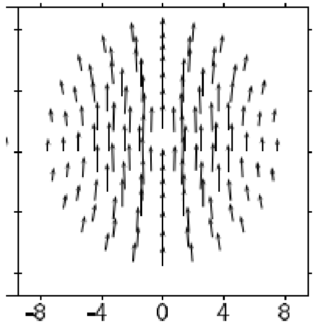
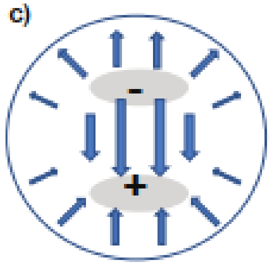
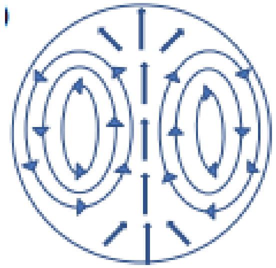
Experimental Signatures of a Toroidal E1 Mode in ^{58}Ni

Peter von Neumann-Cosel
Institut für Kernphysik, Technische Universität Darmstadt

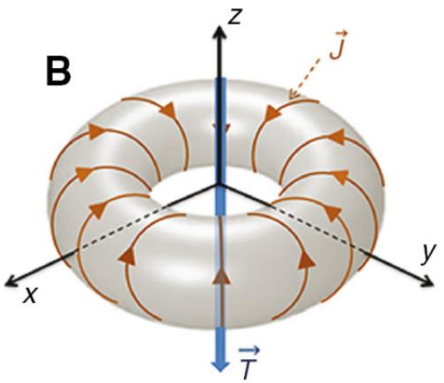
- Fundamental E1 modes
- Properties of the toroidal mode
- Combined analysis of high-resolution (p,p'), (γ,γ') and (e,e') experiments on ^{58}Ni
- Transverse electron scattering as signature for the toroidal mode
- Possible next steps

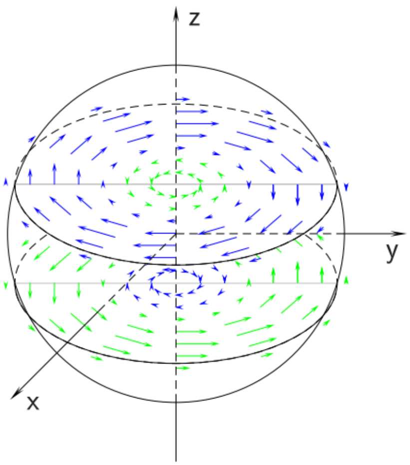
Supported by DFG under contract SFB 1245 (project id 279384907)

Fundamental E1 Modes

Mode	Velocity 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		$\hat{M}^{\mathrm{tor}}_{1\mu}(T=0) = -\frac{1}{10c\sqrt{2}}\int \mathrm{d}\boldsymbol{r}\, r^3 \mathbf{Y}_{11\mu}(\Omega_i)\cdot(\nabla\times\hat{\mathbf{j}}_{\mathrm{nuc}})$

Toroidal E1 Mode



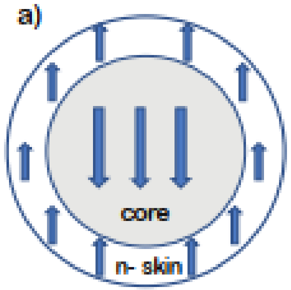


- Toroidal modes appear in a large variety of physics problems from hydrodynamics to solid state physics to cosmology
- Similar to Hill's spherical vortex ring, but corresponds to oscillations along the streamlines
- Quantum phenomenon, contradicts fluid-dynamical pictures of giant resonances
- Transverse "zero sound" mode (Landau) indicating that nuclei can be described as an elastic medium
- Other example orbital M2 twist mode

PvNC et al., PRL 82, 1105 (1999); B. Reitz et al., PLB 532, 179 (2002)

Toroidal E1 Mode in Heavy Nuclei

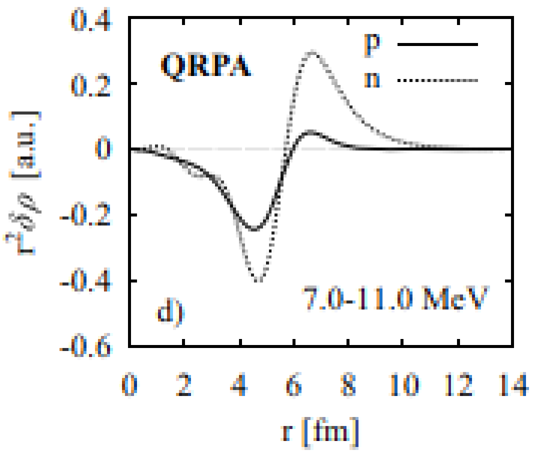
PDR



- Overlaps with isoscalar part of the PDR observed in nuclei with sufficient neutron excess

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

^{120}Sn



- Questions interpretation of the PDR as neutron skin oscillation

A. Repko et al., PRC 024305 (2013)

- Similar transition densities in heavy nuclei

A. Repko et al., EPJA 55, 242 (2019)

Experimental Evidence for a Toroidal E1 Mode?

TECHNISCHE UNIVERSITÄT DARMSTADT

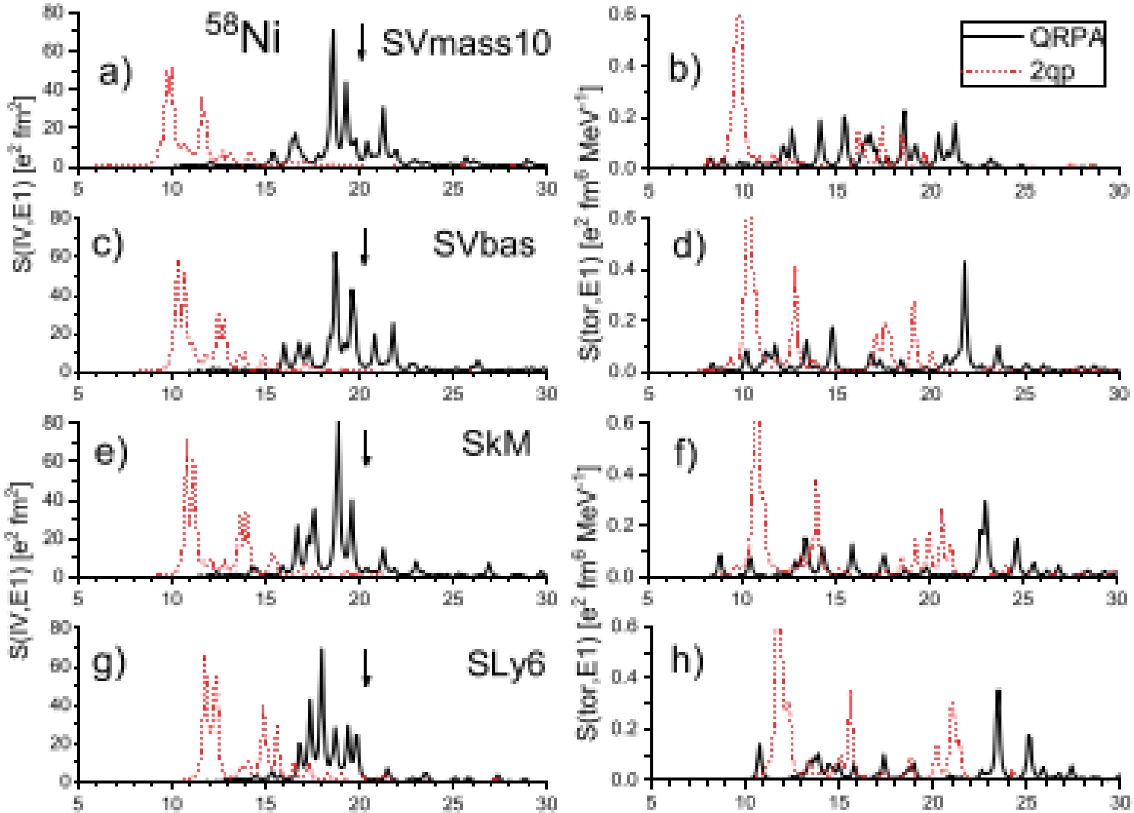
Despite its prediction about 60 years ago and considerable theoretical work, there is no clear experimental evidence for a toroidal E1 mode so far.

A recent review [A. Repko et al., EPJA 55, 242 (2019)] concludes: “*Unfortunately, theory and experiment have no yet come to robust proposals for unambiguous identification of intrinsic vortical electric modes. Such proposals should take into account both nuclear structure and reaction mechanisms and thus may be involved*.”

What is the problem?

Theoretical Predictions: Residual Interaction

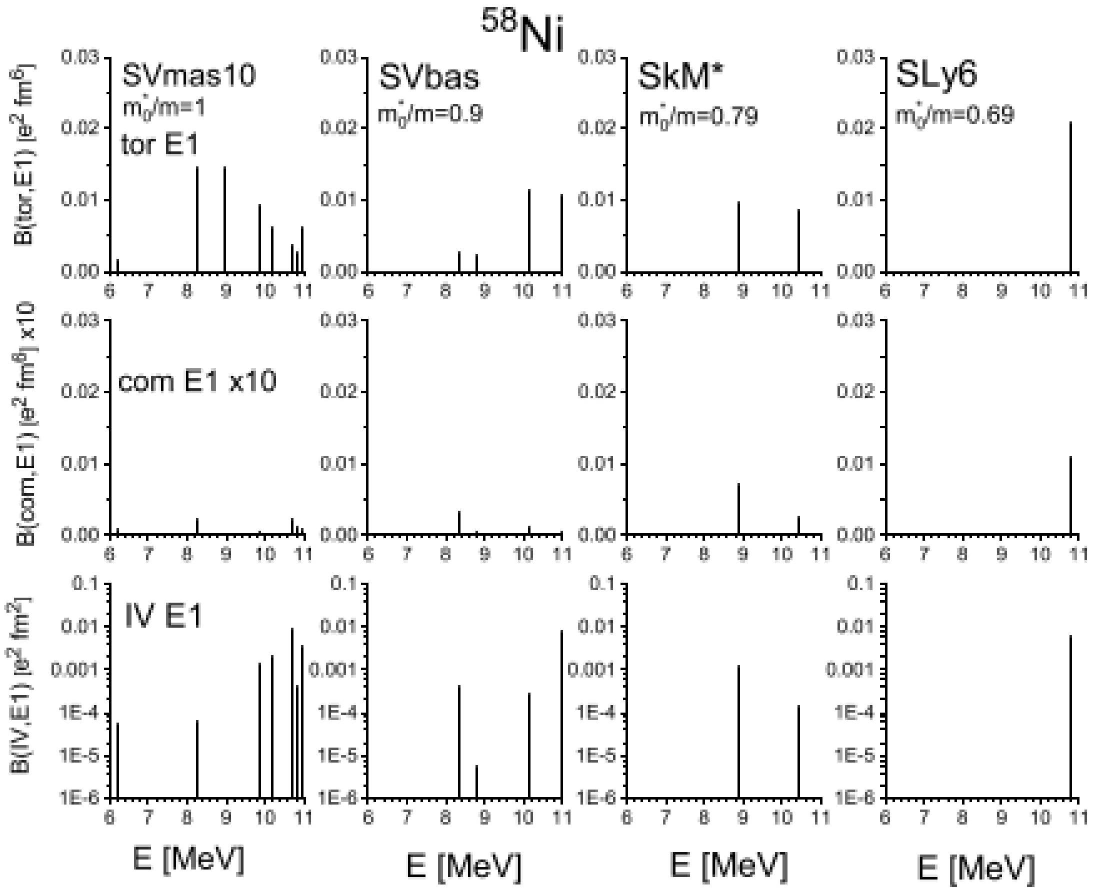
A. Repko et al., EPJA 55, 242 (2019); V. Nesterenko et al. (2022)



- Toroidal strength extremely fragmented → strong mixing
- Residual interaction shifts part of the strength to low energy

Theoretical Predictions: Strength

A. Repko et al., EPJA 55, 242 (2019); V. Nesterenko et al. (2022)

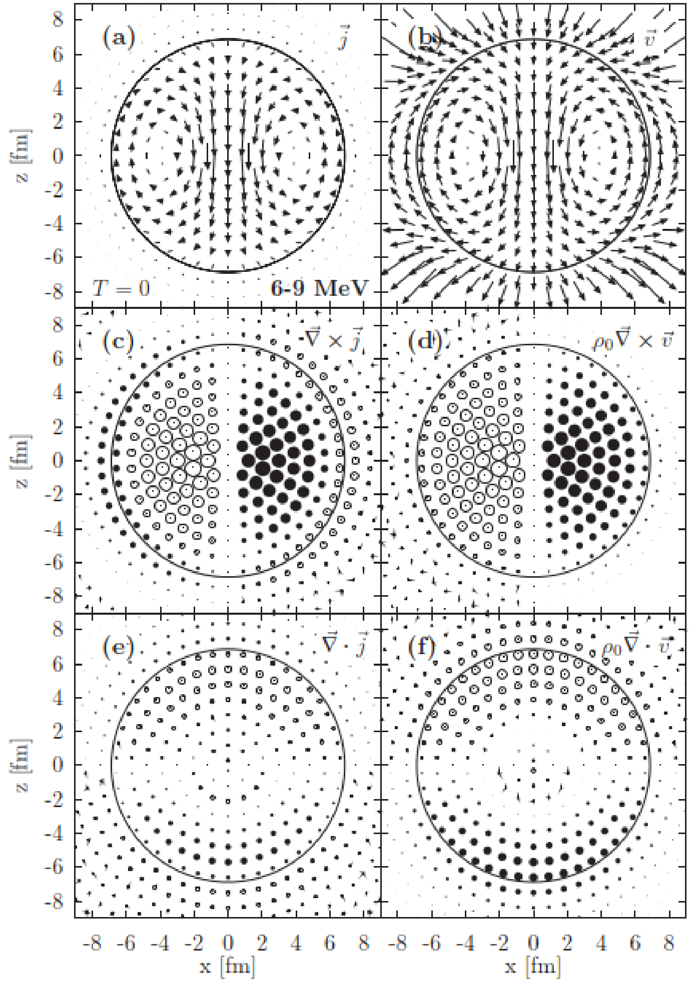


- Excitation energy and collectivity depend on effective mass

Theoretical Predictions: Flow Pattern

P.-G. Reinhard et al., PRC 89, 024321 (2014)

- Current
- Curl
- Gradient

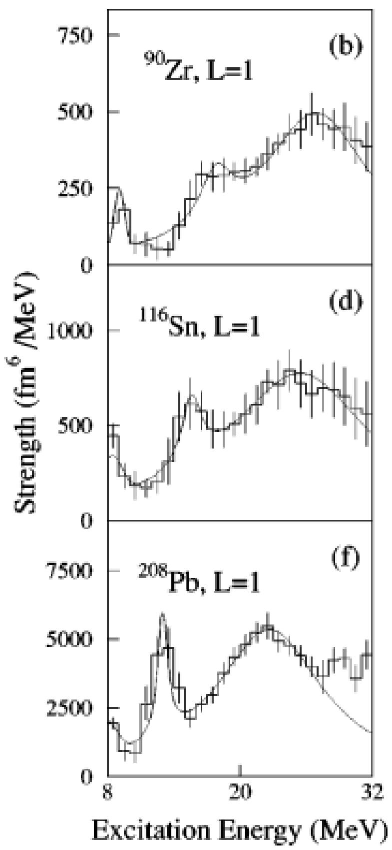


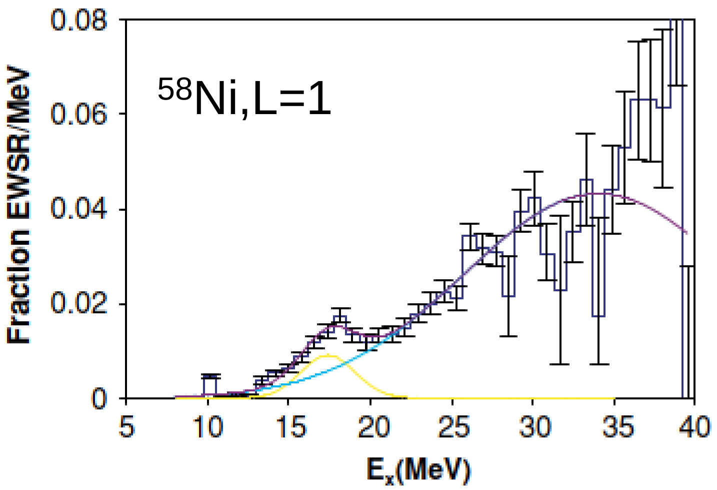
- Velocity
- Curl
- Gradient

Possible Experimental Signatures: Low-Energy Bump in the ISGDR Strength

M. Uchida et al., PRC 69, 051301(R) (2004)

Y.-W. Lui et al, PRC 73, 014314 (2006)



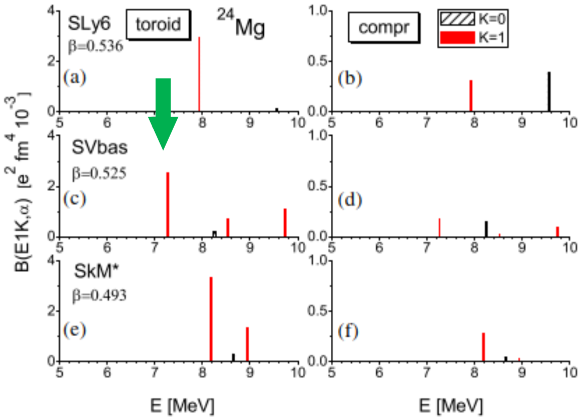


- Interpreted as coupling of compressional and toroidal mode

D. Vretenar et al., PRC 65, 021301(R) (2002)

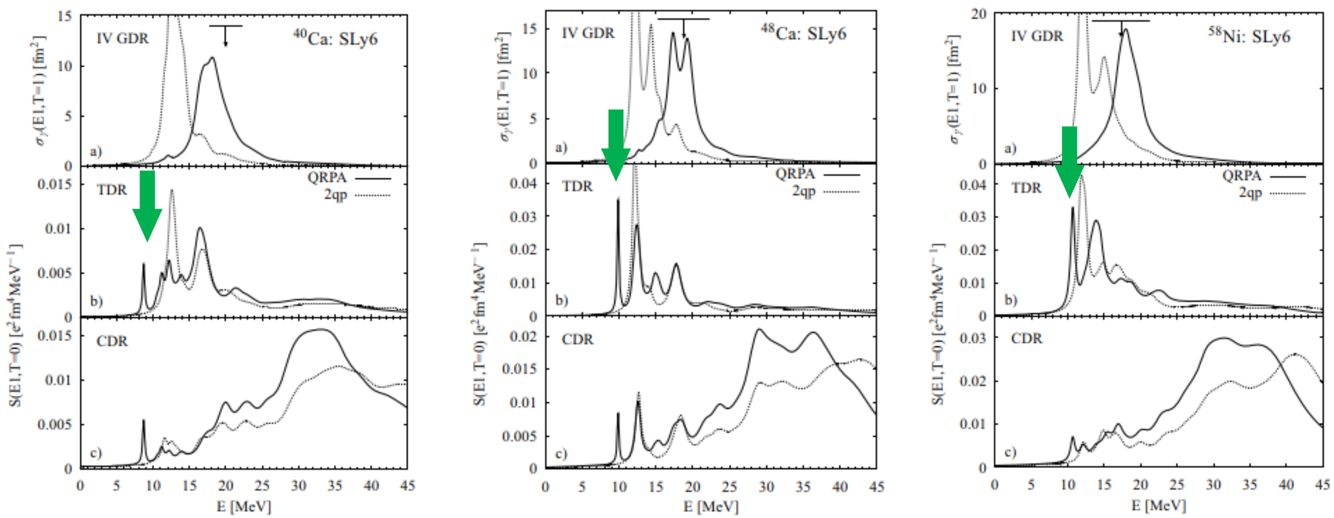
Possible Experimental Signatures: Individual ‘Pure‘ Toroidal States in Light Nuclei

V.O. Nesterenko et al., PRL 120, 182501 (2018)



- Residual interaction shifts part of the strength down in energy leading to rather pure toroidal excitations

A. Repko et al., EPJA 55, 242 (2019)

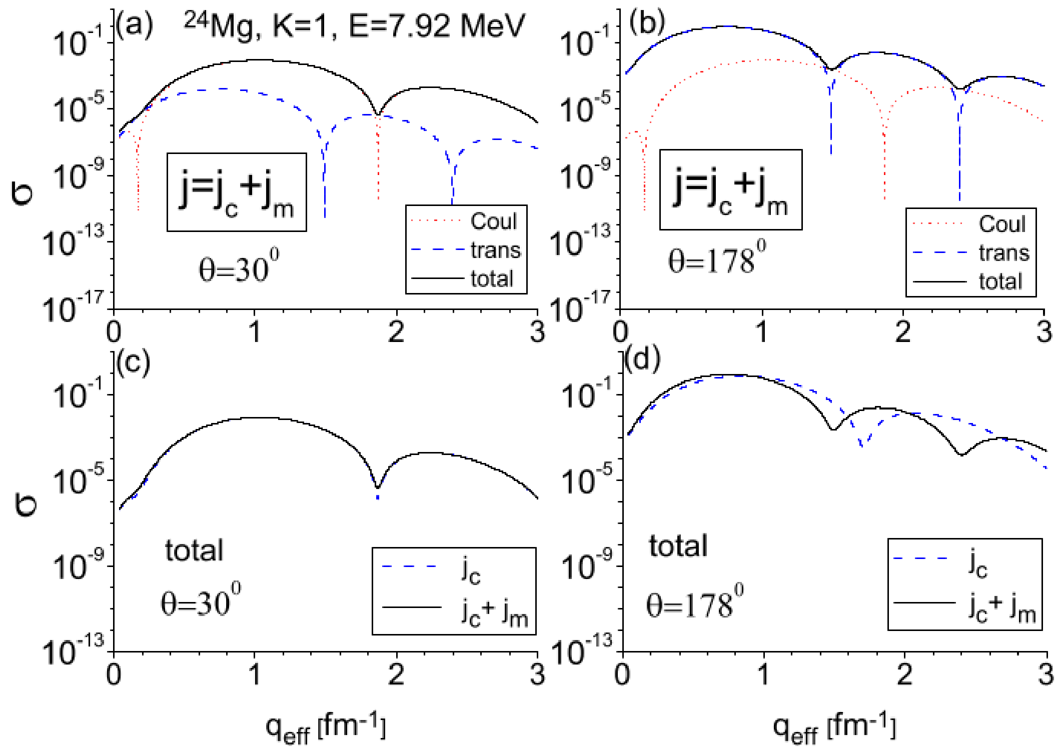


Possible Experimental Signatures: Transverse Electron Scattering

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

V.O. Nesterenko et al., PRC 100, 064302 (2019)

- Large transverse cross sections!
- Dominate at backward angles



The Case of ^{58}Ni

- Low-energy isoscalar dipole strength measured with (α,α‘γ) reaction

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

- Combined analysis of **high-resolution** (p,p’), (γ,γ‘) and (e,e‘) experiments

- (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,M2

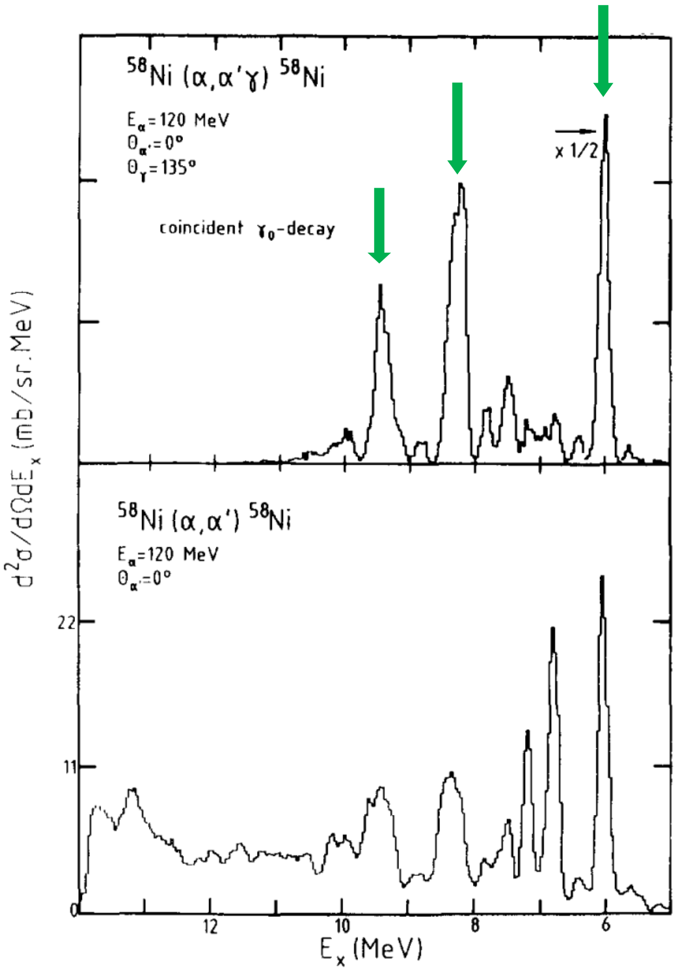
  W. Mettner et al., NPA 473, 160 (1987)

The Case of ^{58}Ni: Low-Energy Isoscalar Strength

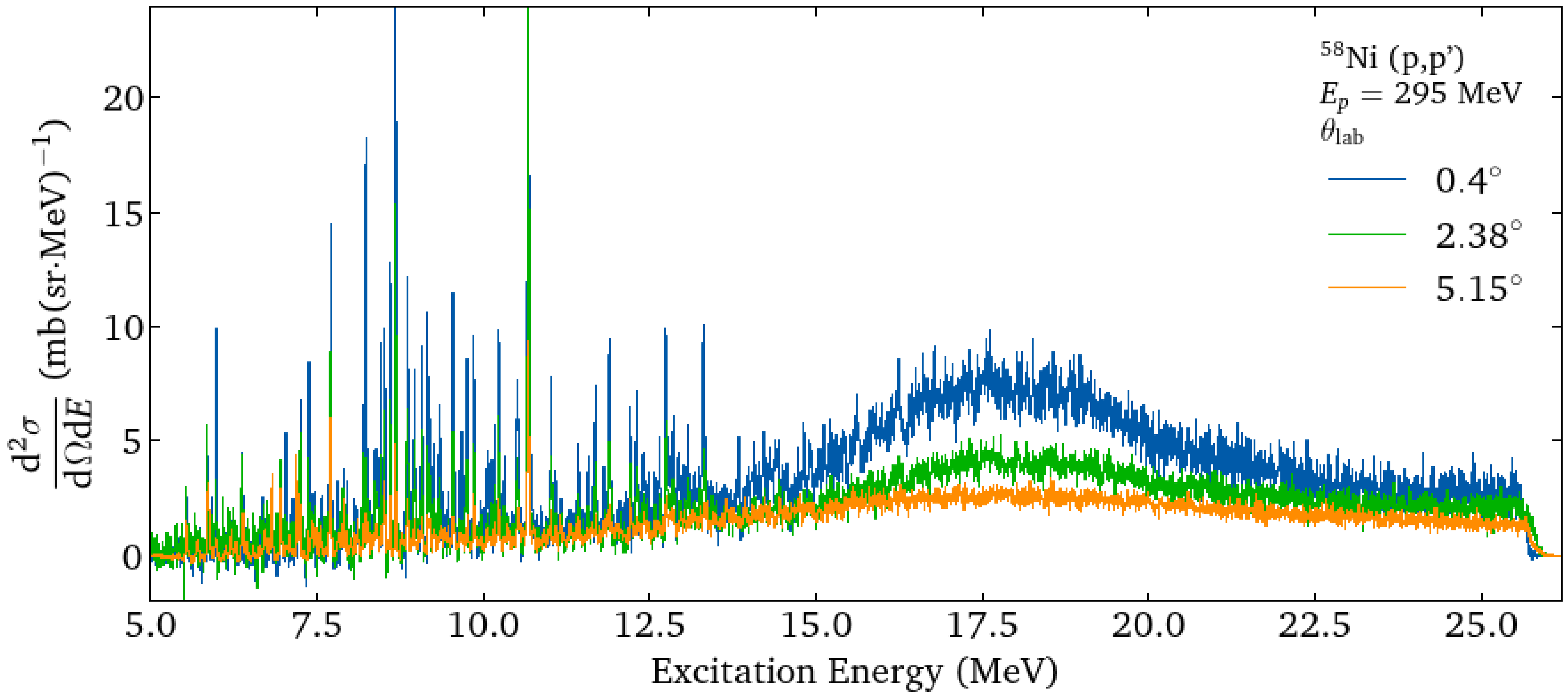
TECHNISCHE UNIVERSITÄT DARMSTADT

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

- Strong peaks at about 6.0 MeV, 8.3 MeV and 9.4 MeV

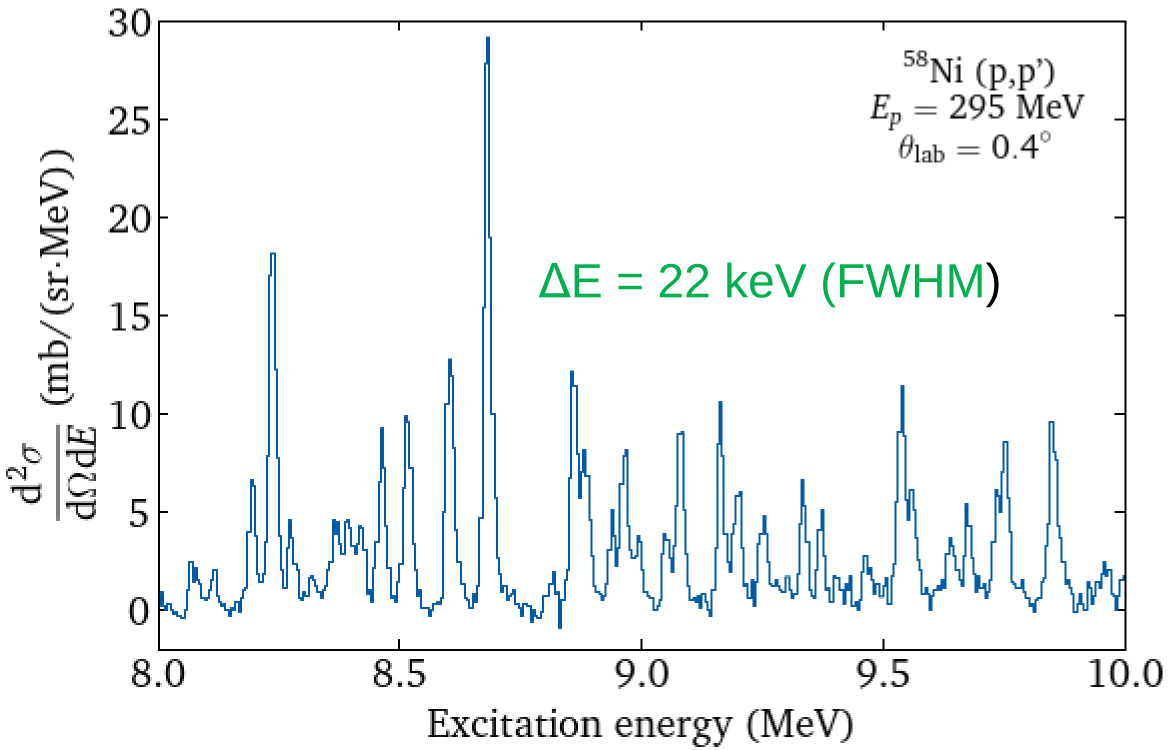


The Case of ^{58}Ni: (p,p‘) Reaction
Spectra



The Case of ^{58}Ni: (p,p') Reaction
Peak-by-Peak Analysis

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

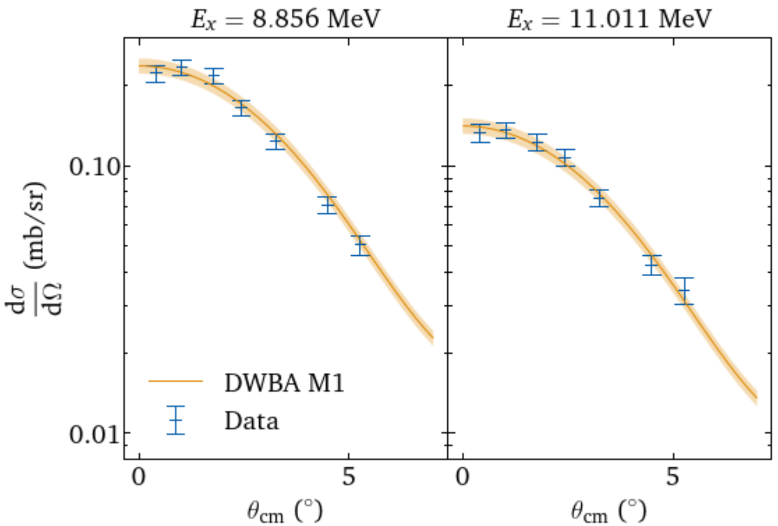


- Peak-by-peak analysis between 5 and 13.3 MeV
- In total 147 transitions

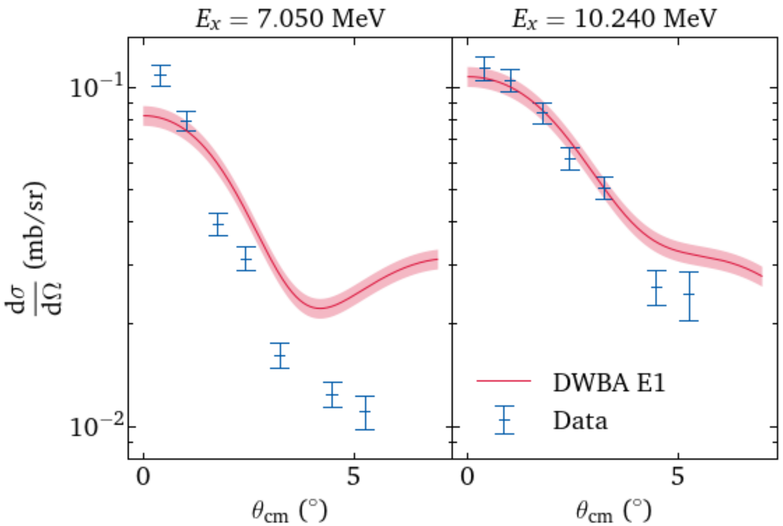
The Case of ^{58}Ni: (p,p‘) Reaction

Examples of MDA Results

M1



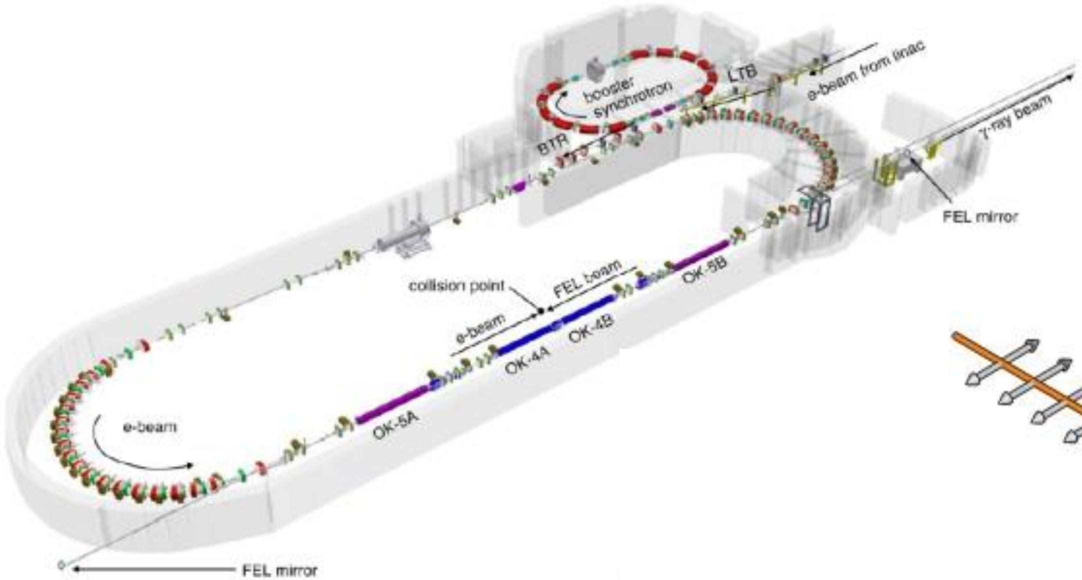
E1



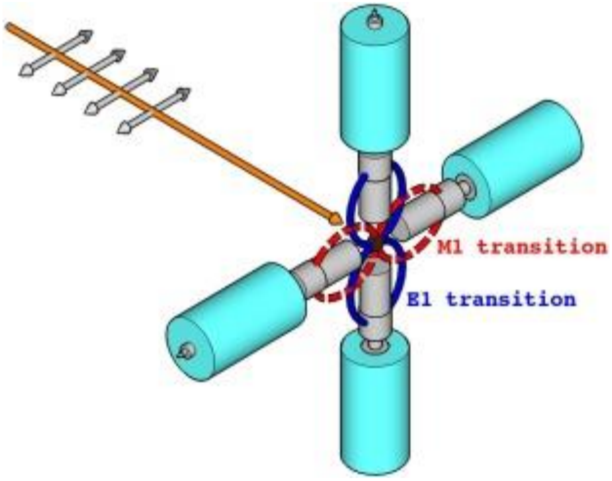
The Case of ^{58}Ni: (γ,γ‘) Reaction

Experiments at HIγS

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



- ΔE = 5 - 10 keV (FWHM)

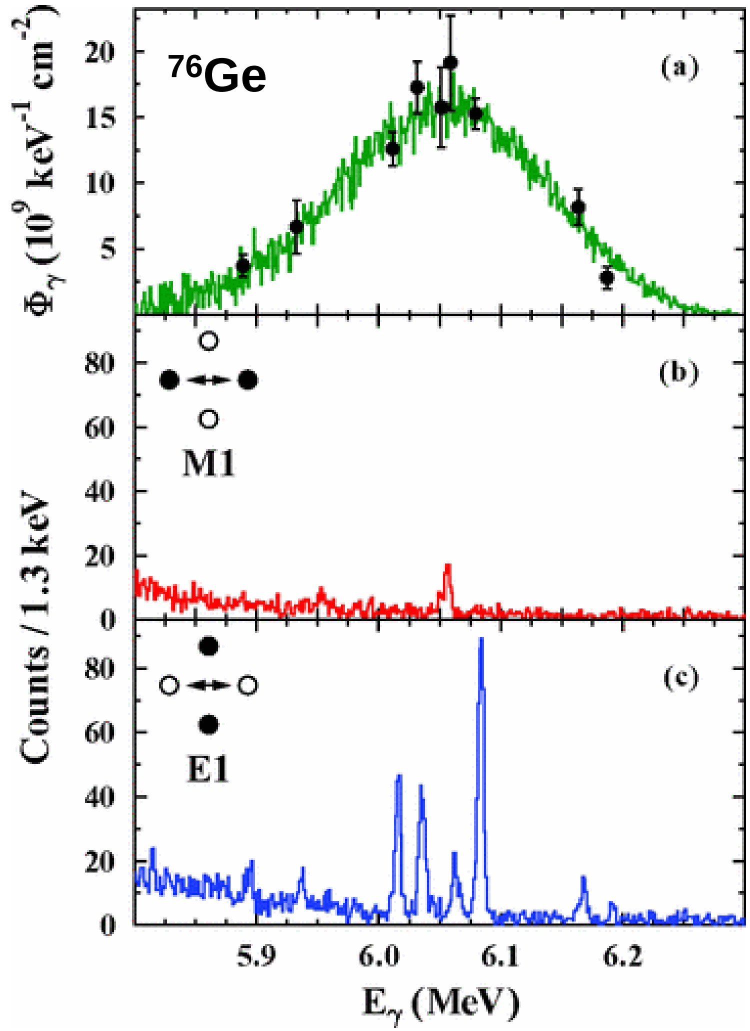


H. R. Weller *et al.*, Prog. Part. Nucl. Phys. **62**, 257 (2009)
N. Pietralla *et al.*, Phys. Rev. Lett. **88**, 012502 (2002)

The Case of ^{58}Ni: (γ,γ‘) Reaction
Parity Determination

TECHNISCHE UNIVERSITÄT DARMSTADT

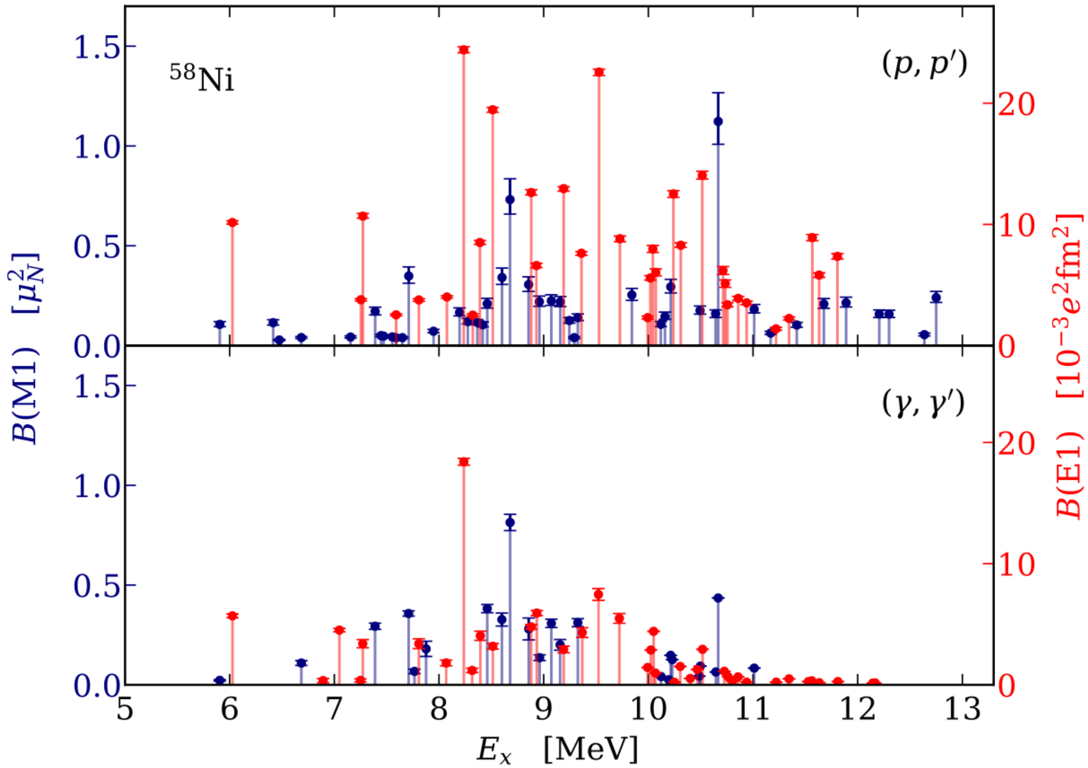
- Unique determination of the electric/magnetic character of dipole transitions and thereby the parity of the excited states



Dipole Strength Distributions

TECHNISCHE UNIVERSITÄT DARMSTADT

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

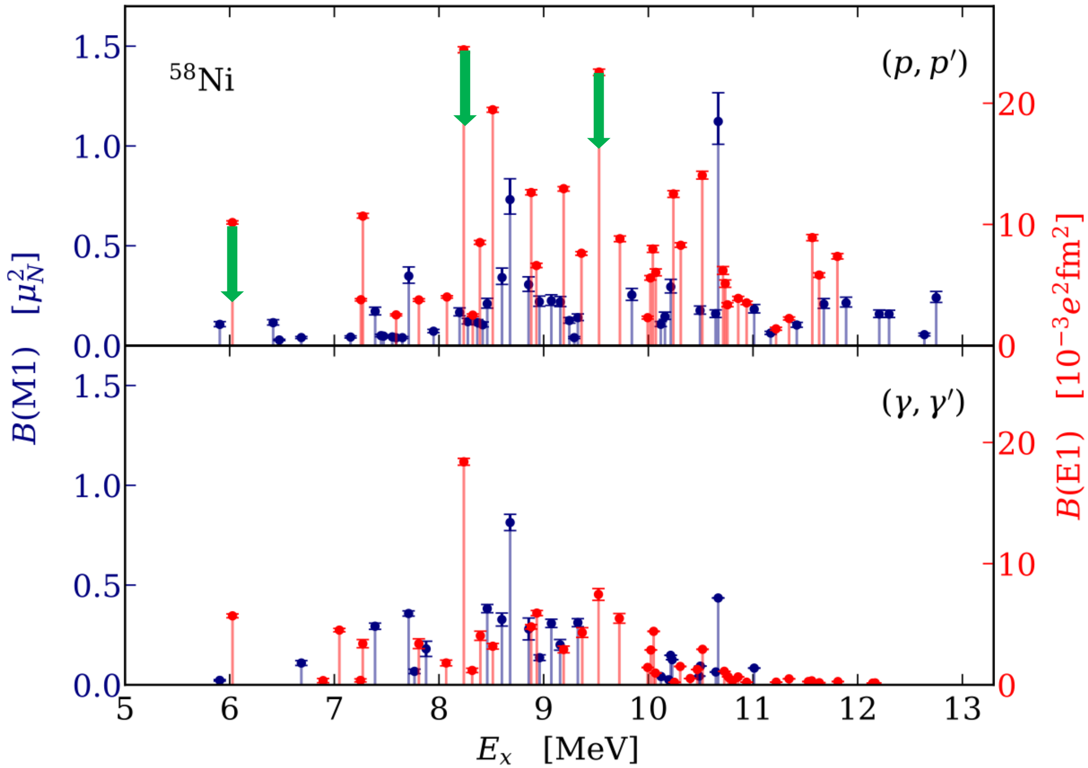


J. Sinclair, PhD thesis, UWS (in preparation)

- Good agreement of observed dipole transitions and their multipolarity
- Strength difference due to unobserved branching ratios in (γ,γ‘)

Dipole Strength Distributions

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



J. Sinclair, PhD thesis, UWS (in preparation)

- Strong transitions at 6.03 MeV, 8.24 MeV and 9.51 MeV (consistent with isoscalar response)

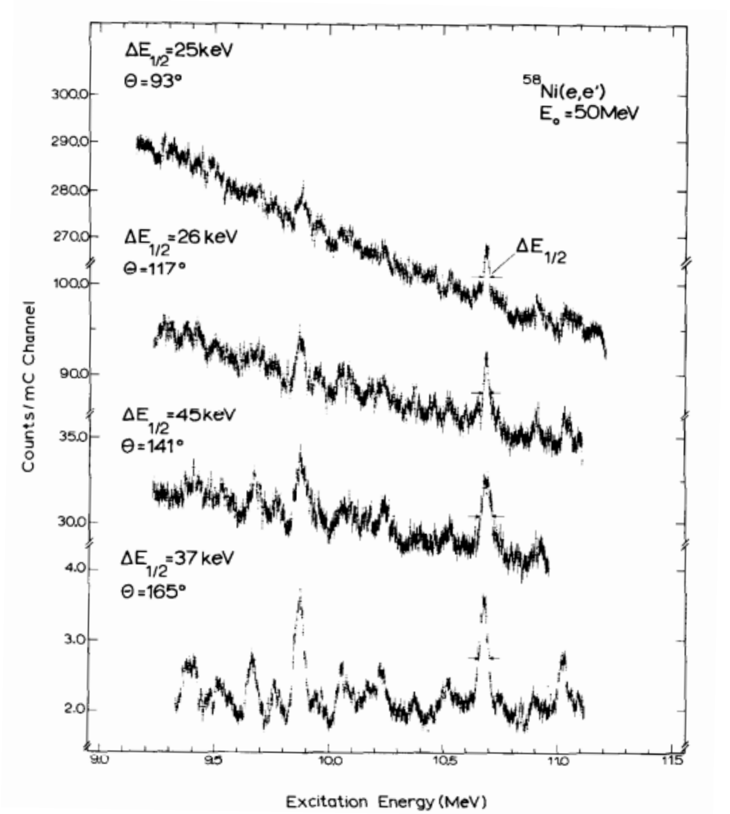
The Case of ^{58}Ni: (e,e') Reaction

Experimental conditions

TECHNISCHE UNIVERSITÄT DARMSTADT

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

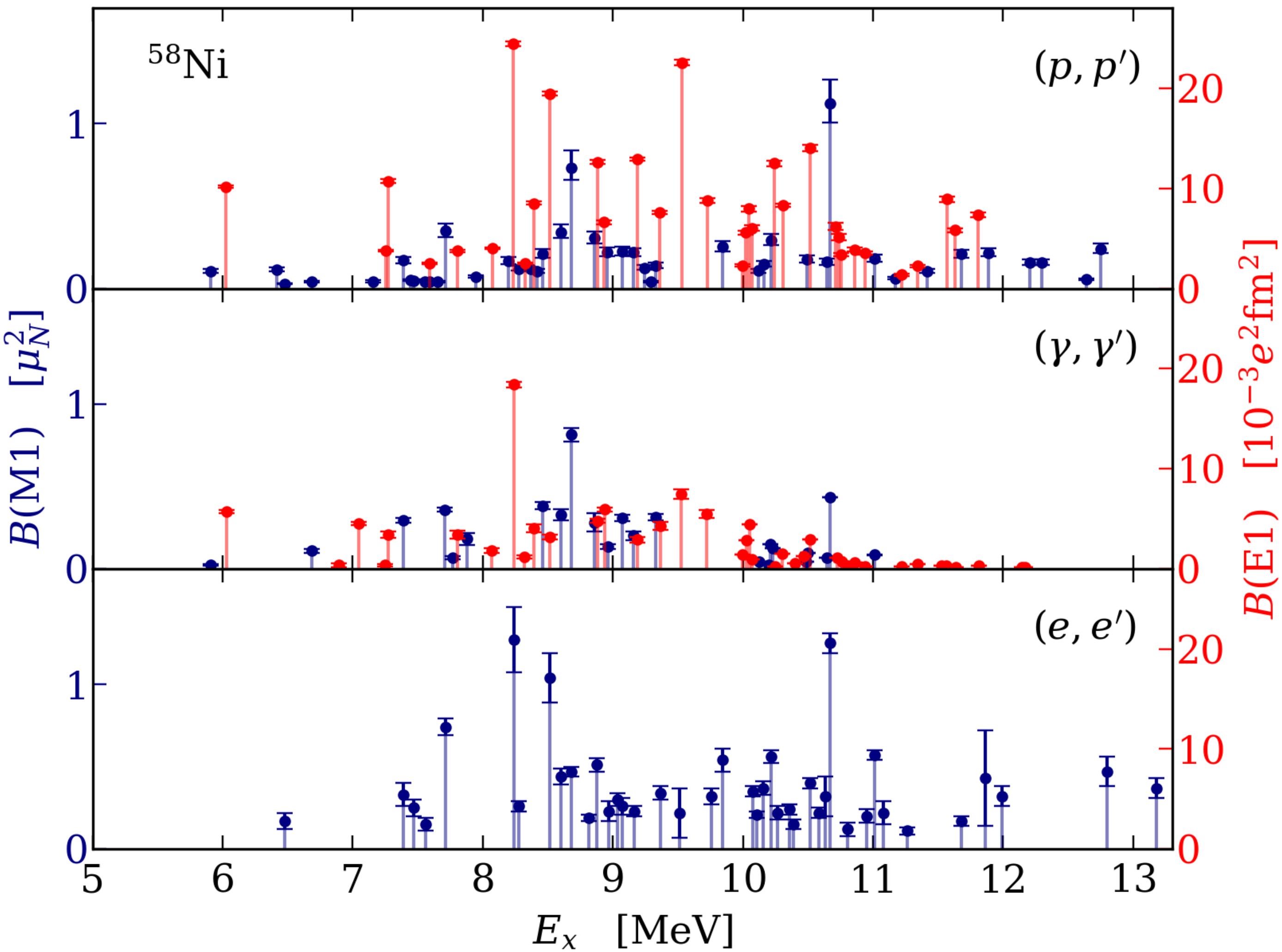
- Most data at $E_0 \approx 50$ MeV
- $\Delta E \approx 30$ keV (FWHM)
- Variation of momentum transfer by changing the angle
  → change of *L/T* ratio
- Increase of σ/σ_{Mott} with angle was taken as signature for magnetic transitions



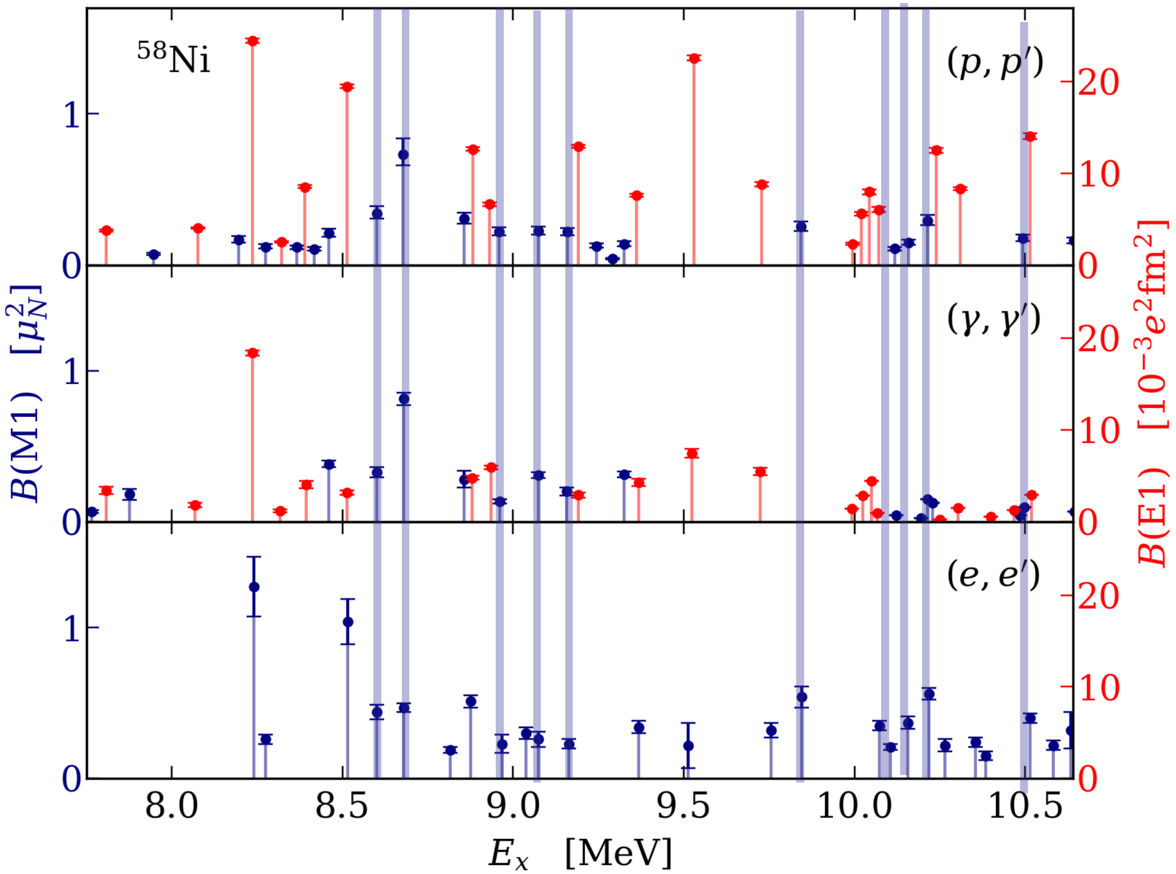
W. Mettner et al., NPA 473, 160 (1987)

Dipole Strength Distributions

TECHNISCHE UNIVERSITÄT DARMSTADT



Do the Experiments Excite the Same States?

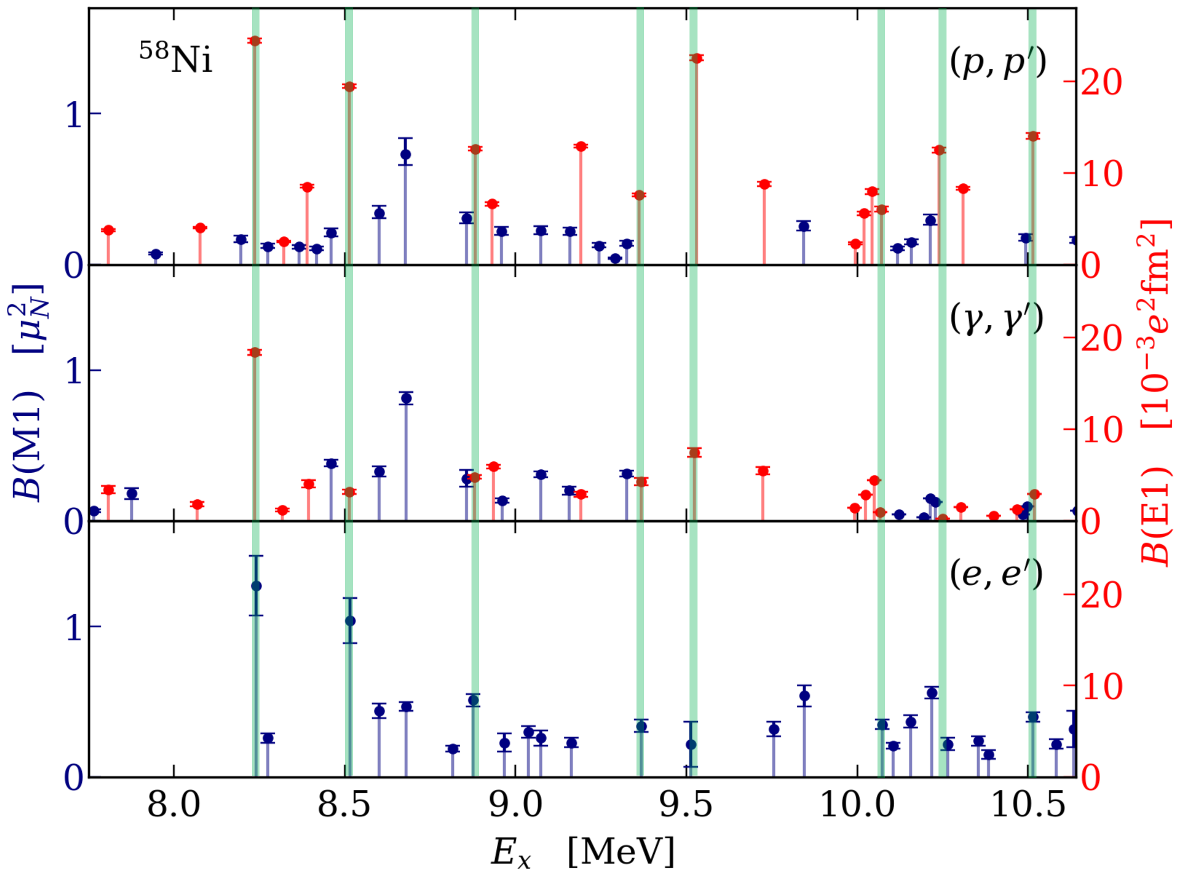


- Criterion

$$\frac{|E_{x,e1} - E_{x,e2}|}{\sqrt{u_{e1}^2(E_x) + u_{e2}^2(E_x)}} \leq \sqrt{2}$$

Do the Experiments Excite the Same States?

TECHNISCHE UNIVERSITÄT DARMSTADT

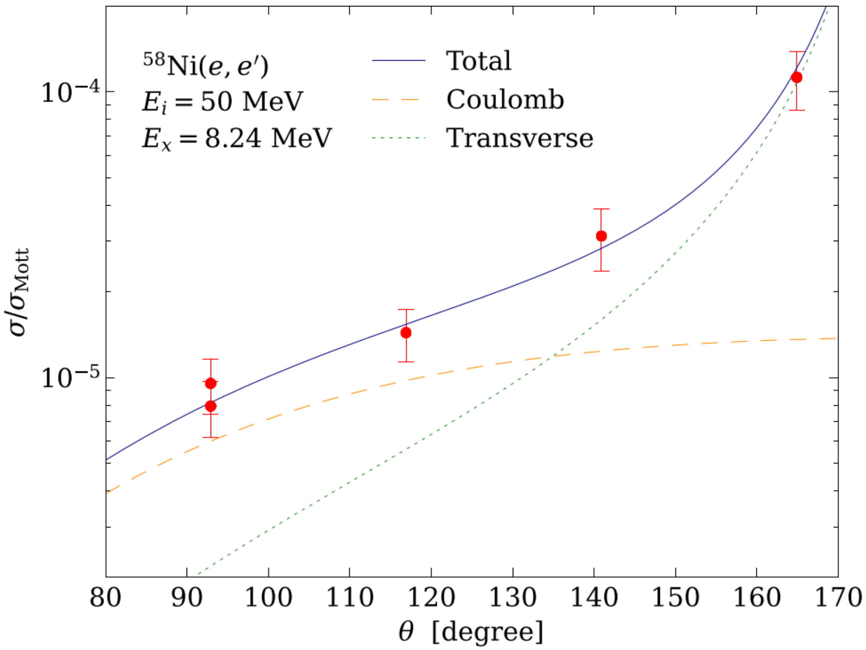


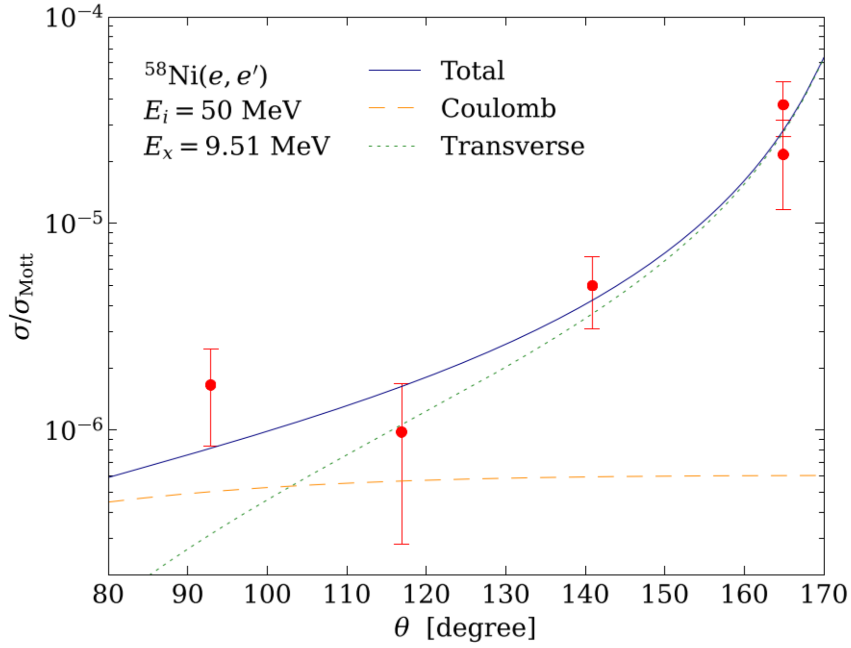
- Assumed to be M1 in (e,e‘) but uniquely assigned E1 in (p,p‘) + (γ,γ‘)

→ E1 transitions with large transverse cross sections

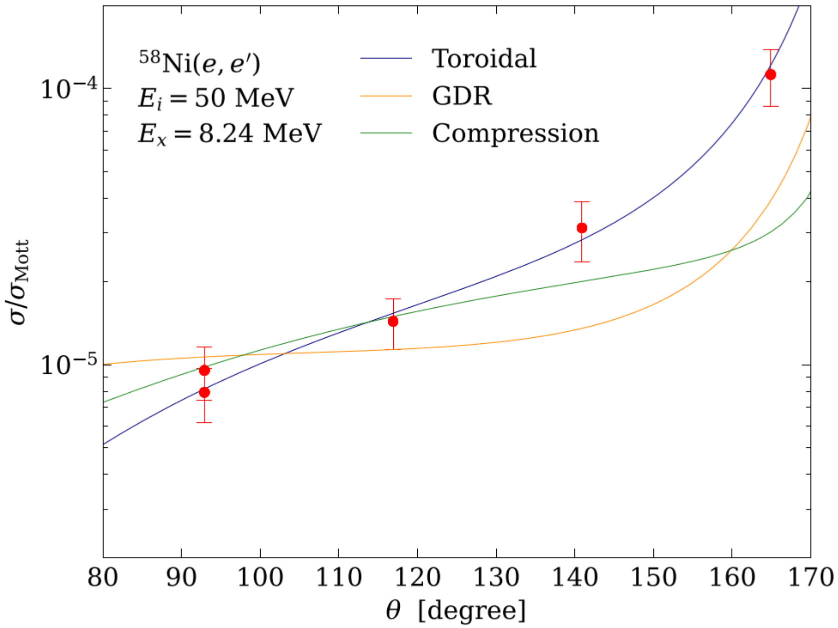
Examples: 8.24 MeV and 9.51 MeV Transitions

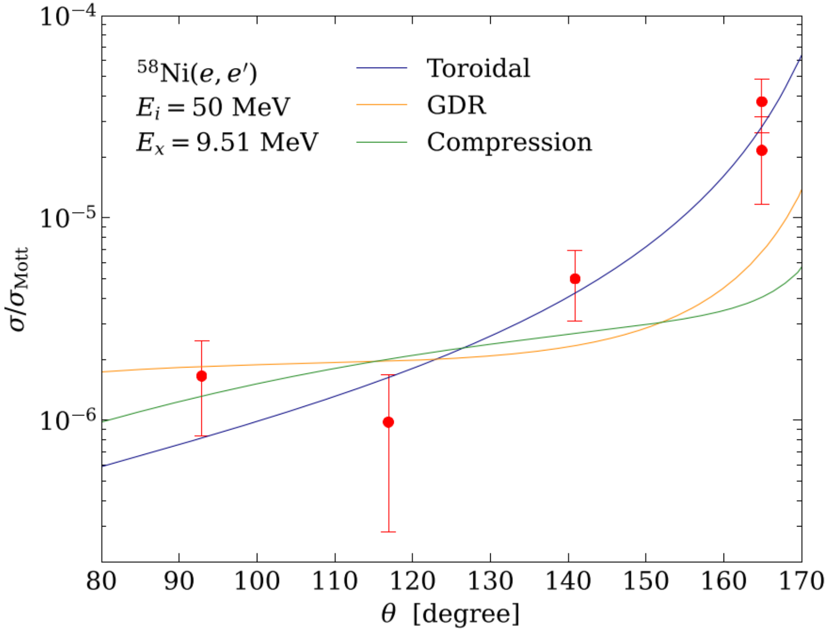
W. Mettner et al., NPA 473, 160 (1987)





Predictions for Different E1 Modes





Summary ^{58}Ni

TECHNISCHE UNIVERSITÄT DARMSTADT

- Combined analysis of high-resolution (p,p’), (γ,γ‘) and (e,e‘) experiments on ^{58}Ni reveals candidates for the long-sought toroidal E1 mode

- Experimental signature: large transverse form factors in inelastic electron scattering

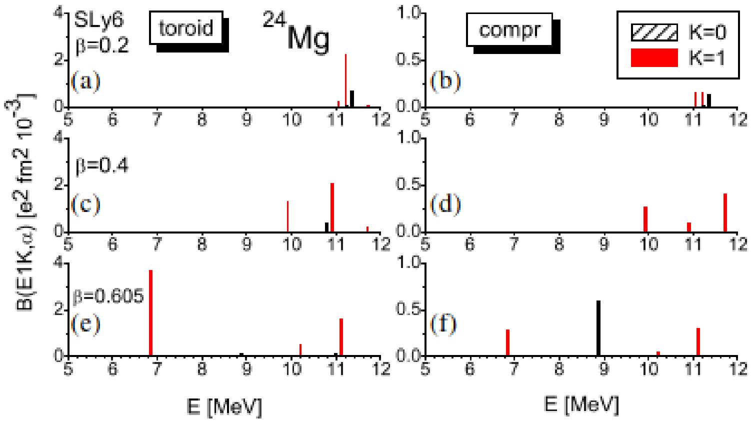
- Some toroidal candidates are also strongly excited with isoscalar probe

- QRPA calculations with the SVmas10 Skyrme interaction can reproduce these features

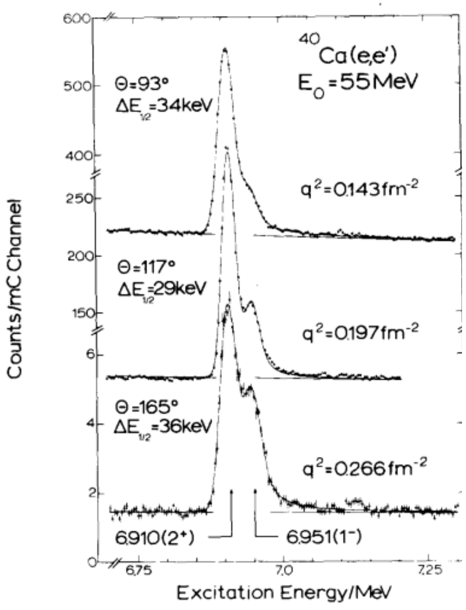
Next steps

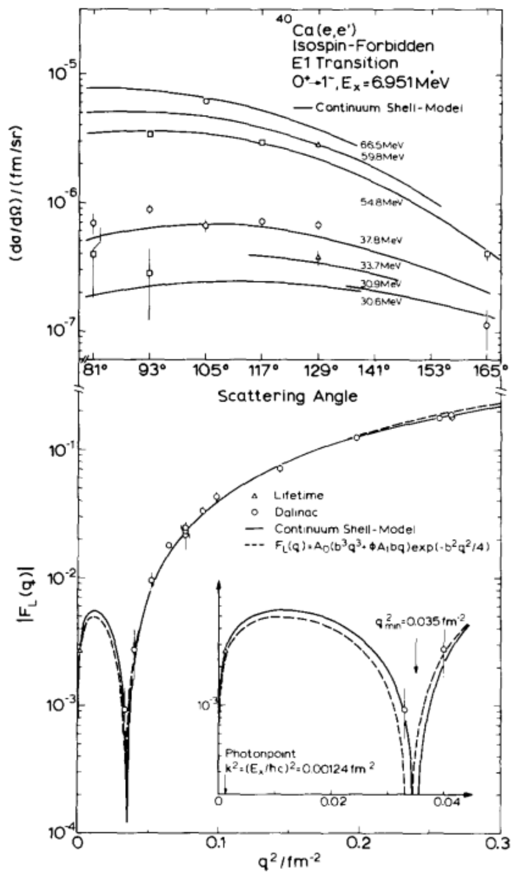
- Investigate other cases (should be a generic mode)

V.O. Nesterenko et al., PRL 120, 182501 (2018)



H.D. Gräf et al., PLB 72, 179 (1977)

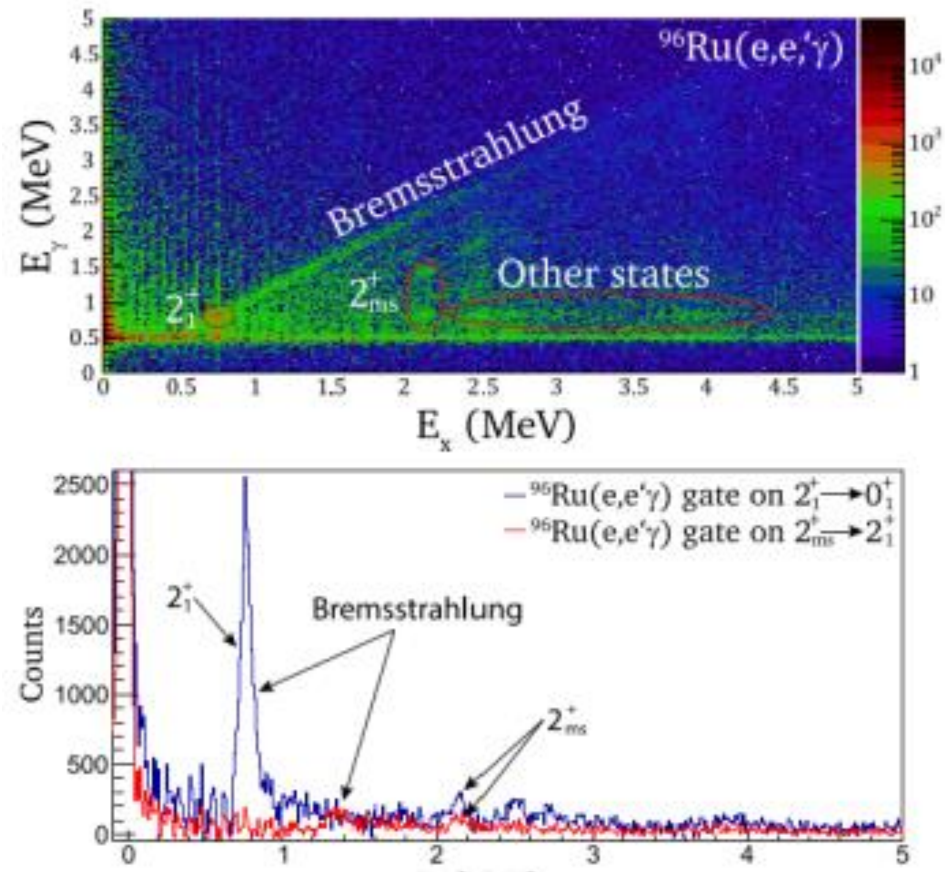




(e,e‘γ) Experiments:
New Experimental Setup at the S-DALINAC

TECHNISCHE UNIVERSITÄT DARMSTADT

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



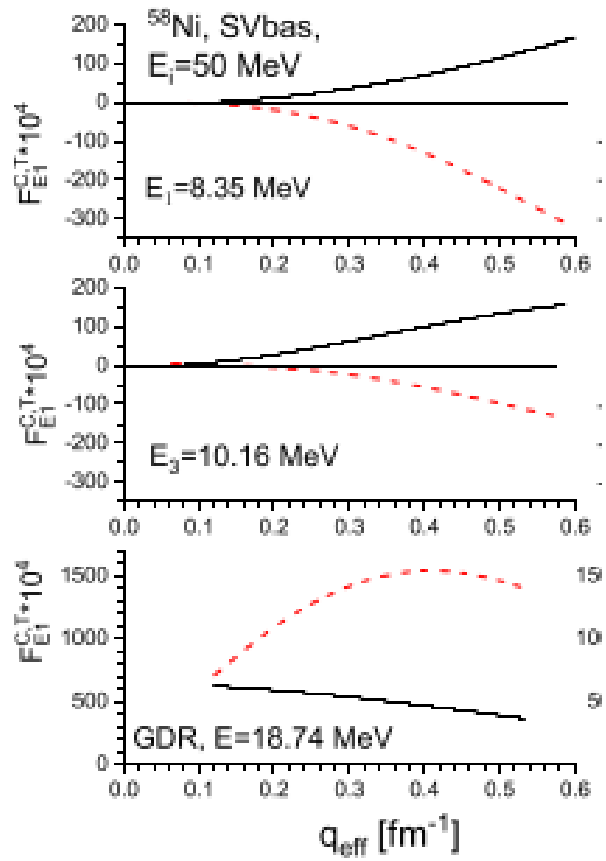
(e,e‘γ) Experiments: Sensitivity to *L/T* Interference Term

- (e,e‘γ) cross sections

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

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

- $F_L \cdot F_T$ interference term sensitive to sign
- Can be separated by proper choice of Φ_γ



Signatures in Isoscalar and Isovector Probes?

TECHNISCHE UNIVERSITÄT DARMSTADT

- ^{58}Ni and lighter nuclei toroidal candidates dominate isoscalar and isovector response (like in the PDR), but Z ≈ N!
- (p,p‘) versus (α,α‘) isocalar response: sensitive to different regions of the transition currents?
- Anomalous (p,p‘) angular distributions of low-energy E1 transitions observed (e.g. in ^{48}Ca)
- Other ideas?

Collaborators

TECHNISCHE UNIVERSITÄT DARMSTADT

I. Brandherm, A. Richter
Institut für Kernphysik, Technische Universität Darmstadt, Germany

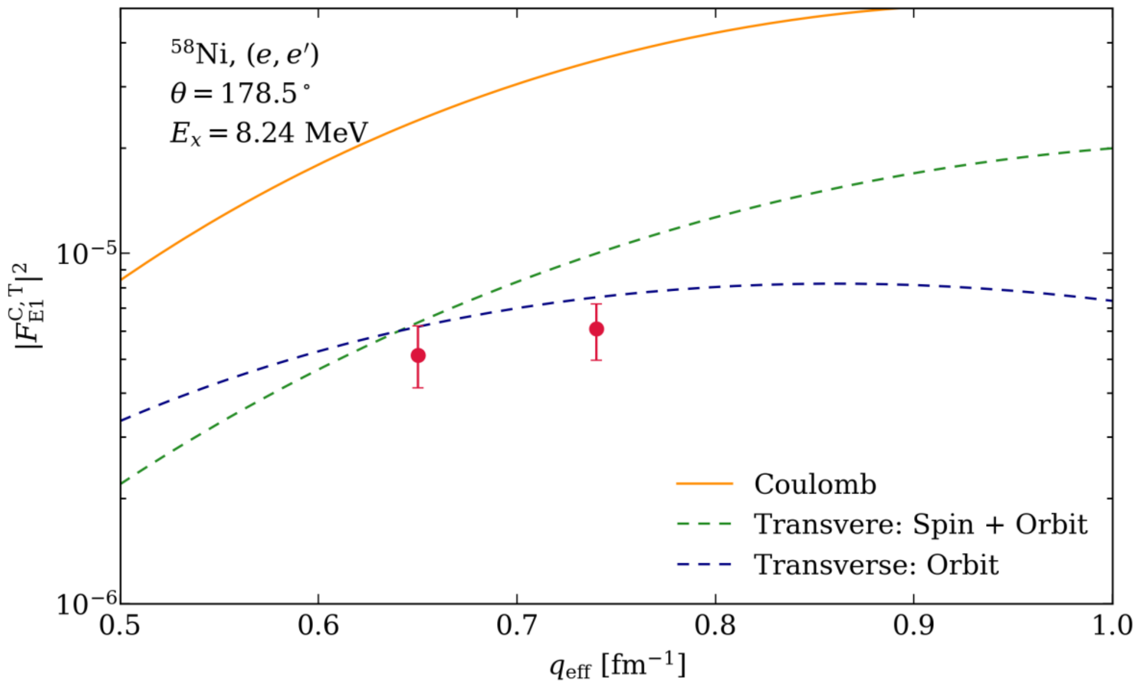
H. Matsubara, A. Tamii
RCNP, Osaka University, Japan

M. Scheck, J. Sinclair
School of Computing, Engineering, and Physical Sciences, University of the West of Scotland, Paisley, UK

V.O. Nesterenko, P.I. Vishnevskiy
Laboratory of Theoretical Physics, JINR, Dubna, Russia

P.-G. Reinhard
Institut für Theoretische Physik, Universität Erlangen, Germany

Form Factors Toroidal E1 Mode



^{140}Ce(e,e‘γ)

TECHNISCHE UNIVERSITÄT DARMSTADT

Structure of PDR from (e,e‘γ) experiments

Transverse form factor in (e,e‘) shows unique sensitivity to structure of E1 transitions, but cross sections small

Enhance by **interference** of longitudinal and transverse parts in coincidence experiment