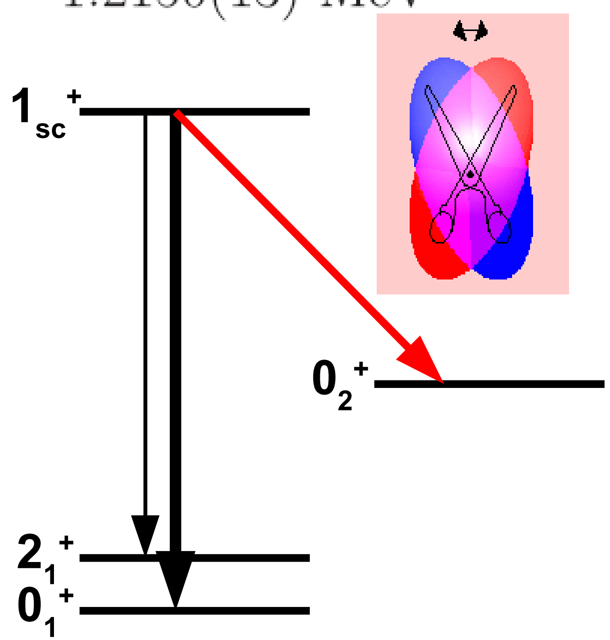
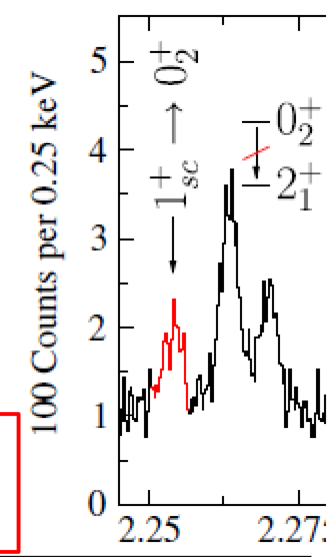




Photon scattering at Darmstadt



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



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

This could be done in one step using a ~mono-energetic γ-beam !

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

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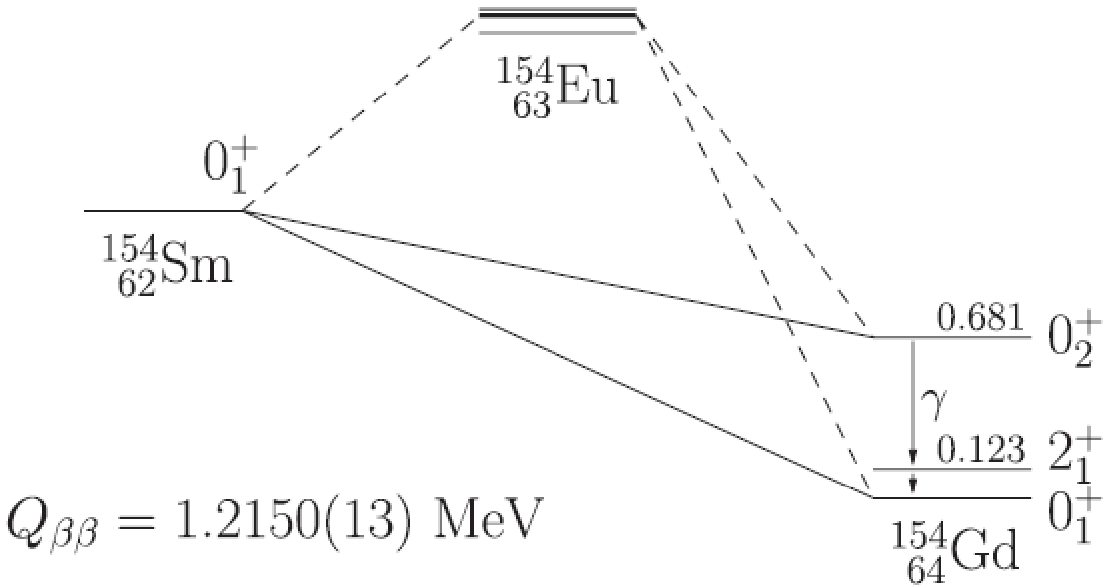

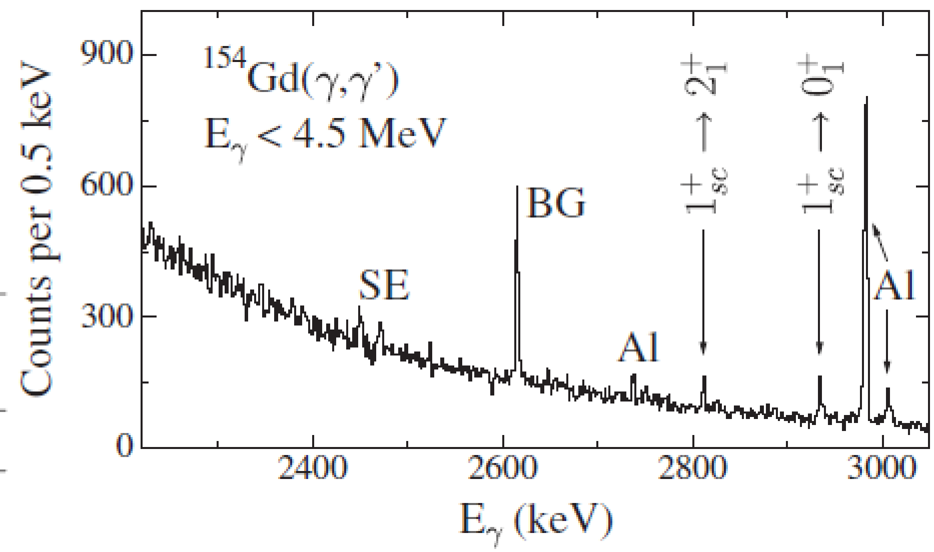

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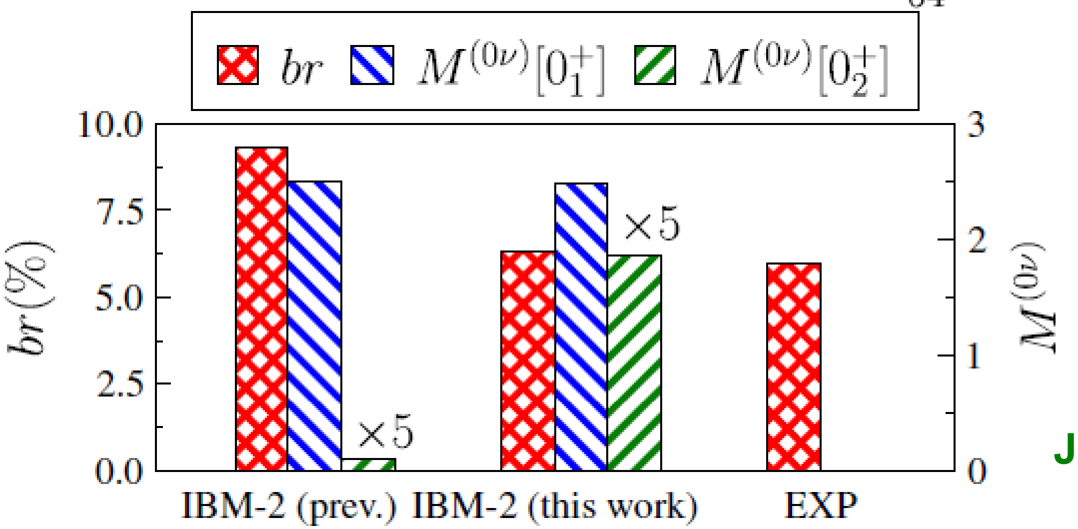

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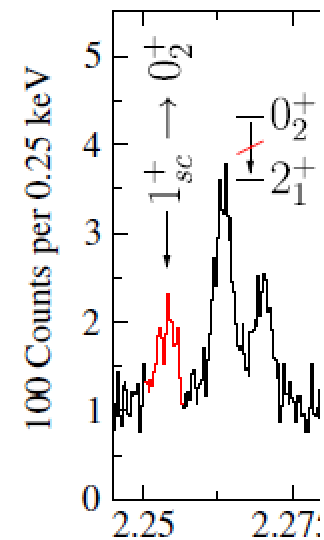


J. Beller, PRL 111, 172501 ('13)

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

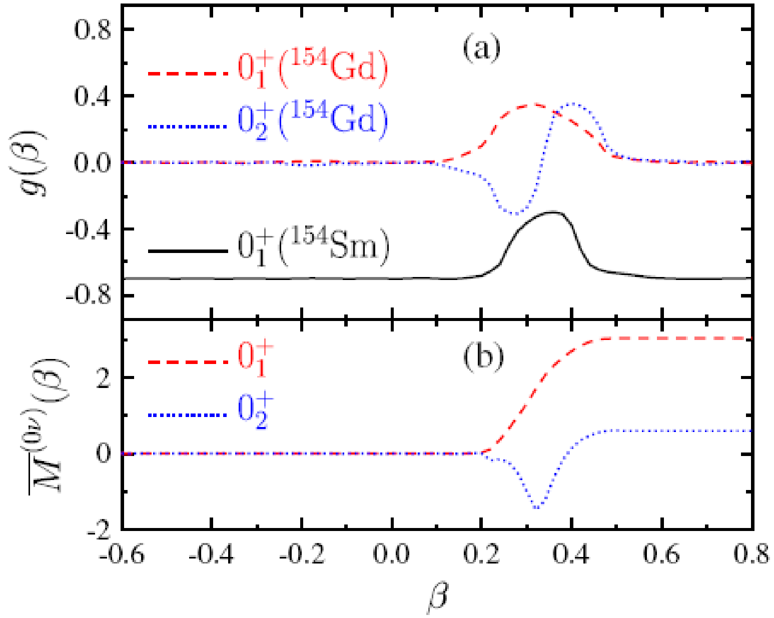
“Application”: Dipole strength and 0νββ-decays

TECHNISCHE UNIVERSITÄT DARMSTADT

PRL **111,** 172501 (2013) PHYSICAL REVIEW LETTERS week ending 25 OCTOBER 2013

Constraint on $0\nu\beta\beta$ Matrix Elements from a Novel Decay Channel of the Scissors Mode: The Case of ^{154}Gd

J. Beller,[1,*] N. Pietralla,[1] J. Barea,[2] M. Elvers,[3,†] J. Endres,[3,‡] C. Fransen,[3] J. Kotila,[4] O. Möller,[1] A. Richter,[1] T. R. Rodríguez,[1] C. Romig,[1] D. Savran,[5,6] M. Scheck,[1,7] L. Schnorrenberger,[1] K. Sonnabend,[8] V. Werner,[9] A. Zilges,[3] and M. Zweidinger[1]



"Application": Dipole strength and 0νββ-decays

TECHNISCHE UNIVERSITÄT DARMSTADT

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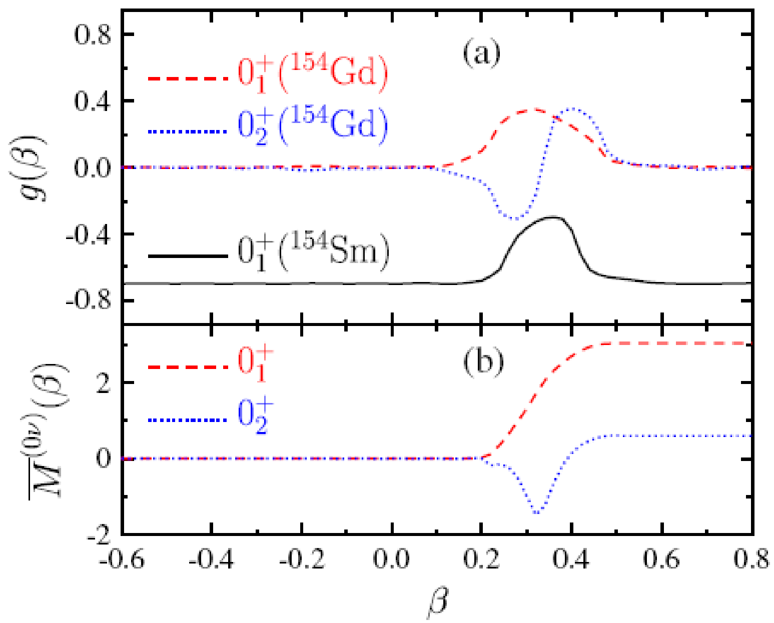
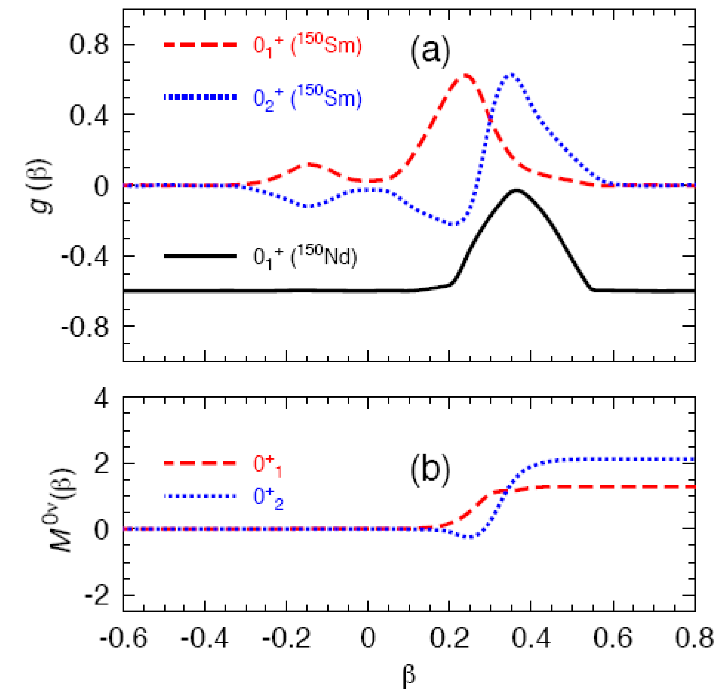


^{150}Nd:

larger **0νββ-** decay branch **to 0^+_2 state** than to gs due to QSPT at N=90.



SFB 1245

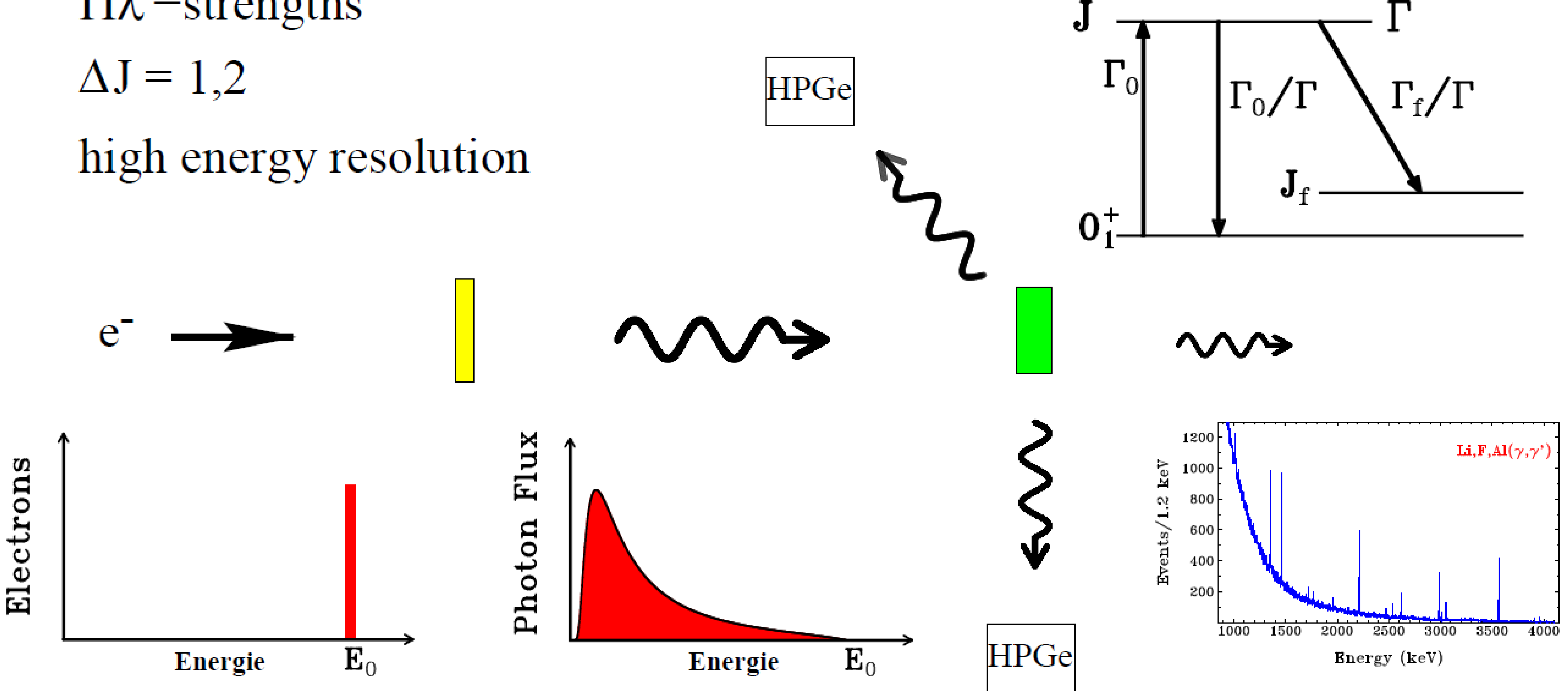
Part of new CRC 1245 "From Fundamental Interactions to Structure and Stars"

Nuclear Resonance Fluorescence

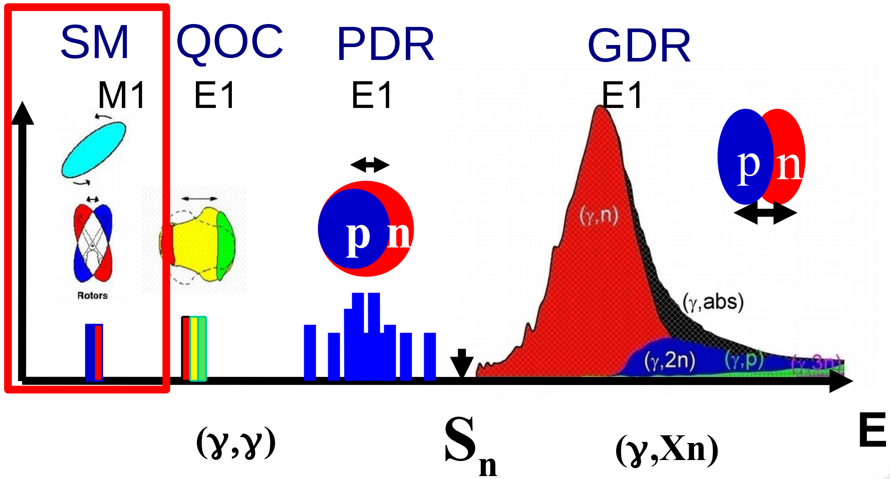
$\Pi\lambda$ −strengths

$\Delta J = 1,2$

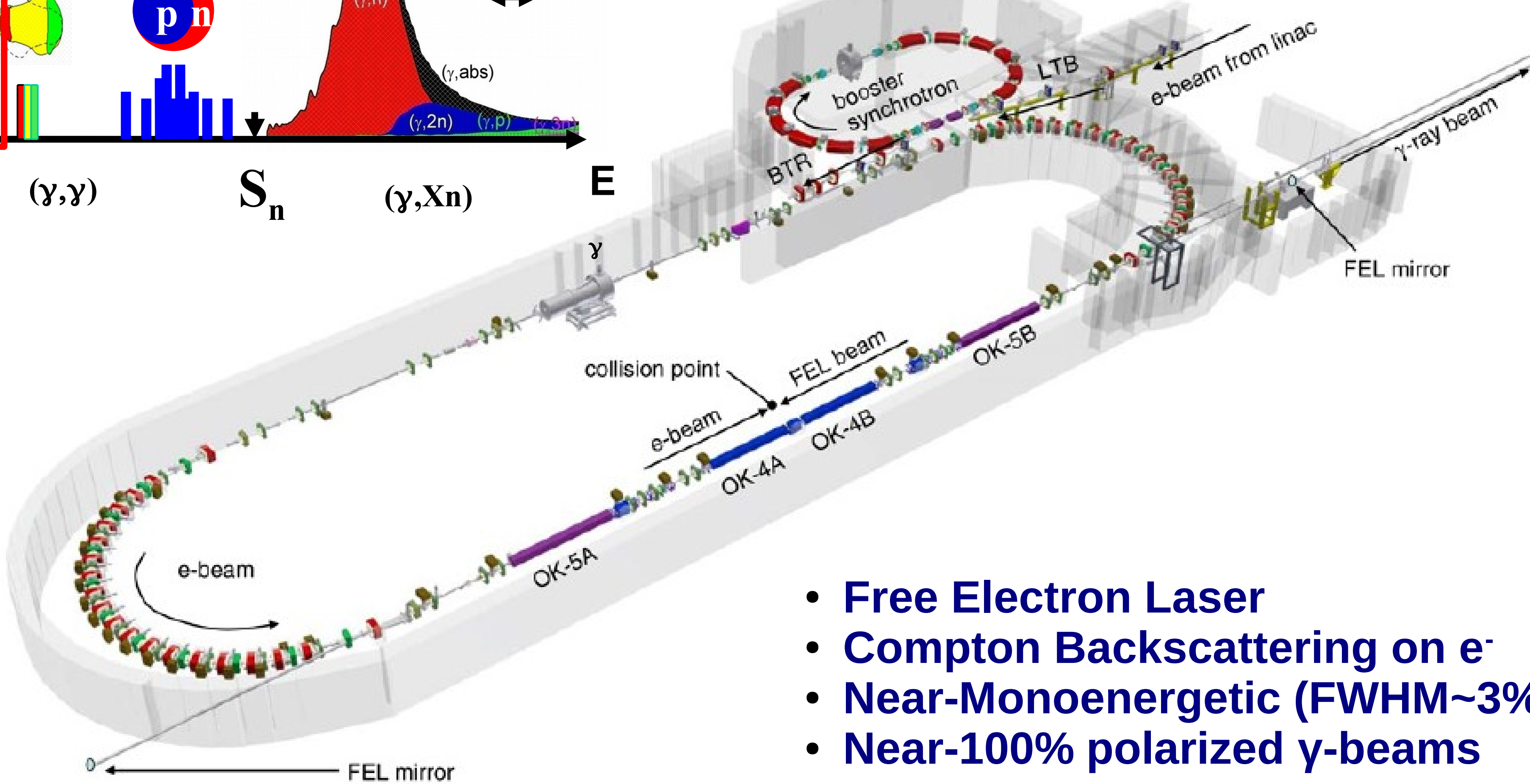
high energy resolution



High-Intensity Gamma-ray Source (HIGS) @ TUNL/Duke U.

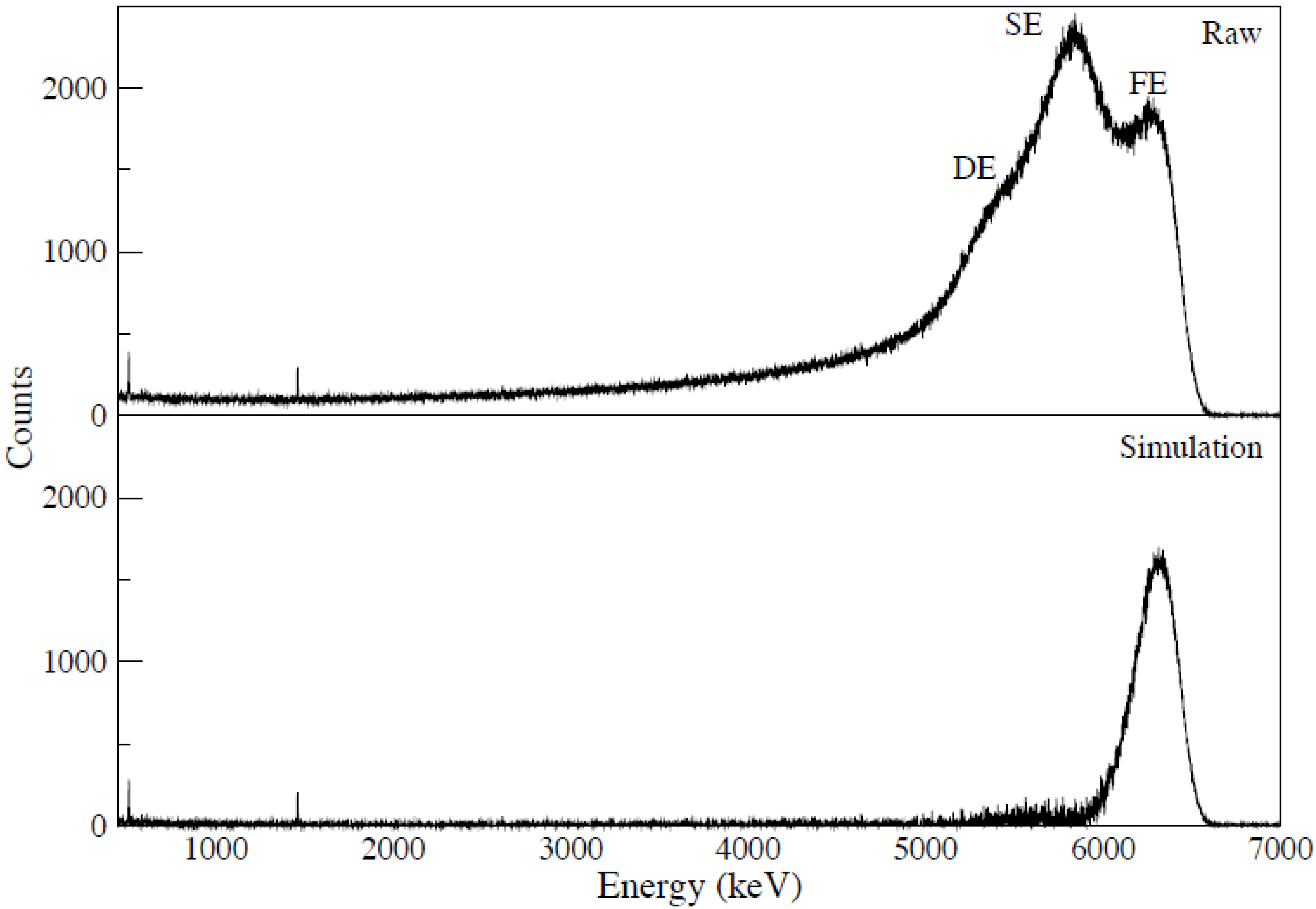


Study of the Nuclear Dipole Response

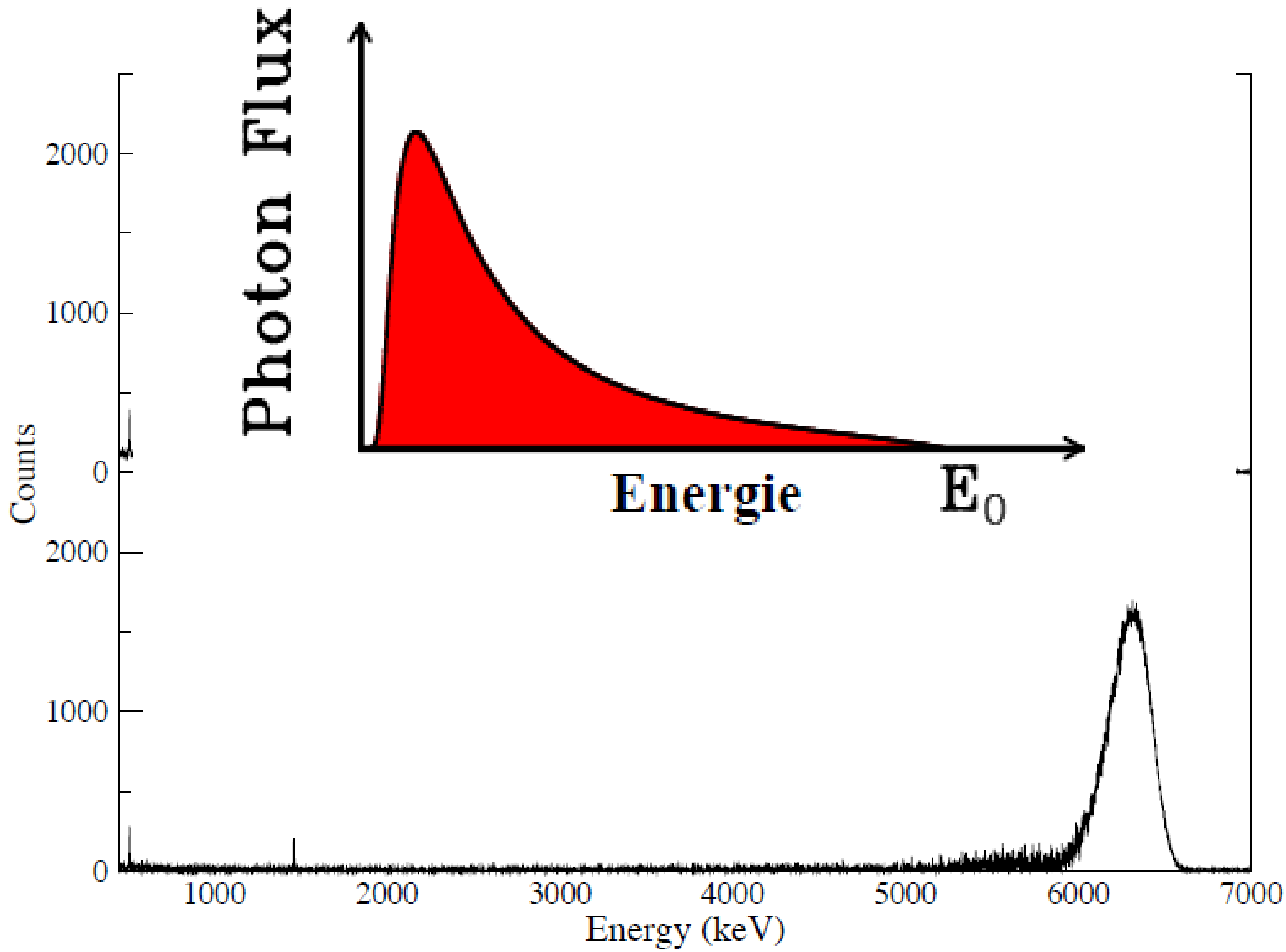


- **Free Electron Laser**
- **Compton Backscattering on e^-**
- **Near-Monoenergetic (FWHM~3%)**
- **Near-100% polarized γ-beams**

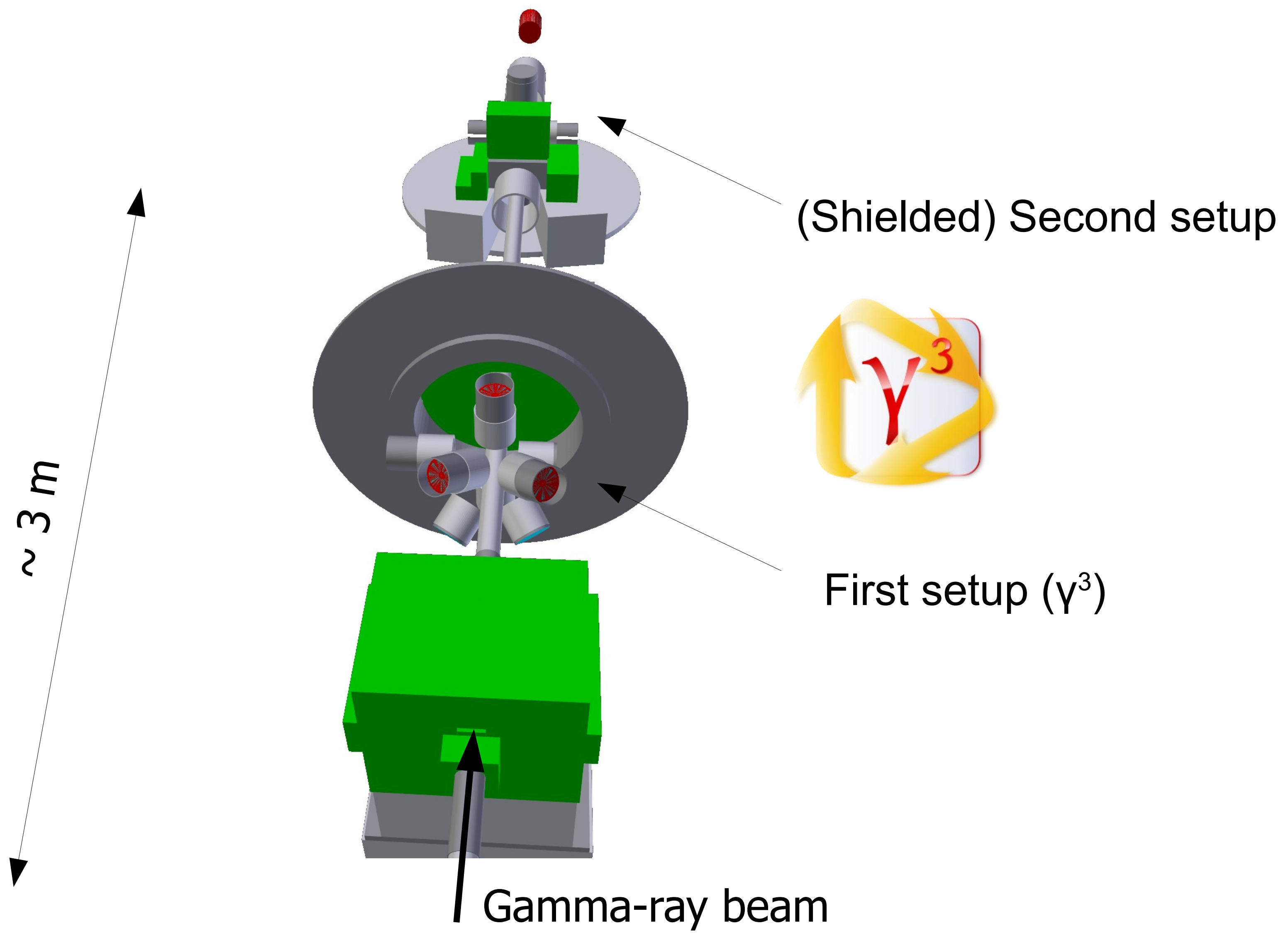
Monoenergetic



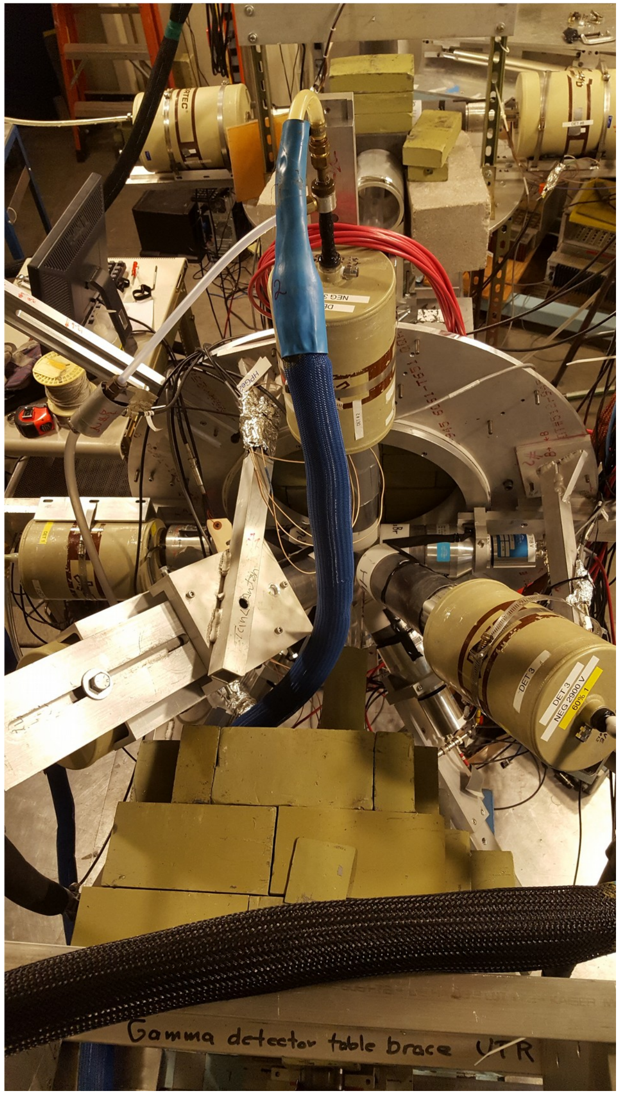
Monoenergetic vs. Bremsstrahlg.

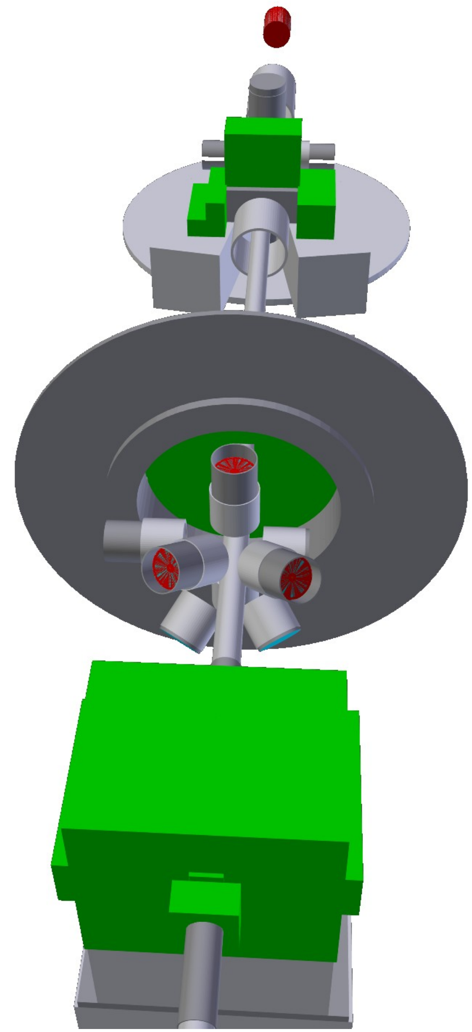


Gamma-Ray Detection: γ^3



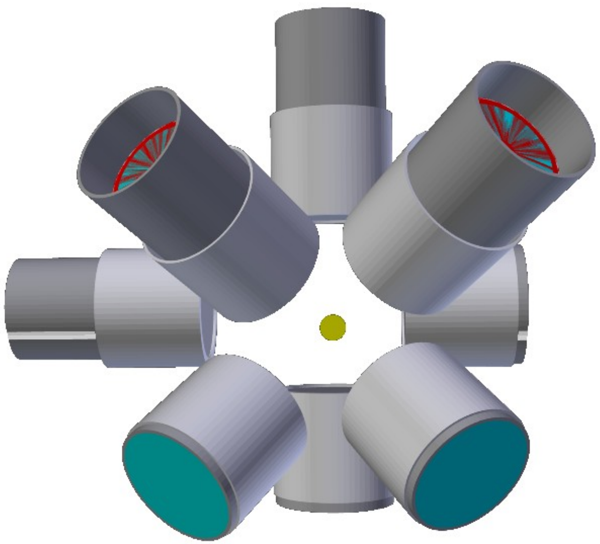
Gamma-Ray Detection: γ^3

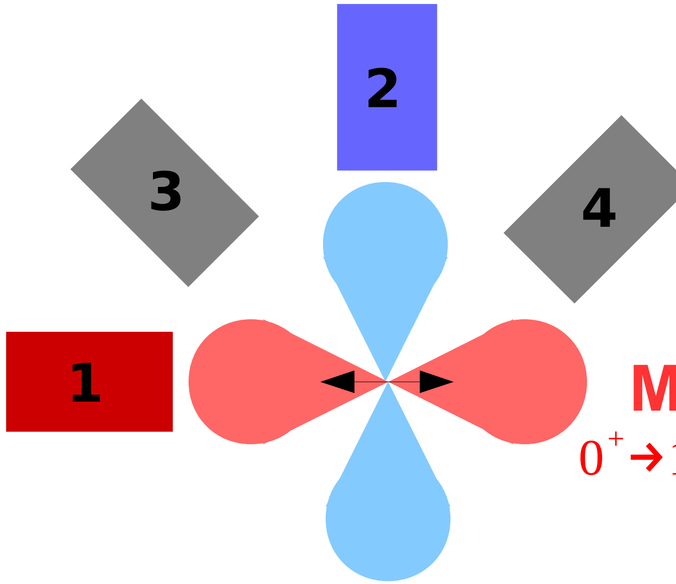




Gamma-Ray Detection: γ³

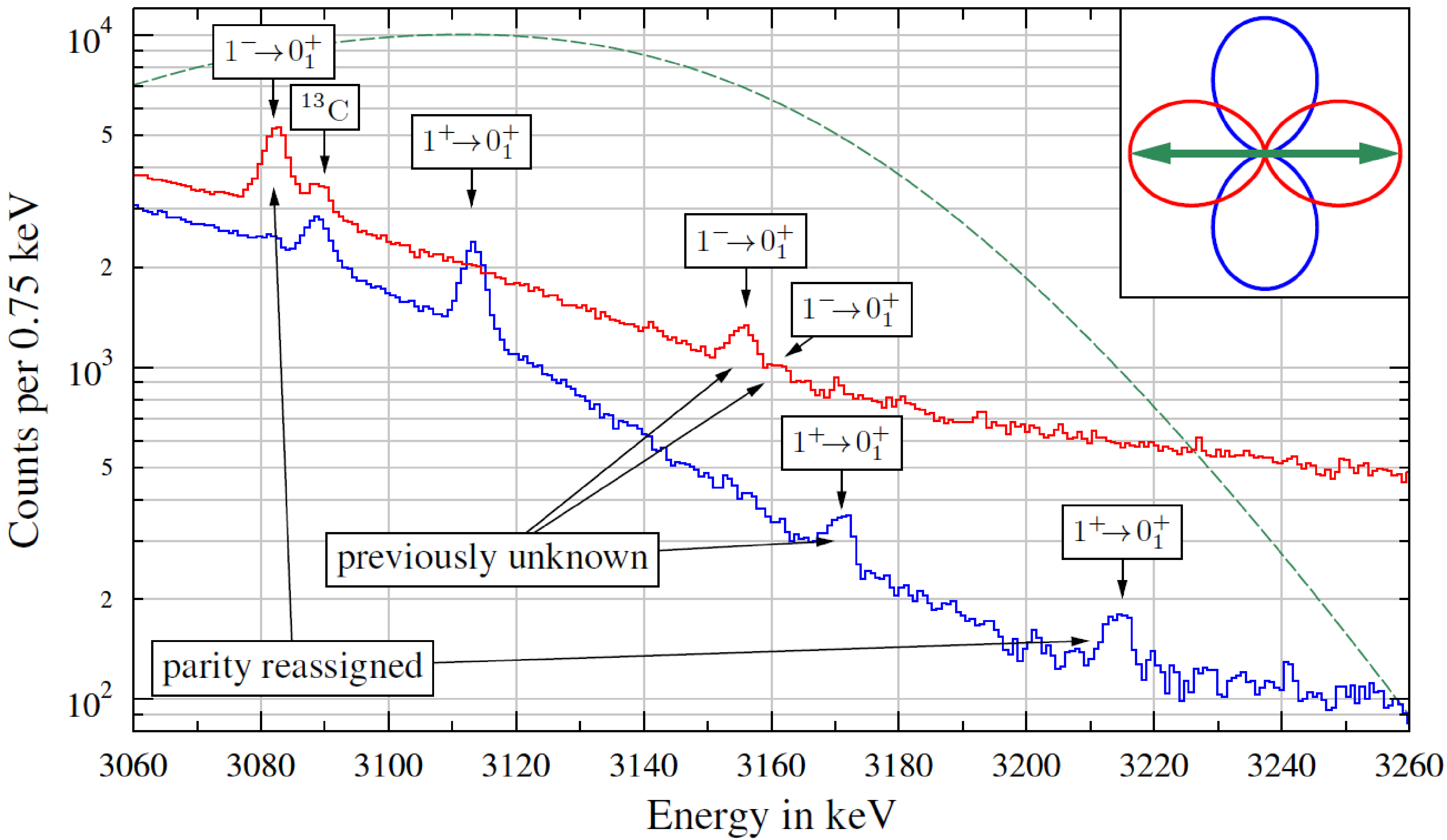
B. Löher et al., NIM A 723 (2013) 136





- 4 x 3x3" LaBr(Ce)
  - Efficiency: ~1 % @ 1.5 MeV
  - Energy Resolution: ~ 30 keV
  - Time Resolution: ~ 0.1 ns
- 4 x 60% HPGe
  - Efficiency: ~0.2%
  - Energy Resolution: ~ 3 keV
  - Time Resolution: ~ 1 ns

^{150}Sm Spectra at 3.11 MeV Beam Energy



Results for ^{150}Sm

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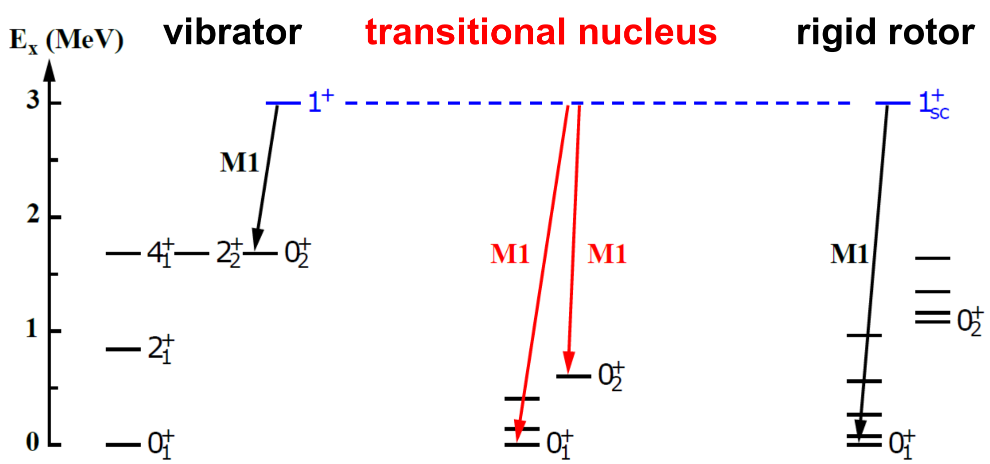
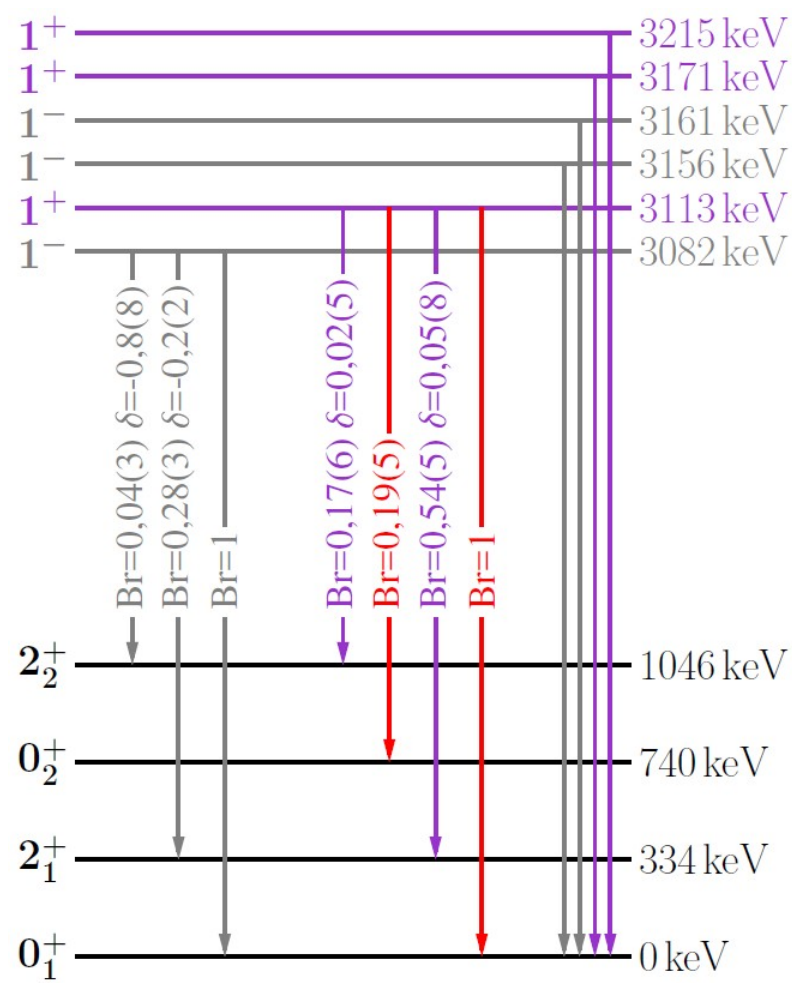
$$Br(1^+_{Sc} \rightarrow 0^+_2) = \frac{\Gamma_{0^+_2}}{\Gamma_{0^+_1}} = 0.19(5)$$

$$B(M1:\ 1^+_{Sc} \rightarrow 0^+_1) = 0.071(10)\ \mu_N{}^2$$

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



J. Beller, Diss. (2014), TU Darmstadt



J. Kleemann, BA-Thesis, TUDa 2016

Analog experiment on ^{150}Nd already performed, analysis in progress !

What's next?

- The scissors mode and 0νββ
  - Use the new data to constrain models
  - First: IBM-2 calculations → derive Majorana parameter
- E0 strength @ S-DALINAC
  - Another signature for shape mixing
  - First experiments with electron-scattering prepared

S-DALINAC Today

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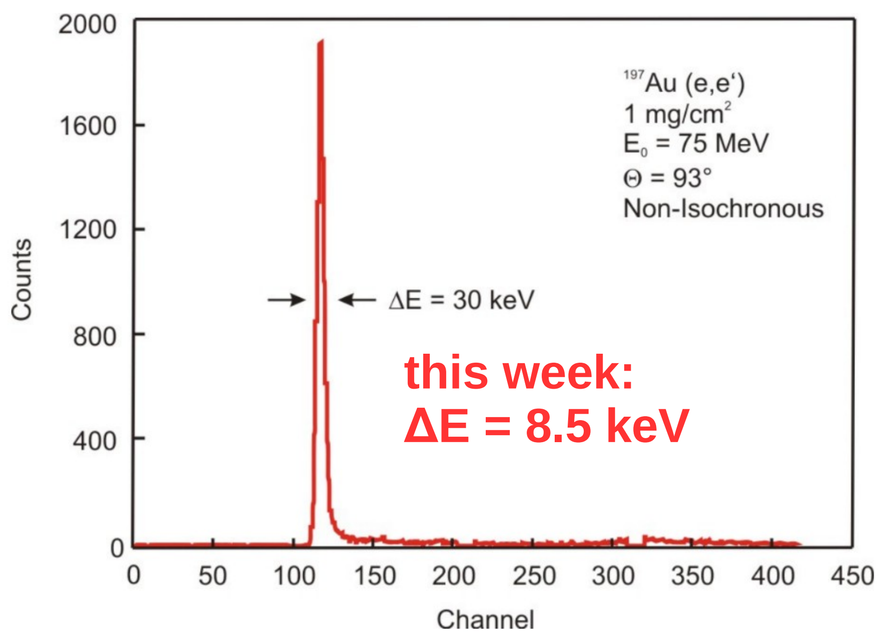
First sc-electron LINAC in Europe (1991)

A. Richter: *Operational Experience at the S-DALINAC*, Proceedings of EPAC 1996, Sitges, Barcelona, (1996) 110.

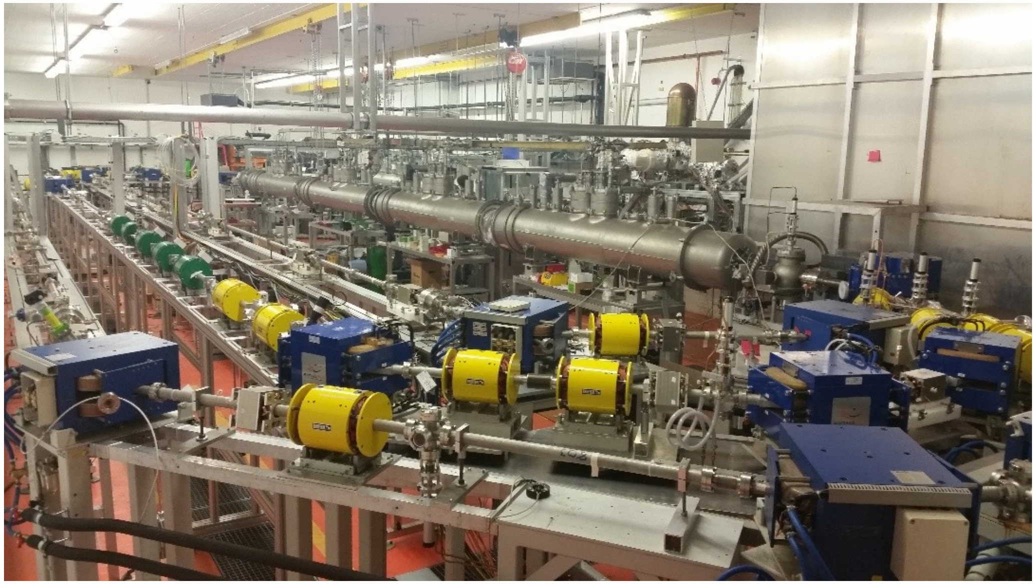
Non-isochronous (Twice recirculating until 2015)



F. Hug, C. Burandt, R. Eichhorn, M. Konrad, N. Pietralla: *Measurements of a Reduced Energy Spread of a Recirculating Linac by Non-Isochronous Beam Dynamics*, Proceedings of LINAC 2012, Tel-Aviv, Israel (2012) 531.

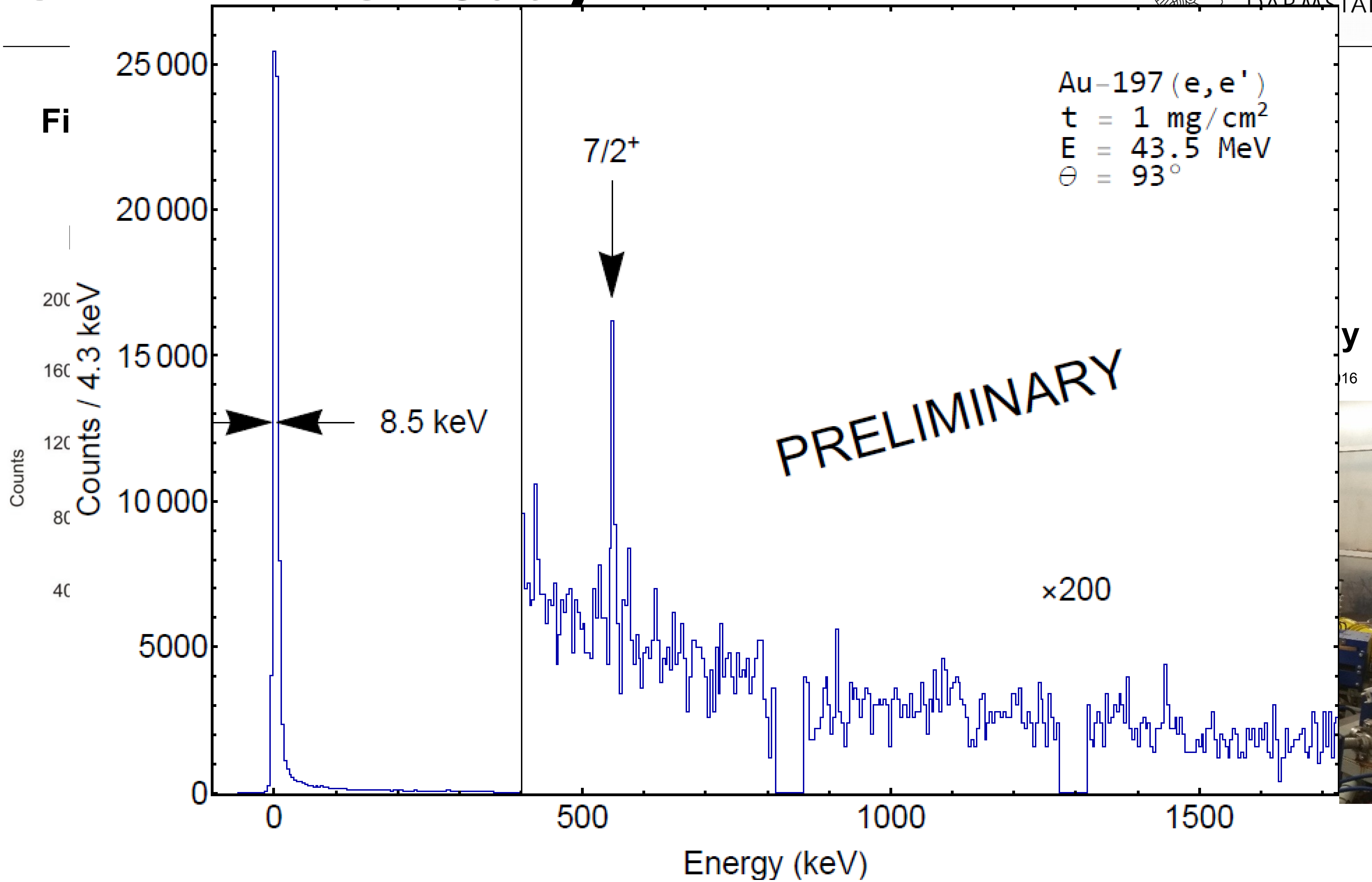
First ERL under commissioning in Germany

M. Arnold, Dissertation, 2016

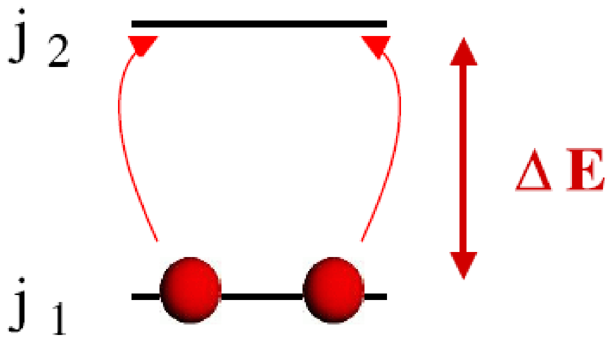


S-DALINAC Today

Fi



E0 Strength and Shape Mixing



$$|0_2^+\rangle = -\beta\ |j_1^2\rangle + \alpha\ |j_2^2\rangle$$

$$|0_1^+\rangle = \alpha\ |j_1^2\rangle + \beta\ |j_2^2\rangle$$

E0 strengths corresponds to different radii (deformations)

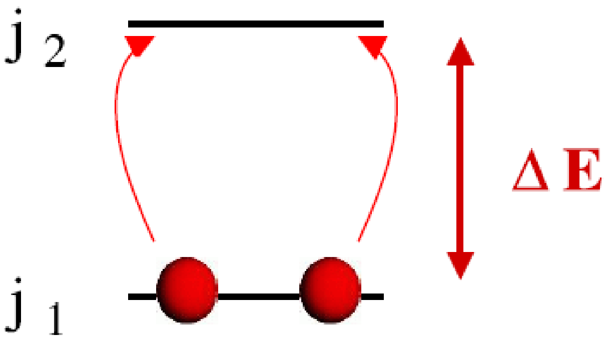
$$\langle 0_1^+|r^2|0_2^+\rangle = (\alpha^2 - \beta^2)\langle j_1^2|r^2|j_2^2\rangle + \alpha\beta\left(\langle j_1^2|r^2|j_1^2\rangle - \langle j_2^2|r^2|j_2^2\rangle\right)$$

E0 is large when

a) the two configurations have different avg. radii (deformations, shapes)

b) the two configurations mix strongly ($\alpha\beta$ term)

E0 Strength and Shape Mixing



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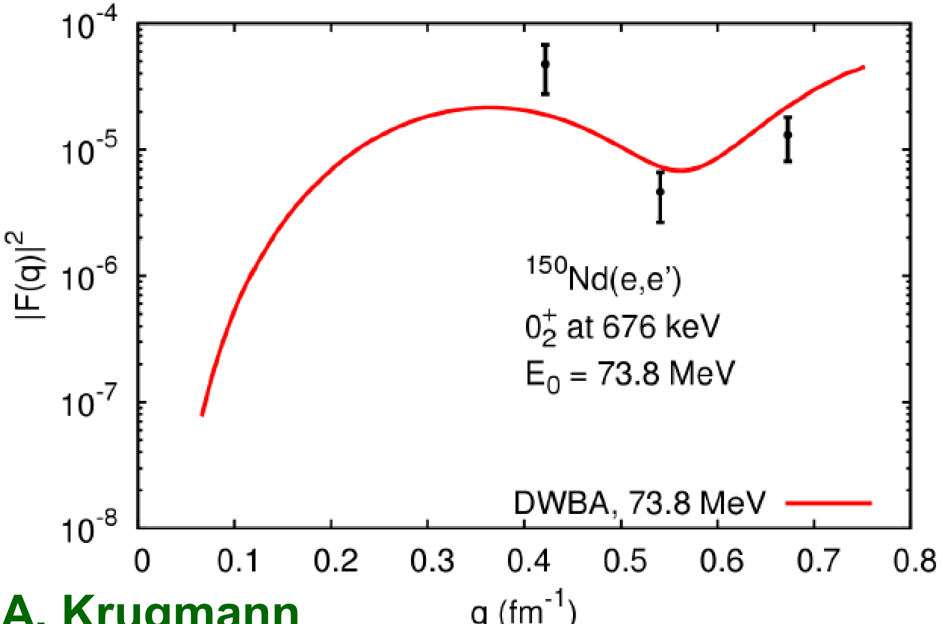
First successful E0 measurement at S-DALINAC



A. Krugmann

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- E0 strength @ S-DALINAC
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  - First experiments with electron-scattering prepared
- Probe material for WIMP detection @ S-DALINAC
  - What if the WIMP-Nucleus interaction is spin-dependent?

Spin-dependent Cross Section ?

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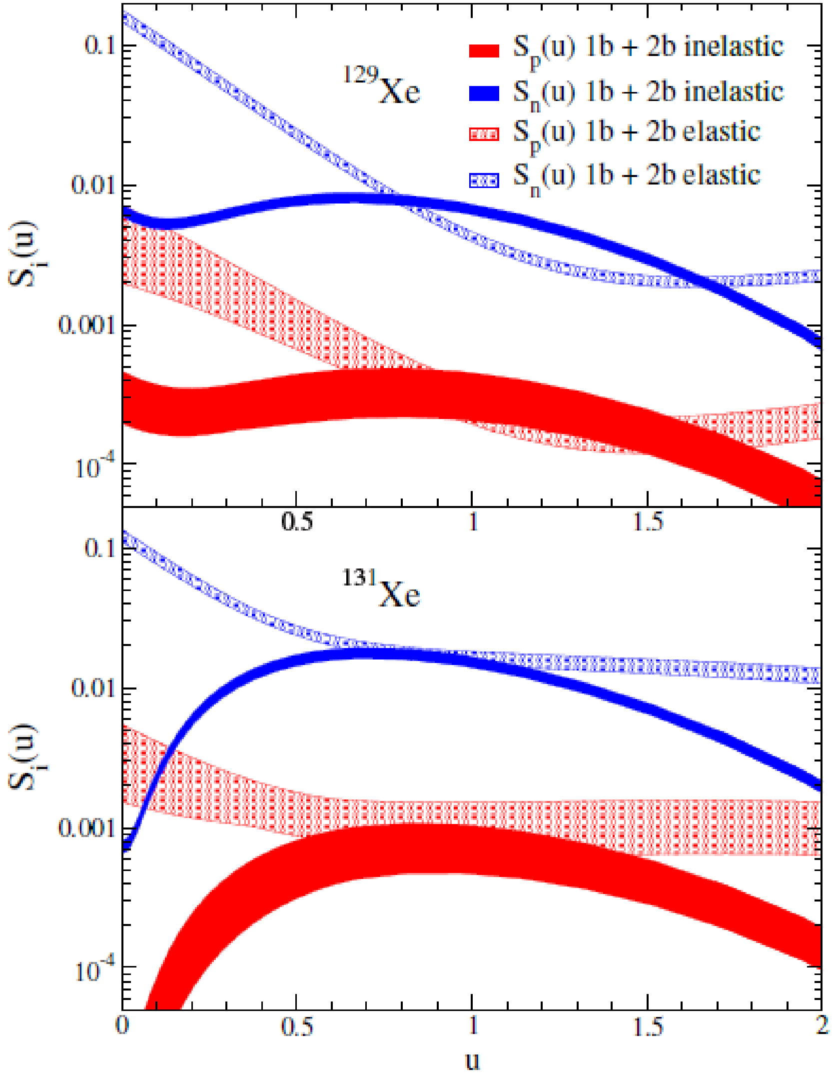
- spin-dependency of WIMP-nucleon interaction unknown
- if spin-dependent, only odd mass number Xe isotopes interact
- large-scale shell-model calculations (e.g. A. Schwenk et al.)
- form factors for spin-dependent interaction calculated
- → significant contribution from *inelastic* WIMP-nucleon scattering
- at low momentum transfer ~0.5 fm^{-1}
- range of operation of S-DALINAC: (e,e') as a "surrogate" for (WIMP,WIMP')



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

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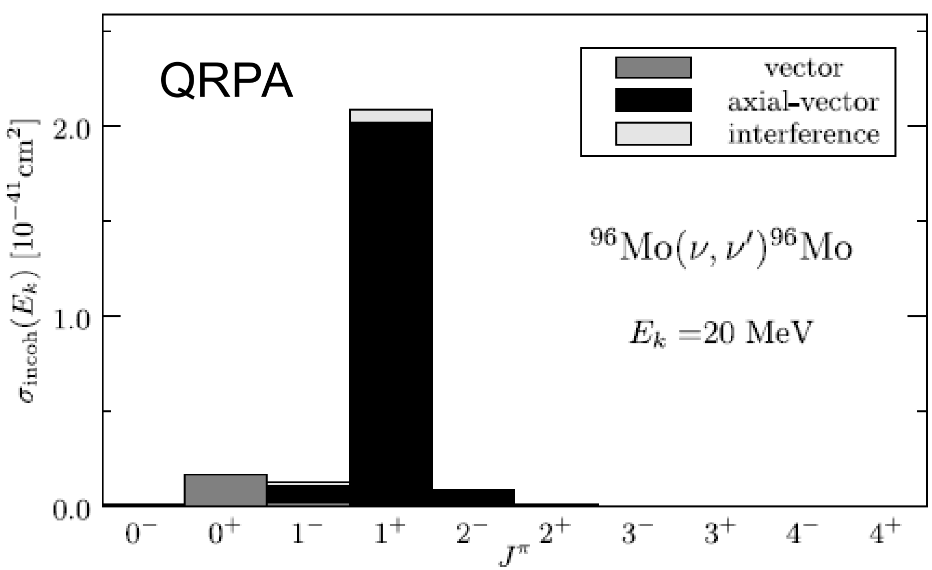
  - First experiments with electron-scattering prepared
- Probe material for WIMP detection @ S-DALINAC
  - What if the WIMP-Nucleus interaction is spin-dependent?
- Probe M1 response for ν-nucleus scattering @ S-DALINAC & HIGS
  - Little known on Spin-Flip M1 resonance

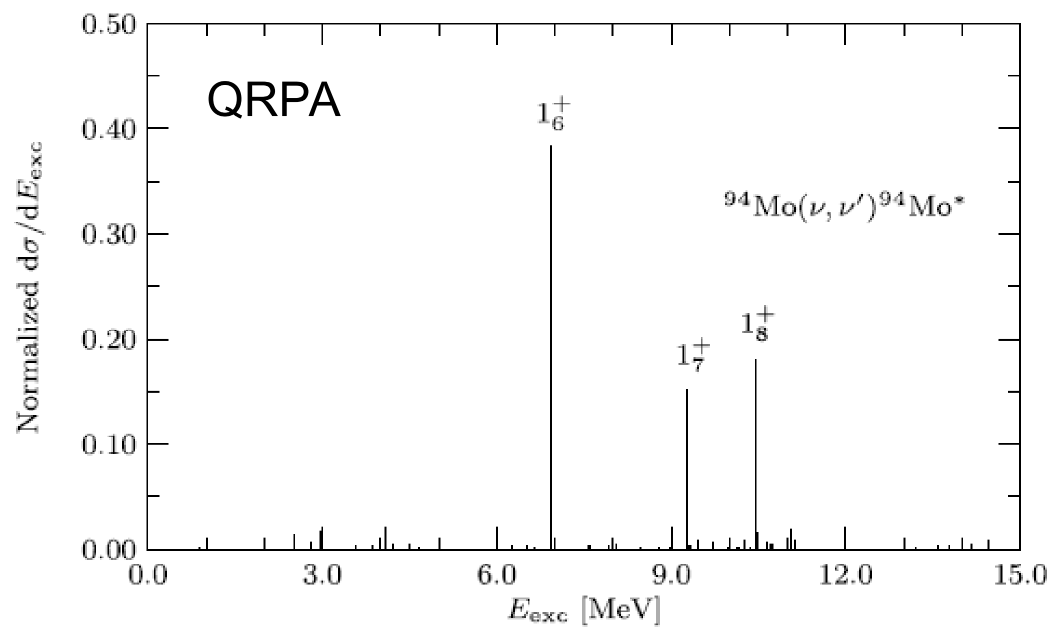
Another Application: (ν,ν')

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.

What's next?

- The scissors mode and 0νββ
  - Use the new data to constrain models
  - First: IBM-2 calculations → derive Majorana parameter
- E0 strength @ S-DALINAC
  - Another signature for shape mixing
  - First experiments with electron-scattering prepared
- Probe material for WIMP detection @ S-DALINAC
  - What if the WIMP-Nucleus interaction is spin-dependent?
- Probe M1 response for ν-nucleus scattering @ S-DALINAC & HIGS
  - Little known on Spin-Flip M1 resonance

Thank you !

Collaboration:

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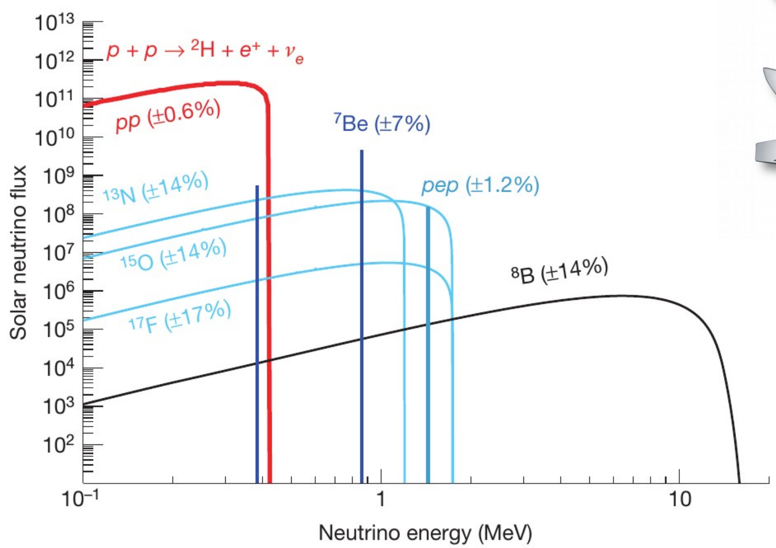
Neutrino Detection, e.g. ^{100}Mo

^{100}Mo as a "Swiss army knife" for neutrino physics [1,2]

Solar neutrino detection

Search for 0νββ decay



Decay rate for 0νββ decay:

$$\lambda_{0\nu} = G_{0\nu}(Q_{\beta\beta})|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Kinematic factor — Nuclear matrix element — Effective neutrino mass

- Neutrinos from the pp-process with low energy, but high flux
- Need material with low reaction Q-value to detect pp-neutrinos
- **Low Q_{EC} value in ^{100}Mo**, use inverse electron capture: $n+\nu_e \rightarrow p+e^-$

- **$G_{0\nu}$ large because of large $Q_{\beta\beta}$**
- $M_{0\nu}$ = ? → Need high-precision nuclear data to benchmark theoretical calculations

[1] H. Ejiri et al., Phys. Rev. Lett. **85**, 2917 (2000)
[2] K. Fushimi et al., J. Phys. Conf. Series **203**, 012064 (2010)
[3] Borexino Collaboration, Nature **512**, 383 (2014)

Weak Interactions and Nuclear Structure

TECHNISCHE UNIVERSITÄT DARMSTADT

Atomic nuclei as testing ground for weak processes

Neutrinoless double beta decay

$$\lambda_{0\nu\beta\beta}\left(\langle {}^{A}_{Z+2}X | V_{weak} | {}^{A}_{Z}X \rangle, m_{\nu}\right)$$

WIMP – nucleus scattering

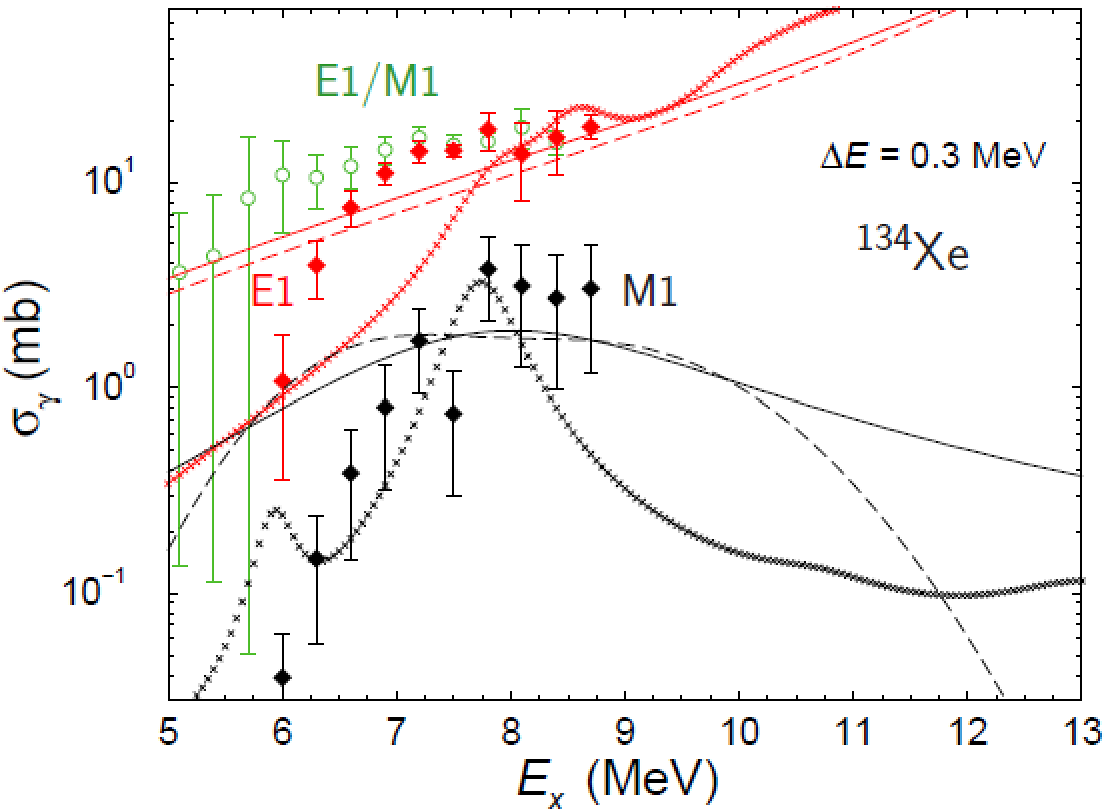
$$\sigma_{(WIMP,\, WIMP')}\left(\langle {}^{A}_{Z}X^{*} | V_{weak} | {}^{A}_{Z}X \rangle, m_{WIMP}, S_{WIMP}, ..\right)$$

High sensitivity detection experiments

Fundamental properties of matter

High-precision nuclear structure information

Determination of E1 and M1 PSFs



R. Massarczyk *et al.*, PRC 90, 054310 (2014)

- In Xe region, M1 makes up about 10% of total strength
- Can have significant impact on photon strength functions
- Direct input for photonuclear / radiative-capture reactions in statistical reaction codes
- Central role in stellar nucleosynthesis