Quenching of the Spin-Isospin Response in Nuclei

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- Quenching of the isovector spin M1 resonance
- Quenching of higher magnetic multipoles - analog transitions to forbidden β decay
- Neutrino response in ^{40}Ar

Supported by DFG under contract SFB 1245

Isovector Spin M1 Resonance

Spinflip M1 Resonance

- Fundamental excitation mode of the nucleus

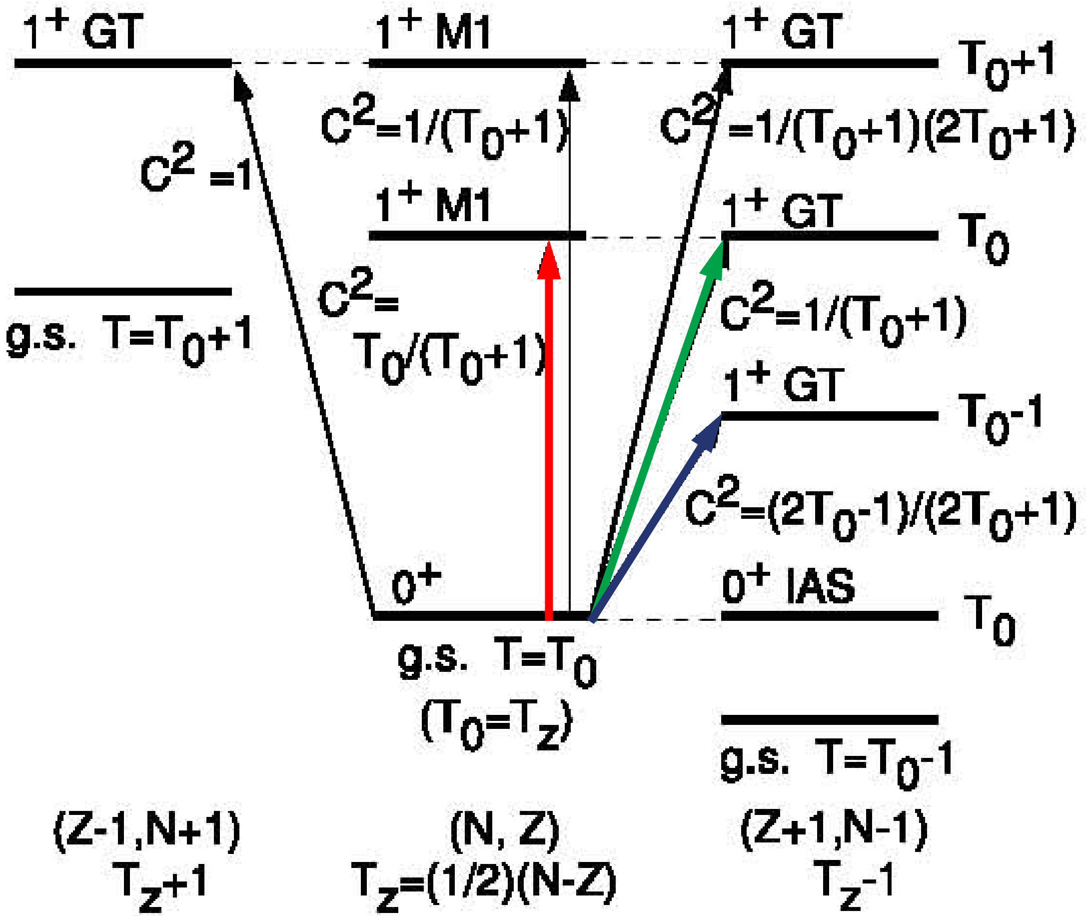
- Analog of Gamow-Teller resonances with $T = T_0$

- 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

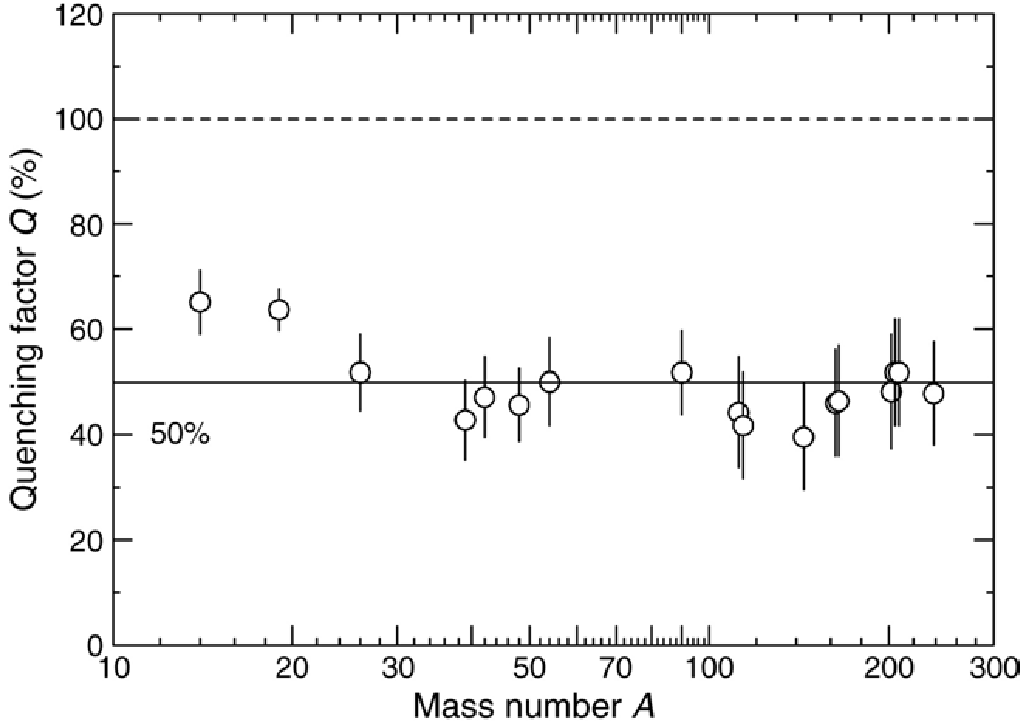
Isospin Symmetry



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

Quenching of GT Strength

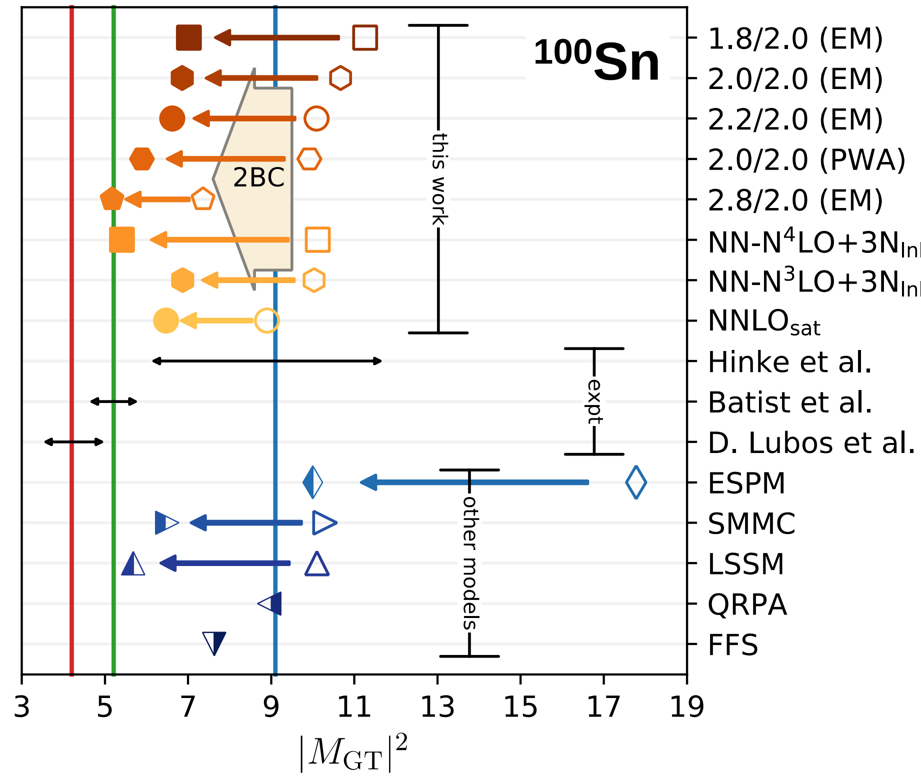
M. Ichimura, H. Sakai, T. Wakasa, Prog. Part. Nucl. Phys. 56, 446 (2006)



- Systematic reduction by a factor of about 2
- Impact on weak interactions (g_A renormalized in nuclei?)
- Same behavior for spin-M1?

Systematic Predictions of Electroweak Processes in Nuclei

- Contributions to quenching
  - Δ resonance
  - many-body correlations
  - meson-exchange currents
- Ab initio calculations promise systematic treatment of electroweak processes
- Two-body currents differ for axial and vector coupling
  → measure relevant observables with electromagnetic probes



P. Gysbers et al., Nature Physics 15, 428 (2019)

Comparison M1/GT Operator

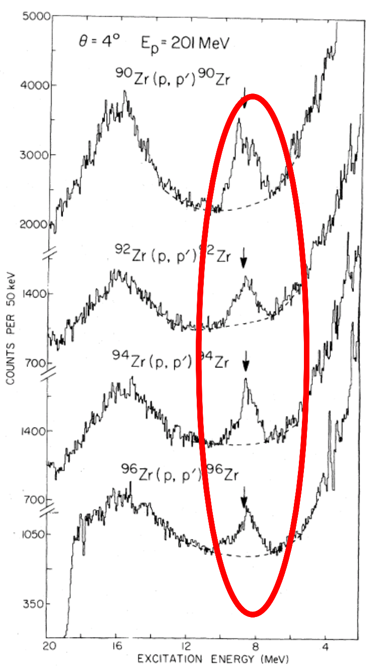
$$T(M1)_{\mathrm{iv}} = \sqrt{\frac{3}{4\pi}} \sum_i [\vec{l}_i \vec{t}_{zi} + (g_s^p - g_s^n) \vec{s}_i \vec{t}_{zi}] \mu_N$$

$$T(GT_0) = 2 \sum_i [\vec{s}_i \vec{t}_{zi}]$$

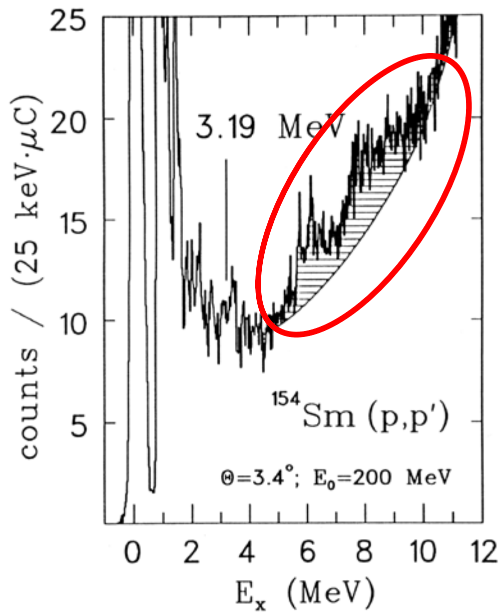
- Spin part dominates because of anomalous magnetic moment
- Isoscalar part weak (but interference)
- Direct measurement of the spin strength with (p,p‘) reaction

Spin M1 Strength in Heavy Nuclei from Proton Scattering

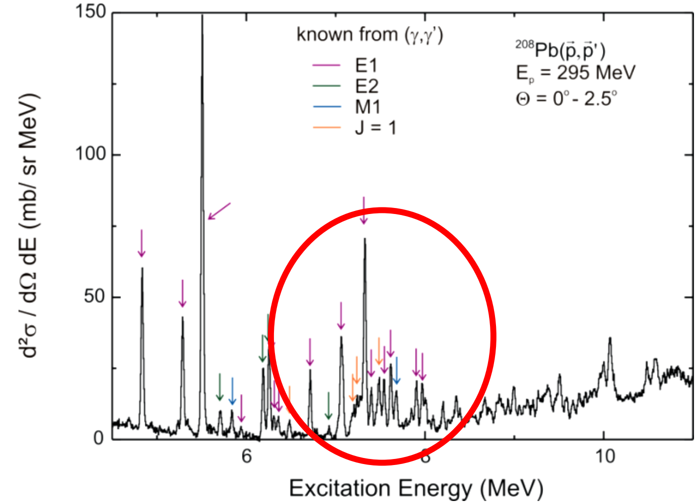
Orsay 1982 | **TRIUMF 1990** | **RCNP Osaka 2006**



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



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



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

- Heavily mixed with E1 strength (Pygmy Dipole Resonance)
- Problem: Conversion of cross sections to transition strengths

Conversion of Cross Section to Transition Strength

- Cross section for GT transitions and B(GT) strength

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

Experimental data extrapolated to 0°

unit cross section

kinematical factor

- For E_p > 100 MeV analogous equation for spin-M1 transitions

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

- Isospin symmetry: $\hat{\sigma}_{M1} \simeq \hat{\sigma}_{GT}$

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)

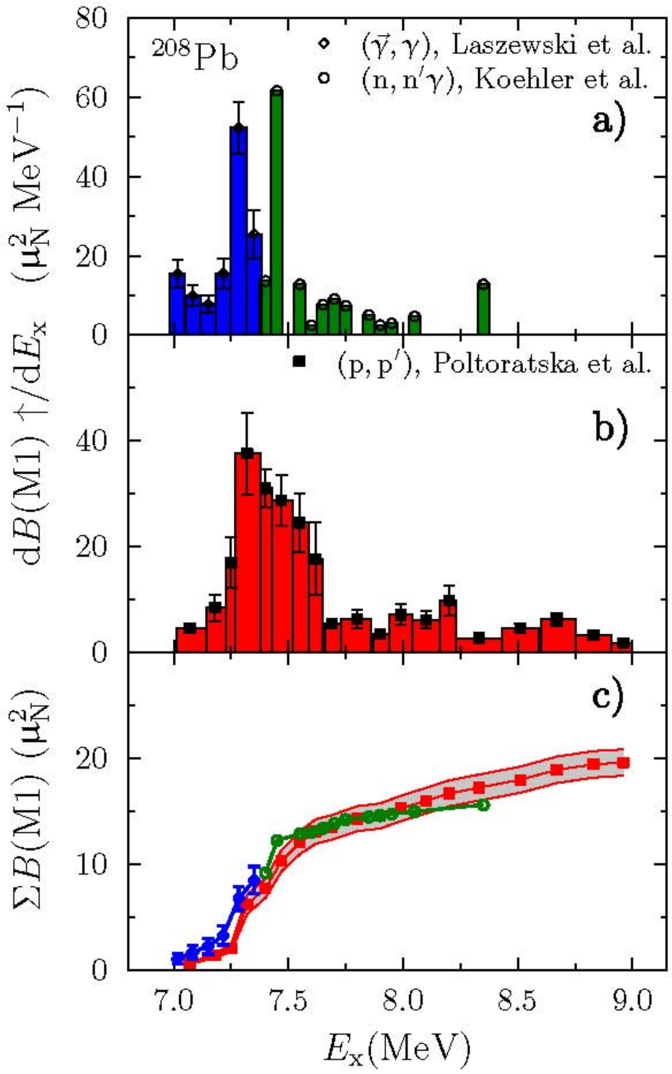
$$\sum B(M1) = 16.0(1.2)\,\mu_N^2$$

for $E_x \leq 8$ MeV

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

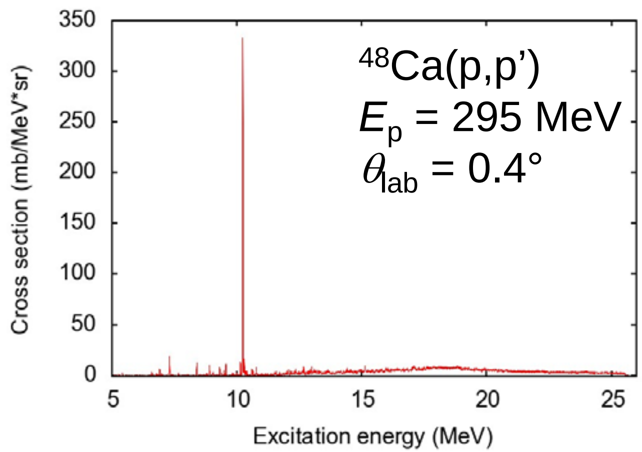
for full resonance

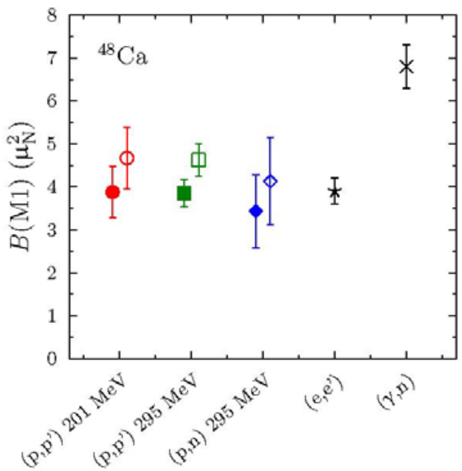
J. Birkhan et al., PRC 93, 041302(R) (2016)



Application to ^{48}Ca

Strong M1 transition

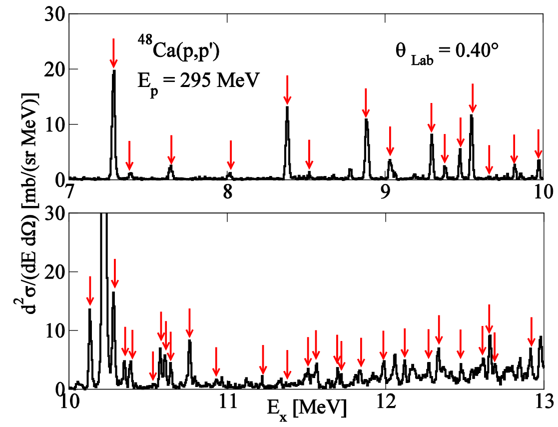


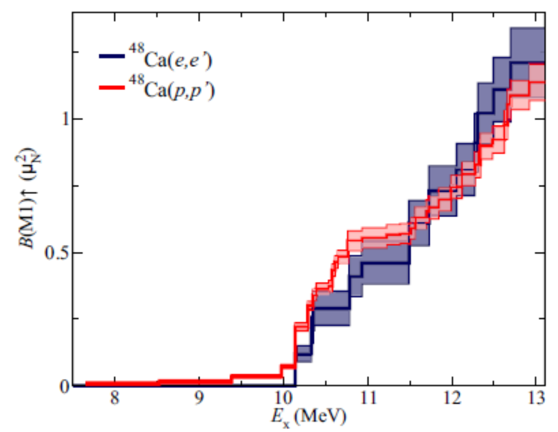


J. Birkhan et al., PRC 93, 041302(R) (2016)

RCNP

Weak M1 transitions

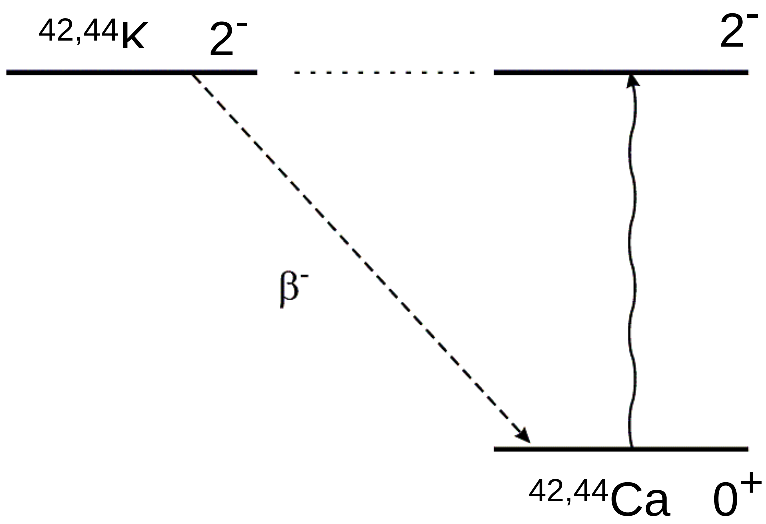


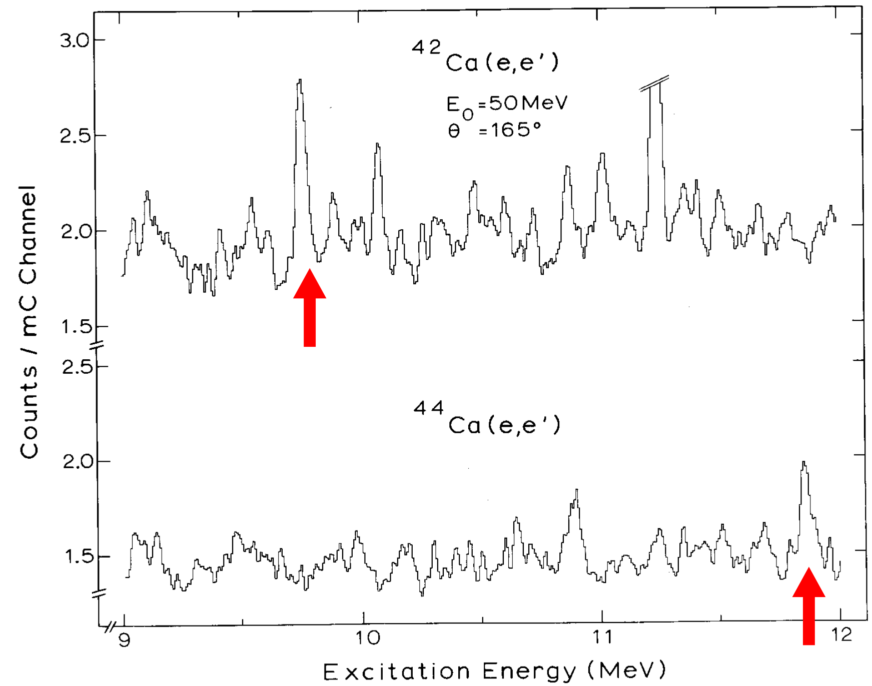


M. Mathy et al., Phys. Rev. C 95, 054316 (2017)

Quenching of Higher Magnetic Multipoles

Analog Transitions to Forbidden β-Decay





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

- Study analog transitions with 180° electron scattering
- Cases for M2, M3, M4 in light nuclei

Why 180° scattering?

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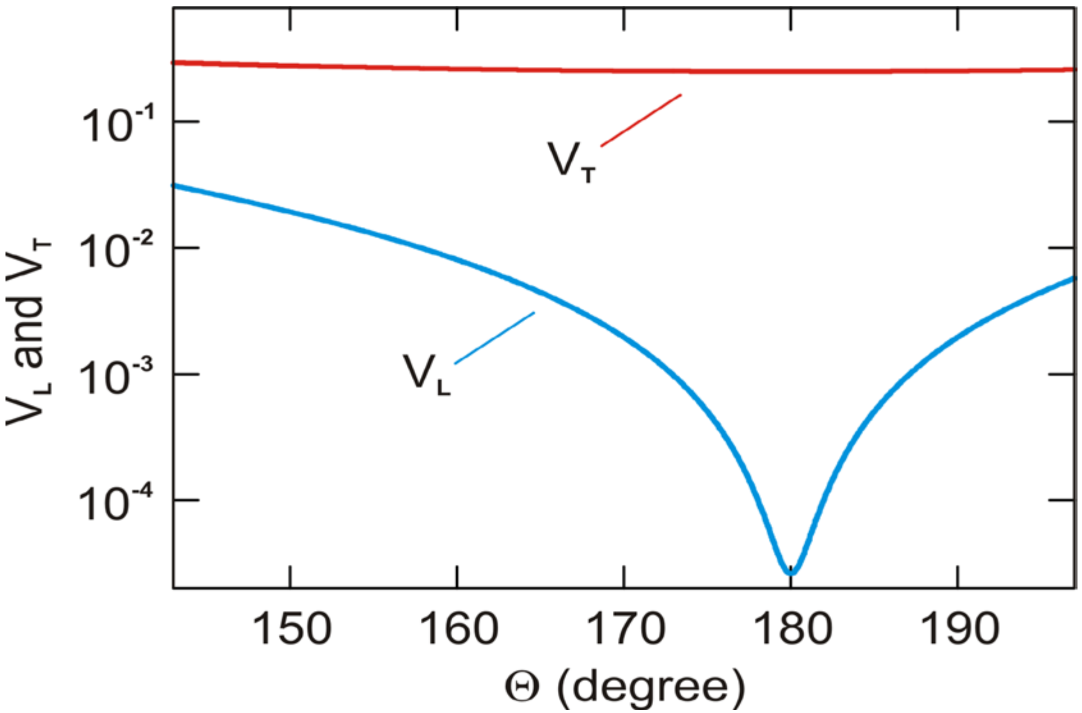
Inclusive (e,e‘) cross sections:

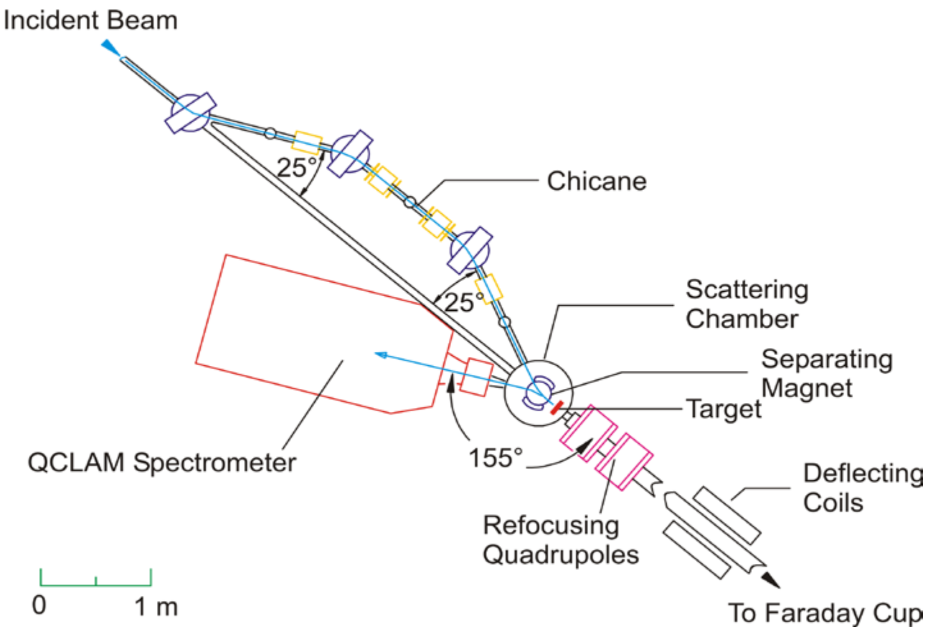
$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_L + \left(\frac{d\sigma}{d\Omega}\right)_T$$

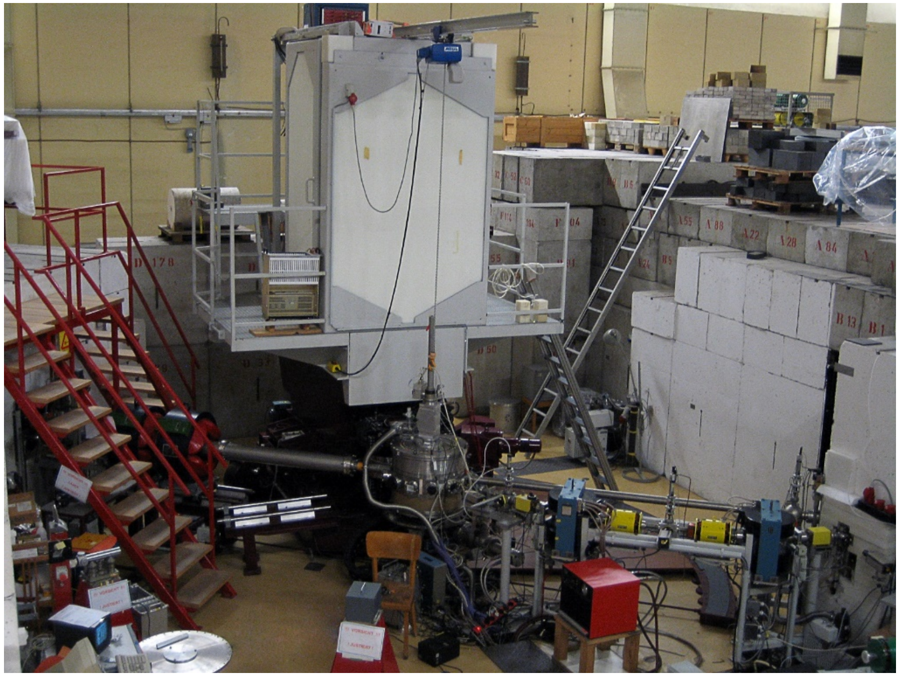
$$V_L \times |F_L(q)|^2 \qquad V_T \times |F_T(q)|^2$$



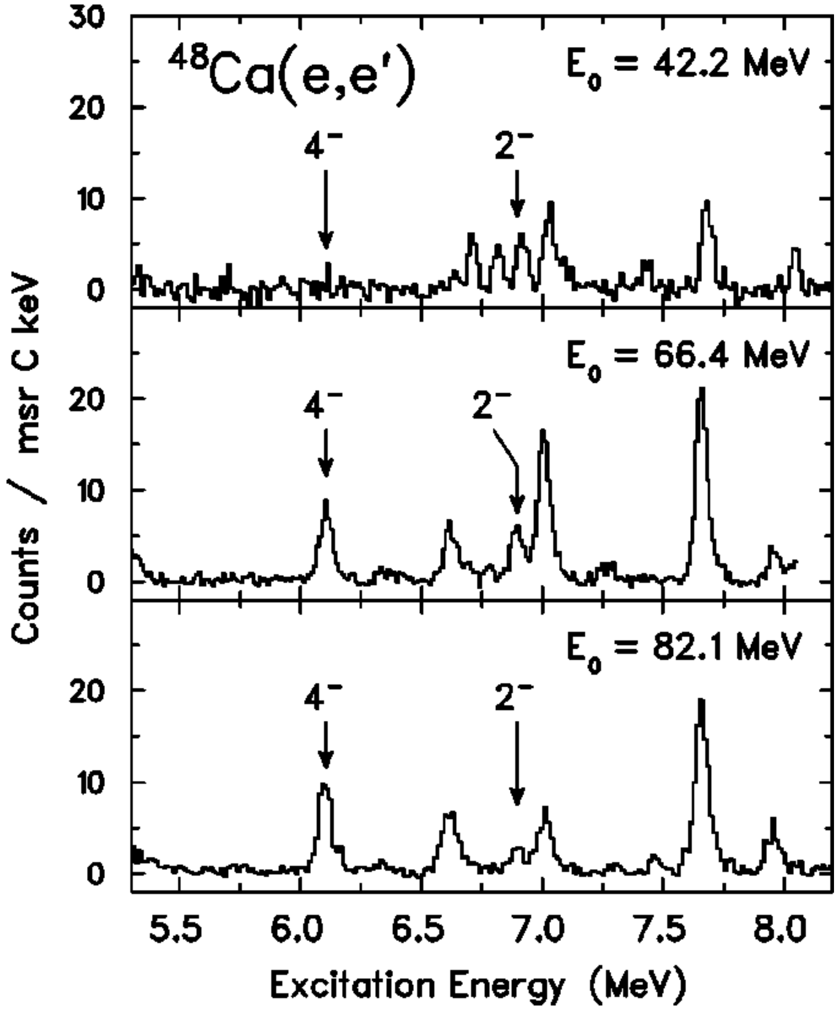
Transverse response enhanced by 3 orders of magnitude!

180° System at the S-DALINAC





Magnetic Transitions in 180° Electron Scattering



PvNC et al., Phys. Rev. C 62, 034307 (2000)

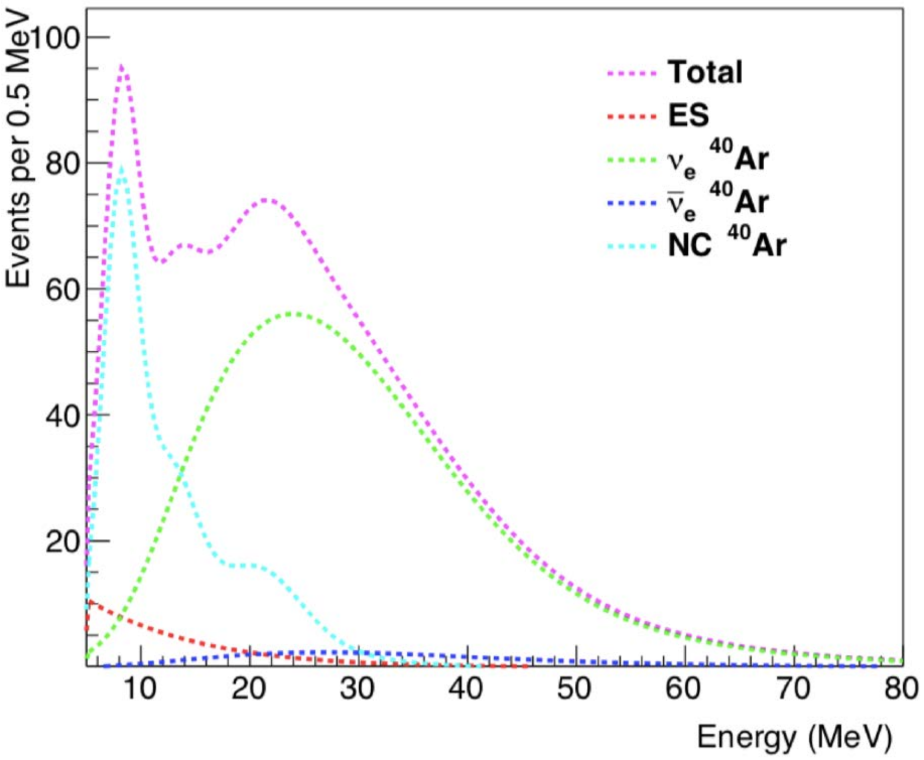
Neutrino Response in ^{40}Ar

Neutrino Detection in Liquid Ar TPCs

- Neutrino response in ^{40}Ar required

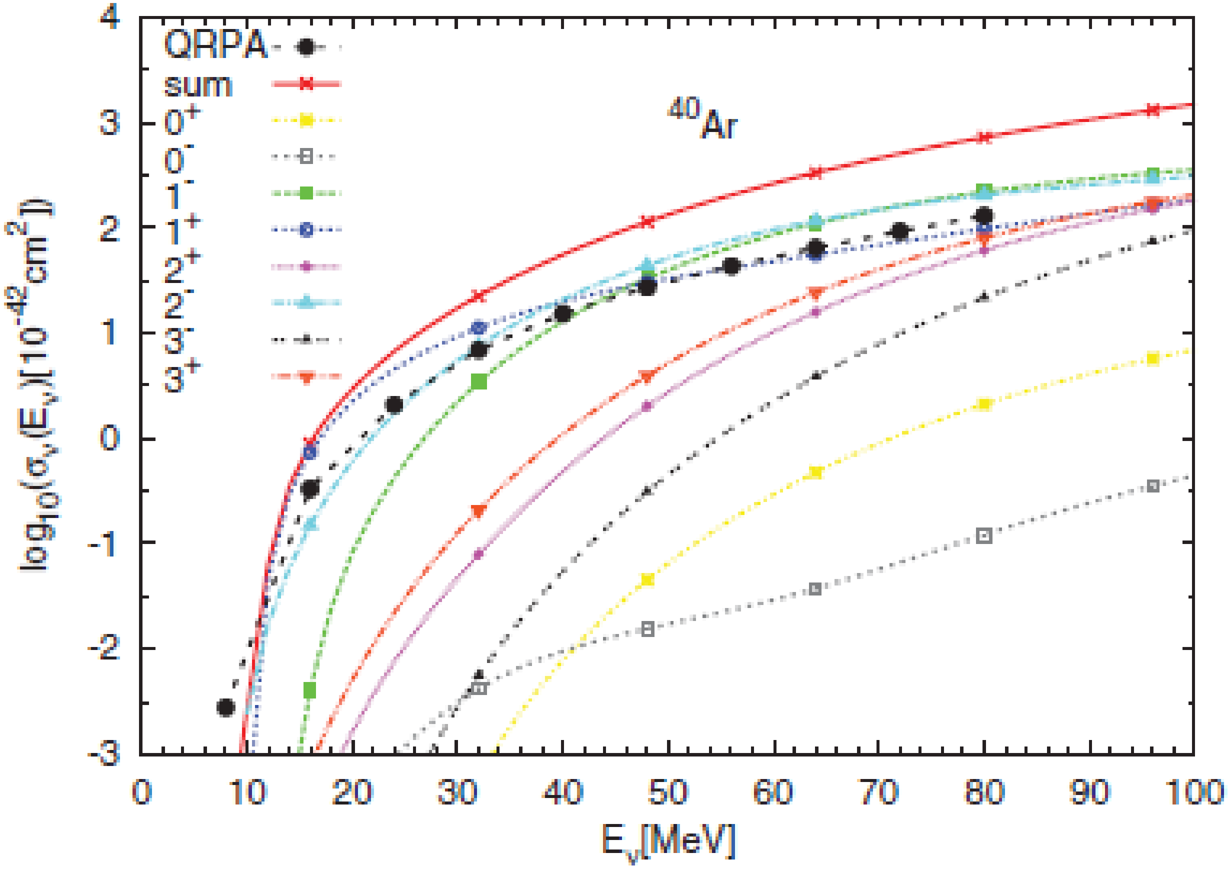
- CC reactions: clear signature
  NC reactions: total ν flux

Response DUNE detector



K. Scholberg, ECT* Workshop (2019)

Predictions of NC Response in ^{40}Ar



M1 dominates

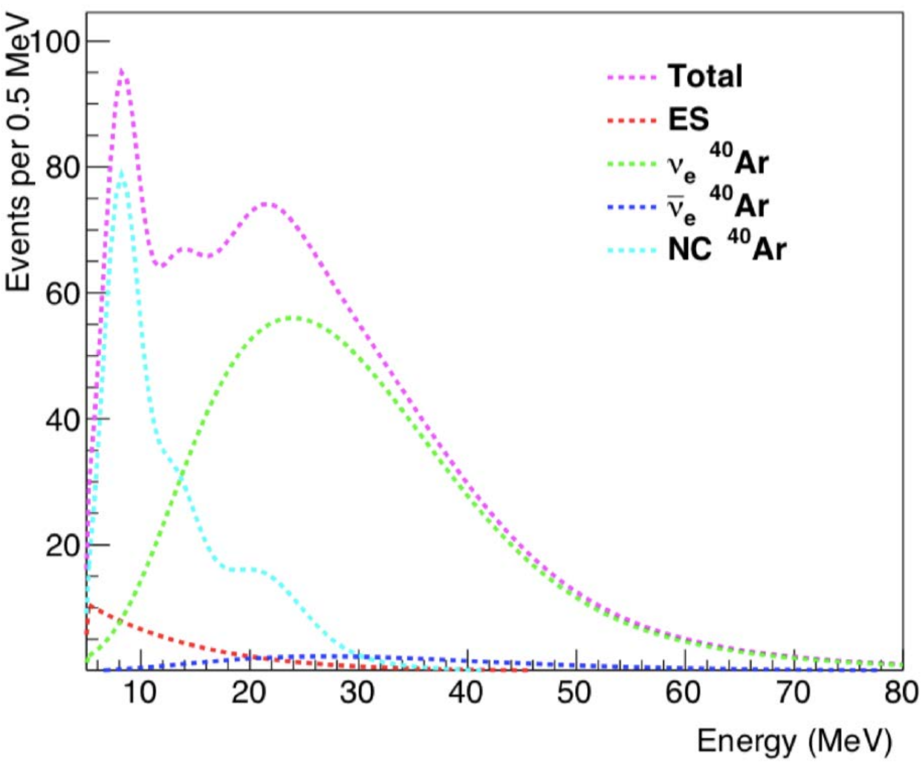
E1 and M2 relevant at higher energies

H. Đapo and N. Paar, Phys. Rev. C 86, 035804 (2012)

Neutrino Detection in Liquid Ar TPCs

- Neutrino response in ^{40}Ar required
- CC reactions: clear signature
  NC reactions: total ν flux
- Combined experimental effort
  - (γ, γ') at HIγS M1
    U. Gayer et al., Phys. Rev. C 100, 034305 (2019)
  - (p, p') at iThemba LABS Spin-M1 E1
  - (e, e') at S-DALINAC M1 M2
  - $(e, e'\gamma)$ at S-DALINAC γ Multiplicity

Response DUNE detector



K. Scholberg, ECT* Workshop (2019)

(e,e'γ) Coincidence Experiments at S-DALINAC

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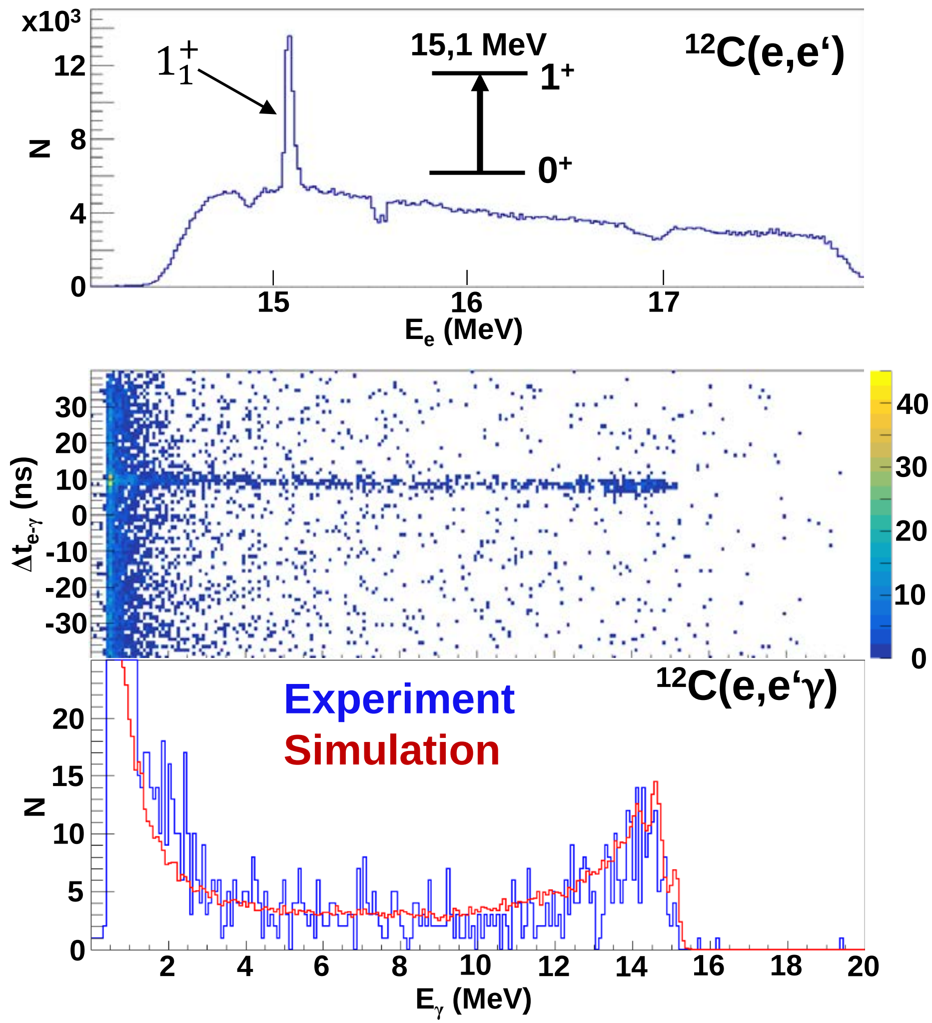
- Proof-of-principle (e,e'γ) experiment at S-DALINAC
  - 3“x3“ LaBr:Ce detectors
  - E_e = 30,5 MeV
  - q = 0,22 fm^{-1}
- Direct γ decay of $1_1^+ \rightarrow$ g.s. in ^{12}C observed

  G. Steinhilber et al., to be published
- Measure γ multiplicity as a function of excitation energy with the ^{40}Ar(e,e'γ) reaction



Summary

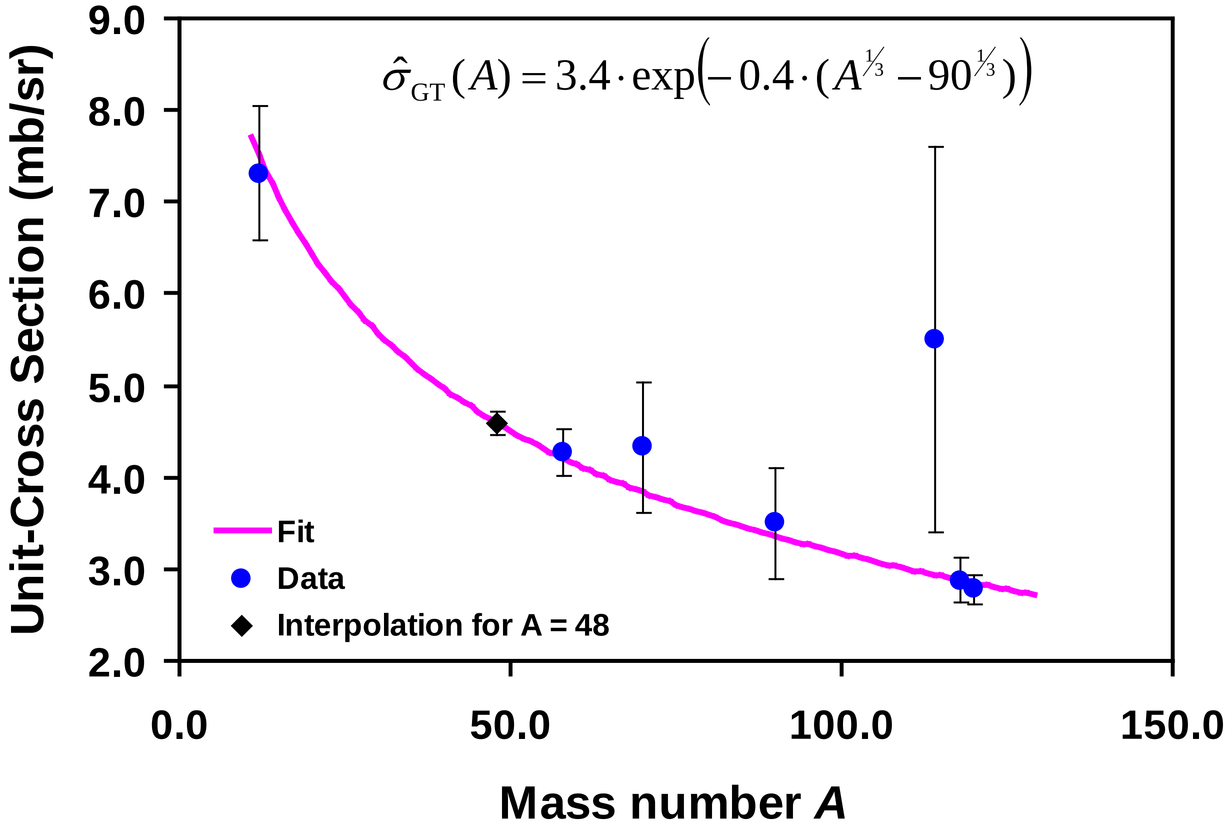
- (p,p') reaction as a new tool to study quenching of the IVSM1 resonance
- Quenching of higher multipoles: investigate transitions analog to forbidden β decay with 180° electron scattering
- Combined effort to measure nuclear response relevant to SN neutrino detection with liquid Ar TPCs

Thank you!

GT Unit Cross Section

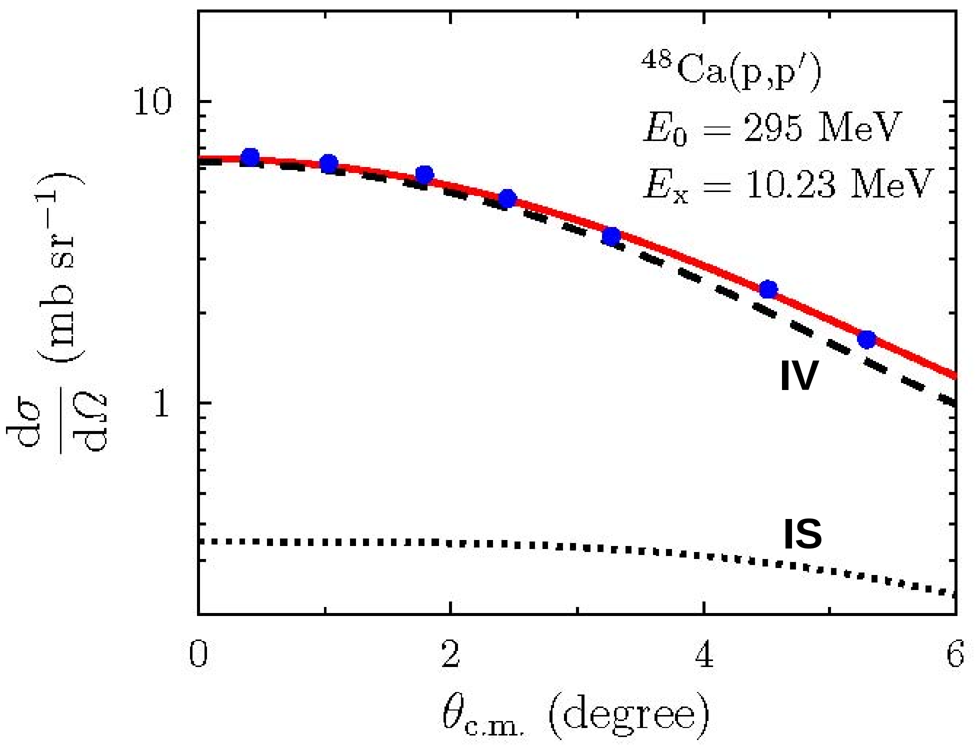
GT unit cross section for (p,n) reaction at 297 MeV

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



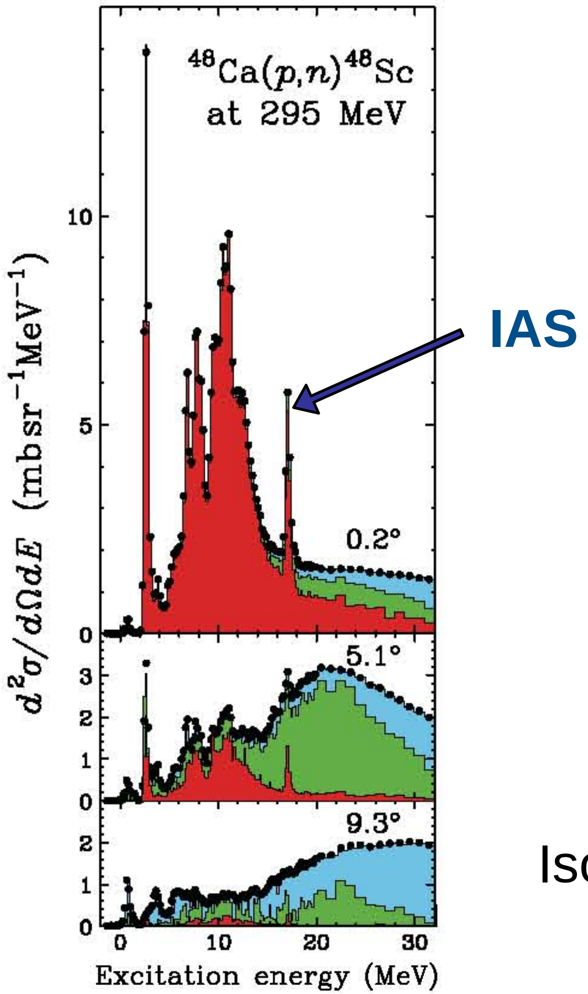
M1 Angular Distribution

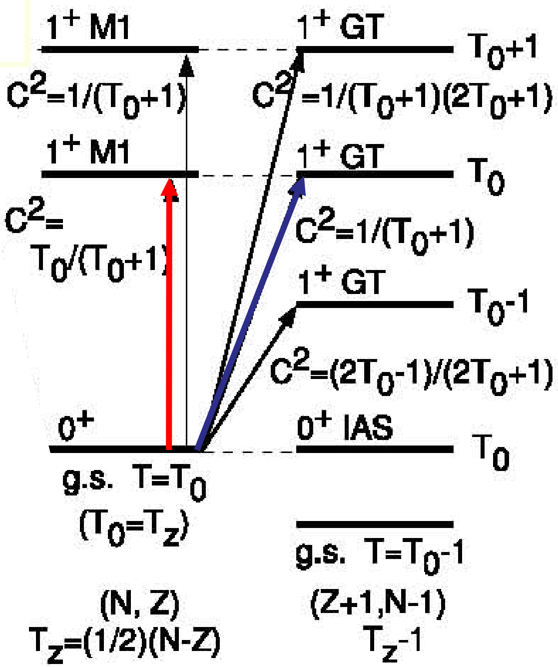
- DWBA calculation
  - code DWBA07
  - effective proton-nucleus interaction (Love & Franey)
  - QPM wave functions



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

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





Isospin symmetry: $B(\mathrm{M1}_{\sigma\tau}) = \frac{1}{2} T_i B(\mathrm{G}T_0)$

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

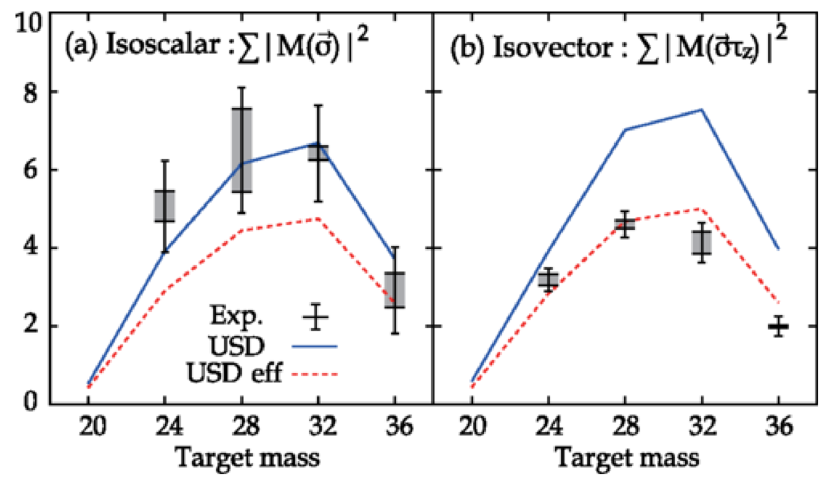
$$B(\mathrm{M1}) = \frac{3}{4\pi}|\langle f||g_l^{\mathrm{IS}}\vec{l} + \frac{g_s^{\mathrm{IS}}}{2}\vec{\sigma} - (g_l^{\mathrm{IV}}\vec{l} + \frac{g_s^{\mathrm{IV}}}{2}\vec{\sigma})\tau_0||i\rangle|^2\,\mu_{\mathrm{N}}^2$$

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

Two extremes:

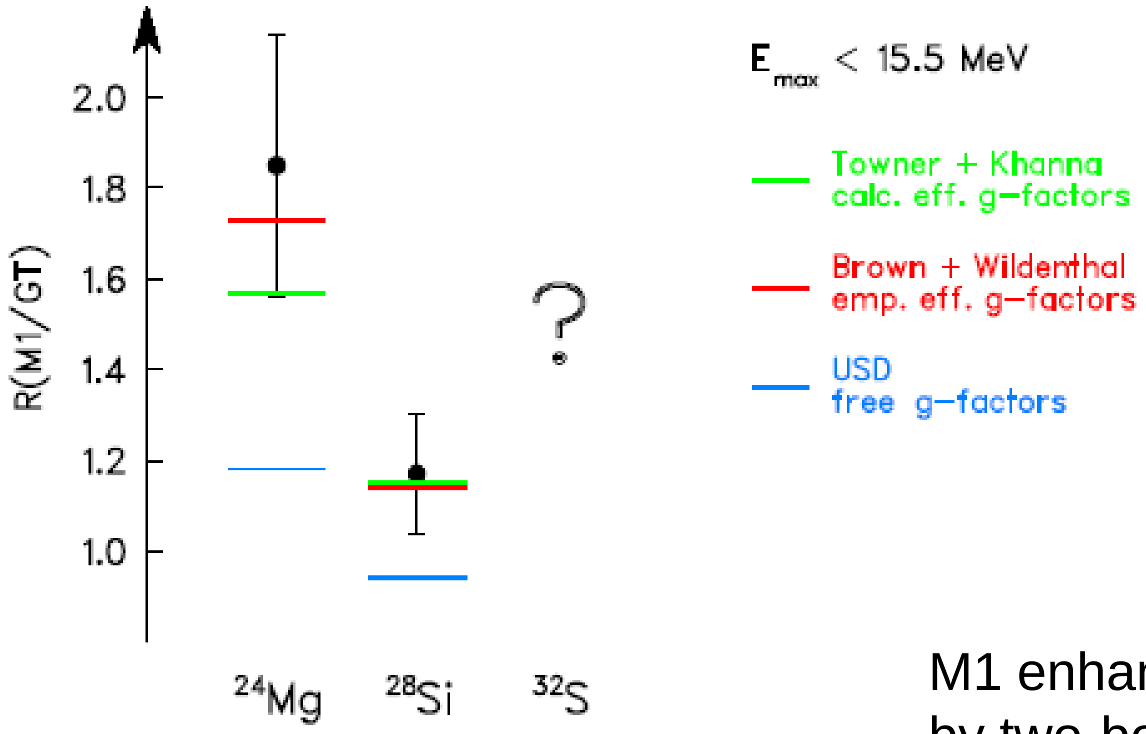
- Assume the same quenching factors
- Assume no IS quenching

H. Matsubara et al.,
PRL 115, 102501 (2015)



Quenching in sd-Shell Nuclei

A. Richter et al., Phys. Rev. Lett. 65, 2519 (1990)
P. von Neumann-Cosel et al., Phys. Rev. C 55, 532 (1997)



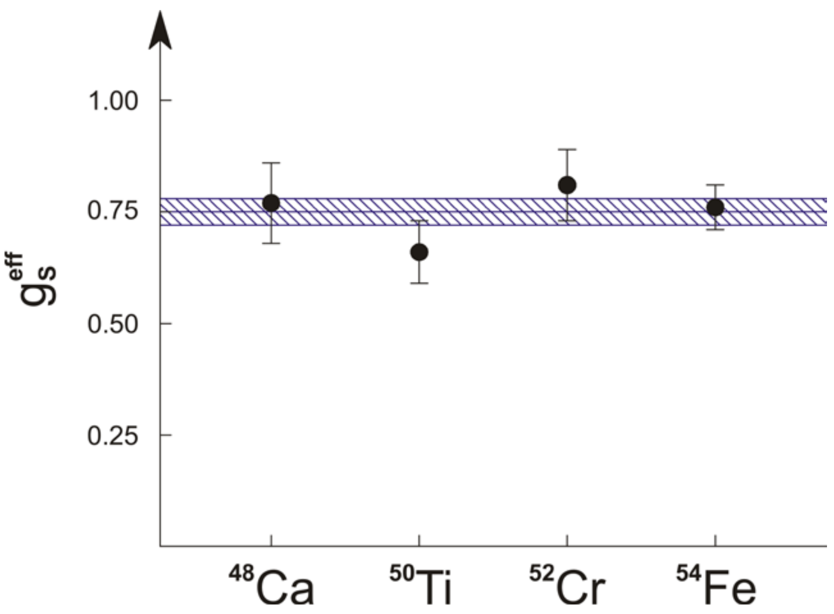
M1 enhanced over GT
by two-body currents

Quenching in fp-Shell Nuclei

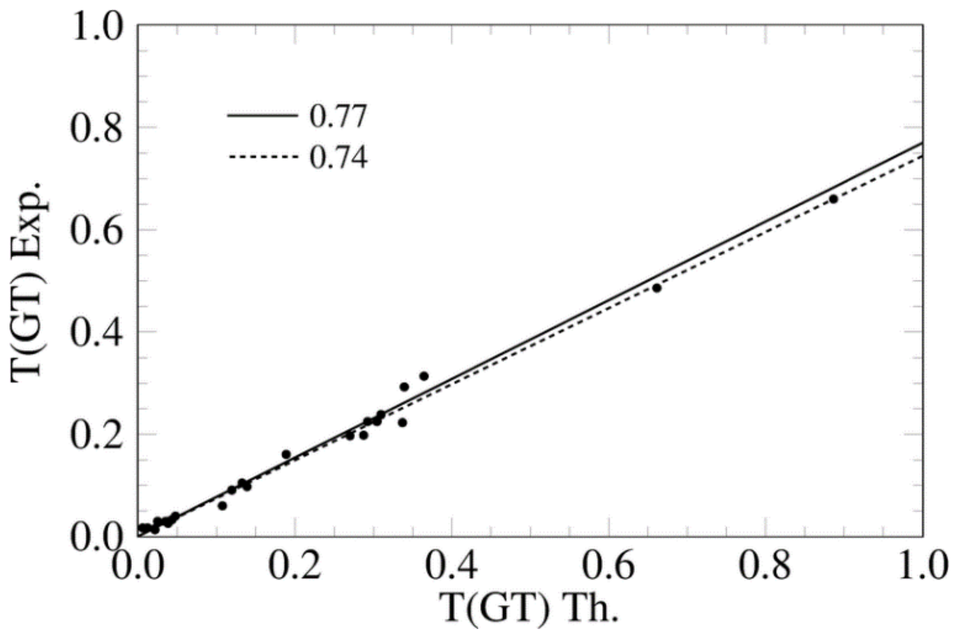
PvNC et al., Phys. Lett. B 443, 1 (1998)

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

M1



GT



Analog transitions to forbidden beta decay

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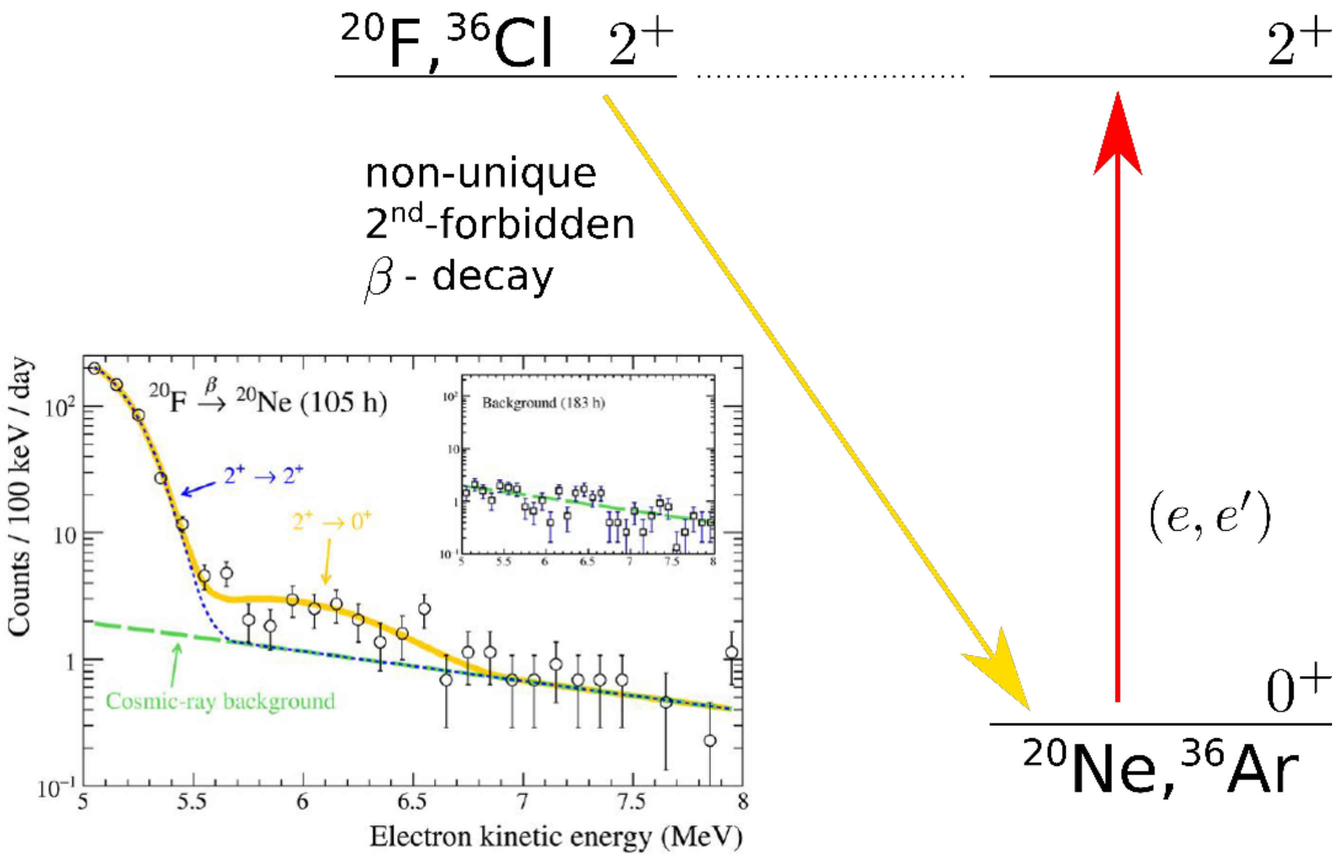
- ^{20}F, ^{36}Cl: dramatic difference of β decay matrix elements



Kirsebom et al., arXiv:1905.09407

The Case of ^{48}Ca

- 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

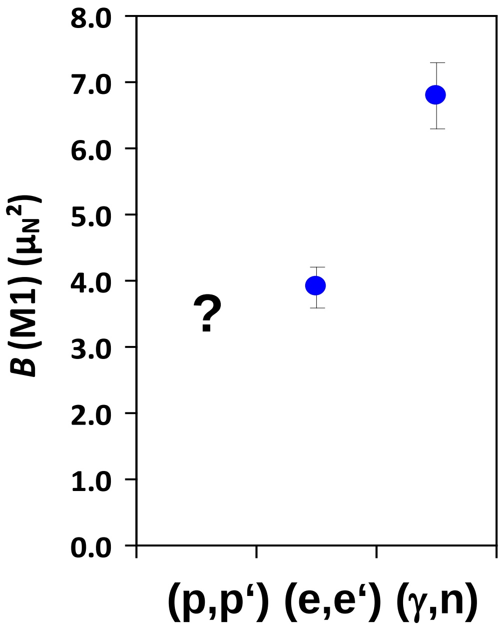
  W. Steffen et al., Nucl. Phys. A 404, 413 (1983)

  $\rightarrow B(M1)\uparrow = (3.9 \pm 0.3)\ \mu_N^2$

- (γ,n) experiment at HIγS)

  J.R. Tompkins et al, Phys. Rev. C 84, 044331 (2011)

  $\rightarrow B(M1)\uparrow = (6.8 \pm 0.5)\ \mu_N^2$



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

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

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