Evidence for a Toroidal Electric Dipole Mode in Nuclei and Implications for the Pygmy Dipole Resonance

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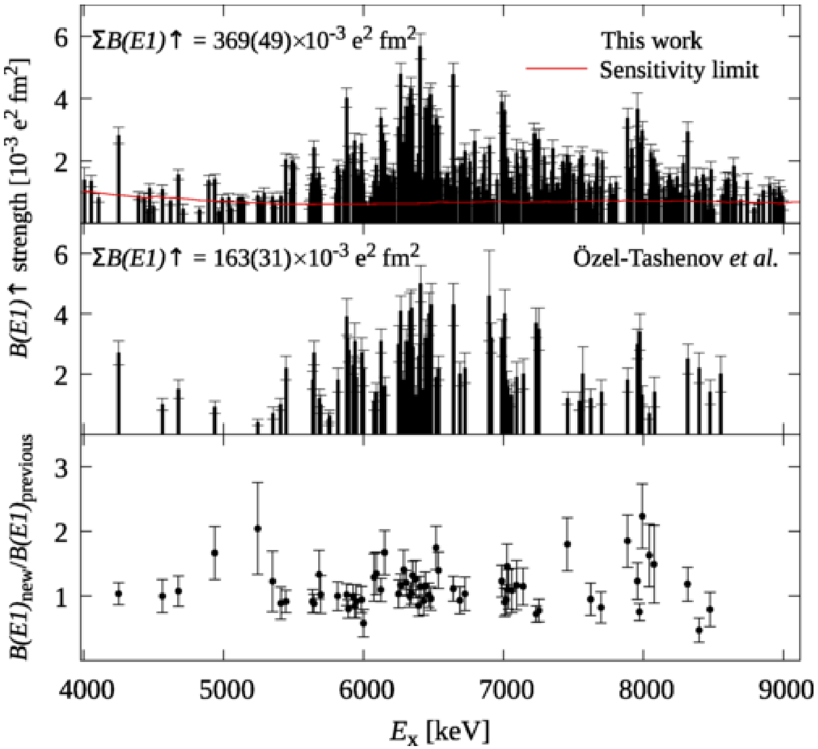
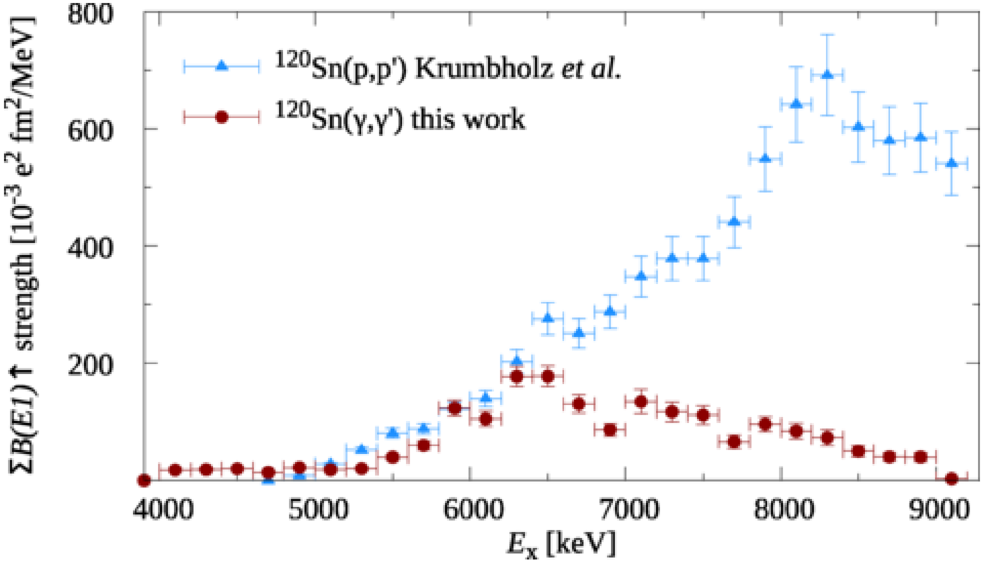
- The PDR: Experimental and theoretical features
- First evidence for a toroidal E1 mode in nuclei
- Implications for the nature of the PDR

PDR Features: Isovector Response

(γ,γ‘): M. Müscher et al., Phys. Rev. C 102, 014317 (2020)



(γ,γ‘): M. Müscher et al., Phys. Rev. C 102, 014137 (2020)
(p,p’): A.M. Krumbholz et al., Phys. Lett. B 744, 7 (2015)



- Decay (γ,γ‘) vs. absorption (p,p‘): large g.s. branching ratios
- PDR is only a fraction of the total low-energy E1 strength

PDR Features: Isoscalar Response

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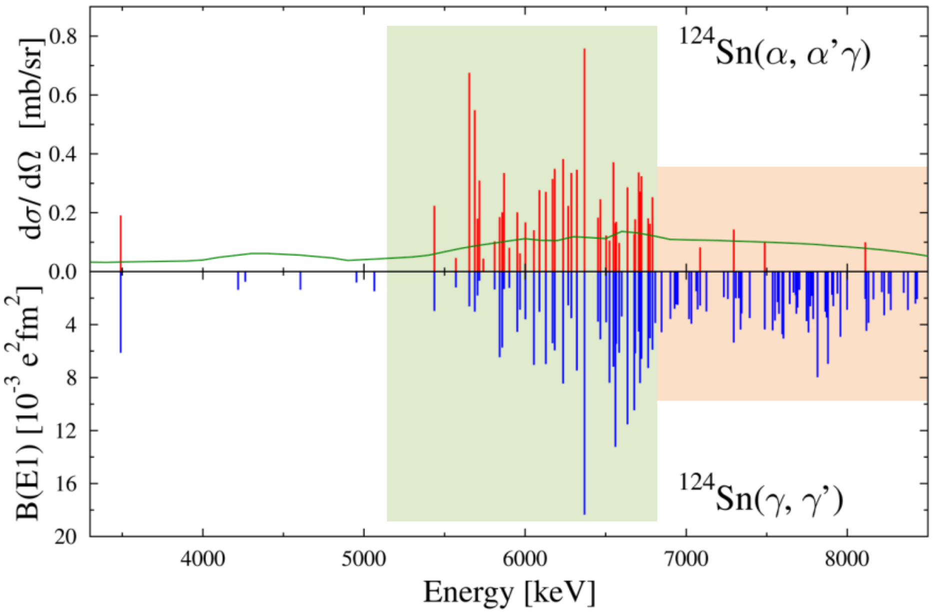
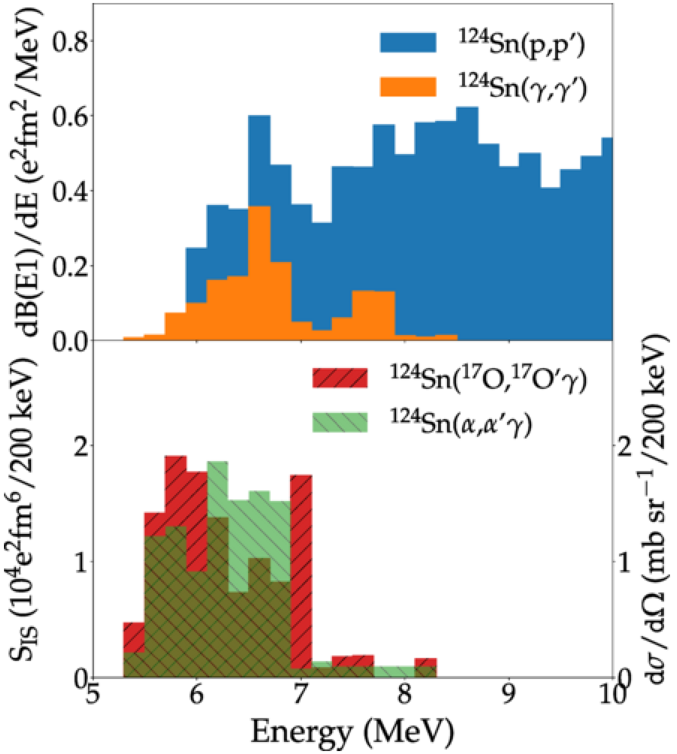
J. Endres et al., PRL 105, 212503 (2010)



S. Bassauer et al., PRC 102, 034327 (2020)

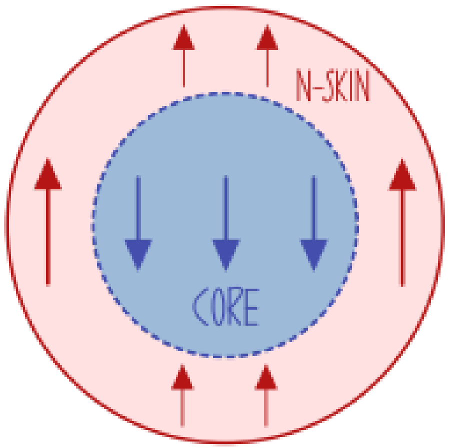


- Strong IS response
- All the states forming the PDR are excited at lower energies
- Dominant IV transitions at higher excitation energies

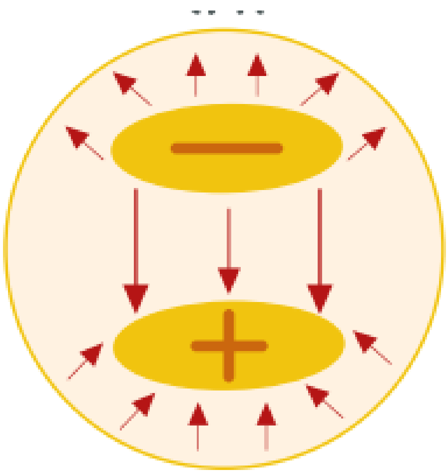
Theoretical Explanations of the PDR

E. Lanza, L. Pellegri, A. Vitturi, M.V. Andrés, PPNP 129, 104006 (2023)

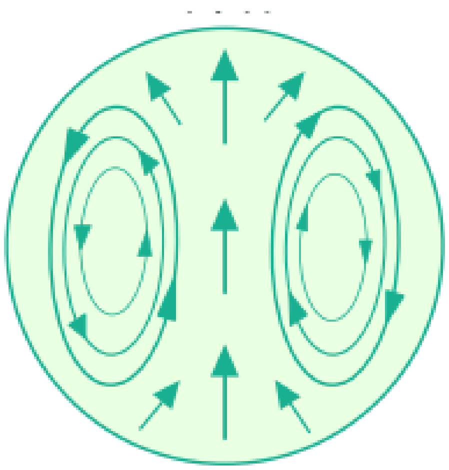
Neutron Skin Ocillations



Compression Mode



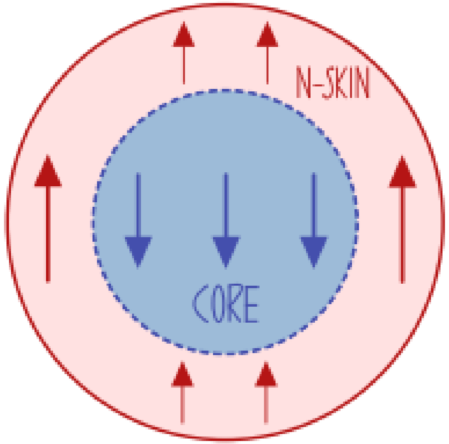
Toroidal Mode



Theoretical Explanations of the PDR

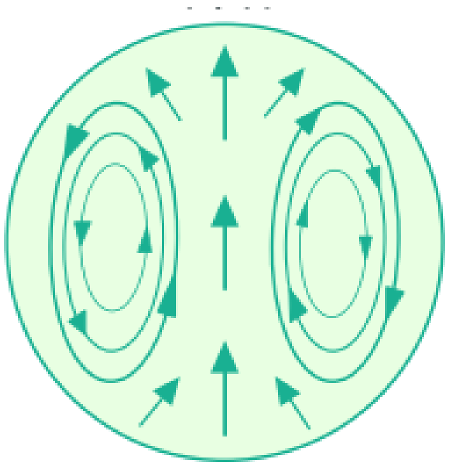
E. Lanza, L. Pellegri, A. Vitturi, M.V. Andrés, PPNP 129, 104006 (2023)

Neutron Skin Ocillations



Compression Mode

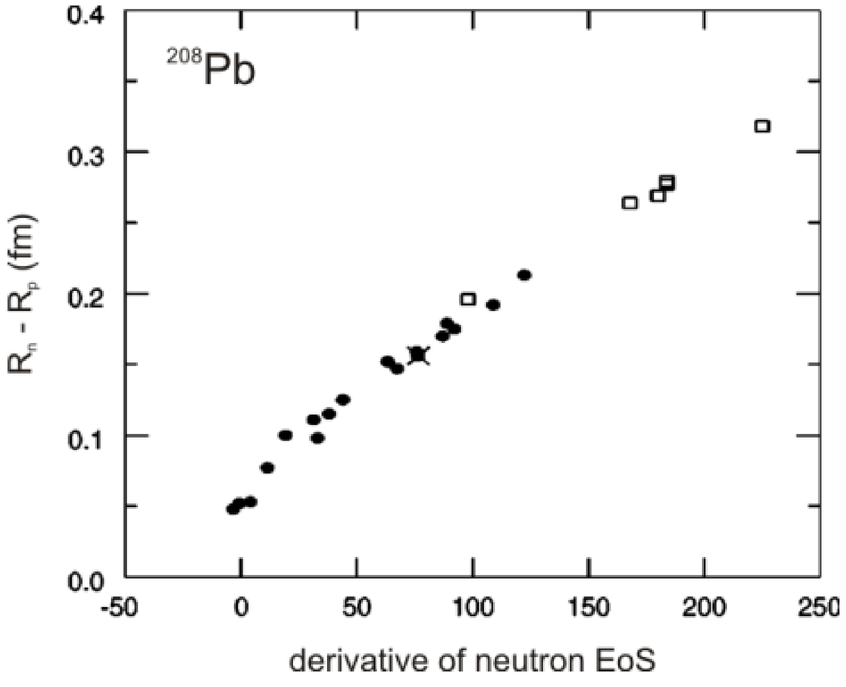
Toroidal Mode



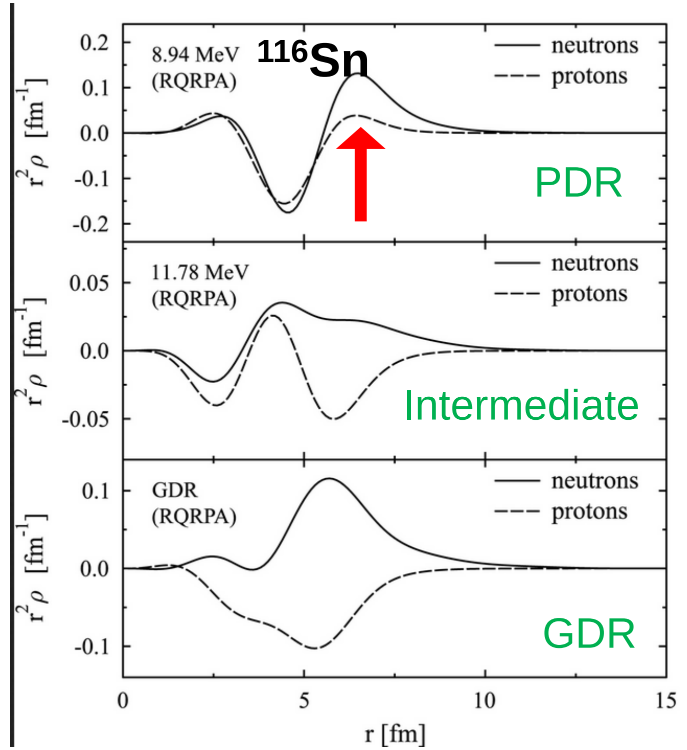
- Excluded by IV response
- Excluded by compressibility

Neutron Skin Oscillations and Symmetry Energy

S. Typel and B. A. Brown, PRC 64, 027302 (2001)



E. Litvinova et al, PRC 79, 054312 (2009)

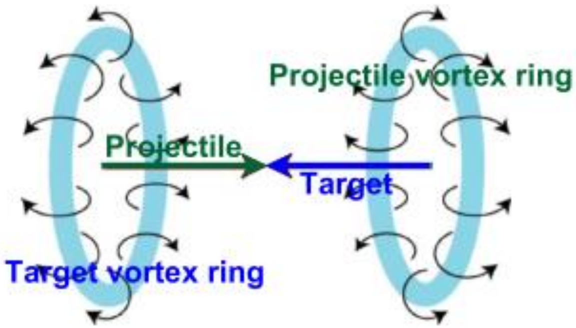


- Relation between neutron skin thickness and symmetry energy
- PDR transition density indicates collective neutron skin oscillation

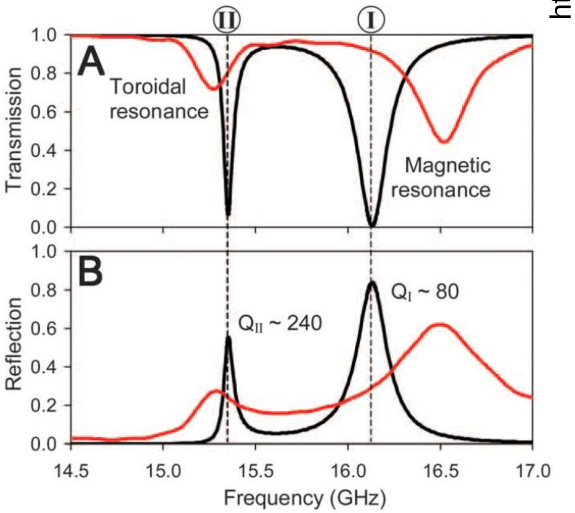
Toroidal Modes

https://www.thecigarstore.com/blog/tips-blowing-cool-cigar-smoke-rings/

https://www.oe24.at/welt/aetna-stoesst-weisse-rauchkringel-aus/591096143



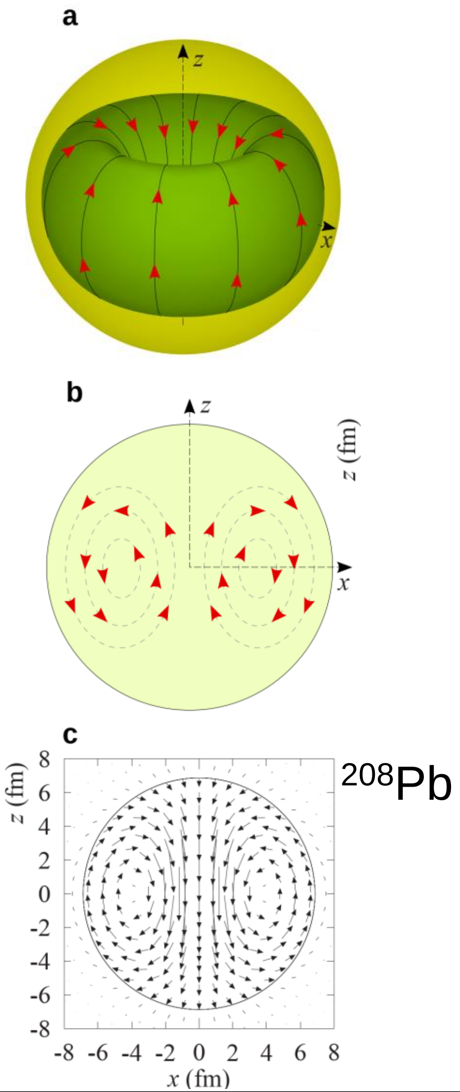
Yu.B. Ivanov, PRC 107, L021902 (2023)



T. Kaelberer et al., Science 330, 1510 (2010)

- Toroidal modes appear in a large variety of physics problems from hydrodynamics, solid state physics, metamaterials and metaphotonics to relativistic heavy-ion collisions and anapole dark matter

Nuclear Toroidal Modes



- Quantum phenomenon, mean-field origin
- Predicted more than 50 years ago in hydro/fluid-dynamical models, QPM, relativistic and nonrelativistic QRPA
- Simplest mode has E1 multipolarity
- Similar to Hill‘s spherical vortex ring, but corresponds to oscillations along the streamlines
- Dominantly IS at low excitation energies

Fundamental E1 Modes

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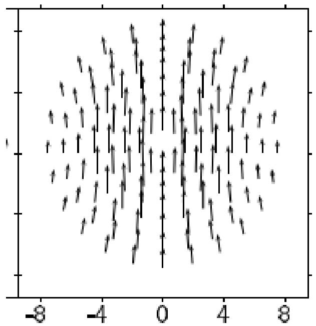
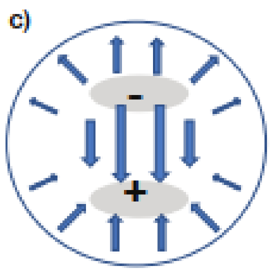
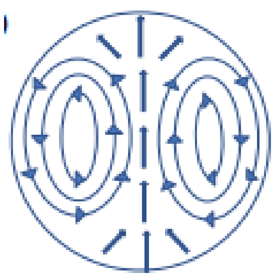
Mode	Current Distribution	Operator
IV GDR		$\hat{M}^{\mathrm{el}}_{1\mu}(T=1) = e \sum_{q=n,p} e^q_{\mathrm{eff}} \sum_{i\in q} r_i Y_{1\mu}(\Omega_i)$
IS Compression		$\hat{M}^{\mathrm{com}}_{1\mu}(T=0) = -i\frac{1}{10c}\int \mathrm{d}\boldsymbol{r}\, r^3 Y_{1\mu}(\Omega)(\nabla\cdot\hat{\mathbf{j}}_{\mathrm{nuc}})$
IS Toroidal		$\hat{M}^{\mathrm{tor}}_{1\mu}(T=0) = -\frac{1}{10c\sqrt{2}}\int \mathrm{d}\boldsymbol{r}\, r^3 \mathbf{Y}_{11\mu}(\Omega_i)\cdot(\nabla\times\hat{\mathbf{j}}_{\mathrm{nuc}})$

Theoretical Predictions

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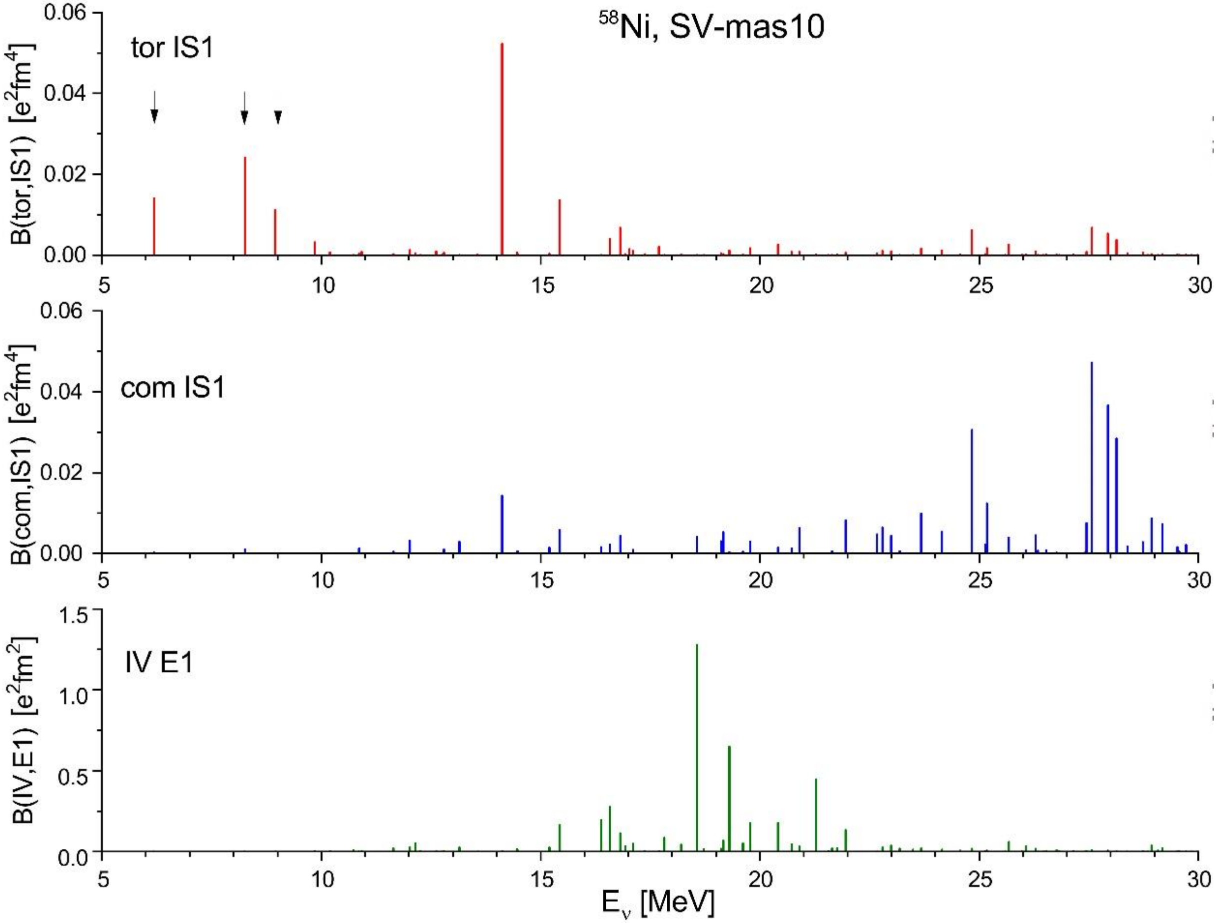

- Toroidal strength very fragmented

Experimental Approach: The Case of ^{58}Ni

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- Combined analysis of **high-resolution** (p,p'), (γ,γ') and (e,e') experiments on **^{58}Ni**
  I. Brandherm et al., arXiv:2404.15906

- (p,p') reaction at several hundred MeV and very forward angles selective to E1, spinflip M1
  PvNC and A. Tamii, EPJA 55, 110 (2019)

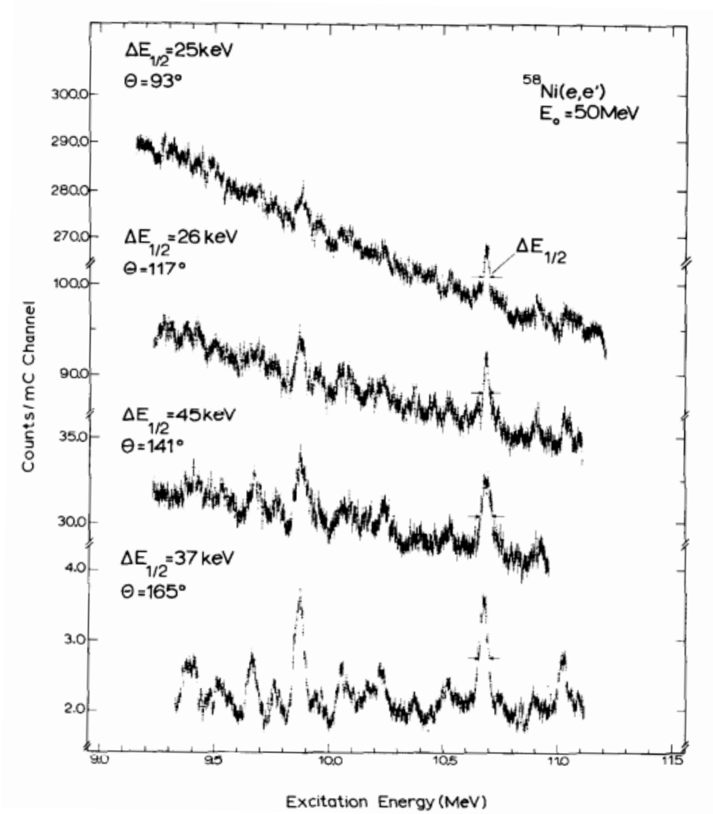
- (γ,γ') reaction selective to E1,M1; unique parity information with polarized beam
  A. Zilges et al., PPNP 122, 103903 (2022)

- (e,e') reaction at low momentum transfer and backward angles selective to M1
  W. Mettner et al., NPA 473, 160 (1987)

^{58}Ni(e,e‘) Data

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} f_{rec} \left[|F_L(q)|^2 + \left(\frac{1}{2} + \tan^2\left(\frac{\theta}{2}\right)\right)|F_T(q)|^2\right]$$

- Most data at $E_0 \approx 50$ MeV
- ΔE ≈ 25 - 35 keV (FWHM)
- Variation of momentum transfer by changing the scattering angle
  → change of *L/T* ratio
- Increase of σ/σ_{Mott} with angle was taken as signature for magnetic transitions

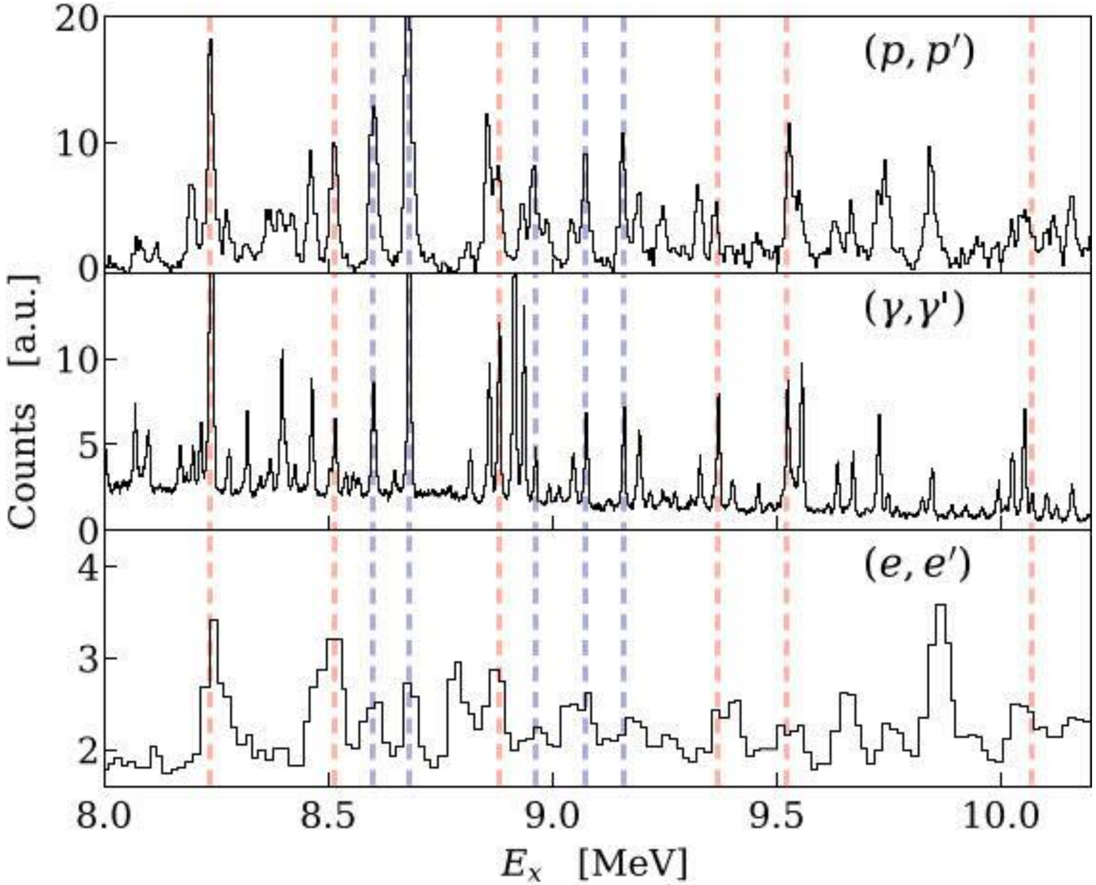


W. Mettner et al., Nucl. Phys. A 473, 160 (1987)

Identification of E1 and M1 Transitions in ^{58}Ni

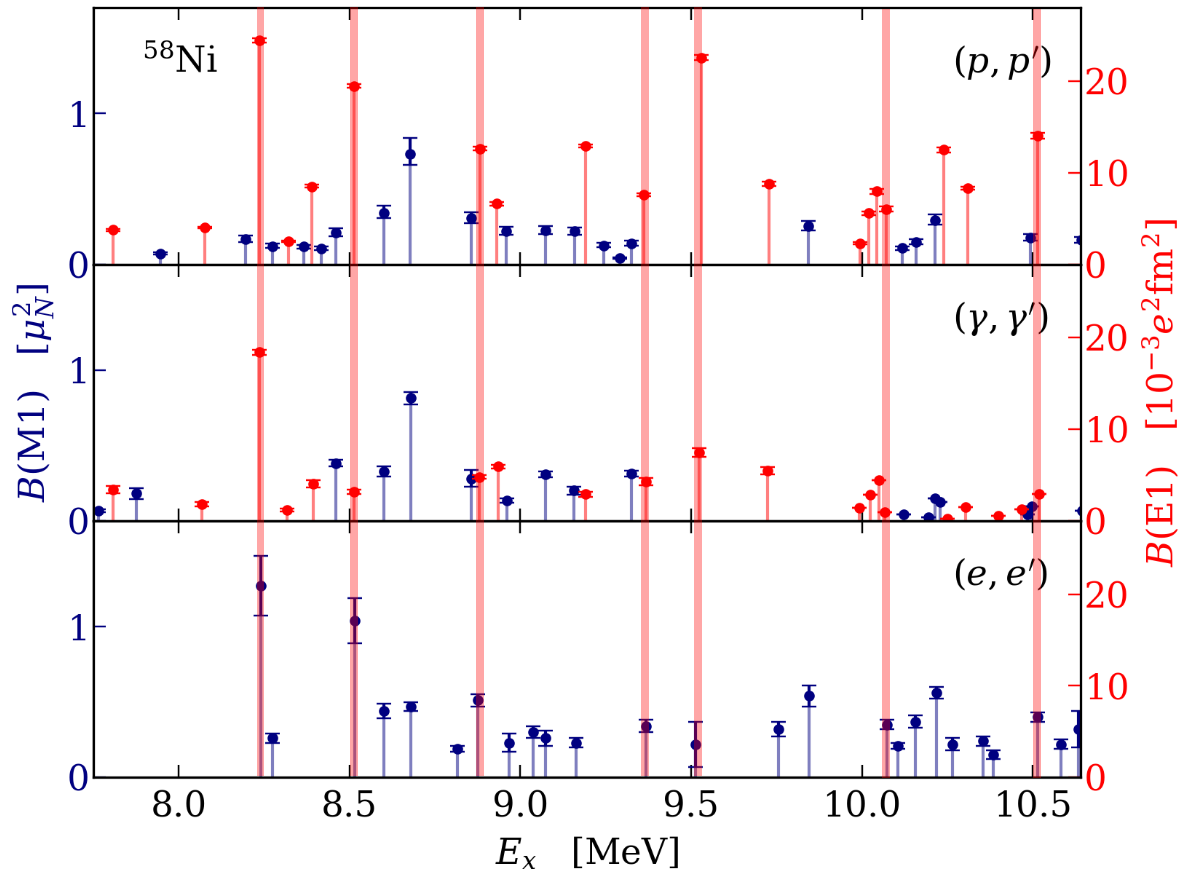
TECHNISCHE UNIVERSITÄT DARMSTADT

I. Brandherm et al., arXiv:2404.15906



- Excitation energy region covered 7 - 13 MeV

Identification of Toridal Candidates



- Assumed to be M1 in (e,e‘) but uniquely assigned E1 in (p,p‘) + (γ,γ‘)

→ E1 transitions with large transverse cross sections

Evidence of Toroidal Nature from (e,e‘) Data

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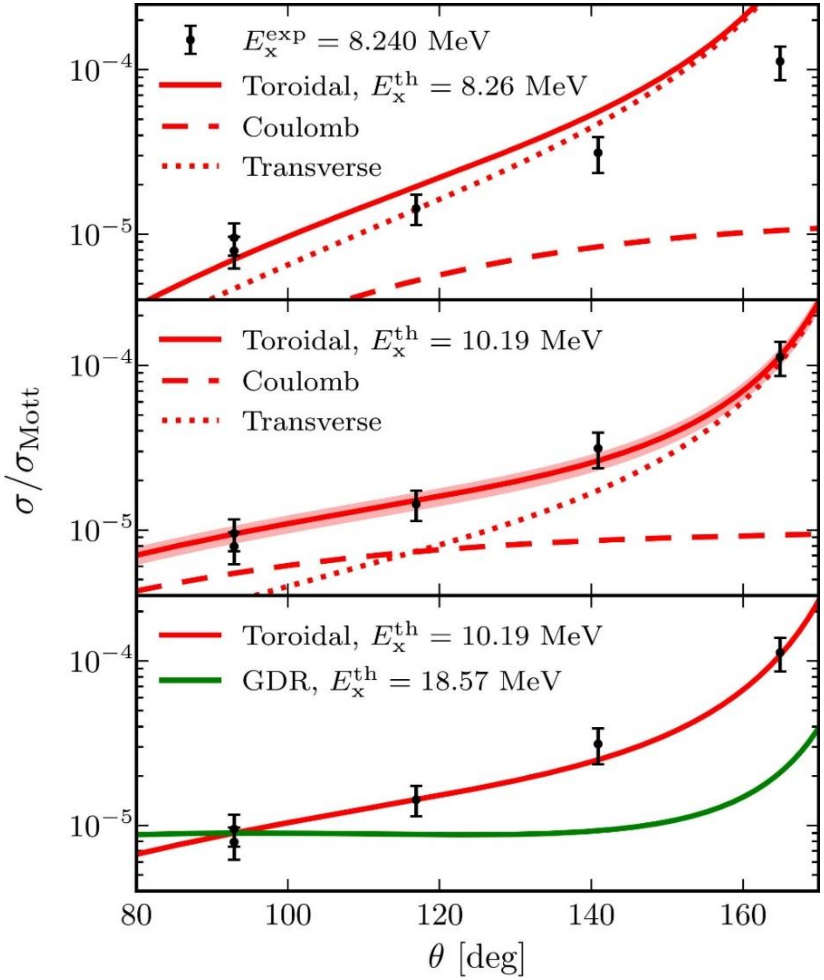
P. von Neumann-Cosel et al., arXiv: 2310.04736

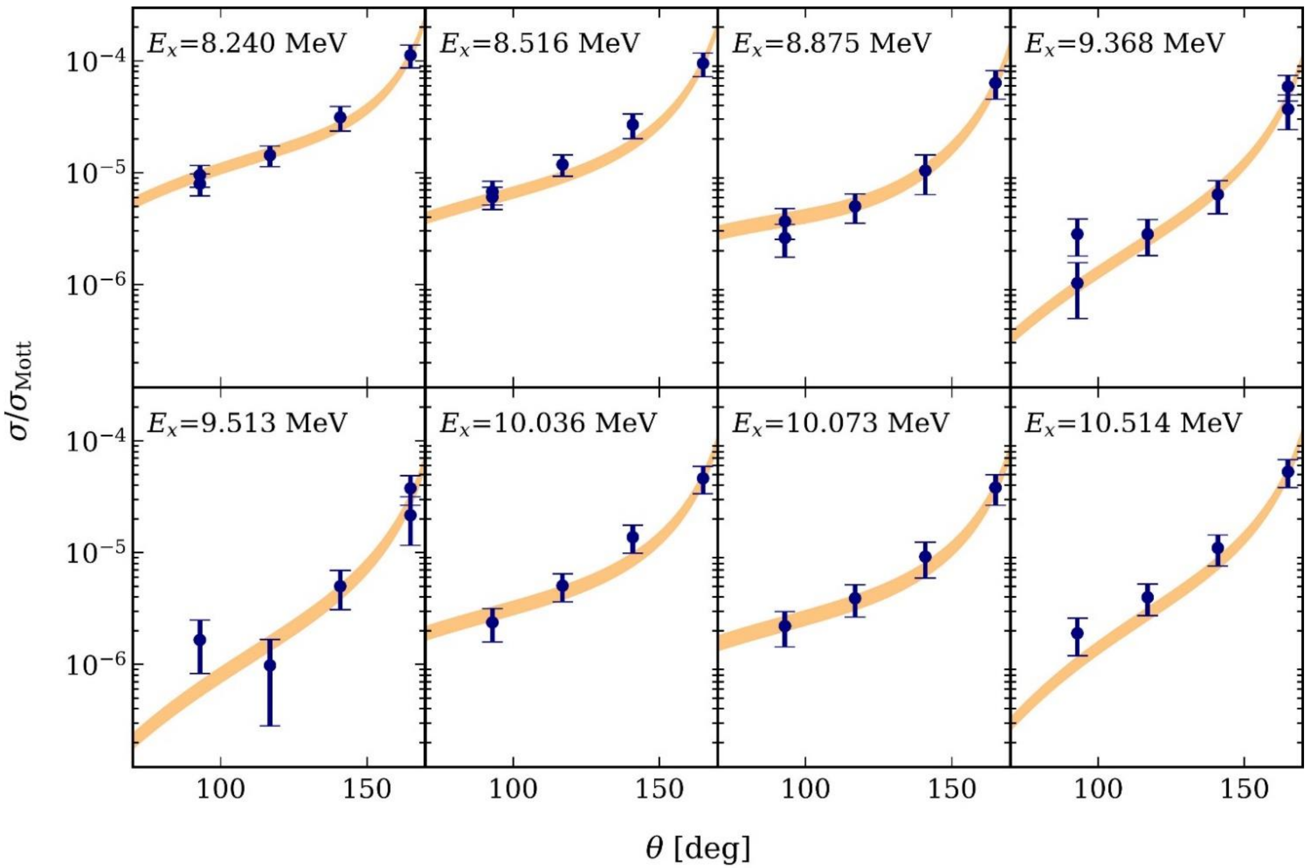


- Very small transverse form factors of IV and IS compressional E1 excitations

Evidence of Toroidal Nature from (e,e‘) Data

TECHNISCHE UNIVERSITÄT DARMSTADT

P. von Neumann-Cosel et al., arXiv: 2310.04736

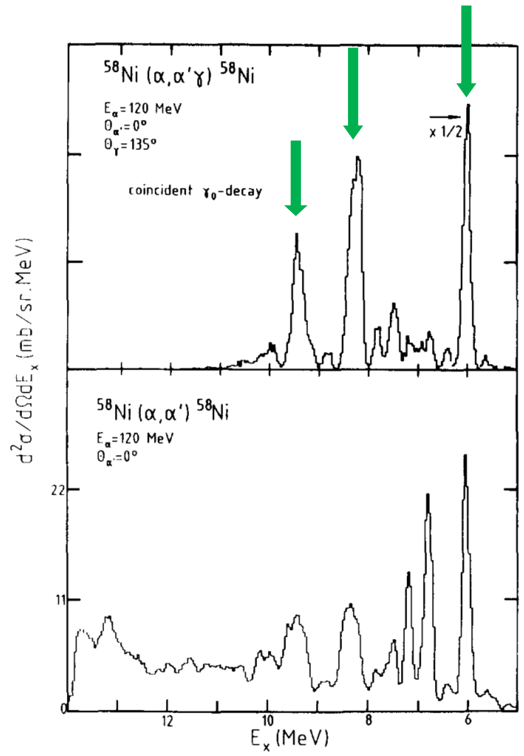


- Very good description of **all** toroidal candidates

Implications of the ^{58}Ni results for the PDR

- IS response: Strong peaks corres-pond to lowest toroidal candidates

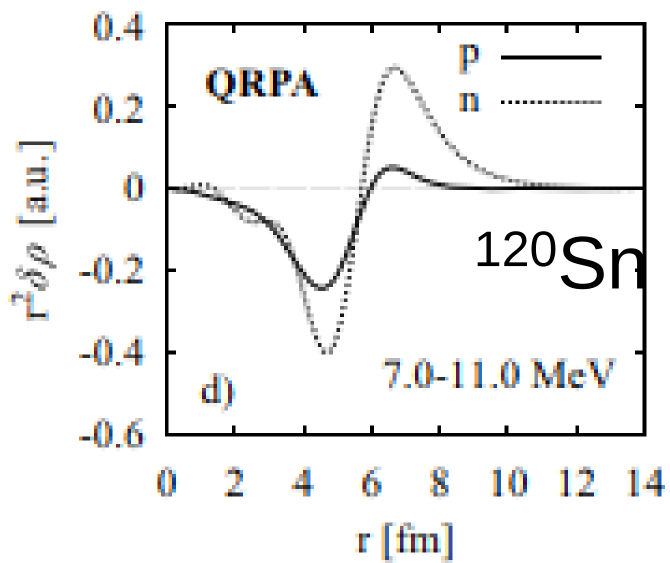
T.D. Poelhekken et al., PLB 278, 423 (1992)



- QRPA models successfully describing the toroidal mode in ^{58}Ni predict a toroidal character of the PDR

- They also reproduce the specific form of the PDR transition density

A. Repko et al., Eur. Phys. J. A 55, 242 (2019)



Implications of the ^{58}Ni results for the PDR

Experimental features of the toroidal mode

- large g.s. branching ratios (observation in (γ,γ‘) experiments)

- strong IV response (on the scale of low-energy E1 transitions)

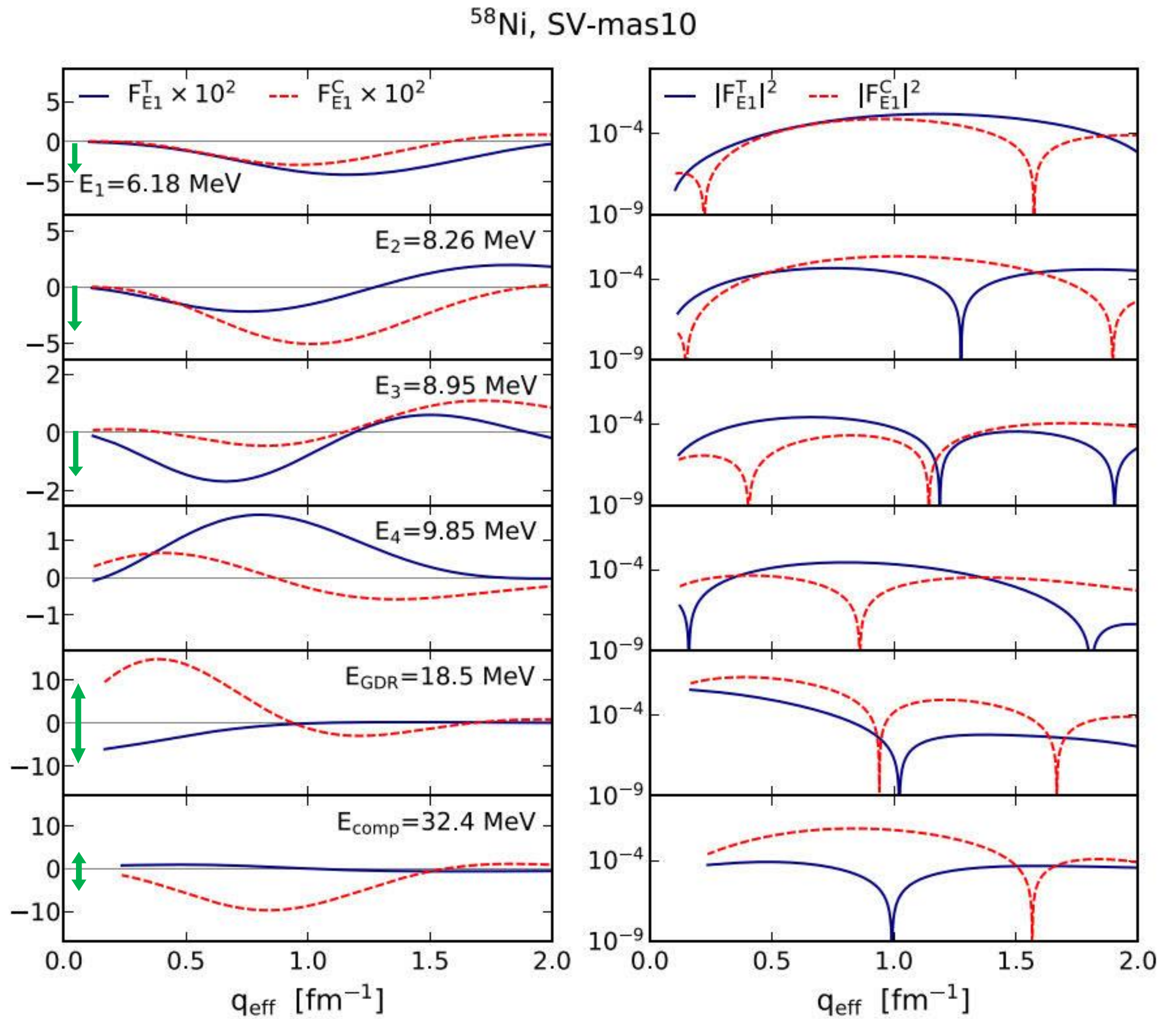
- strong IS response (from (α,α‘γ) experiment)

→ **same signatures as PDR!**

Summary

- Nature of the PDR: neutron skin oscillation or toroidal excitation?
- Evidence for an E1 toroidal mode in ^{58}Ni
- Although ^{58}Ni has Z ≈ N, toroidal excitations show same experimental features as the PDR: large g.s. branching ratios, IV **and** IS response
- Models successfully describing the toroidal mode in ^{58}Ni predict a toroidal character of the PDR including the specific transition density
- Systematic study of the Sn isotopic chain shows that the IV PDR strength is much smaller than QRPA predictions → talk by Maria Markova

New Signature: F^{LT} Sign Difference



(e,e‘γ) Experiments:
Sensitivity to L/T Interference Term

- (e,e‘γ) cross sections

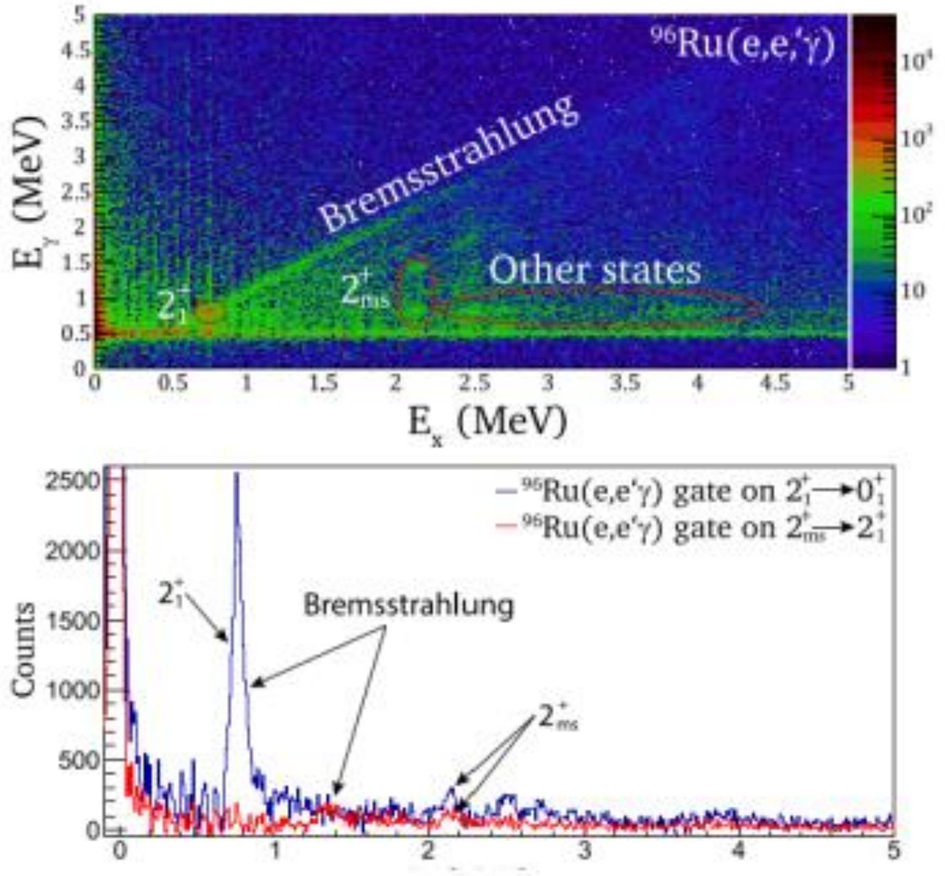
$$\frac{d^4\sigma}{d\Omega_\gamma d\Omega_e\, d\omega\, dE_\gamma} = \sigma_{\rm Mott}\left(\frac{\Gamma_{\gamma f}}{\Gamma}\right)\Big\{ V_L U_L |F_L(q)|^2 + V_T U_T |F_T(q)|^2$$

$$+ V_I U_I \cos\phi_\gamma F_L(q) F_T(q) + V_S U_S \cos 2\phi_\gamma F_T(q) F_T(q) \Big\}$$

- $F_L \cdot F_T$ interference term sensitive to sign
- Can be separated by proper choice of Φ_γ
- F_T can be extracted if F_L is known

(e,e‘γ) Experiments: New Experimental Setup at the S-DALINAC

G. Steinhilber, Doctoral thesis, TU Darmstadt (2022)



Thanks to

I. Brandherm, A. Richter (*TU Darmstadt, Germany*)

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A. Repko (*Slovak Academy of Science, Bratislava, Slovakia*)

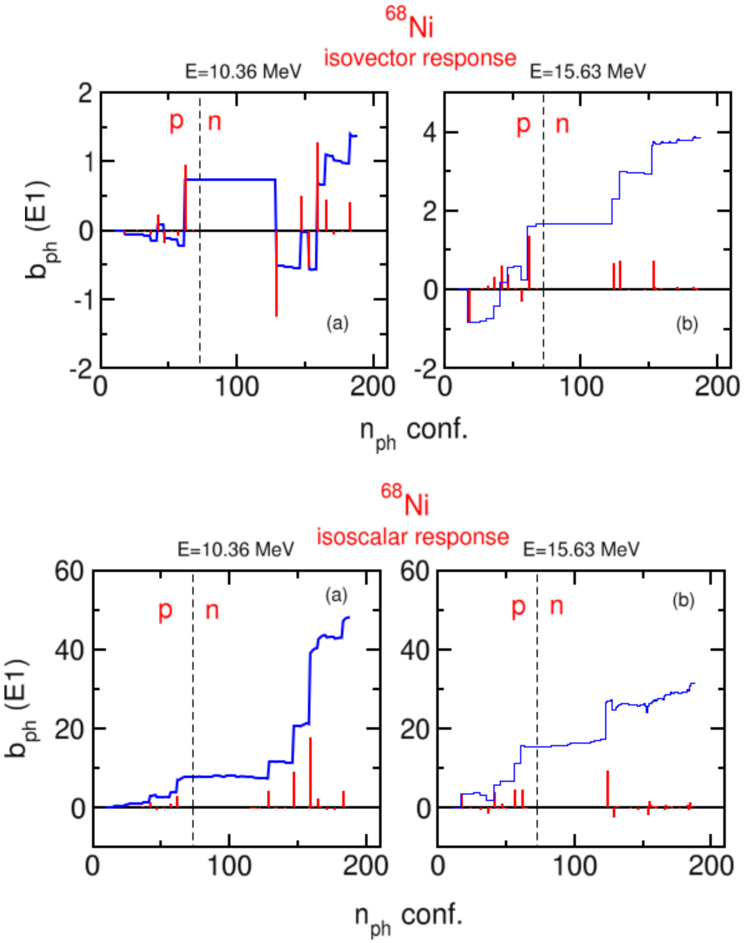
J. Kvasil (*U Prague, Czech Republic*)

M. Markova, A.C. Larsen (*U Oslo, Norway*)

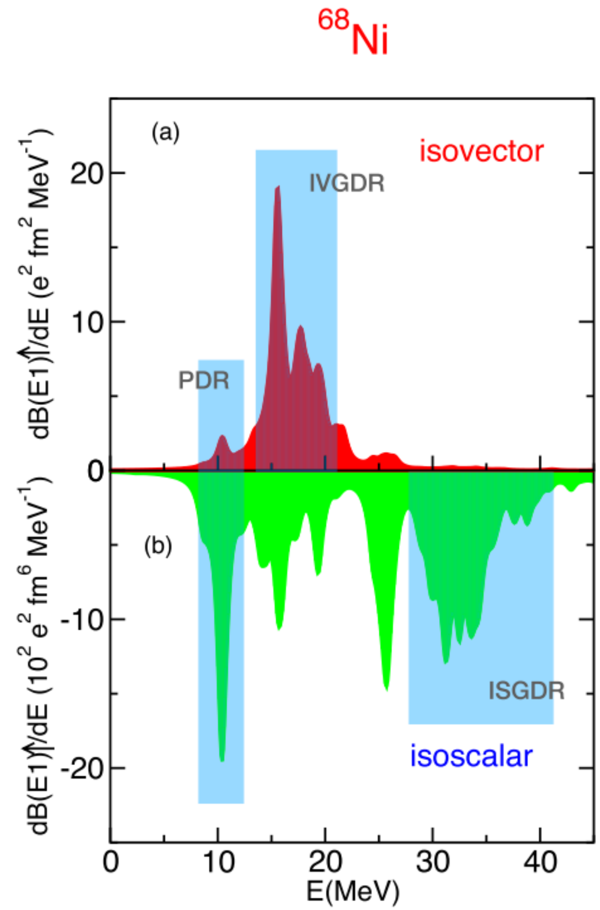
E. Litvinova (*WMU, Kalamazoo, USA*)

Neutron Skin Oscillations: Collectivity

A. Bracco et al., PPNP 106, 360 (2019)



E. Lanza et al., PPNP 129, 104006 (2023)



- Coherence in IS channel, no coherence in IV channel

^{58}Ni(p,p‘) Data

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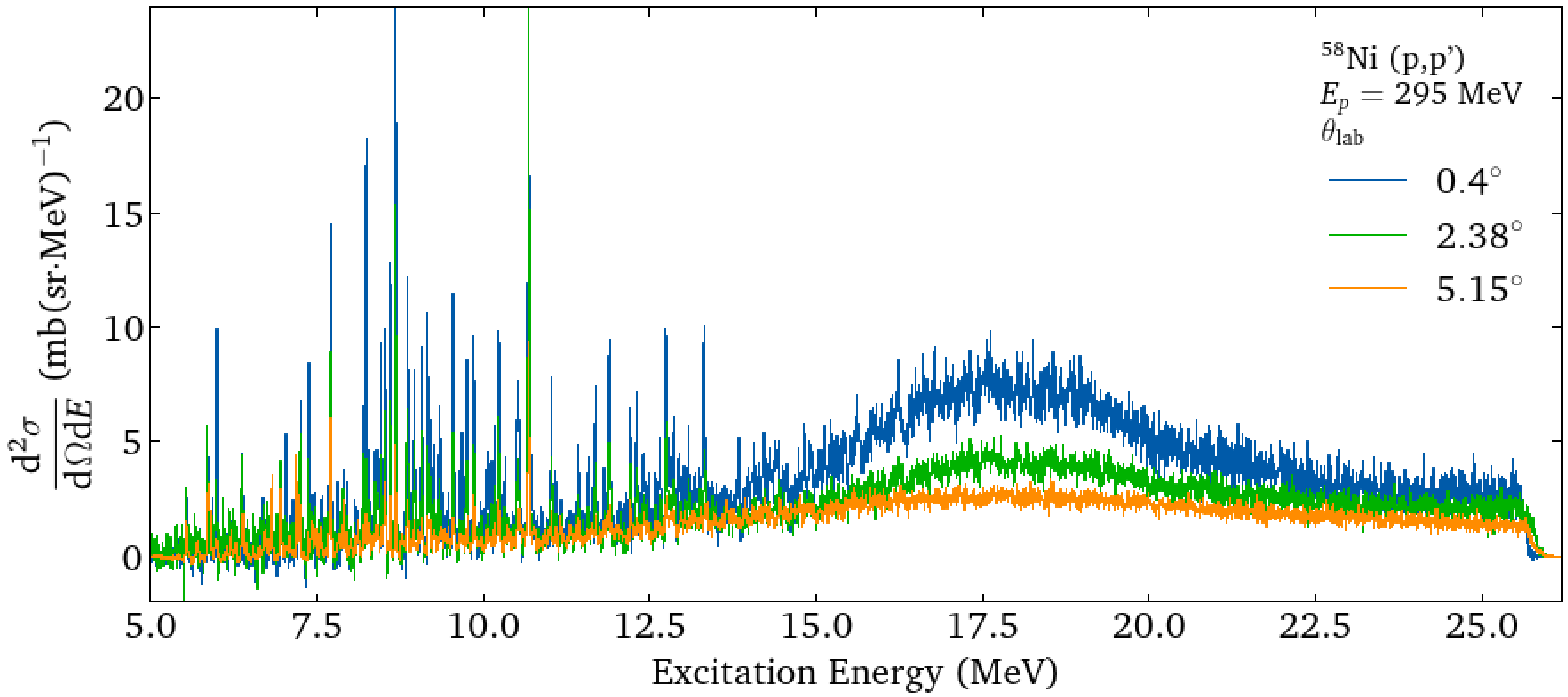
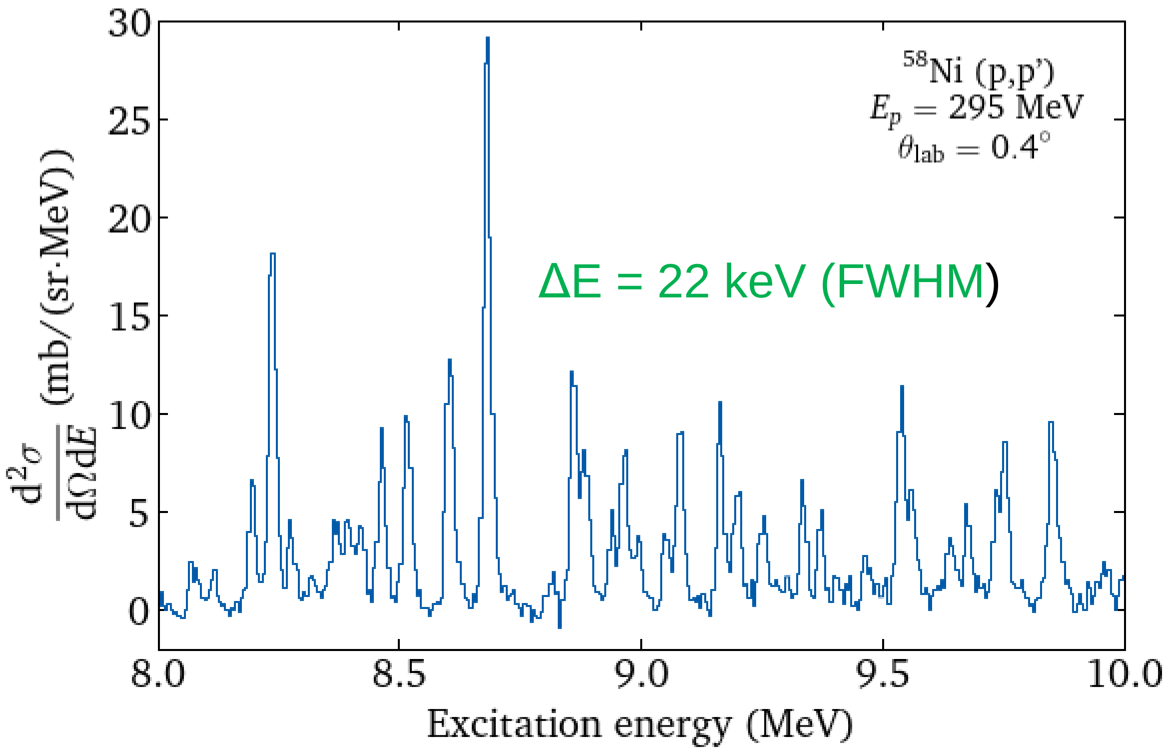
I. Brandherm et al., arXiv:2404.15906



- Measured at RCNP with GRAND RAIDEN spectrometer

^{58}Ni(p,p‘) Data

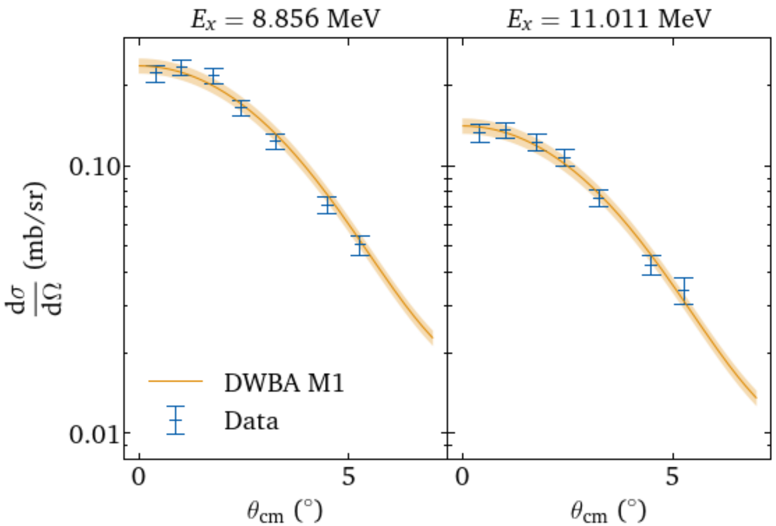
I. Brandherm, MSc thesis, TU Darmstadt (2020)



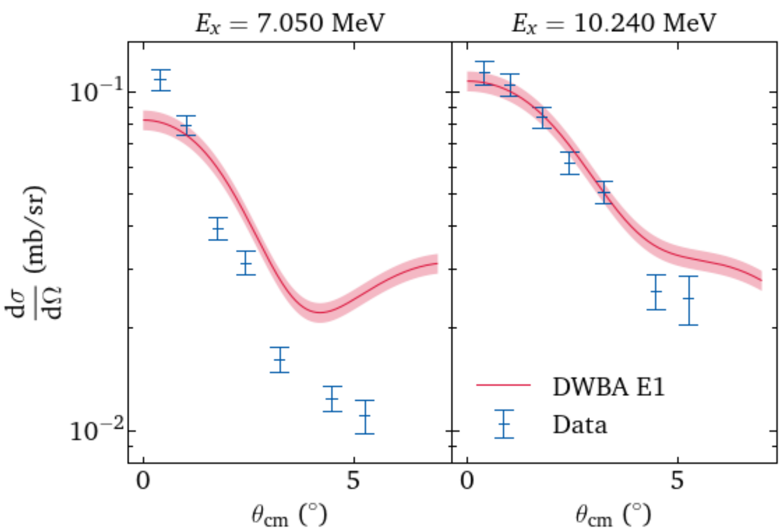
- Peak-by-peak analysis between 5 and 13.3 MeV
- In total 147 transitions

Examples of ^{58}Ni(p,p') MDA Results

M1

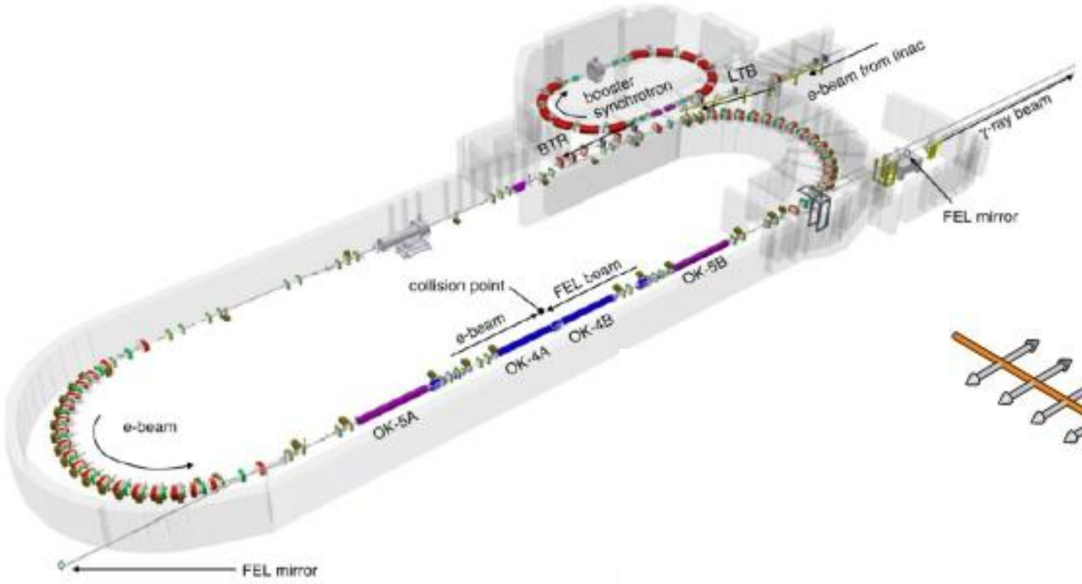


E1

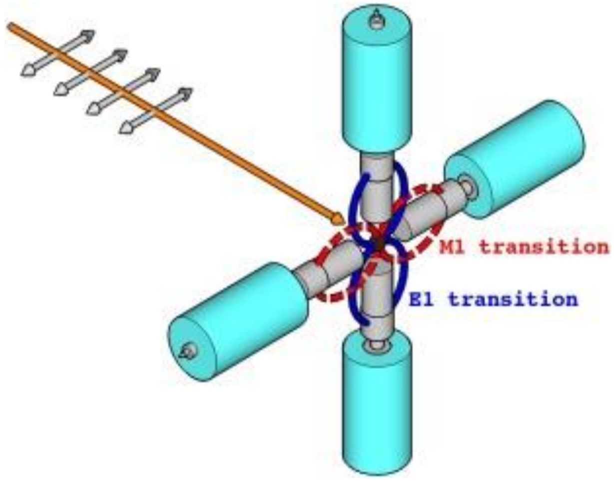


^{58}Ni(γ,γ‘) Experiments at HIγS

- High-Intensity Gamma-Ray Source (HIγS) @ Duke University
- Quasi-monoenergetic, 100% linearly polarized photon beam



- ΔE = 5 - 10 keV (FWHM)

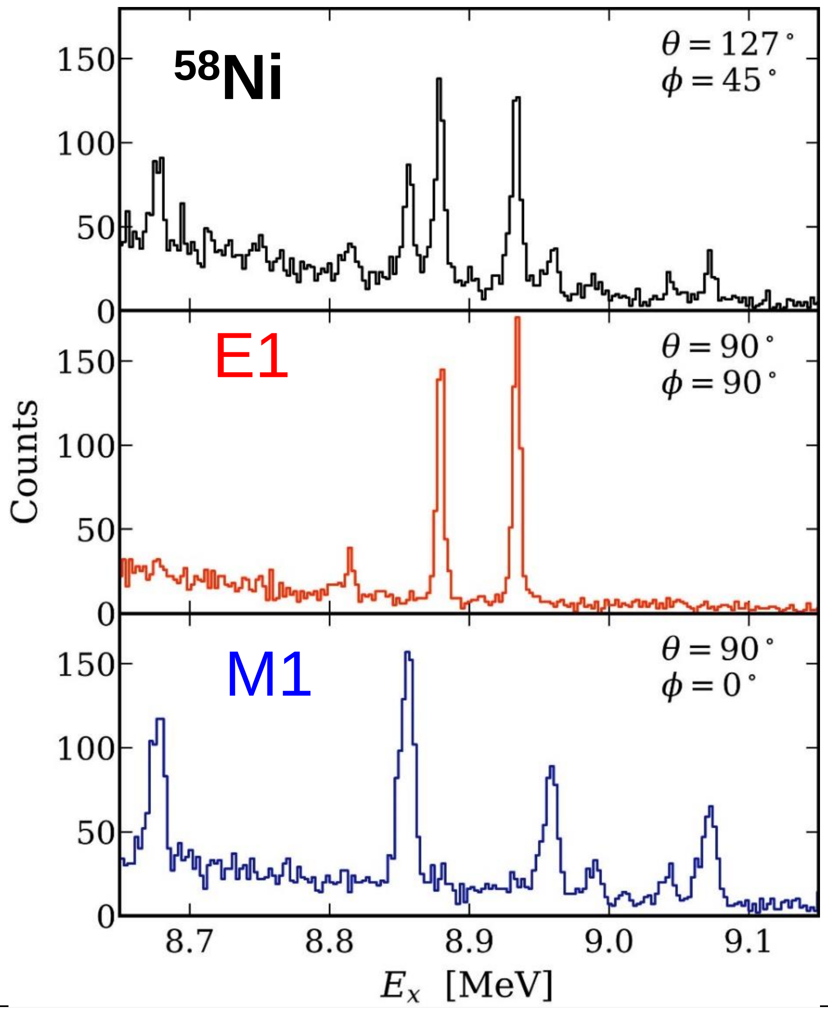


H. R. Weller *et al.*, Prog. Part. Nucl. Phys. **62**, 257 (2009)
N. Pietralla *et al.*, Phys. Rev. Lett. **88**, 012502 (2002)

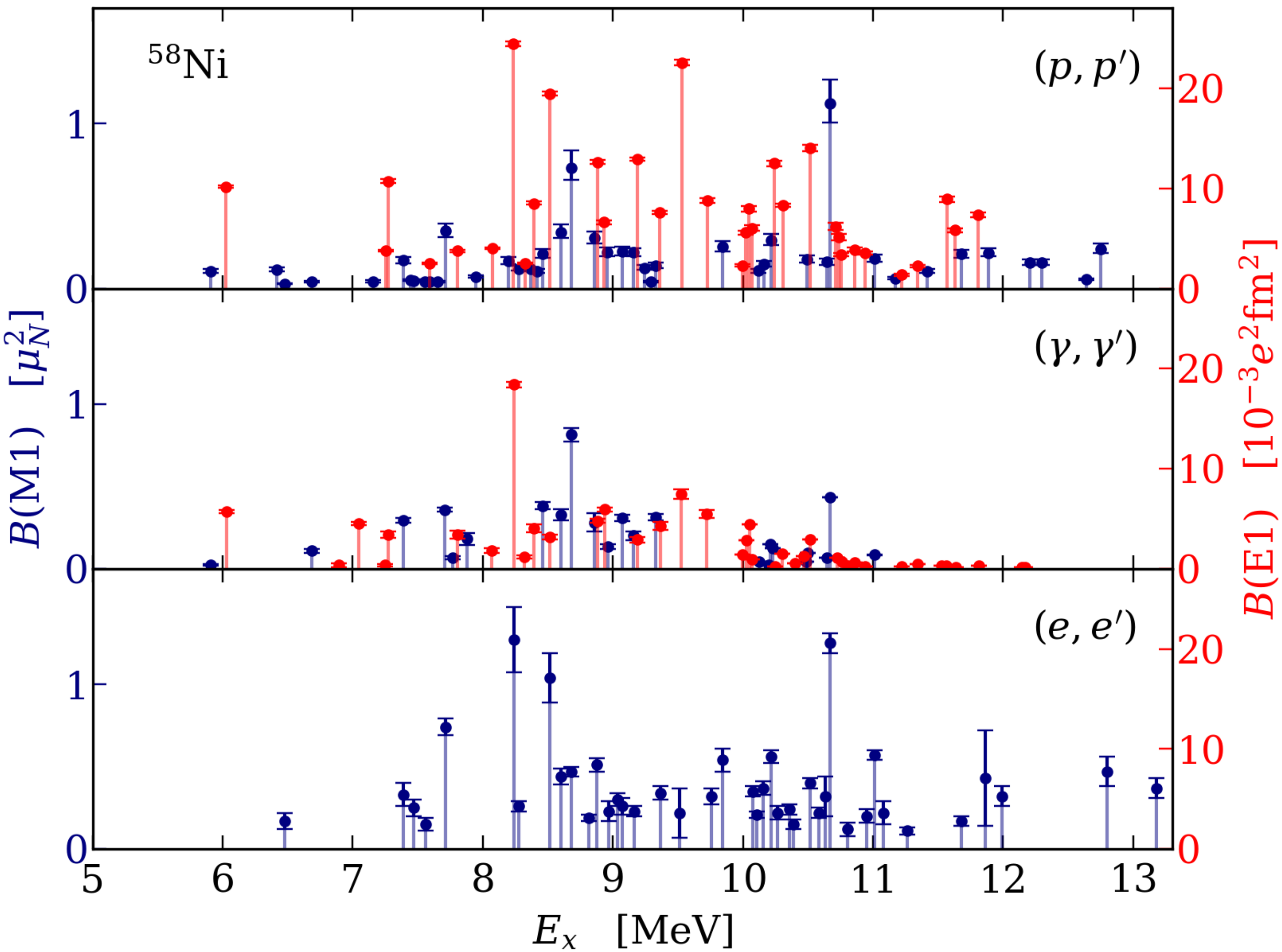
^{58}Ni(γ,γ‘) Parity Determination

M. Scheck, private communication

- Unique determination of the electric/magnetic character



Dipole Strength Distributions



Do the Experiments Excite the Same States?

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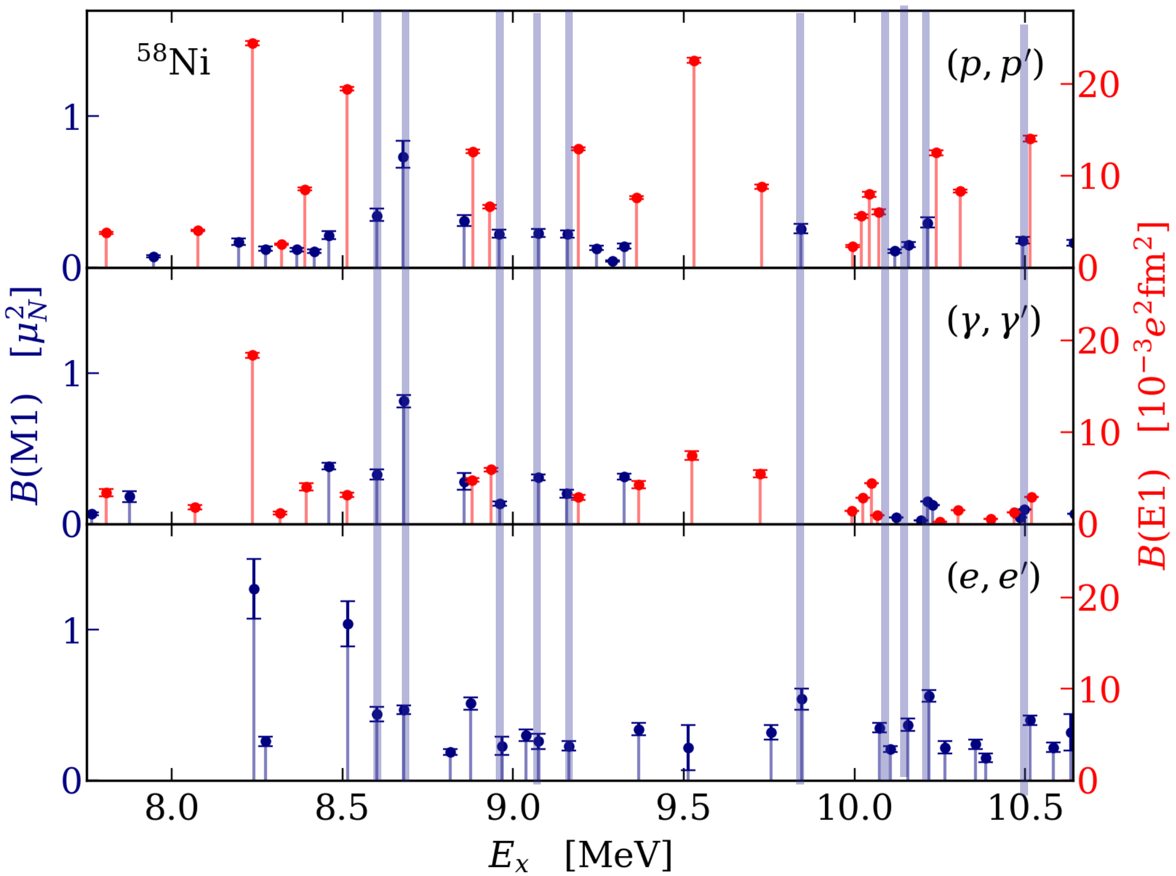

- Criterion

$$\frac{|E_{x,\mathrm{e}1} - E_{x,\mathrm{e}2}|}{\sqrt{u_{\mathrm{e}1}^2(E_x) + u_{\mathrm{e}2}^2(E_x)}} \leq \sqrt{2}$$