Evidence for a Toroidal E1 Mode in ^{58}Ni

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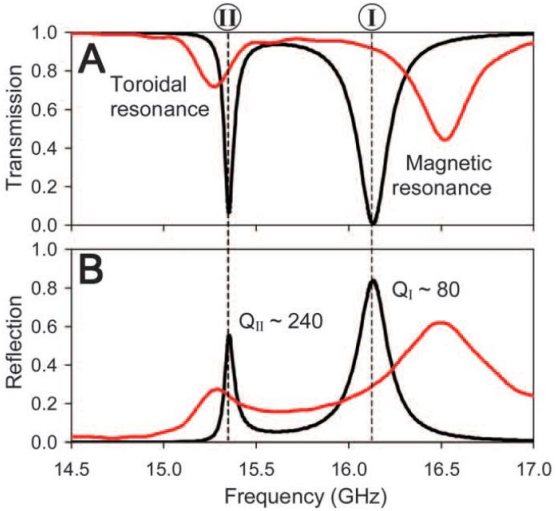
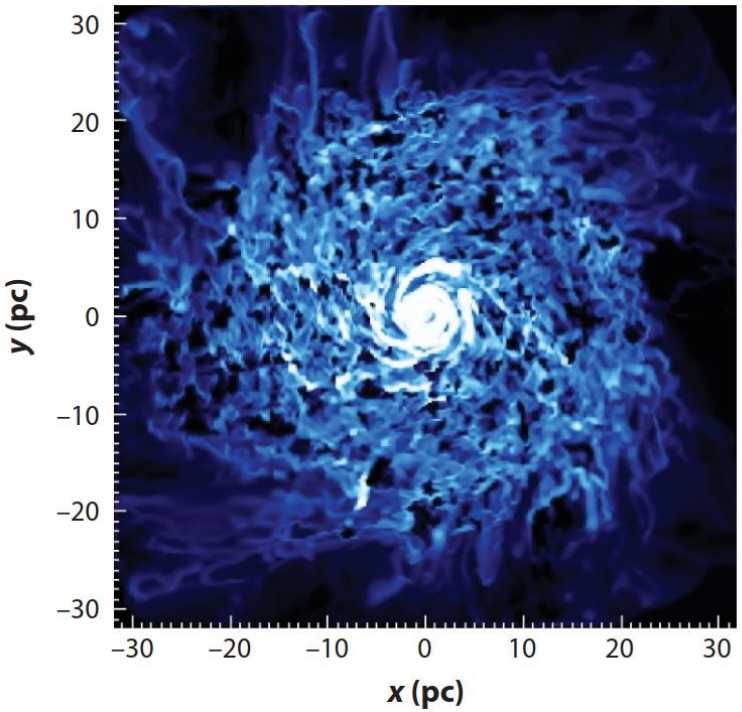
Toroidal Modes

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



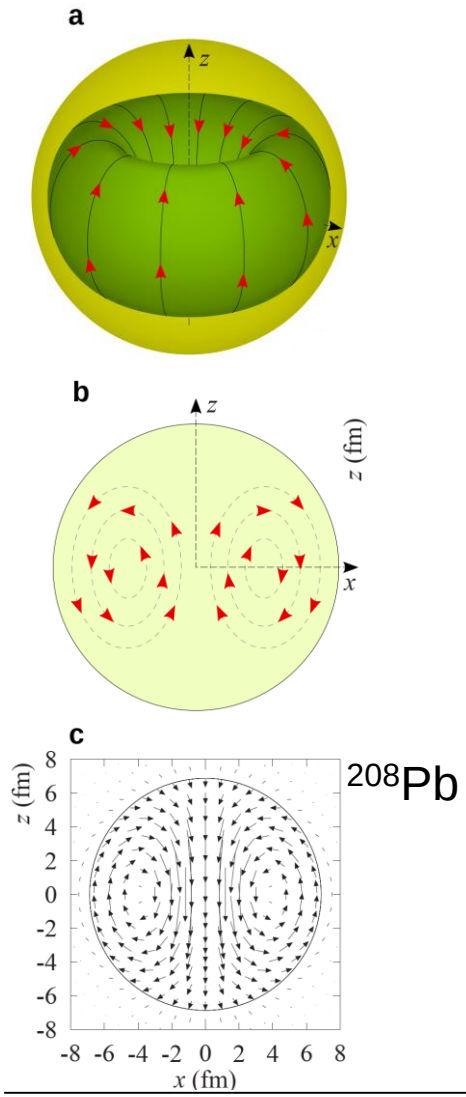
T. Kaelberer et al., Science 330, 1510 (2010)

- Toroidal modes appear in a large variety of physics problems from hydrodynamics to solid state physics to cosmology



H. Netzer, Annu. Rev. Astron. Astrophys. 53, 365 (2015)

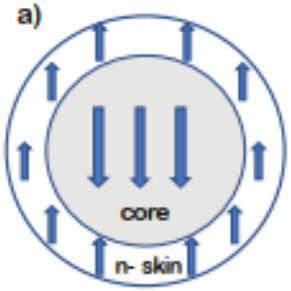
Nuclear Toroidal Modes



- Quantum phenomenon, mean-field origin
- Predicted more than 50 years ago, hydro/fluid-dynamical models, QPM, relativistic and nonrelativistic QRPA
- Similar to Hill‘s spherical vortex ring, but corresponds to oscillations along the streamlines
- Simplest mode has E1 multipolarity
- No clear experimental evidence so far

Toroidal E1 Mode in Heavy Nuclei

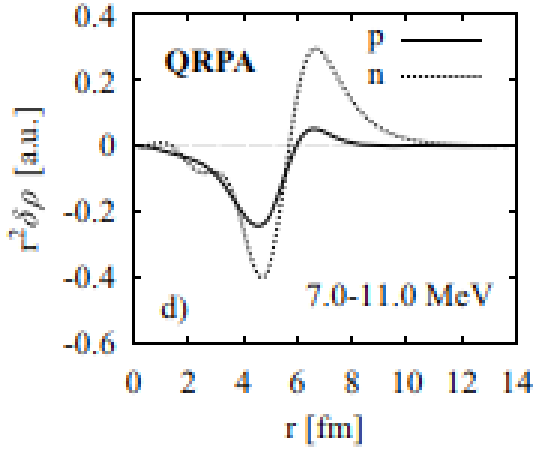
PDR



- Energy range overlaps with the pygmy dipole resonance (PDR) observed in nuclei with sufficient neutron excess

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

^{120}Sn



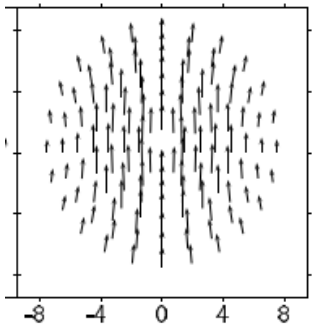
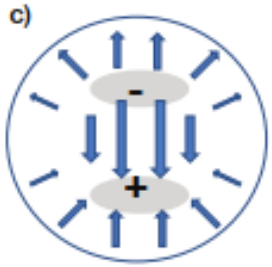
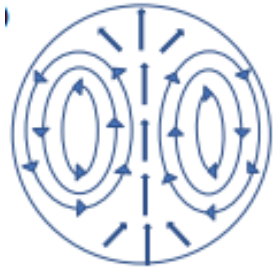
- Questions interpretation of the PDR as neutron skin oscillation

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

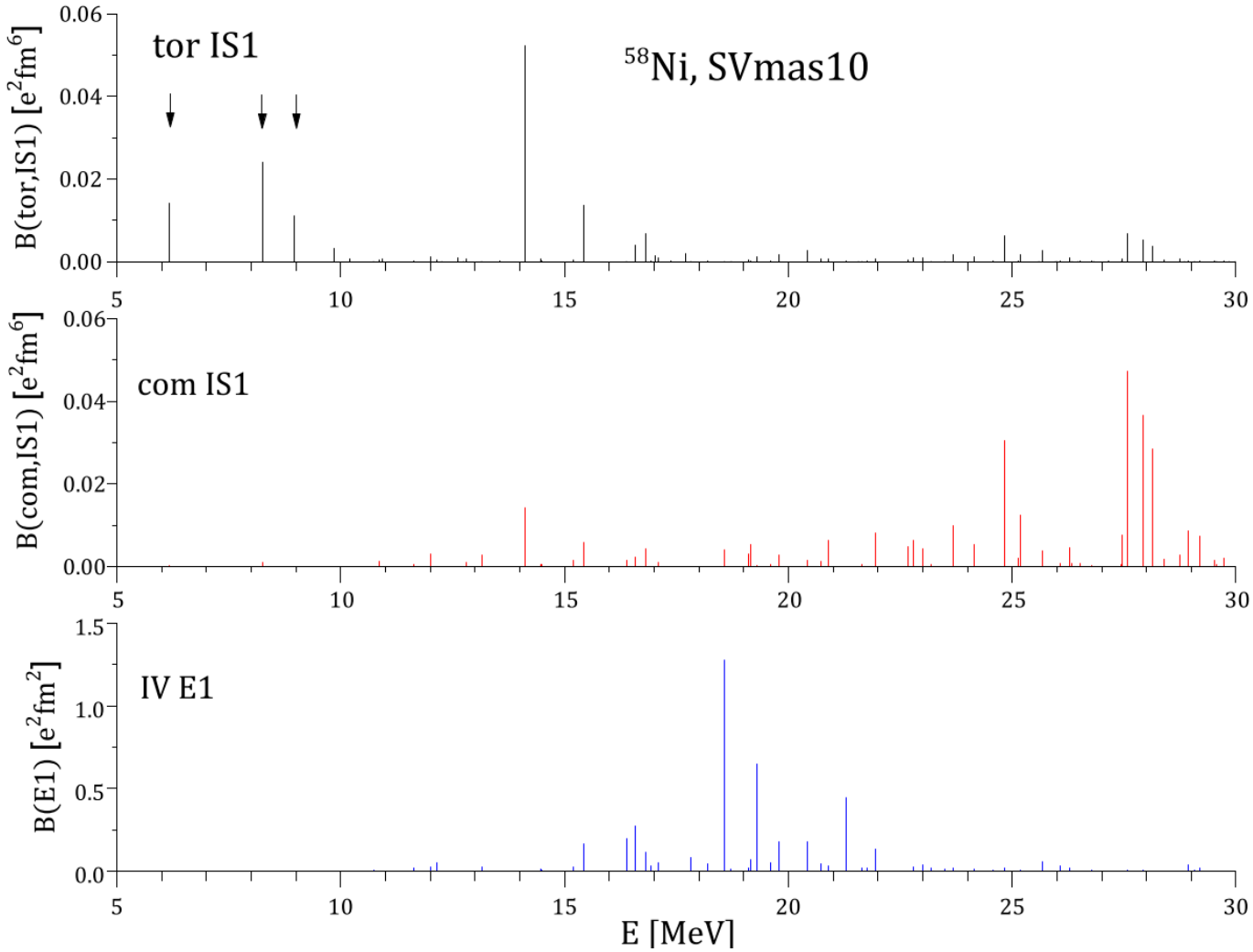
- Similar transition densities in heavy nuclei

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

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

Theoretical Predictions from QRPA



Experimental Approach

TECHNISCHE UNIVERSITÄT DARMSTADT

- Combined analysis of **high-resolution** (p,p'), (γ,γ') and (e,e') experiments in **^{58}Ni**

- (p,p') reaction at several hundred MeV and very forward angles selective to E1, spinflip M1

  PvNC and A. Tamii, EPJA 55, 110 (2019)

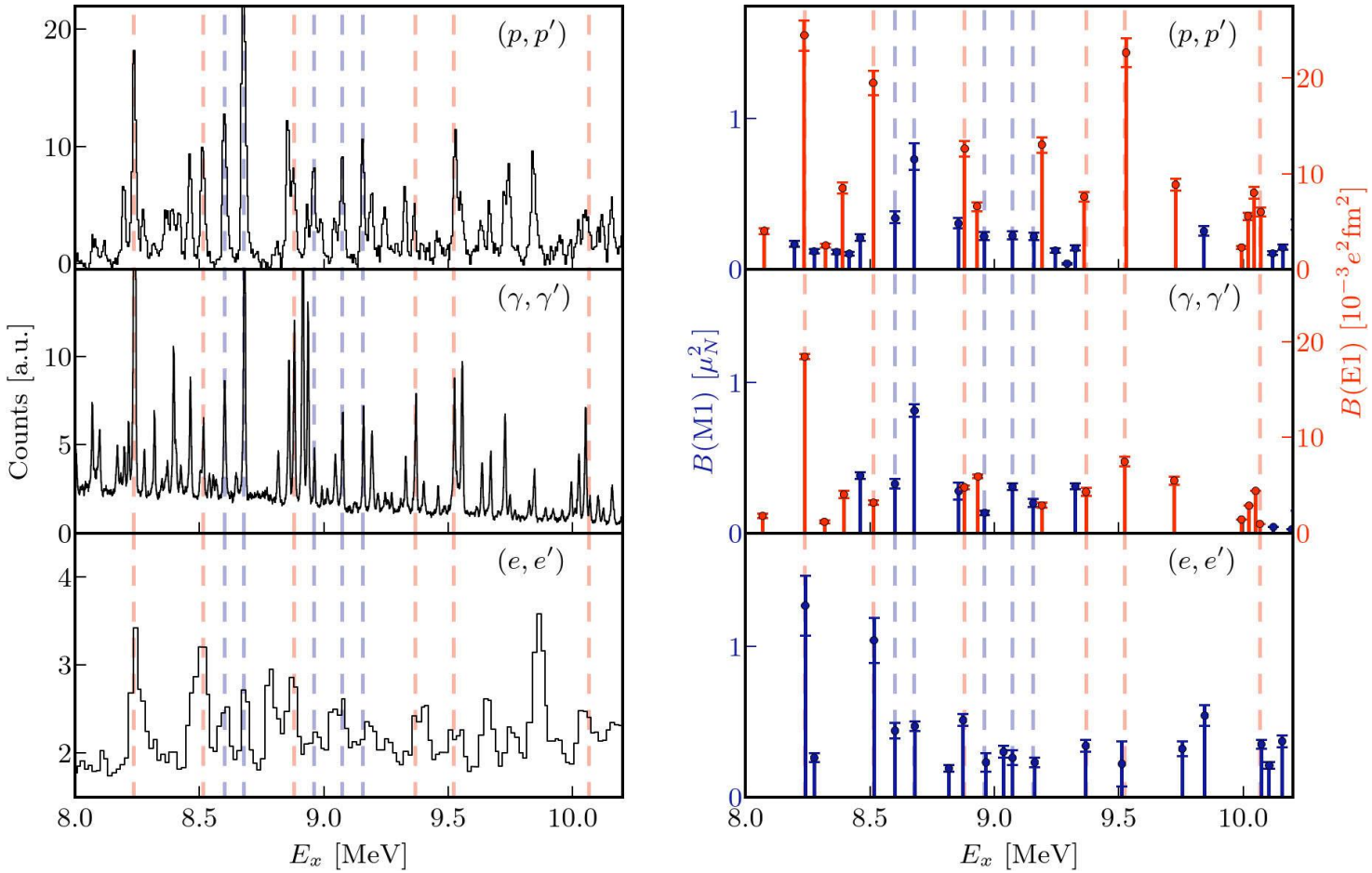
- (γ,γ') reaction selective to E1,M1; unique parity information with polarized beam

  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)

Identification of Toroidal Candidates in ^{58}Ni

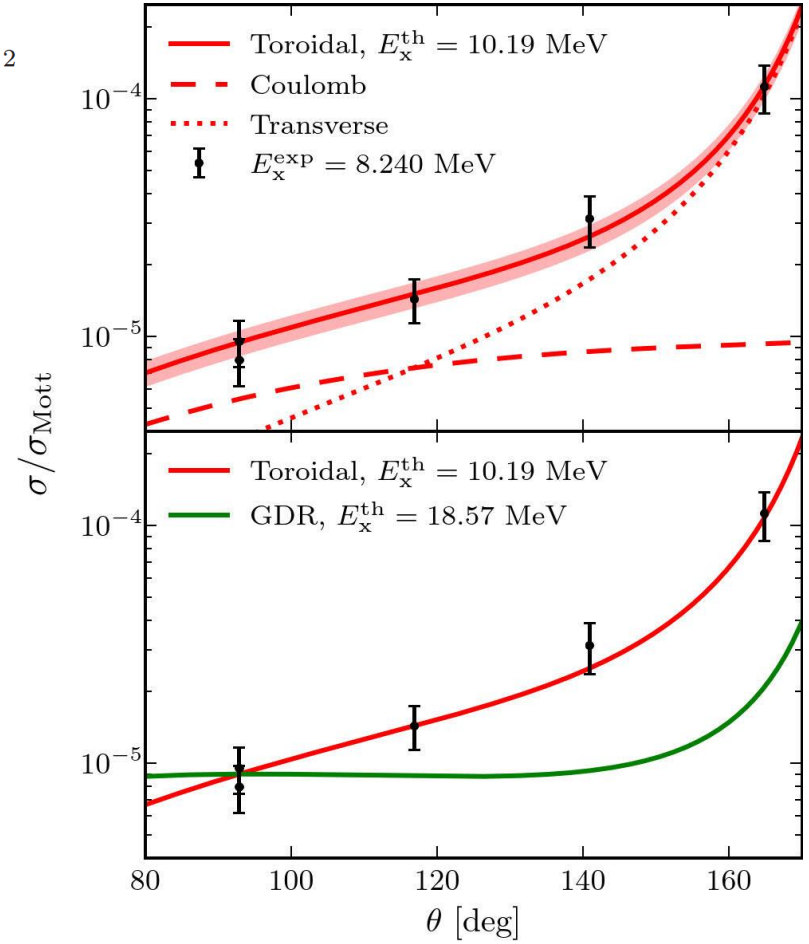


- Energy region covered by all experiments 7 - 12 MeV

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

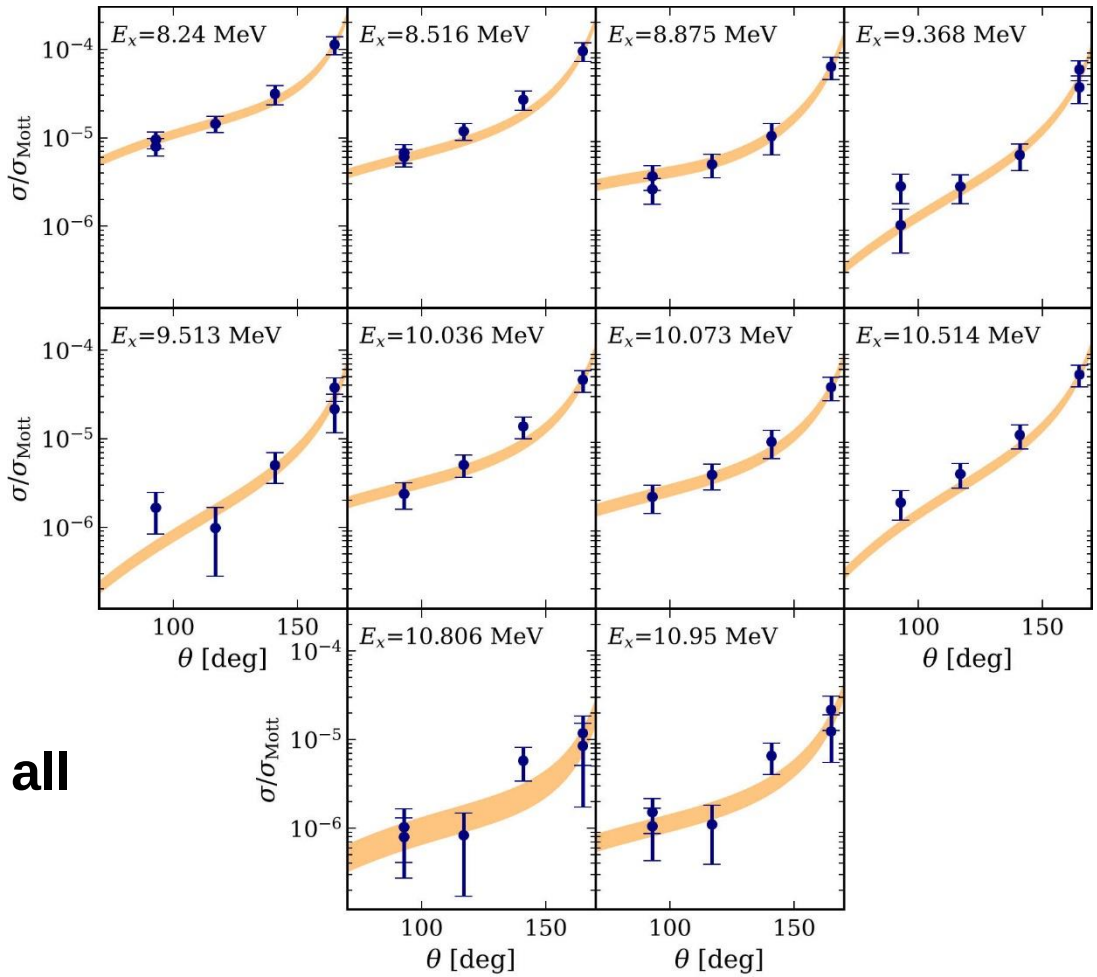
$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} f_{rec} \left[|F_L(q)|^2 + \left(\frac{1}{2} + \tan^2\left(\frac{\theta}{2}\right)\right)|F_T(q)|^2\right.$$

- All data at $E_0 \approx 50$ MeV
- Variation of 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)

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



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

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

Summary and Outlook

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

Next steps

- Establish mode as a generic feature, should appear in all nuclei
- Advanced tests with (e,e'γ) experiments