# E1 Strength measurement

## SFB - Workshop 2022

TECHNISCHE UNIVERSITÄT DARMSTADT

### B04: Dipole response and neutron equation of state

**Outline:**

- Introduction
- Experiment at RCNP
- Data analysis
- Dipole polarizability
- Summary and outlook

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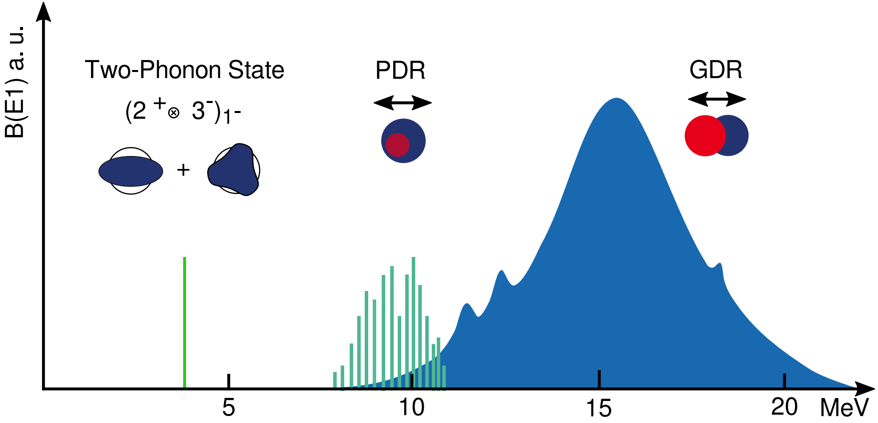
SFB 1245

# Introduction

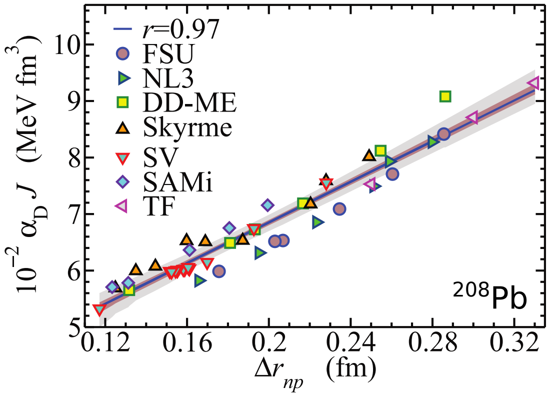


# Dipole polarizability

- Dipole polarizability

$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}^{E1}}{E^2} dE$$

- Correlated to
  - Neutron skin thickness
  - Symmetry energy
- Systematics over isotopic chains:
  $^{40,48}Ca$, $^{68}Ni$
  stable even mass Sn, $^{208}Pb$




X. Roca-Maza et al., Phys. Rev. C88, 024316 (2013)

# Inelastic proton scattering

- Scattering at extreme forward angles:
  selectivity for electric and magnetic dipole excitations

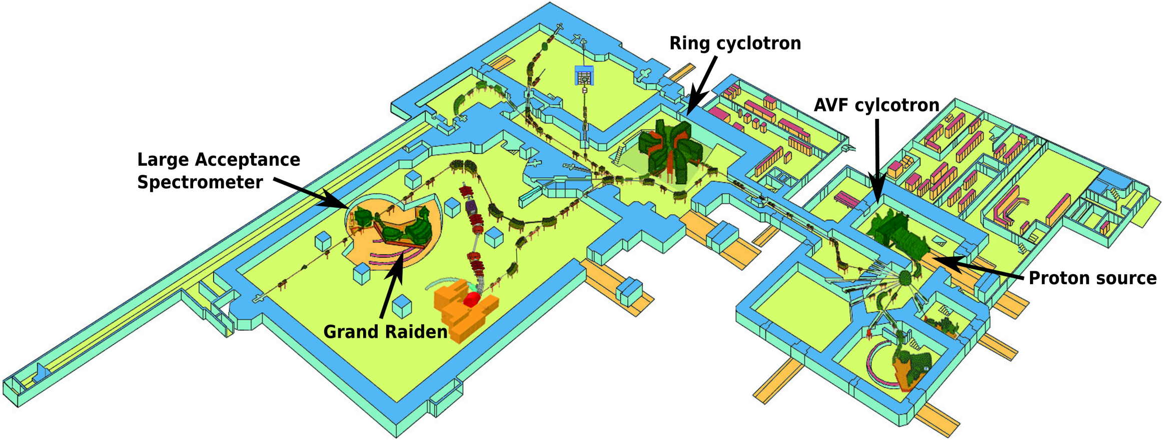
- Consistent measurement below and above particle separation threshold

- Electric dipole transitions:
  Relativistic Coulomb excitation

- Virtual photon method

$$\frac{\mathrm{d}^2\sigma_{\mathrm{E1}}}{\mathrm{d}\Omega\mathrm{d}E} = \frac{1}{E}\frac{\mathrm{d}N_{\mathrm{E1}}}{\mathrm{d}\Omega}\sigma_{\mathrm{abs}}^{\mathrm{E1}}$$

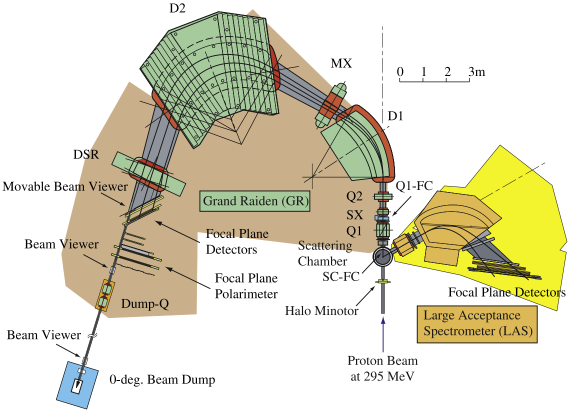
# Research Center for Nuclear Physics (RCNP)



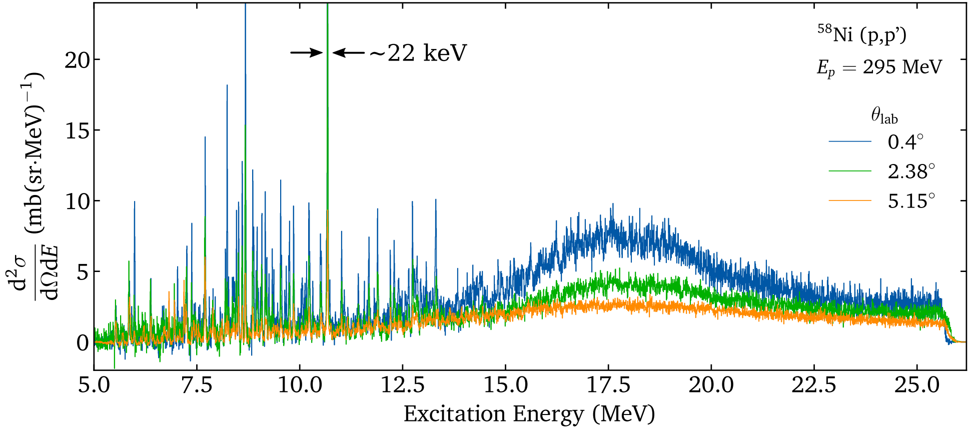
# Experiment at Grand Raiden Spectrometer
## $^{58}$Ni

- Proton beam with $E_p = 295\,\mathrm{MeV}$
- Spectrometer angles: 0°, 2.5°, and 4.5°
- Raw data analysis: H. Matsubara, Dissertation, Osaka University (2010)
- Excitation energy spectra for seven scattering angles between 0.4° and 5.15°

### Spectrometer setup at 0°

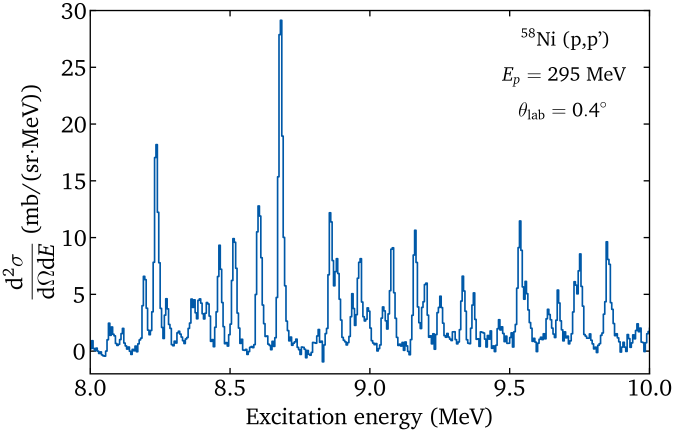


# $^{58}$Ni Spectra



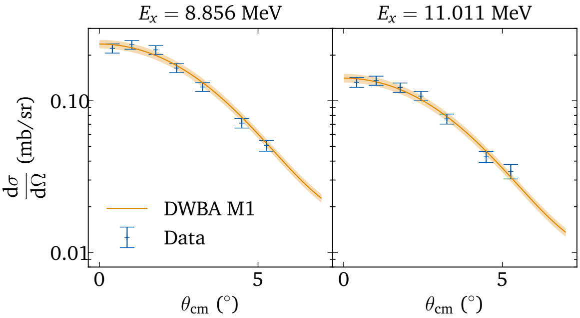
# State-by-state analysis

- Statewise analysis between 5 MeV and 13.3 MeV
- 185 transitions found
  - 147 present in at least five spectra
- Multipolarities: Angular distributions
- DWBA calculations
  V. Yu. Ponomarev (2019)

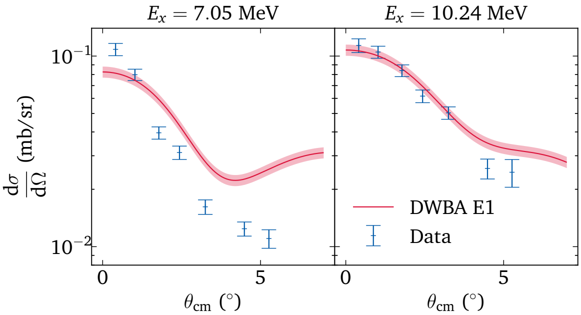


# State-by-state analysis

- Identification of low energy M1 transitions works well




- Identification of low energy E1 transitions more difficult



# State-by-state analysis

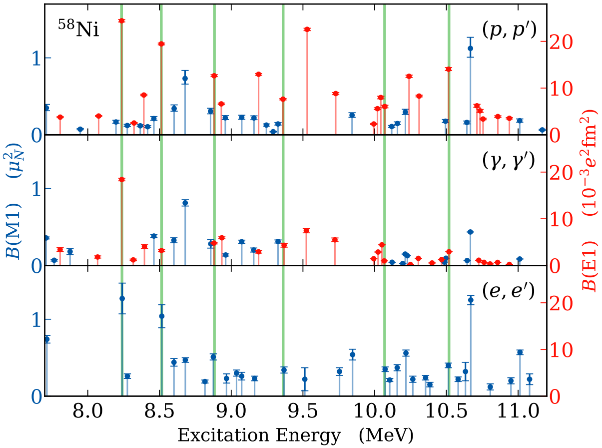
- Dipole character from angular distributions
- Multipolarity unique from combination with other experiments

- Nuclear resonance fluorescence $(\gamma, \gamma')$:
  F. Bauwens et al., Phys. Rev. C 62, 024302 (2000)
  M. Scheck et al., Phys. Rev. C 88, 044304 (2013)
  J. Sinclair, priv. comm. (2019)
  **E1, M1**
- Inelastic electron scattering $(e, e')$ :
  W.Mettner et al., Nucl. Phys. A473, 160 (1987)
  **M1, M2**
- $(p, p')$ at 160 MeV + $^{58}$Ni$(^{3}$He,$t)^{58}$Cu:
  H.Fujita et al., Phys. Rev. C 75, 034310 (2007)
  **E1, IVSM1**

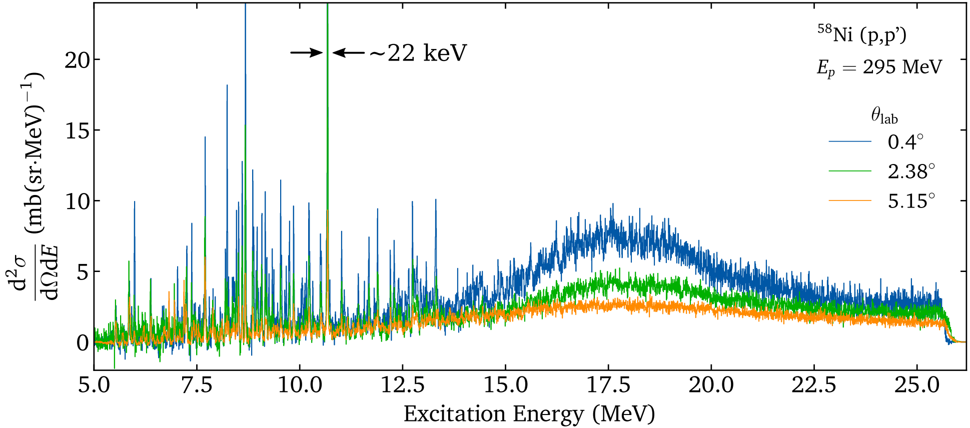
# E1 and M1 strength

- $(e,e')$ and $(\gamma,\gamma')/(p,p')$ see different parity for some states
- $(e,e')$ measured under backward angles
  - Sensitive to transverse cross section
  - M1, M2

**?** Electric transitions with a strong transverse component



# $^{58}$Ni Spectra



# Multipole decomposition analysis

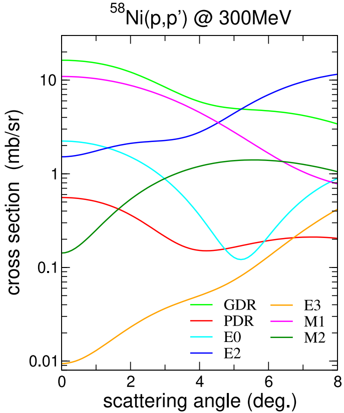
- Spectrum in 200 keV bins
- Fit of DWBA curves to experimental angular distributions

$$\frac{d\sigma}{d\Omega}(\theta_{cm}, E_x)\bigg|_{\text{Exp.}} = \sum_{J^\pi} a^{J^\pi} \frac{d\sigma}{d\Omega}(\theta_{cm}, E_x, J^\pi)\bigg|_{\text{DWBA}}$$

- $\chi^2_{red}$ weighted contribution for each multipolarity

$$\left\langle \frac{d\sigma}{d\Omega}(\theta, E_x)^{J^\pi} \right\rangle = \frac{\sum_i \omega_i \frac{d\sigma}{d\Omega}(\theta, E_x)_i^{J^\pi}}{\sum_i \omega_i} \quad \text{with} \quad \omega = \frac{1}{\chi^2_{red}}$$

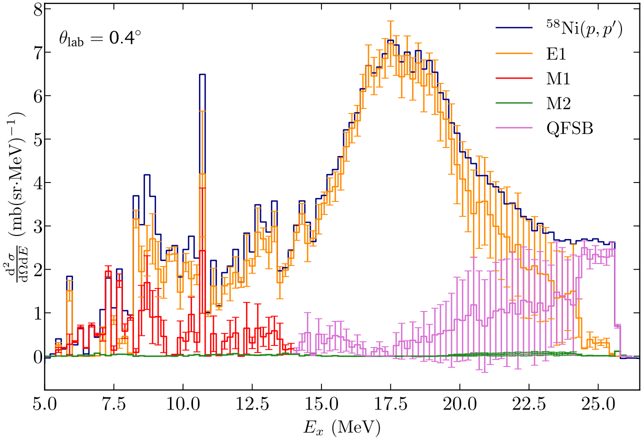
- MDA uncertainty from weighted variance



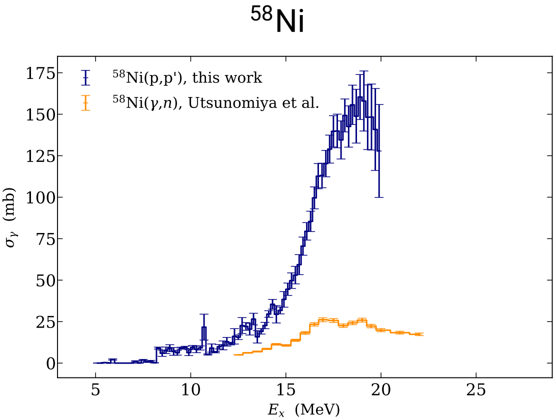

V. Yu. Ponomarev (2019)

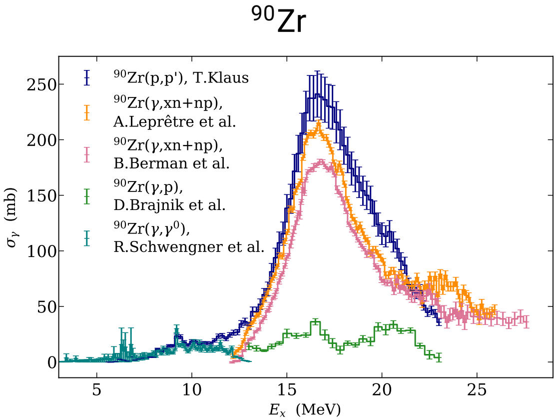
# Multipole decomposition analysis

- Subtraction of ISGMR and ISGQR
  Y.-W. Lui et al., Phys. Rev. C 73, 014314 (2006)
- Below 13 MeV: isovector spin-flip M1 resonance
- Phenomenological background from quasi-free scattering
  S. Bassauer et al., Phys. Rev. C 102, 034327 (2020)
- Above 20 MeV: large uncertainties
  - Limited input from theory



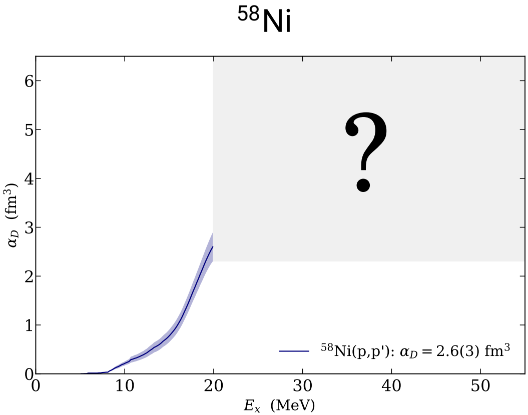
# Photoabsorption cross section

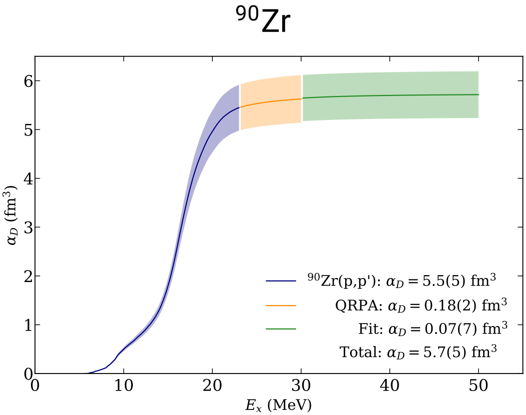



T. Klaus, Dissertation, TU Darmstadt (2020)

# Dipole polarizability



# Comparison to Migdal model

- Hydrodynamic model with interpenetraiting proton and neutron fluids

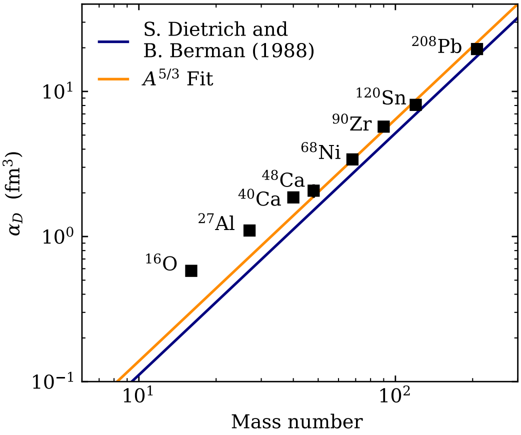
$$\alpha_D = \frac{e^2 R^2 A}{40 \cdot a_{\mathrm{sym}}} \propto A^{5/3}\,\mathrm{fm}^3$$

- $a_{\mathrm{sym}}$: Symmetry energy parameter in the Bethe-Weizsäcker mass formula

- S.Dietrich and B.Bermann,
  At. Data Nucl. Data Tables 38, 199 (1988)

$$\alpha_D = 2.4 \times 10^{-3} \cdot A^{5/3}\,\mathrm{fm}^3$$

- Fit: $\alpha_D = 3.0(3) \times 10^{-3} \cdot A^{5/3}\,\mathrm{fm}^3$



# Comparison to Migdal model

- More realistic model: $a_{\mathrm{sym}}$ mass dependent

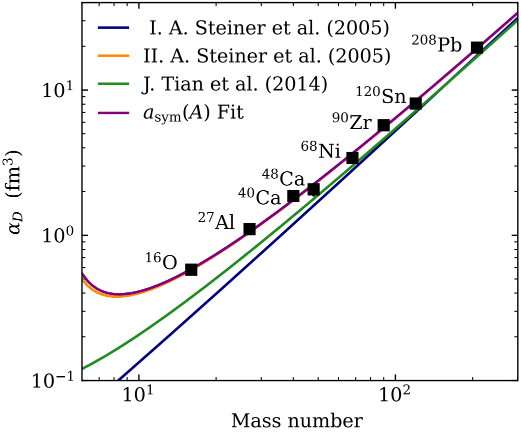
$$\alpha_D = \frac{0.0518 \cdot A^2}{S_v(A^{1/3} - \kappa)} \,\mathrm{fm}^3, \quad \kappa = \frac{S_s}{S_v}$$

(I.) A.W. Steiner et al., Phys. Rep. 411, 325 (2005) — $S_v = 24.1$ MeV, $\kappa = 0.545$

(II.) A.W. Steiner et al., Phys. Rep. 411, 325 (2005) — $S_v = 27.3$ MeV, $\kappa = 1.68$

J.Tian et al., Phys. Rev. C 90, 024313 (2014) — $S_v = 28.3$ MeV, $\kappa = 1.27$

Fit — $S_v = 27.3(8)$ MeV, $\kappa = 1.69(6)$



# Summary and outlook

- Dipole strength and inelastic proton scattering
- Dipole polarizability in $^{58}$Ni and $^{90}$Zr
- Ab initio calculation of E1 response and polarizability
  - Extension to open-shell nuclei with $\pm$ 1 or 2 nucleons outside shell closures
  - Experiment on $^{42}$Ca at iThemba Labs planned
- Discussions about puzzling states in $^{58}$Ni