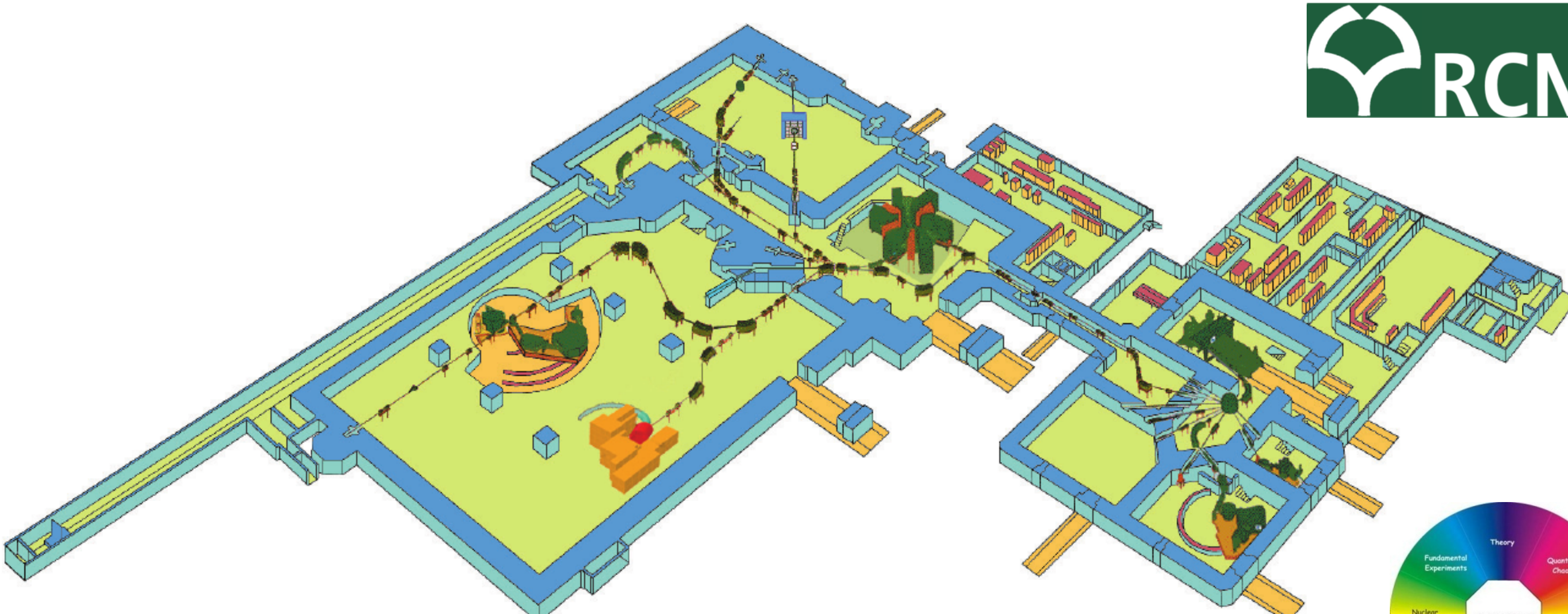
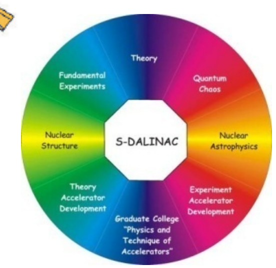
# Do we understand Gamma Strength Functions? The case of $^{96}$Mo*

## 4th Workshop on Nuclear Level Density and Gamma Strength

Dirk Martin for the E376 collaboration






*Supported by the DFG through SFB 634 and NE679/3-1

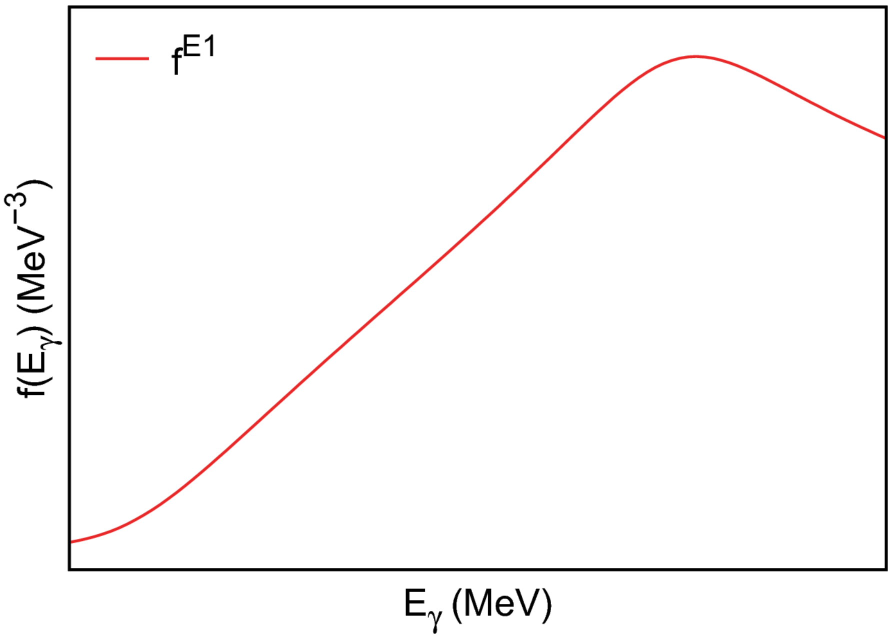
# Outline

- Gamma Strength Function and Axel-Brink Hypothesis
- Polarized proton scattering at 0°
- Data analysis
- First results
- Summary and outlook

# Gamma Strength Function (GSF)

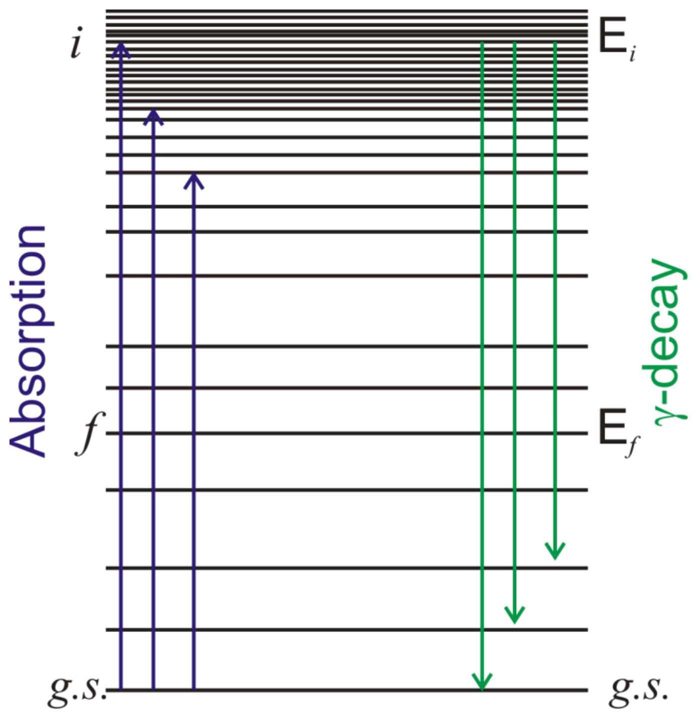
- Describes the (average) energy distribution of photon emission from highly-excited states or cross section for photon absorption

$$\langle \Gamma(E_i) \rangle \propto \sum_{X\lambda} \int_0^{E_i} E_\gamma^{2L+1} \frac{f^{X\lambda}(E_\gamma)\rho(E_f)}{\rho(E_i)} \mathrm{d}E_\gamma$$



# Gamma Strength Function (GSF)

- Principle of detailed balance:

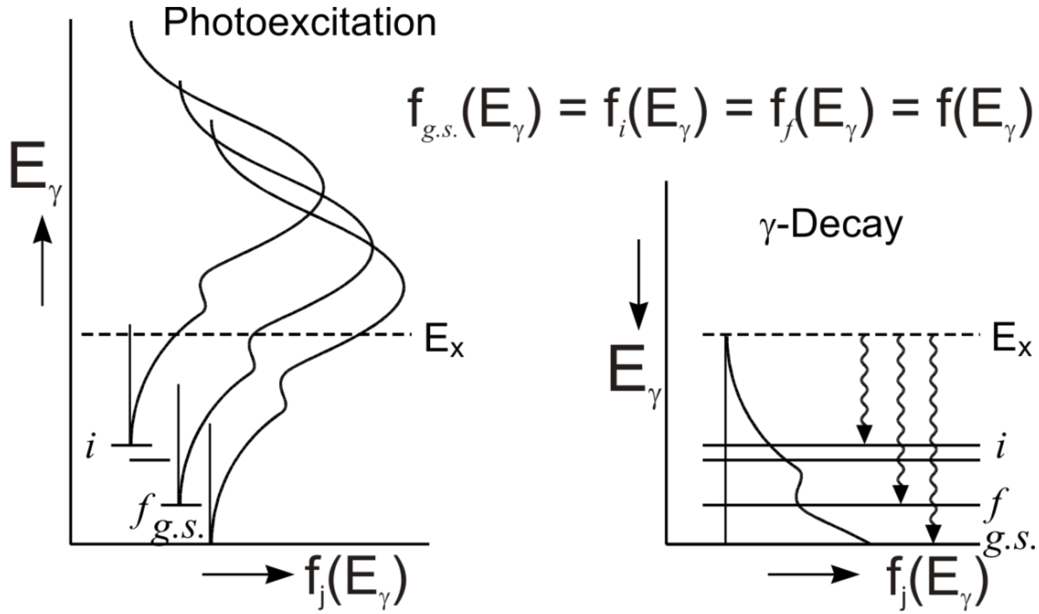



$$\langle \Gamma_{i \rightarrow g.s.} \rangle = \frac{f^{E1}(E_\gamma) \cdot E_\gamma^3}{\rho(E_i)}$$

$$\Updownarrow$$

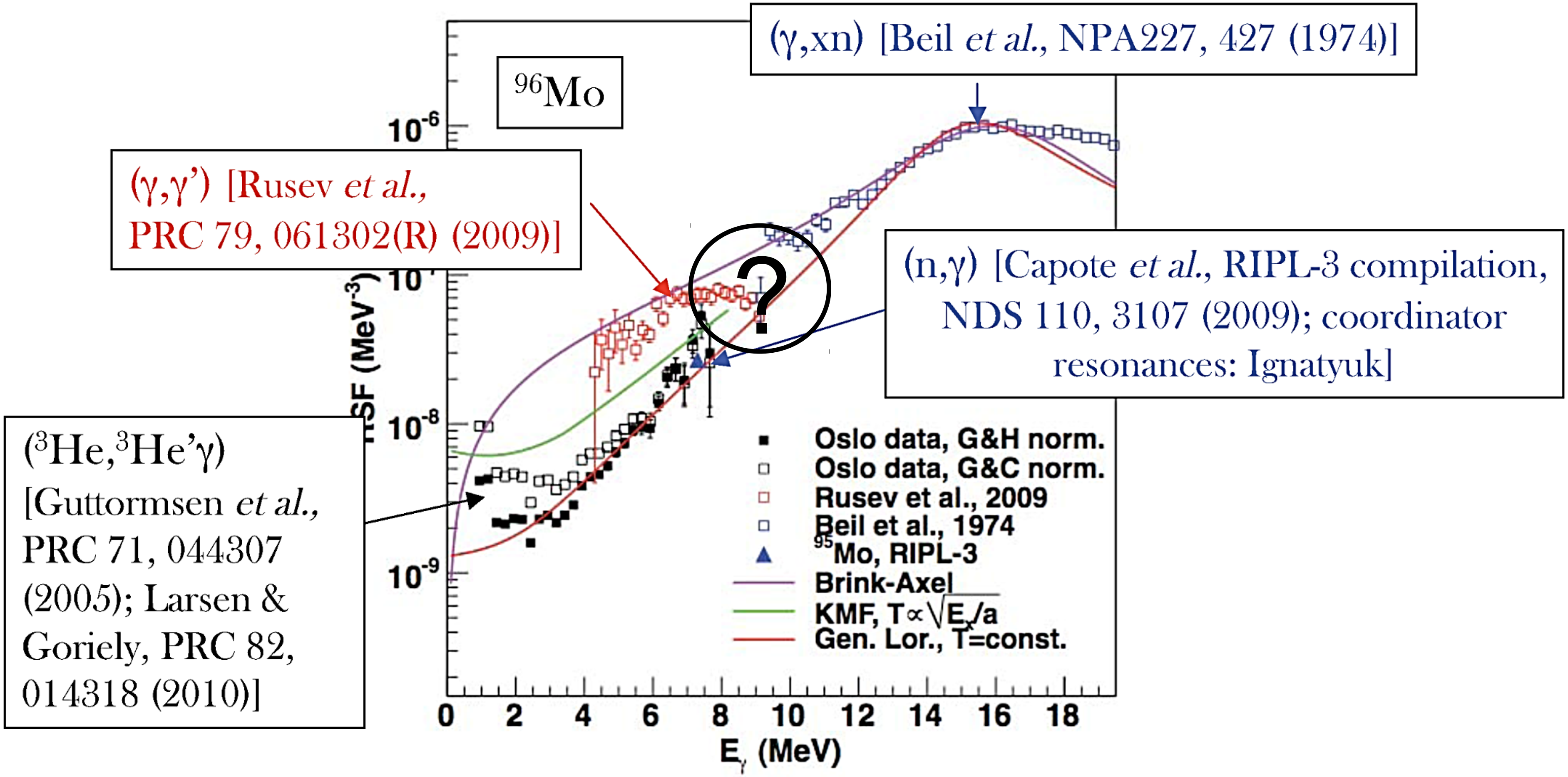
$$f^{E1}(E_\gamma) = \frac{\sigma_{abs}(E_i)}{3(\pi \hbar c)^2 \cdot E_\gamma}$$

# Axel-Brink Hypothesis




- Gamma Strength Function:
  - only depends on $E_\gamma$
  - is independent of the initial state structure: excitation energy $E_x$, $J^\pi$,…
- Same GSF for absorption and gamma emission
- Used for correction of stellar cross sections due to thermal population of excited states

# Experimental discrepancies in GSF



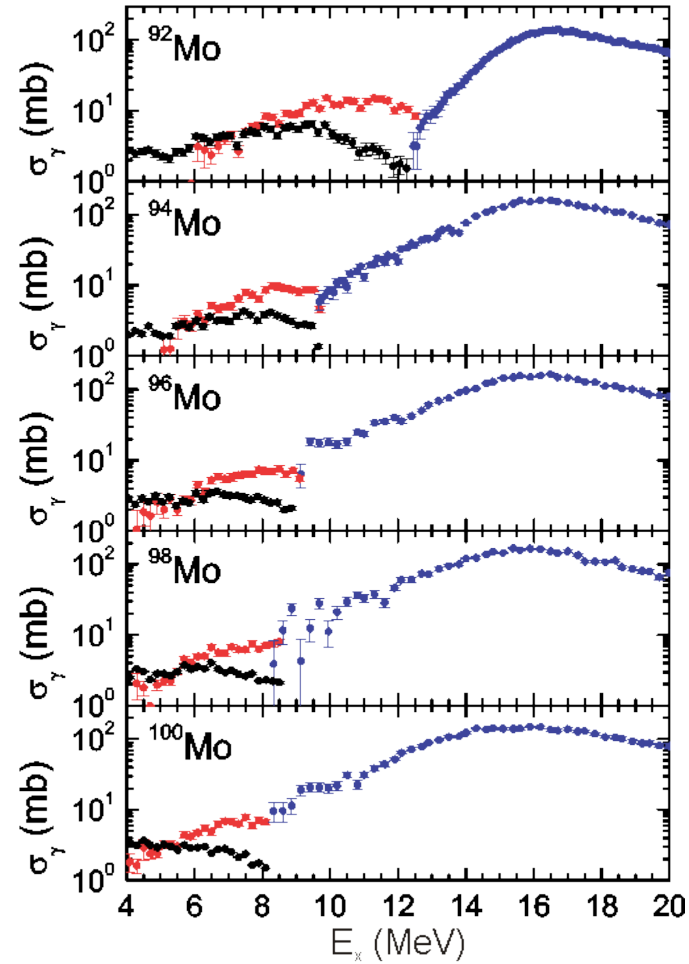

Ann-Cecilie Larsen, 3rd Workshop on Level Density and Gamma Strength, Oslo, Norway, May 23 — 27, 2011

# Experimental problems

- $(\gamma, \gamma')$ experiments:
  - Measure strength up to neutron threshold only
  - Experimental quantity $\Gamma_0 \cdot \frac{\Gamma_0}{\Gamma}$
  - Assumption in most analyses: $\frac{\Gamma_0}{\Gamma} = 1$

    ⟶ lower limit
  - Alternatively: correction with statistical model calculations

    ⟶ upper limit

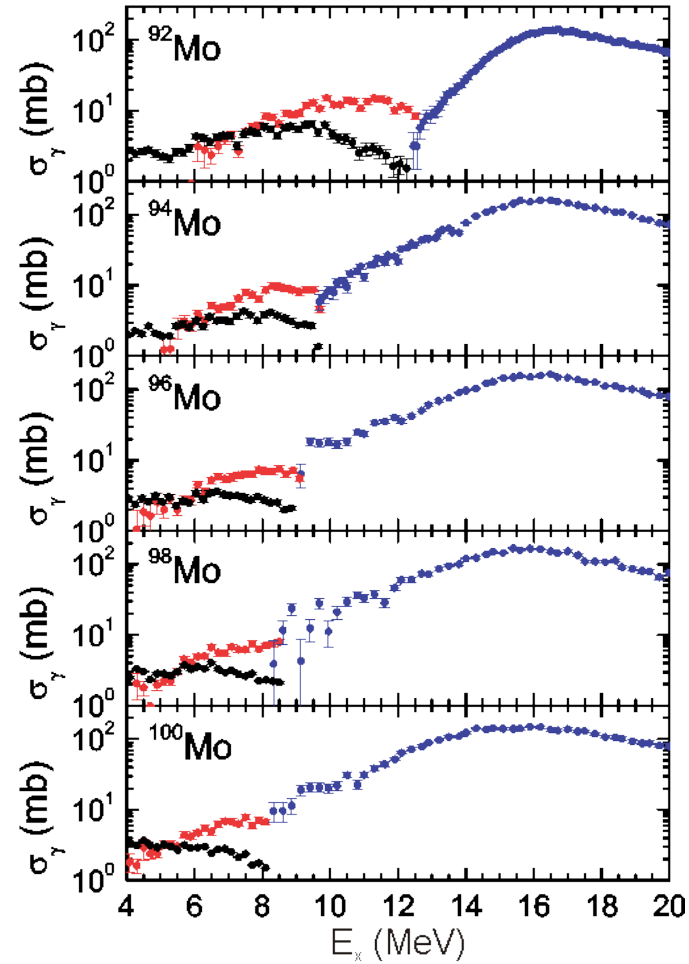



[G. Rusev et al., PRC **79** (2009) 061302]

# Experimental problems (continued)

- (γ, xn) reactions provide information only above threshold
- Decay reactions:
  - Normalization at the $S_n$ energy
  - Level densities needed

Consistent data on strength below and above the neutron threshold highly important!




[G. Rusev et al., PRC **79** (2009) 061302]

# Complete E1 and M1 strength distributions

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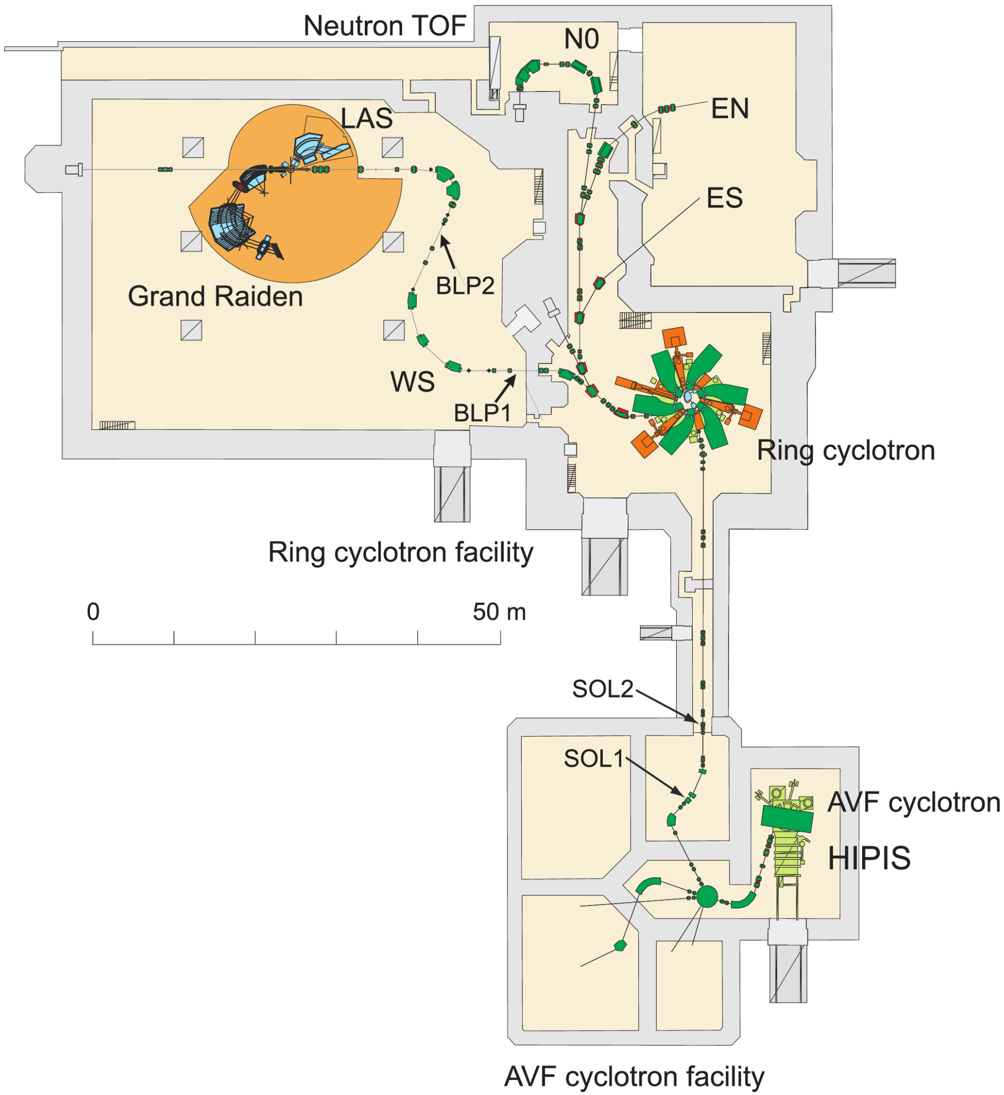
- Polarized proton scattering at 0°
  - Intermediate energy: 300 MeV optimal
  - High energy resolution: ΔE = 25-30 keV (FWHM)
  - Angular distributions: E1 / M1 separation via multipole decomposition analysis
  - Polarization observables: spinflip / non-spinflip separation

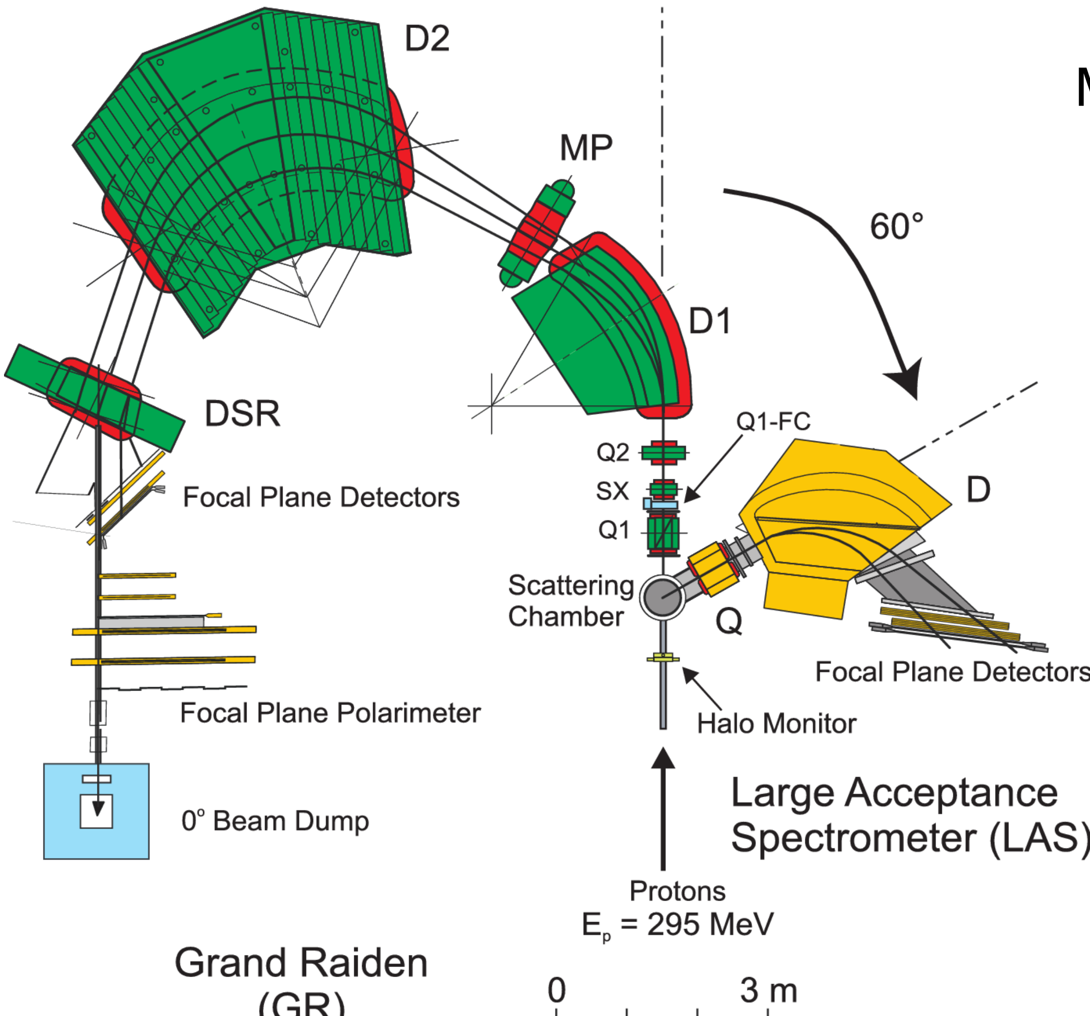
- $^{208}$Pb as a reference case (I. Poltoratska, doctoral thesis)
- Low-energy dipole modes in the heavy deformed nucleus $^{154}$Sm
- Complete dipole response in $^{120}$Sn

# Research Center for Nuclear Physics (RCNP) in Osaka, Japan




- $E_p$ = 295 MeV
- Beam intensity: 1-2 nA
- Dispersion matching: $\Delta E$ = 25-30 keV
- Polarization: ~70%
- Beam polarization was periodically flipped to avoid instrumental asymmetries

# 0° setup at RCNP in Osaka




Measured observables for $^{208}$Pb:

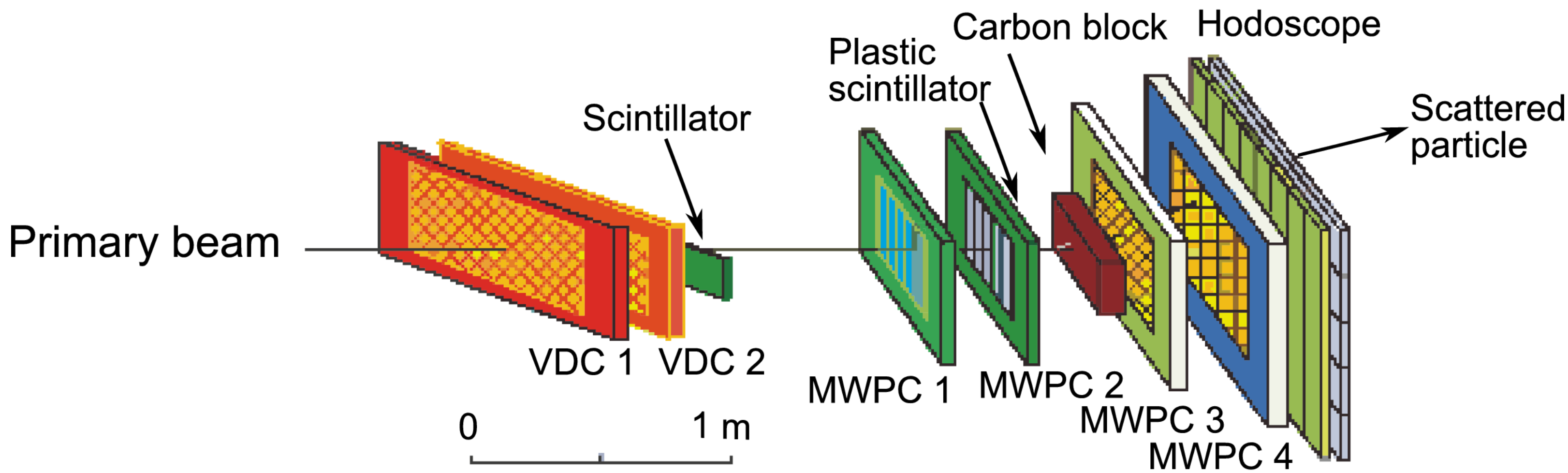
- $d\sigma^2/d\Omega dE$ @ 0°, 2.5°
- $D_{SS}$ @ 0° (sidewards PT)
- $D_{LL}$ @ 0° (longitudinal PT)

Small vertical magnification

↓

Mild under-focus mode

# Grand Raiden detector system




Focal plane polarimeter

- Focal plane detector system:

  Determination of positions $x_{fp}$, $y_{fp}$ and angles $\theta_{fp}$, $\phi_{fp}$

- Focal plane polarimeter:

  Measurement of the polarization p'' after a secondary scattering off a carbon slab

# E1/M1 decomposition by spin observables

Polarization observables at 0° → spinflip / non-spinflip separation*

(model-independent)

$$D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S = 1 \\ 3 \text{ for } \Delta S = 0 \end{cases}$$

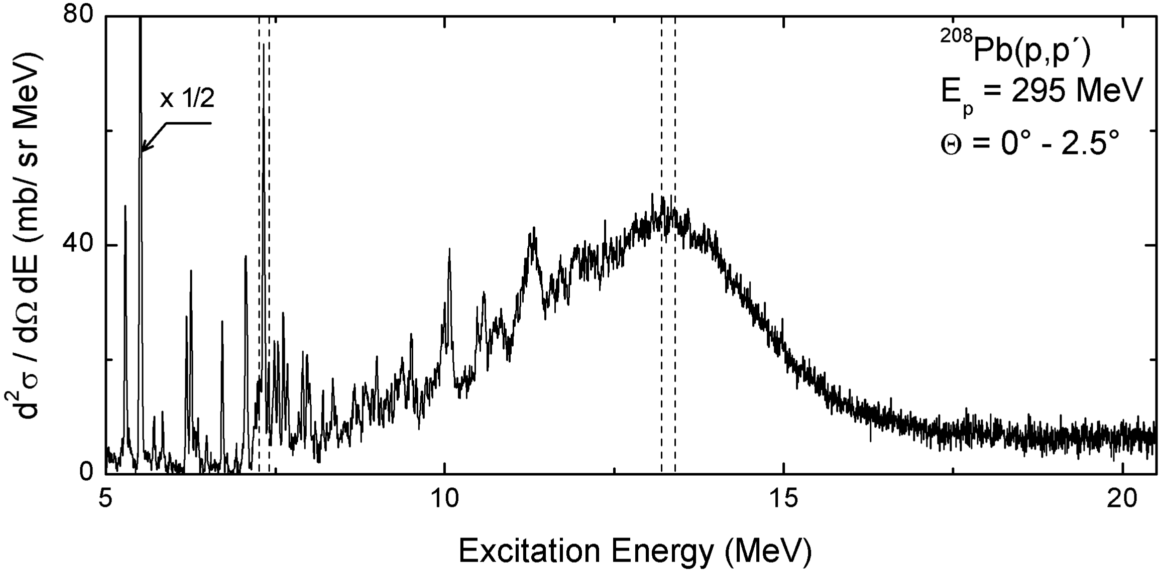
→ E1 and M1 cross sections can be decomposed

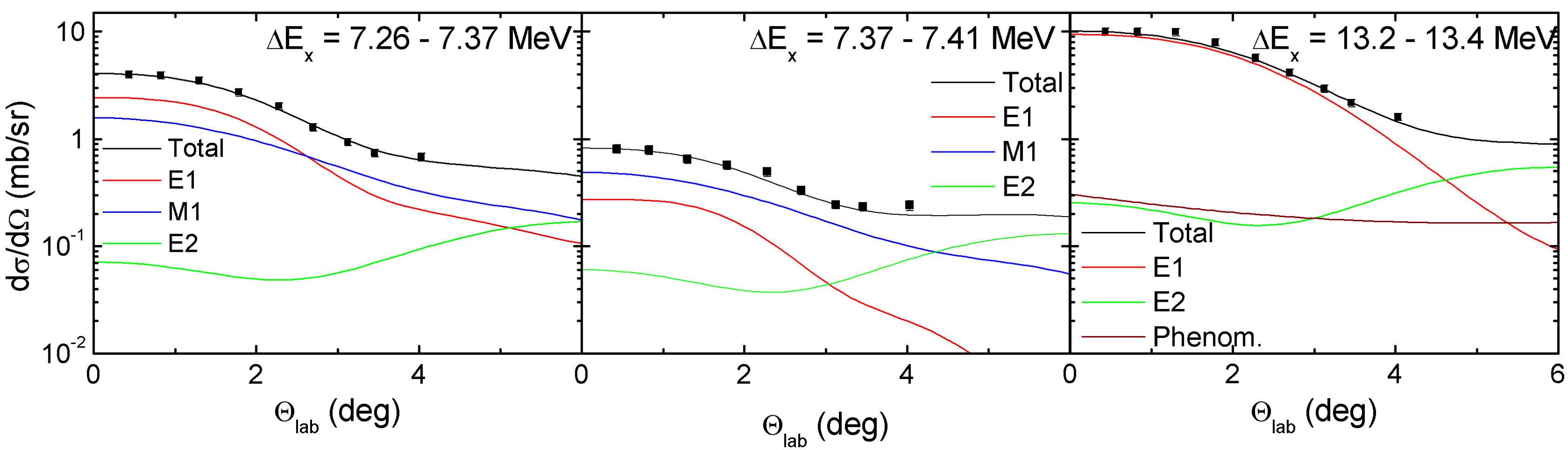
At 0°: $D_{SS} = D_{NN}$

$$\text{Total Spin Transfer } \Sigma \equiv \frac{3-(2D_{NN}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 & \textbf{(M1)} \\ 0 \text{ for } \Delta S = 0 & \textbf{(E1)} \end{cases}$$

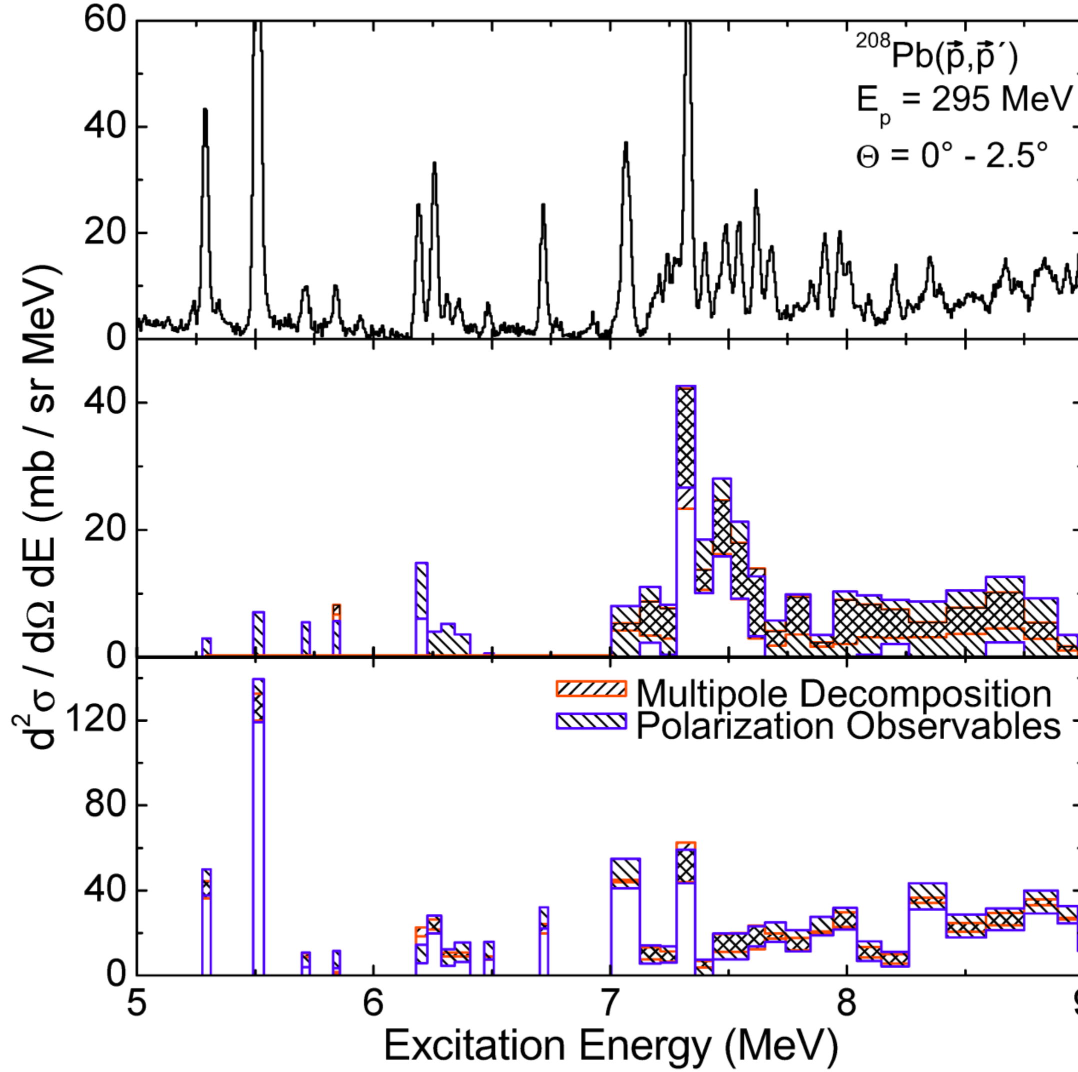
* [T. Suzuki, Prog. Theo. Phys. **103** (2000) 859]

# Multipole decomposition of angular distributions



# Comparison of both methods for $^{208}Pb$

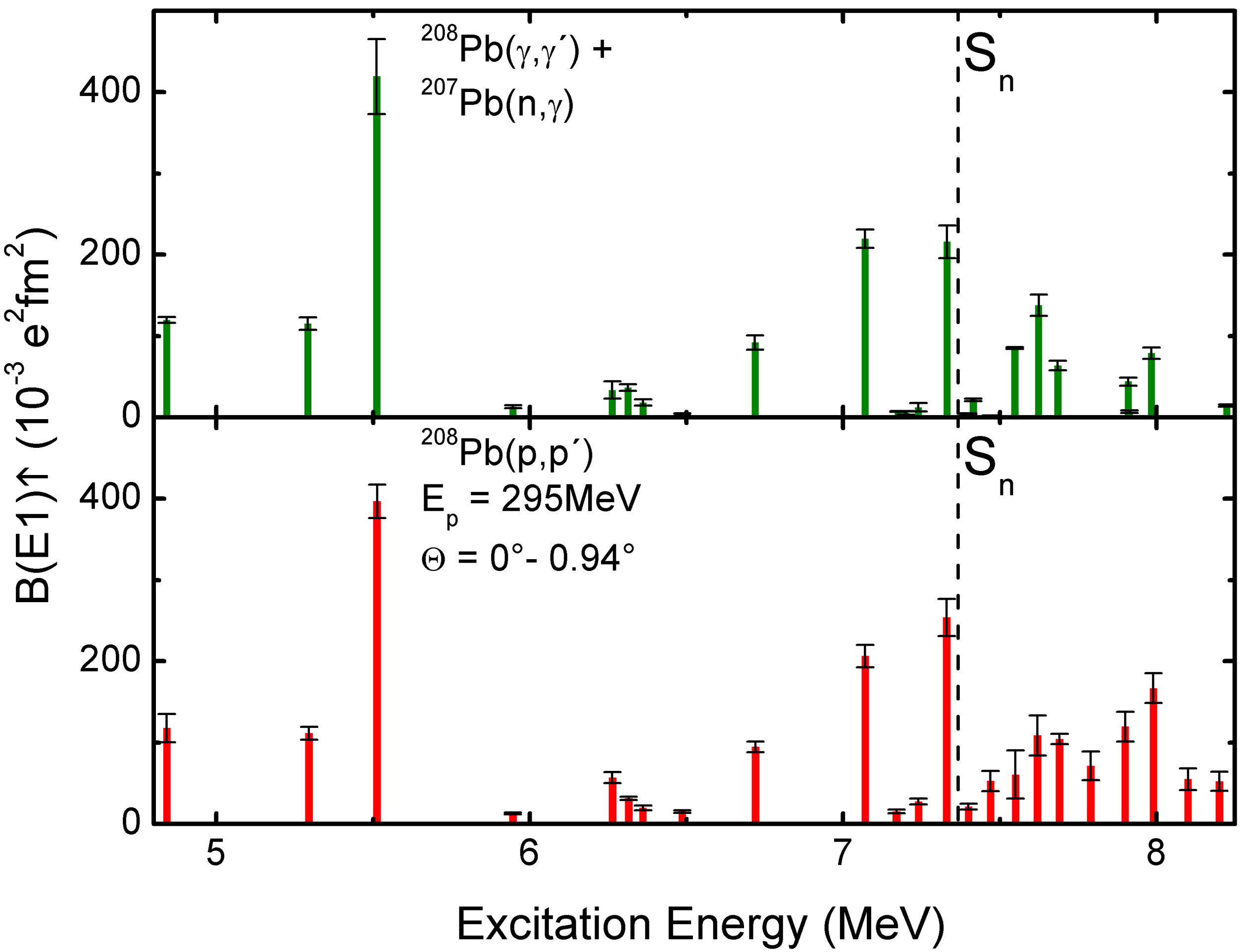



Total

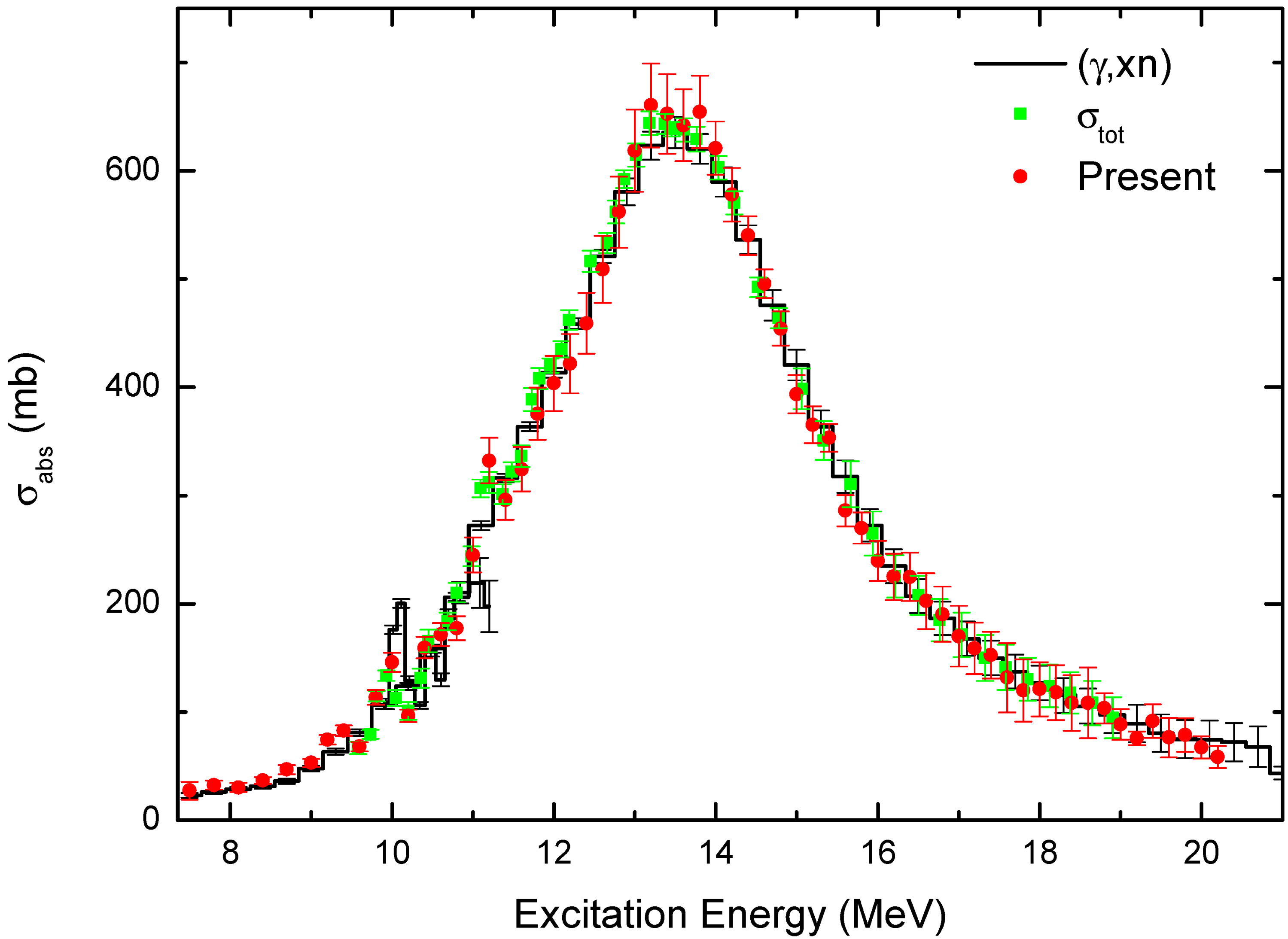
$\Delta S = 1$

$\Delta S = 0$

# B(E1) strength: low-energy region



# Photoabsorption cross section of $^{208}$Pb



# Gamma Strength Function in $^{208}$Pb

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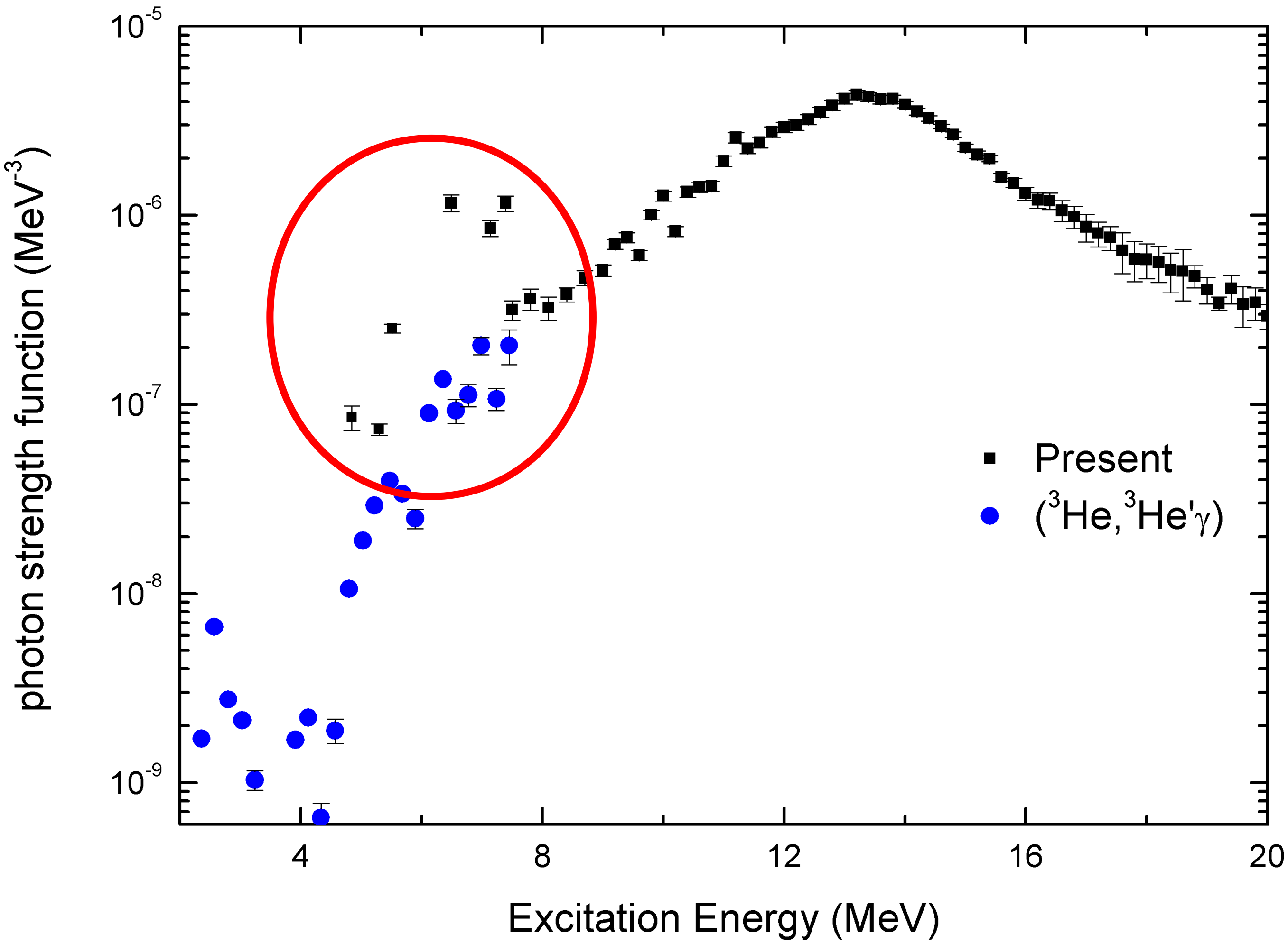
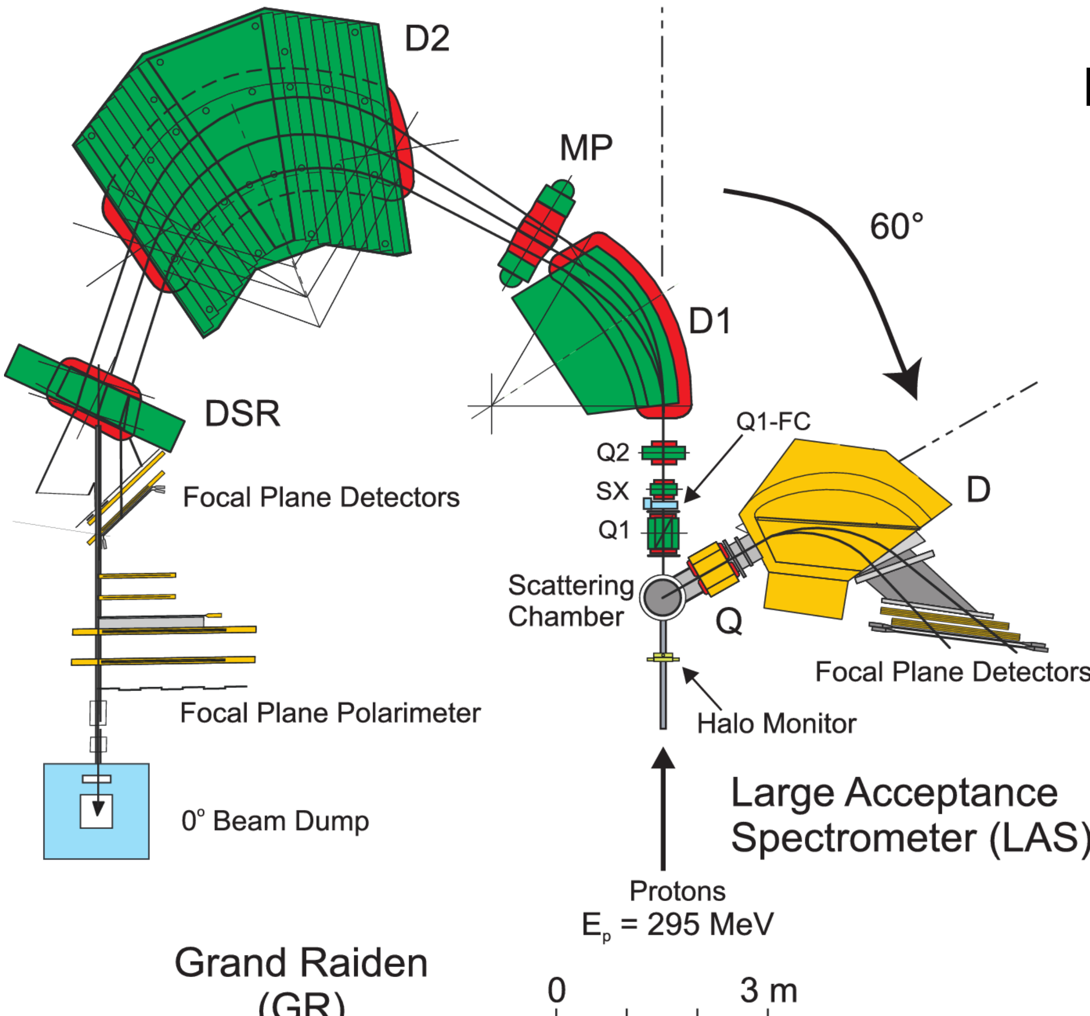



► ($^3$He,$^3$He'$\gamma$) normalized to (n,$\gamma$) data

# 0° setup at RCNP in Osaka




Measured observables for $^{96}$Mo:

- $d\sigma^2/d\Omega dE$ @ 0°, 3° and 4.5°
- $D_{NN}$ @ 0° (normal PT)
- $D_{LL}$ @ 0° (longitudinal PT)

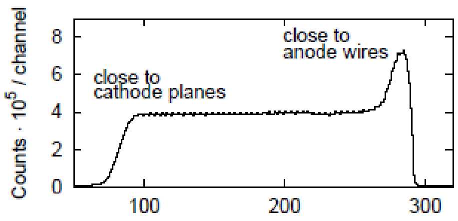
Small vertical magnification

↓

Mild under-focus mode

# Analysis steps

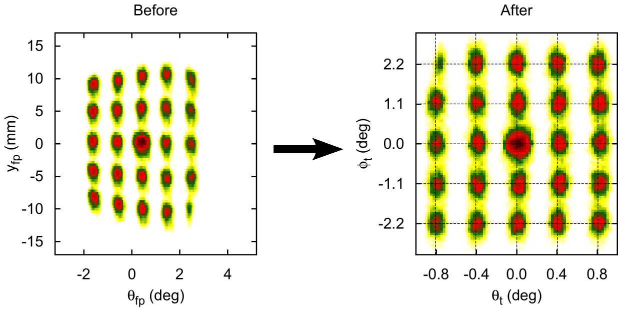
- Drift time to drift length conversion




- Determination of efficiency of VDCs

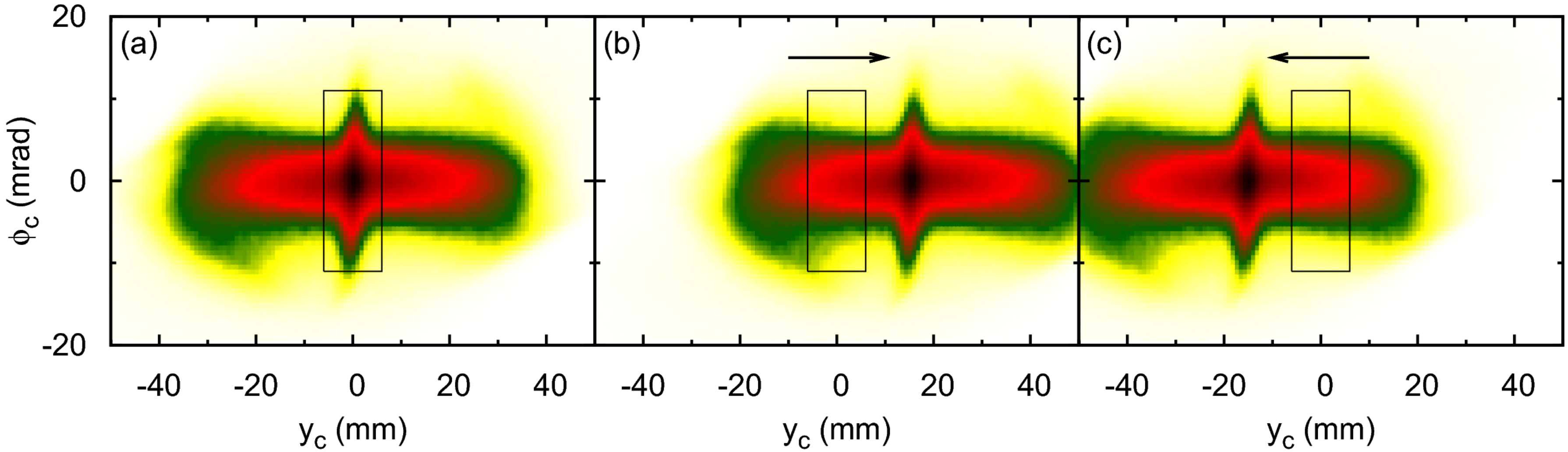
$$\epsilon_{total} = 88\%$$

- Calibration of scattering angles



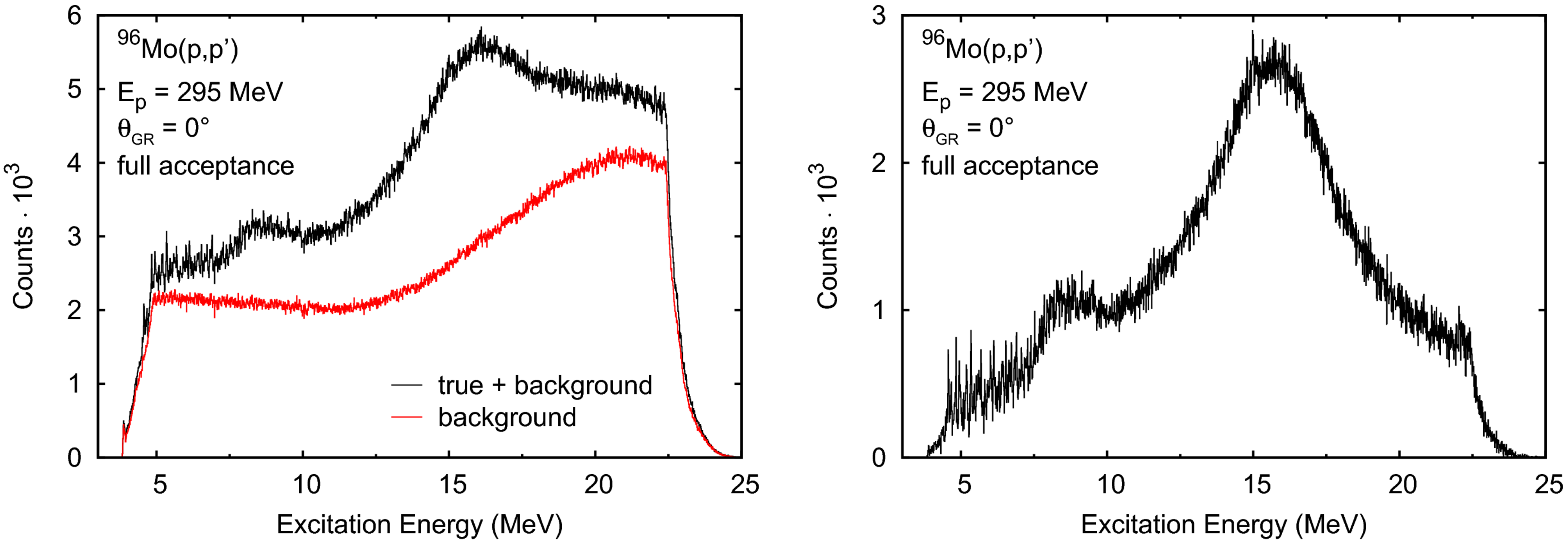

- High-resolution correction and excitation energy calibration
  - $^{26}$Mg runs before each $^{96}$Mo run
  - Many prominent $1^+$ states in $^{26}$Mg
  - Test of the polarization transfer analysis (spinflip M1 transitions)

# Background subtraction



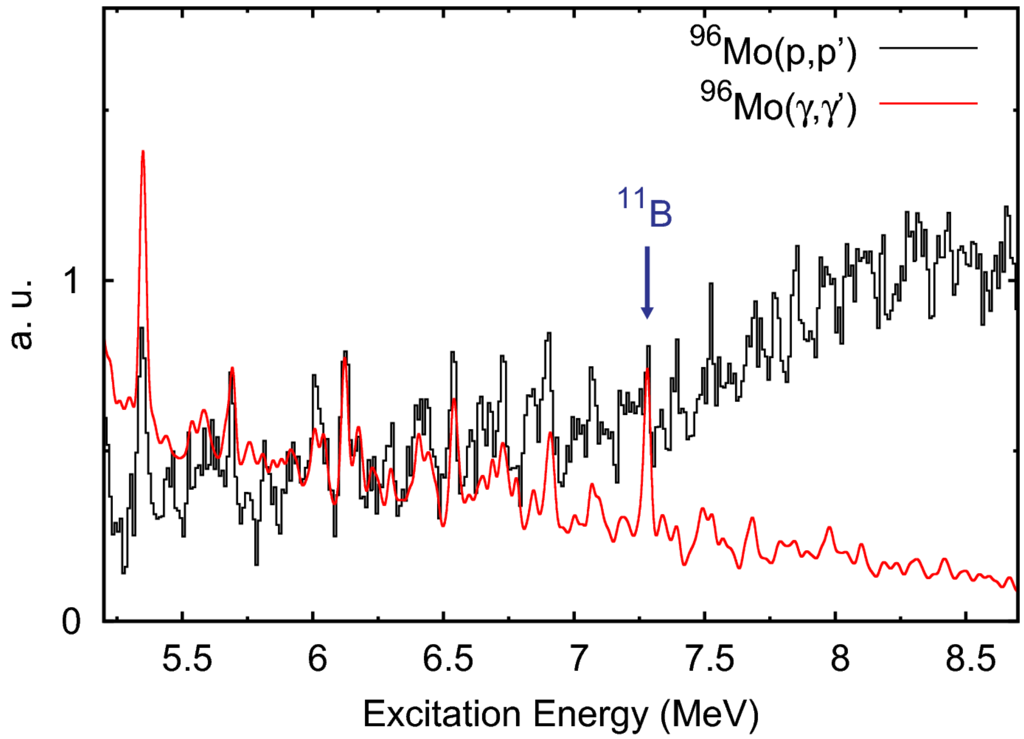

- Background events: flat distribution in non-dispersive focal plane
- True events focus at $y_c = 0$

# Background subtraction



# Qualitative comparison to (γ, γ') experiments

- Measured at the Helmholtz-Zentrum Dresden-Rossendorf
- Endpoint energy: 13.2 MeV
- θ = 127°
- Convoluted with a Gaussian with ΔE = 25 keV
- Arbitrarily normalized to peaks between 6 MeV and 6.5 MeV



# Polarization transfer analysis

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- Second scattering off a carbon slab (~9 cm thick):

$$p_N''^{\,t} = D_{NN} p_N$$
$$p_N''^{\,b} = p_N$$

$$p_S''^{\,t} = D_{SS} p_S \cos \chi_p + D_{LL} p_L \sin \chi_p$$
$$p_S''^{\,b} = p_S \cos \chi_p + p_L \sin \chi_p$$

- Spin precession angle $\chi_p$ of the GR spectrometer
- $p_L$, $p_S$ and $p_N$: longitudinal, sidewards and normal beam polarization
- Background events do not contribute to the depolarization, i.e. $D_{NN} = D_{SS} = D_{LL} = 1$

# Estimator method

- Estimator for measured asymmetries after secondary scattering:

$$\varepsilon_N^t = p_N''^{\,t} \langle A_y \rangle^{FPP}$$
$$\varepsilon_N^b = p_N''^{\,b} \langle A_y \rangle^{FPP}$$

$$\varepsilon_S^t = p_S''^{\,t} \langle A_y \rangle^{FPP}$$
$$\varepsilon_S^b = p_S''^{\,b} \langle A_y \rangle^{FPP}$$

$\Rightarrow$

$$\frac{\varepsilon_N^t}{\varepsilon_N^b} = \frac{D_{NN} p_N}{p_N} = D_{NN}$$
$$\frac{\varepsilon_S^t}{\varepsilon_S^b} = \frac{D_{SS} p_S \cos\chi_p + D_{LL} p_L \sin\chi_p}{p_S \cos\chi_p + p_L \sin\chi_p}$$
$$D_{NN} = D_{SS} \quad (\text{at } 0^\circ)$$

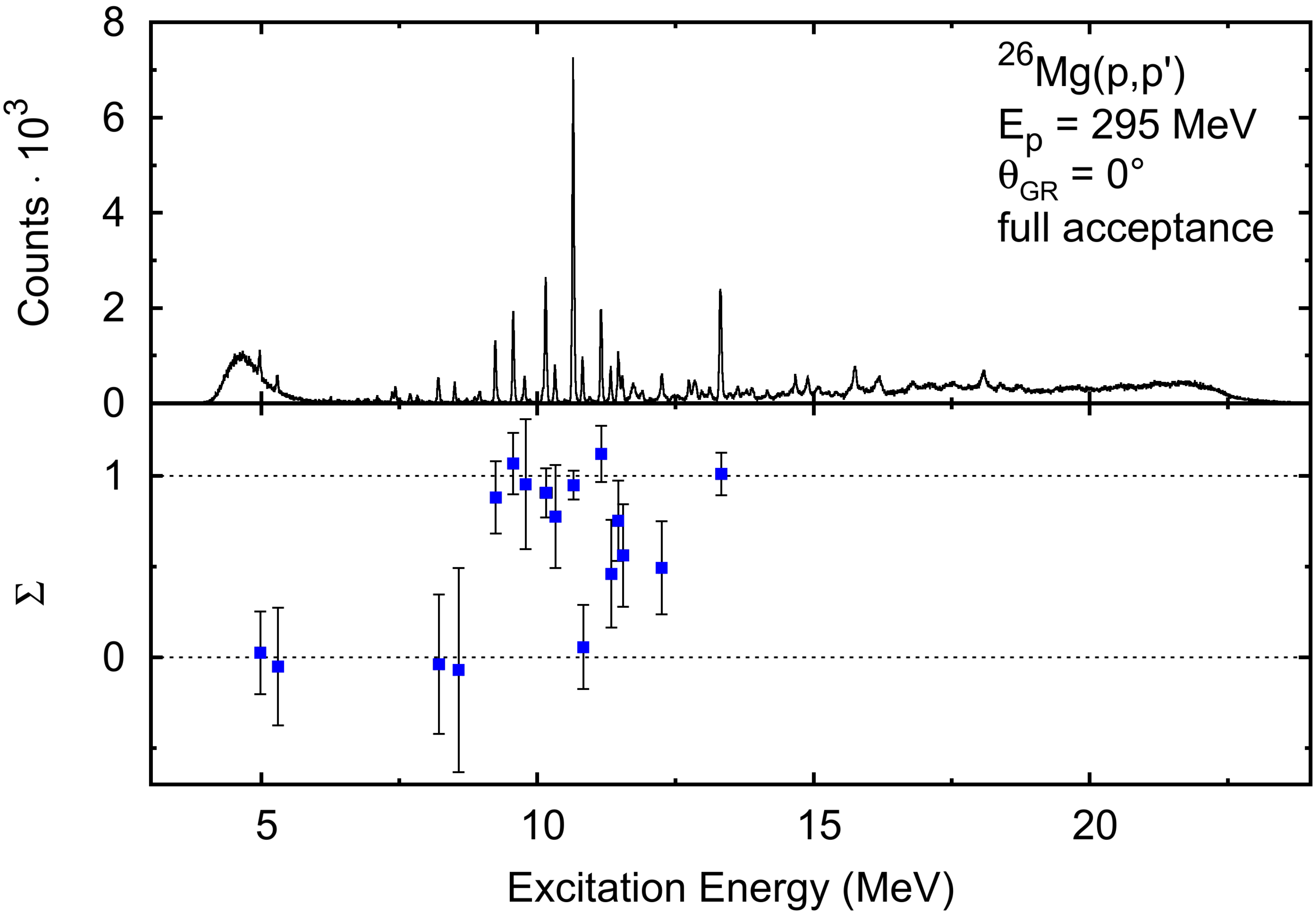
- Close to maximum use of data (compared to sector method e.g.)

- Calculation of uncertainties with covariance matrix

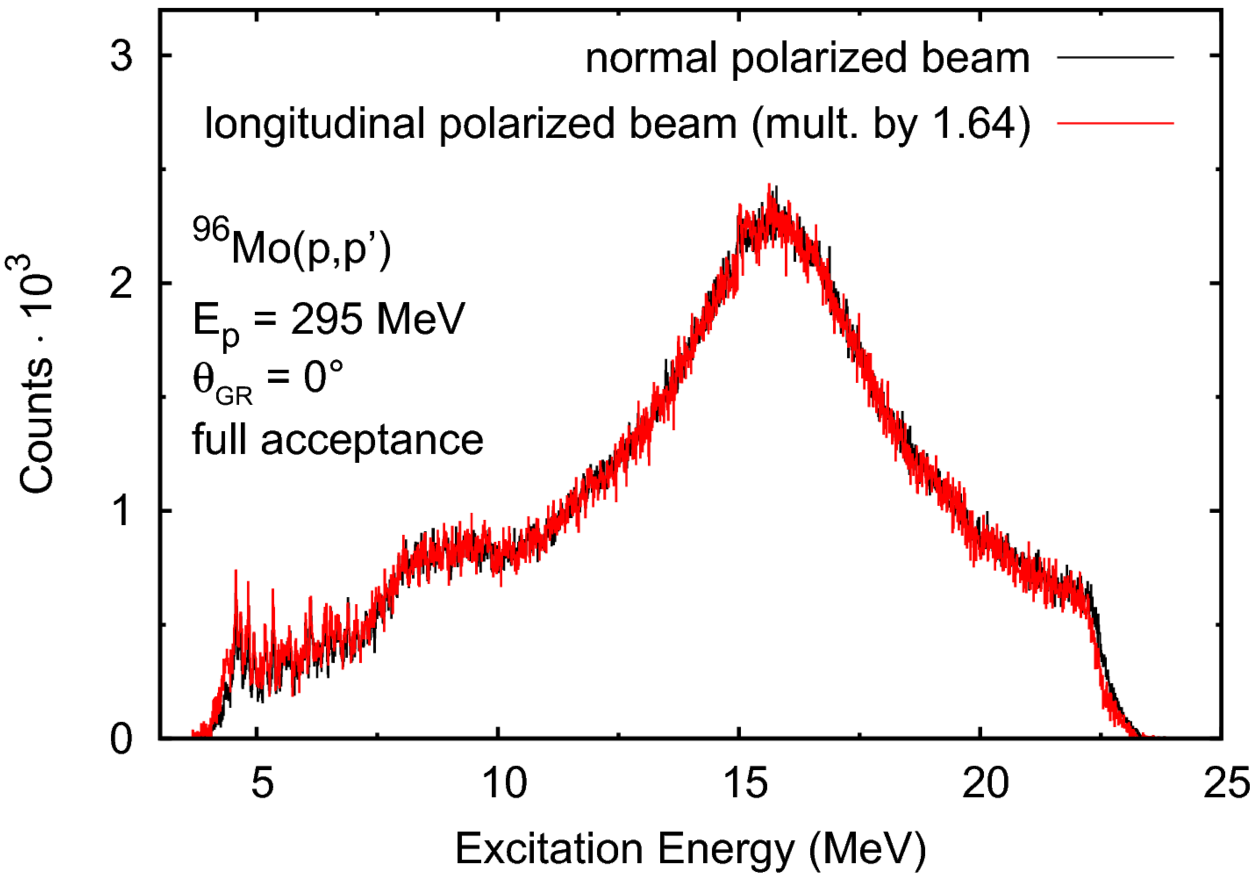
- Statistical treatment is well-defined and clear

  [D. Besset et al., Nucl. Instr. Meth. **166** (1979) 515]

# Polarization transfer observables in $^{26}$Mg

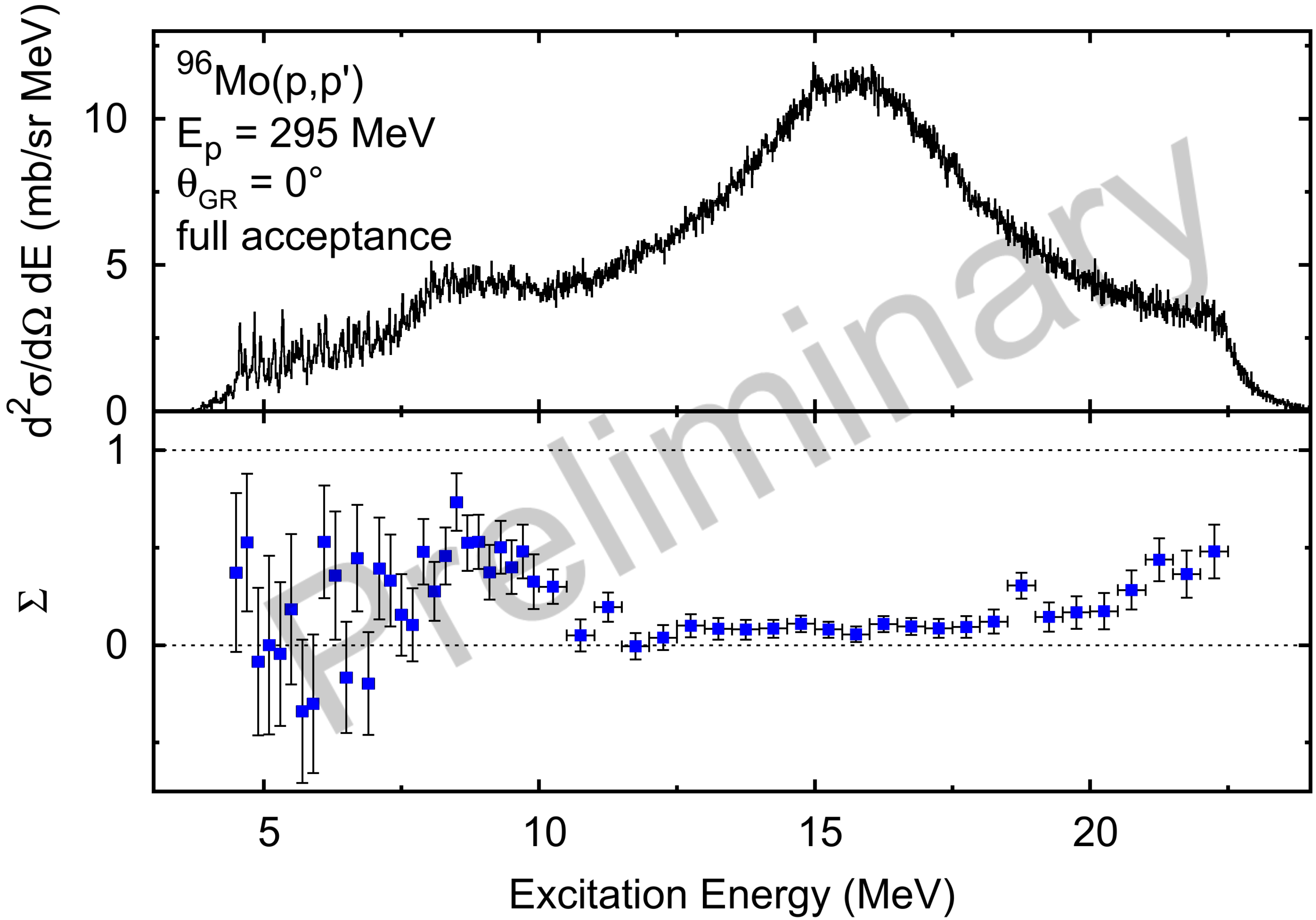


# Consistency check of both polarization transfer measurements



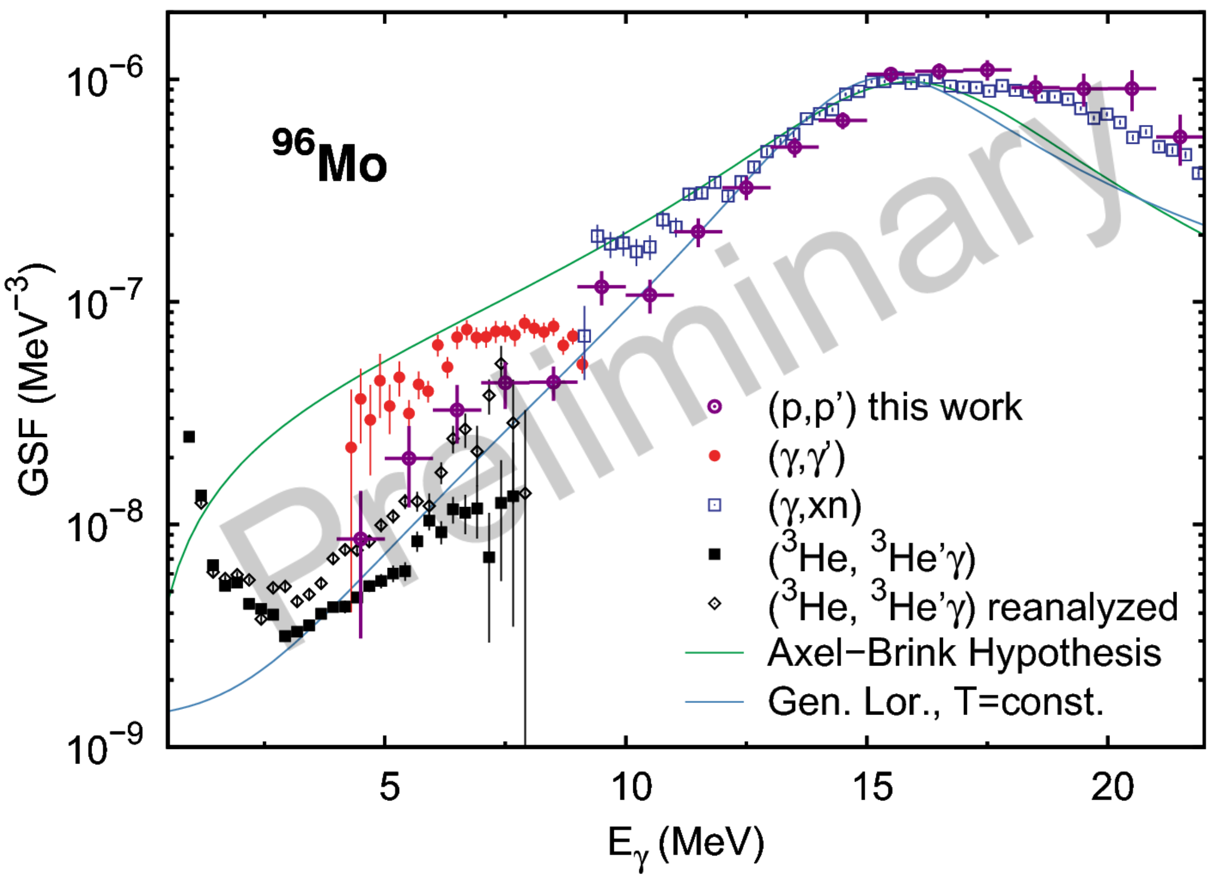

$$\Sigma = \frac{3 - (2D_{NN} + D_{LL})}{4}$$

# Polarization transfer observables in $^{96}$Mo



# Gamma Strength Function of $^{96}$Mo

- Gating on very forward angles $\theta_t$ and $\phi_t$: $\sum_{X\lambda} f^{X\lambda}(E_\gamma) \approx \sum_{X} f^{X\lambda=1}(E_\gamma)$



# Summary

- Gamma Strength Function and Axel-Brink hypothesis
- Incompatible experimental data for $^{96}$Mo
- Polarized proton scattering at 0° as the tool to study the GSF below and above the threshold
- Two different methods to extract E1 and M1 strength
  - Multipole decomposition analysis
  - Polarization transfer observables
- Preliminary results: polarization transfer observable analysis and GSF

# Outlook

- Angular distribution for multipole decomposition analysis (defining scattering angle cuts for measurements at 0°, 3° and 4.5°)
- Compare GSF deduced from absorption and decay experiments
- Check of Axel-Brink Hypothesis
- Extraction of level densities

# Thank you for your attention!

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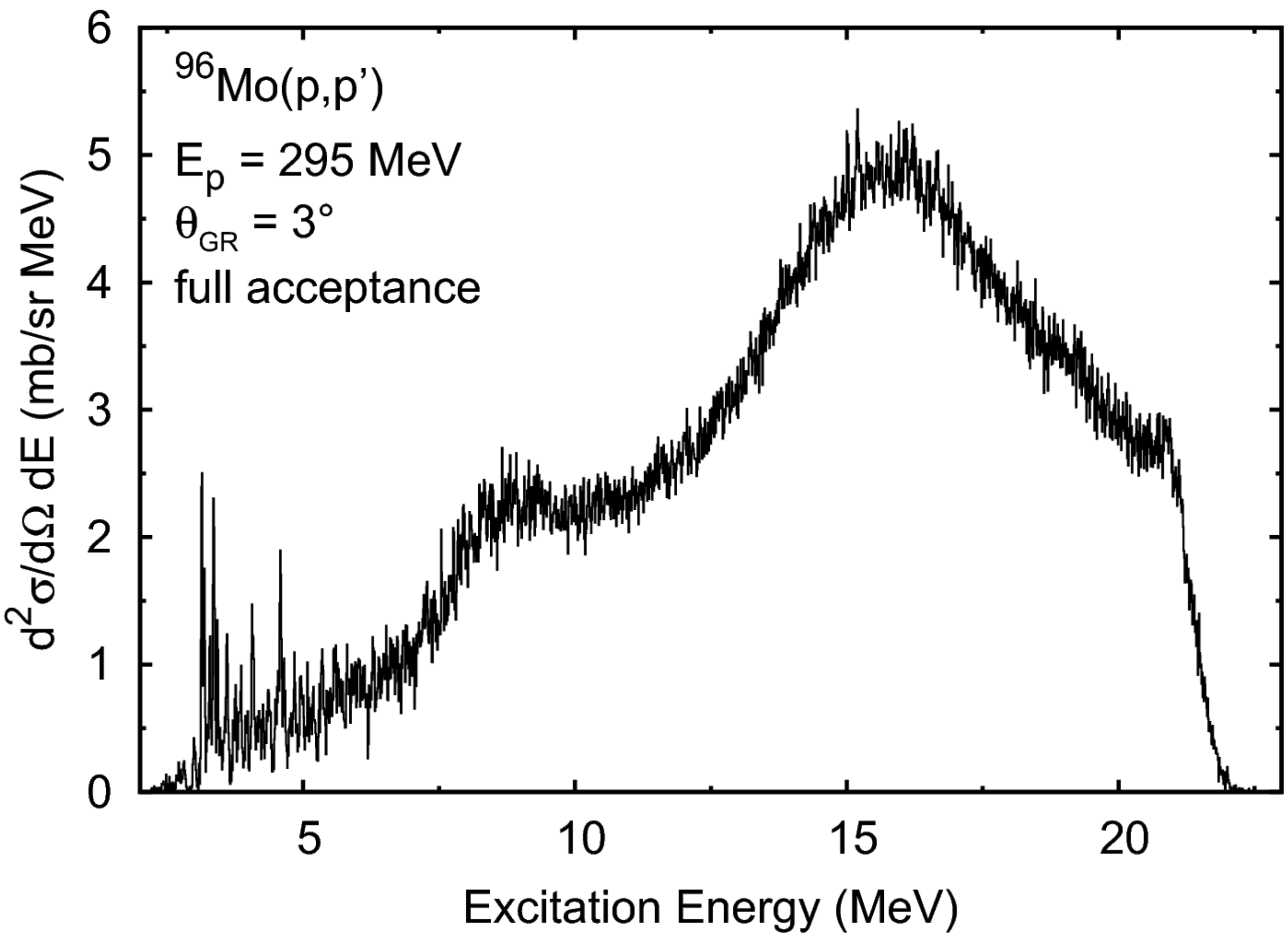
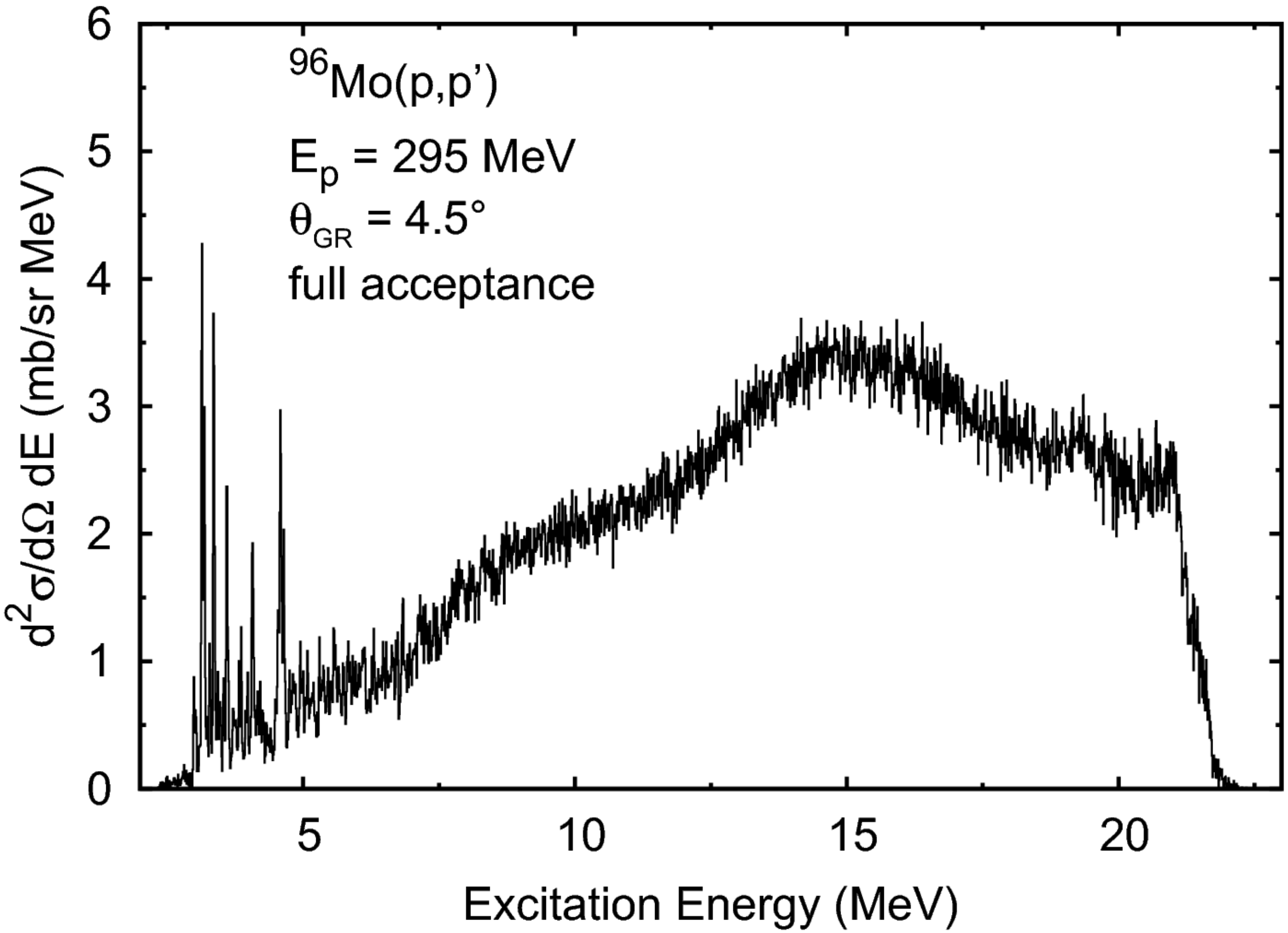
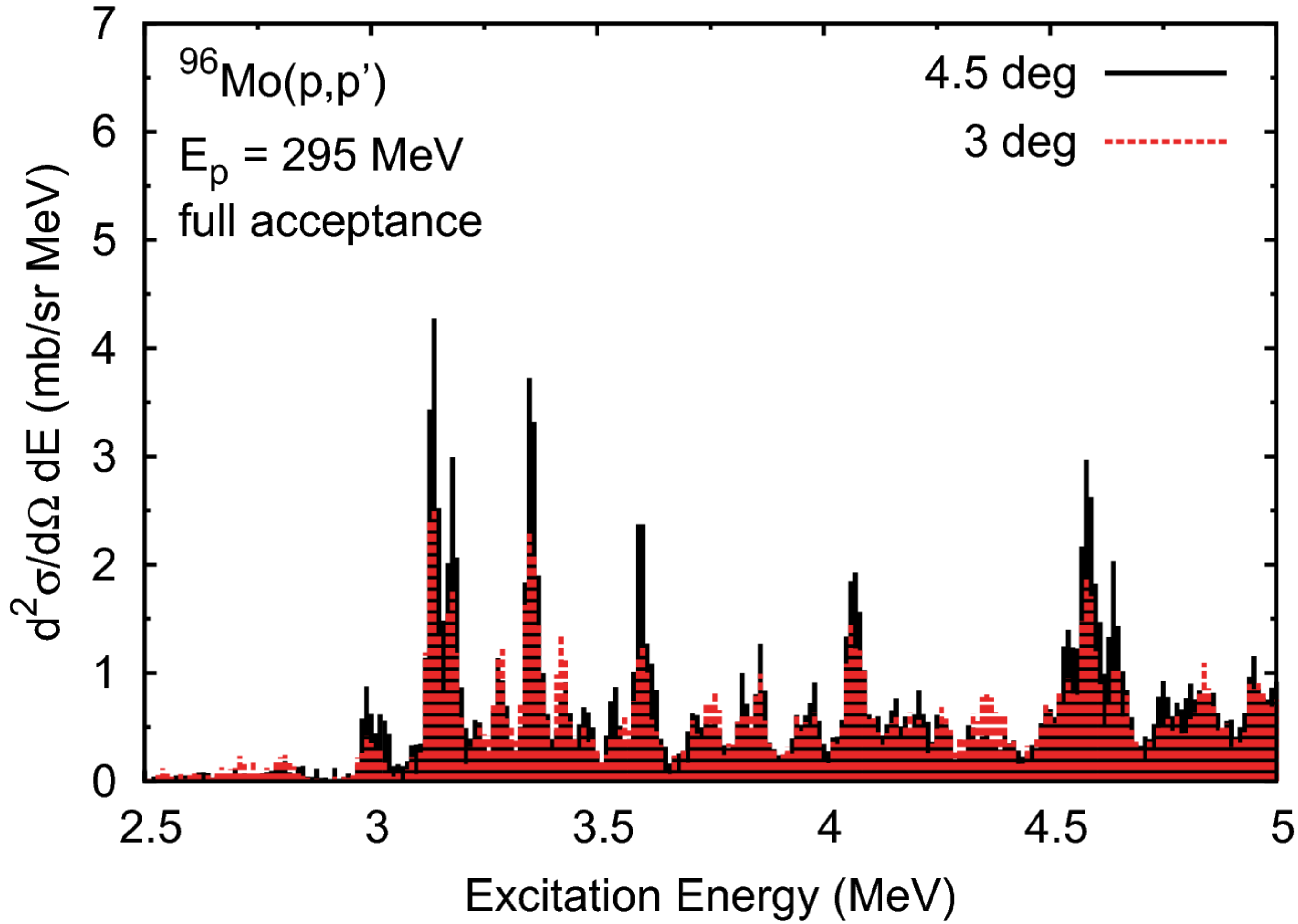
# Appendix 1: 3° spectrum



# Appendix 2: 4.5° spectrum



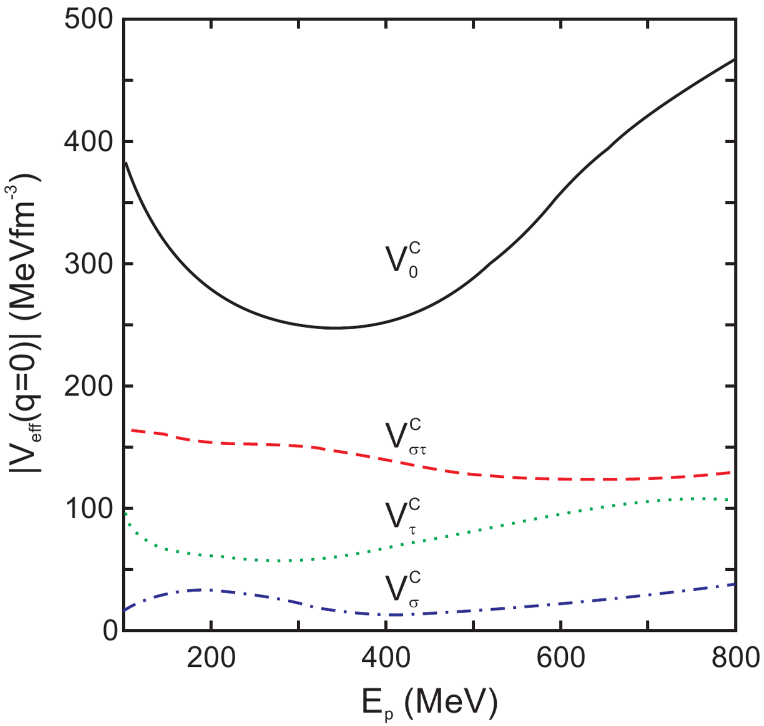
# Appendix 3: 3° and 4.5° spectra



# Appendix 4: Franey-Love interaction

Small momentum transfer: spin-orbit and tensor part of effective interaction negligible:

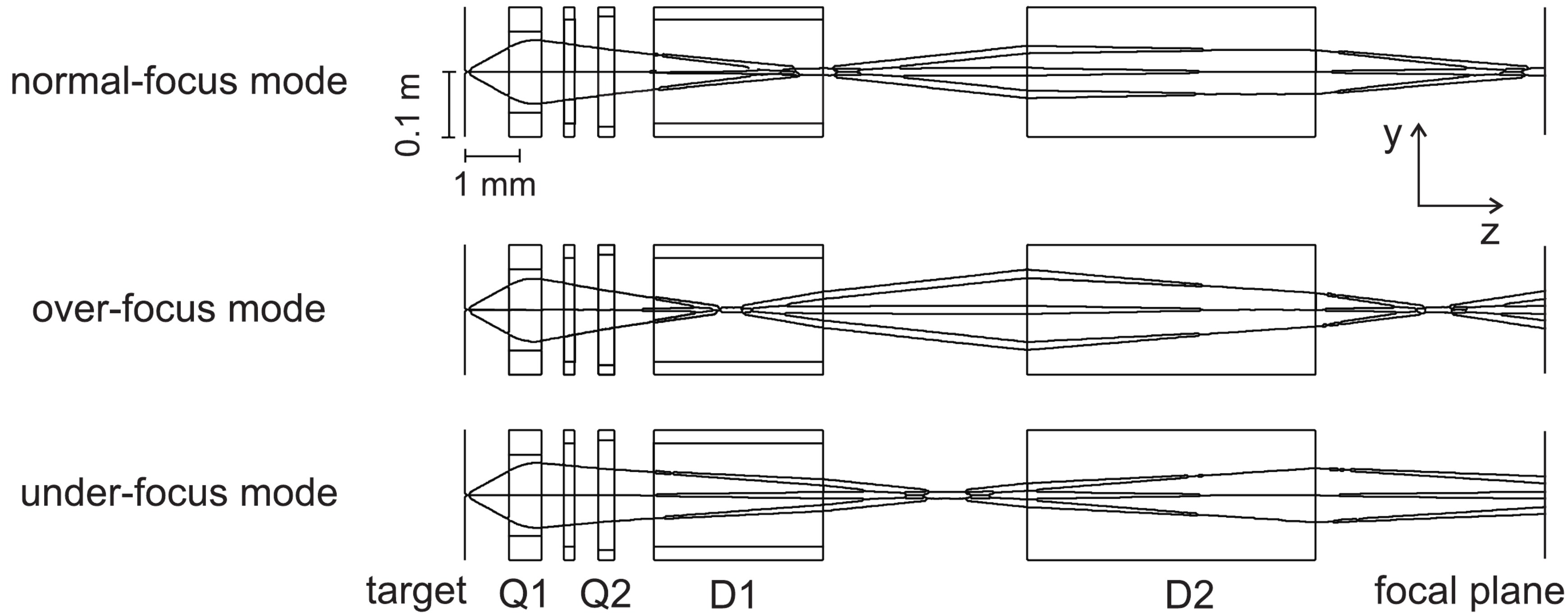
$$V(\vec{r}) = V_0^C(r) + V_\sigma^C(r)\vec{\sigma}_1 \cdot \vec{\sigma}_2 + V_\tau^C(r)\vec{\tau}_1 \cdot \vec{\tau}_2 + V_{\sigma\tau}^C(r)\vec{\sigma}_1 \cdot \vec{\sigma}_2\, \vec{\tau}_1 \cdot \vec{\tau}_2$$



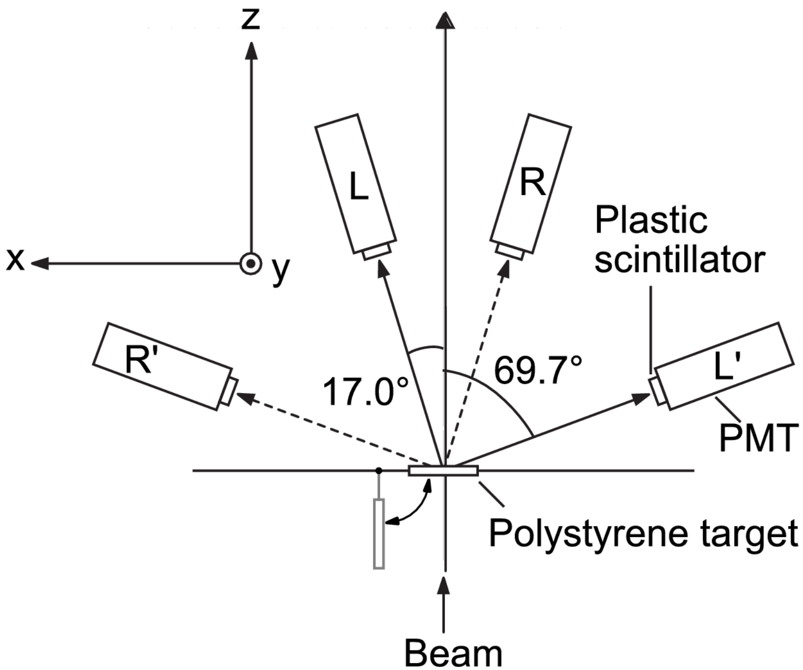

- Measurements with $E_p$ = 300 MeV
- Spin-isospin independent term has a minimum
- Good conditions to observe spin M1 transitions mediated by the spin-isosopin dependent part

[W.G. Love and M.A. Franey, PRC **24** (1981) 1073]

# Appendix 5: Focus modes



# Appendix 6: Beam polarization




$$p_{N(S)} = \frac{1}{A_y^{BLP}} \frac{1 - X_{N(S)}}{1 + X_{N(S)}}$$

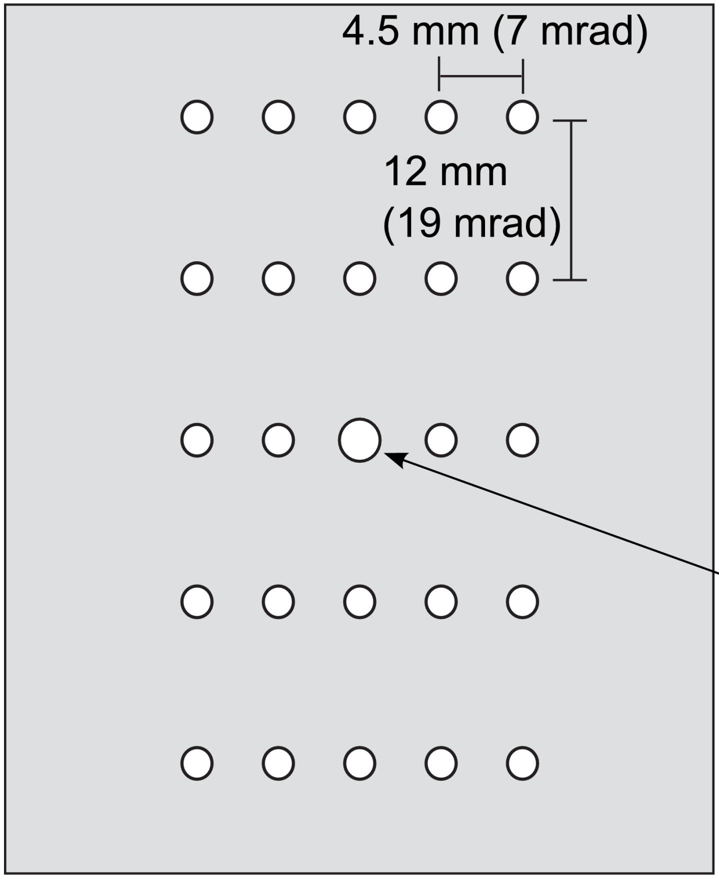
$$X_{N(S)} = \sqrt{\frac{N^{\uparrow}_{L(D)} N^{\downarrow}_{R(U)}}{N^{\downarrow}_{L(D)} N^{\uparrow}_{R(U)}}}$$

$$p_N = p_N^1 = p_N^2$$

$$p_S = p_S^1$$

$$p_L = \frac{p_S^1 \cos \chi_{BLP} - p_S^2}{\sin \chi_{BLP}}$$

# Appendix 7: Reconstruction of the scattering angles

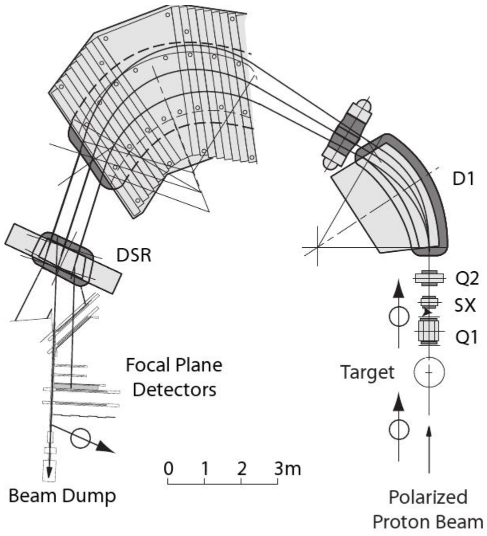



center hole:
3 mm diameter

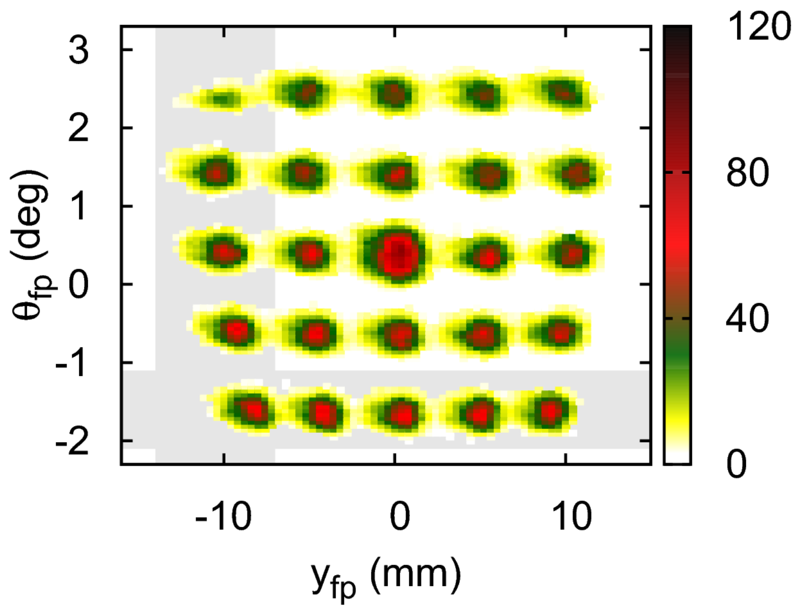
other holes:
2 mm diameter

material: brass
thickness: 5 mm

- $^{58}$Ni (100.1 mg/cm²)
- $\theta_{GR} = 10°$
- Several settings of the magnetic field
- Vertical positions: 0, ±1 mm



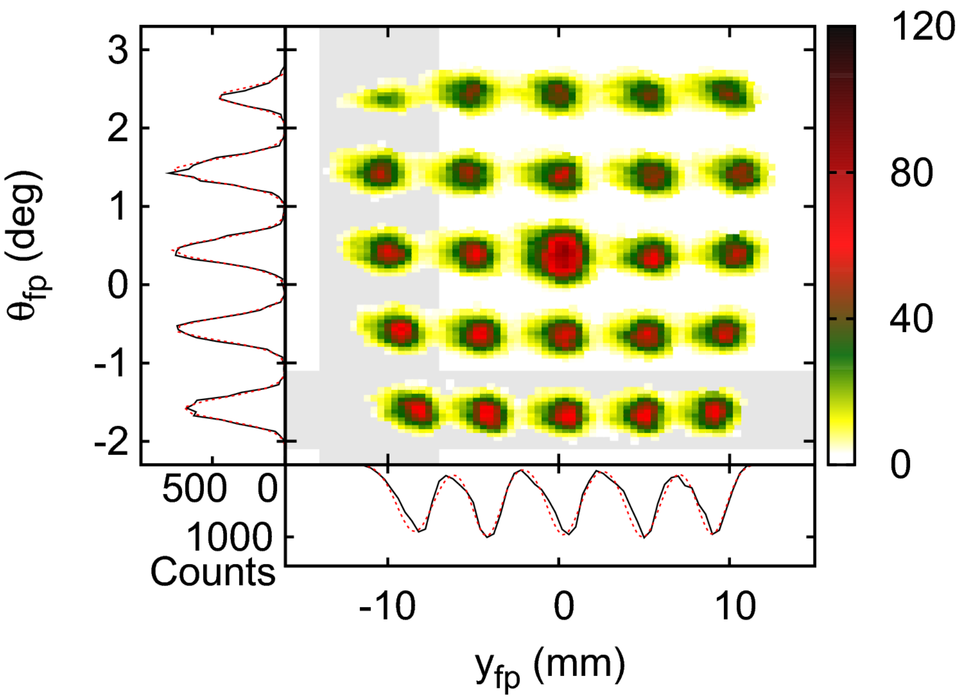
# Appendix 8: Sieve slit analysis




Determination of centers:

- Plane divided into sectors

# Appendix 8: Sieve slit analysis



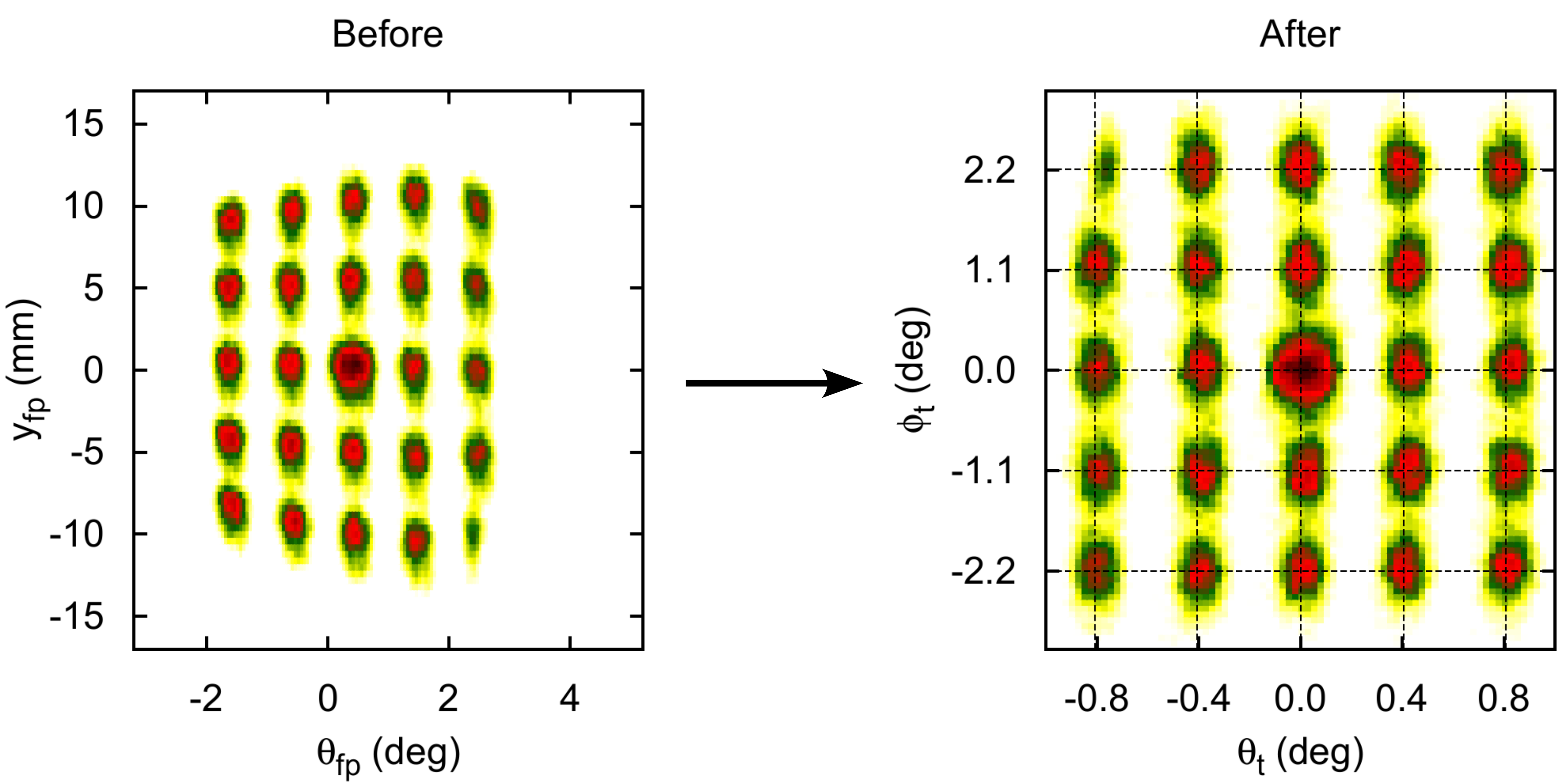

Determination of centers:

- Plane divided into sectors
- Fit with gaussian functions
- Additionally: established dependences on $x_{fp}$, $\phi_{fp}$ and $y_{LAS}$

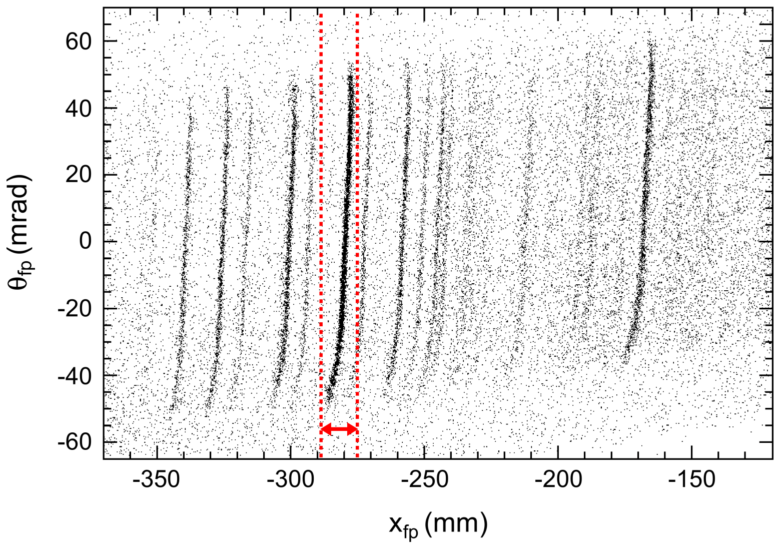
$$\theta_t(x_{fp}, \theta_{fp}) = \sum_{i=0}^{2} \sum_{j=0}^{2} a_{ij} \cdot x_{fp}^i \theta_{fp}^j$$

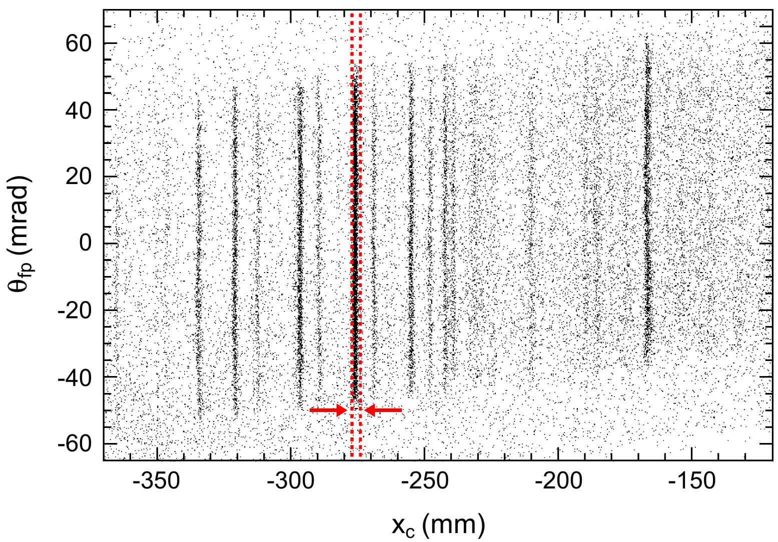
$$\phi_t(x_{fp}, \theta_{fp}, y_{fp}, \phi_{fp}, y_{LAS}) = \sum_{i=0}^{2} \sum_{j=0}^{2} \sum_{k=0}^{2} \sum_{l=0}^{2} b_{ijkl} \cdot x_{fp}^i \theta_{fp}^j y_{fp}^k \phi_{fp}^l + \sum_{m=0}^{1} c_m \cdot x_{fp}^m y_{LAS}$$

# Appendix 8: Sieve slit analysis



# Appendix 9: High-resolution corrections

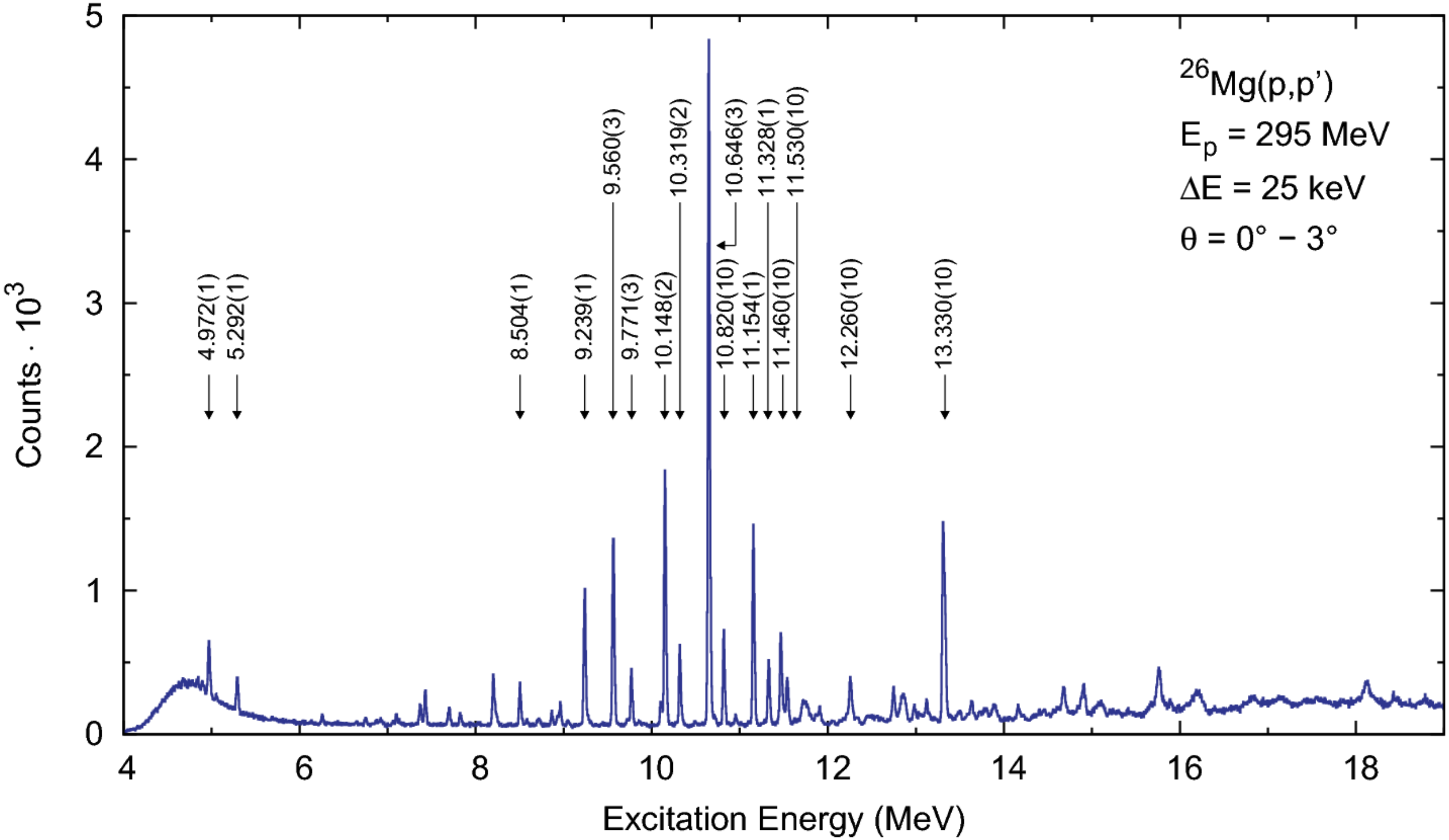



- Discrete transitions in $^{26}$Mg
- Curved lines in the focal plane
- Aberration effects (→ optics)
- Polynomial fit:

$$x_c = x_{fp} + \sum_{i=0}^{3} \sum_{j=0}^{4} d_{ij} \cdot x_{fp}^{i} \, \theta_{fp}^{j}$$

# Appendix 10: Energy calibration




- $2^{nd}$ order polynomial + energy shifts using the highest peak of $^{26}$Mg

# Appendix 11: Estimator method

- Effective estimator $\hat{\varepsilon} = \mathbf{F}^{-1}\mathbf{B} = \begin{pmatrix} \hat{\varepsilon}_N \\ \hat{\varepsilon}_S \end{pmatrix}$ with

$$\mathbf{B} = \begin{pmatrix} \sum_N \cos \phi_{FPP} \\ \sum_N \sin \phi_{FPP} \end{pmatrix}$$

$$\mathbf{F} = \begin{pmatrix} \sum_N \cos^2 \phi_{FPP} & \sum_N \sin \phi_{FPP} \cos \phi_{FPP} \\ \sum_N \sin \phi_{FPP} \cos \phi_{FPP} & \sum_N \sin^2 \phi_{FPP} \end{pmatrix}$$

- Sums over all events

- Calculation of uncertainties with the covariance matrix $V(\hat{\varepsilon}) = \mathbf{F}^{-1}$