Project B02: Testing and Simulating Electroweak Interactions

TECHNISCHE
UNIVERSITÄT
DARMSTADT

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Peter von Neumann-Cosel, Maxim Singer

- Spectrometer upgrade and new data acquisition
- Isovector spin-M1 response in nuclei
- Plans for next SFB period

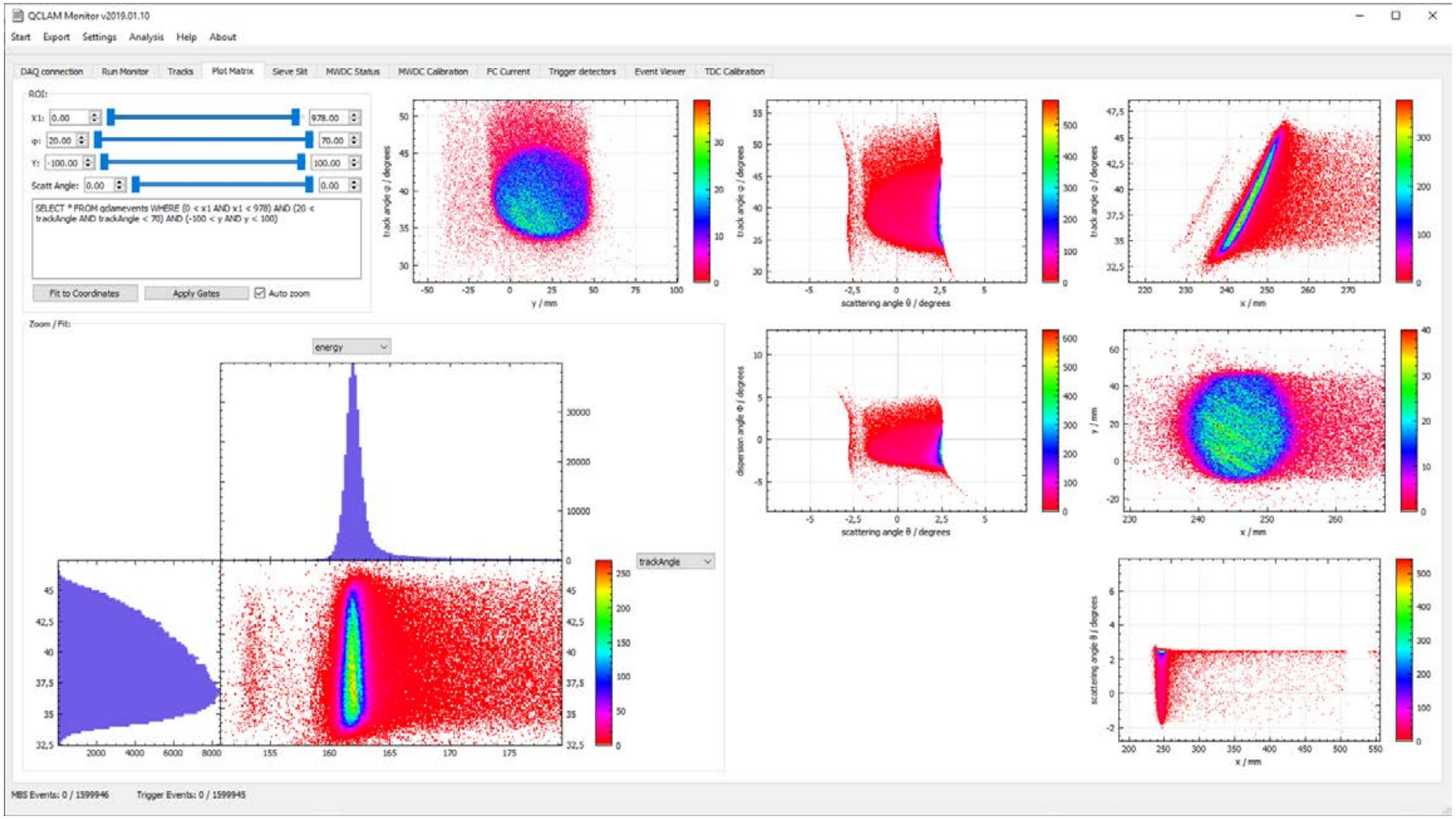
SFB 1245

Spectrometer upgrade and new data acquisition

Spectrometer Upgrade and New DAQ

- Combined effort with projects A01, A03, A07, B03, B04 and ACCELENCE to upgrade spectrometers
- New DAQ at QCLAM Spectrometer (Maxim Singer)
- 180° system (Johann Isaak)
- MSc: Antonio D'Alessio, Andreas Ebert, Michaela Hilcker, Gerhart Steinhilber
- BSc: Marvin Acker, Isabelle Brandherm, Maximilian Spall, Mark Studlek

New Data Acquisition for QCLAM Spectrometer



X1: 0.00 – 978.00

φ: 20.00 – 70.00

Y: -100.00 – 100.00

Scatt Angle: 0.00 – 0.00

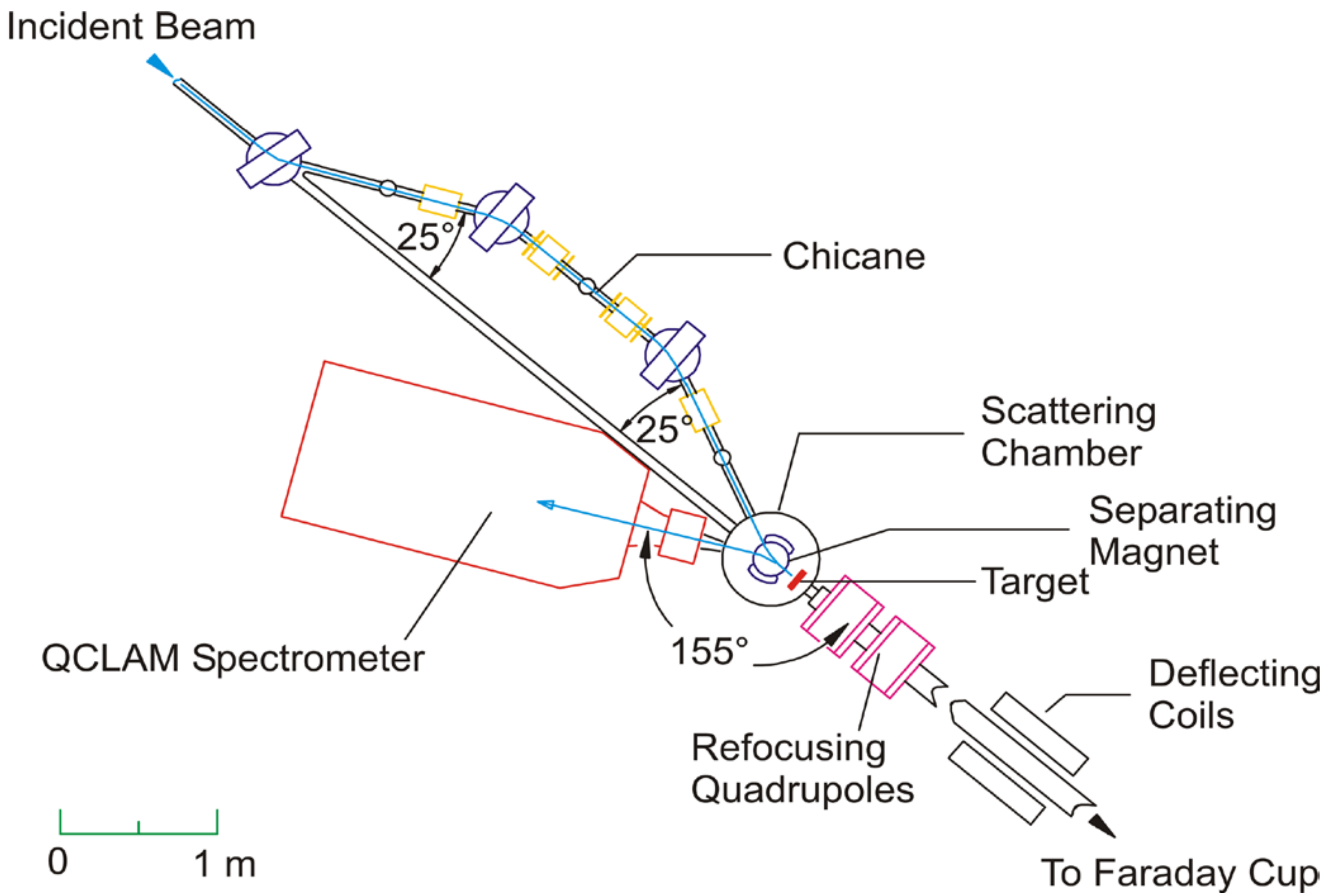
```
SELECT * FROM qclamevents WHERE (0 < x1 AND x1 < 978) AND (20 <
trackAngle AND trackAngle < 70) AND (-100 < y AND y < 100)
```

☑ Auto zoom

MBS Events: 0 / 1599946 Trigger Events: 0 / 1599945

M. Singer et al., in preperation

180° System

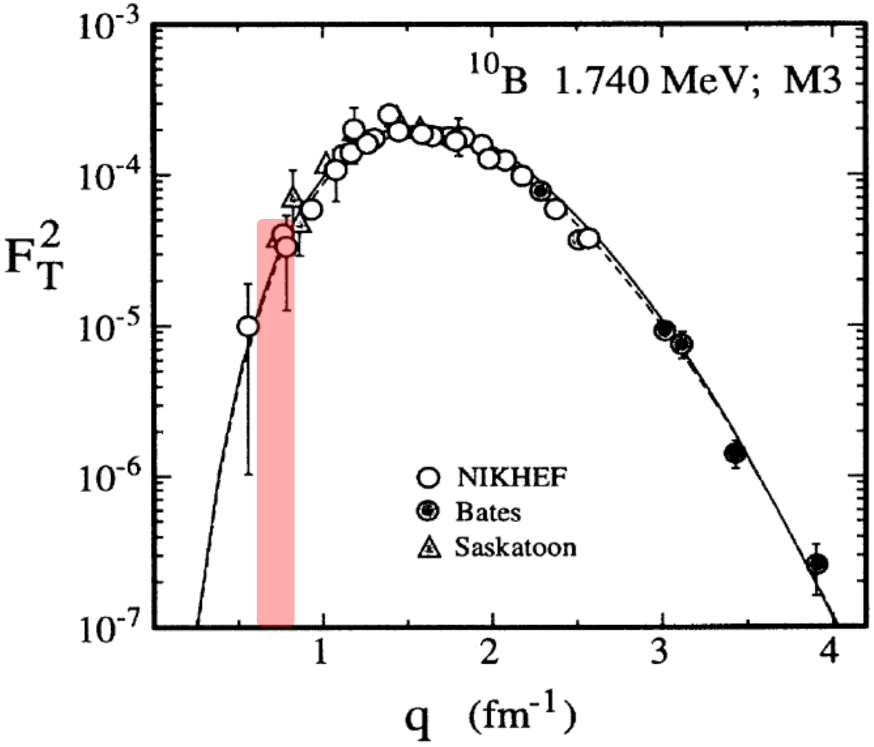

Incident Beam
25°
Chicane
25°
Scattering Chamber
Separating Magnet
Target
QCLAM Spectrometer
155°
Deflecting Coils
Refocusing Quadrupoles
0
1 m
To Faraday Cup

Commissioning Run 2019

- Focal plane calibration for 180° setup

- ^{10}B: $3^+_{g.s.} \rightarrow 0^+_1$
  - analog to second-forbidden β decay of ^{10}Be

- ^{16}O: $0^+_{g.s.} \rightarrow 2^-$
  - analog to first-forbidden β decay of ^{16}N
    E_x = 12.9 MeV
    using Mylar foil as target



A. Cichocki et al., Phys. Rev C 51, 5 (1995).

Isovector spin M1 response in nuclei

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

Quenching of Spin-M1 and GT Strength

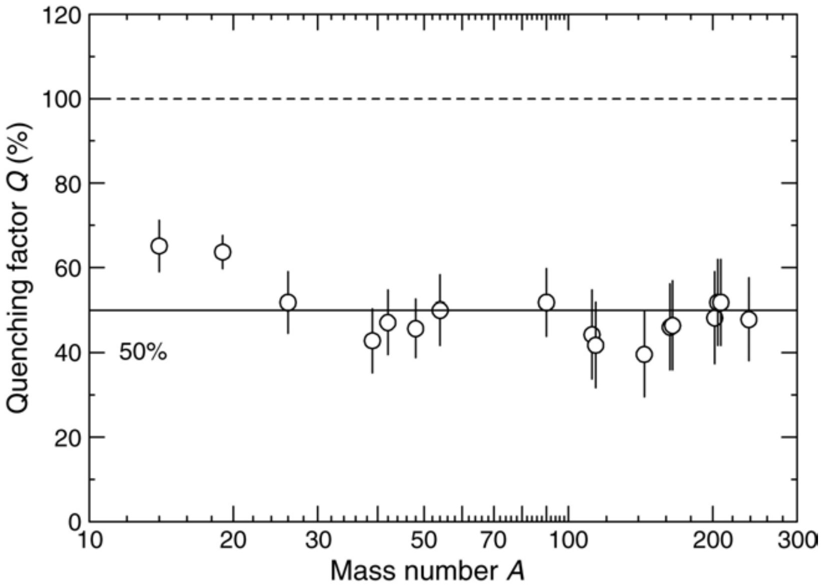
- What is meant by quenching?
- M1 or GT resonances are valence-shell ($0\,\hbar\omega$) excitations
  → confined in a certain excitation energy region
- Quenching

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

- Quenching affected by many-body correlations and two-body currents

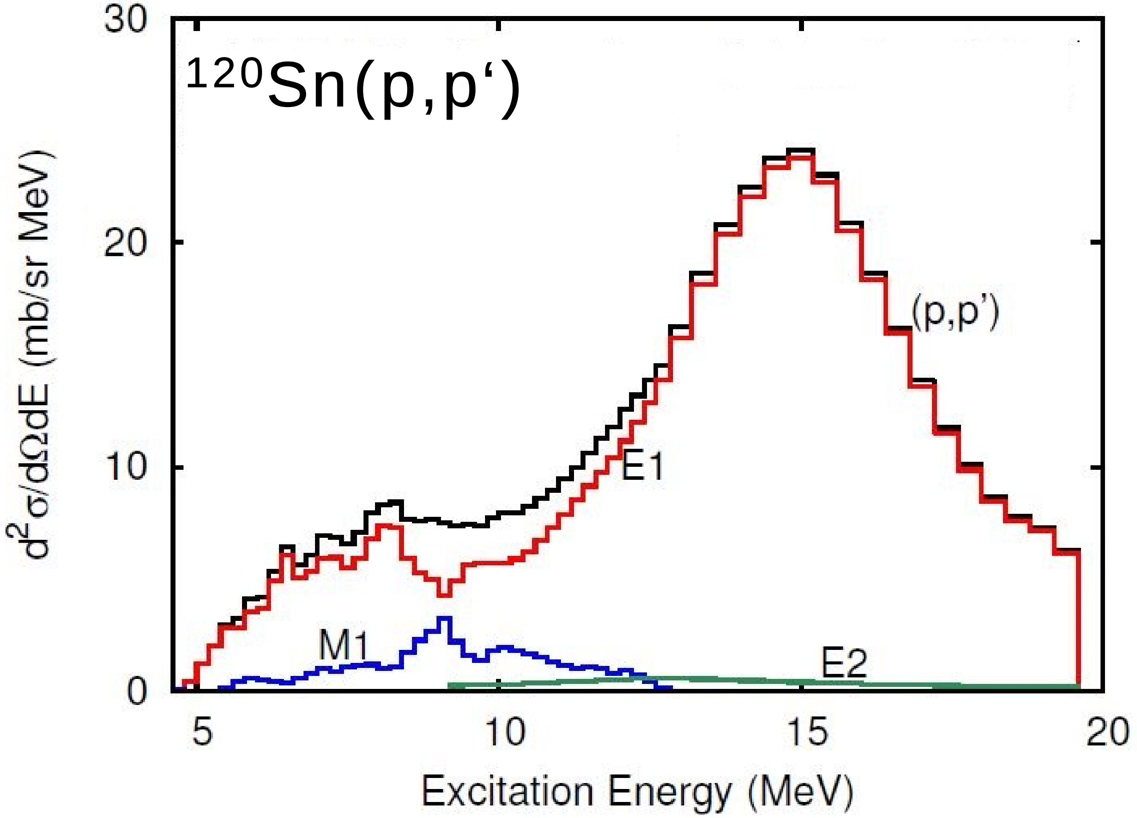
Quenching of GT Strength

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



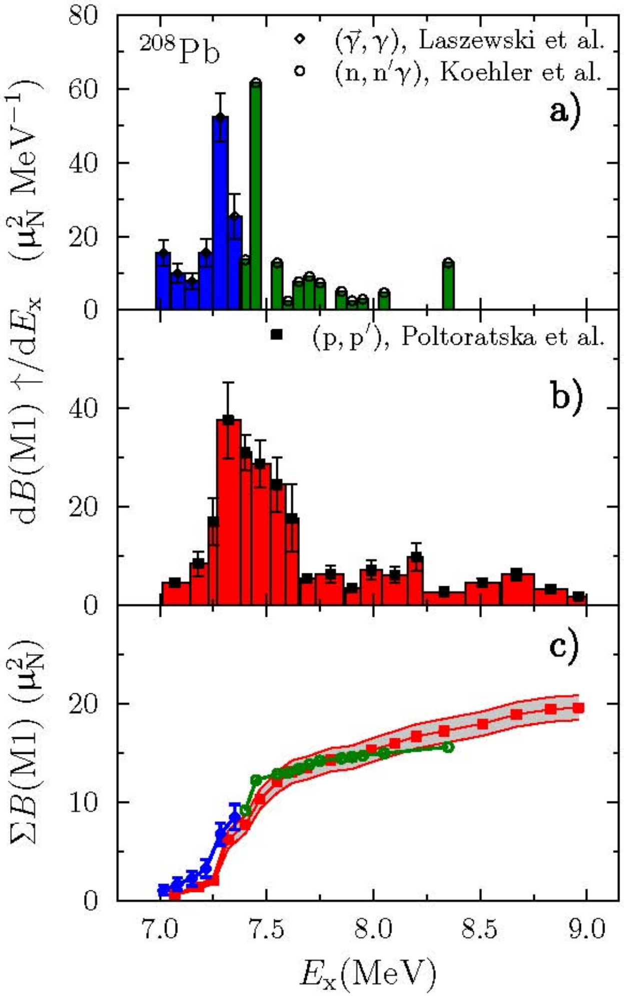
- Systematic reduction by a factor of about two
- Impact on weak interactions (g_A is renormalized in nuclei)
- Same behavior for spin-M1?

Spin-M1 Cross Sections from (p,p´) Experiments at RCNP



Conversion by „unit cross section method" for GT strength using isospin symmety

Application to ^{208}Pb



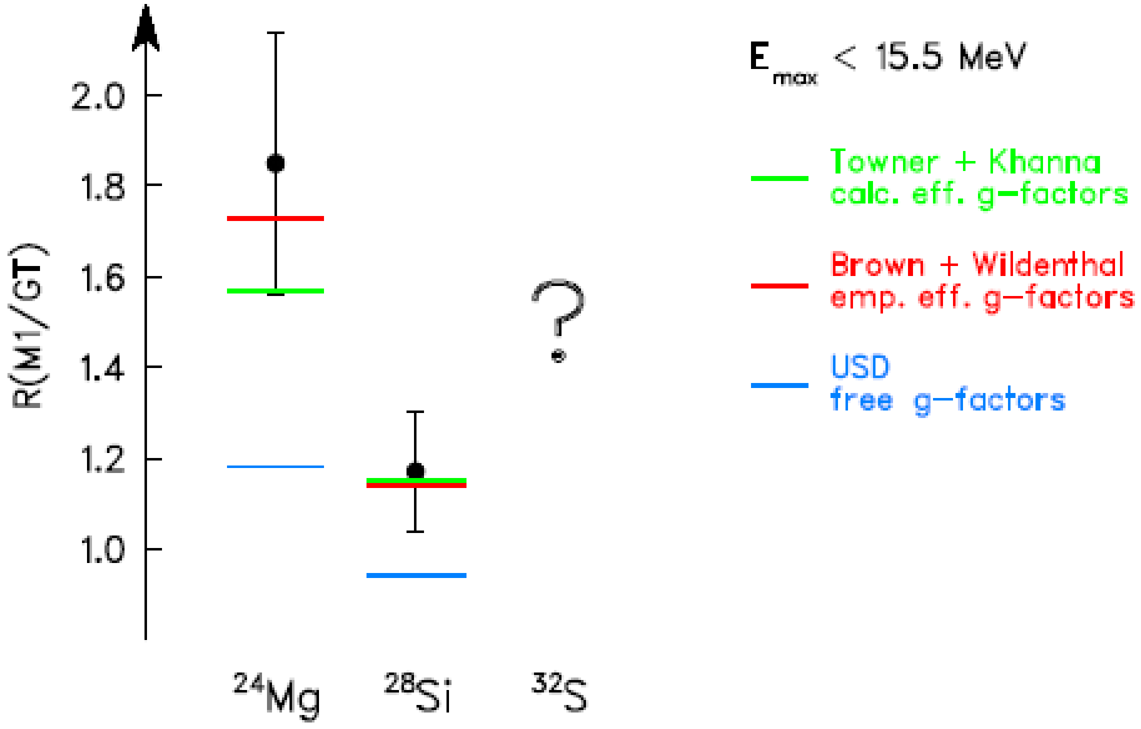
R.M. Laszewsi et al., PRL 61, 1710 (1988)
R. Köhler et al., PRC 35, 1646 (1987)

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

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

Quenching in sd-Shell Nuclei

A. Richter et al., Phys. Rev. Lett. 65, 2519 (1990)
PvNC et al., Phys. Rev. C 55, 532 (1997)



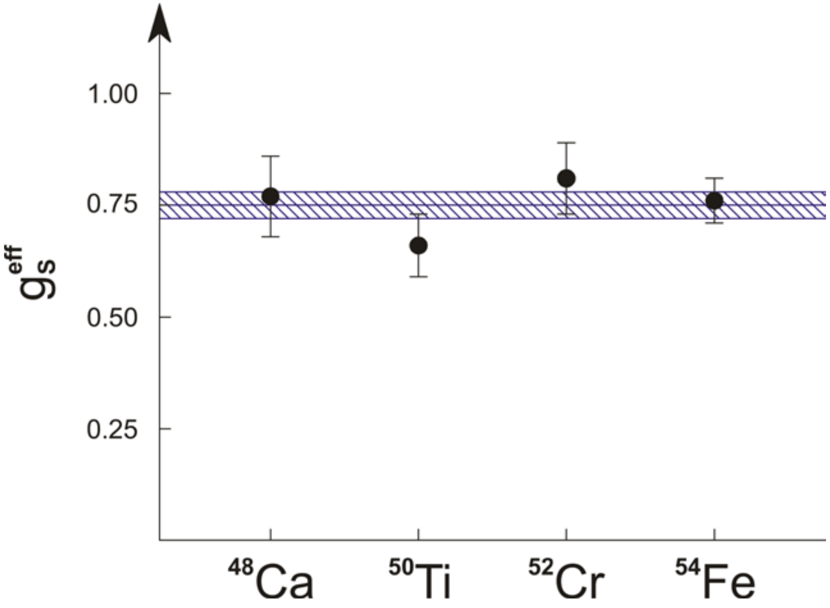
M1 enhanced over GT by two-body currents

Quenching in fp-Shell Nuclei

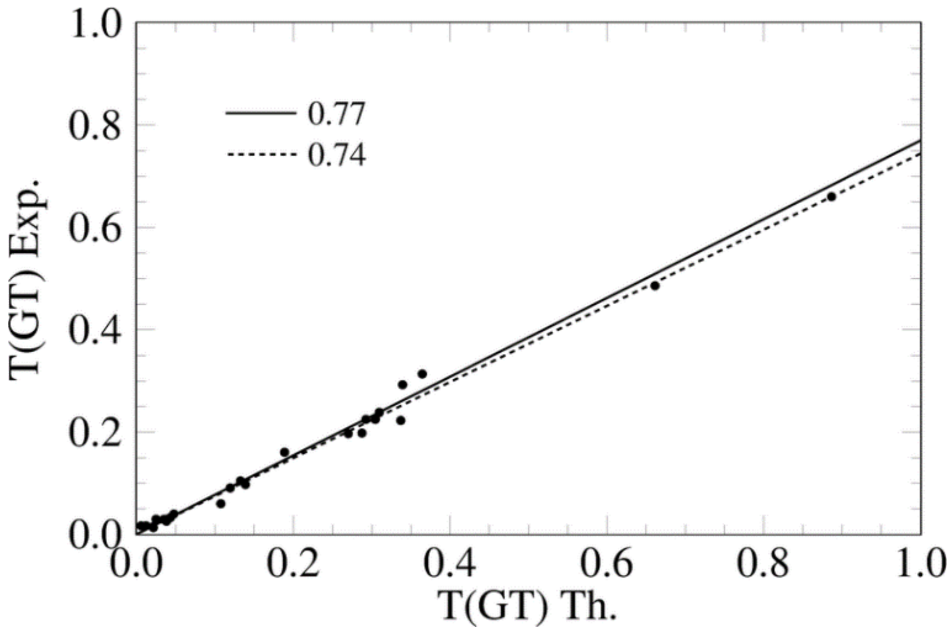
PvNC et al., Phys. Lett. B 443, 1 (1998)

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

M1

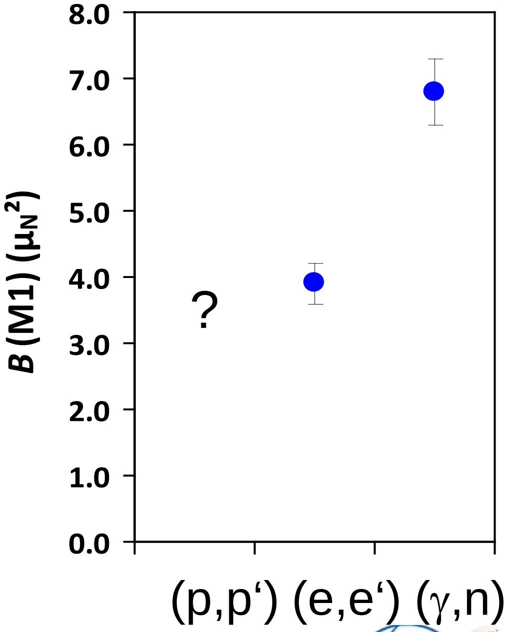


GT

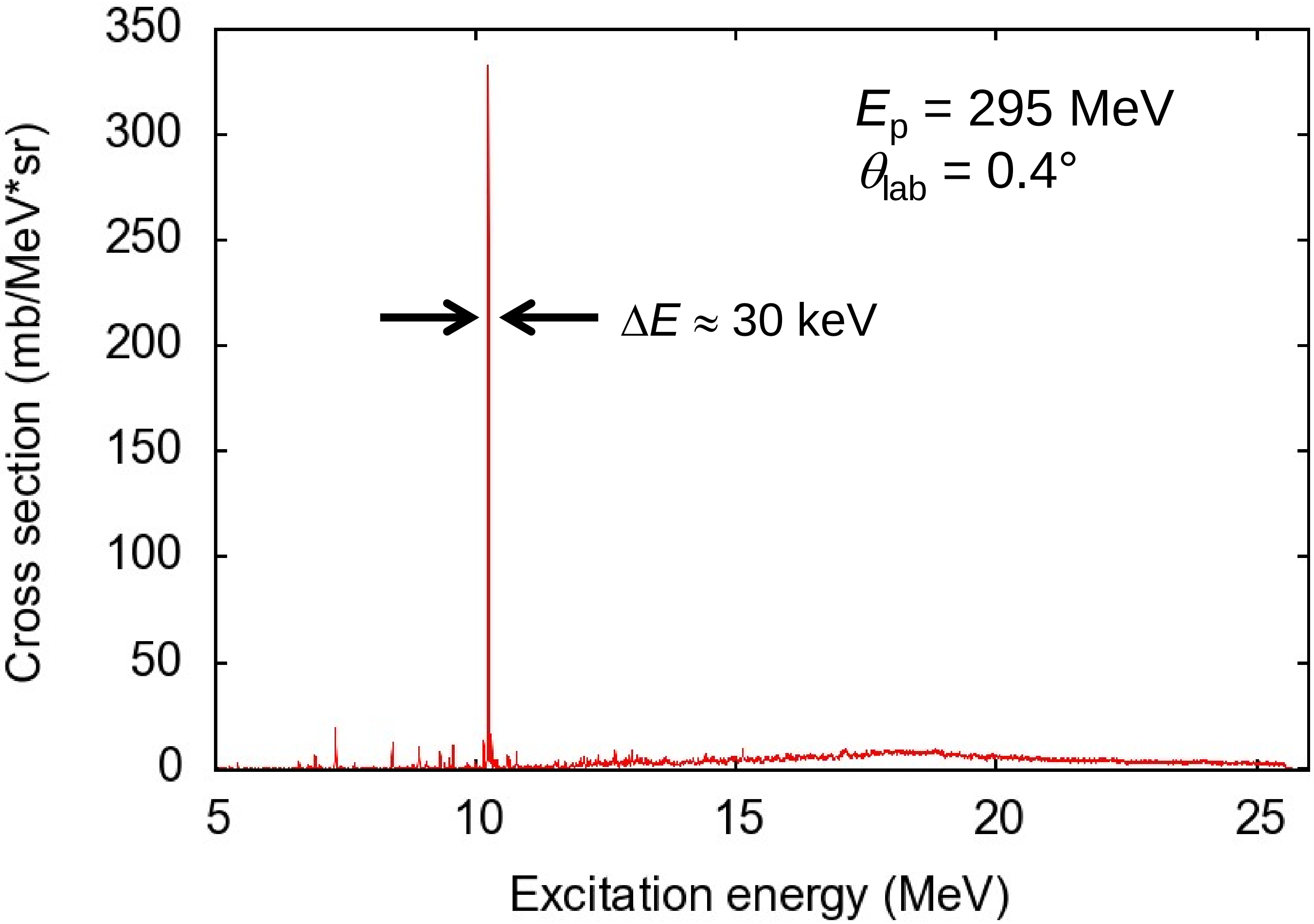


The Case of ^{48}Ca

- 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)
  $B(\mathrm{M1})\uparrow = (3.9 \pm 0.3)\ \mu_N^2$
- (γ,n) experiment at HIγS)
  J.R. Tompkins et al, Phys. Rev. C 84, 044331 (2011)
  $B(\mathrm{M1})\uparrow = (6.8 \pm 0.5)\ \mu_N^2$

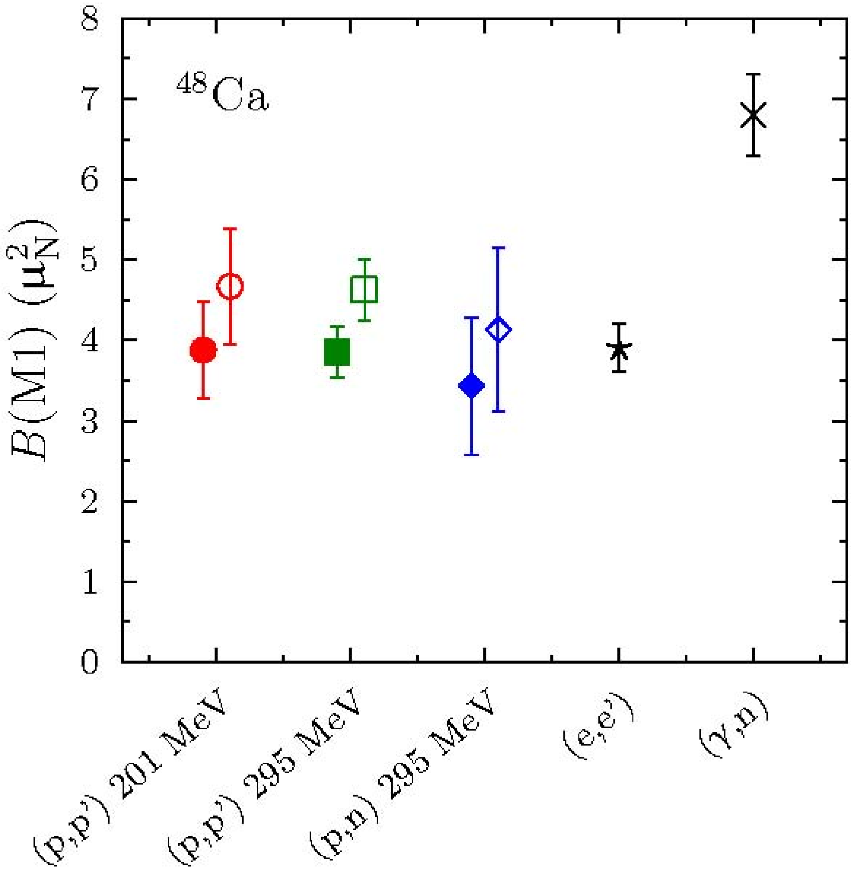


The Case of ^{48}Ca: (p,p‘) Data



RCNP

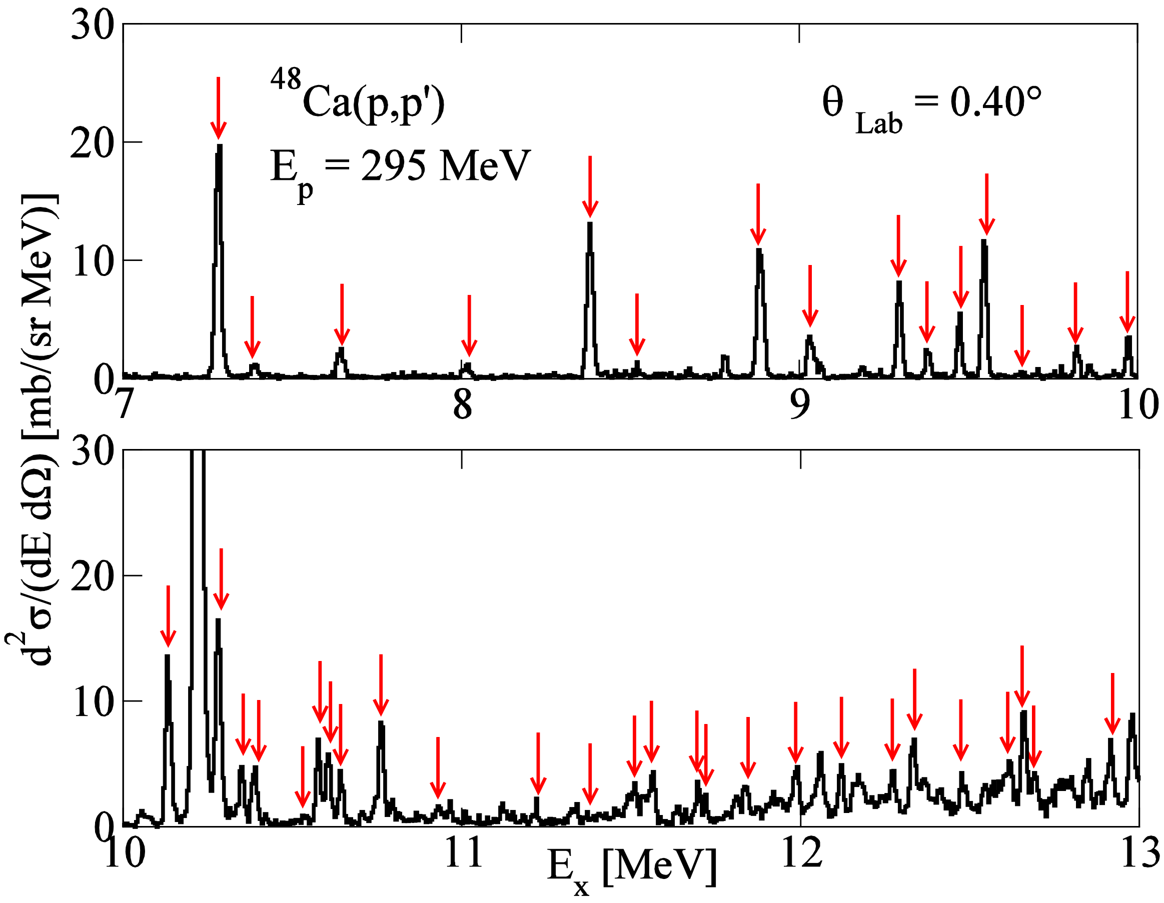
B(M1) Strength in ^{48}Ca from (p,p‘) and (p,n)



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

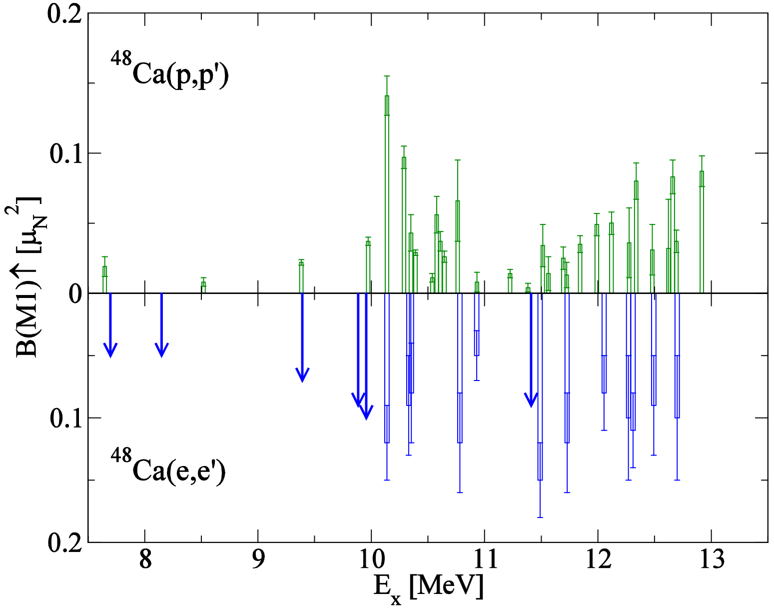
J. Birkhan et al., Phys. Rev. C **93**, 041302(R) (2016)

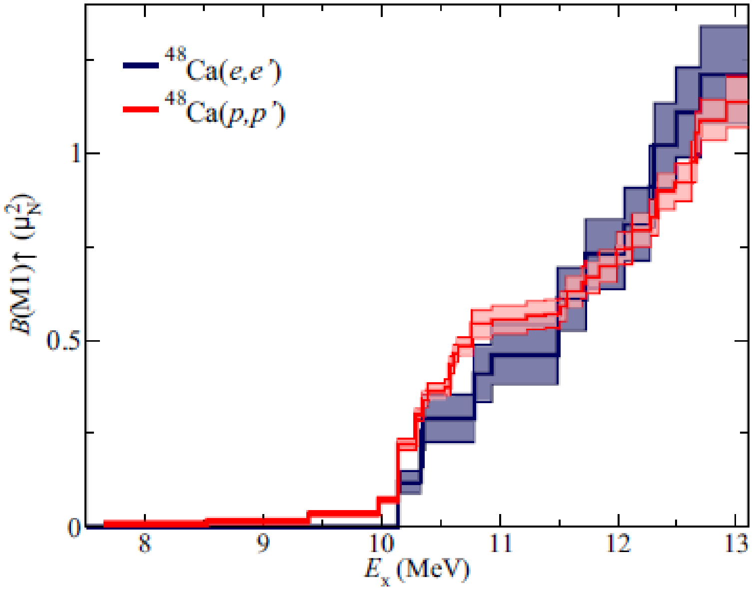
Search for Weak M1 Transitions



About 25% of the B(M1) strength in weak transitions

M1 Transitions from (e,e‘) and (p,p‘)

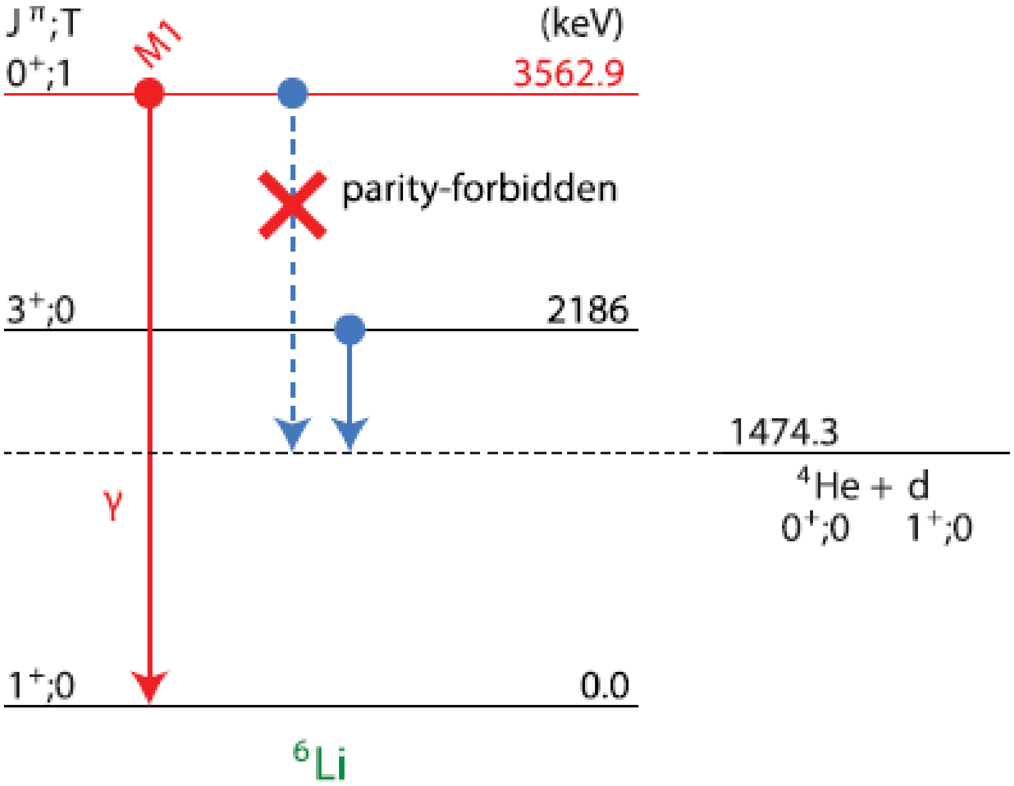




- Many transitions close to detection limit
- Good correspondence between (e,e‘) and (p,p‘) analysis

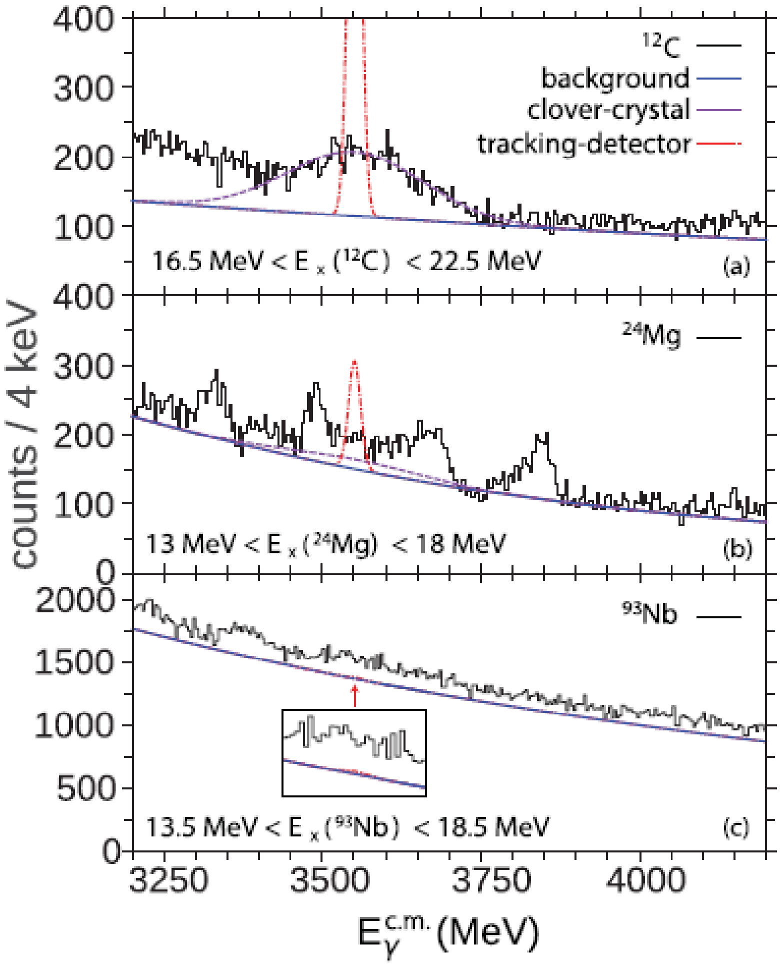
M. Mathy et al., Phys. Rev. C **95**, 054316 (2017)

Pure IV Spin-M1 Strength from the (^{6}Li,^{6}Li´γ) Reaction



Pure IV spin response → determine ν-nucleus scattering cross sections in astrophysical scanarios

Exploratory study at RCNP within campaign CAGRA@GRAND RAIDEN



- Reconstruction of γ peak in light nuclei up to *sd*-shell
- No signal in heavier nuclei due to Doppler braodening
- No access (yet) to astrophysically relevant *fp*-shell nuclei

C. Sullivan et al., Phys. Rev. C **98**, 015804 (2018)

Plans for next SFB period

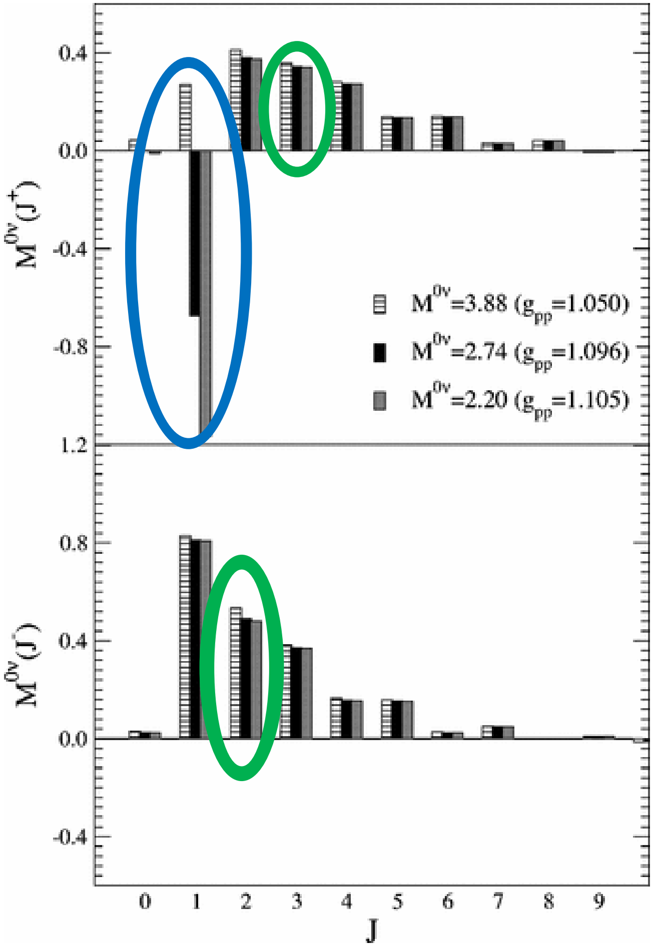
Quenching of Forbidden Transitions and Neutrino-Nucleus Interaction

- Quenching of forbidden transitions
  - neutrinoless double beta decay
  - electron capture-induced explosion of intermediate-mass stars

- Response of supernova neutrino detectors

- Microscopic description of quenching: role of many-body correlations and two-body currents → **B01**

Forbidden Transitions in 0νββ Decay



F.Šimkovic, A. Faessler, V. Rodin, P. Vogel, J. Engel, Phys. Rev. C 77, 045503 (2008)

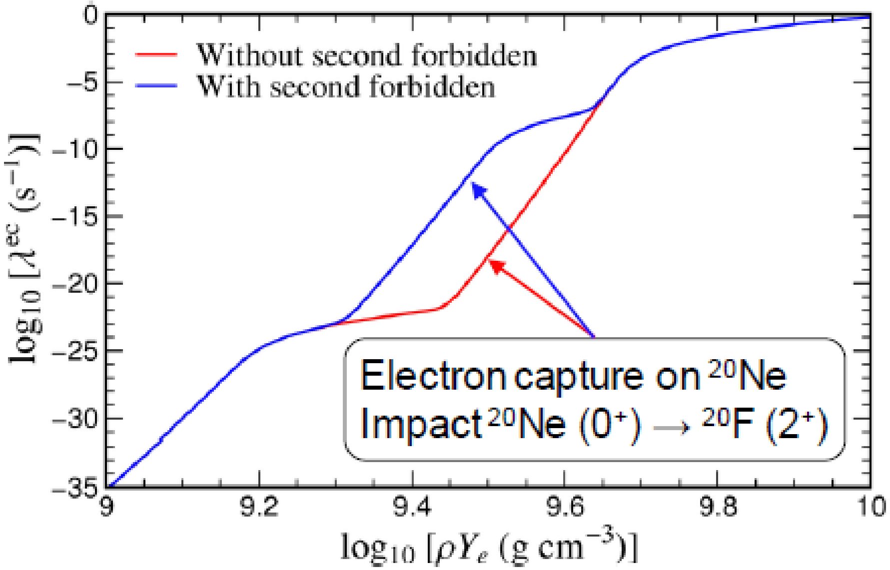
Contributions of forbidden transitions relevant!

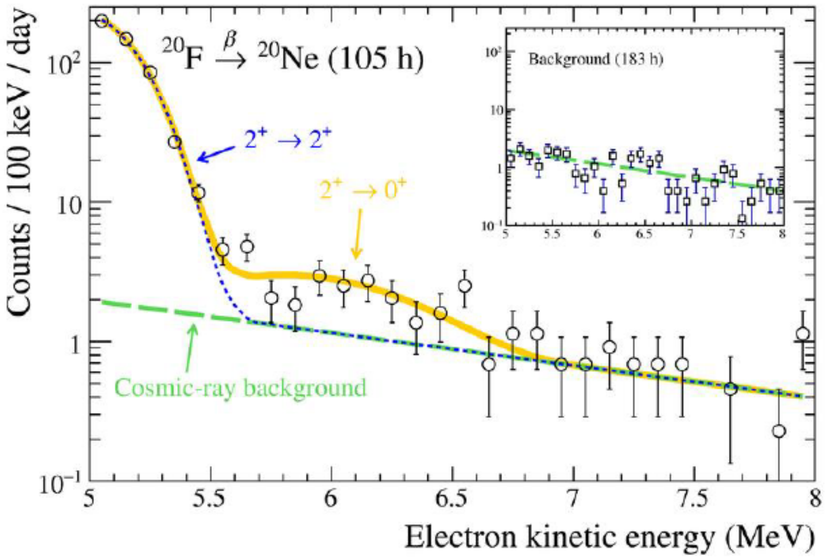
$$\lambda_{0\nu\beta\beta} \propto |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Quenching factor enters with 4th power

Electron Capture-Induced Explosion of Intermediate-Mass Stars

O. Kirsebom et al., arXiv:1805.08149





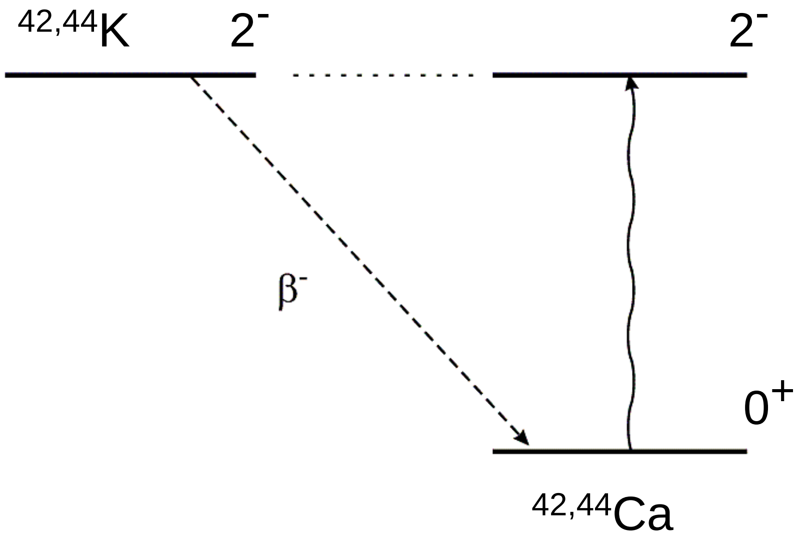
Non-unique second forbidden transition

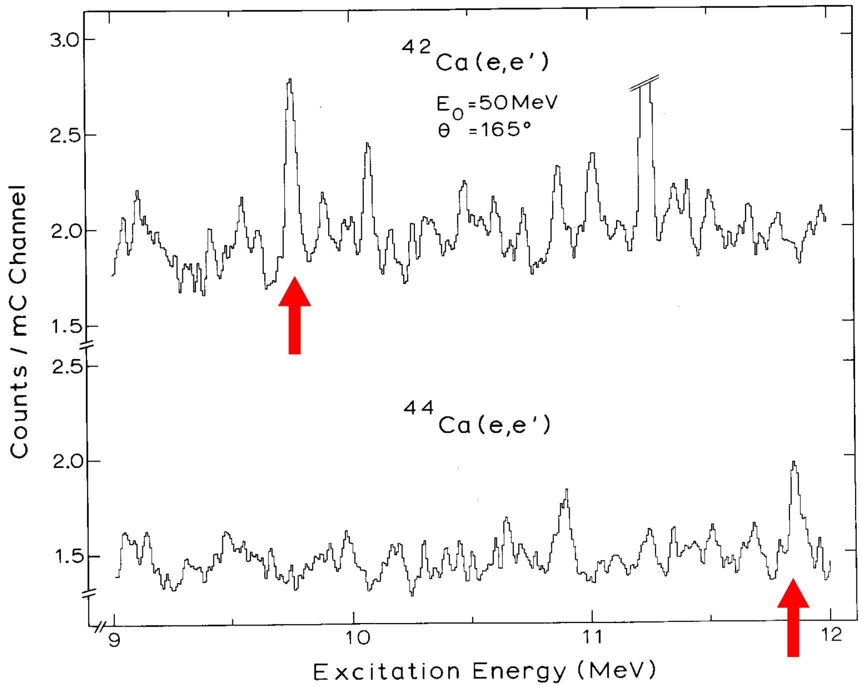
log ft (^{20}F →^{20}Ne) = 10.47(11)
log ft (^{36}Cl→^{36}Ar) = 13.58(3)

What causes the difference?

Analog Transition in Electron Scattering

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

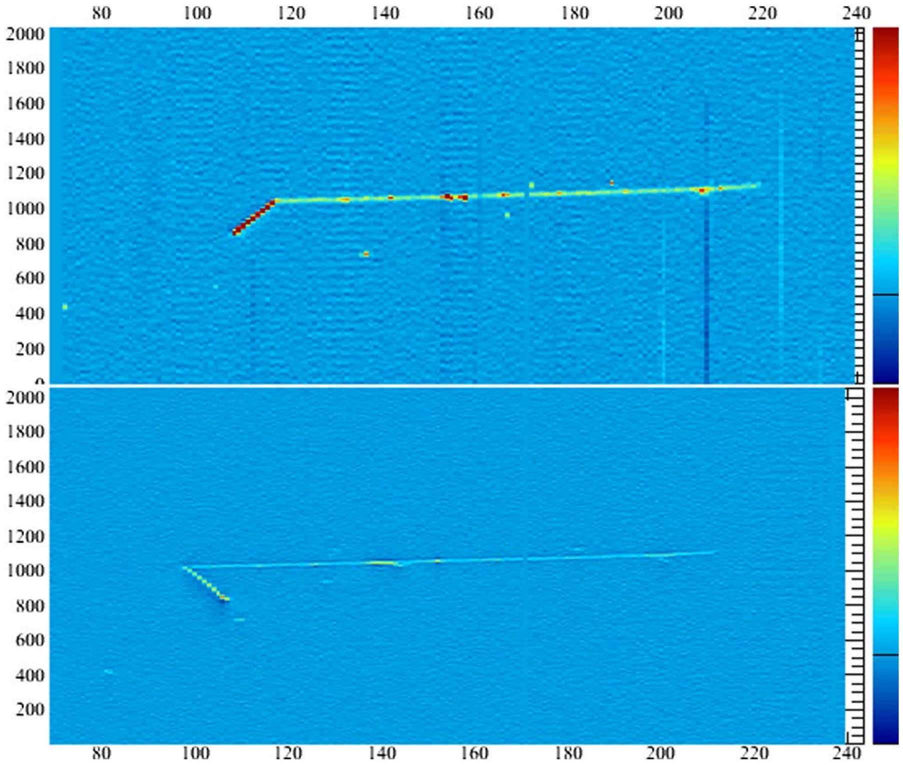




Study analog transitions with 180° electron scattering

Liquid Argon SN Neutrino Detectors

R. Acciari et al. Phys. Rev. D 99, 012002 (2019)

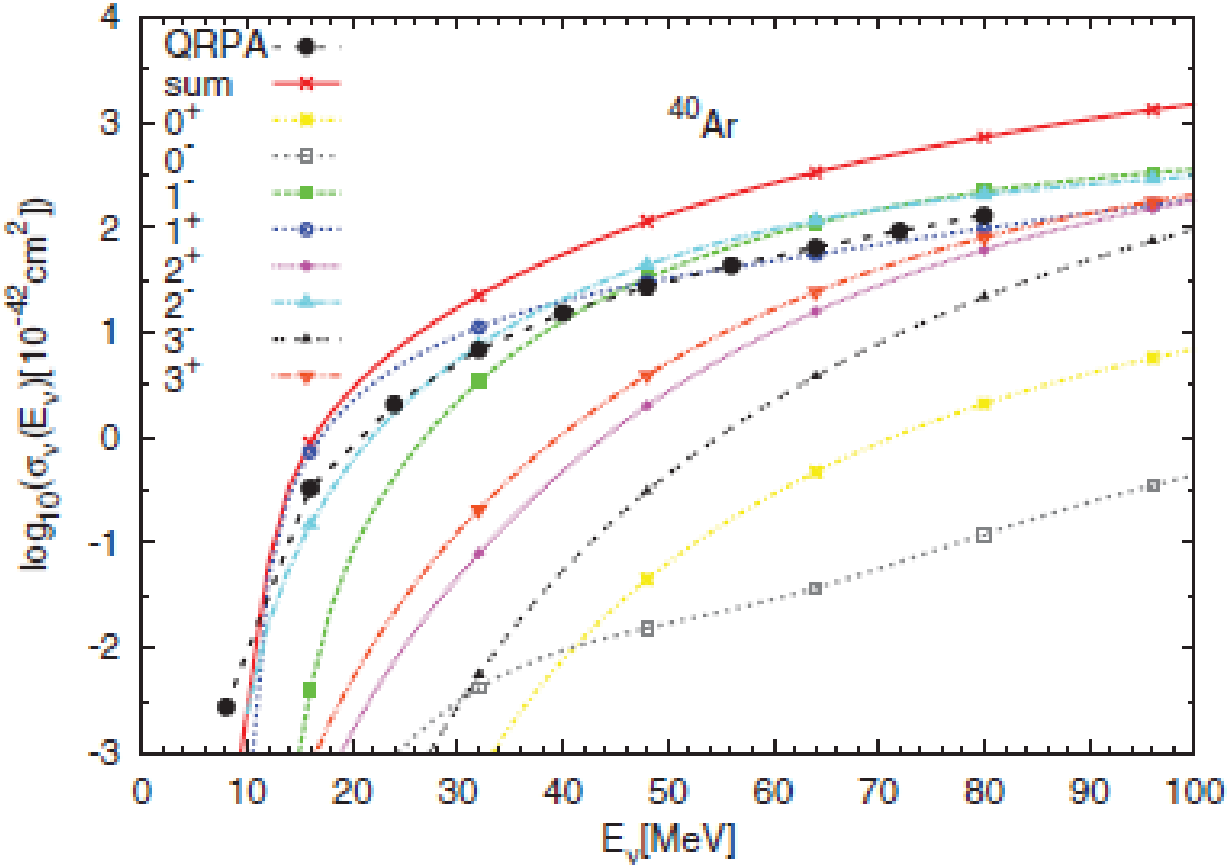


First observation of a MeV ν-nucleus interaction with Liquid Ar TPC ArgoNeuT
→ detection of SN neutrinos

Knowledge of ^{40}Ar nuclear response required

Predictions of NC ν-^{40}Ar Response

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



M1 dominates, but E1 and M2 relevant at higher energies

Experimental Program (→ B03)

- Systematic study of analog transitions to forbidden decay in light nuclei with 180° electron scattering
  - M2 (first forbidden): ^{42,44}Ca
  - M3 (second forbidden): ^{10}B, (^{22}Ne)
  - M4 (third forbidden): ^{40}Ar

- Analog transitions to non-unique second forbidden decay with 180° and forward-angle electron scattering: ^{20}Ne, ^{36}Ar

- Nuclear response relevant to v-^{40}Ar interaction
  - Spin-M1, E1: 0° proton scattering at RCNP (see B04)
  - M2: 180° electron scattering

- Technical development: liquid Ar target → improved energy resolution

Statistics

- Publications: 8

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

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

  C. Sullivan et al., Phys. Rev. C **98**, 015804 (2018)

- Collaborations:

  - combined effort with projects A01,A03,A07,B03,B04 and ACCELENCE to upgrade spectrometers and responsible for new DAQ
  - campaign CAGRA@GRAND RAIDEN, RCNP Osaka

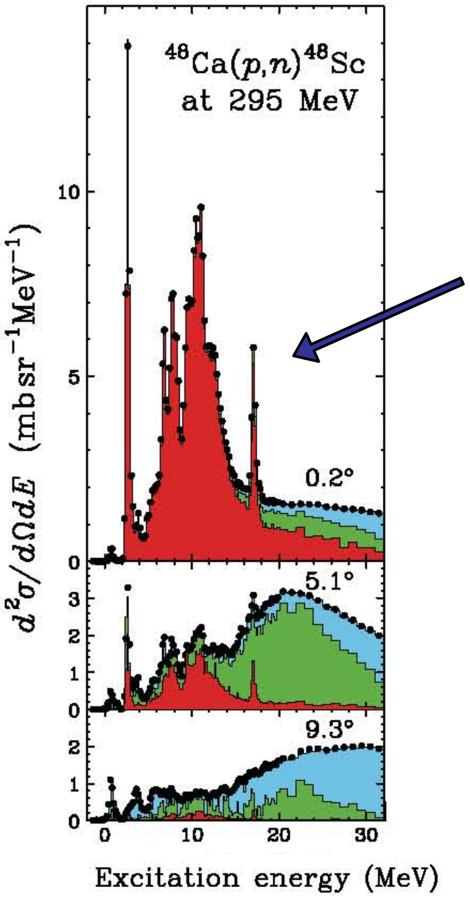
- Workshop co-organization:

  Neutrino Nuclear Responses for Double Beta Decay and Astro Neutrinos (NNR 16), Osaka University, 2016

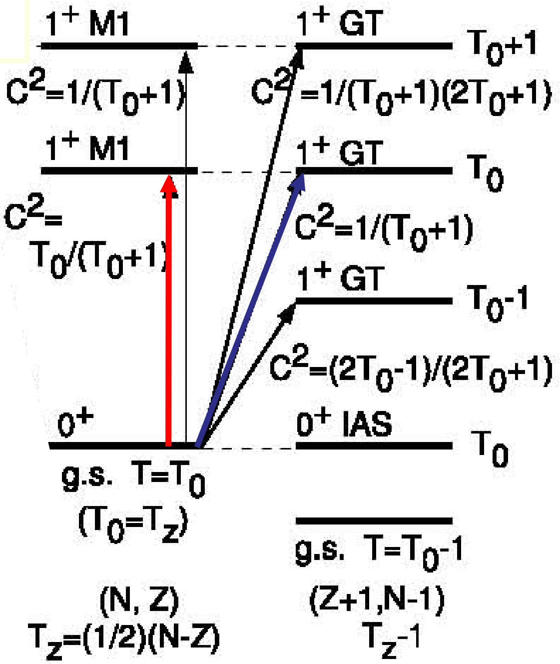
Thank you!

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

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



IAS



1^+ M1

1^+ GT

T_0+1

$C^2=1/(T_0+1)$

$C^2=1/(T_0+1)(2T_0+1)$

1^+ M1

1^+ GT

T_0

$C^2= T_0/(T_0+1)$

$C^2=1/(T_0+1)$

1^+ GT

T_0-1

$C^2=(2T_0-1)/(2T_0+1)$

0^+

0^+ IAS

T_0

g.s. $T=T_0$

$(T_0=T_z)$

g.s. $T=T_0-1$

(N, Z)

$T_z=(1/2)(N-Z)$

(Z+1,N-1)

T_z-1

Isospin symmetry:

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

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

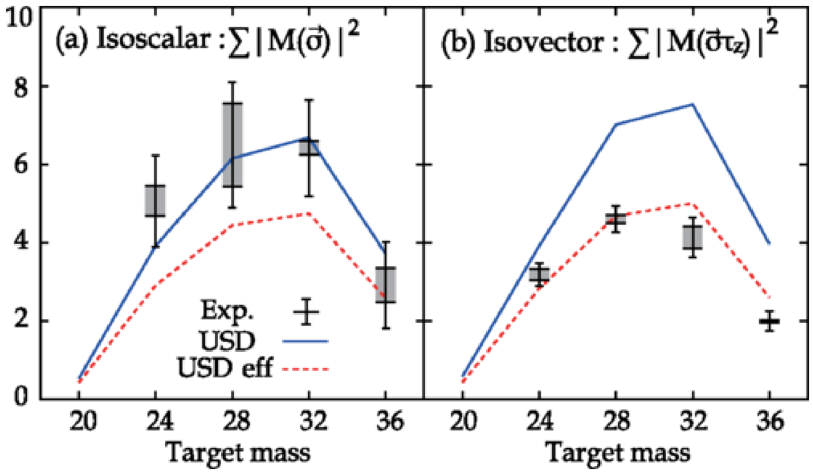
$$B(\mathrm{M1}) = \frac{3}{4\pi}\left|\langle f||\xcancel{g_l^{\mathrm{IS}}}\vec{l} + \frac{g_s^{\mathrm{IS}}}{2}\vec{\sigma} - (\xcancel{g_l^{\mathrm{IV}}}\vec{l} + \frac{g_s^{\mathrm{IV}}}{2}\vec{\sigma})\tau_0||i\rangle\right|^2 \mu_{\mathrm{N}}^2$$

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)



Conversion to Spin-M1 Strength

- GT unit cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(q=0) = \hat{\sigma}_{\mathrm{GT}} F(q, E_x) B(\mathrm{GT})$$

- Spin M1 unit cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(q=0) = \hat{\sigma}_{\mathrm{M1}} F(q, E_x) B(\mathrm{M1}_{\sigma\tau})$$

- Transition strengths

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

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

- Isospin symmetry

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

$$B(\mathrm{M1}_{\sigma\tau}) = \frac{1}{2} \frac{T_i}{T_i+1} B(\mathrm{GT}_-)$$

Spin-M1 and B(M1) Strength

- B(M1) strength

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

Spin M1 and B(M1) Strength

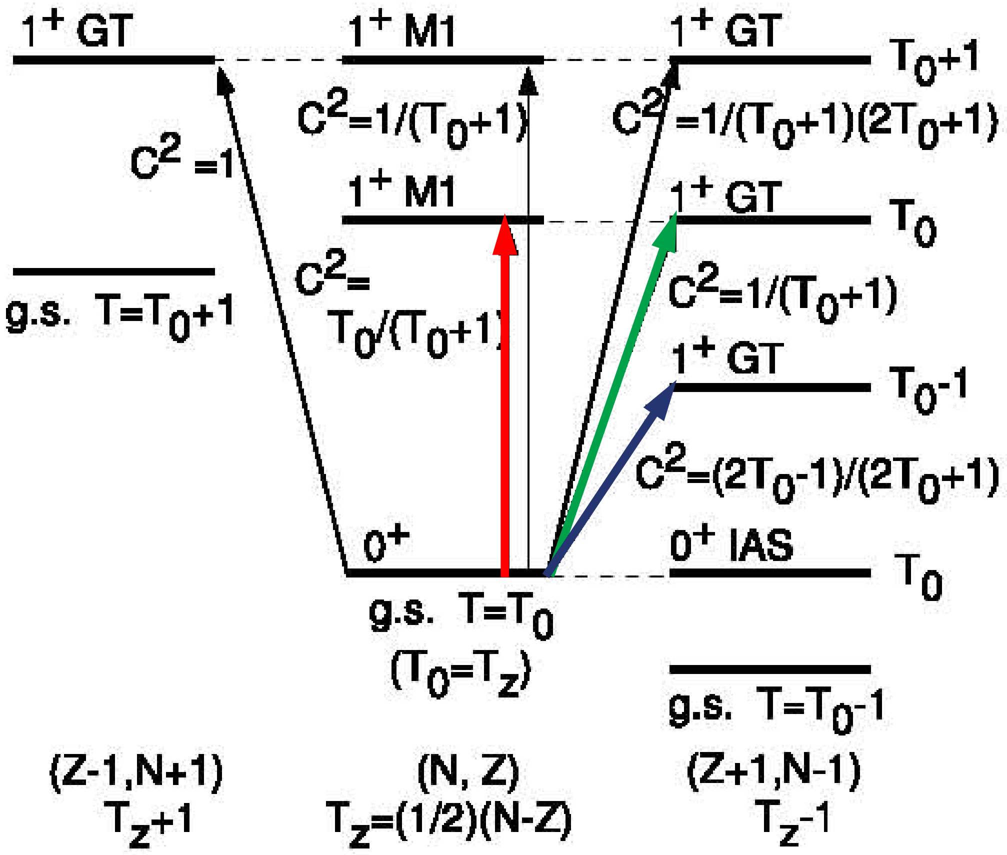
- B(M1) strength

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

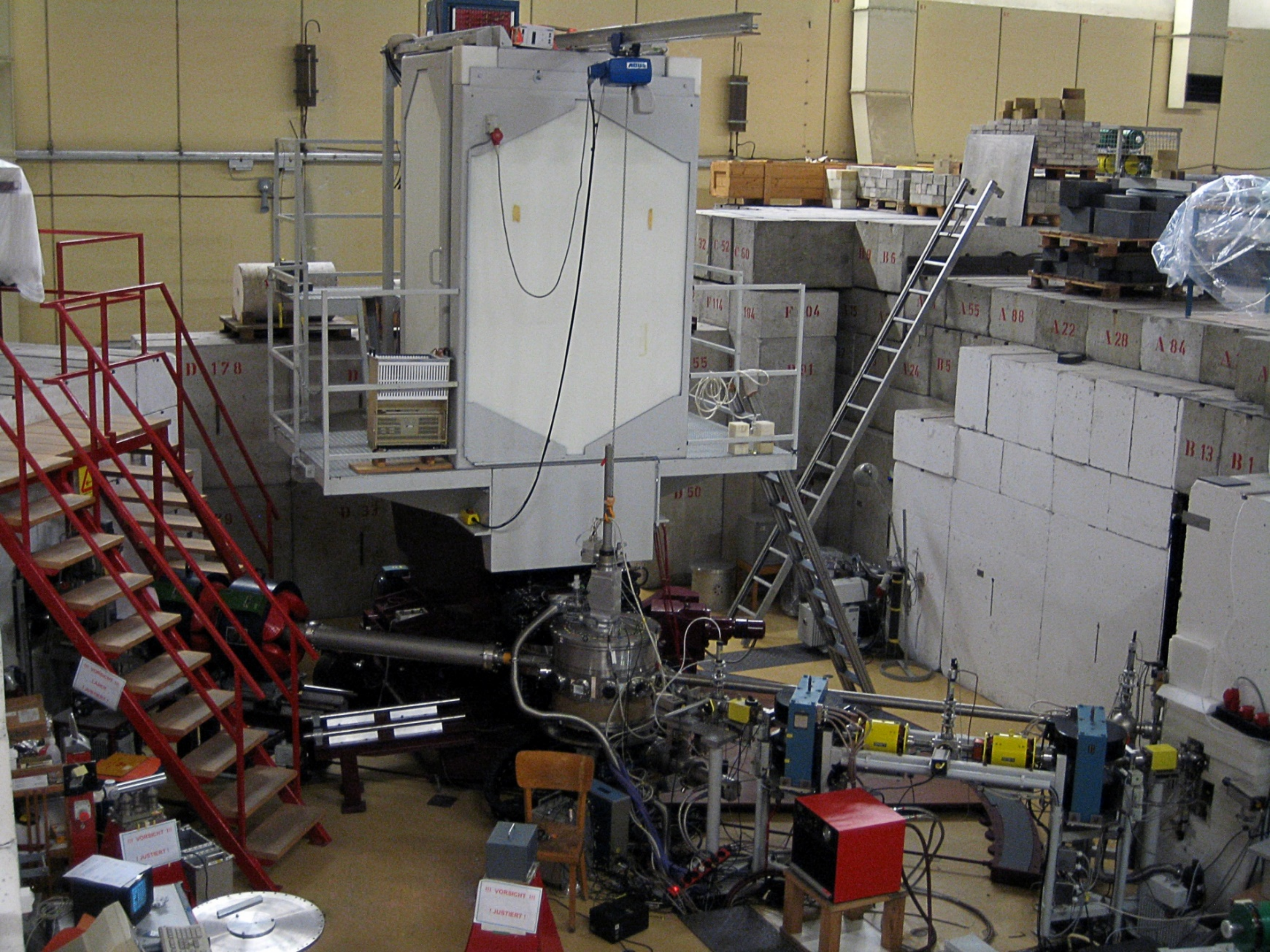
$$\Big\downarrow$$

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

Relation to GT Strength



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


ABUS
C 52
C 60
B 6
F 114
F 04
D 178
A 55
A 88
A22
A28
A 84
B5
B 13
D 50
!!! VORSICHT !!!
! JUSTIERT !
!!! VORSICHT !!!
! JUSTIERT !