# Quenching of Spin-Isospin Strength in Electron and Proton Scattering

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*Institut für Kernphysik, Technische Universität Darmstadt*

- Introduction
- Electromagnetic B(M1) transition strengths from (p,p') scattering
- The case of $^{208}$Pb
- The case of $^{48}$Ca
- Forbidden beta decay and its magnetic analogue

Supported by DFG under contract SFB 1245

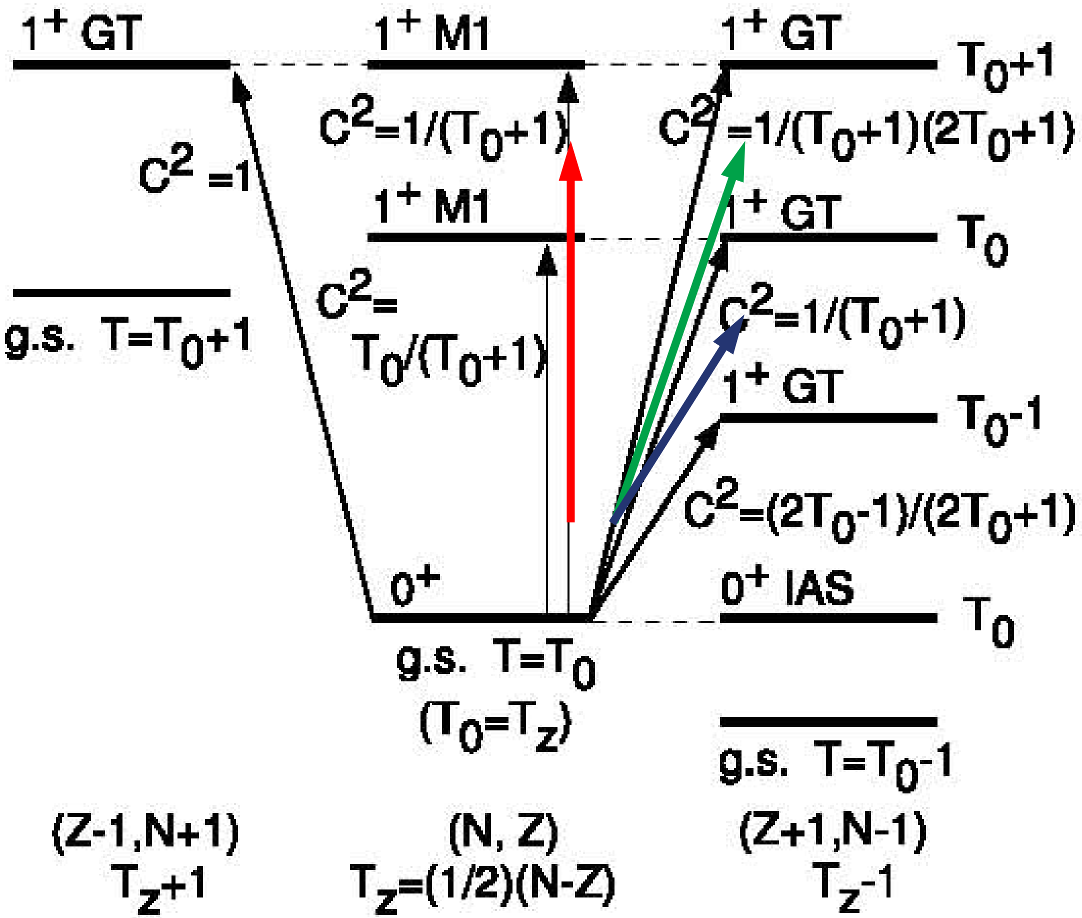
# Spinflip M1 Resonance



- Fundamental excitation mode of the nucleus
- Analog of Gamow-Teller resonances with $T = T_0$
- Impact on current problems in nuclear structure and astrophysics
  - neutral-current neutrino interactions in supernovae
  - reaction cross sections in nucleosynthesis network calculations
  - neutrinoless double beta decay
  - tensor interaction and the evolution of shell structure
- Fairly well studied in *sd*- and *fp*-shell nuclei
- Little is known in heavy nuclei

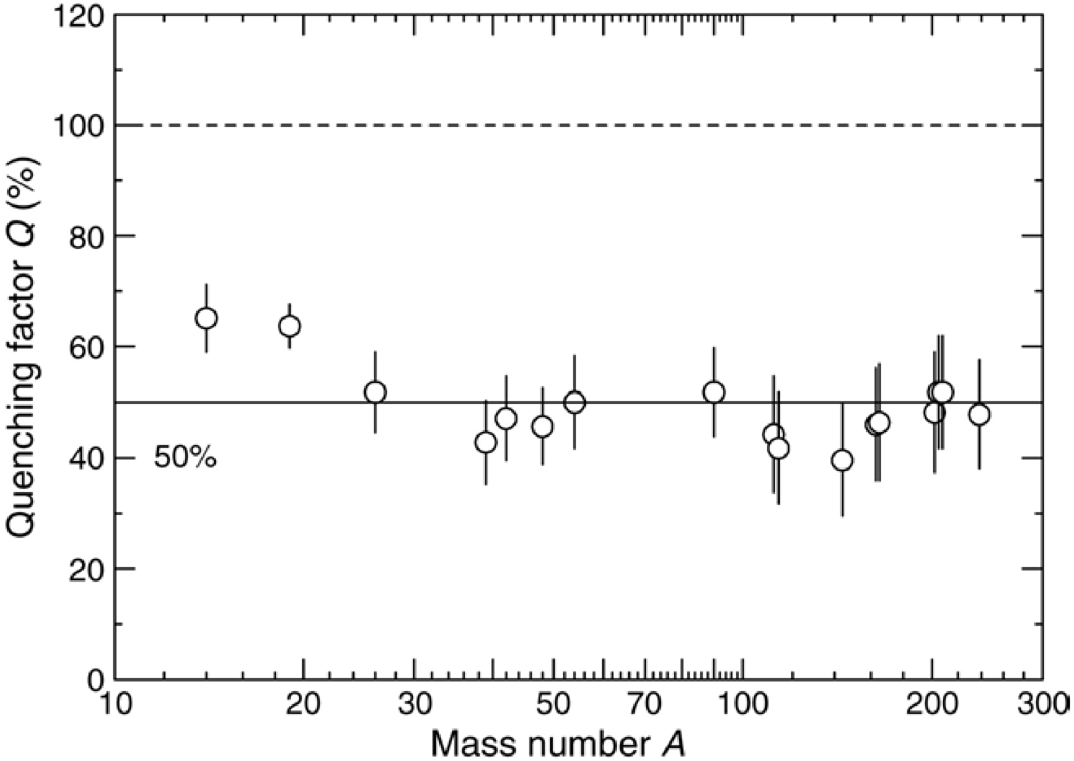
# Isospin Symmetry

Y. Fujita, B. Rubio, W. Gelletly, Prog. Part. Nucl. Phys. 66, 549 (2011)



# Quenching of GT Strength

M. Ichimura, H. Sakai, T. Wakasa, Prog. Part. Nucl. Phys. 56, 446 (2006)




Systematic reduction by a factor of about 2

Impact on weak interactions ($g_A$ is renormalized in nuclei)

Same behavior for spin-M1?

# Quenching of Spin-M1 and GT Strength



What is meant by **quenching**?

M1 or GT resonances are valence-shell (0 $\hbar\omega$) excitations
$\rightarrow$ confined in a certain excitation energy region

$$\text{Quenching} = \frac{\text{experimental strength in that region}}{\text{theoretical or sum rule prediction in that region}}$$

In model calculations quenching is often included by an effective *g*-factor

Quenching affects the spin part of the operators only, the orbital *g*-factor is found to be close to the free value.

# Spin M1 and GT Strength

- (p,n) at 0°

$$\frac{d\sigma_{pn}^{GT}}{d\Omega}(0°) = \hat{\sigma}_{GT} F(q,\omega) B(GT)$$

- (p,p‘) at 0°

$$\frac{d\sigma_{pp'}^{GT}}{d\Omega}(0°) = \hat{\sigma}_{M1} F(q,E_x) B(M1_{\sigma\tau})$$

- Transition strengths

$$B(\mathrm{GT}) = \frac{C_{\mathrm{GT}}^2}{2(2T_f+1)} |\langle f ||| \sum_k^A \sigma_k \tau_k ||| i \rangle|^2$$

$$B(\mathrm{M1}_{\sigma\tau}) = \frac{C_{\mathrm{M1}}^2}{4(2T_f+1)} |\langle f ||| \sum_k^A \sigma_k \tau_k ||| i \rangle|^2$$

- Isospin symmetry

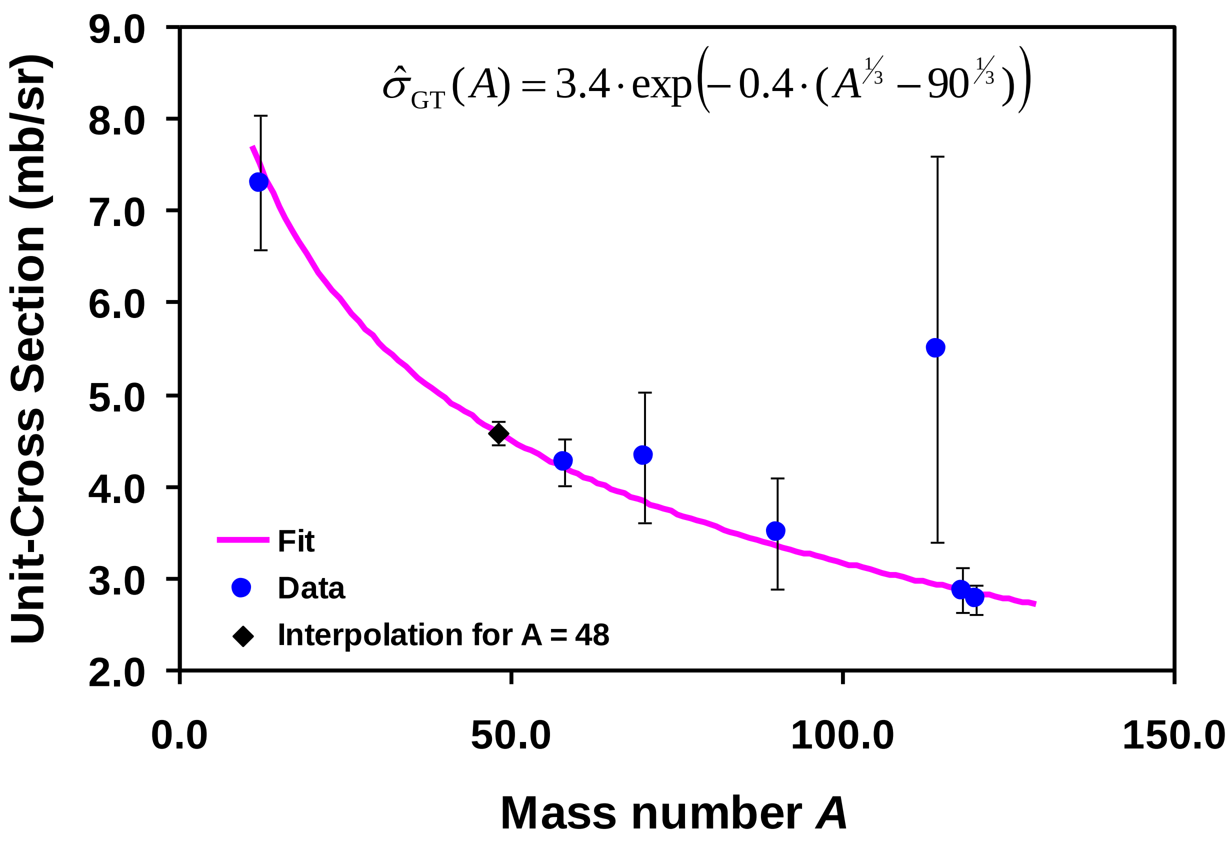
$$\hat{\sigma}_{\mathrm{M1}} \simeq \hat{\sigma}_{\mathrm{GT}}$$

J. Birkhan et al., Phys. Rev. C 93, 041302(R) (2016)

# GT Unit Cross Section

GT unit cross section for (p,n) reaction at 297 MeV

M. Sasano et al., Phys. Rev. C 79, 024602 (2009)



# Spin M1 and B(M1) Strength



- B(M1) strength

$$B(\mathrm{M1}) = \frac{3}{4\pi} |\langle f || g_l^{\mathrm{IS}} \vec{l} + \frac{g_s^{\mathrm{IS}}}{2} \vec{\sigma} - (g_l^{\mathrm{IV}} \vec{l} + \frac{g_s^{\mathrm{IV}}}{2} \vec{\sigma}) \tau_0 || i \rangle|^2 \, \mu_{\mathrm{N}}^2$$

# Spin M1 and B(M1) Strength

- B(M1) strength

$$B(\mathrm{M1}) = \frac{3}{4\pi} \left|\langle f || g_l^{\mathrm{IS}}\vec{l} + \frac{g_s^{\mathrm{IS}}}{2}\vec{\sigma} - \left(g_l^{\mathrm{IV}}\vec{l} + \frac{g_s^{\mathrm{IV}}}{2}\vec{\sigma}\right)\tau_0 || i\rangle\right|^2 \mu_{\mathrm{N}}^2$$

$$B(\mathrm{M1}) \cong \frac{3}{4\pi} \left(g_s^{\mathrm{IV}}\right)^2 B(\mathrm{M1}_{\sigma\tau})\, \mu_{\mathrm{N}}^2$$

# Application to $^{208}$Pb

R.M. Laszewsi et al., PRL 61, 1710 (1988)
R. Köhler et al., PRC 35, 1646 (1987)

$$\sum B(M1) = 14.8^{+1.5}_{-1.9}\,\mu_N^2$$

for $E_x \leq 8$ MeV

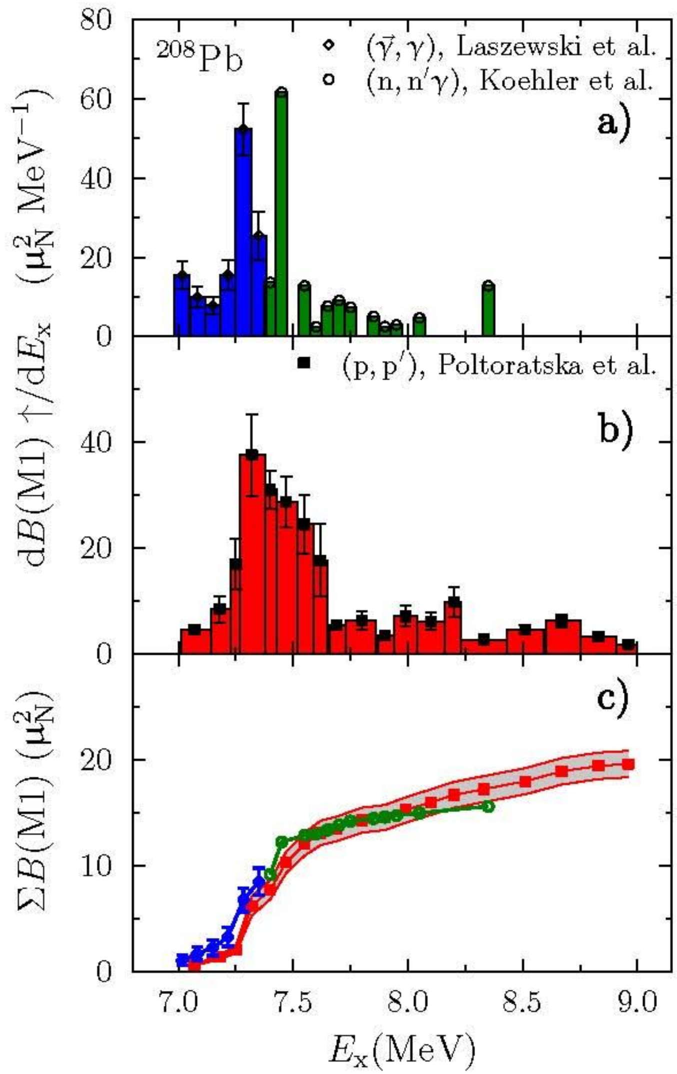
I. Poltoratska et al., PRC 85, 041304 (2012)

$$\sum B(M1) = 16.0(1.2)\,\mu_N^2$$

for $E_x \leq 8$ MeV

$$\sum B(M1) = 20.5(1.3)\,\mu_N^2$$

for full resonance



# Spinflip M1 Transition in $^{48}$Ca

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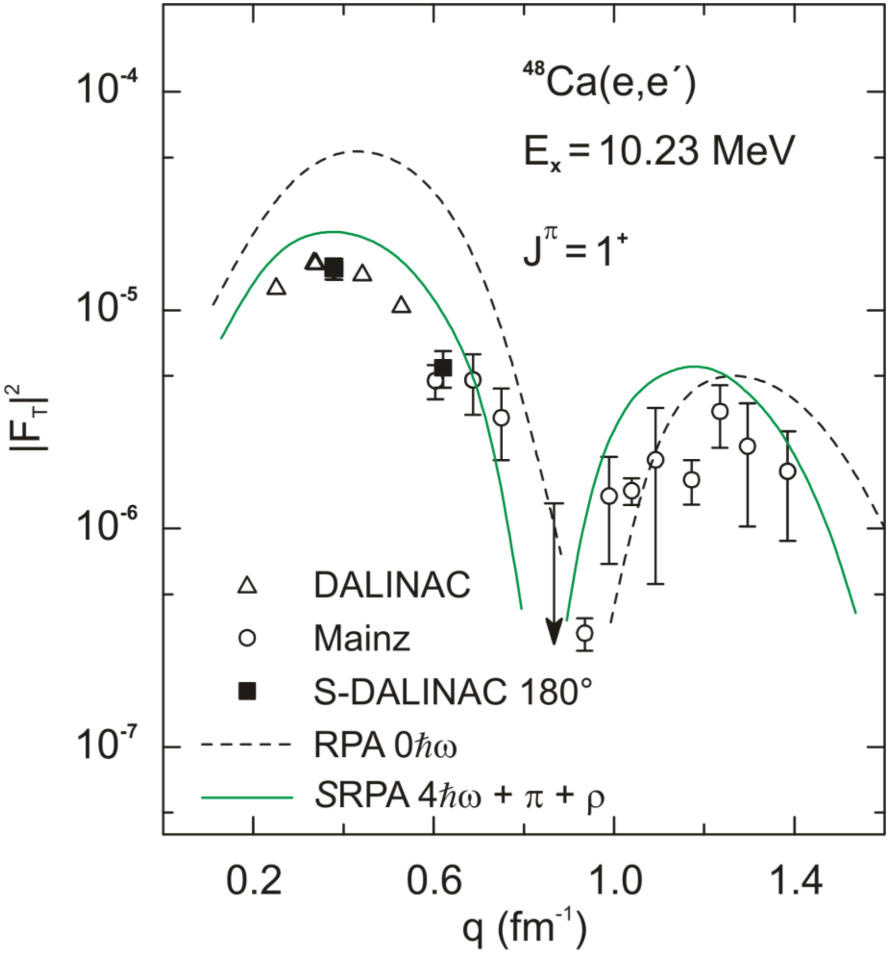
W. Steffen et al., Nucl. Phys. A 404, 413 (1983)




- Spinflip transition
- Very strong: $B(M1)\uparrow \approx 4\ \mu_N^2$
- Test case for quenching

# The Case of $^{48}$Ca

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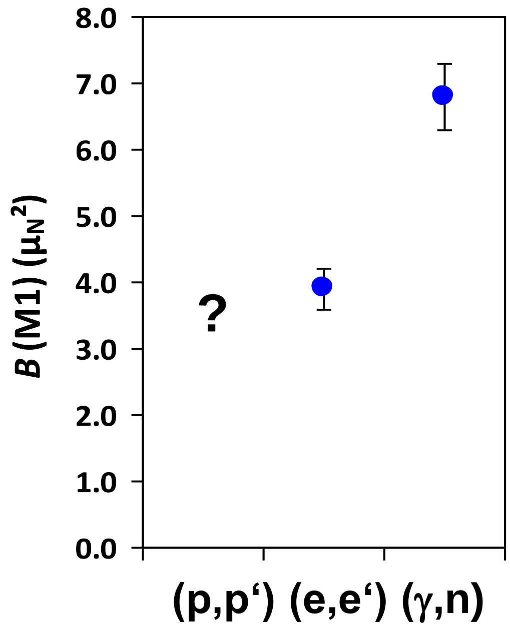
- 75% of spin M1 strength concentrated in single peak
- Simple structure: almost pure neutron $1f_{7/2} \rightarrow 1f_{5/2}$ transition
- Reference case for quenching of spin-isospin strength
- (e,e') experiment at DALINAC
  W. Steffen et al., Nucl. Phys. A 404, 413 (1983)
  $\rightarrow B(M1)\uparrow = (3.9 \pm 0.3)\ \mu_N^2$
- ($\gamma$,n) experiment at HI$\gamma$S)
  J.R. Tompkins et al, Phys. Rev. C 84, 044331 (2011)
  $\rightarrow B(M1)\uparrow = (6.8 \pm 0.5)\ \mu_N^2$

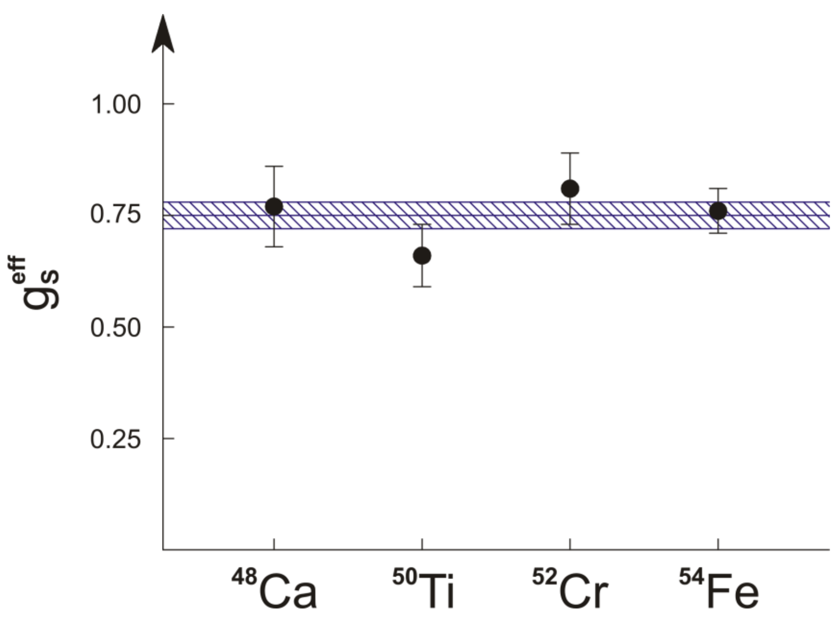


# Quenching in fp-Shell Nuclei

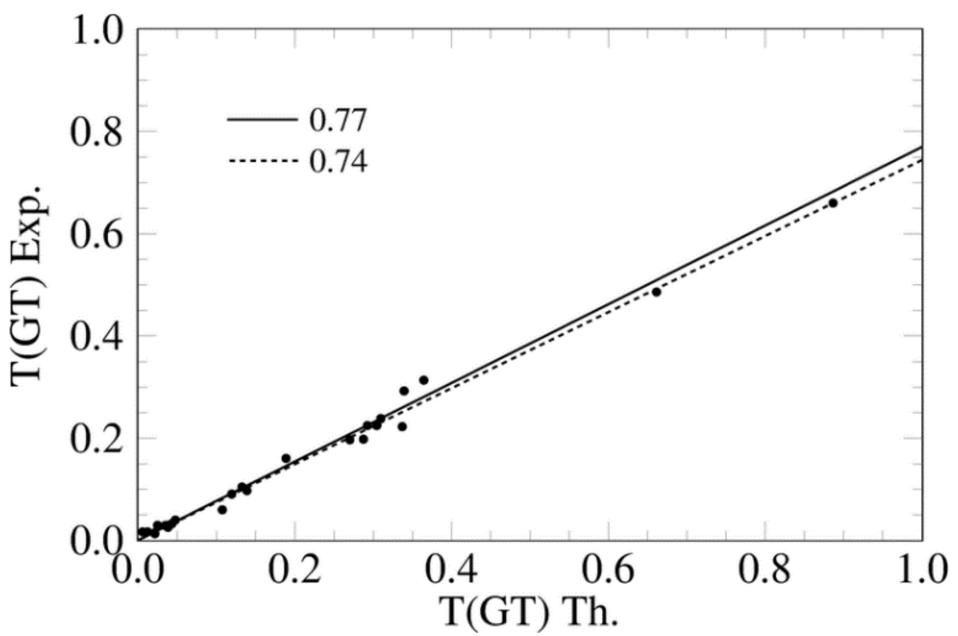
PvNC et al., Phys. Lett. B 443, 1 (1998)

G. Martínez-Pinedo et al.,
Phys. Rev. C 53, 2602(R) (1996)

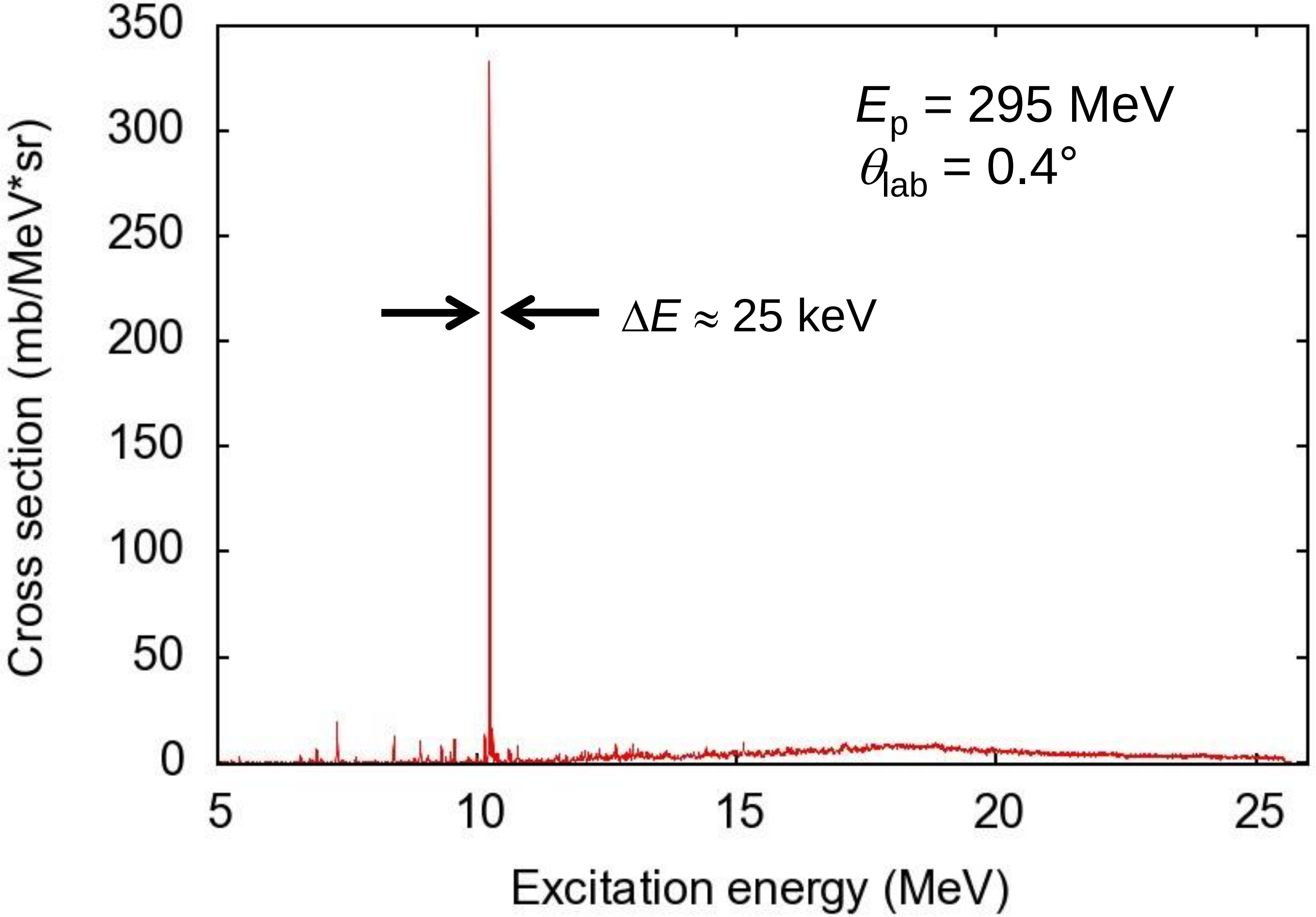
## M1




## GT

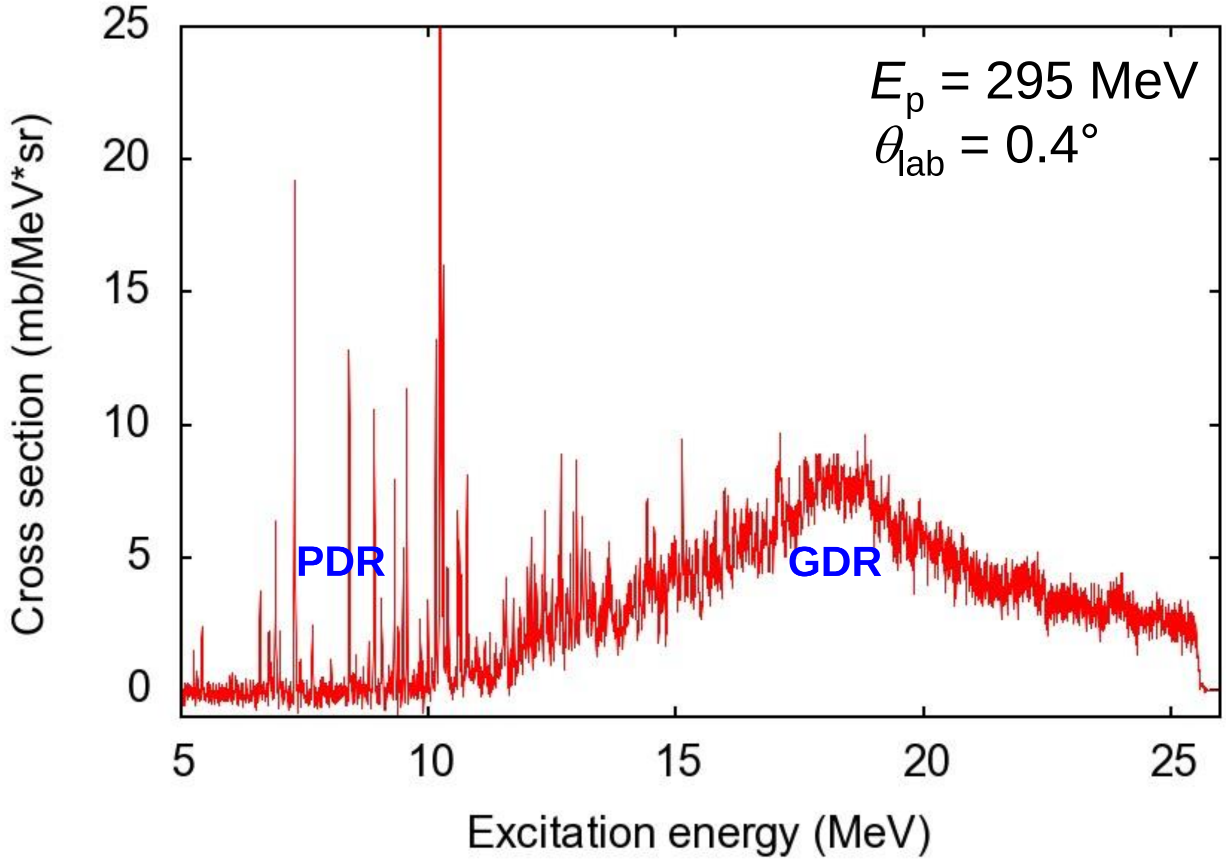


# The Case of $^{48}$Ca: (p,p') Data




**RCNP**

# The Case of $^{48}$Ca: (p,p‘) Data




Complete E1 response can be extracted from the data → Project B04

# $^{48}$Ca: Quenching of IS and IV part

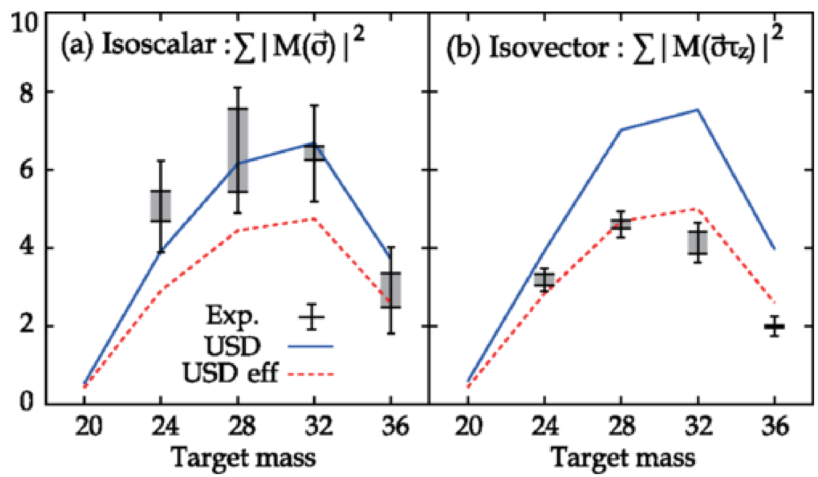
$$B(\mathrm{M1}) = \frac{3}{4\pi} |\langle f || g_l^{\mathrm{IS}} \vec{l} + \frac{g_s^{\mathrm{IS}}}{2} \vec{\sigma} - (g_l^{\mathrm{IV}} \vec{l} + \frac{g_s^{\mathrm{IV}}}{2} \vec{\sigma}) \tau_0 || i \rangle|^2 \, \mu_{\mathrm{N}}^2$$

IV quenching factor is known but IS quenching can be dfifferent.

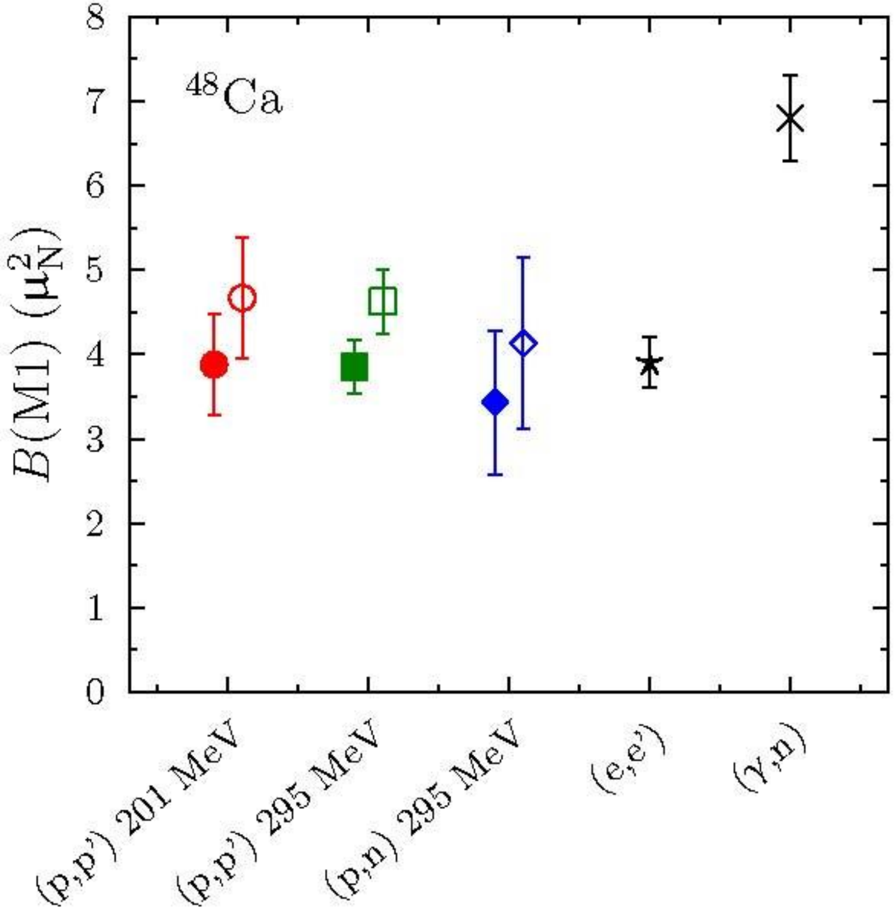
Two extremes:

- Assume the same quenching factors
- Assume no IS quenching

H. Matsubara et al.,
Phys. Rev. Lett. 115, 102501 (2015)



# B(M1) Strength in $^{48}$Ca from (p,p‘) and (p,n)




Results from hadronic reactions consistent with (e,e‘)

# Search for Weak B(M1) Transitions

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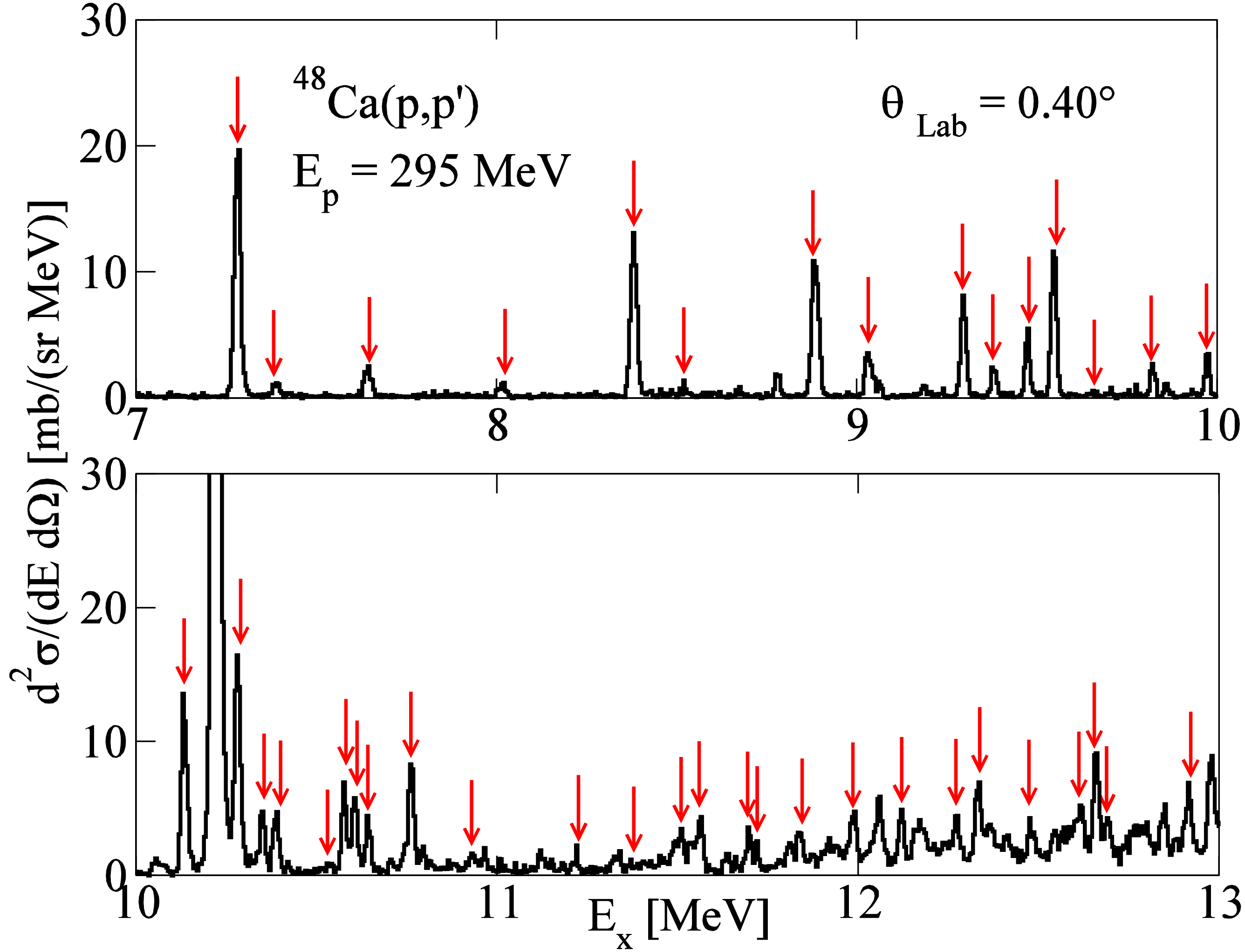
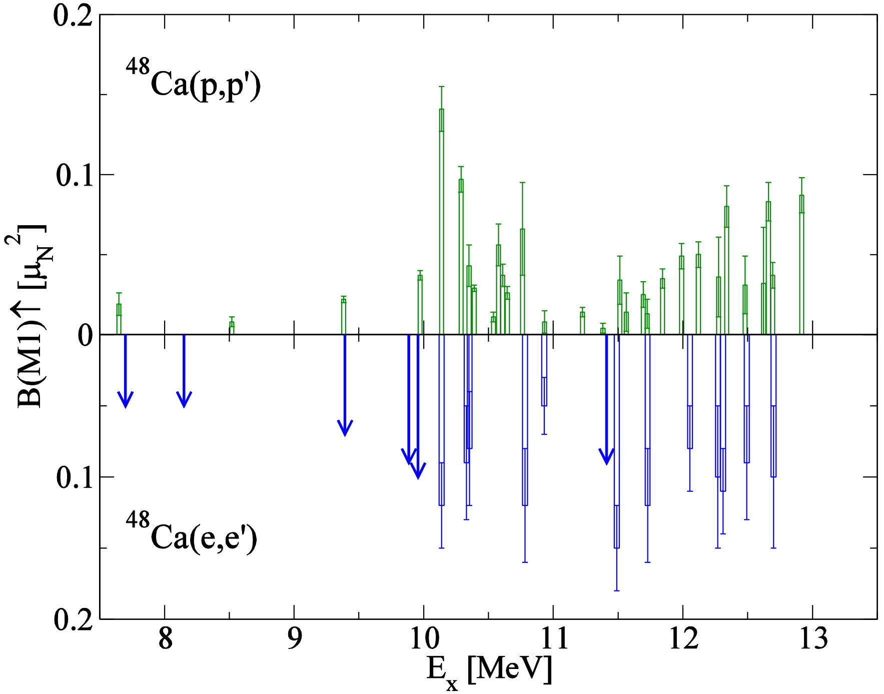
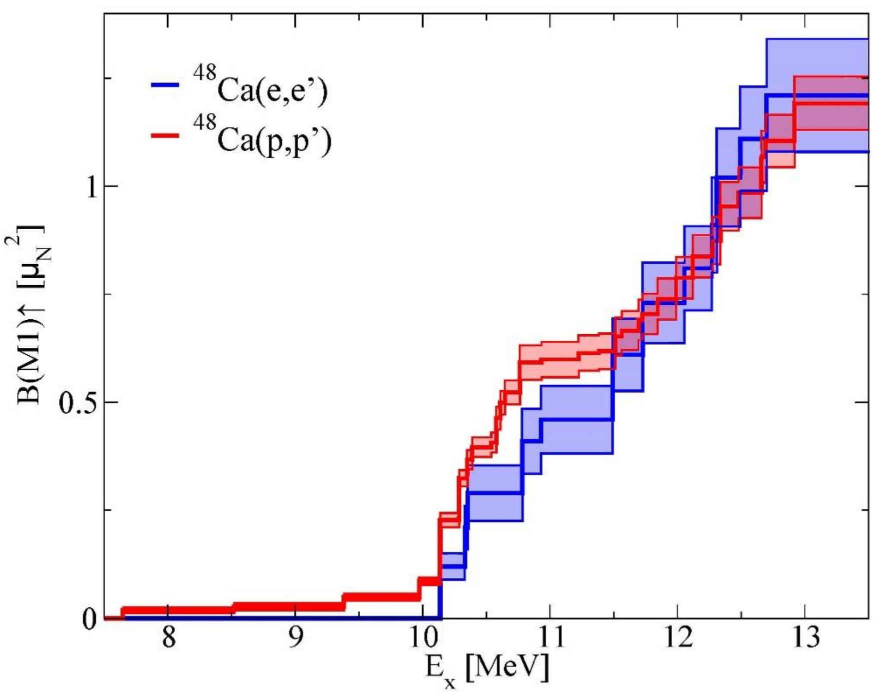


# M1 Strength from (e,e‘) and (p,p‘)

TECHNISCHE UNIVERSITÄT DARMSTADT

M. Mathy et al., Phys. Rev. C, in preparation



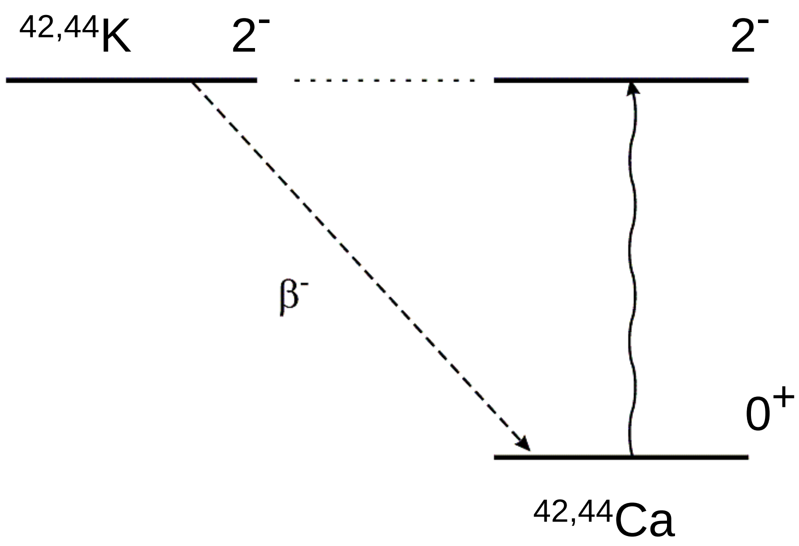



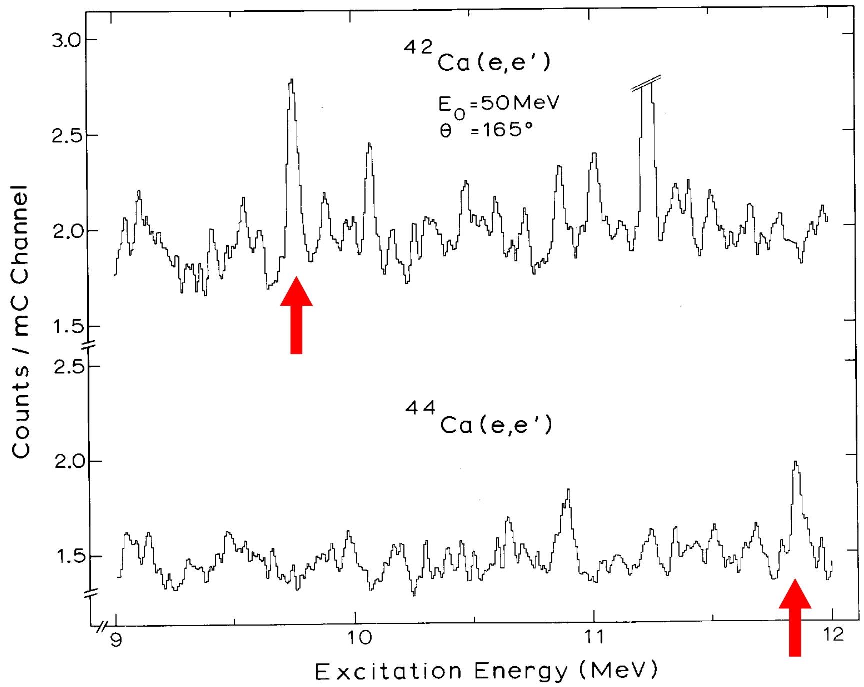

Strength from (p,p‘) and (e,e‘) comparable for non-quenched isoscalar part

# Relation between Spin-M2 and First-Forbidden Matrix Elements



C. Rangacharyulu et al., Phys. Lett. B 135, 29 (1984)




Orbital matrix elements are zero within error bars

# 180° Experiments

- Systematic study of analog transitions to forbidden decay in light nuclei
  - M2 (first forbidden): $^{16}O$, $^{42,44}Ca$
  - M3 (second forbidden): $^{10}B$, $^{22}Ne$
  - M4 (third forbidden): $^{40}Ar$, $^{40}Ca$

- Momentum transfer dependence of quenching: $^{40,48}Ca$

# Why 180° scattering?

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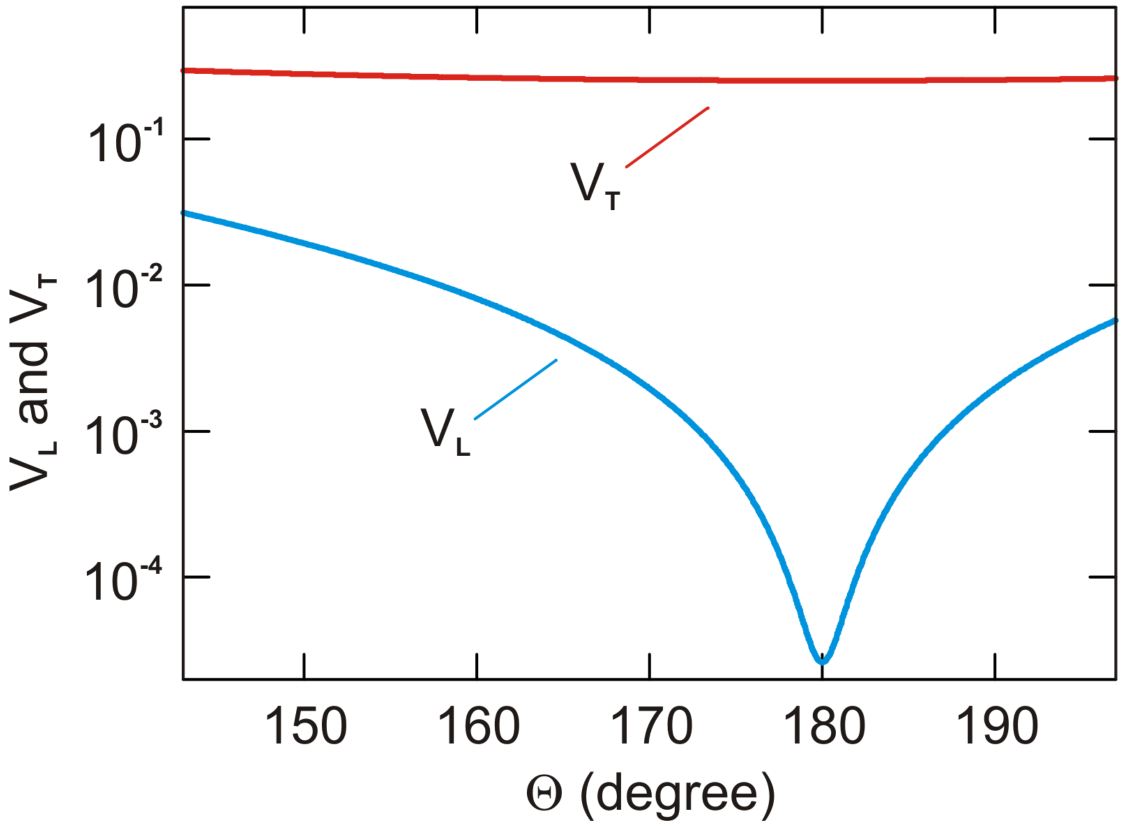
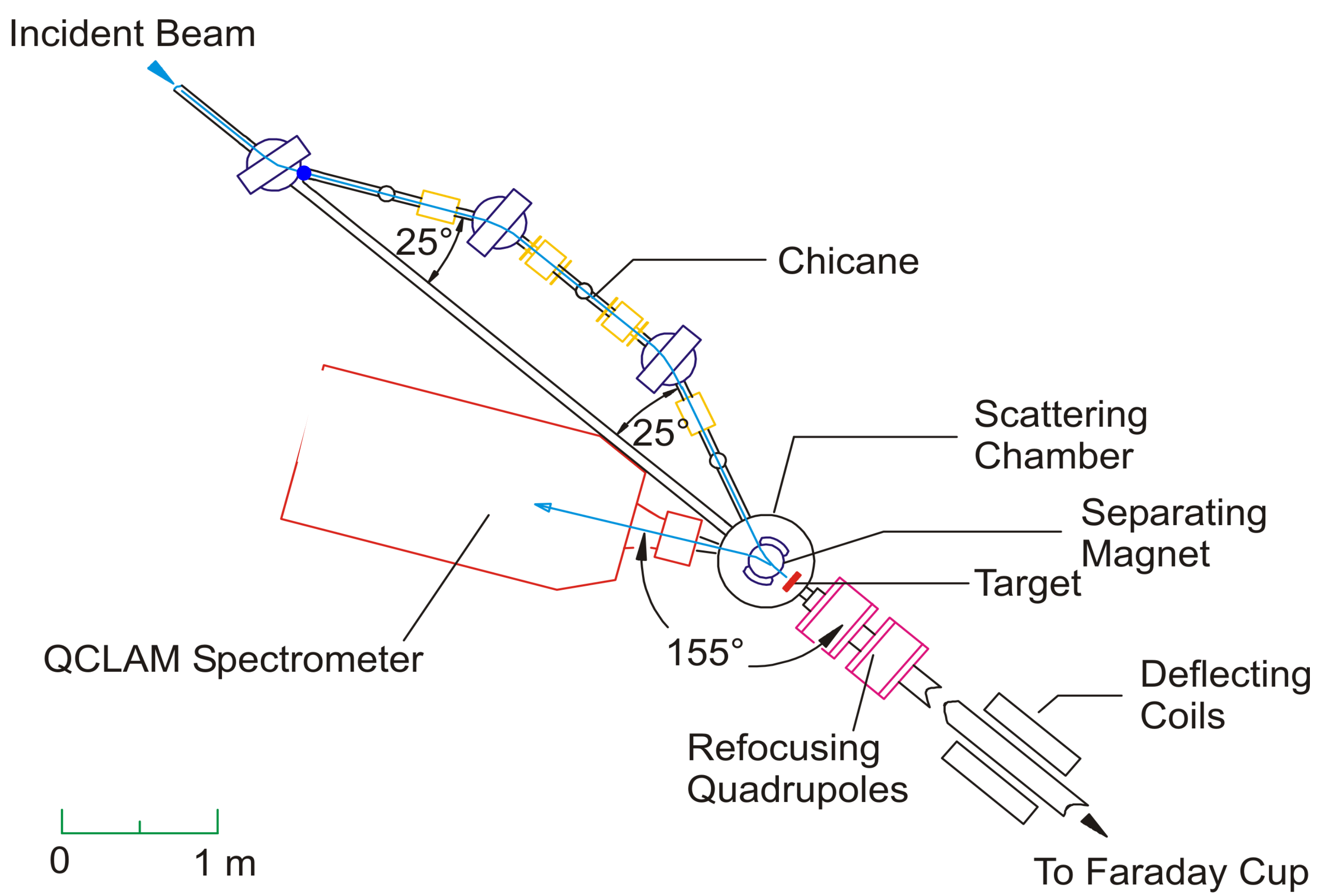
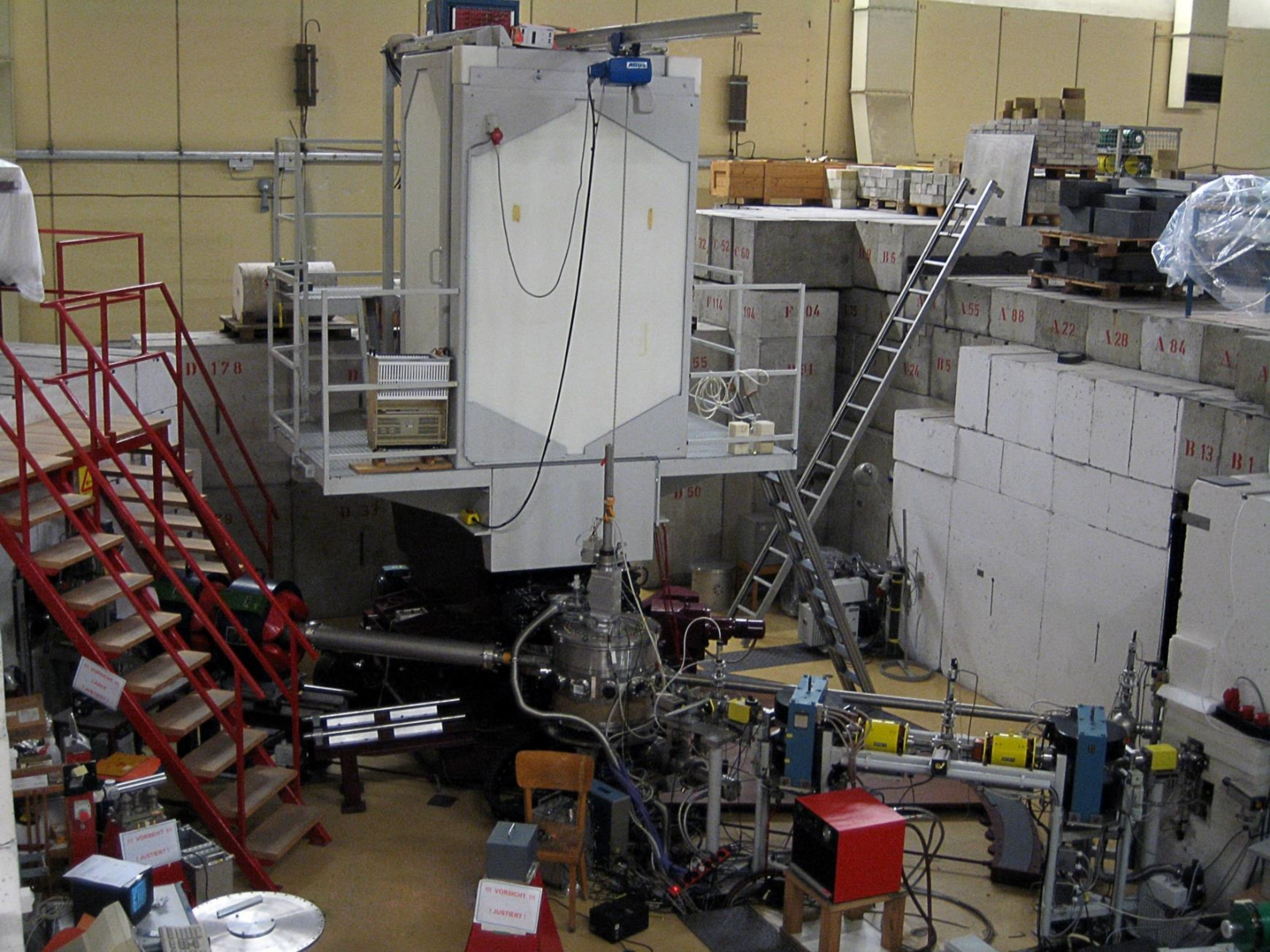



Transverse response enhanced by 3 orders of magnitude!

# 180° System at the S-DALINAC





D 178
F 114
F 04
A 55
A 88
A 22
A 28
A 84
B 13
B 6
C 60
D 50
!!! VORSICHT !!!
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! JUSTIERT !

# Summary and Outlook

- New method for extraction of B(M1) transition strengths from forward-angle proton scattering
- Conflict between previous experimental results for the strong M1 transition in $^{48}$Ca resolved, contribution from weak transitions verified
- Applicability to heavy nuclei demonstrated for $^{208}$Pb
- Future CRC project: Systematic study of quenching in magnetic transitions analogue to forbidden β decay

# Collaborators Project B02

## Spin-M1 resonance:

J. Birkhan, M. Mathy, N. Pietralla, V.Yu. Ponomarev, A. Richter, J. Wambach, *Institut für Kernphysik, TU Darmstadt, Germany*
H. Matsubara, A. Tamii, *RCNP, Osaka, Japan*

## Magnetic analogue of forbidden transitions:

S. Bassauer, A. D'Alessio, J. Enders, M. Hilcker, T. Klaus, C. Kremer, A. Krugmann, Miguel Molero Gonzalez (2/2017), P. Ries, M. Singer, G. Steinhilber, V. Werner

# Quenching of Spin – Isospin Strength

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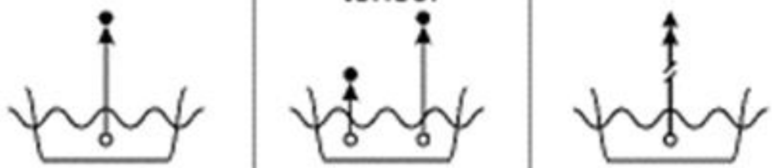
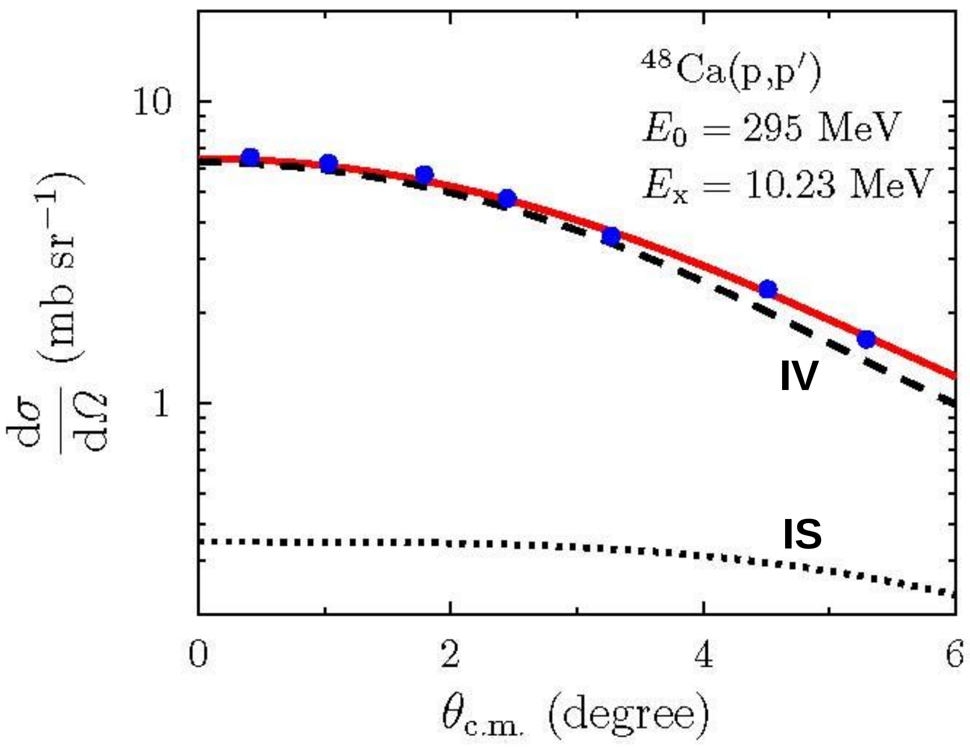
| mechanism / probing field $\vec{\sigma}\cdot\vec{\tau}e^{i\vec{q}\vec{r}}$, $q \to 0$ | highly excited (1p-1h) | configuration mixing (2p-2h); tensor | Δ-admixture ($\Delta$ - $N^{-1}$) |
|---|---|---|---|
| M1 | ≈0 | ≈40% | ≈10% |
| GT | ↓ | ↓ | ↓ |
| M2 | | | |
| M3 | increase | | decrease |
| . | | | |
| . | | | |
| . | | | |
| Mλ (high spin) | ≈10% | ≈40% | |



$\vec{\sigma}\cdot\vec{\tau}$ strength ≈ 50% reduced

# M1 Angular Distribution

- DWBA calculation
  - code DWBA07
  - effective proton-nucleus interaction (Love & Franey)
  - QPM wave functions



# B(M1) Strength from IAS in $^{48}$Sc

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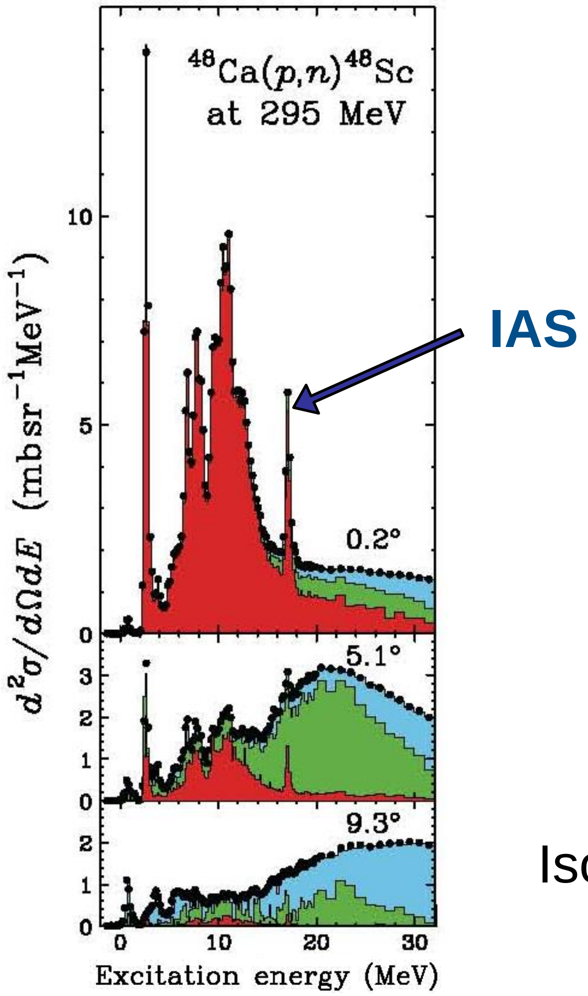
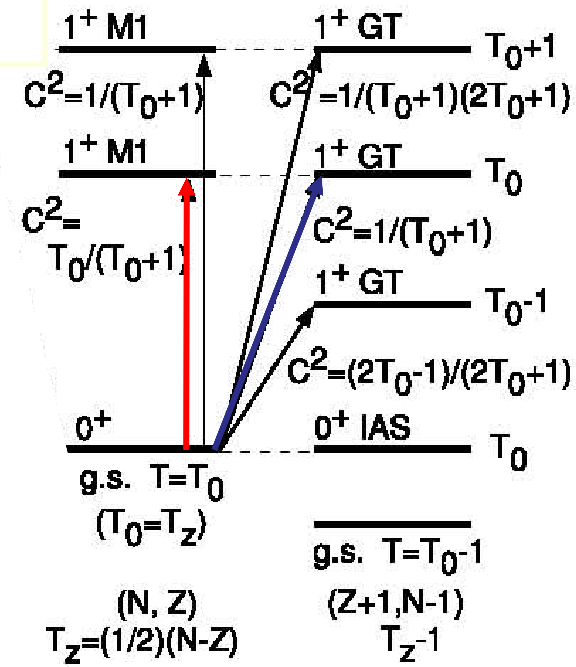
K. Yako et al, Phys. Rev. Lett. 103, 012503 (2009)

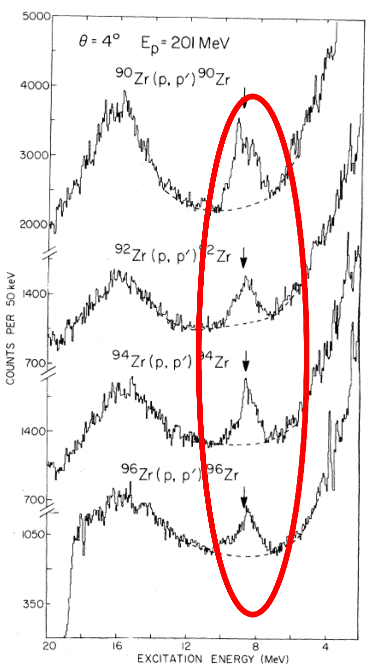



Isospin symmetry: $$B(\mathrm{M1}_{\sigma\tau}) = \frac{1}{2} T_i B(\mathrm{GT}_0)$$

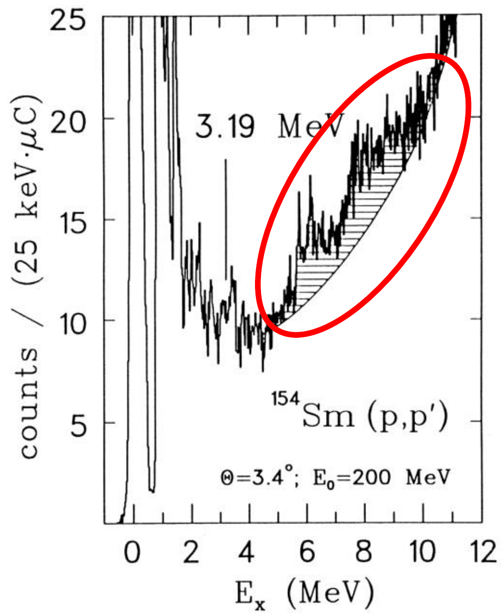
# Spin M1 Strength in Heavy Nuclei from Proton Scattering

**Orsay 1982**



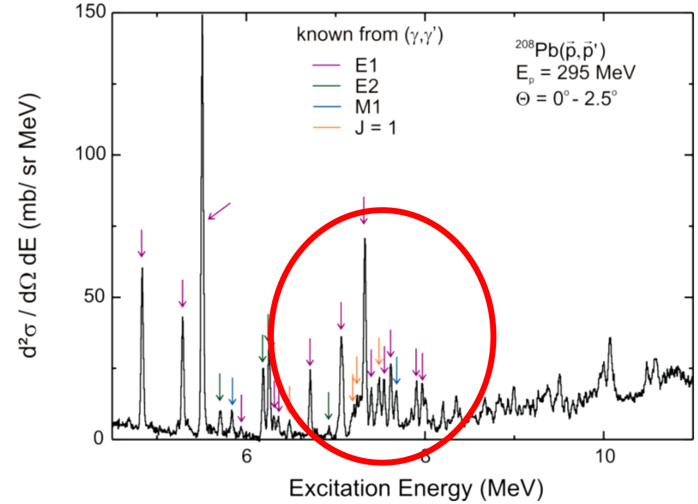

C. Djalali et al., NPA 388, 1 (1982)

**TRIUMF 1990**




D. Frekers et al., PLB 244, 178 (1990)

**RCNP Osaka 2008**

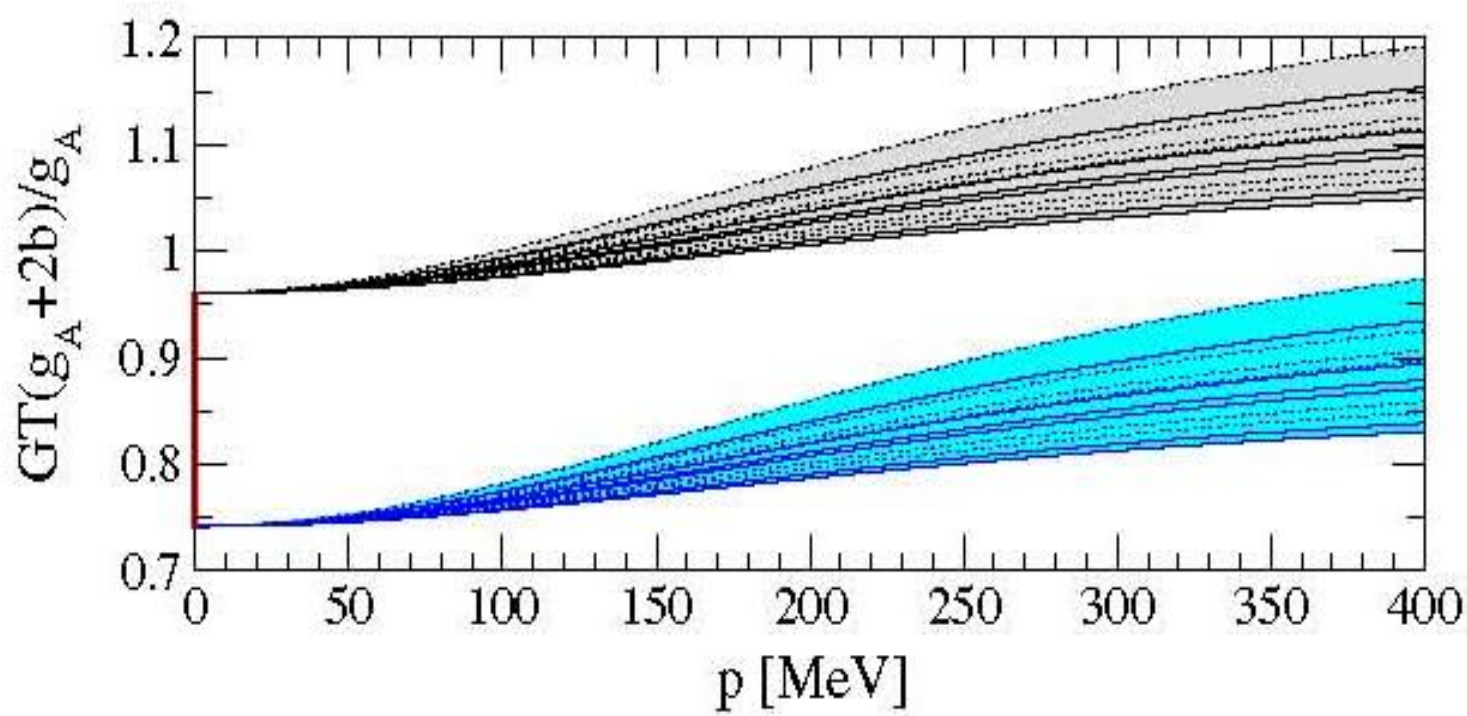



A. Tamii et al., PRL107, 062502 (2011)

- Heavily mixed with E1 strength (Coulomb excitation of PDR)
- Problem: Conversion of cross sections to transition strengths

# Momentum Transfer Dependence of GT Quenching

J. Menéndez, D. Gazit, A. Schwenk, Phys. Rev. Lett 107, 062501 (2011)




- Difficult (if not impossible) to test with hadronic probes
- Test of selected M1 cases with electron scattering
- Two-body currents differ (vector vs. axialvector coupling)