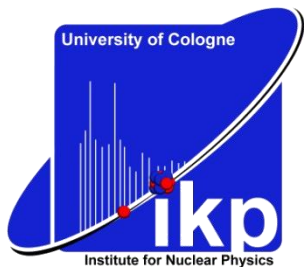


A pygmy quadrupole resonance in the stable Sn isotopes

Mark Spieker, Simon Glynn Pickstone, Sarah Prill*, and Andreas Zilges

Institute for Nuclear Physics, University of Cologne, Germany

**6th Workshop on Nuclear Level Density and Gamma Strength
Oslo (Norway)**



Supported by the DFG (ZI 510/7-1)

Special thanks to Nadia Tsoneva, Pavel Petkov and Elena Litvinova

*Supported by the Bonn-Cologne Graduate School of Physics and Astronomy



Bonn-Cologne Graduate School
of Physics and Astronomy

6th Workshop on Nuclear Level Density & γ Strength



4th in 2013

Attendance:
50 %

Talks:

2013: Double-octupole states
in the actinides

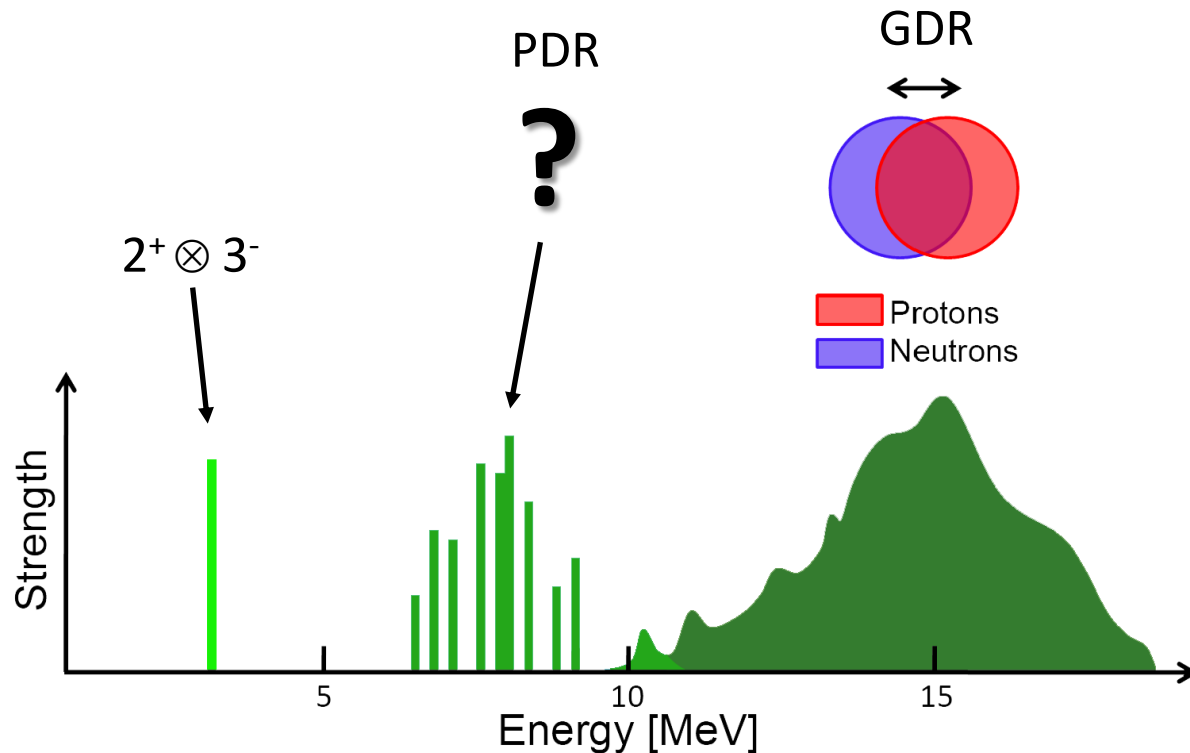
2015: α -cluster 1^- states in the
rare earths



5th in 2015

The pygmy dipole resonance (PDR)

The $E1$ response of nearly spherical nuclei



GDR: M.N. Harakeh, A. van der Woude, Giant Resonances, Oxford University Press (2001)

PDR: D. Savran, T. Aumann, A. Zilges, PPNP **70**, 210 (2013)

A. Bracco, F.C.L. Crespi, E.G. Lanza, EPJA **51**, 99 (2015)

QOC: U. Kneissl, N. Pietralla, and A. Zilges, J. Phys. G **32**, R217 (2006)

The pygmy dipole resonance (PDR)

E1 distribution studied via NRF with bremsstrahlung

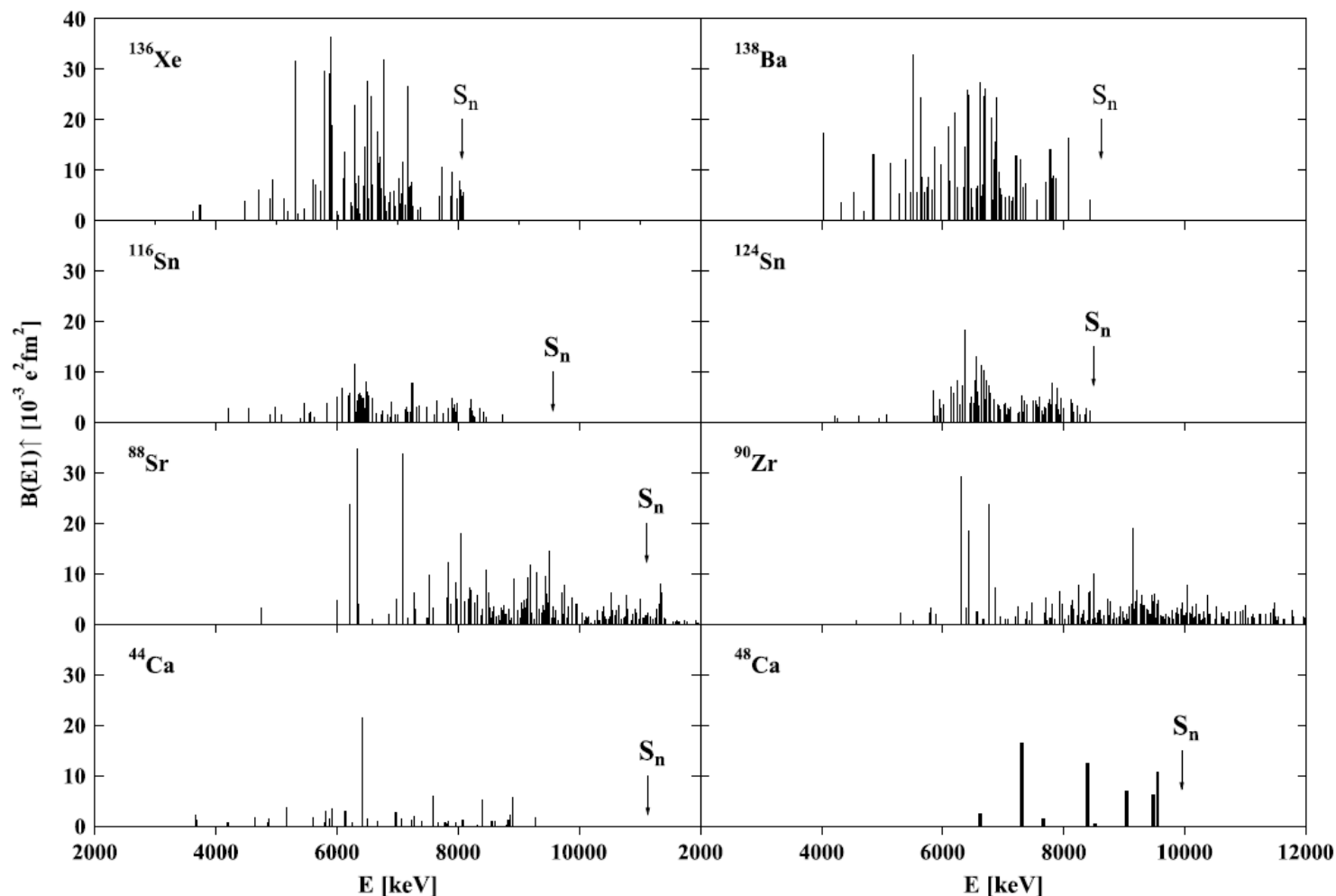


Figure: D. Savran, T. Aumann, and A. Zilges, PNP **70**, 210 (2013)

The pygmy dipole resonance (PDR)

$E1$ distribution studied via NRF with bremsstrahlung

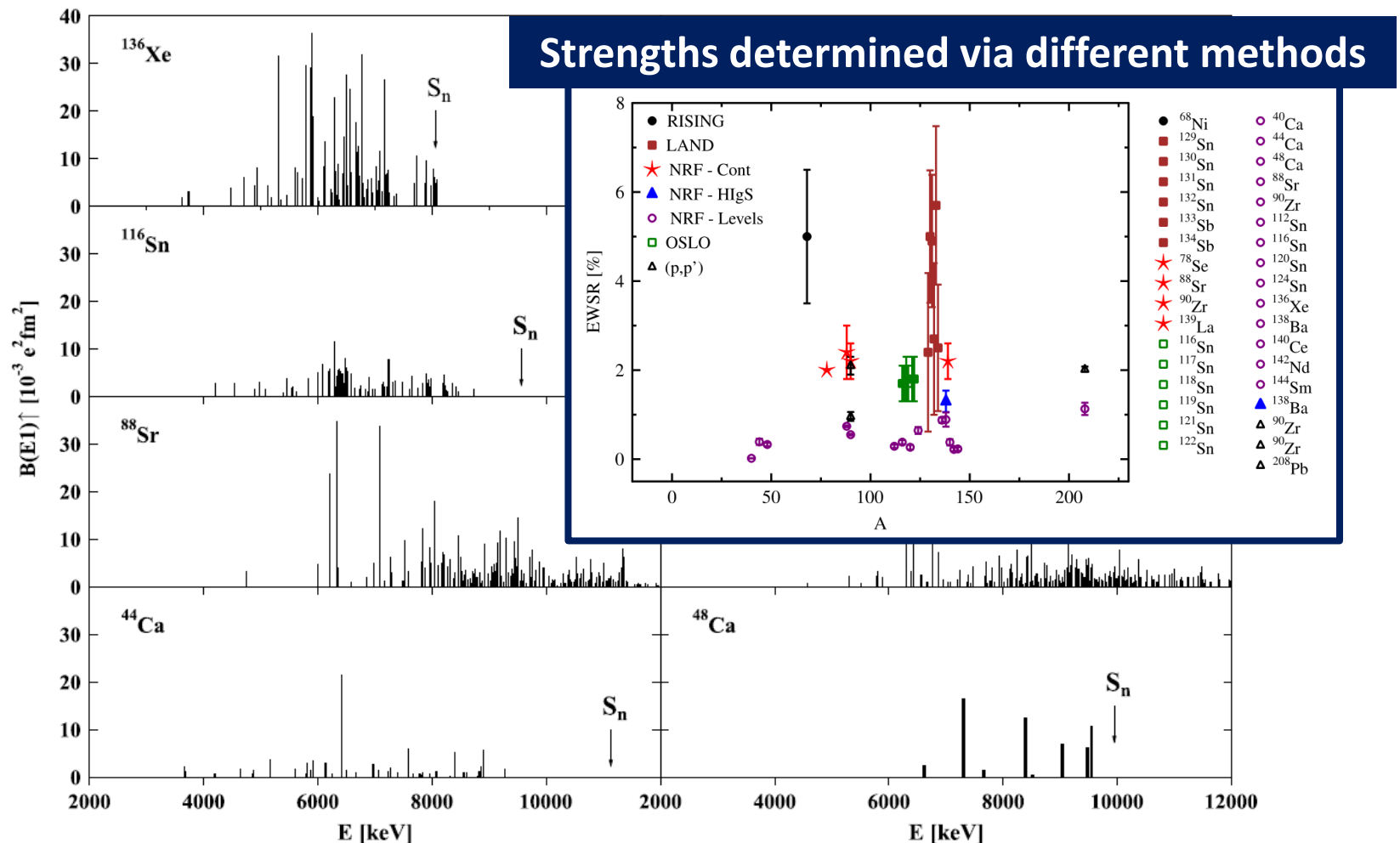


Figure: D. Savran, T. Aumann, and A. Zilges, PPNP **70**, 210 (2013)

The pygmy dipole resonance (PDR)

E1 distribution studied via NRF with bremsstrahlung

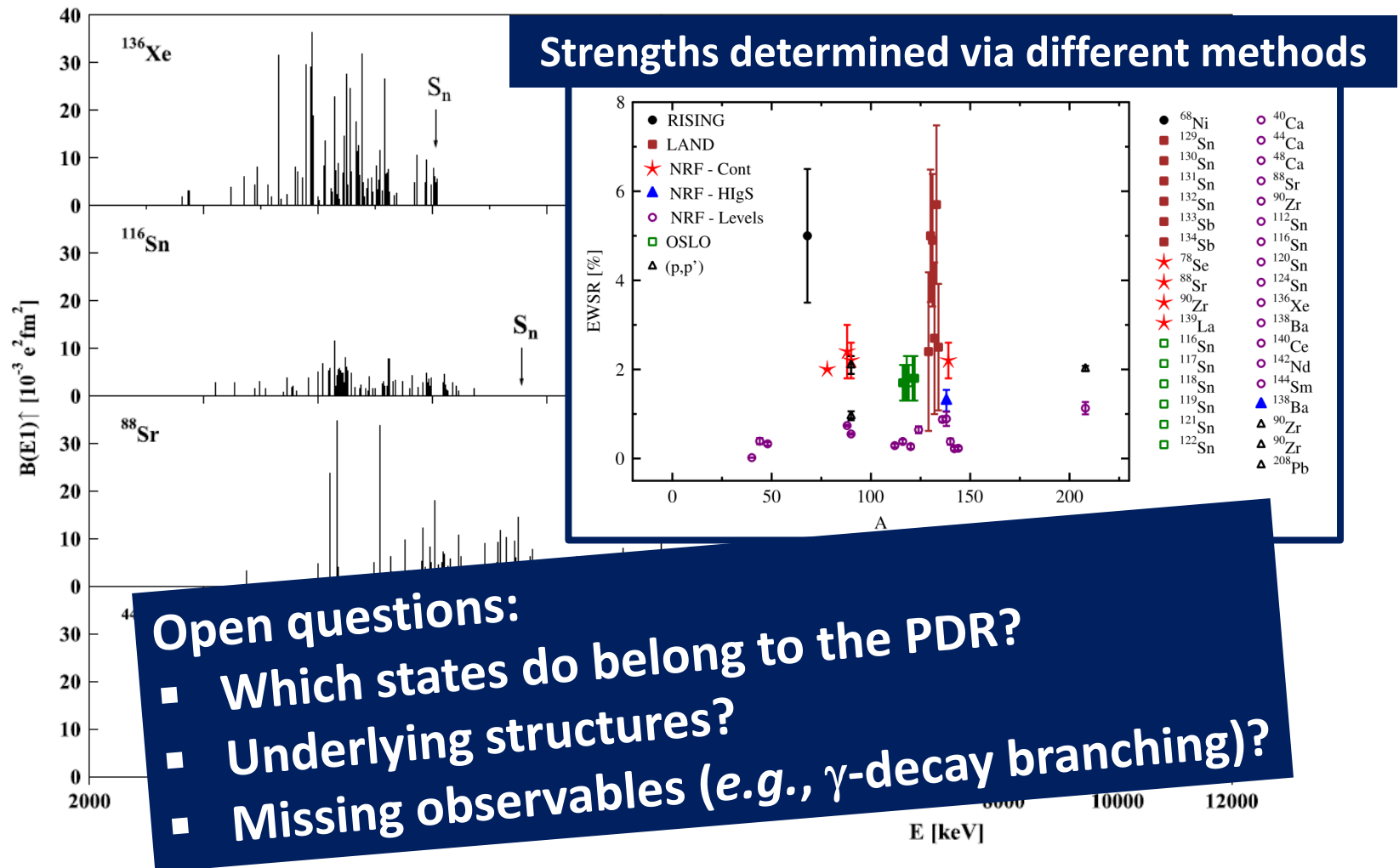
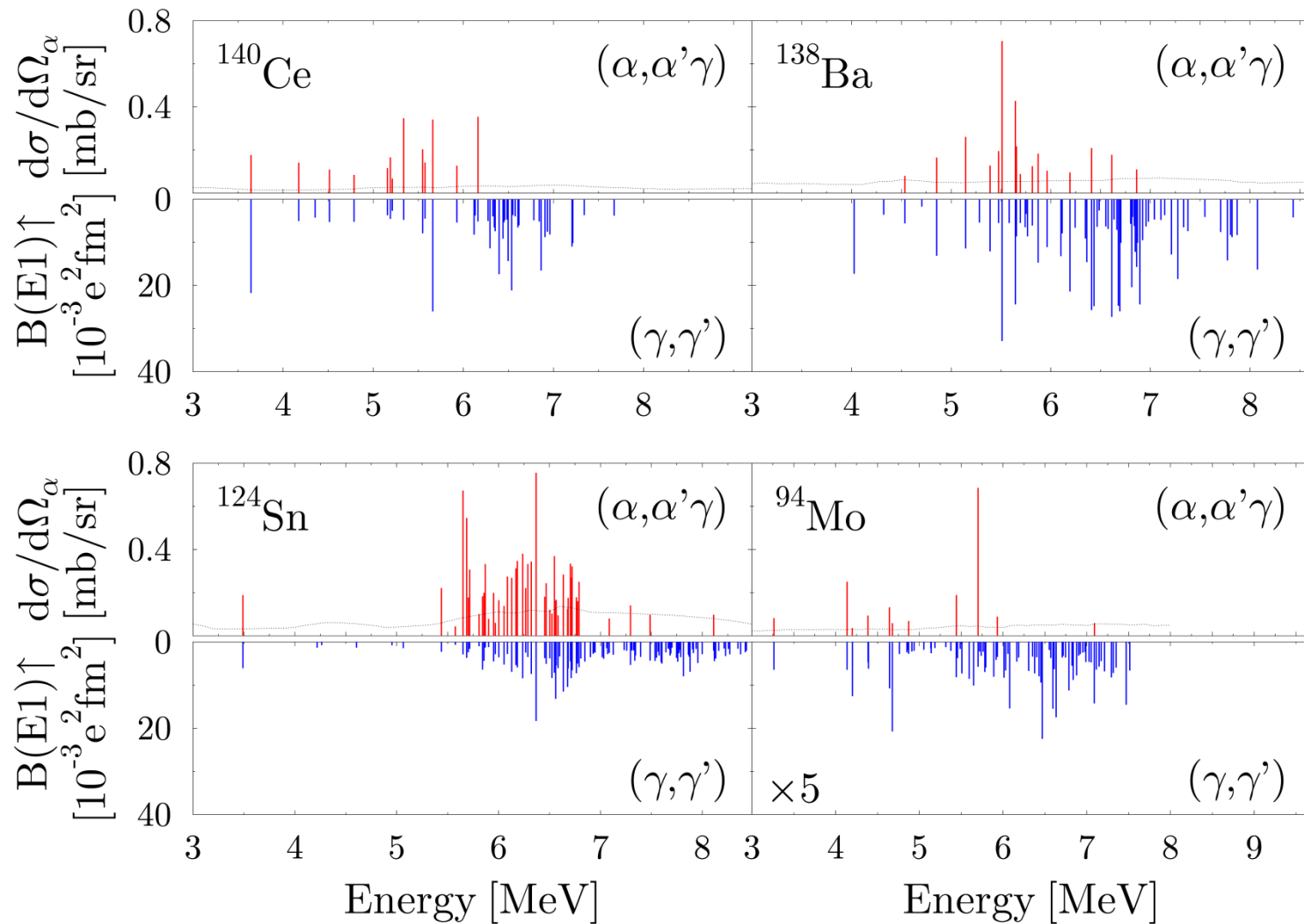


Figure: D. Savran, T. Aumann, and A. Zilges, PPNP **70**, 210 (2013)

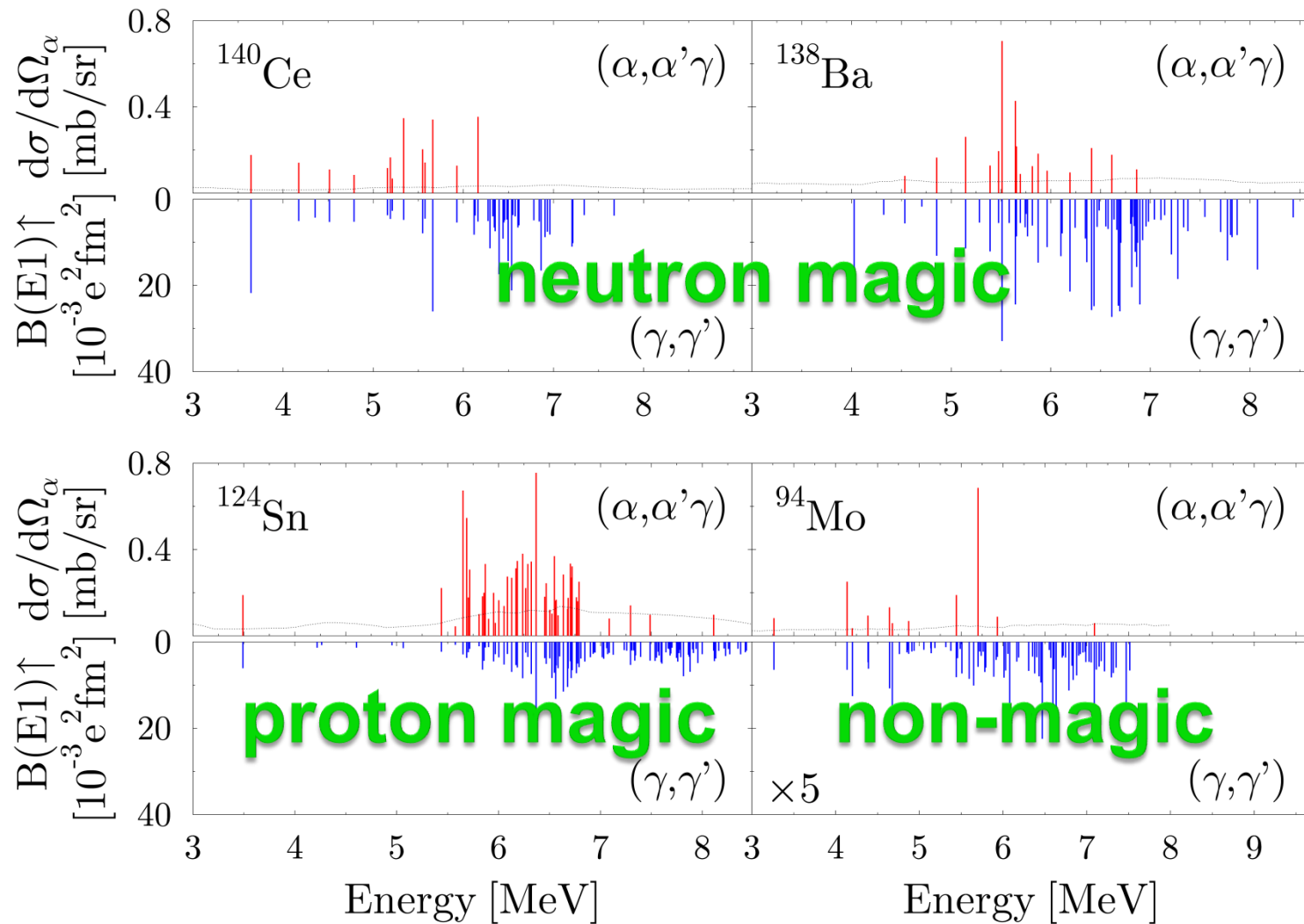
Isospin character studied in $(\alpha, \alpha'\gamma)$



D. Savran *et al.*, PRL **97** (2006) 172502
 J. Endres, E. Litvinova *et al.*, PRL **105** (2010) 212503

J. Endres *et al.*, PRC **80** (2009) 034302
 V. Derya *et al.*, NPA **906** (2013) 94

Isospin character studied in $(\alpha, \alpha'\gamma)$



D. Savran *et al.*, PRL **97** (2006) 172502
 J. Endres, E. Litvinova *et al.*, PRL **105** (2010) 212503

J. Endres *et al.*, PRC **80** (2009) 034302
 V. Derya *et al.*, NPA **906** (2013) 94

Isospin-mixed character confirmed in ($^{17}\text{O}, ^{17}\text{O}'\gamma$)

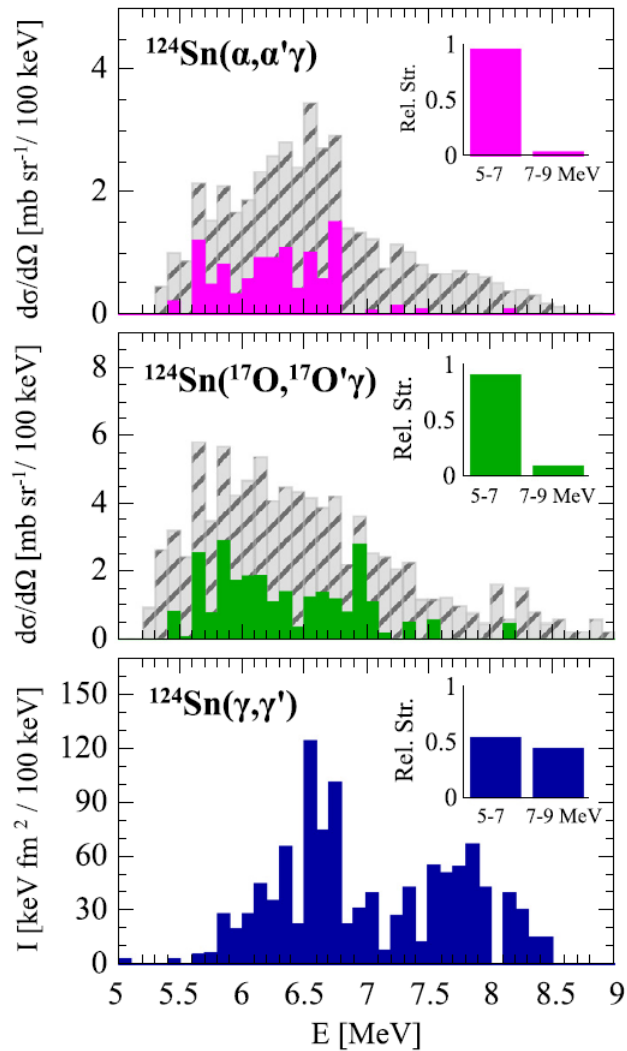


Figure: L. Pellegrini *et al.*, PLB **738**, 519 (2014)

Isospin-mixed character confirmed in ($^{17}\text{O}, ^{17}\text{O}'\gamma$)

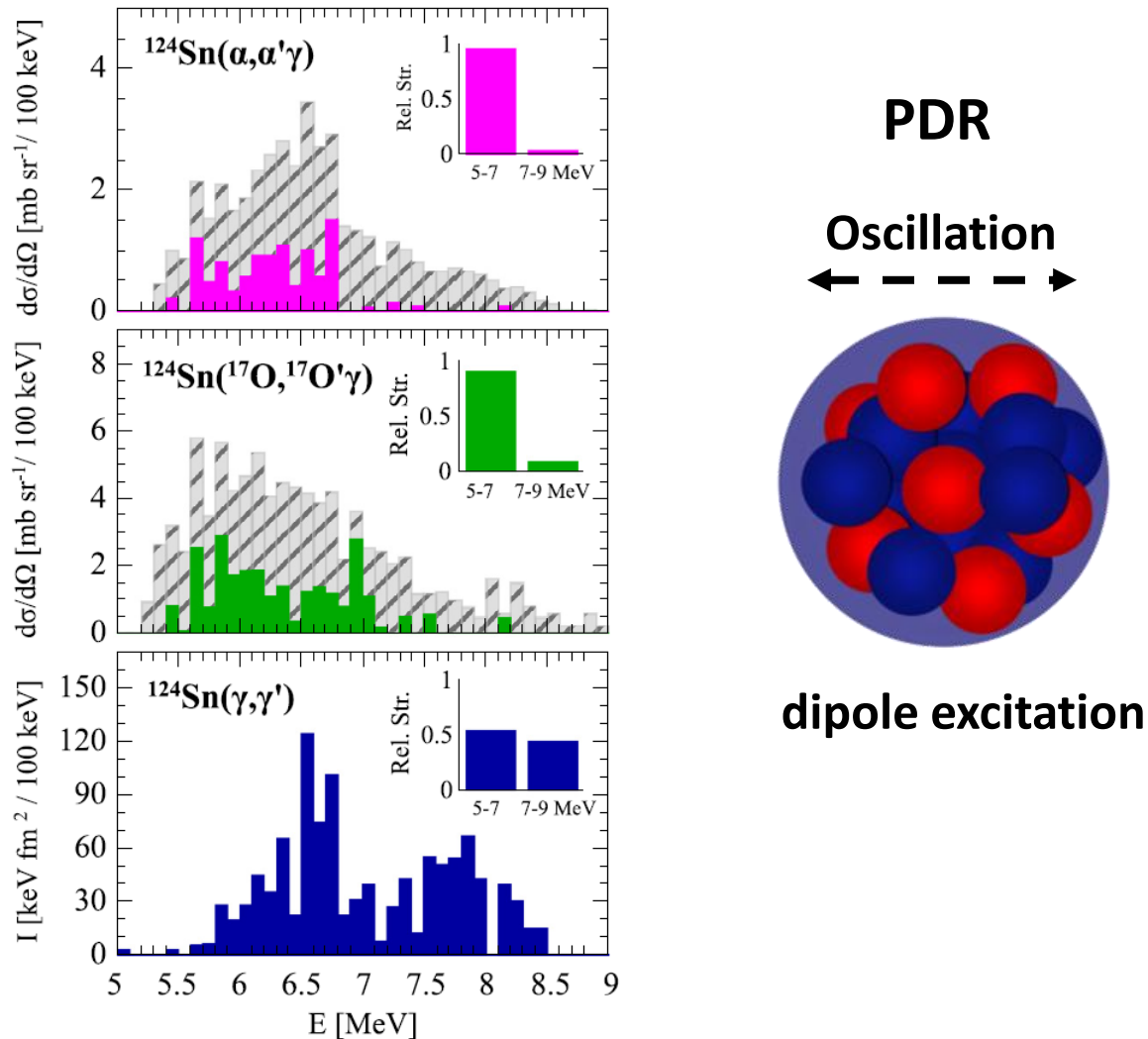
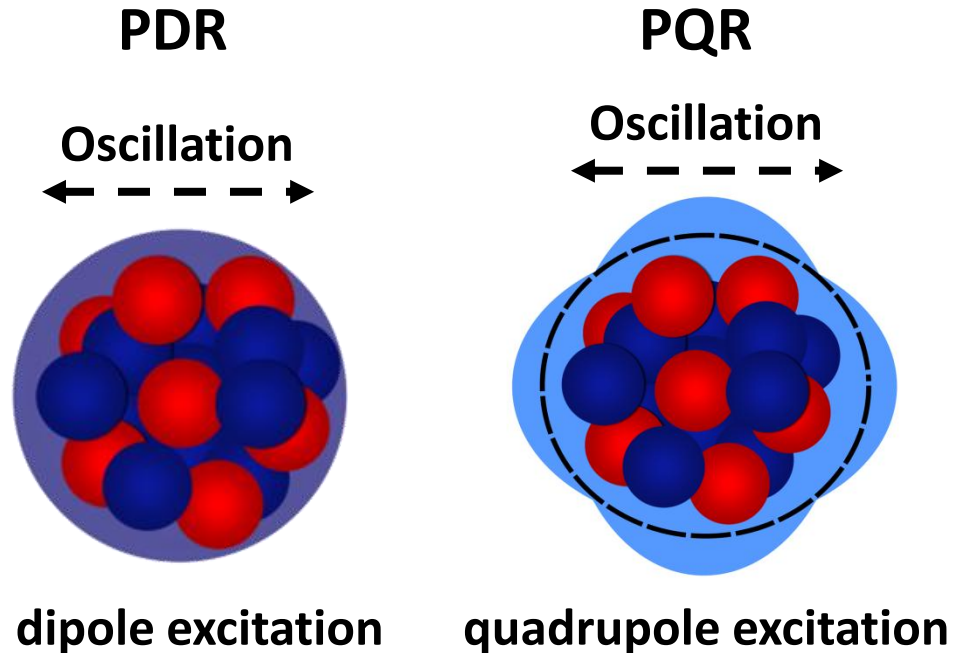
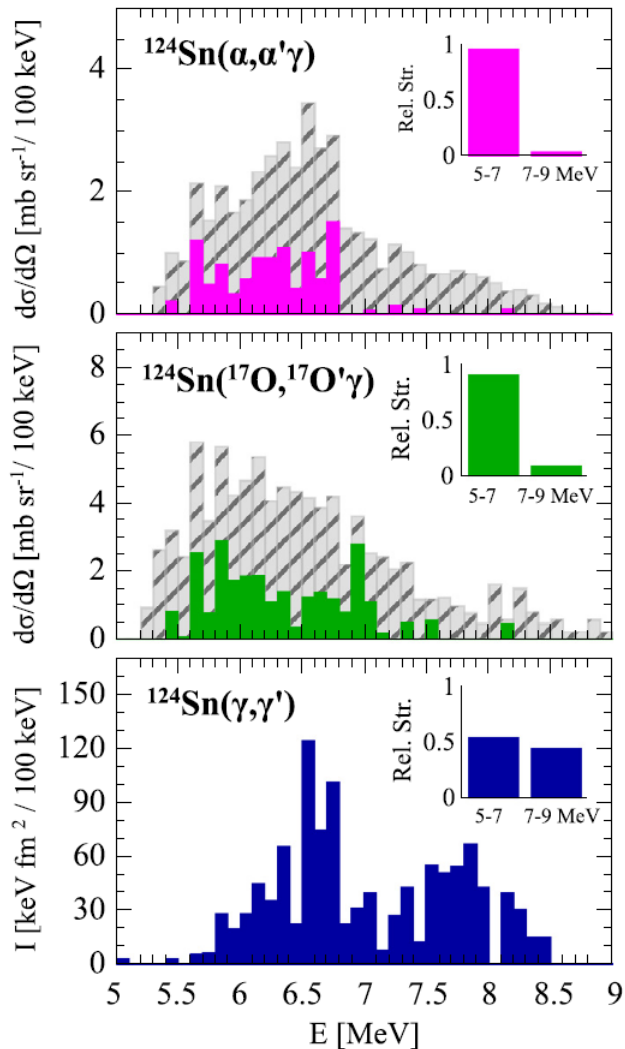


Figure: L. Pellegrini *et al.*, PLB **738**, 519 (2014)

Neutron-skin excitations?



... does the neutron skin oscillate?

First idea of a PQR in Sn isotopes:

N. Tsoneva, H. Lenske, PLB **695**, 174 (2011)

Figure: L. Pellegrini *et al.*, PLB **738**, 519 (2014)

A pygmy quadrupole resonance (PQR)?

Prediction of the Quasiparticle-Phonon Model (QPM)

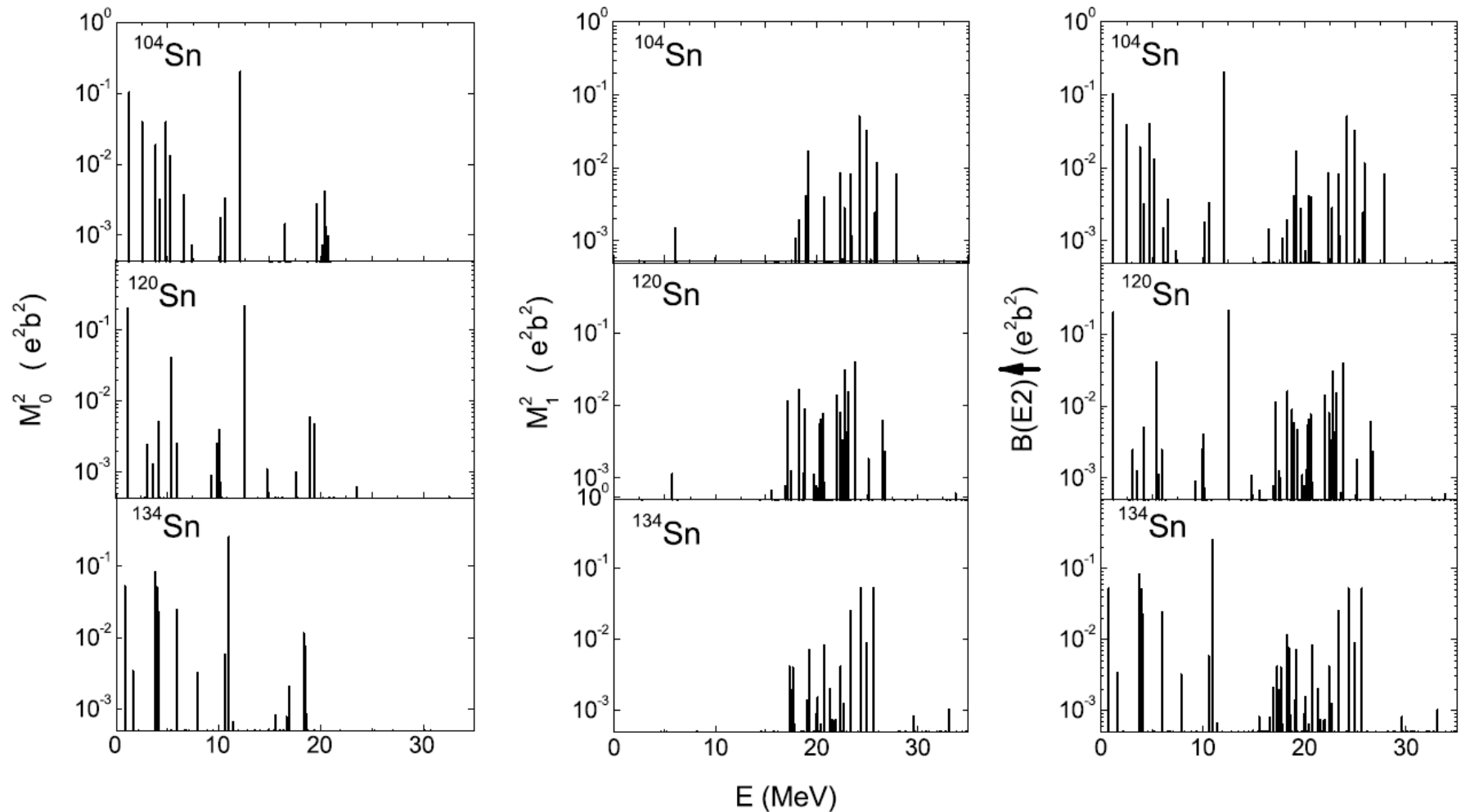


Figure: N. Tsoneva, H. Lenske, PLB **695**, 174 (2011)

A pygmy quadrupole resonance (PQR)?

Prediction of the Quasiparticle-Phonon Model (QPM)

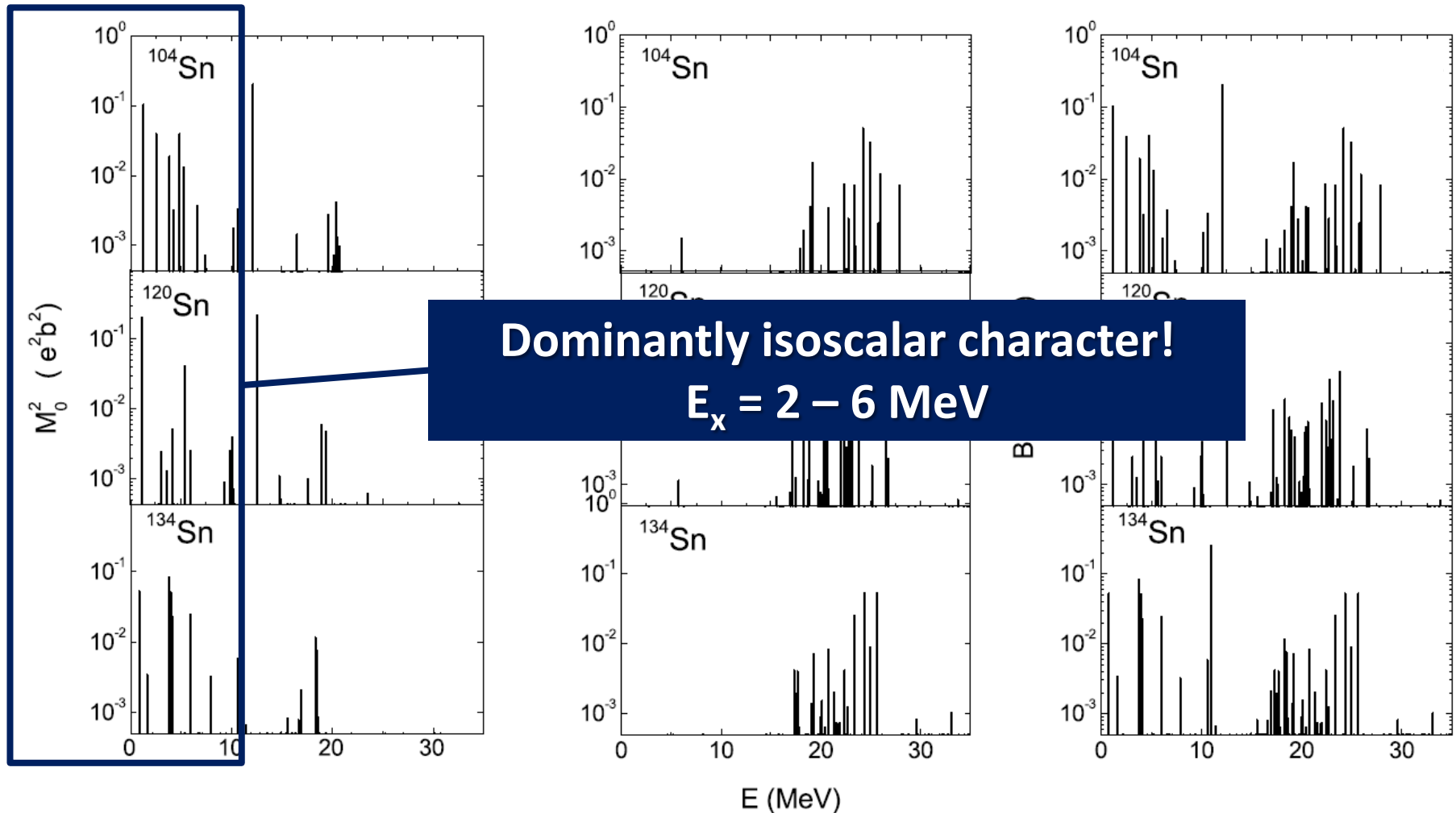
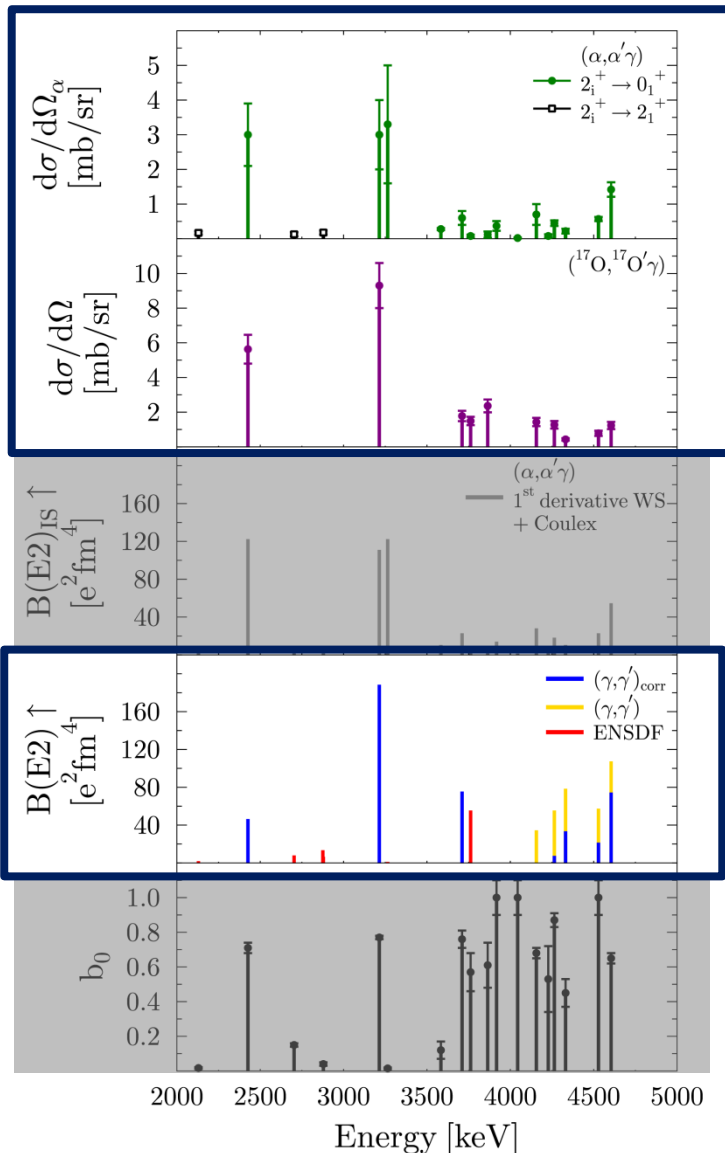


Figure: N. Tsoneva, H. Lenske, PLB **695**, 174 (2011)

The isospin character of 2^+ states in ^{124}Sn



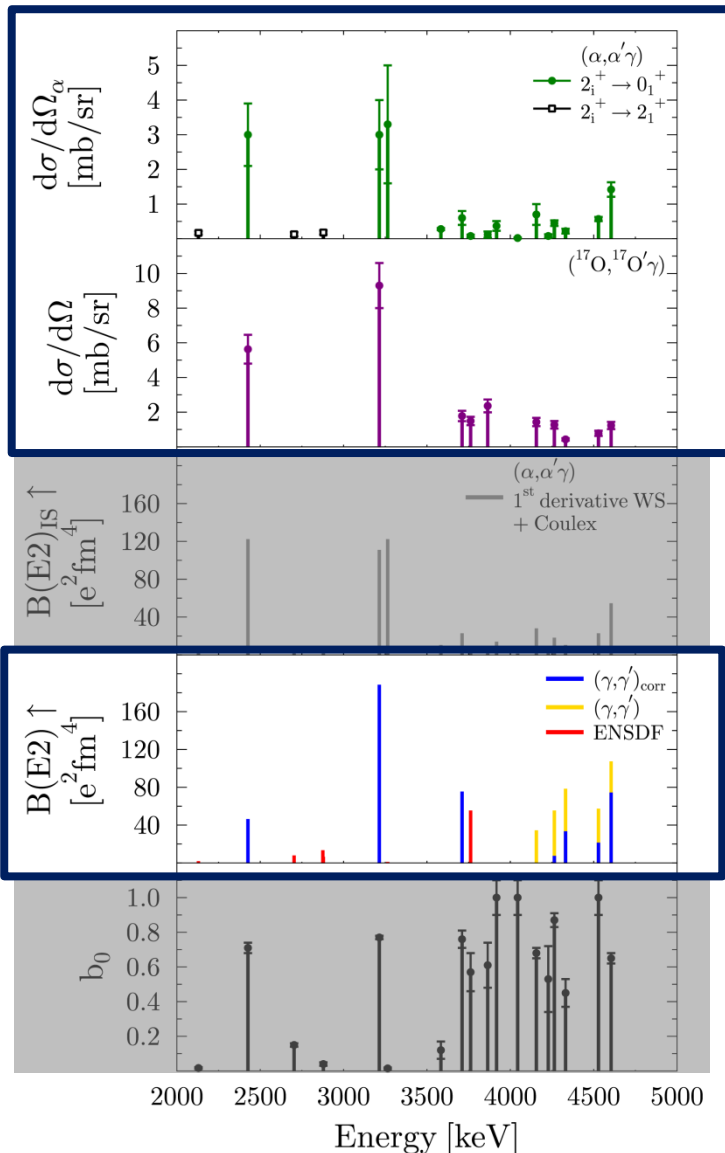
- **$(\alpha, \alpha'\gamma)$ @ Big-Bite Spectrometer**
KVI (Groningen, Netherlands)
 $E_\alpha = 34 \text{ MeV/u}$
- **$(^{17}\text{O}, ^{17}\text{O}'\gamma)$ with AGATA for γ -ray detection**
LNL (Legnaro, Italy)
 $E_{^{17}\text{O}} = 20 \text{ MeV/u}$
- **(γ, γ') using bremsstrahlung**
DHIPS (TU Darmstadt, Germany)
 $E_{e^-} = 7.8 \text{ MeV}$

$(^{17}\text{O}, ^{17}\text{O}'\gamma)$: L. Pellegrini *et al.*, PRC **92**, 014330 (2015)

$(\alpha, \alpha'\gamma)$ and $(\gamma, \gamma')_{4-5\text{MeV}}$: M. Spieker *et al.*, PLB **752**, 102 (2016)

$(\gamma, \gamma')_{2-4\text{MeV}}$: J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

The isospin character of 2^+ states in ^{124}Sn



- $(\alpha, \alpha'\gamma)$ @ Big-Bite Spectrometer
KVI (Groningen, Netherlands)
 $E_\alpha = 34 \text{ MeV/u}$
- $(^{17}\text{O}, ^{17}\text{O}'\gamma)$ with AGATA for γ -ray detection
LNL (Legnaro, Italy)
 $E_{^{17}\text{O}} = 20 \text{ MeV/u}$
- (γ, γ') using bremsstrahlung
DHIPS (TU Darmstadt, Germany)
 $E_{e^-} = 7.8 \text{ MeV}$

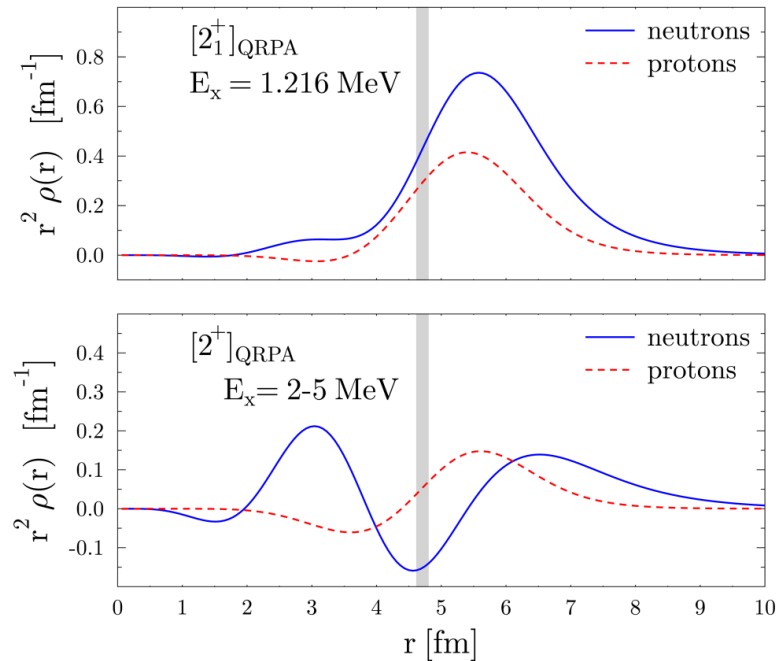
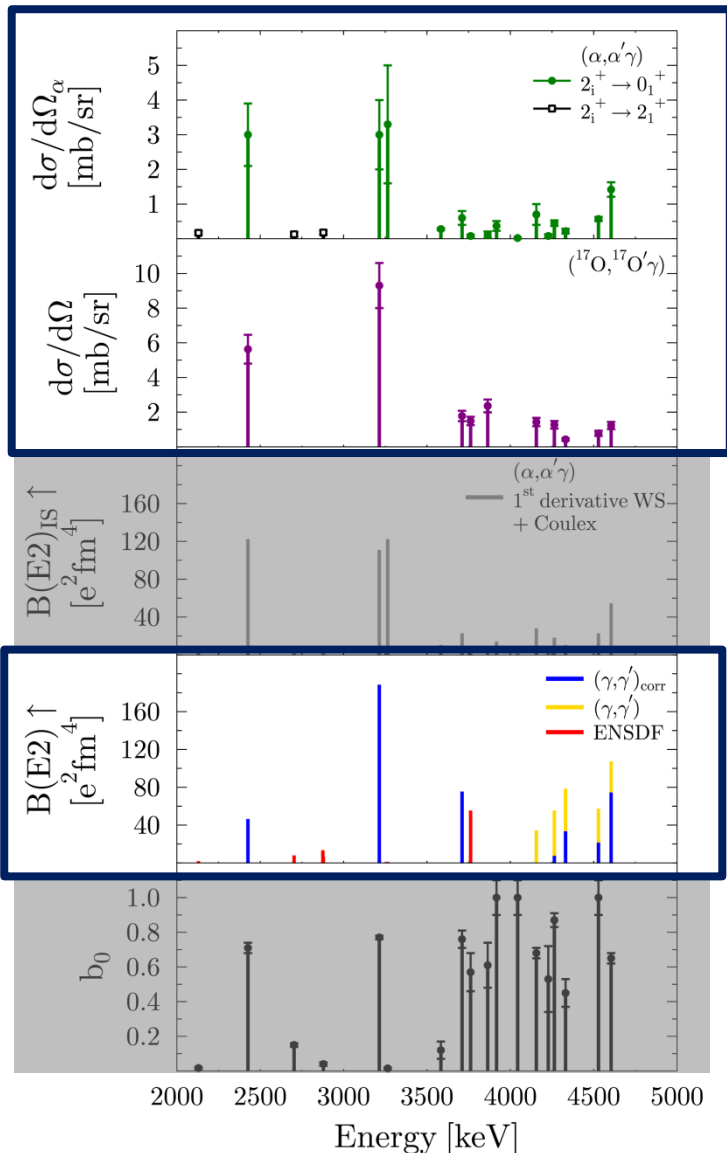
Isoscalar character of quadrupole excitations in ^{124}Sn confirmed!

$(^{17}\text{O}, ^{17}\text{O}'\gamma)$: L. Pellegrini *et al.*, PRC **92**, 014330 (2015)

$(\alpha, \alpha'\gamma)$ and $(\gamma, \gamma')_{4-5\text{MeV}}$: M. Spieker *et al.*, PLB **752**, 102 (2016)

$(\gamma, \gamma')_{2-4\text{MeV}}$: J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

The isospin character of 2^+ states in ^{124}Sn



Isoscalar character of quadrupole excitations in ^{124}Sn confirmed!

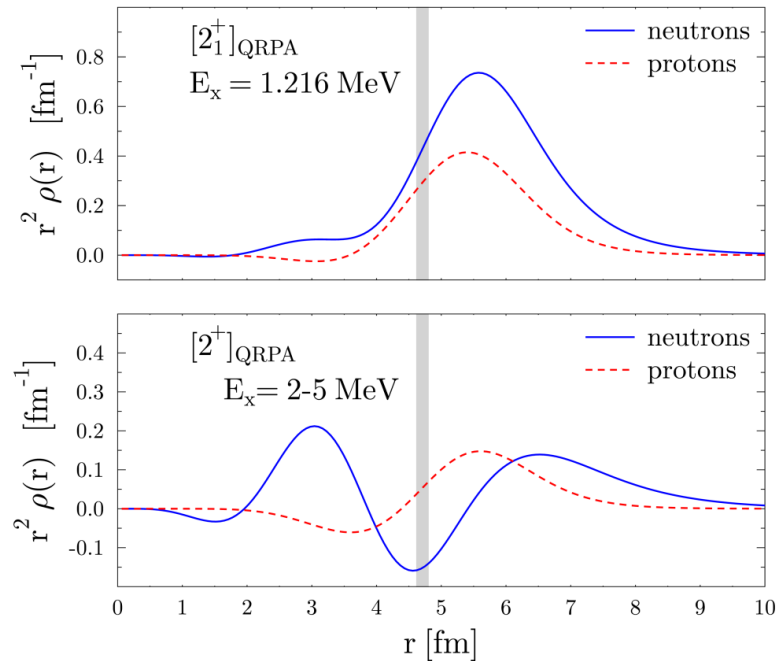
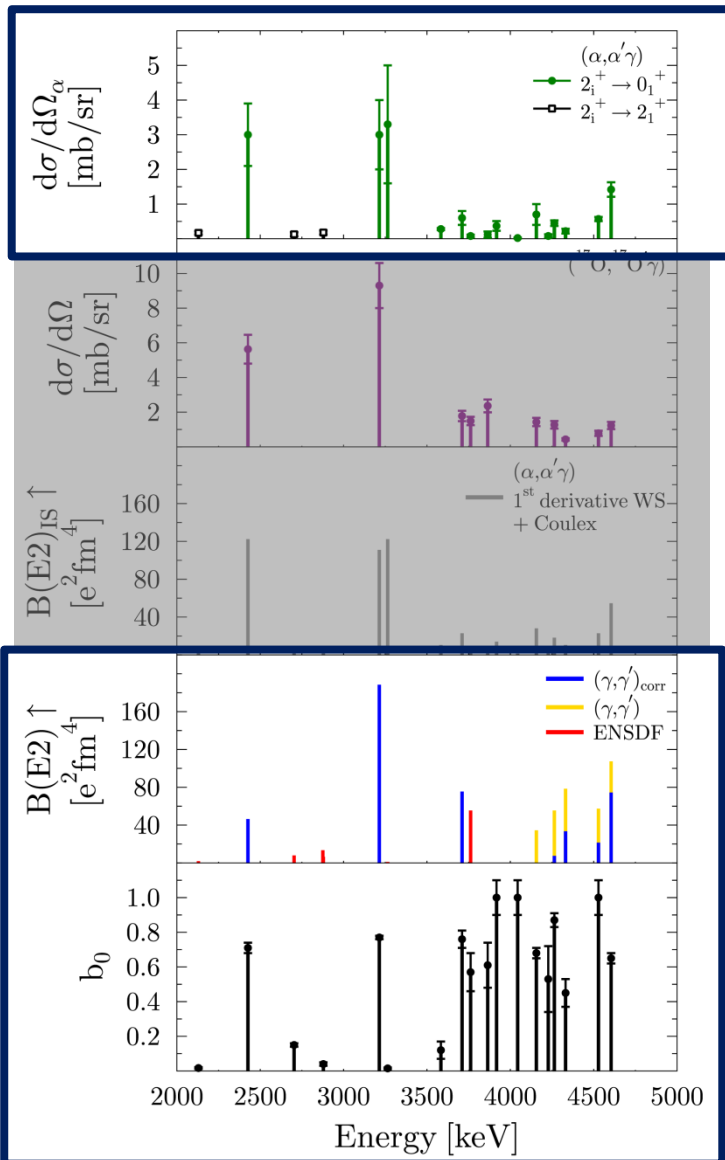
... also multiphonon states will be dominantly isoscalar

$(^{17}\text{O}, ^{17}\text{O}'\gamma)$: L. Pellegrini *et al.*, PRC **92**, 014330 (2015)

$(\alpha, \alpha'\gamma)$ and $(\gamma, \gamma')_{4-5\text{MeV}}$: M. Spieker *et al.*, PLB **752**, 102 (2016)

$(\gamma, \gamma')_{2-4\text{MeV}}$: J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

The isospin character of 2^+ states in ^{124}Sn



Isoscalar character of quadrupole excitations in ^{124}Sn confirmed!

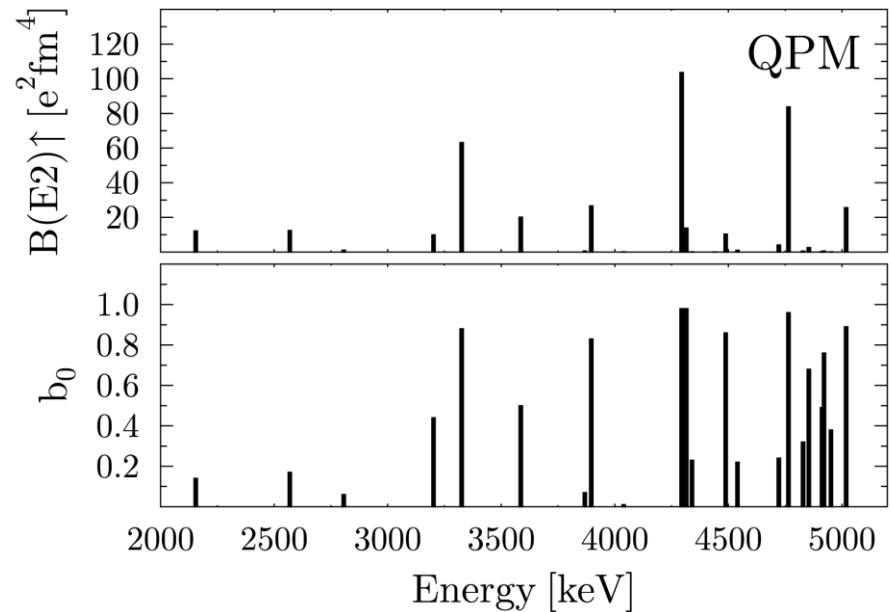
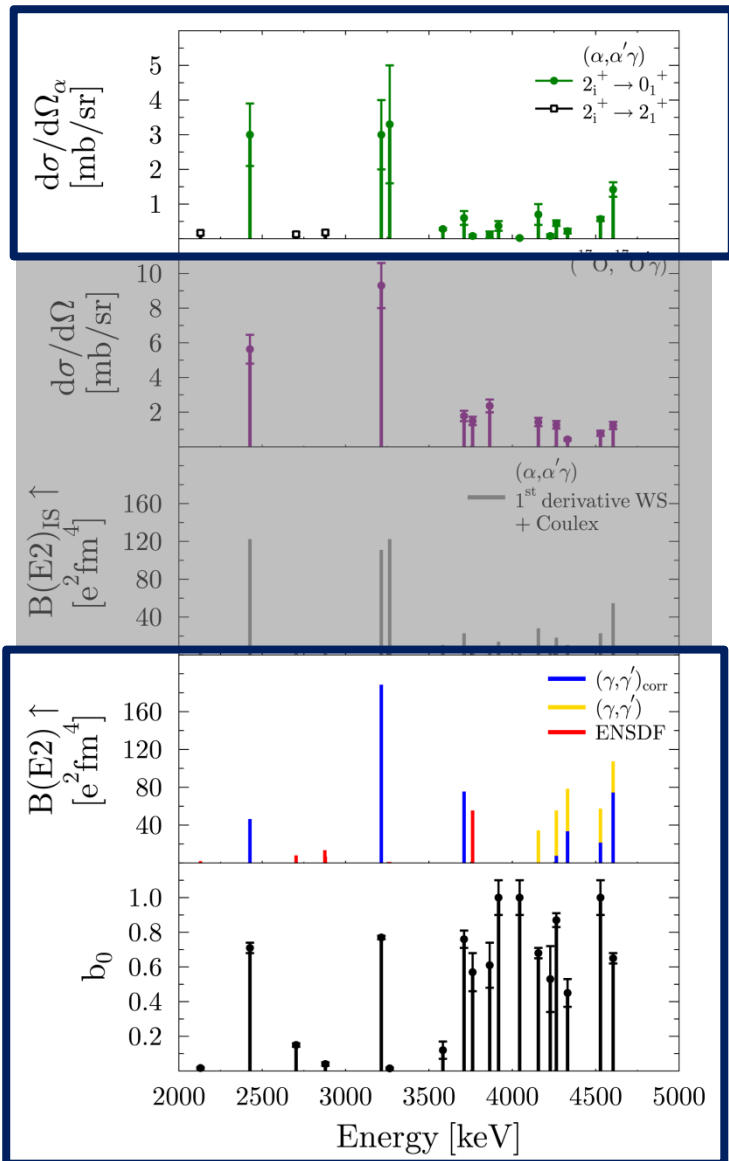
... also multiphonon states will be dominantly isoscalar

$(^{17}\text{O}, ^{17}\text{O}'\gamma)$: L. Pellegrini *et al.*, PRC **92**, 014330 (2015)

$(\alpha, \alpha'\gamma)$ and $(\gamma, \gamma')_{4-5\text{MeV}}$: M. Spieker *et al.*, PLB **752**, 102 (2016)

$(\gamma, \gamma')_{2-4\text{MeV}}$: J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

The isospin character of 2^+ states in ^{124}Sn

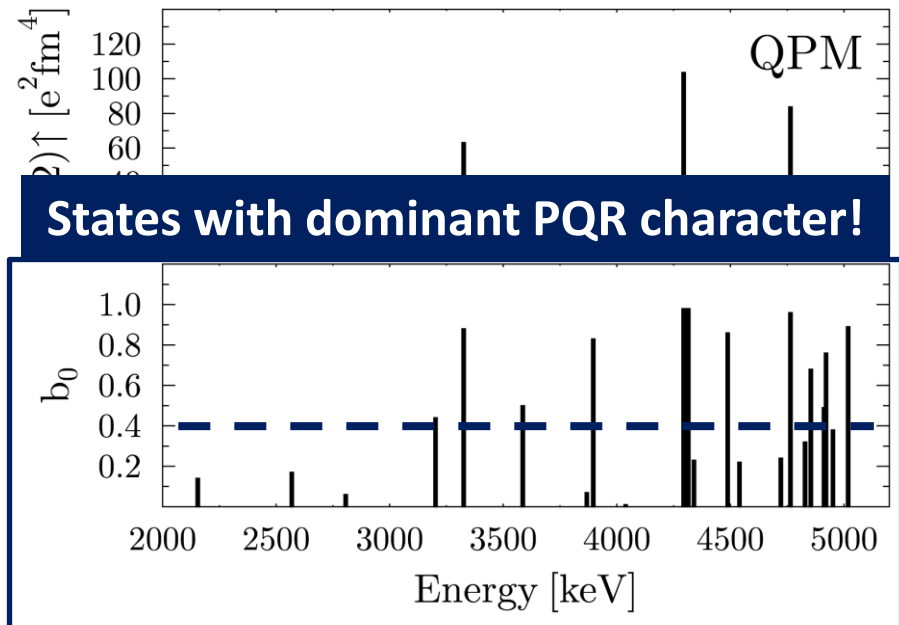
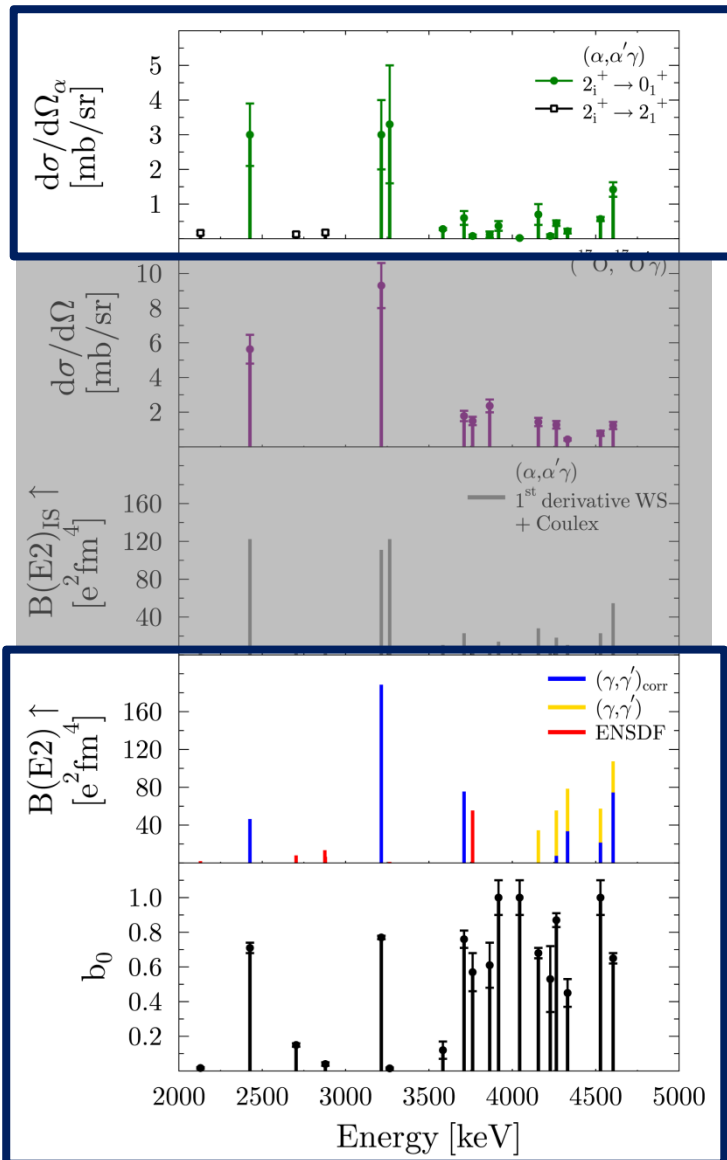


$(^{17}\text{O}, ^{17}\text{O}'\gamma)$: L. Pellegrini *et al.*, PRC **92**, 014330 (2015)

$(\alpha, \alpha'\gamma)$ and $(\gamma, \gamma')_{4-5\text{MeV}}$: M. Spieker *et al.*, PLB **752**, 102 (2016)

$(\gamma, \gamma')_{2-4\text{MeV}}$: J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

The isospin character of 2^+ states in ^{124}Sn



States with dominant PQR character!

Dominant ground-state decays are observed in experiment and theory!

→ A clear signature for the PQR?

$(^{17}\text{O}, ^{17}\text{O}'\gamma)$: L. Pellegrini *et al.*, PRC **92**, 014330 (2015)

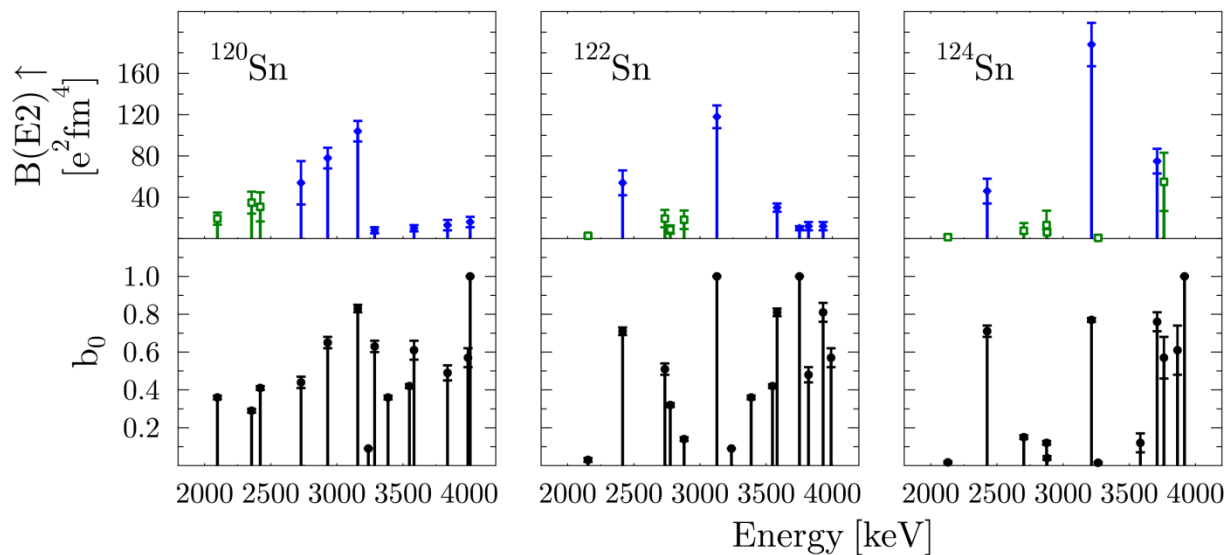
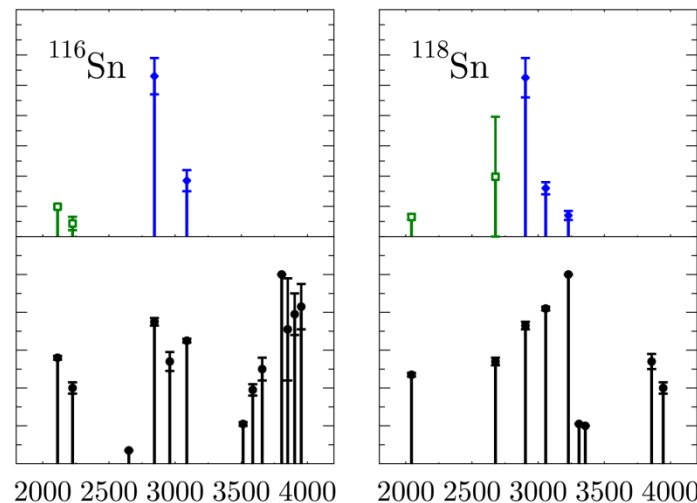
$(\alpha, \alpha'\gamma)$ and $(\gamma, \gamma')_{4-5\text{MeV}}$: M. Spieker *et al.*, PLB **752**, 102 (2016)

$(\gamma, \gamma')_{2-4\text{MeV}}$: J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

Systematic study of $E2$ strength in Sn isotopes

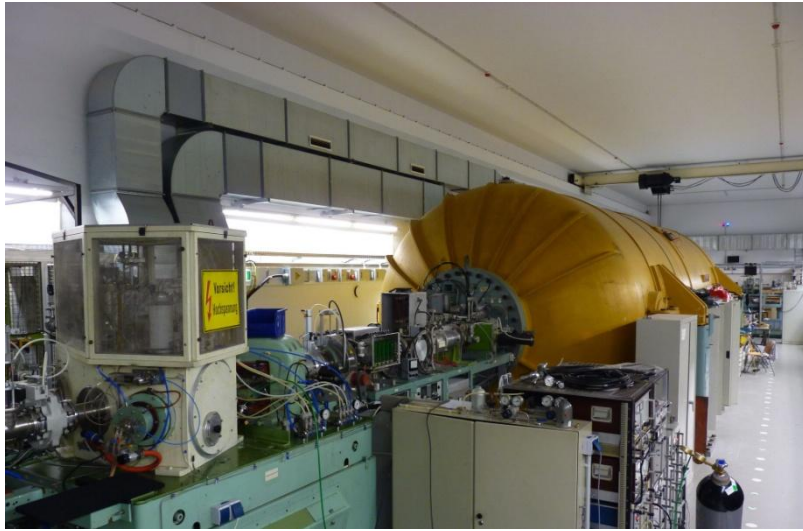
112,114Sn?

$B(E2) \uparrow$
[$e^2 \text{fm}^4$]
 b_0



(γ, γ') : J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

Particle- γ coincidences with SONIC@HORUS



10 MV FN Tandem ion accelerator

- Three ion sources available
→ typically ions up to $Z = 30$
- Terminal voltages from 1 MV to 10 MV
- Current on target up to 1 μA (protons)
- **Experimental setups:**
new AMS beamline, Plunger setup, Orange spectrometer, LYCCA, HORUS spectrometer

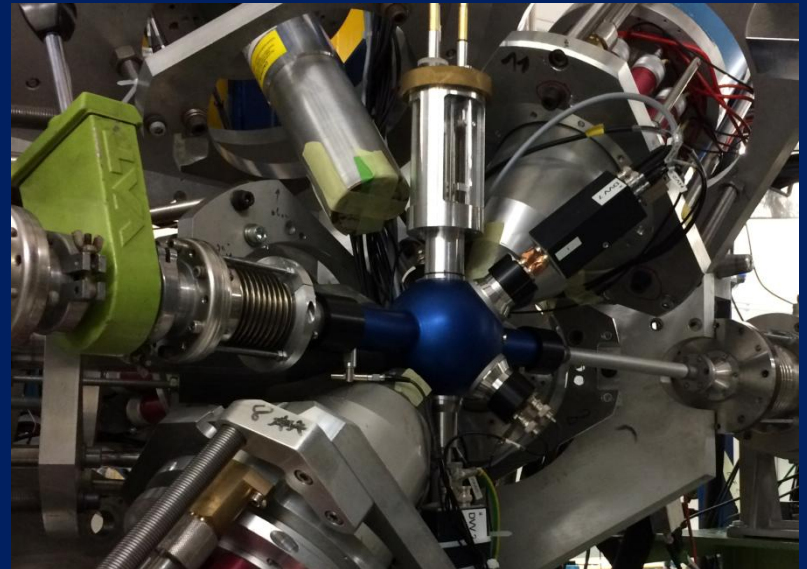
The SONIC@HORUS setup

HORUS for γ -ray detection

- Up to 14 HPGe detectors
→ Six BGO shields and two Clover HPGe detectors available

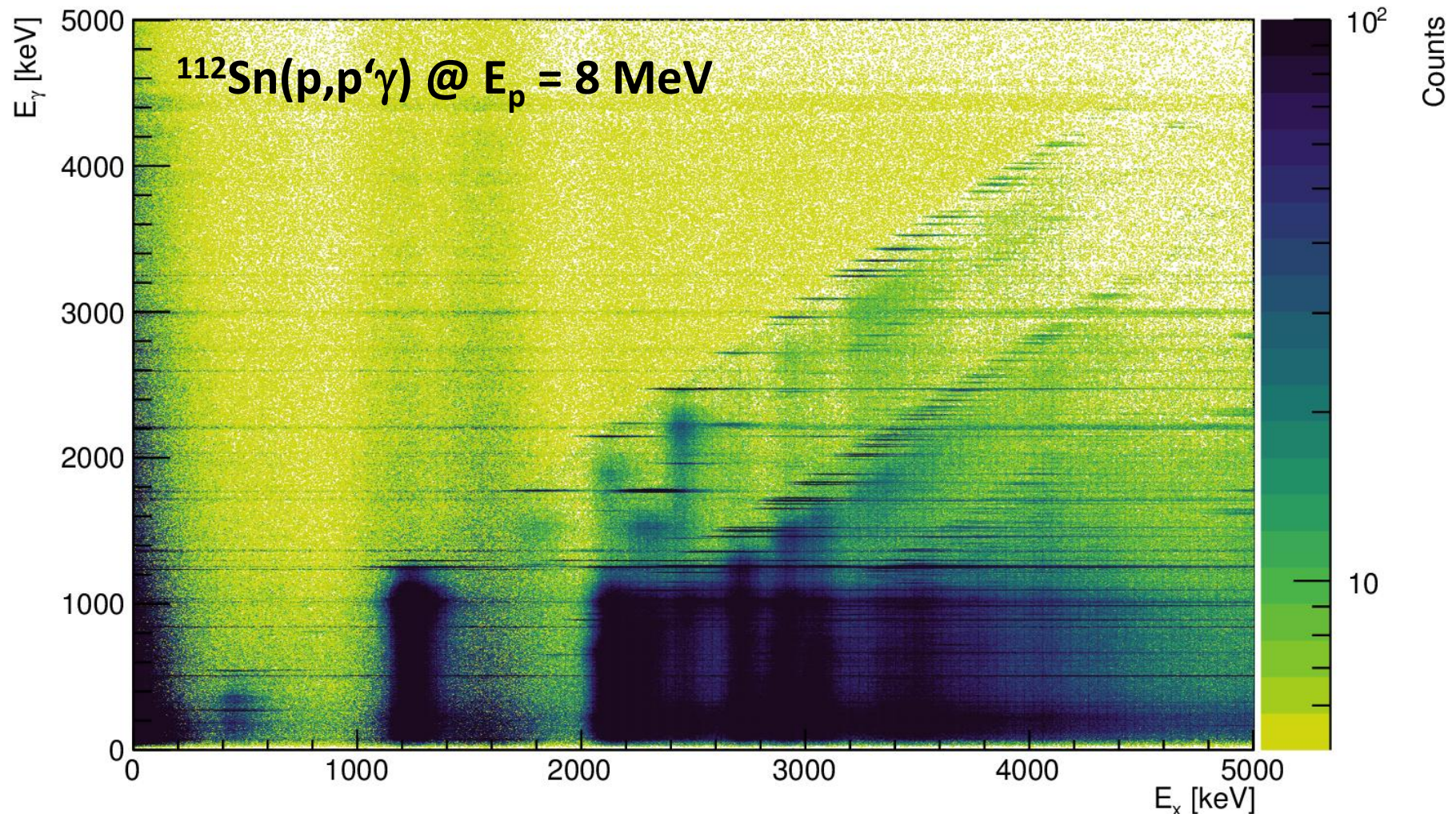
SONIC for particle detection

- 7-12 silicon detectors (thickness ≤ 1.5 mm)
- Particle- γ coincidences (Lifetimes, branching ratios, angular correlations)



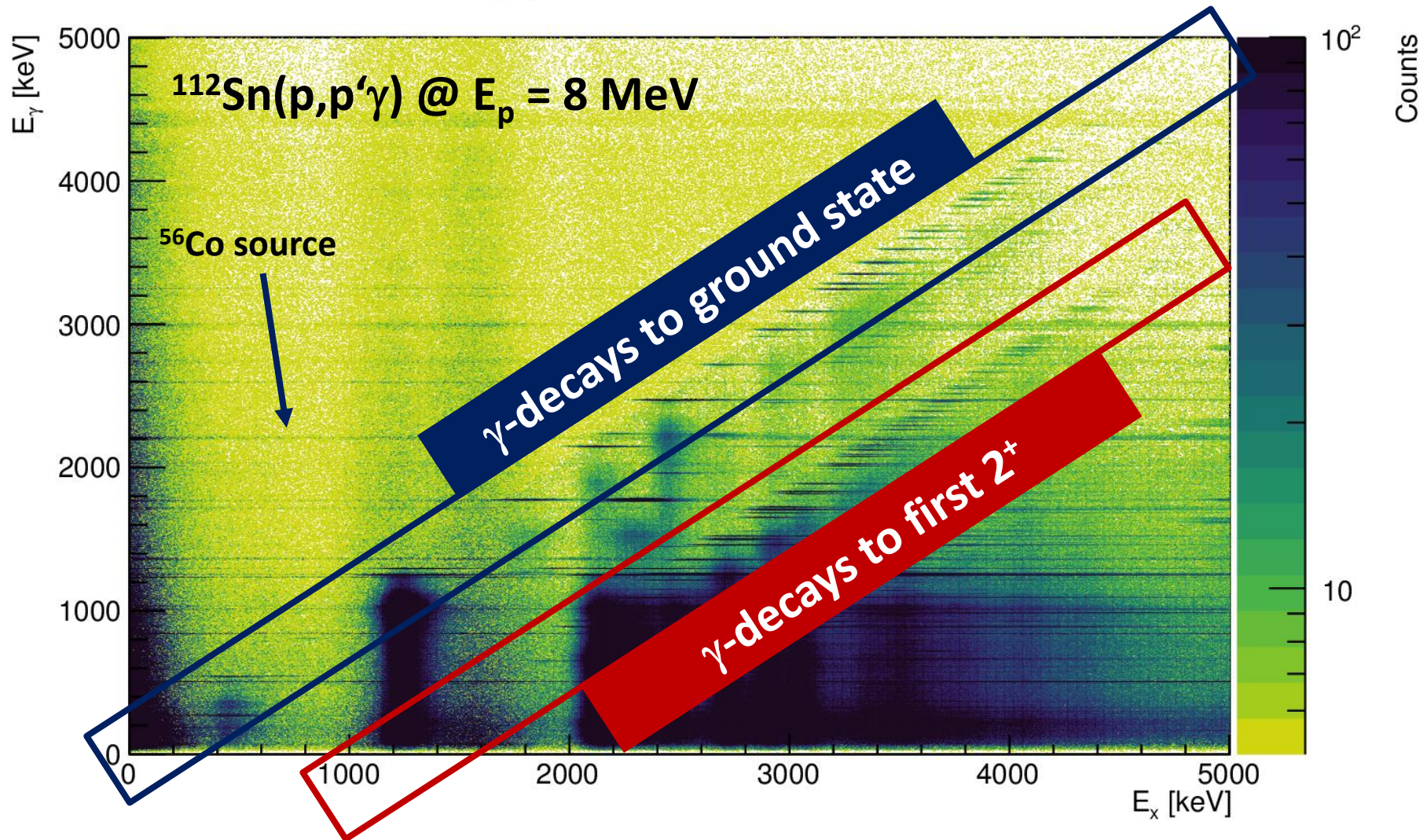
Particle- γ coincidences with SONIC@HORUS

py-coincidence matrix

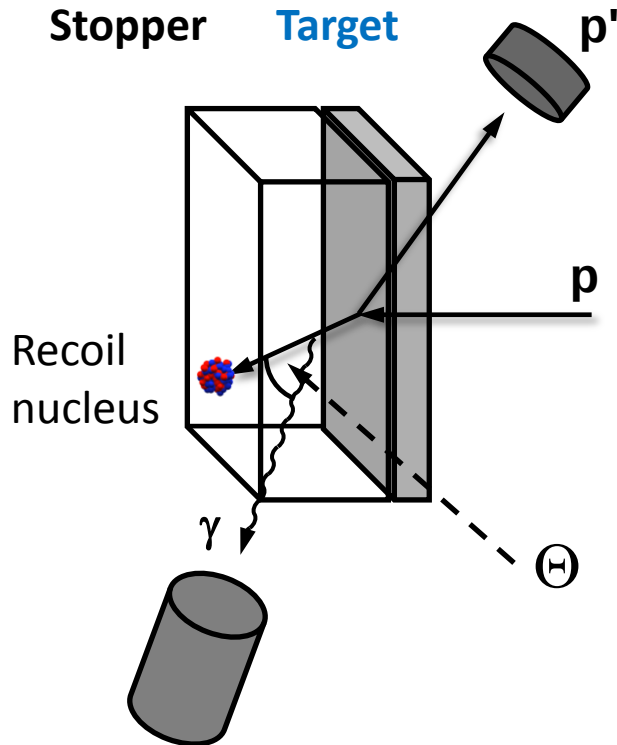


Particle- γ coincidences with SONIC@HORUS

py-coincidence matrix



Determination of γ -energy centroid shifts due to Doppler effect



$$E_{\gamma}(\Theta, t) = E_{\gamma}^0 \left(1 + F(\tau) \frac{v_0}{c} \cos \Theta \right)$$

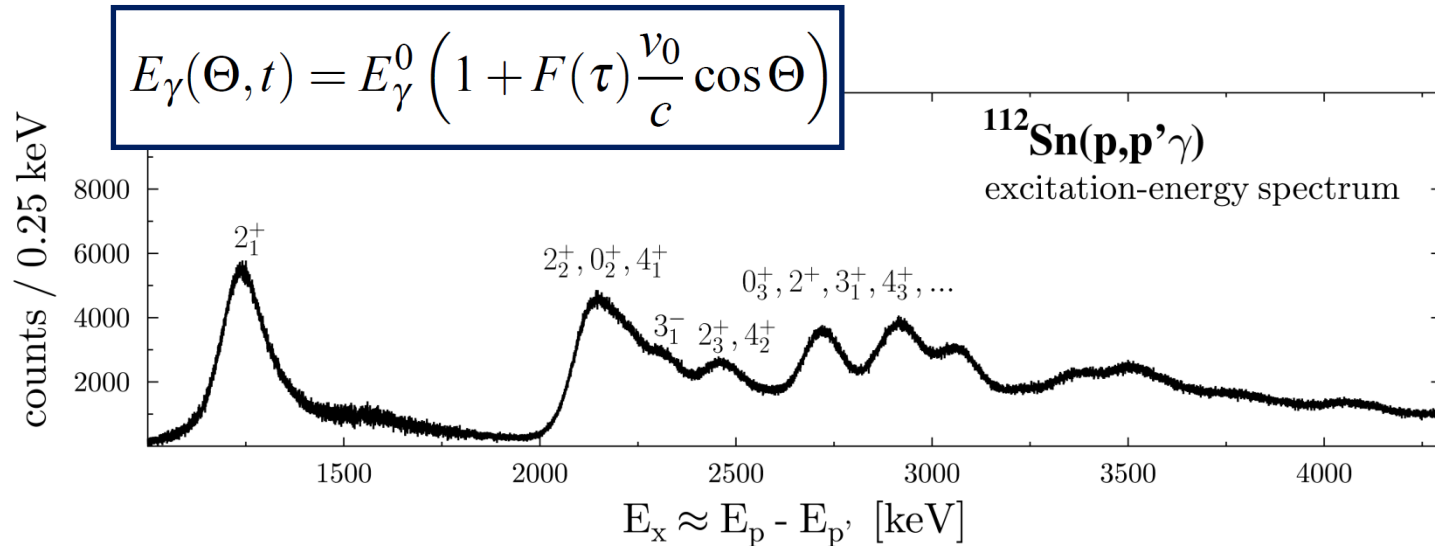
The (p,p'γ) DSA coincidence technique

- Lifetimes from 10 fs to 1 ps can be measured
- Feeding from higher-lying states excluded due to pγ coincidences (excitation gate)
- γ -decay branching can be measured
→ Partial decay widths accessible
- Dozens of lifetimes in one experiment!
- $J = 0 - 5$ are excited with (p,p'γ)

(p,p'γ) DSA coincidence technique: A. Hennig *et al.*, NIM **794**, 171 (2015)

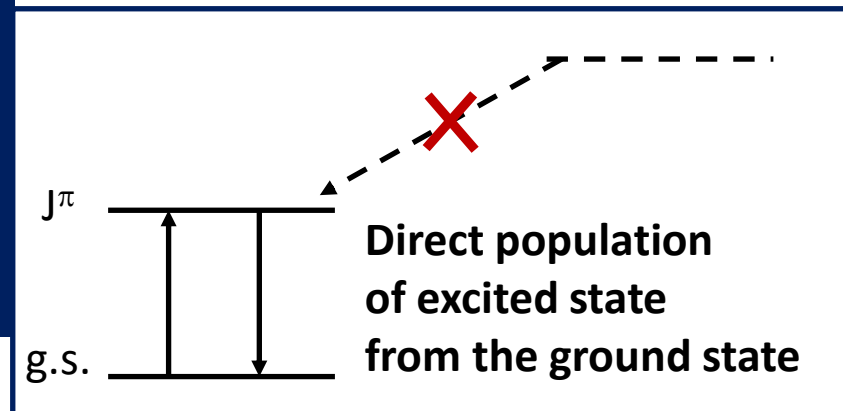
DSA lifetime measurements with SONIC@HORUS

Determination of γ -energy centroid shifts due to Doppler effect



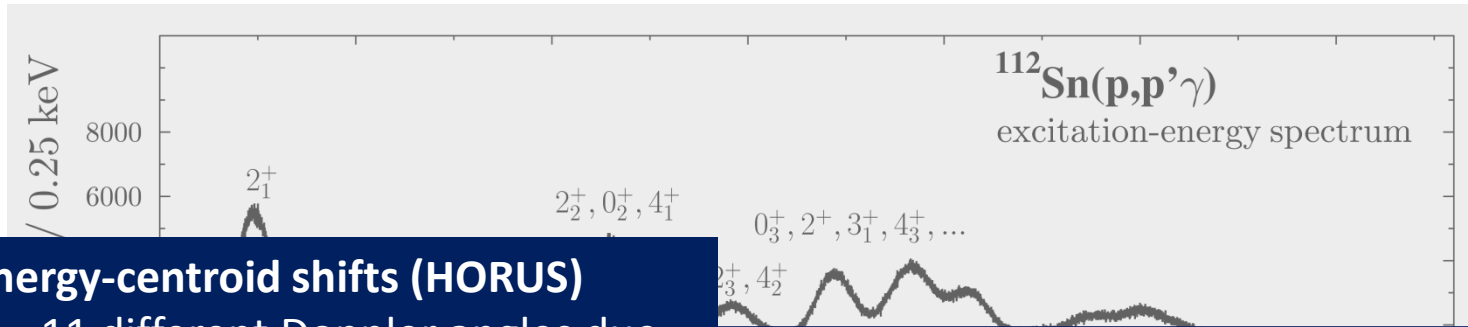
Excitation-energy gate (SONIC)

- v_0 is known from kinematics
→ Relevant angles and energies are measured
- Feeding can be excluded!
→ Extraction of real lifetime



DSA lifetime measurements with SONIC@HORUS

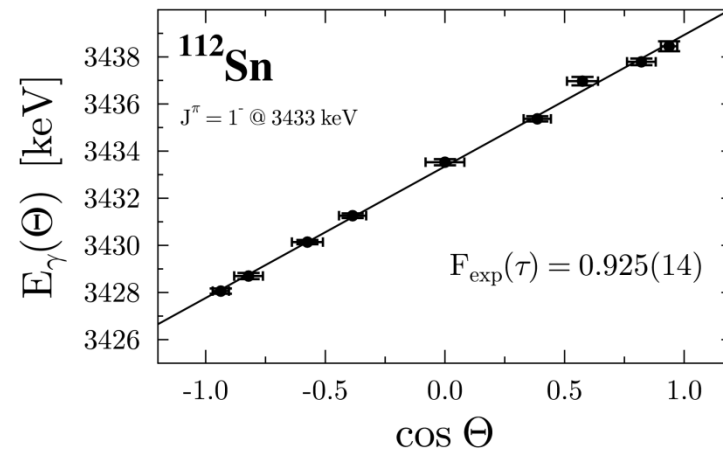
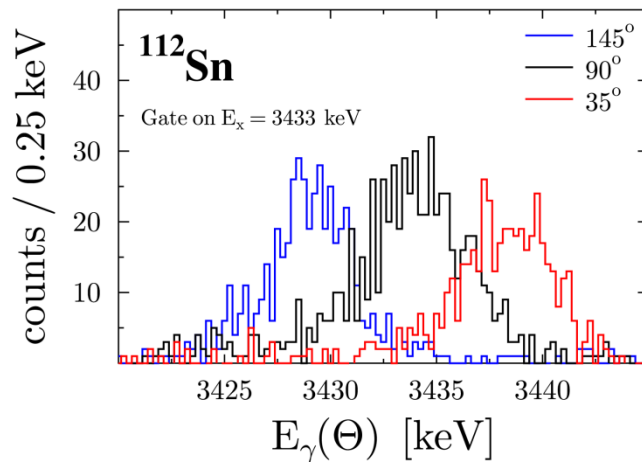
Determination of γ -energy centroid shifts due to Doppler effect



Energy-centroid shifts (HORUS)

- 11 different Doppler angles due to Si-HPGe correlation groups
- Clear observation of energy shifts

$$E_\gamma(\Theta, t) = E_\gamma^0 \left(1 + F(\tau) \frac{v_0}{c} \cos \Theta \right)$$



DSA lifetime measurements with SONIC@HORUS

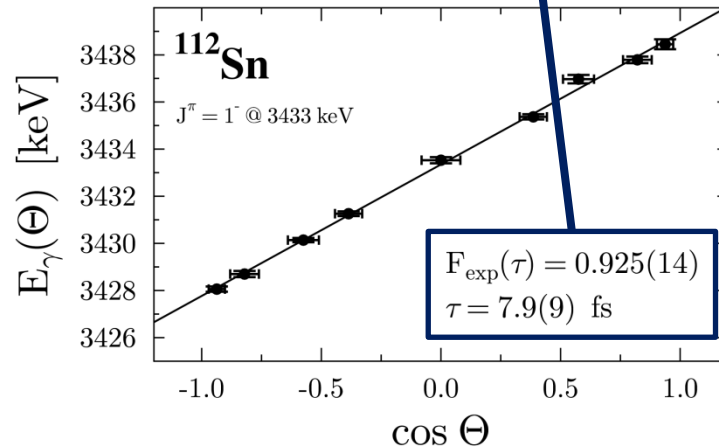
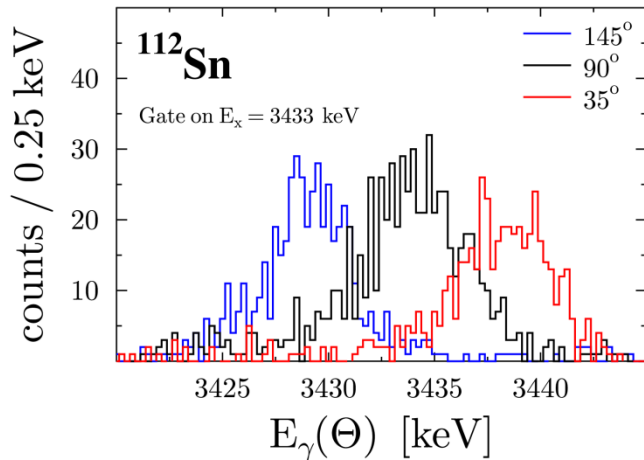
Determination of γ -energy centroid shifts due to Doppler effect

Comparison of simulated and measured $F(\tau)$ yields lifetime τ

Energy-centroid shifts (HORUS)

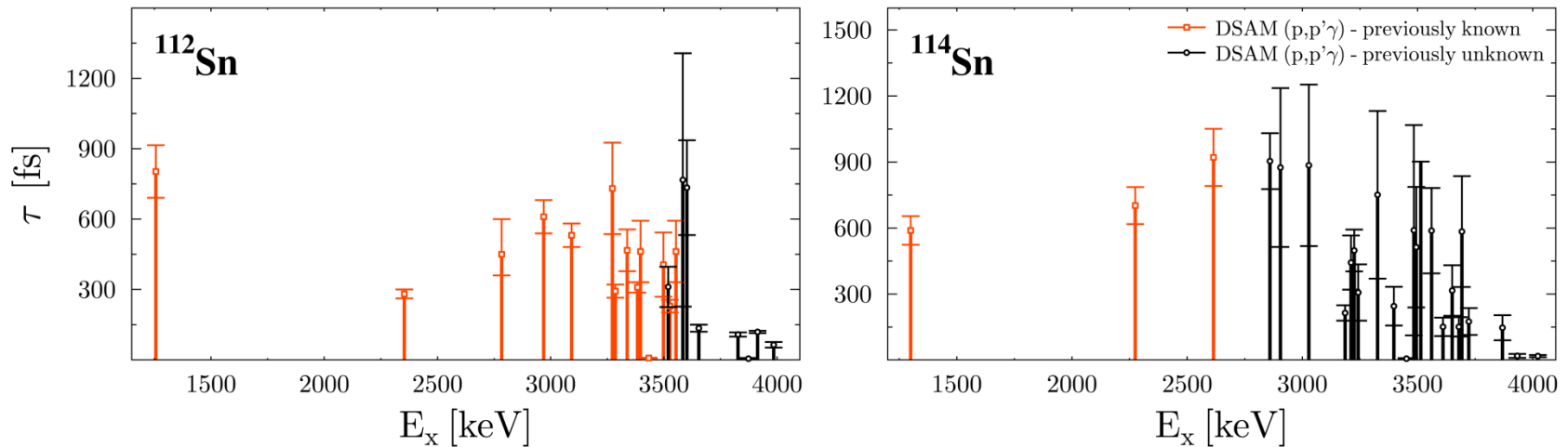
- 11 different Doppler angles due to Si-HPGe correlation groups
- Clear observation of energy shifts

$$E_{\gamma}(\Theta, t) = E_{\gamma}^0 \left(1 + F(\tau) \frac{v_0}{c} \cos \Theta \right)$$



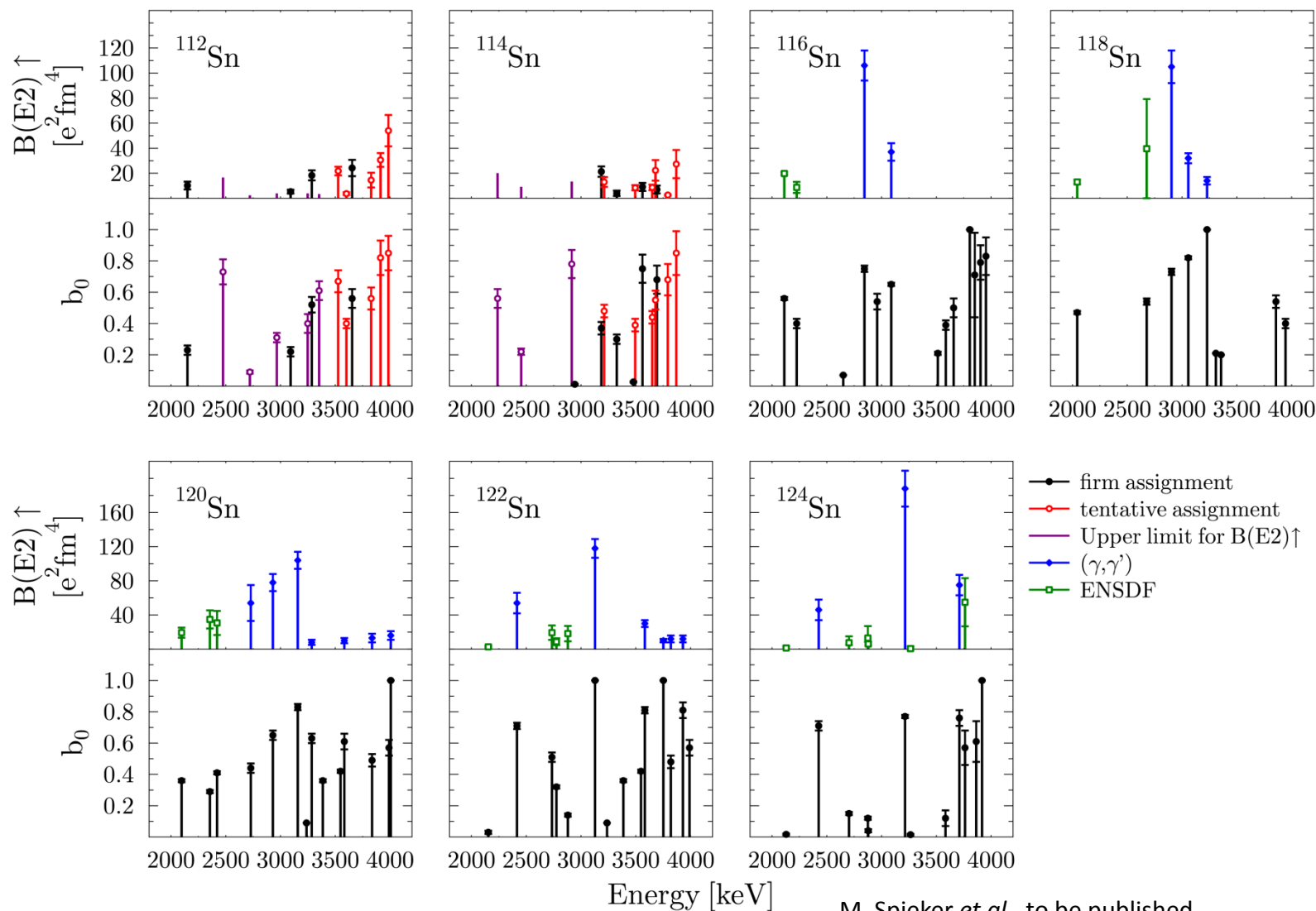
DSA lifetime measurements with SONIC@HORUS

New lifetimes in ^{112}Sn and ^{114}Sn



From these lifetimes, *e.g.*, $B(E2)$ values can be calculated!

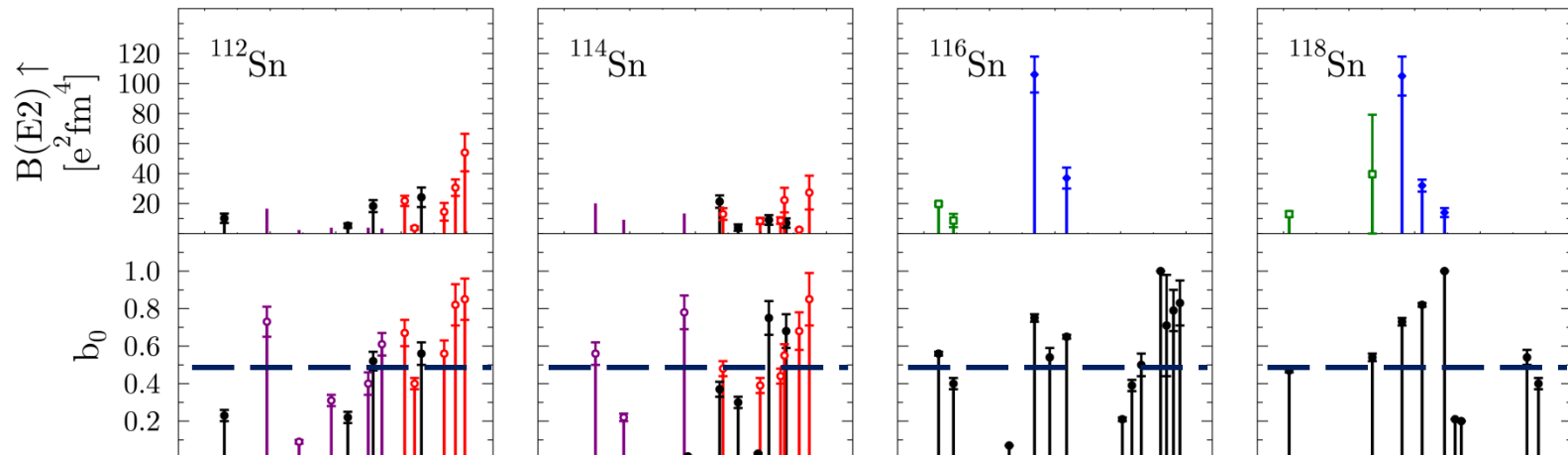
E2 strength and γ -decay branching ratios in Sn



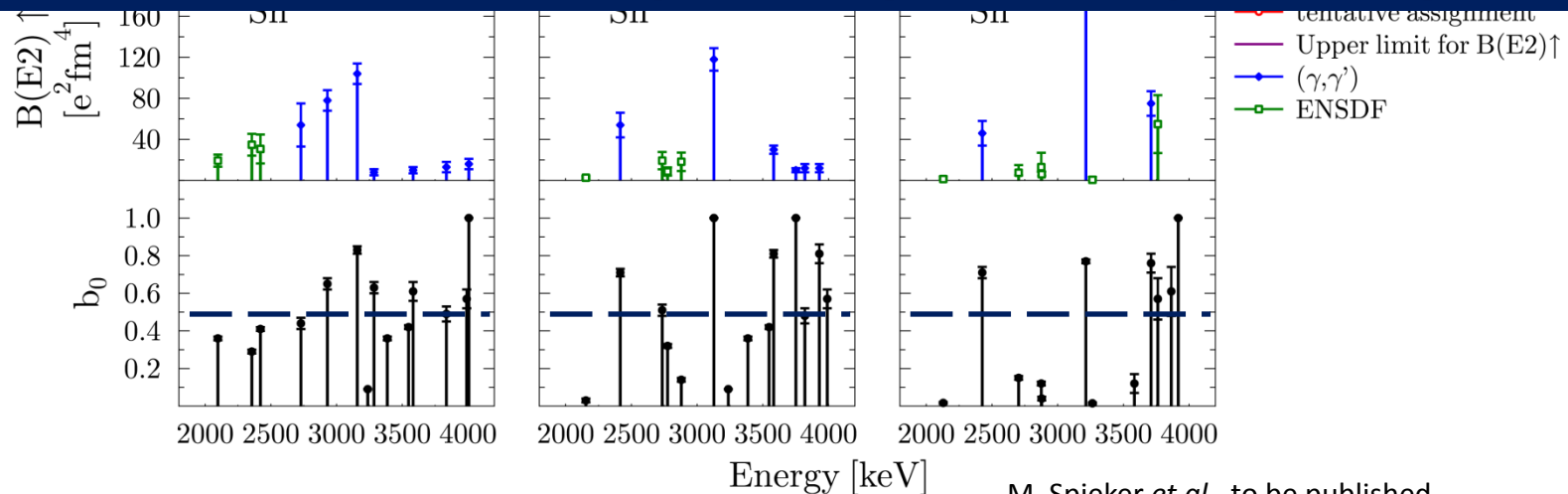
M. Spieker *et al.*, to be published

(γ, γ'): J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

E2 strength and γ -decay branching ratios in Sn



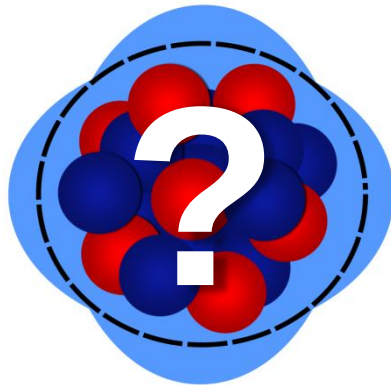
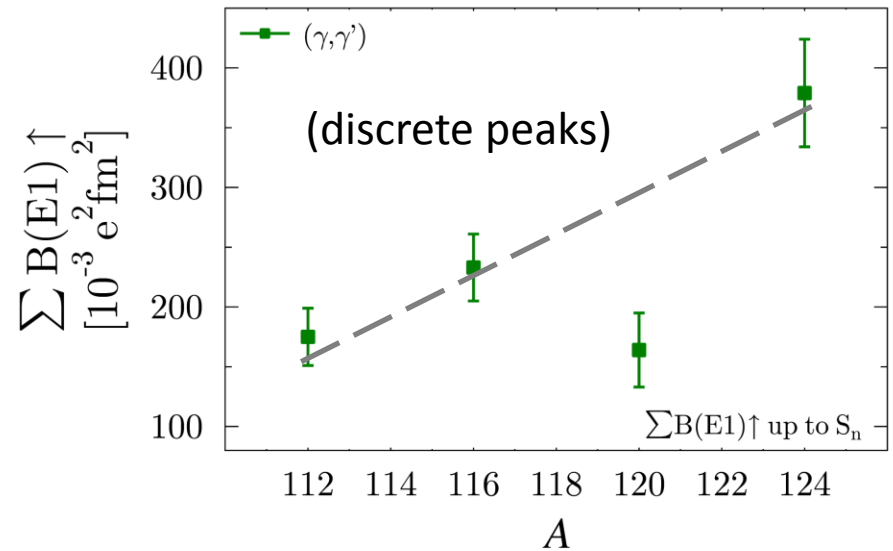
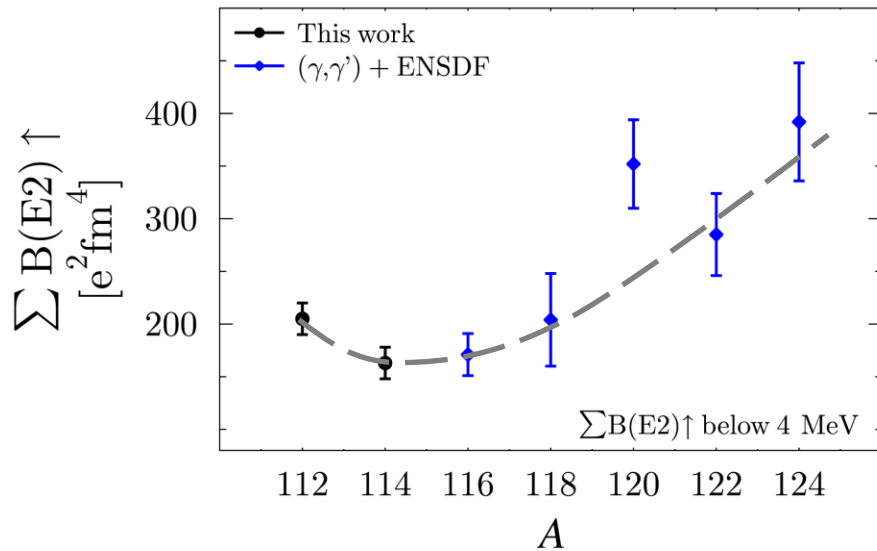
States with large b_0 values are observed in all even-even Sn isotopes
... are these really caused by the PQR as predicted by the QPM?



M. Spieker *et al.*, to be published

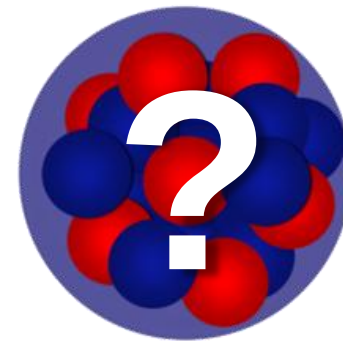
(γ, γ') : J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

Summed $E1$ and $E2$ strength in Sn



quadrupole excitation

M. Spieker *et al.*, to be published

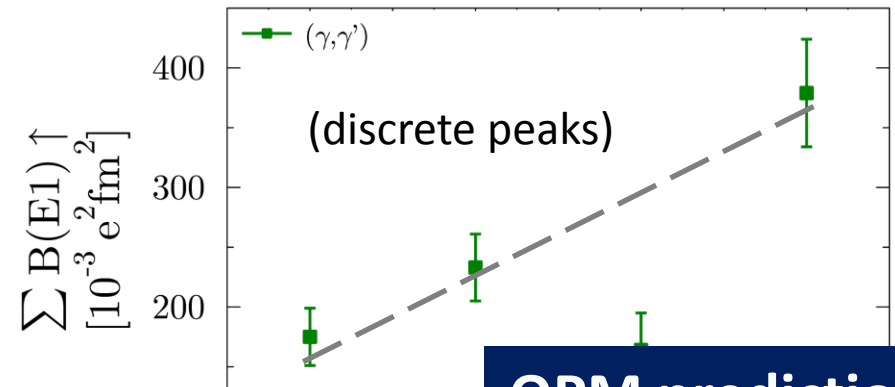
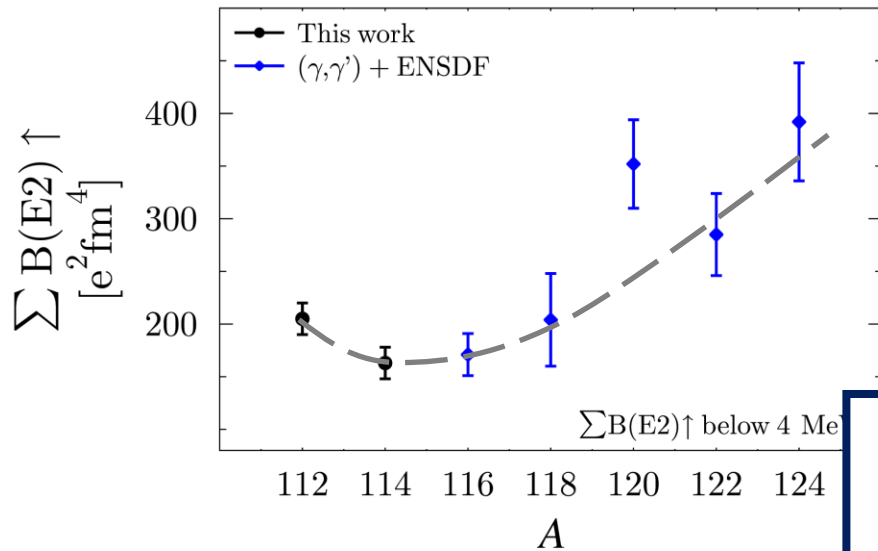


dipole excitation

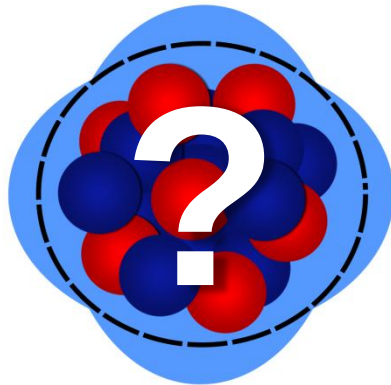
$(\gamma, \gamma') - E2$: J. Bryssinck *et al.*, PRC **61**, 024309 (2000)

$(\gamma, \gamma') - E1$: B. Özel-Tashenov *et al.*, PRC **90**, 024304 (2014)

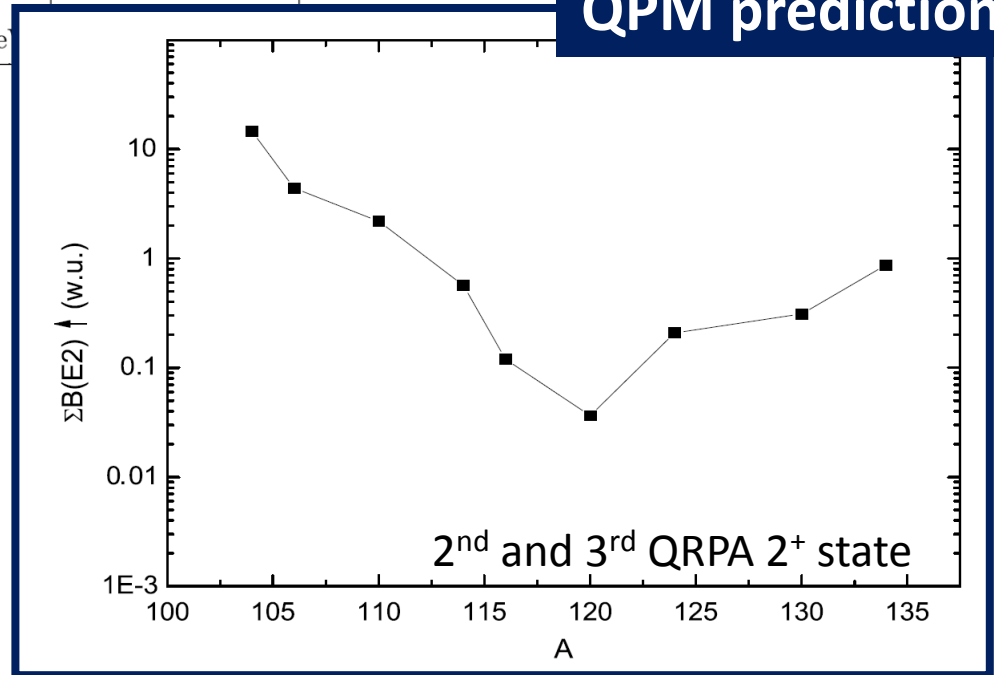
Summed $E1$ and $E2$ strength in Sn



QPM prediction



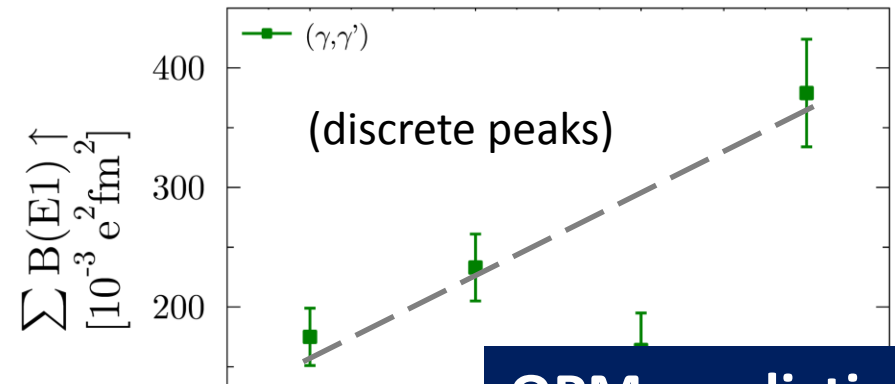
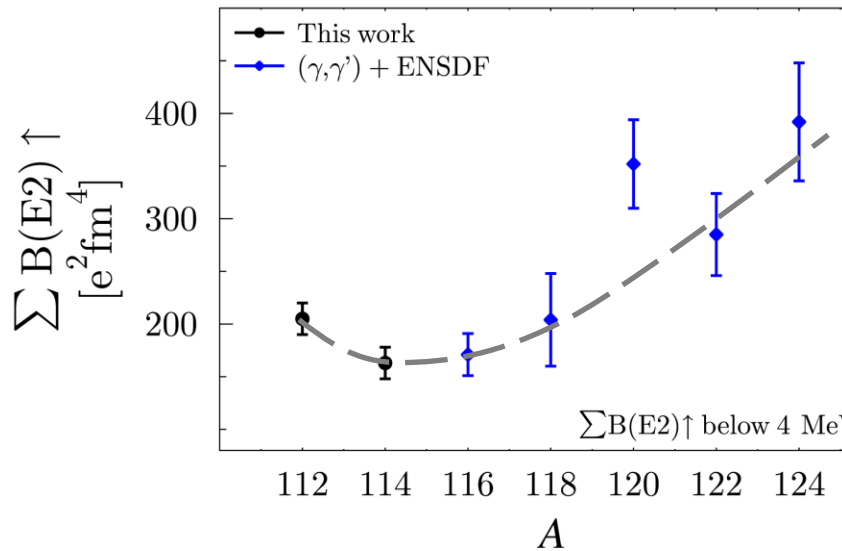
quadrupole excitation



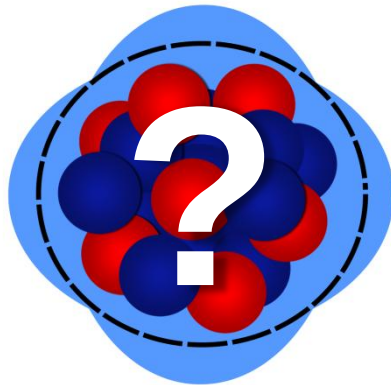
M. Spieker *et al.*, to be published
QPM: N. Tsoneva, H. Lenske, PLB **695**, 174 (2011)

$(\gamma, \gamma') - E2$: J. Bryssinck *et al.*, PRC **61**, 024309 (2000)
 $(\gamma, \gamma') - E1$: B. Özel-Tashenov *et al.*, PRC **90**, 024304 (2014)

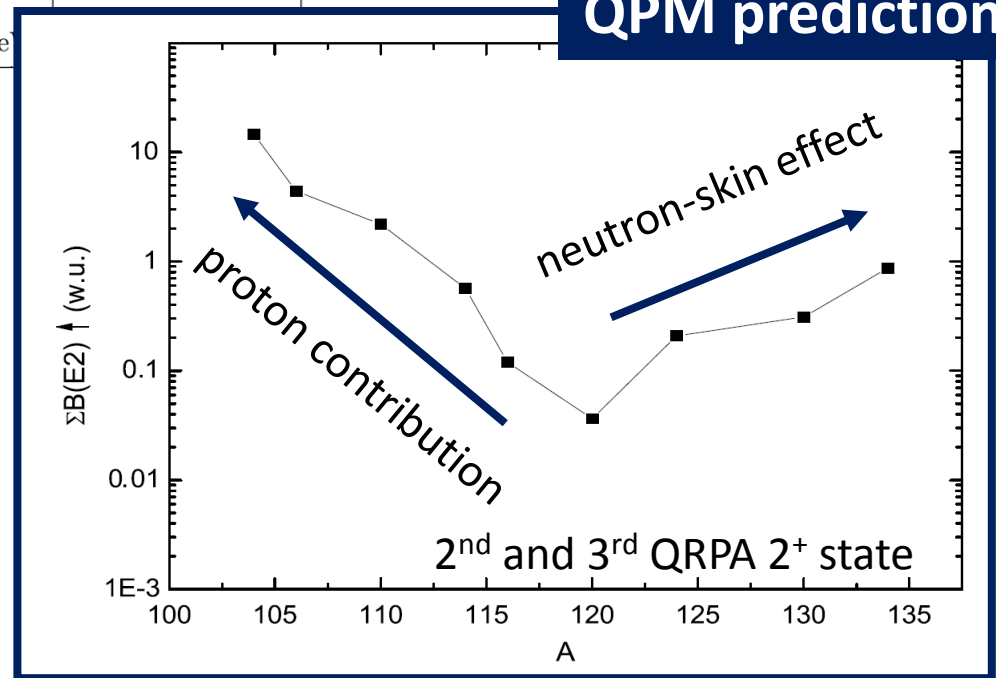
Summed $E1$ and $E2$ strength in Sn



QPM prediction



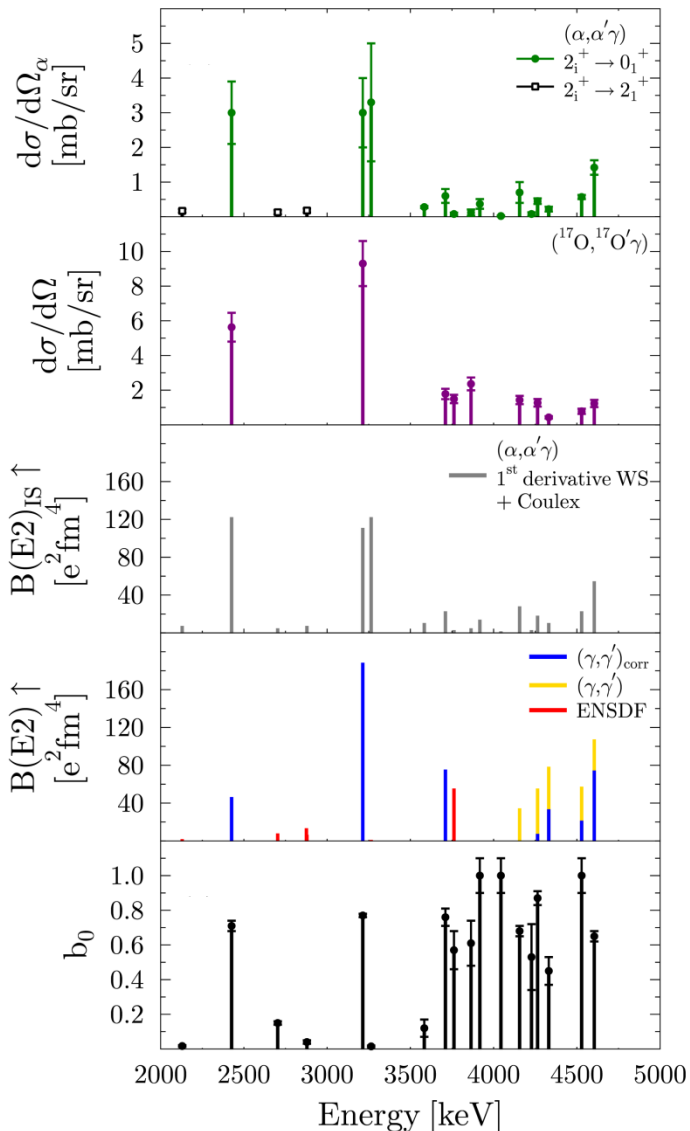
quadrupole excitation



M. Spieker *et al.*, to be published
QPM: N. Tsoneva, H. Lenske, PLB **695**, 174 (2011)

$(\gamma, \gamma') - E2$: J. Bryssinck *et al.*, PRC **61**, 024309 (2000)
 $(\gamma, \gamma') - E1$: B. Özel-Tashenov *et al.*, PRC **90**, 024304 (2014)

Summary



The PQR in the Sn isotopes

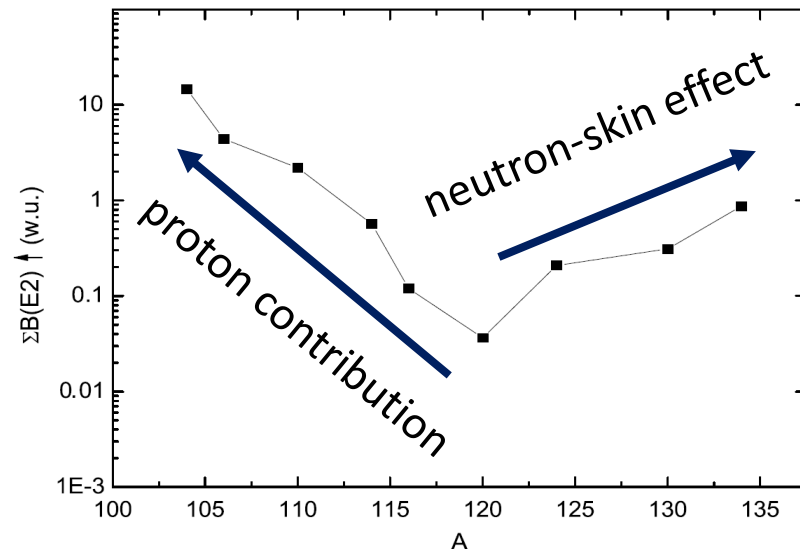
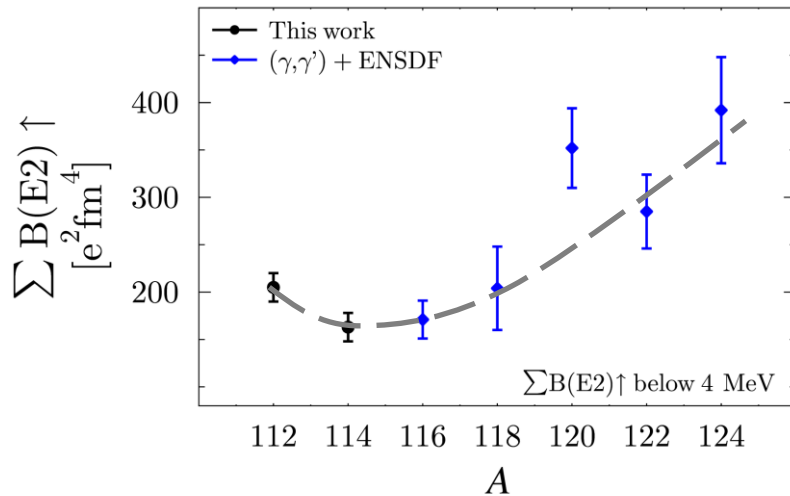
- Dominantly isoscalar character confirmed in ^{124}Sn
- Large b_0 values, i.e. dominant ground-state decays are a possible signature for the PQR
 - Observed in all stable Sn isotopes!
 - Systematic QPM study planned!

^{124}Sn results:

$(^{17}\text{O}, ^{17}\text{O}'\gamma)$: L. Pellegrini *et al.*, PRC **92**, 014330 (2015)

$(\alpha, \alpha'\gamma)$ and $(\gamma, \gamma')_{4-5\text{MeV}}$: M. Spieker *et al.*, PLB **752**, 102 (2016)

Summary



The PQR in the Sn isotopes

- Dominantly isoscalar character confirmed in ^{124}Sn
- Large b_0 values, i.e. dominant ground-state decays are a possible signature for the PQR
 - Observed in all stable Sn isotopes!
 - Systematic QPM study planned!
- Summed strength evolves similarly to the QPM predictions
 - Increase beyond $A = 116$ and observation of large b_0 values in $^{112,114}\text{Sn}$ in contradiction?

^{124}Sn results:

$(^{17}\text{O}, ^{17}\text{O}'\gamma)$: L. Pellegrini *et al.*, PRC **92**, 014330 (2015)

$(\alpha, \alpha'\gamma)$ and $(\gamma, \gamma')_{4-5\text{MeV}}$: M. Spieker *et al.*, PLB **752**, 102 (2016)

Outlook (1)

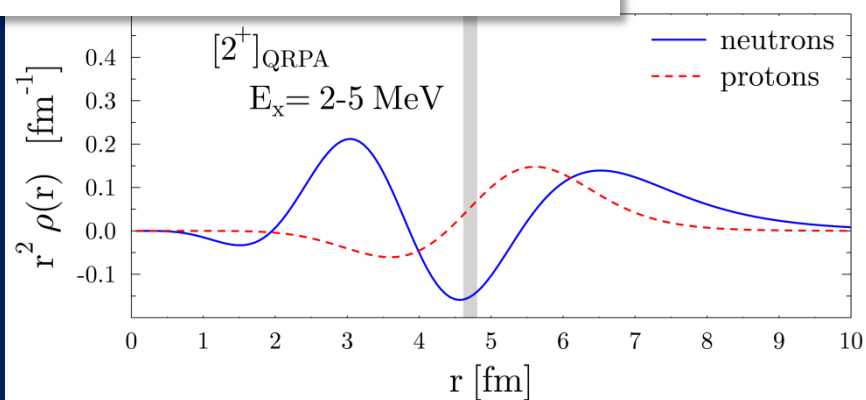
Theory

- PQR states predicted using different theoretical approaches?
→ Transition densities in RQTBA?

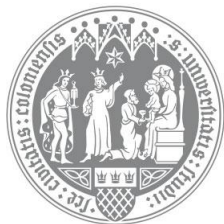
Experiment

- Extend information on $E2$ strength distribution to Cd and Te isotopes
→ $^{128,130}\text{Te}(p,p'\gamma)$ DSA experiments

Neutron-skin oscillation?



Acknowledgment



Michelle Färber, Felix Heim, Elena Hoemann, Jan Mayer, Miriam Müscher, Simon G. Pickstone, Sarah Prill, Philipp Scholz, Vera Vielmetter, Michael Weinert, Julius Wilhelmy, and Andreas Zilges
Institute for Nuclear Physics, University of Cologne (Germany)

Pavel Petkov
IFIN-HH, Bucharest-Magurele (Romania)

Nadia Tsoneva and Horst Lenske
Institute for Theoretical Physics, University Gießen (Germany)

Deniz Savran
GSI research division, Darmstadt (Germany)

Muhsin N. Harakeh
KVI-CART, Groningen (Netherlands)

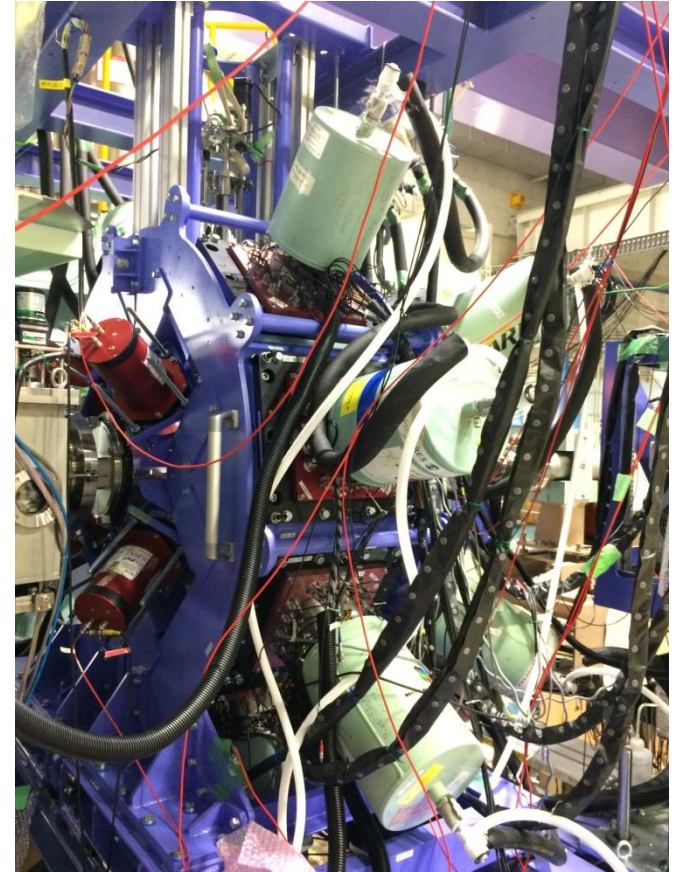
Elena Litvinova
Western Michigan University and Michigan State University (USA)

supported by



Outlook (2)

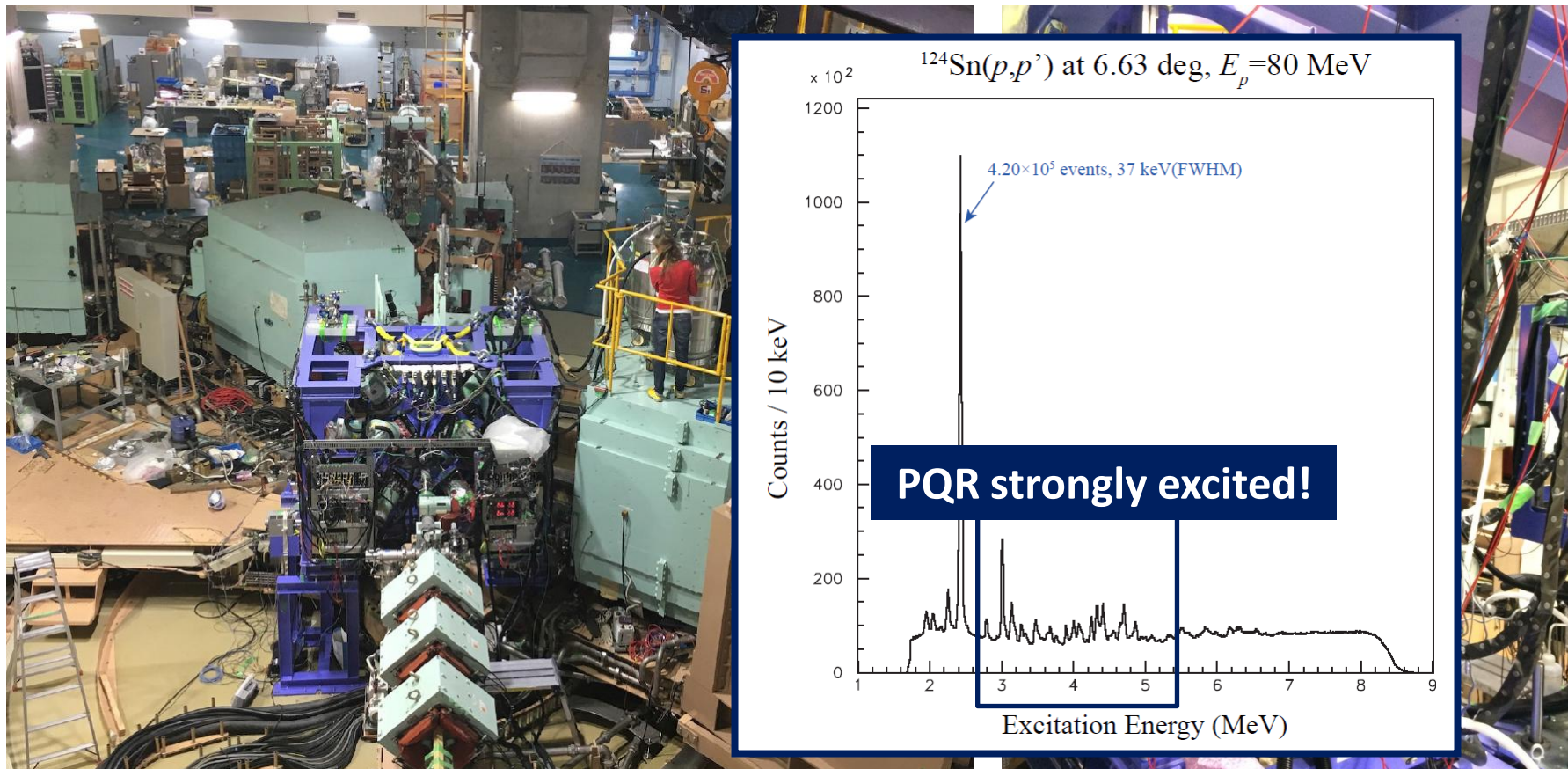
CAGRA@Grand Raiden Collaboration, RCNP, Osaka (Japan)



- $(p,p'\gamma)$ @ $E_p = 80$ MeV and $(\alpha,\alpha'\gamma)$ @ $E_\alpha = 130$ MeV (Oct 2016 – Dec 2016)
- **CAGRA** (12 Clover HPGe detectors and 4 large-volume LaBr₃:Ce detectors)
- **Grand Raiden** spectrometer (energy resolution superior to BBS)

Outlook (2)

CAGRA@Grand Raiden Collaboration, RCNP, Osaka (Japan)



- $(p,p'\gamma)$ @ $E_p = 80$ MeV and $(\alpha,\alpha'\gamma)$ @ $E_\alpha = 130$ MeV (Oct 2016 – Dec 2016)
- **CAGRA** (12 Clover HPGe detectors and 4 large-volume LaBr₃:Ce detectors)
- **Grand Raiden** spectrometer (energy resolution superior to BBS)