Magnetic Excitation Modes in Nuclei

Prof. Dr. Peter von Neumann-Cosel

Institut fuer Kernphysik, TU Darmstadt, Germany
and
Research Center for Nuclear Physics, Osaka University, Japan

The lecture series reviews nuclear magnetic excitation modes which contribute to our understanding of the strong interaction in unique ways. They provide information on diverse topics like spin and orbital nuclear currents, bulk properties of nuclear matter, quenching of the spin-isospin response, tensor interaction, pseudospin symmetry etc. A rough outline of the content is

1. Qualitative nature of the magnetic response
2. Orbital magnetic dipole excitations (the scissors mode)
3. Spin magnetic dipole strength and quenching of the spin-isospin response
4. Special topics of magnetic dipole excitations
   - impact of meson-exchange currents
   - forbidden transitions and pseudospin symmetry
5. Higher magnetic multipoles
   - orbital magnetic quadrupole excitations (the twist mode)
   - spin-dipole excitations
   - magnetic octupole modes
   - stretched magnetic transitions

Schedule:

Thursday, March 5, 2015

10:30-12:00	Lecture I
13:30-15:00	Lecture II

Friday, March 6, 2015

10:30-12:00	Lecture III
13:30-15:00	Lecture IV

Place:
Lecture Room 1, RCNP Main Building 6th Floor

Magnetic Excitation Modes in Nuclei

Peter von Neumann-Cosel
Institut für Kernphysik, Technische Universität Darmstadt
and
RCNP, University Osaka

1. Qualitative nature of the magnetic response
2. Experimental techniques
3. Orbital M1 strength (the scissors mode)
4. Spin M1 strength and quenching of spin-isospin response
5. Special topics
   - meson-exchange currents
   - forbidden transitions
6. Higher magnetic multipoles
   - orbital M2 strength (the twist mode)
   - spin-dipole mode
   - M3 strength
   - stretched transitions

1. Qualitative nature of the magnetic response

Nuclear Magnetism

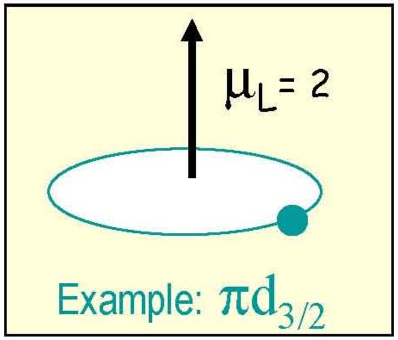
Orbiting charged particles induce a magnetic field

→ orbital magnetic moment with strength g_L

and proportional to **orbital angular momentum l**

protons : $g_{L,\pi}$ = 1

neutrons have no charge → $g_{L,\nu}$ = 0



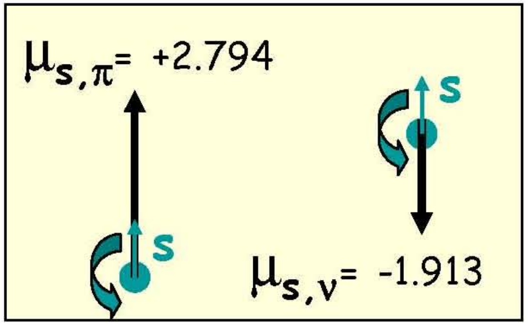
Intrinsic spin of the nucleons induces a magnetic field

→ spin magnetic moment with a strength g_S

and proportional to **instrinsic spin s=1/2**

protons : $g_{S,\pi}$ = + 5.587

neutrons : $g_{S,\nu}$ = - 3.826



(slide borrowed from G. Neyens)

M1 Operator

TECHNISCHE UNIVERSITÄT DARMSTADT

$$\hat{O}(M1) = \left[\sum_{k=1}^{Z} (g_l{}^{\pi}\mathbf{l}_k + g_s{}^{\pi}\mathbf{s}_k) + \sum_{k=Z+1}^{A} (g_l{}^{\nu}\mathbf{l}_k + g_s{}^{\nu}\mathbf{s}_k) \right] \mu_N$$

$$g_l{}^{\pi} = 1 \qquad g_l{}^{\nu} = 0$$

$$g_s{}^{\pi} = 5.586 \qquad g_s{}^{\nu} = -3.826$$

$$= \left[\sum_{k=1}^{A} \left\{ \left(g_l{}^{IS}\mathbf{l}_k + g_s{}^{IS}\frac{\sigma_k}{2} \right) + \left(g_l{}^{IV}\mathbf{l}_k + g_s{}^{IV}\frac{\sigma_k}{2} \right) \tau_z(k) \right\} \right] \mu_N$$

$$g_l^{IS} = 0.5 \qquad g_l^{IV} = 0.5$$

$$g_s^{IS} = 0.880 \qquad g_s^{IV} = 4.706$$

M1 Operator

$$\hat{O}(M1) \;=\; \left[\sum_{k=1}^{Z}({g_l}^{\pi}\mathbf{l}_k + {g_s}^{\pi}\mathbf{s}_k) + \sum_{k=Z+1}^{A}({g_l}^{\nu}\mathbf{l}_k + {g_s}^{\nu}\mathbf{s}_k)\right]\mu_N$$

$${g_l}^{\pi} = 1 \qquad {g_l}^{\nu} = 0$$

$${g_s}^{\pi} = 5.586 \qquad {g_s}^{\nu} = -3.826$$

$$= \left[\sum_{k=1}^{A}\left\{\left({g_l}^{IS}\mathbf{l}_k + {g_s}^{IS}\frac{\sigma_k}{2}\right) + \left({g_l}^{IV}\mathbf{l}_k + {g_s}^{IV}\frac{\sigma_k}{2}\right)\tau_z(k)\right\}\right]\mu_N$$

$$g_l^{IS} = 0.5 \qquad g_l^{IV} = 0.5$$

$$g_s^{IS} = 0.880 \qquad g_s^{IV} = 4.706$$ large

M1 Operator

$$\hat{O}(M1) = \left[\sum_{k=1}^{Z} ({g_l}^{\pi}\mathbf{l}_k + {g_s}^{\pi}\mathbf{s}_k) + \sum_{k=Z+1}^{A} ({g_l}^{\nu}\mathbf{l}_k + {g_s}^{\nu}\mathbf{s}_k)\right] \mu_N$$

$${g_l}^{\pi} = 1 \qquad {g_l}^{\nu} = 0$$

$${g_s}^{\pi} = 5.586 \qquad {g_s}^{\nu} = -3.826$$

$$= \left[\sum_{k=1}^{A} \left\{ \left({g_l}^{IS}\mathbf{l}_k + {g_s}^{IS}\frac{\sigma_k}{2}\right) + \left({g_l}^{IV}\boxed{\mathbf{l}_k} + {g_s}^{IV}\frac{\sigma_k}{2}\right)\tau_z(k)\right\}\right] \mu_N$$

rewrite as

$\vec{L}_\pi - \vec{L}_\nu$

rotation generator

$$g_l^{IS} = 0.5 \qquad g_l^{IV} = 0.5$$

$$g_s^{IS} = 0.880 \qquad g_s^{IV} = 4.706$$

dominates

M1 Operator: Radial Dependence

The M1 operator does not change the radial quantum number
$\rightarrow$ only transitions between spin-orbit partners allowed

Question: In ^{16}O virtually no M1 strength is experimentally observed. Why?

M1 Operator

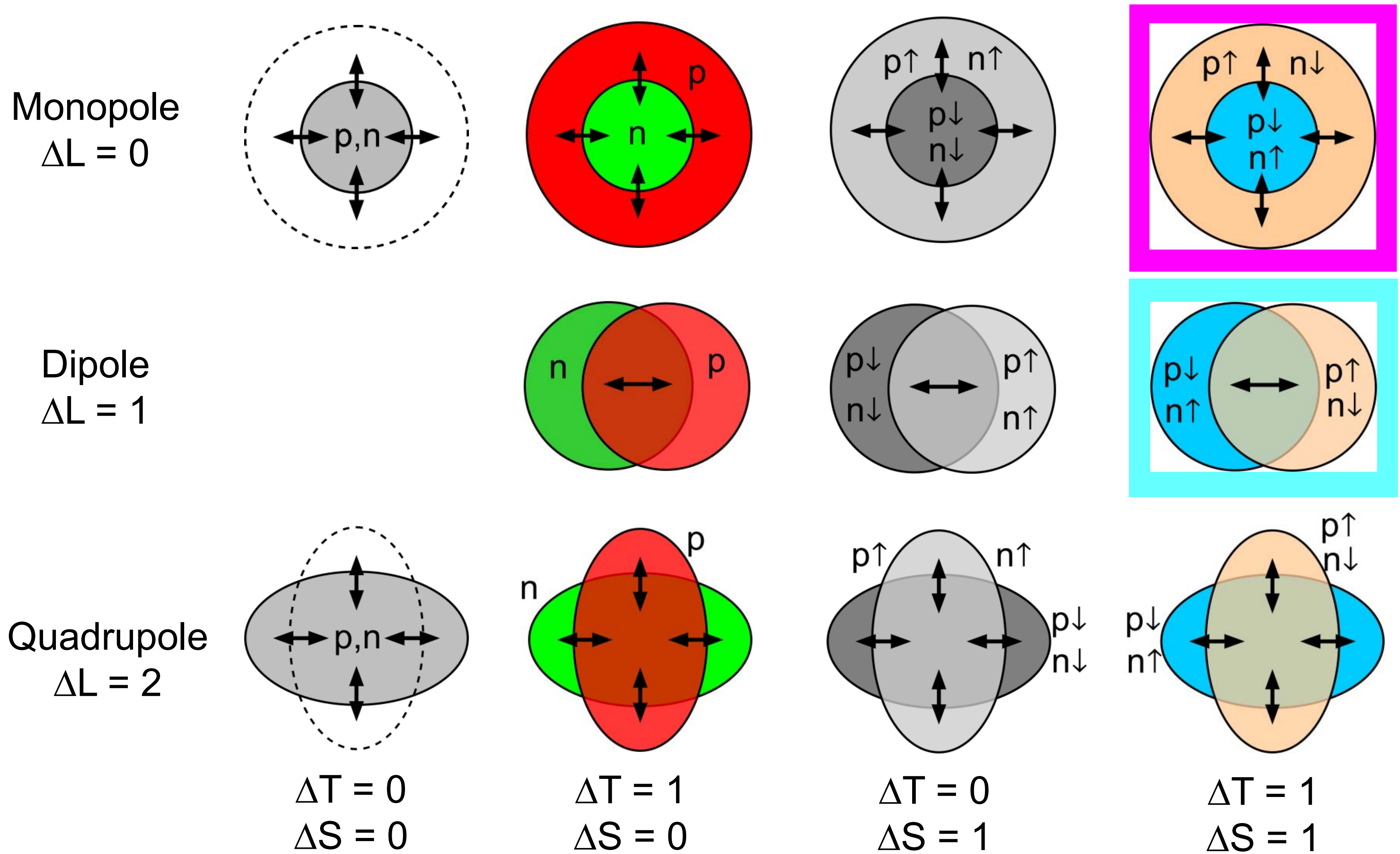
The M1 operator does not change radial quantum number
→ only transitions between spin-orbit partners allowed

Question: In ^{16}O virtually no M1 strength is experimentally observed. Why?

Answer: ^{16}O is a doubly magic nucleus. All possible spin-orbit partner states are full, so one can't create a particle-hole state. The lowest filled shell-model state is $j_< = l - ½$ state ($1p_{1/2}$ in ^{16}O). The spin-orbit partner ($1p_{3/2}$) is lower in energy (spin-orbit force!).

This phenomenon is called ***LS* saturation**.

Spin-Flip Giant Resonances



Relation of Spin-Flip and Magnetic Strength

Spin-M1 Resonance: $\Delta L = 0, \Delta S = 1\ \Delta T = 1, J^{\pi} = 1^{+}$

Spin-Dipole Resonance: $\Delta L = 1, \Delta S = 1\ \Delta T = 1, J^{\pi} = 0^{-}, 1^{-}, 2^{-}$

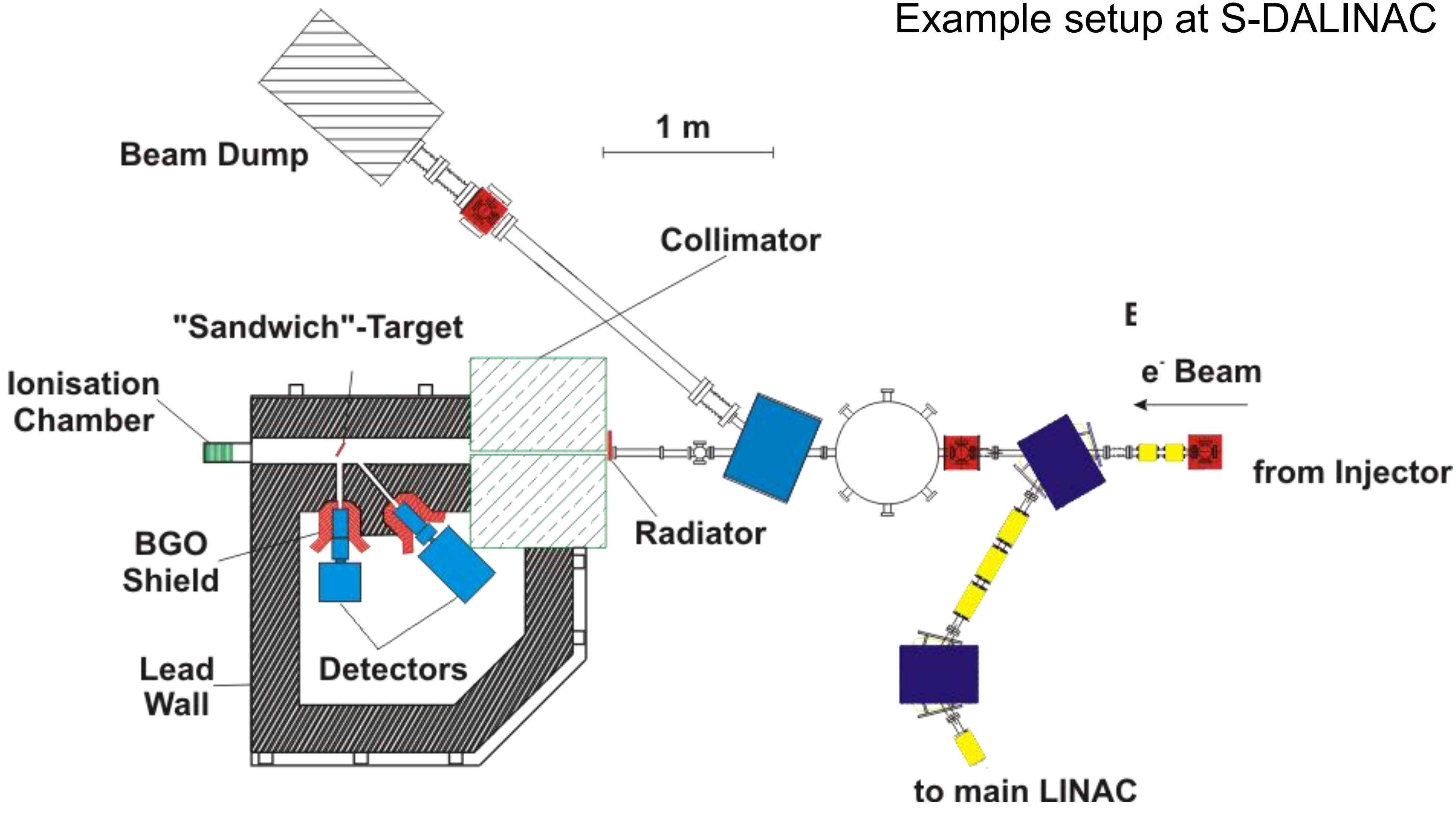
Hadronic and electromagnetic excitation by the same operators

Comparison yields important information on subtle aspects of the nuclear interaction

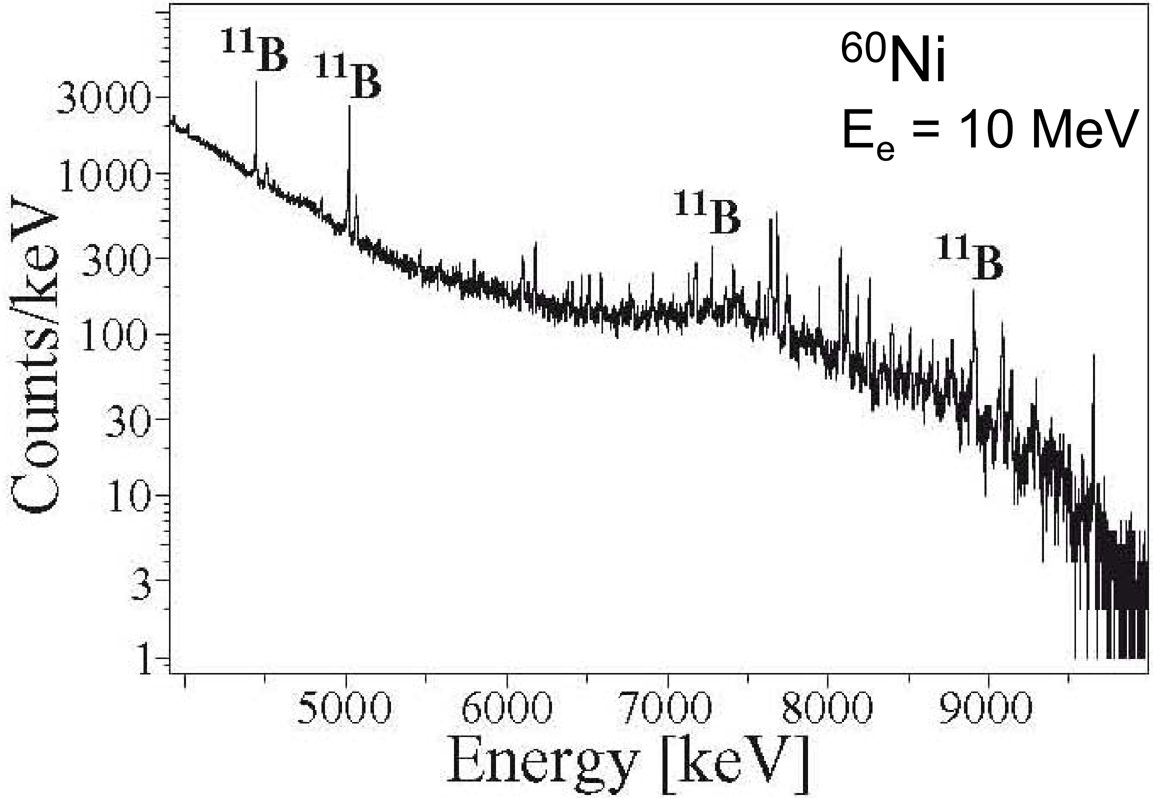
2. Experimental techniques

Nuclear Resonance Fluorescence

Example setup at S-DALINAC



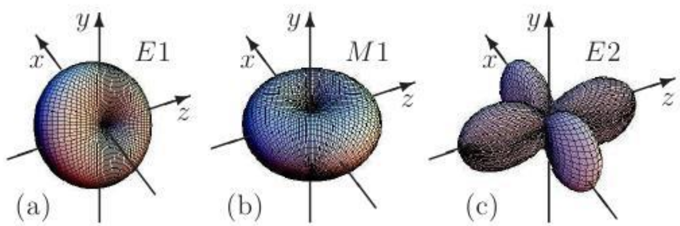
Nuclear Resonance Fluorescence



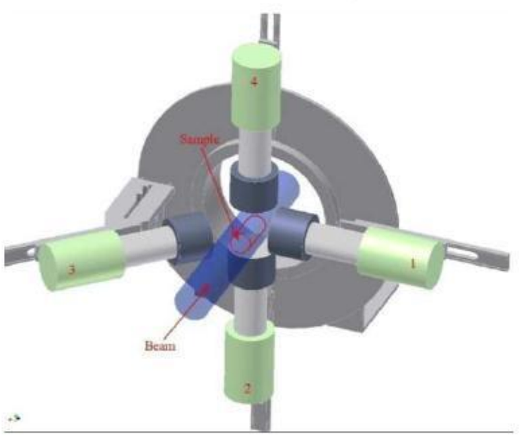
+ selective to dipole transitions, many transitions simultanously excited
- E1 strength dominates

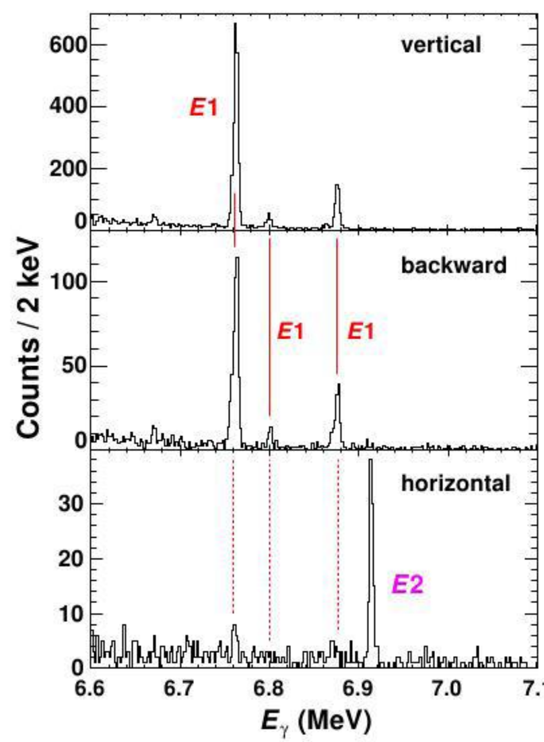
Parity determination

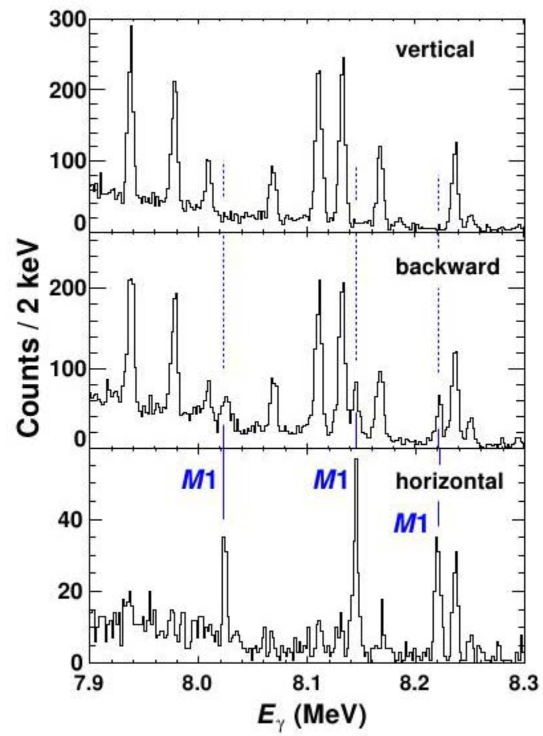
Parity can be determined with quasi-monochromatic 100% polarized photon beam from laser Compton backscattering (HIγS, Spring 8)



z axis: beam direction; x axis: vector of polarization

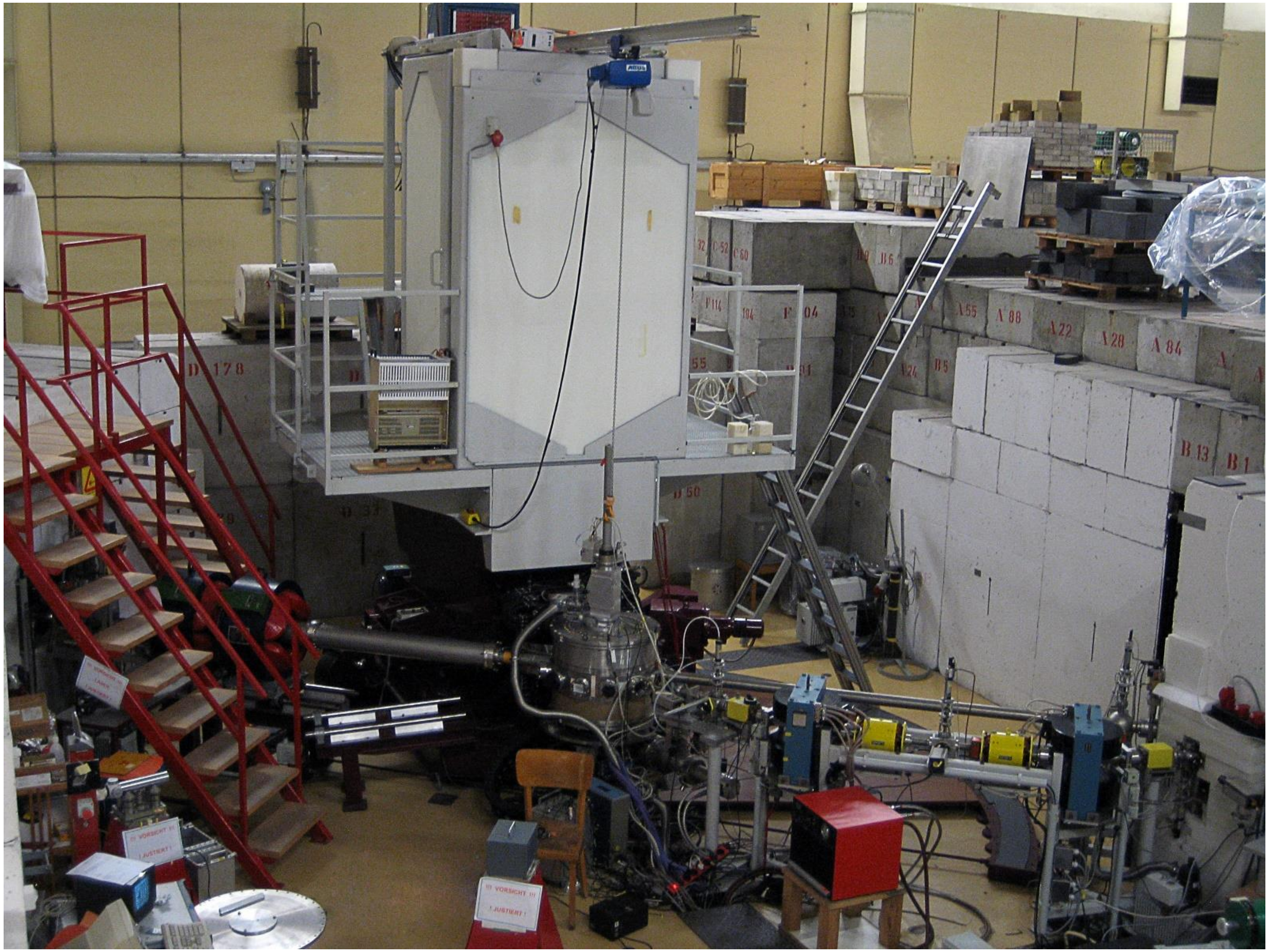






Electron Scattering: S-DALINAC

Electron Scattering: Spectrometer



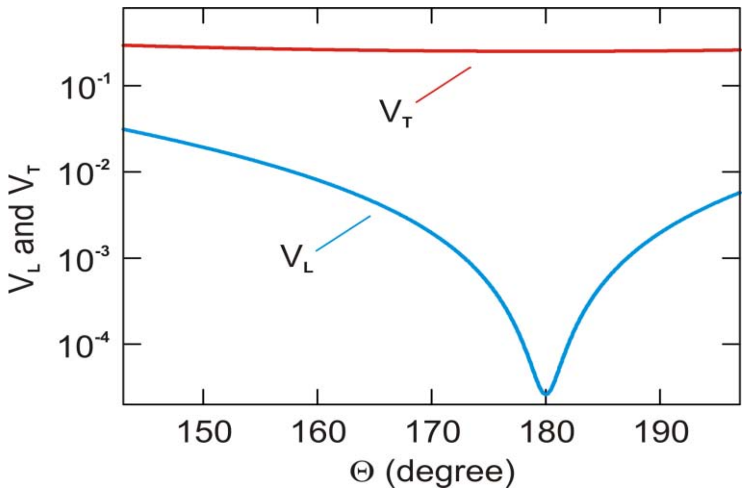
Transverse Electron Scattering

Inclusive (e,e‘) cross sections:

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

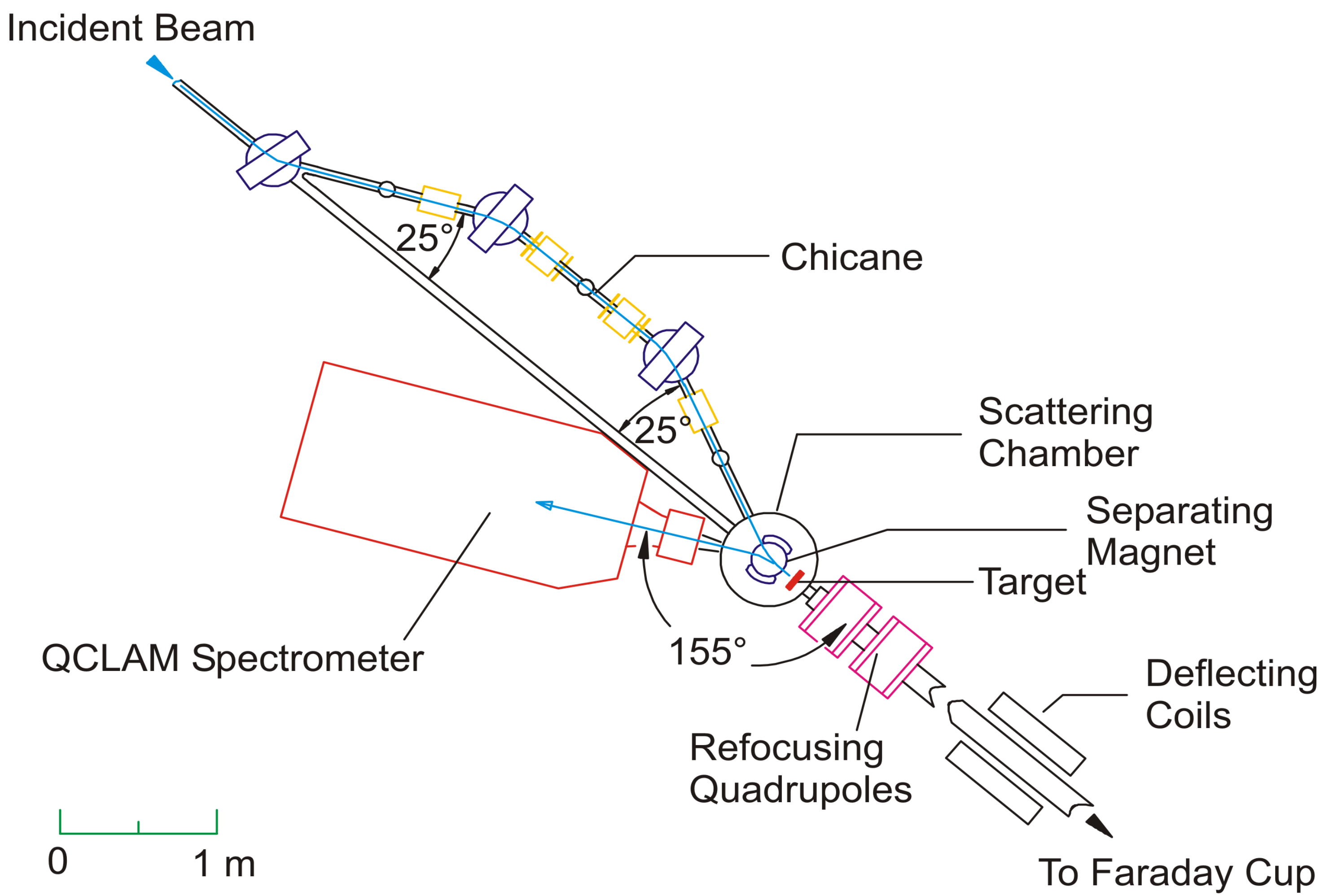
$$V_L \times \left|F_L(q)\right|^2 \qquad V_T \times \left|F_T(q)\right|^2$$

L,T = longitudinal/transverse polarization of the virtual photon
= interaction with charge/current distribution
→ magnetic transitions are purely transverse

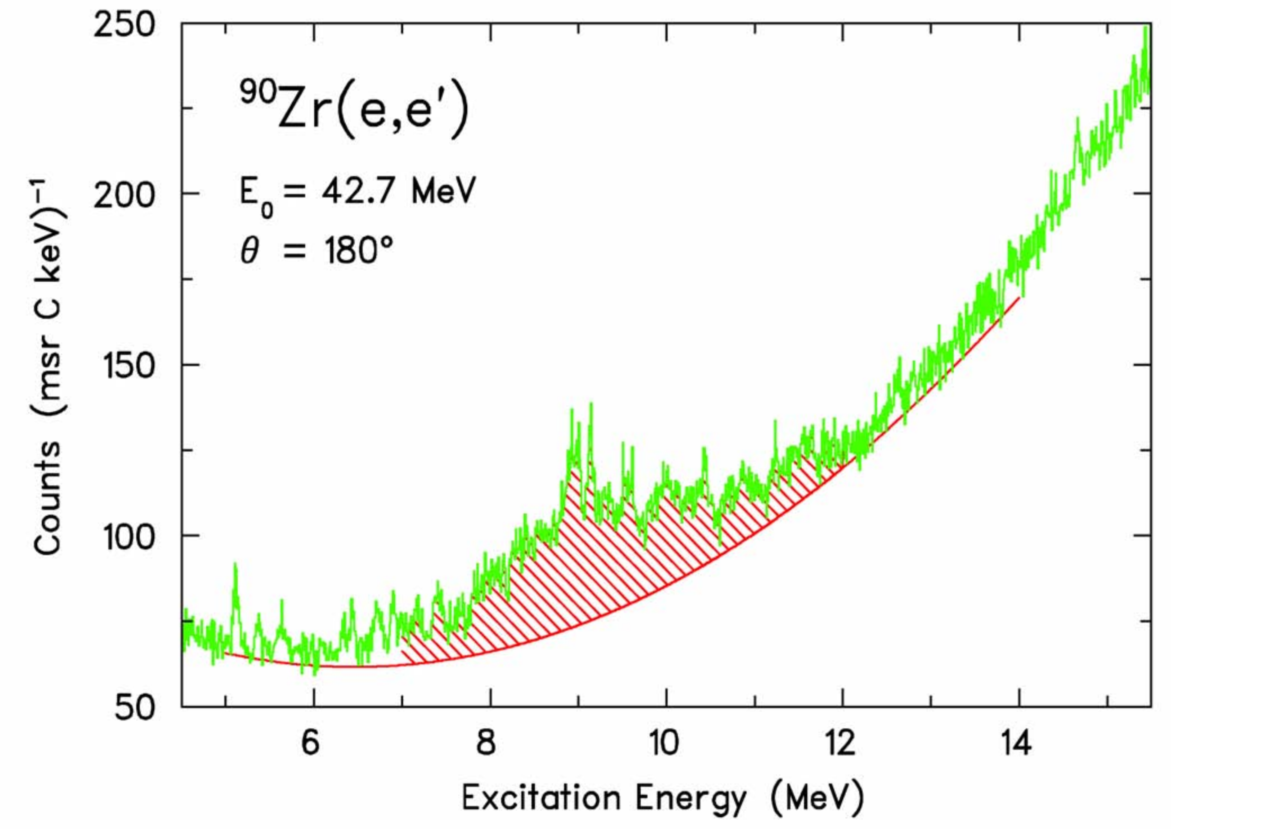


→ measure at 180°

180° Electron Scattering



180° Electron Scattering



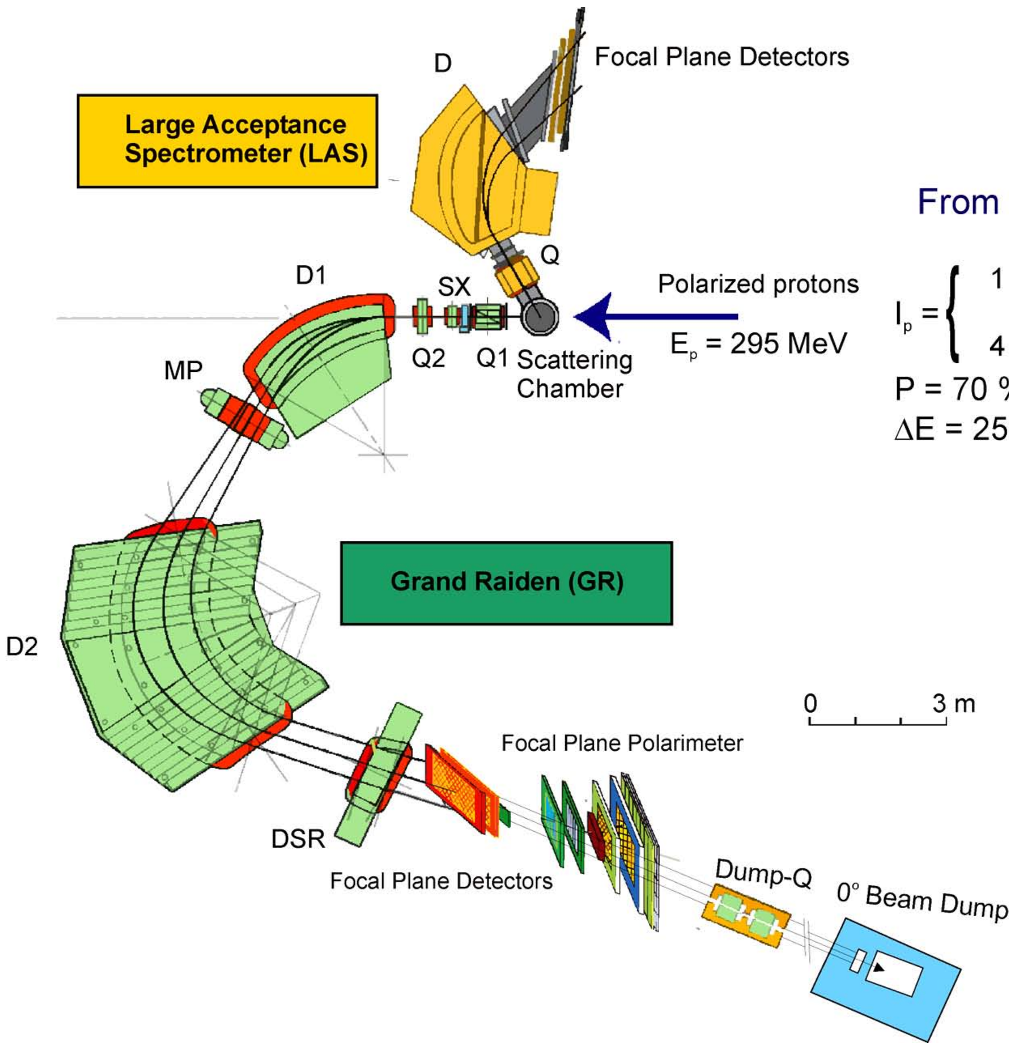
+ by variation of momentum transfer all multipoles can be excited
- physical background (radiative tail), small cross sections

Proton Scattering: Accelerators

RCNP Osaka

iThemba LABS Cape Town

Proton Scattering: Spectrometer



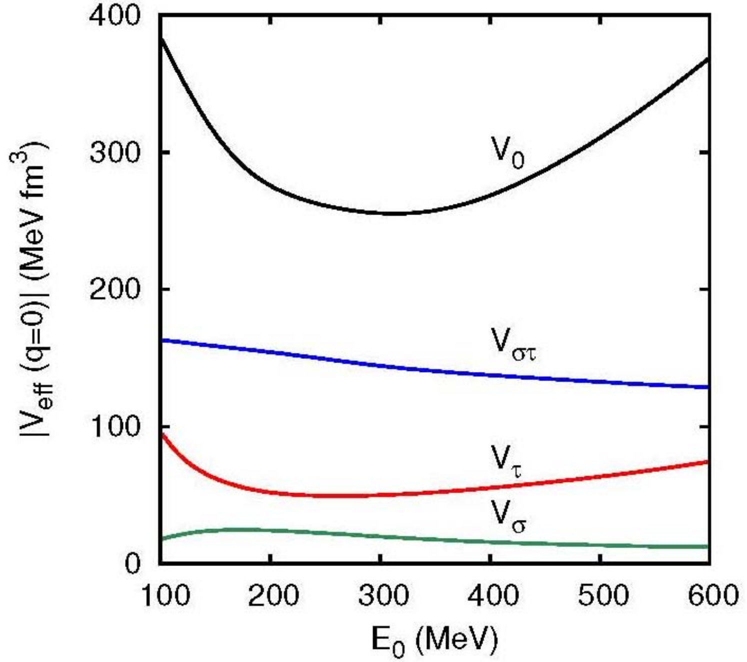
From cyclotrons:

$$I_p = \begin{cases} 1\ \text{nA}\ (\Theta = 0^\circ) \\ 4\ \text{nA}\ (2.5^\circ < \Theta < 10^\circ) \end{cases}$$

P = 70 %

ΔE = 25 - 30 keV

Proton Scattering: Effective Interaction

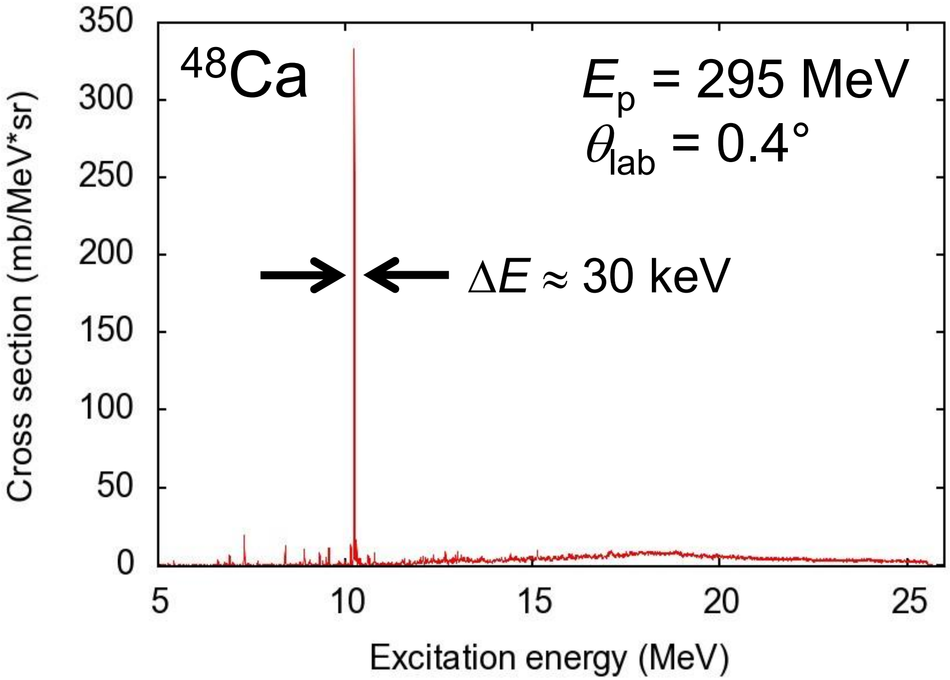


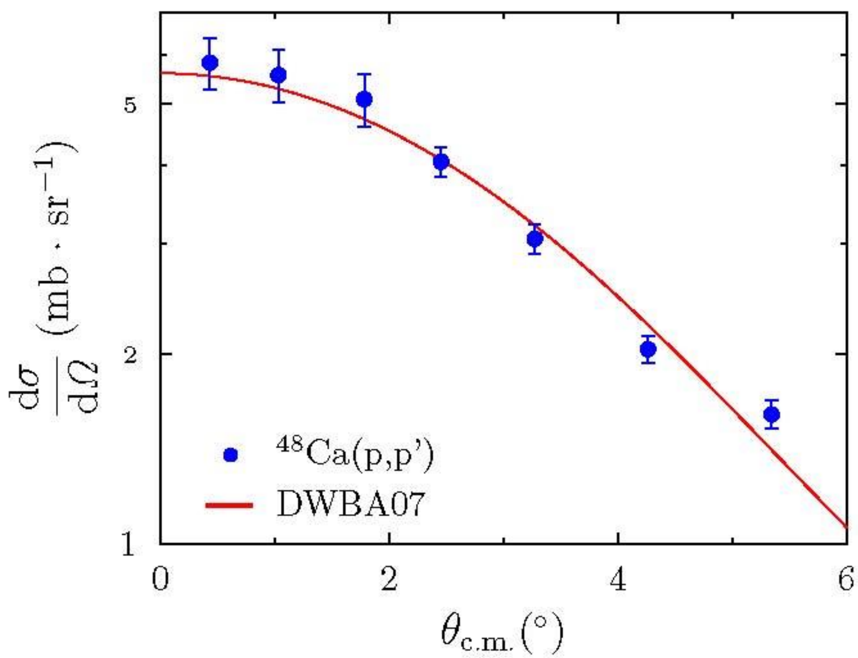
Excitation of 1^+ states requires a spin flip in the scattering process ($V_{\sigma\tau}$ or V_σ)

$\sigma\tau$ operator is the same as for the isovector spin part of M1 operator

Selective excitation at very forward angles (*ΔL = 0*)

Proton Scattering: M1 Selectivity at 0°



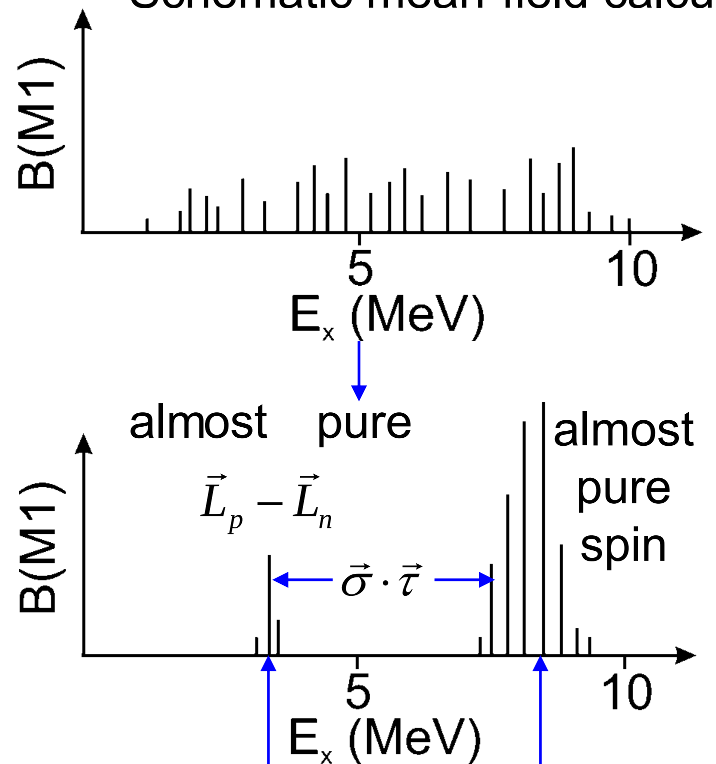


+ Selective to spin part of M1 operator only
- Difficult experiment, model dependence of ME extraction

3. Orbital M1 strength (the scissors mode)

Qualitative Nature of the M1 Response in Nuclei

Schematic mean-field calculation



unperturbed p-h strength

Interaction turned on

weakly strongly collective

“Scissors Mode“

Discovery of the Scissors Mode

G.F. Bertsch, Nature 280, 263 (1979)

Review article on nuclear giant resonances

What is the likelihood of discovering more vibrations? The possibility of more complex motion always exists, and other vibrations can be calculated in RPA. However, all the other modes of particle displacement have a higher mean frequency. …Thus it is unlikely that a coherent mode, containing most of the sum rule, will be resolved as a distinct peak.

Discovery of the Scissors Mode

D. Bohle et al., Phys. Lett. B 137, 27 (1984)

Volume 137B, number 1,2 PHYSICS LETTERS 22 March 1984

NEW MAGNETIC DIPOLE EXCITATION MODE STUDIED IN THE HEAVY DEFORMED NUCLEUS ^{156}Gd BY INELASTIC ELECTRON SCATTERING ☆

D. BOHLE, A. RICHTER, W. STEFFEN
Institut für Kernphysik der Technischen Hochschule Darmstadt, 6100 Darmstadt, Germany

A.E.L. DIEPERINK
Kernfysisch Versneller Instituut, Rijksuniversiteit Groningen, 9747 AA Groningen, The Netherlands

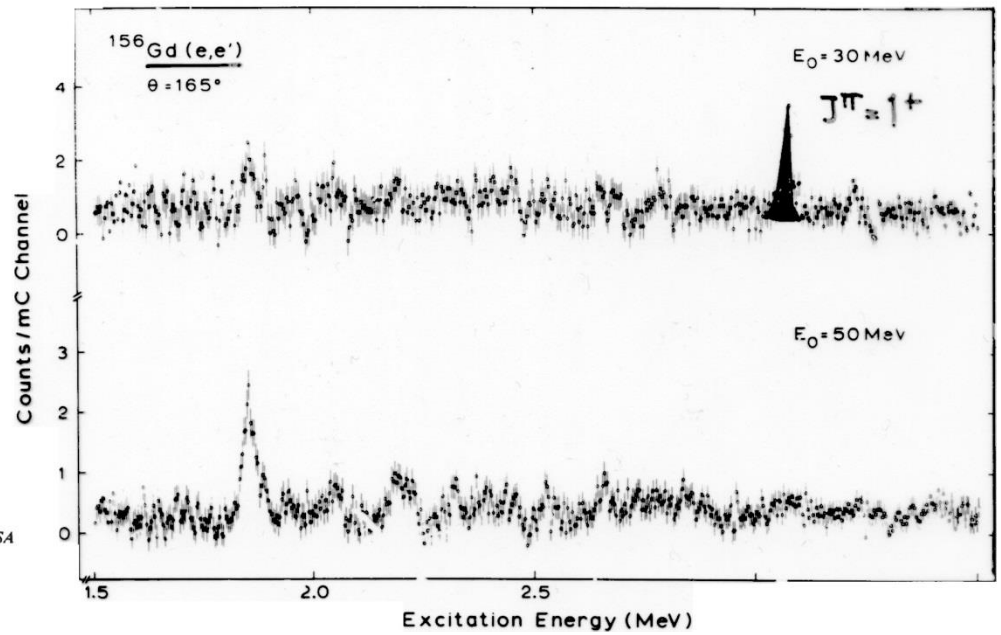
N. LO IUDICE
Istituto di Fisica Teorica dell' Universitá di Napoli, Naples, Italy
and Instituto Nazionale di Fisica Nucleare, Sezione di Napoli, Naples, Italy

F. PALUMBO
Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, 0044 Frascati, Italy

and

O. SCHOLTEN
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824-1321, USA

Received 9 December 1983

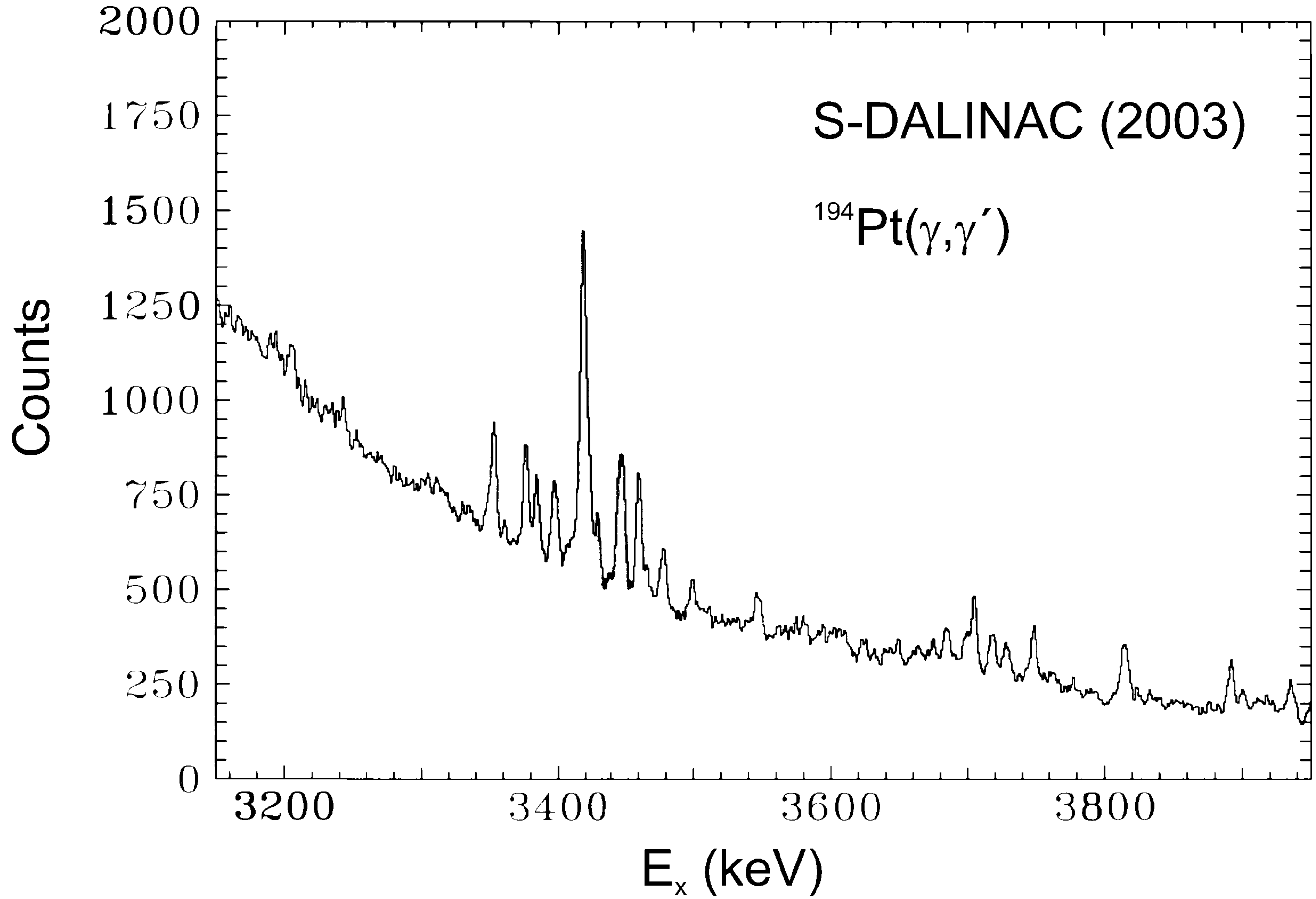


Achim Richter and coworkers (TU Darmstadt)

Web of Science: more than 600 citations!

Fragmentation of Scissors Mode Strength

A. Linnemann et al., Phys. Lett. B 554, 15 (2003)

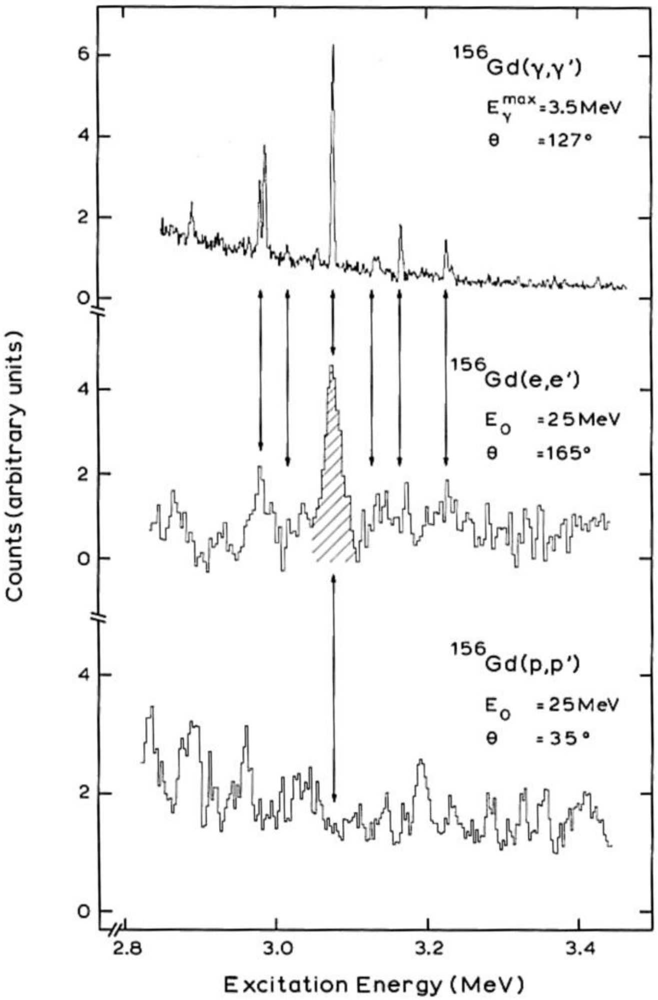


Orbital Nature of the Scissors Mode

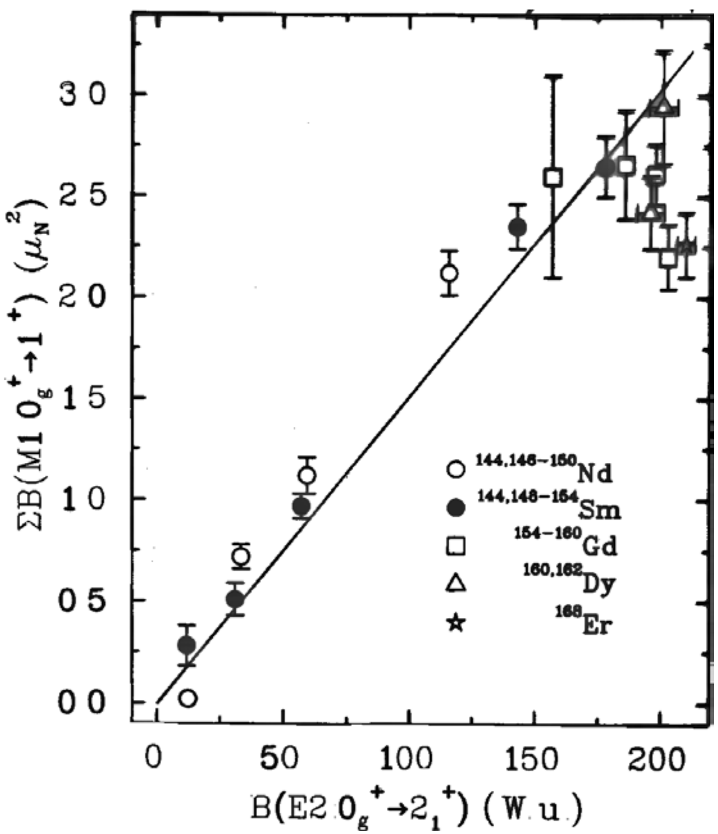
A. Richter, Nucl. Phys. A 507, 99c (1990)

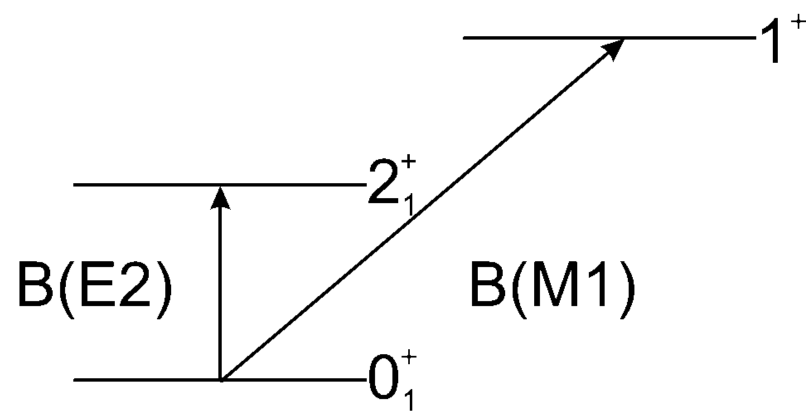
Strongly observed in with electromagnetic probes but not with hadronic probe

→ **orbital excitation**



Correlation between B(M1) and B(E2) strengths

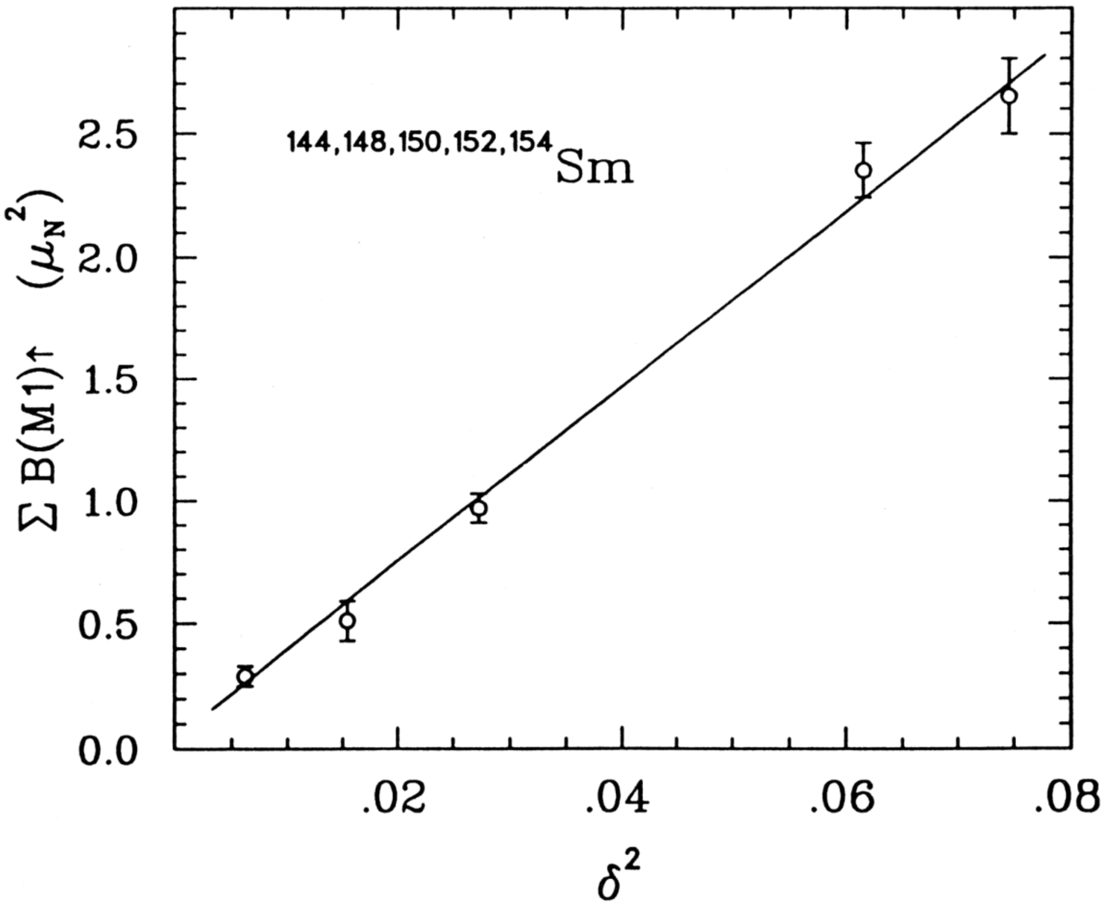




B(E2) ~ δ^2 → strong dependence of scissors mode on deformation

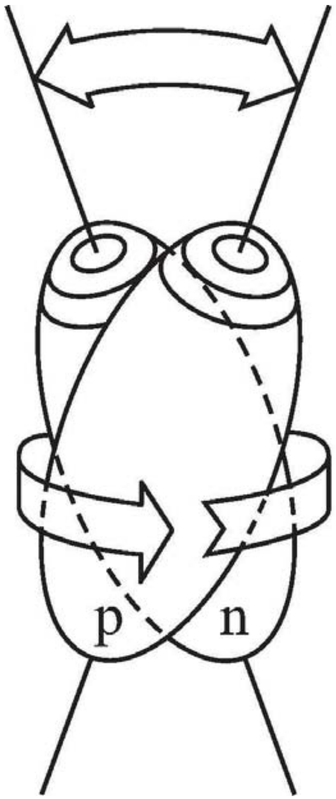
Expectation: B(M1) ~ δ^2

Deformation Dependence of the Scissors Mode

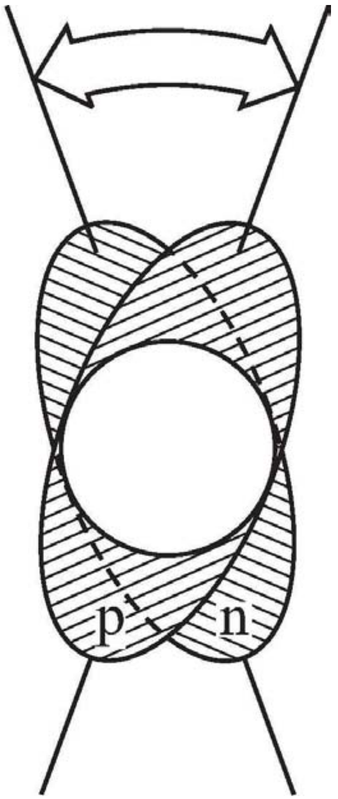


W. Ziegler et al., Phys. Rev. Lett. 65, 2515 (1990)

A Macroscopic Picture of the Scissors Mode

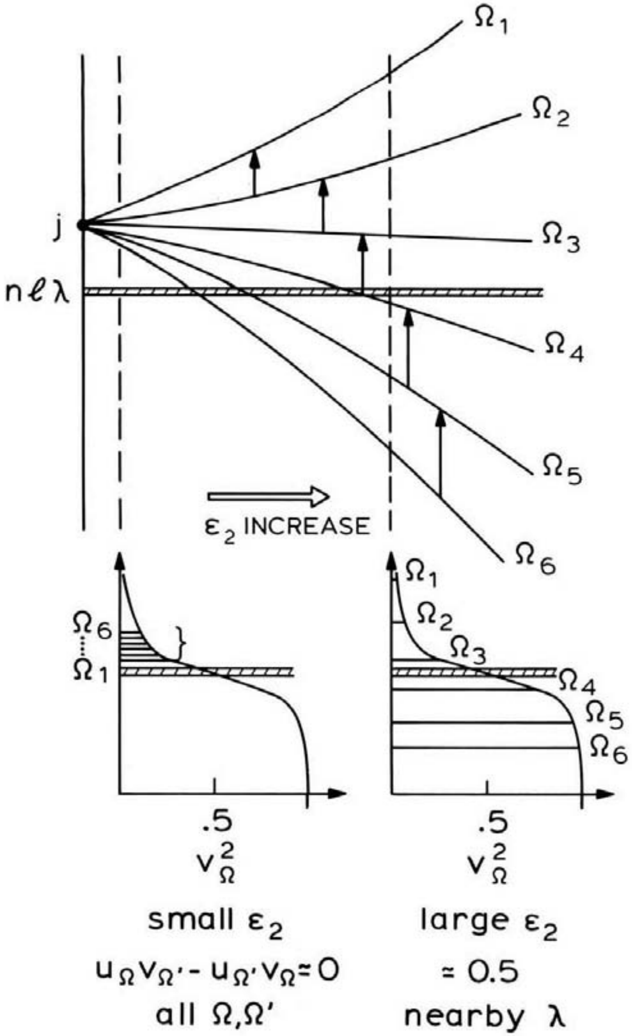


Counter rotation of deformed proton and neutron bodies leads to scissors-like motion



In reality only nucleons in the valence shell contribute

A Microscopic Picture of the Scissors Mode



The substates of a given shell-model state split energetically with increasing deformation

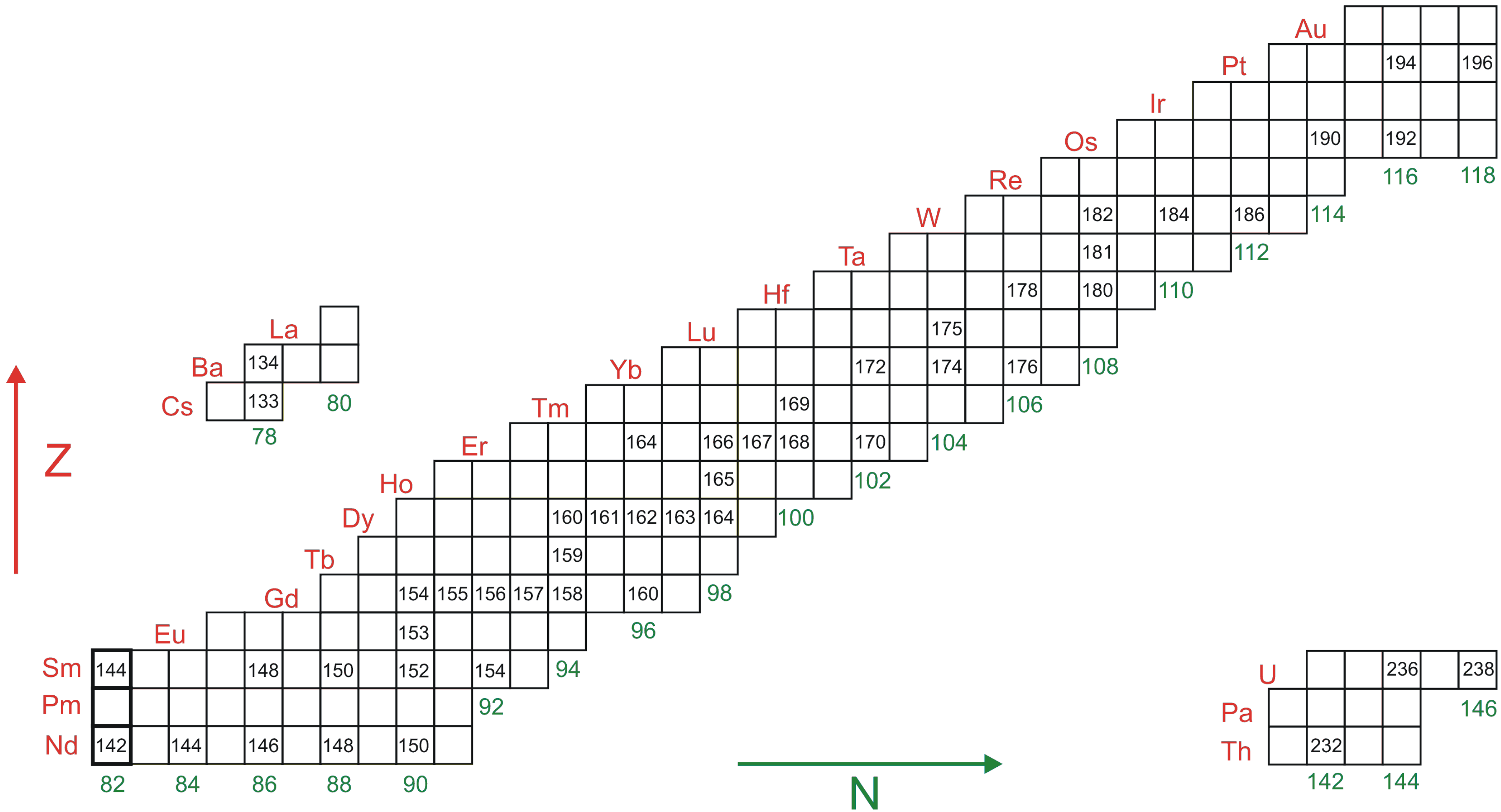
In the deformed limit (Nilsson model) different *K* quantum numbers

Scissors mode corresponds to transitions with *ΔΩ* = 1

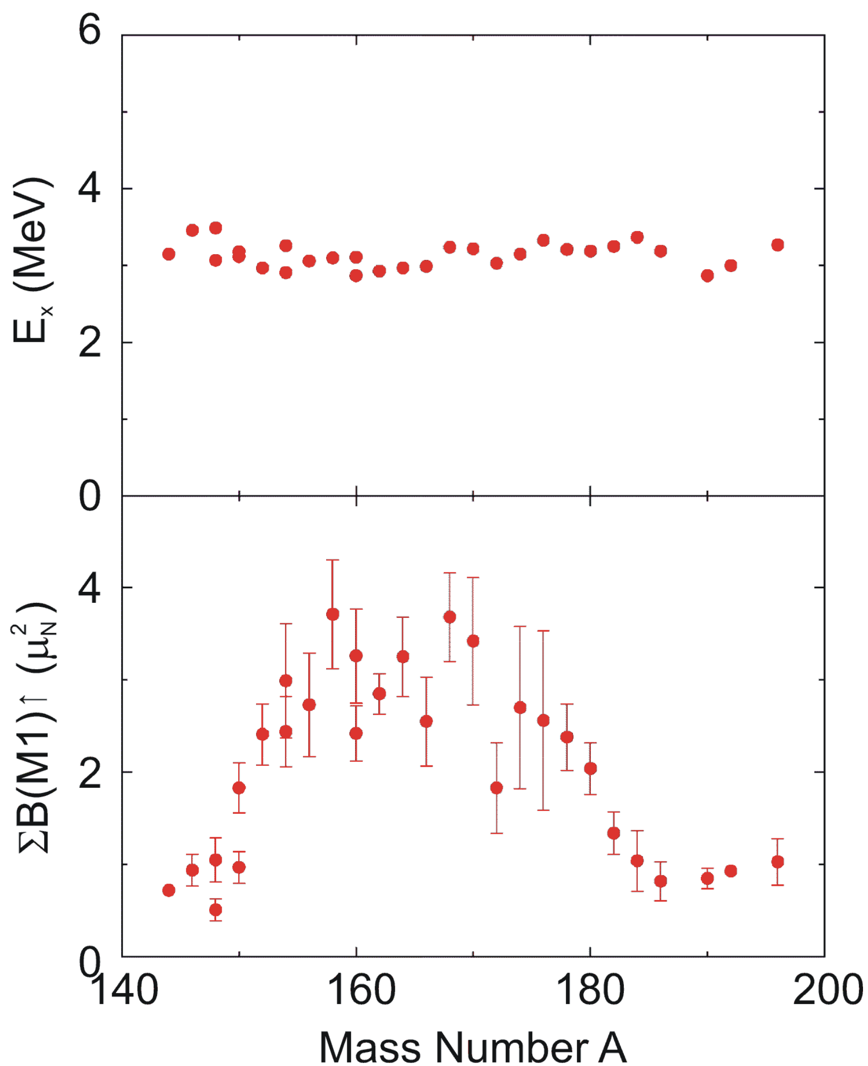
Strength is strongly dependent on occupation factor
→ pairing important!

$$B(M1) = \frac{3}{4\pi}(u_1 v_2 - u_2 v_1)^2 |\langle \Omega_1 | g_l \hat{l}_+ + g_s \hat{s}_+ | \Omega_2 \rangle|^2$$

Systematic Study of the Scissors Mode



Energy and Strength of the Scissors Mode



Excitation energy approximately constant, independent of deformation

Strength depends strongly on deformation: $B(M1) \sim \delta^2 \sim B(E2)$

Sum-Rule Approach

E. Lipparini and S. Stringari, Phys. Rep. 175, 103 (1989)

- Sum rules $$S_j(\mathcal{M}) = \sum_i B_i(\mathcal{M})\, E_{xi}^j$$

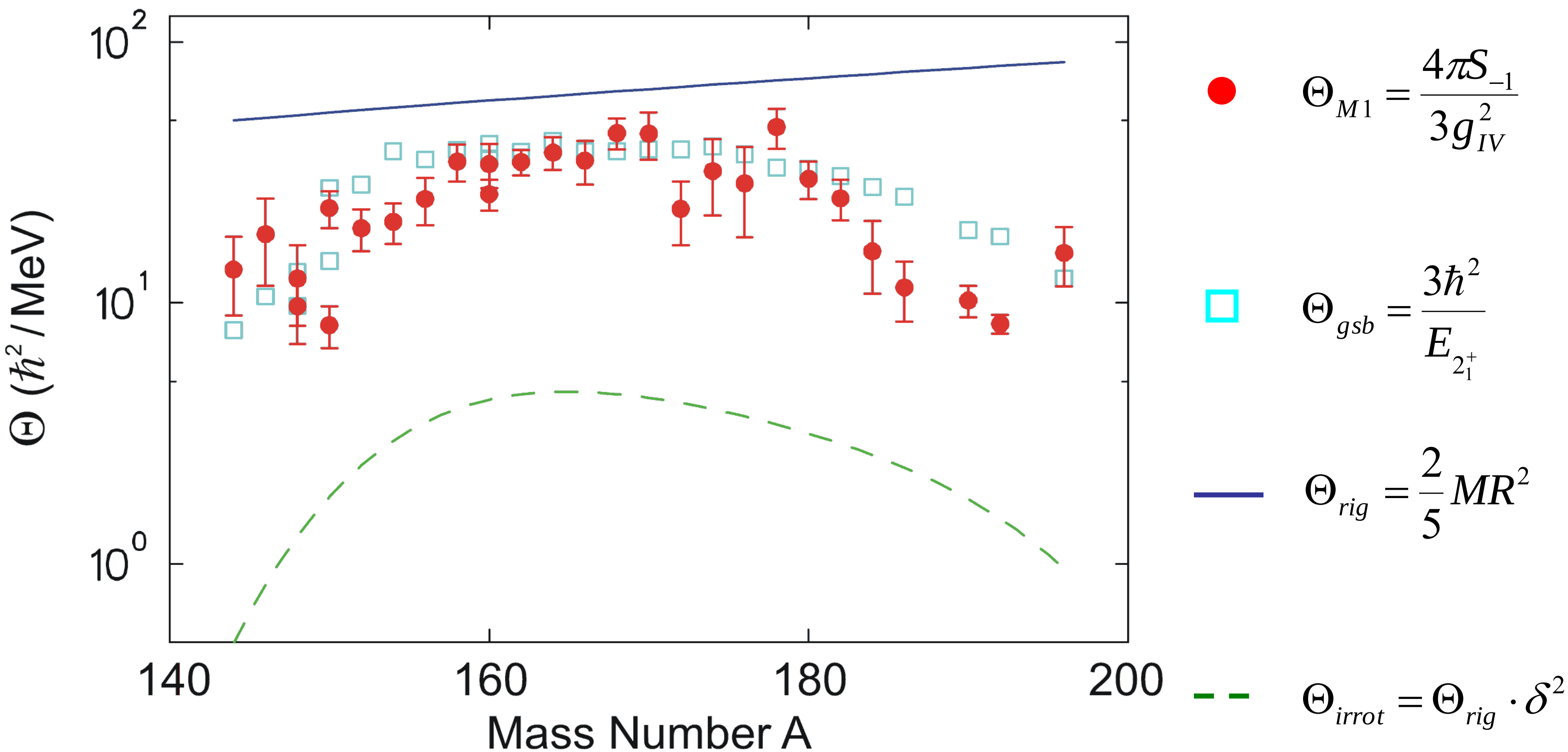
$$\left.\begin{aligned} S_{+1}(M1) &= \frac{3}{5\pi}\, r_0^2\, A^{5/3}\, \delta^2\, E_{GDR}^2\, m_N\, g_{IV}^2 \\ S_{-1}(M1) &= \frac{3}{16\pi}\, \Theta_{M1}\, g_{IV}^2 \end{aligned}\right\} \qquad \begin{aligned} E_x &= \sqrt{S_{+1}/S_{-1}} \\ B(M1) &= \sqrt{S_{+1} \cdot S_{-1}} \end{aligned}$$

- Sum rules depend on two parameters:

$$g_{IV} \approx g_{IS} = g(2_1^+) \qquad \Theta_{IV} = \Theta_{IS} = 3\hbar^2 / E_{2_1^+}$$

Moments of Inertia

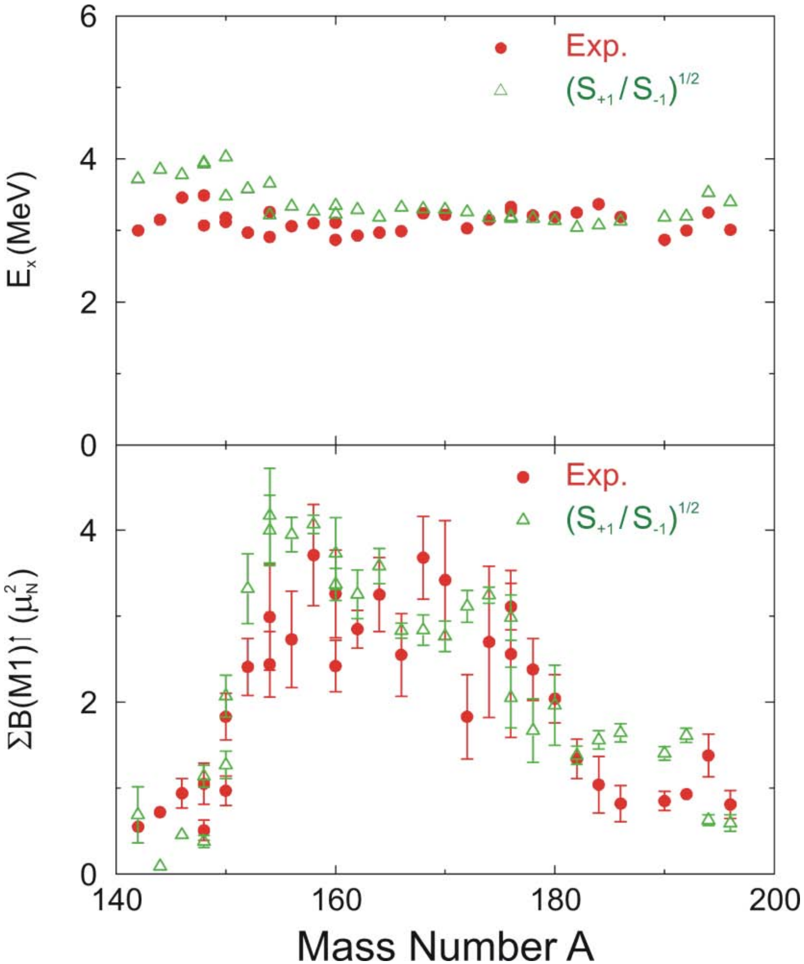
TECHNISCHE UNIVERSITÄT DARMSTADT



- Strong effect of pairing (nuclear superfluidity) is evident

Parameter-Free Sum Rule Description

J. Enders, PvNC, C. Rangacharyulu, A.Richter, Phys. Rev. C 71, 014306 (2005)



$$E_x \sim \sqrt{E_{2_1^+}} \cdot \delta \approx const.$$

contributions from deformation and moment of inertia cancel each other

$$B(M1) \sim \frac{\delta}{\sqrt{E_{2_1^+}}} \sim \delta^2$$

"δ^2 law" results from an interplay of deformation and the moment of inertia

Collectivity

Signatures of collectivity

Exhaustion of sum rules
Coherent addition of many components of the wave functions
Transition strength large compared to single-particle estimate (W.U.)

Collectivity of the scissors mode

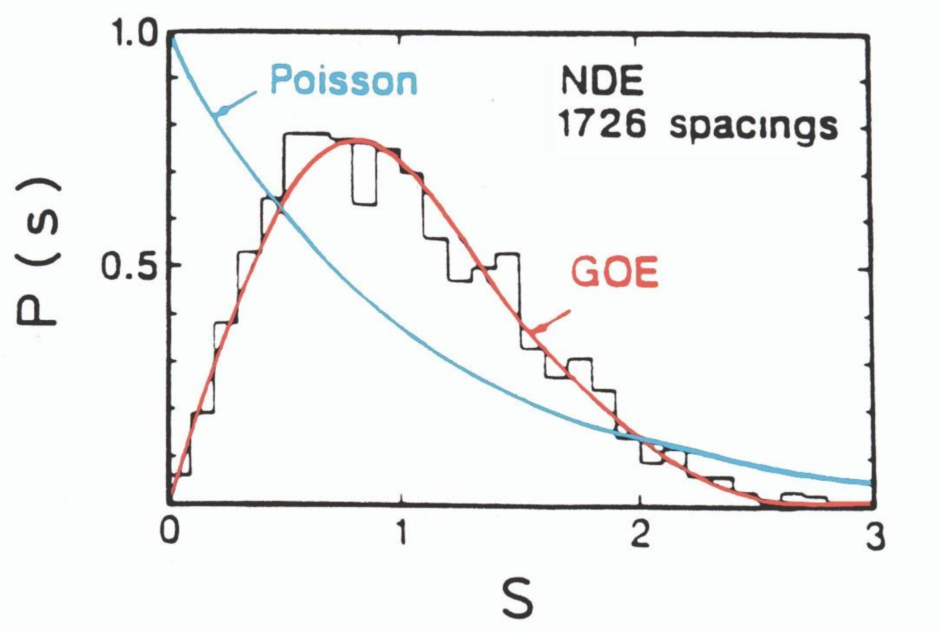
Sum rules can predict energy and strength
Coherence not so clear (model-dependent)
Transition strength ≈ 2 W.U.

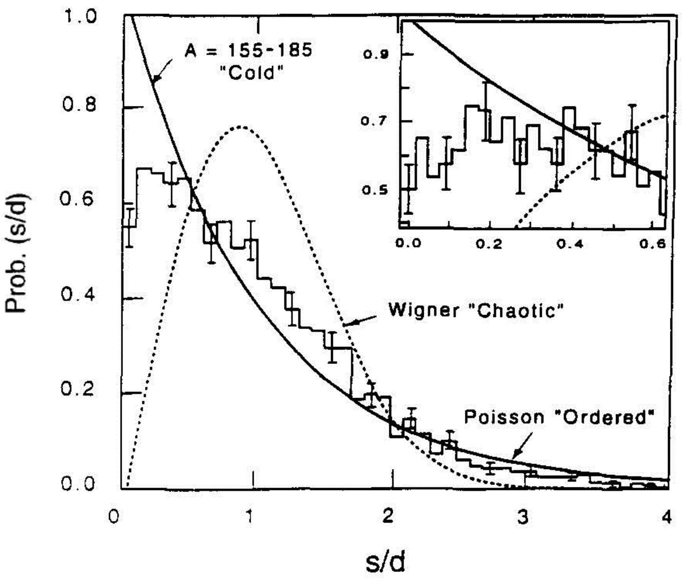
Are there other tests of collectivity?

Level Statistics

R.U. Haq, A. Pandey, O. Bohigas,
Phys. Rev. Lett. 48, 1086 (1982).

J.D. Garrett et al.,
Phys. Lett. B 392, 24 (1997)





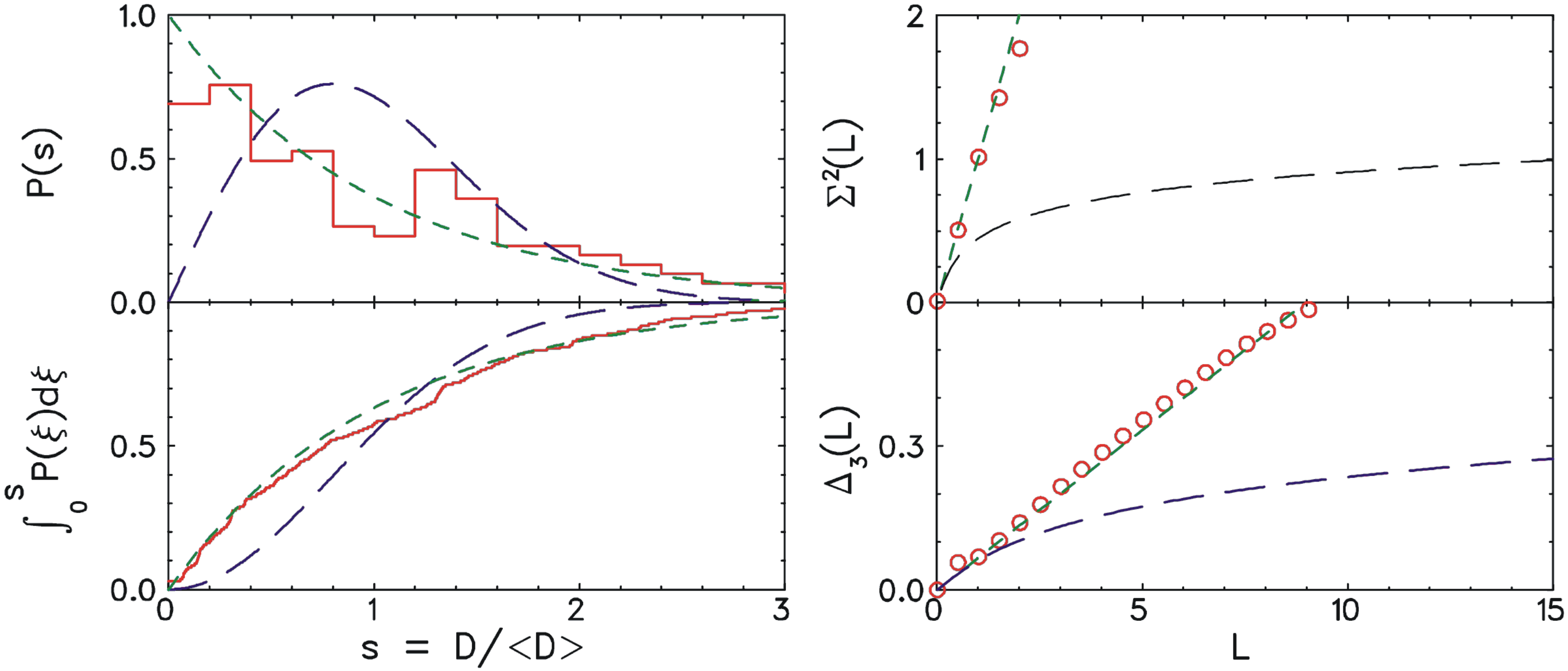
Neutron capture s-wave resonances

Yrast transitions in deformed nuclei

Level Spacing Distribution of Scissors Mode

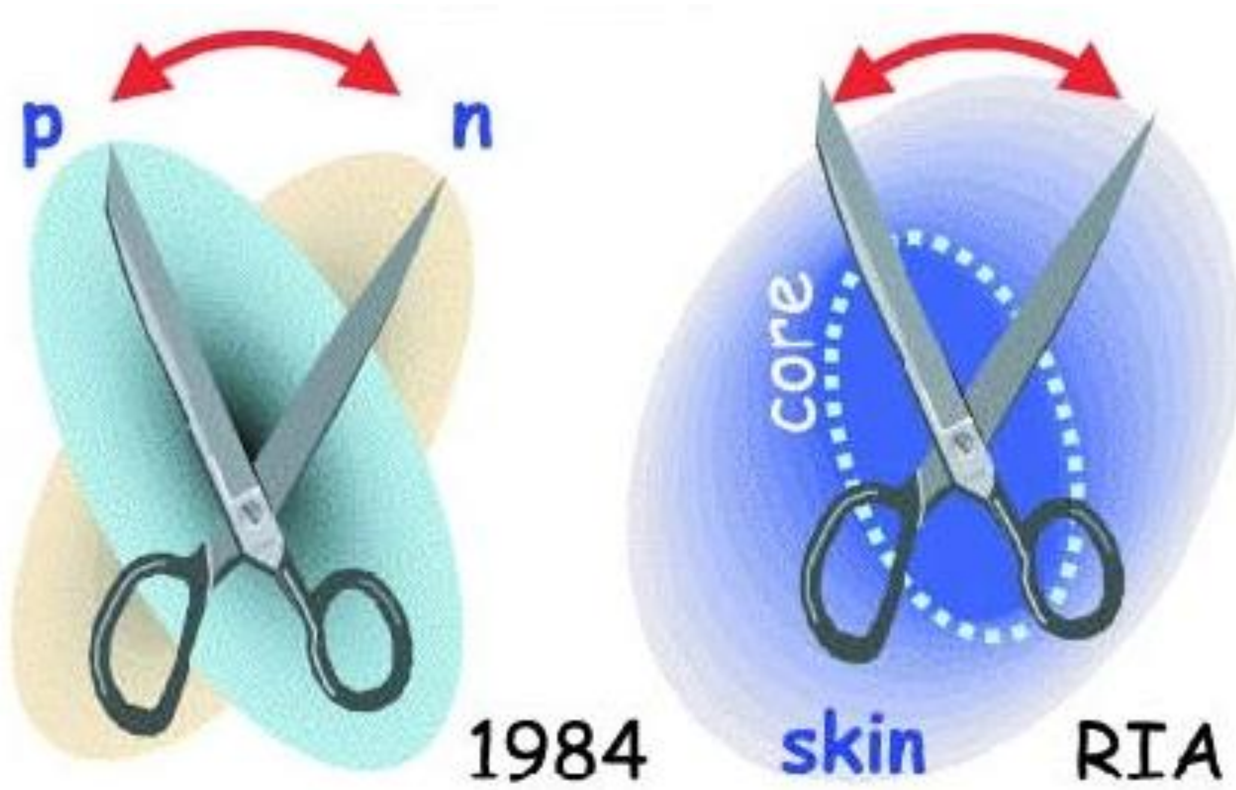
J. Enders et al., Phys. Lett. B 486, 273 (2000)

Nuclear data ensemble: 152 $J^{\pi} = 1^{+}$ states from 13 nuclei



- Proof of a simple collective excitation

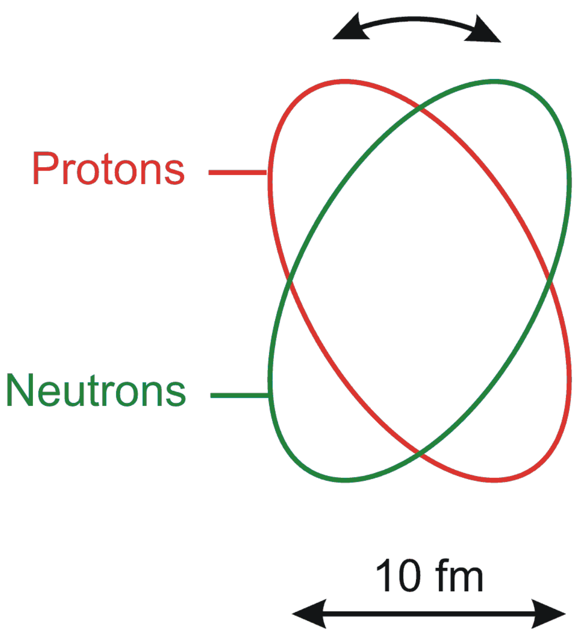
Scissors Mode Coupled to a Neutron Skin



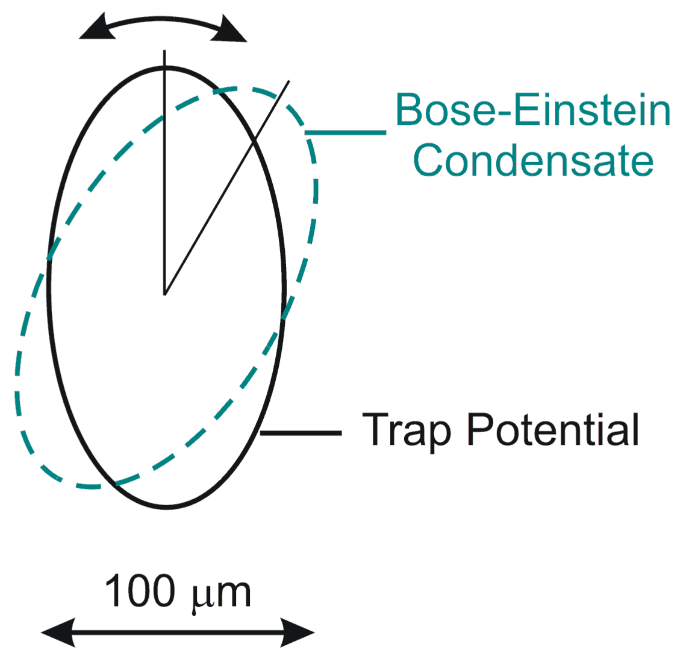
- Theoretical studies needed
- M1 strength at threshold in nuclei along the r-process path

Scissors Mode in a Trapped BEC

Deformed Nucleus



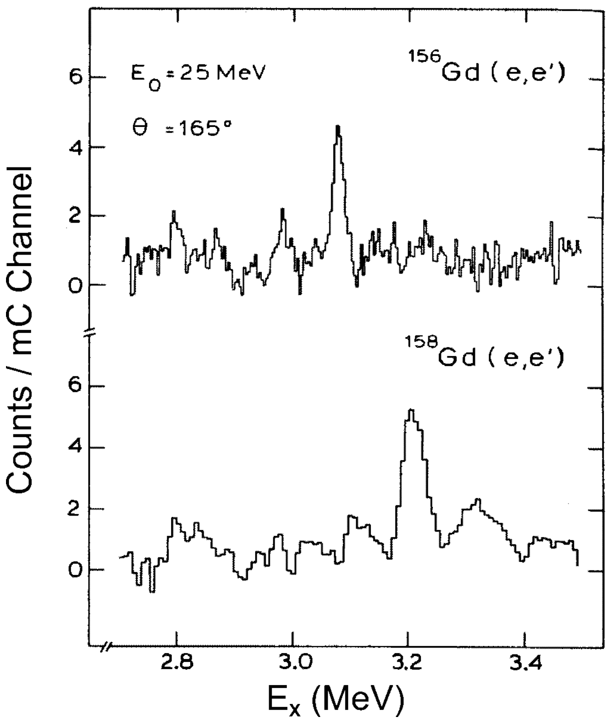
Trapped BEC

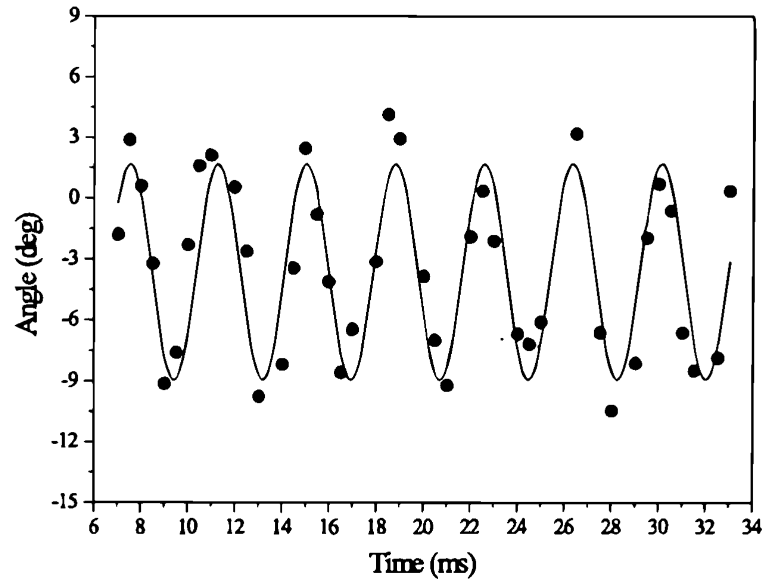


- Superfluidity ?
- Moment of inertia ?

D. Guéry-Odelin and S. Stringari
Phys. Rev. Lett. 83, 4452 (1999)

Scissors Mode in a Trapped BEC





$\nu \approx 7 \cdot 10^{20}\ s^{-1}$

$\alpha \approx 6.0°$ (collective model)

D. Bohle et al.,
Phys. Lett. B 137, 27 (1984)

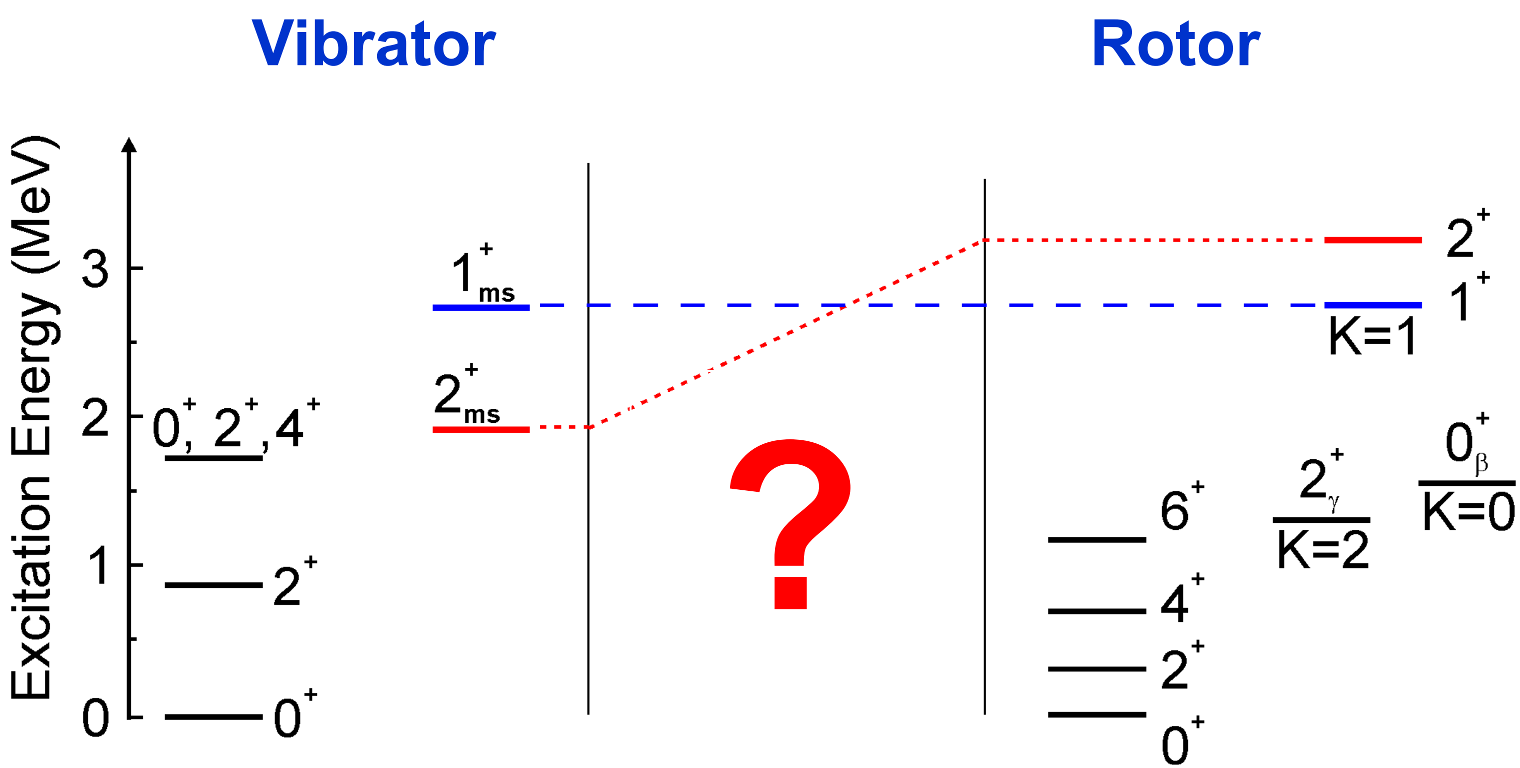
$\nu \approx 3 \cdot 10^{2}\ s^{-1}$

$\alpha \approx 5.5°$ (measured)

O.M. Marago et al.,
Phys. Rev. Lett. 84, 2056(2000)

Transition Deformed-Spherical Nuclei

What happens to the scissors mode when approaching spherical nuclei?



Interacting Boson Model

TECHNISCHE UNIVERSITÄT DARMSTADT

Pairing of nucleons to *s* and *d* bosons (IBM-1)

Distinguish proton and neutron bosons (IBM-2)

Introduce *F*-spin in analogy to isospin

π boson: $F_0 = +1/2$

υ boson: $F_0 = -1/2$

$$\frac{|N_\pi - N_\upsilon|}{2} \leq F \leq F_{max} = \frac{N_\pi + N_\upsilon}{2}$$

$F = F_{max} \rightarrow$ symmetric (isoscalar) state

$F < F_{max} \rightarrow$ mixed-symmetric (isovector) state

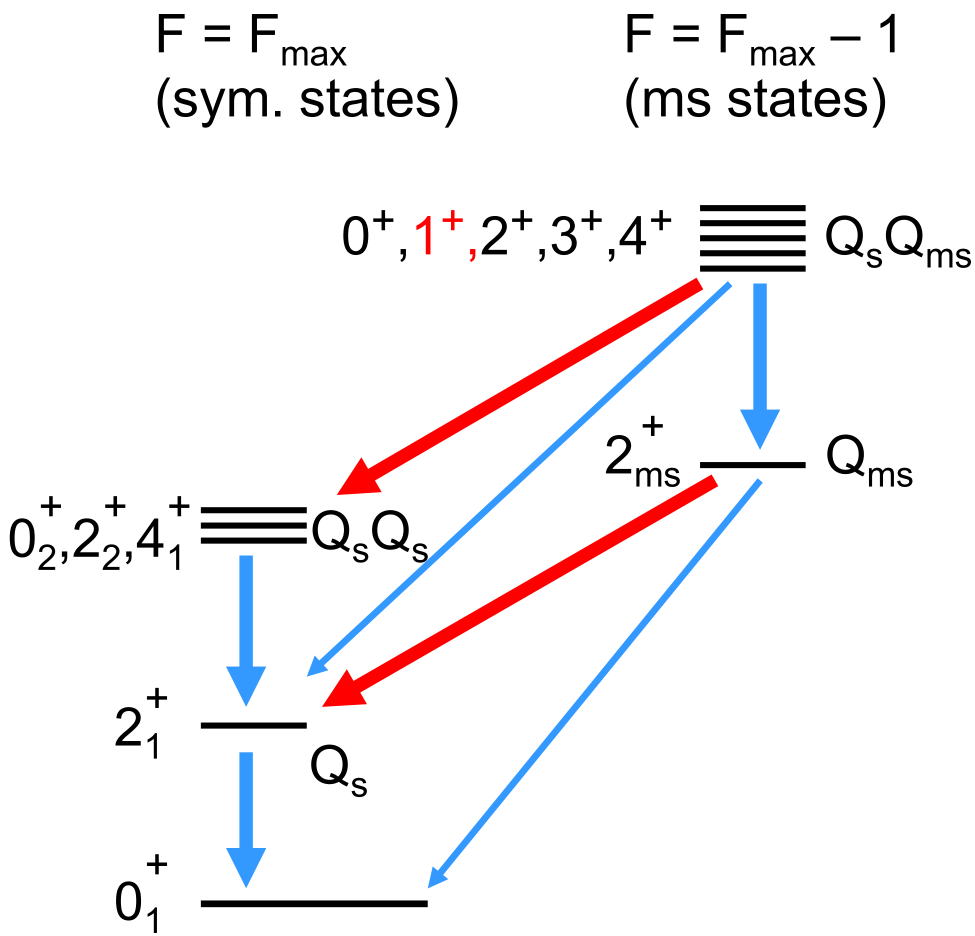
Q-phonon scheme

Isoscalar $\quad Q_s = Q_\pi + Q_\nu \qquad |2_1^+\rangle \propto Q_S |0_1^+\rangle$

Isovector $\quad Q_{ms} = \frac{N}{2}\left(\frac{Q_p}{N_\pi} - \frac{Q_\nu}{N_\nu}\right) \qquad |2_{ms}^+\rangle \propto Q_{ms} |0_1^+\rangle$

only valence-shell excitations!

Mixed-Symmetry States in Vibrational Nuclei



Strong E2 transitions for decay of symmetric Q-phonon

Weak E2 transitions for decay of ms Q-phonon

Strong M1 transitions for decay of ms states to symmetric states

M1 transitions are orbital because of operator $(\boldsymbol{L}_p - \boldsymbol{L}_n)$

Demonstrated for ^{94}Mo: N. Pietralla et al., Phys. Rev. Lett. 83, 1303 (1999)

TECHNISCHE
UNIVERSITÄT
DARMSTADT

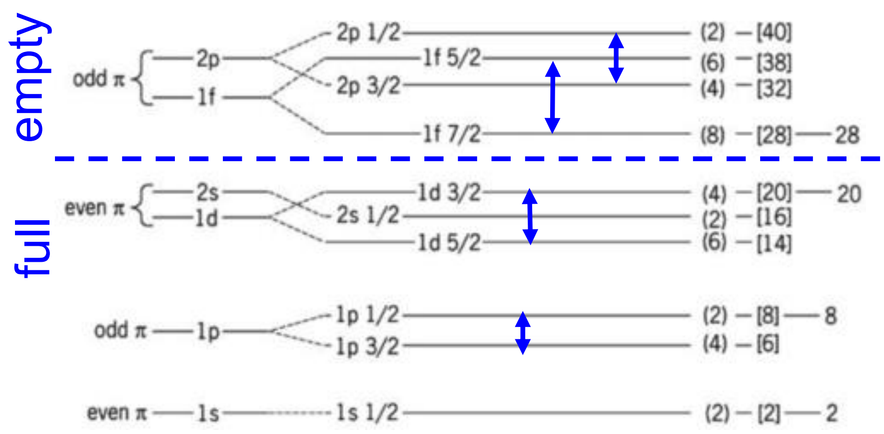
Further reading

K. Heyde, PvNC, A. Richter
Rev. Mod. Phys. 82, 2375 (2010)

4. Spin M1 strength and quenching of spin-isospin response

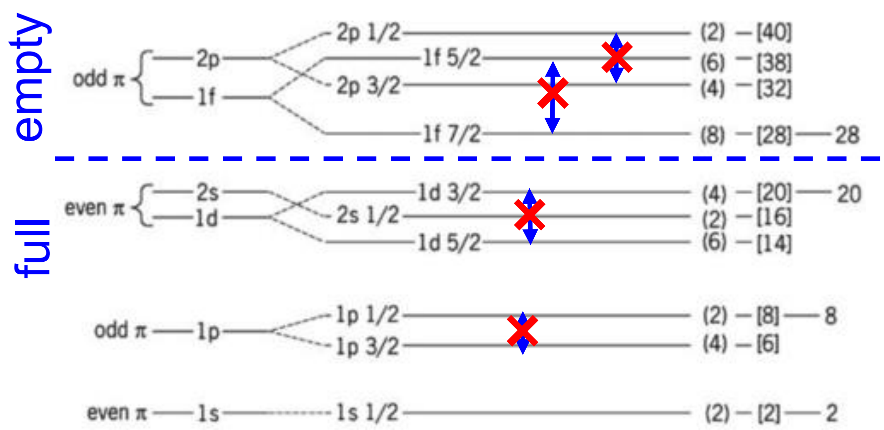
Spin-M1 Strength in 40Ca

^{40}Ca is doubly magic (N = Z = 20)



Spin-M1 Strength in 40Ca

^{40}Ca is doubly magic (N = Z = 20)



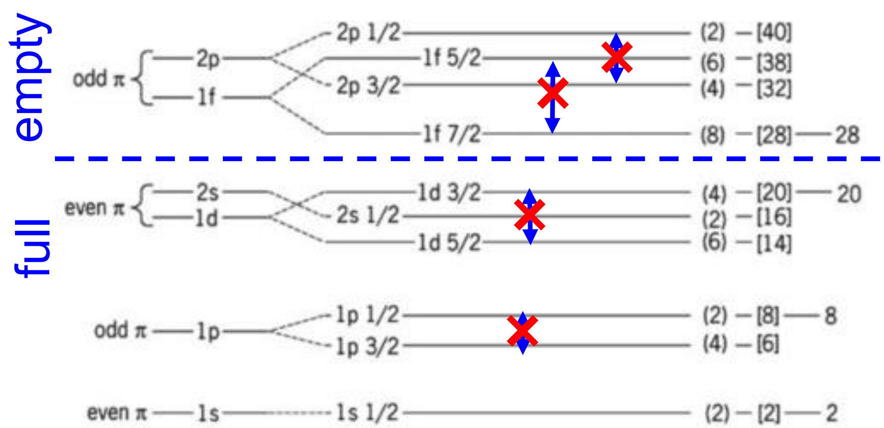
^{40}Ca is *LS* saturated

No particle-hole transitions between spin-orbit partners possible
→ no spin-M1 strength

yet….

Spin-M1 Strength in 40Ca

^{40}Ca is doubly magic (N = Z = 20)

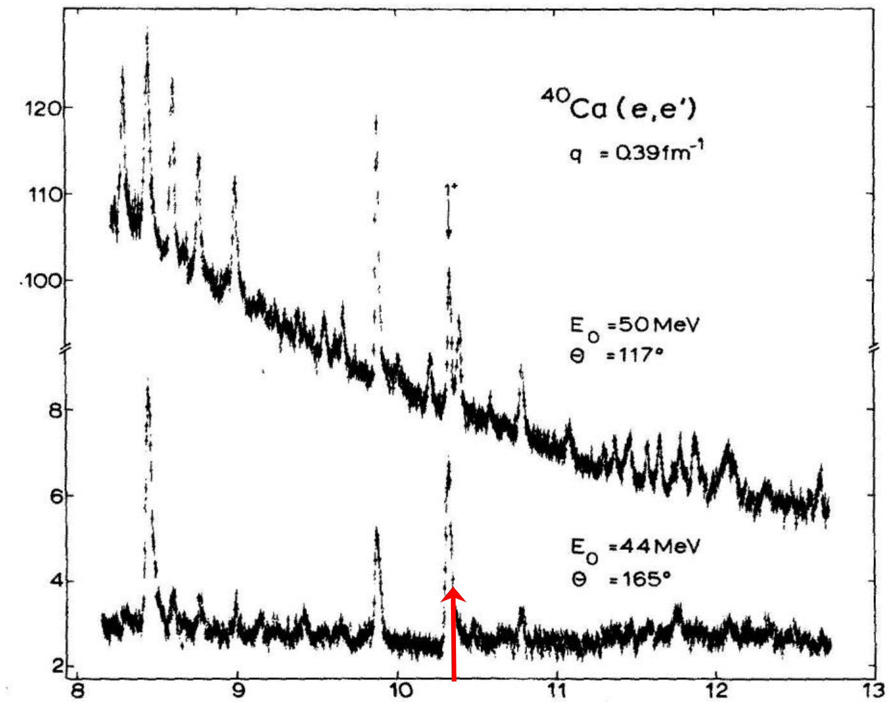


^{40}Ca is *LS* saturated

No particle-hole transitions between spin-orbit partners possible
→ no spin-M1 strength

yet….

D. Meuer et al., Phys. Lett. B 84, 296 (1979)



Strong M1 transition: B(M1) = 1.1 μ_N^2

Shell closure is broken

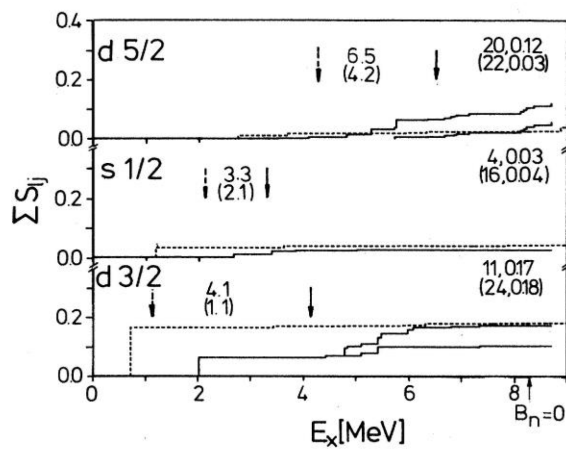
^{40}Ca shell closure

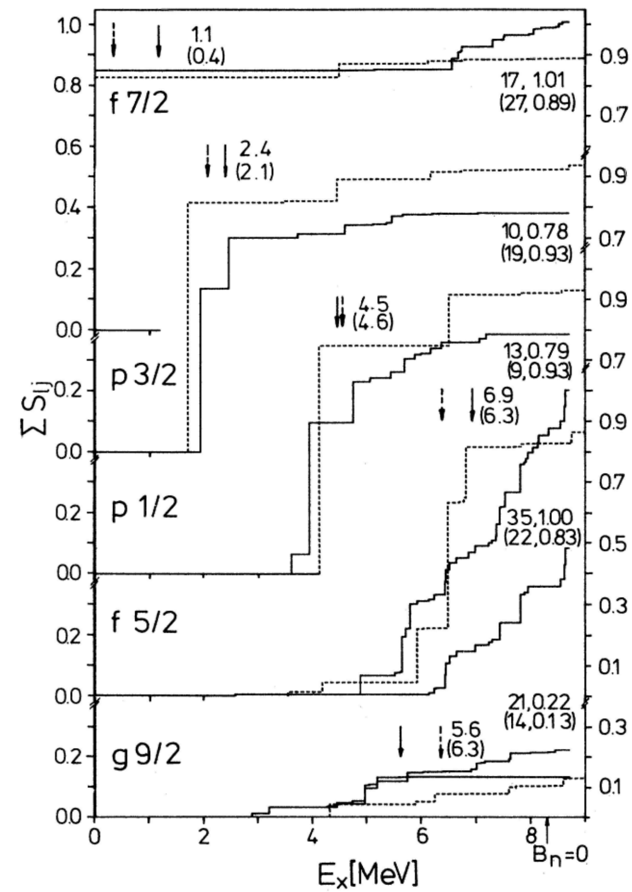
F.J. Eckle et al., Phys. Rev. C 39, 1662(R) (1989)

Study with ^{40}Ca(pol d, p)^{41}Ca reaction

Summed spectroscopic factor for a given single-paticle orbital = number of particles which can be transferred to the orbital

Closed shell = 0, empty shell = *2j+1*





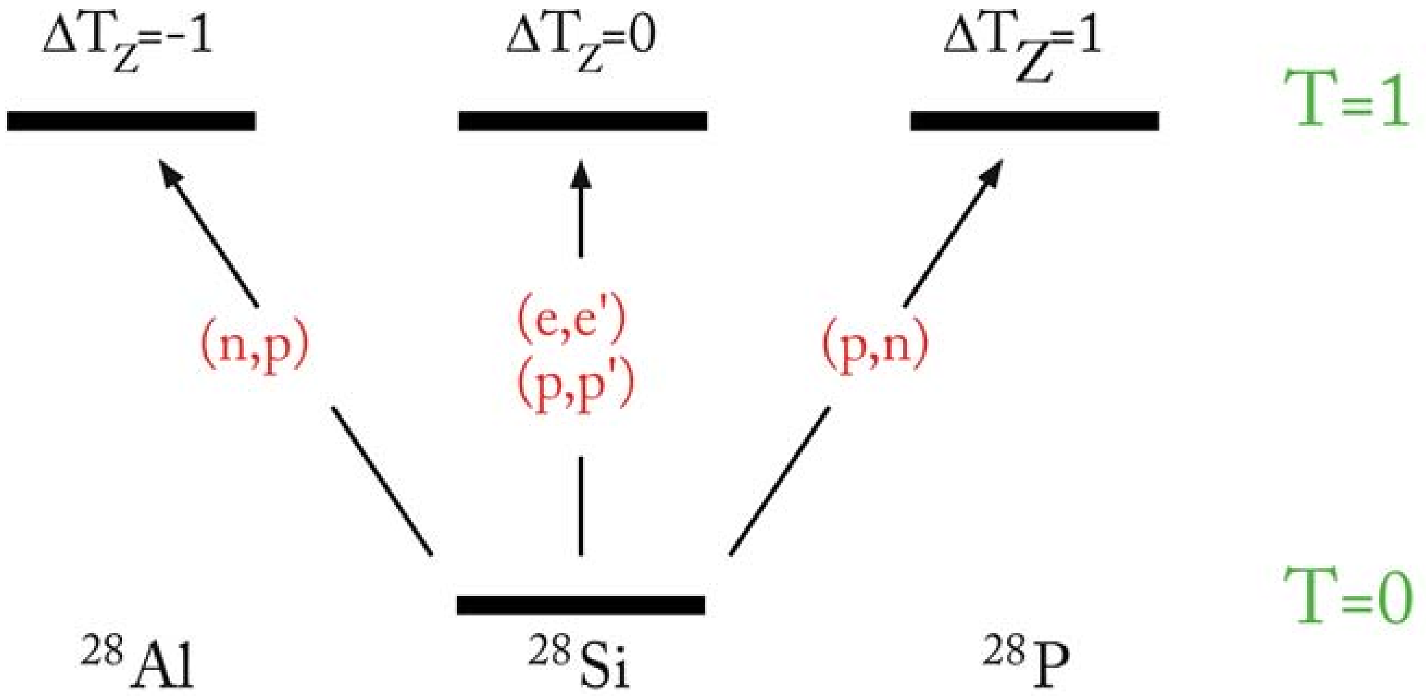
Residual interaction between alike π and ν orbitals is particularly strong

Relation of M1 and Gamow-Teller Strength

Spin-M1 and GT transitions are mediated by the same (στ) operator

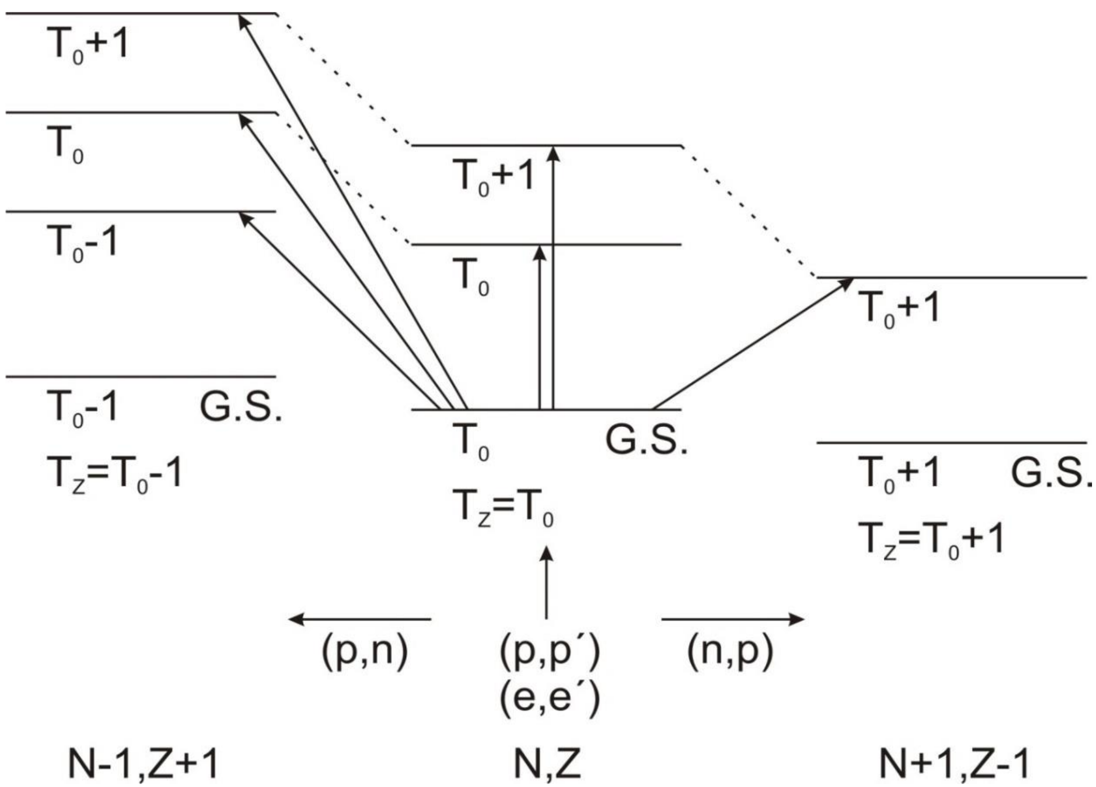
→ excited states are **isospin-analogue states**

Simple example ($T_0 = 0$)



General Isospin Symmetry

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



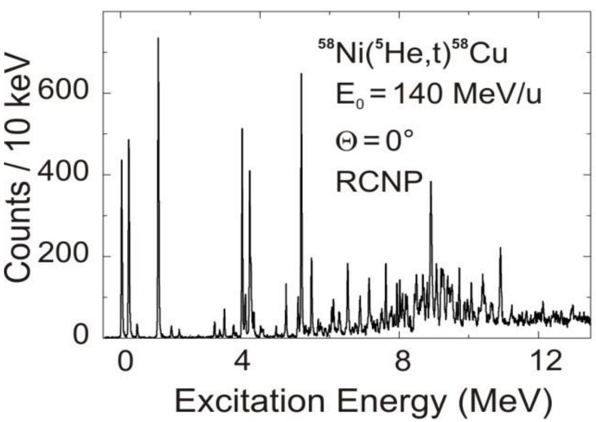
β^- decay

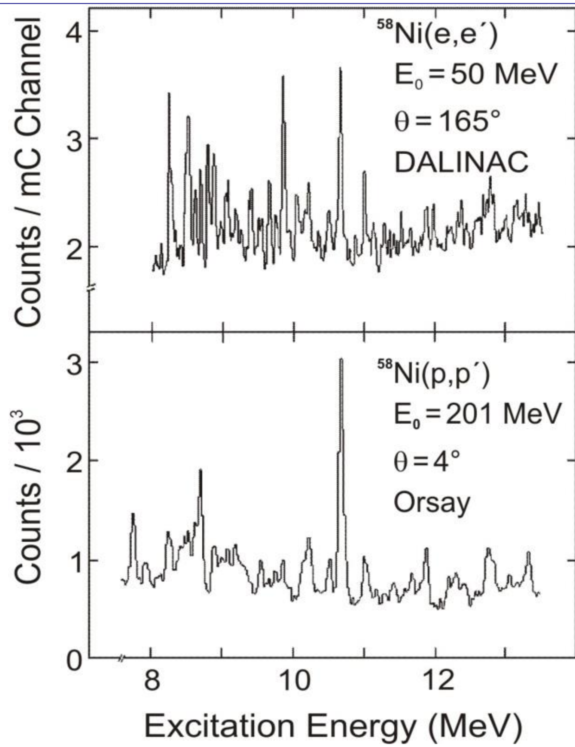
β^+ decay

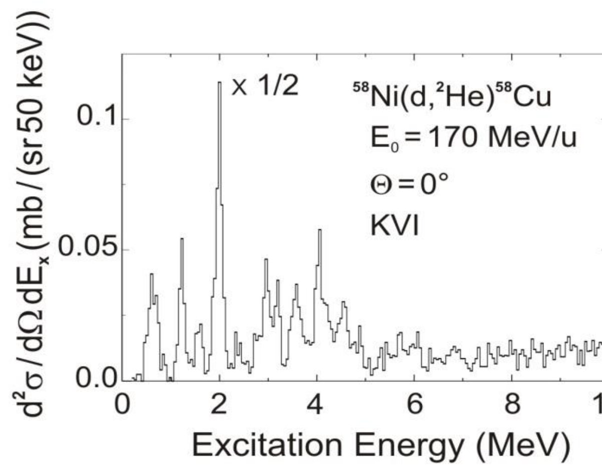
Example: ^{58}Ni

TECHNISCHE UNIVERSITÄT DARMSTADT

GT^- | GT_0 | GT^+







H. Fujita et al.,
Phys. Rev. C 75, 034310 (2007)

W. Mettner et al.,
Nucl. Phys. A 473, 160 (1987)

M. Hagemann et al.,
Phys. Lett. B 579, 251 (2004)

- Benchmark tests of modern microscopic nuclear theory

Quenching of Spin-M1 and GT Strength

What is meant by **quenching**?

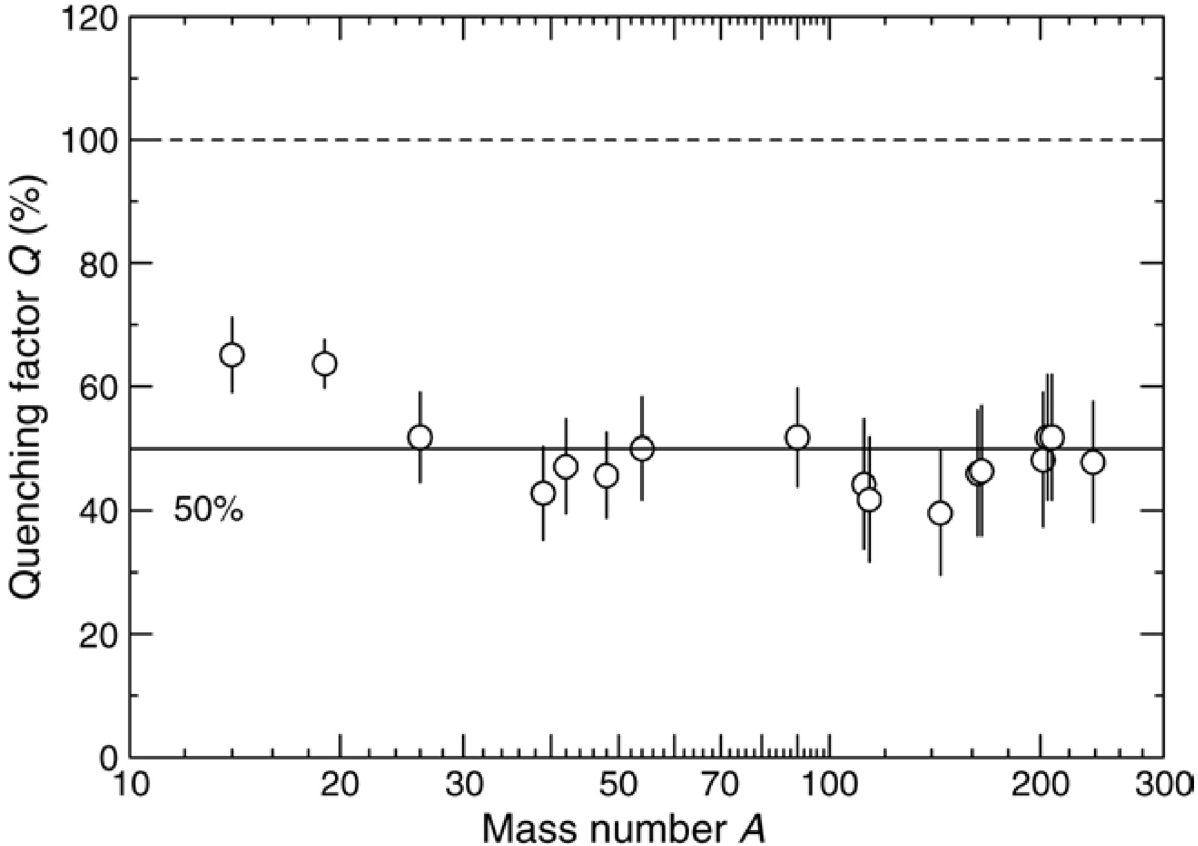
Spin-M1 (or GT) resonance is a valence-shell (0 $\hbar\omega$) excitation
$\rightarrow$ confined in a certain excitation energy region

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

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

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

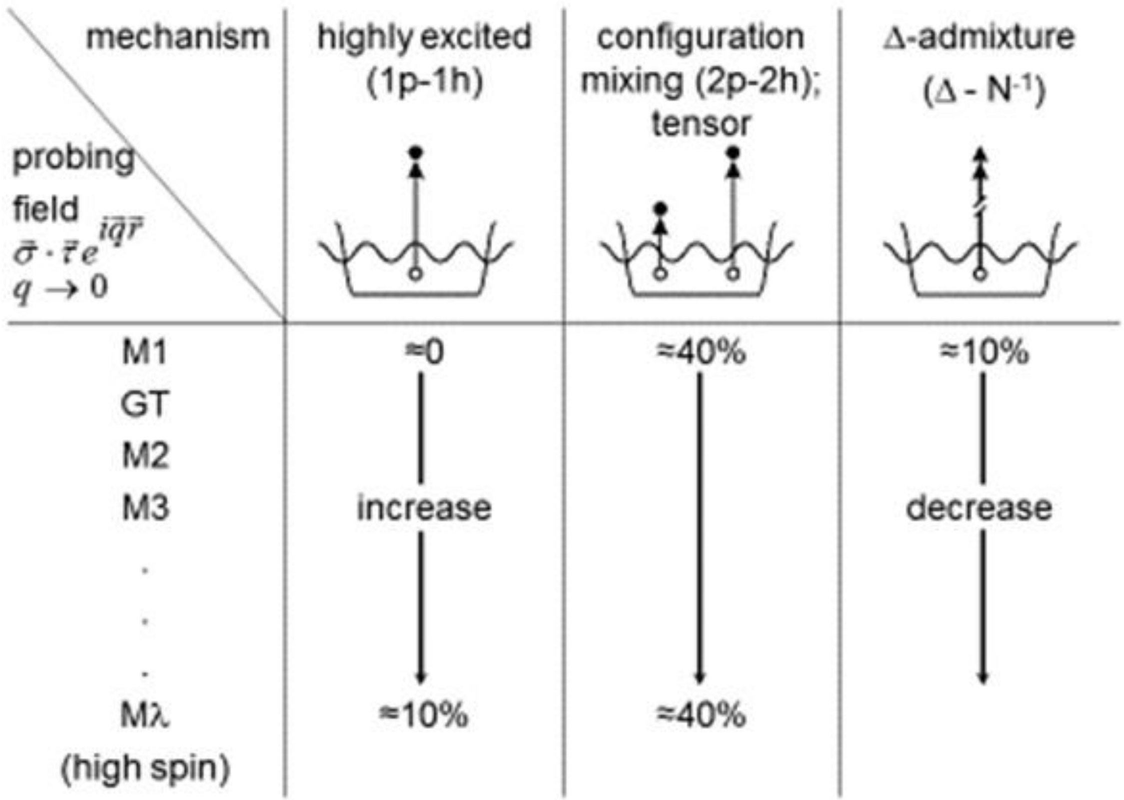
Quenching of GT Strength



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 – Isospin Strength

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



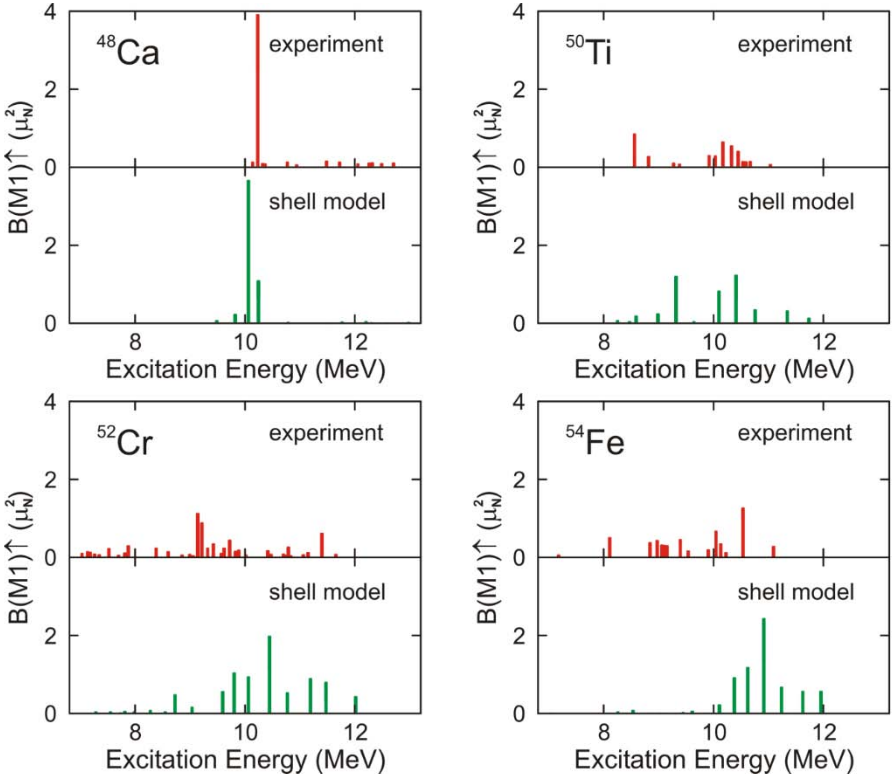
$\vec{\sigma}\cdot\vec{\tau}$ strength ≈ 50% reduced

M1 Strength: Theoretical Approaches

- 2nd RPA (2p - 2h) + $n\hbar\omega$
- SM (np - nh) + $0\hbar\omega$ (one major shell)
- Example: N=28 isotones

N=28 Isotones: Experiment vs. Shell Model

Data from (e,e‘) scattering: D. Sober et al., Phys. Rev. C 31, 2054 (1985)

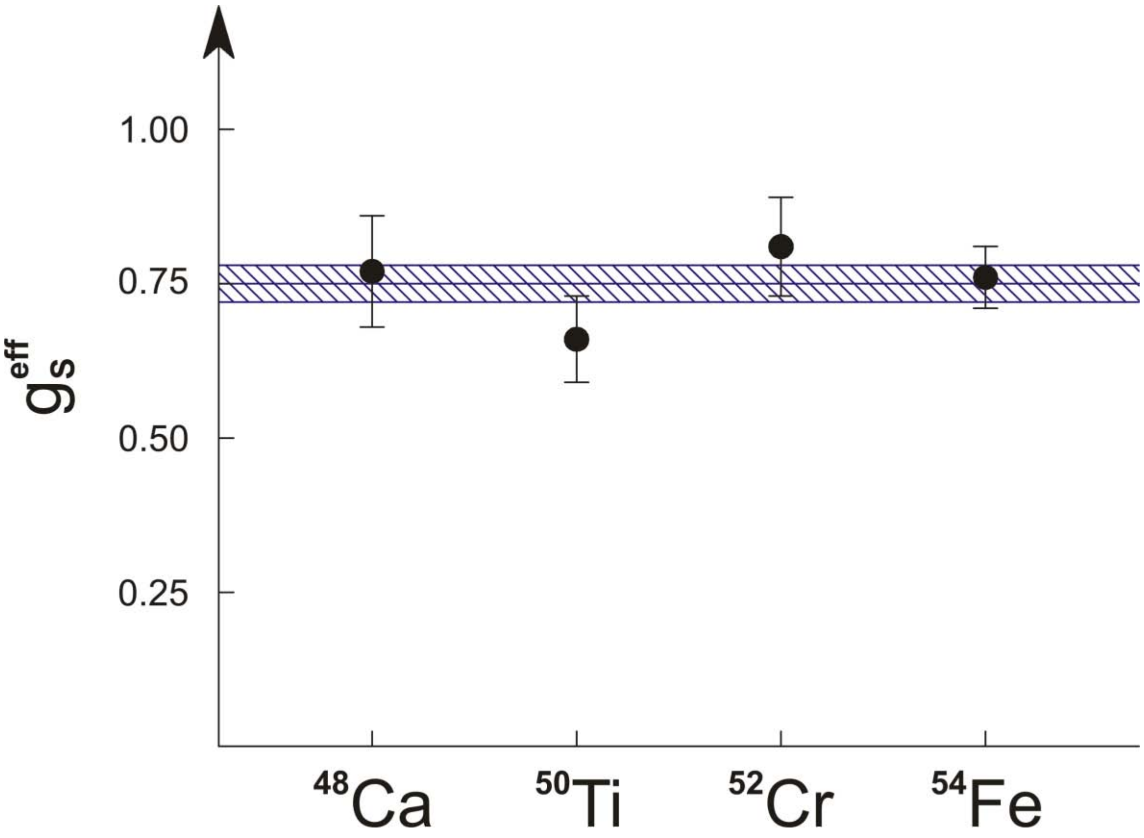


Data show considerable fine structure: sign of configuration mixing

Global description quite good (apart from the interaction KB3 → KB3G)

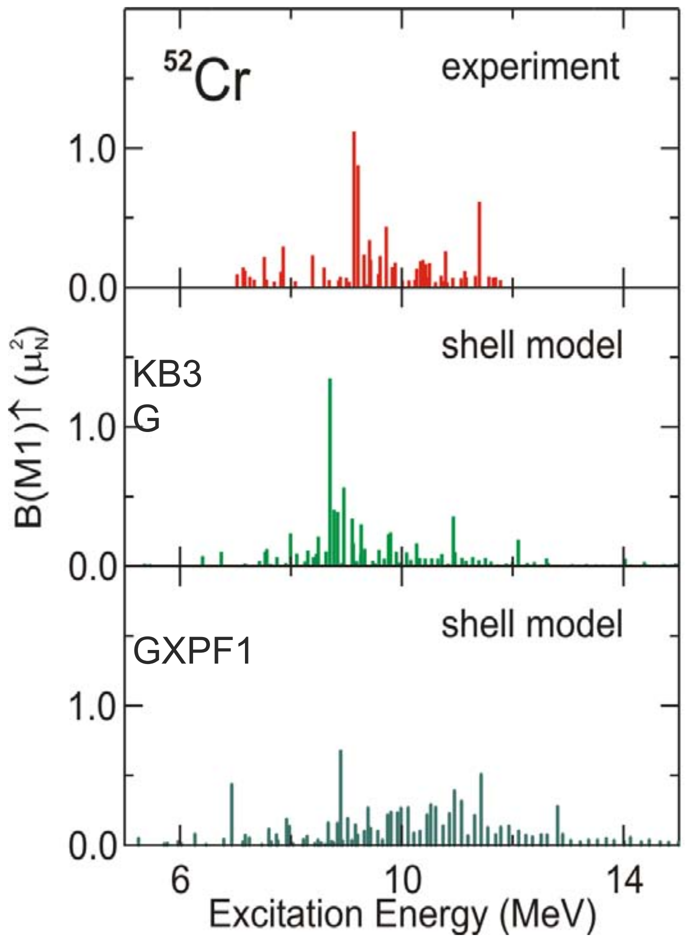
N=28 Isotones: Extraction of Quenching Factor

PvNC, A. Poves, J. Retamosa, A. Richter, Phys. Lett. B 443, 1 (1998)



Quenching factor agrees with quenching of g_A in *fp*-shell

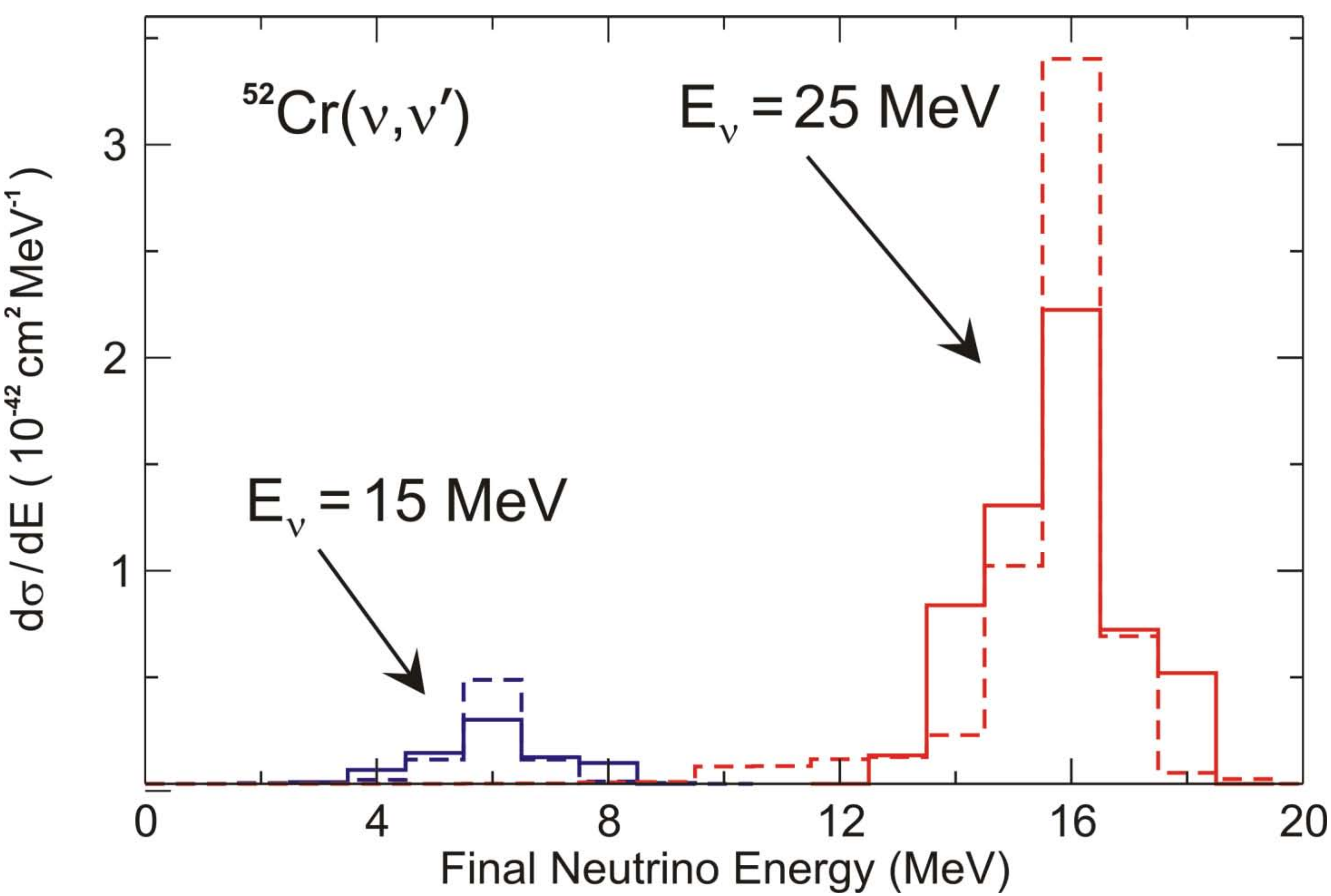
^{52}Cr: Experiment vs. “State of the Art” Shell-Model Calculations



K. Langanke, G. Martínez-Pinedo, PvNC, A. Richter, Phys. Rev. Lett. 93, 202501 (2004)

Still significant differences between different effective interactions

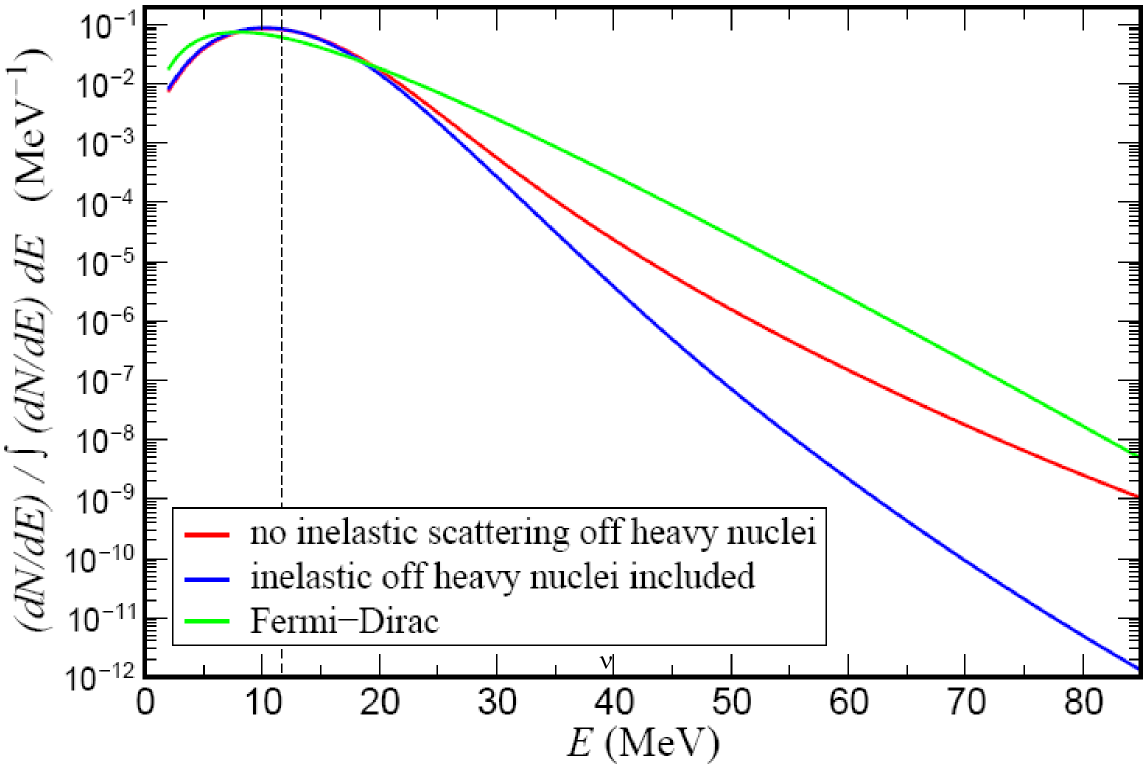
Supernova ν-Nucleus Cross Sections

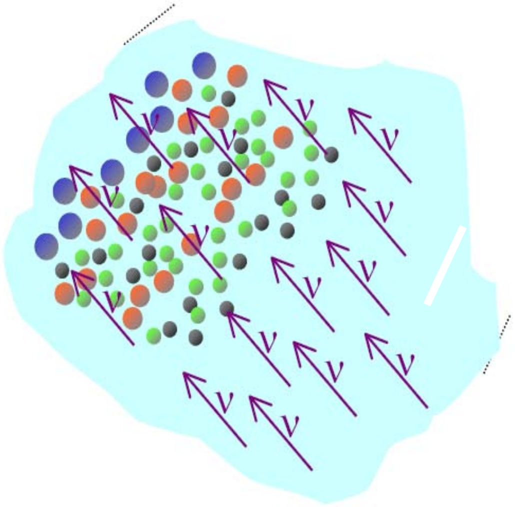


Influence on Supernova Neutrino Spectra

TECHNISCHE UNIVERSITÄT DARMSTADT

K. Langanke et al., Phys. Rev. Lett. 100, 011101 (2008)

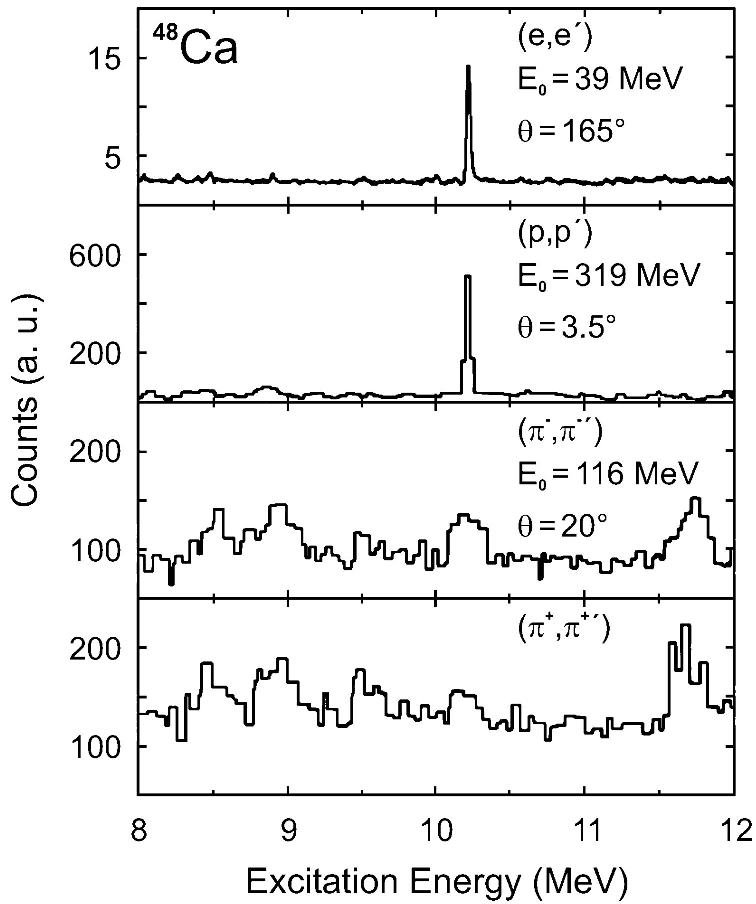




- Spectrum of the initial ν_e burst is affected
- Impact on supernova neutrino detection

M1 Transition in ^{48}Ca: A Prime Example of Quenching

A. Richter, Prog. Part. Nucl. Phys. 13, 1 (1985)



M1 Transition in ^{48}Ca: A Pure Neutron Transition

W. Dehnhard et al., Phys. Rev. C 30, 242 (1985)

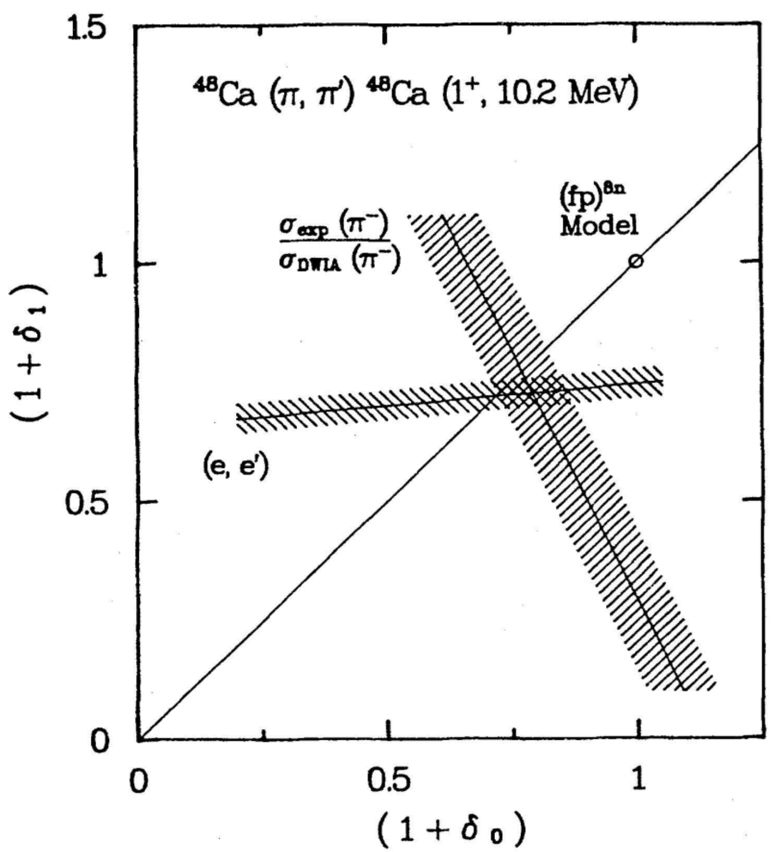
(e,e‘) dominantly isovector

(π^-,π^-‘) dominantly isocalar (if excited through Δ resonance)

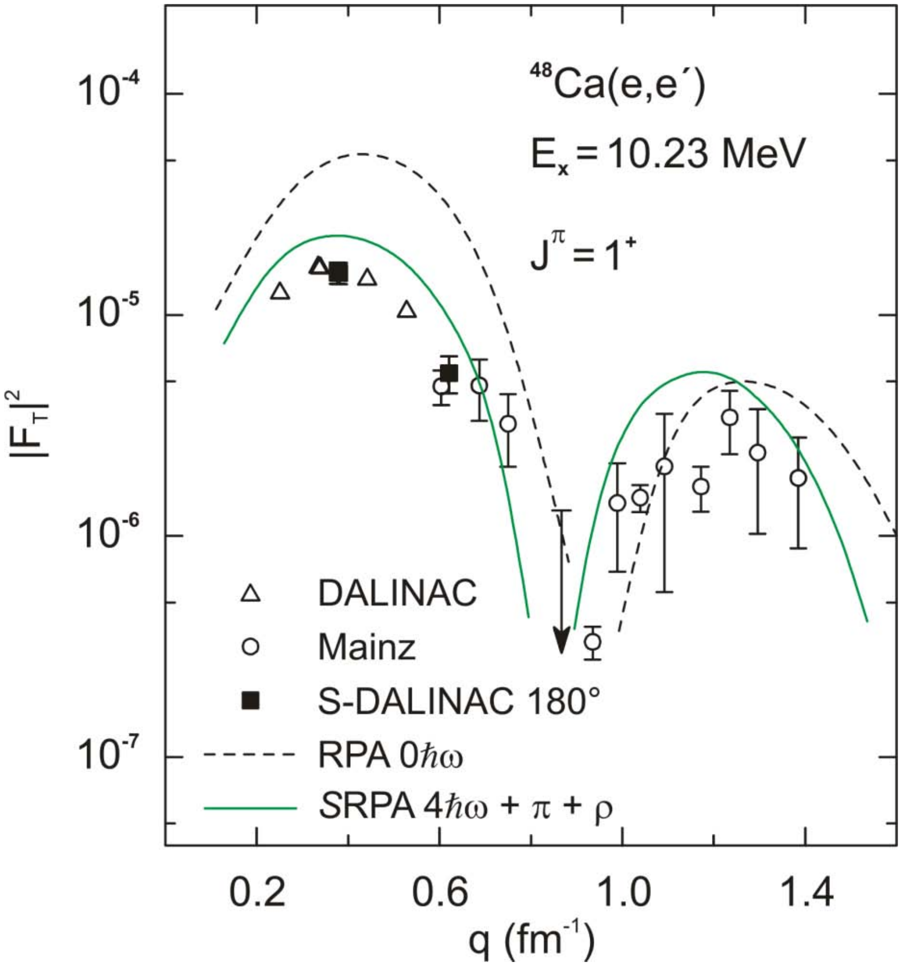
Combination allows to determine proton/neutron ratio

→ pure neutron transition

→ pure spin transition



M1 Transition in ^{48}Ca: (e,e') Form Factor

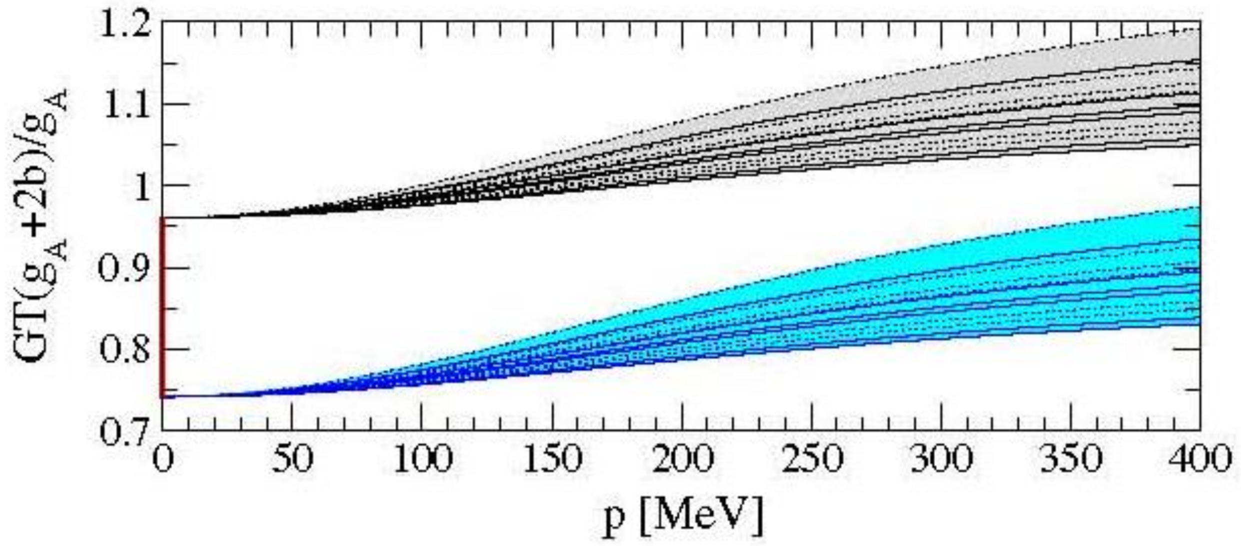


Still sizable discrepancies between experiment and best theory

Momentum Transfer Dependence of Quenching

TECHNISCHE UNIVERSITÄT DARMSTADT

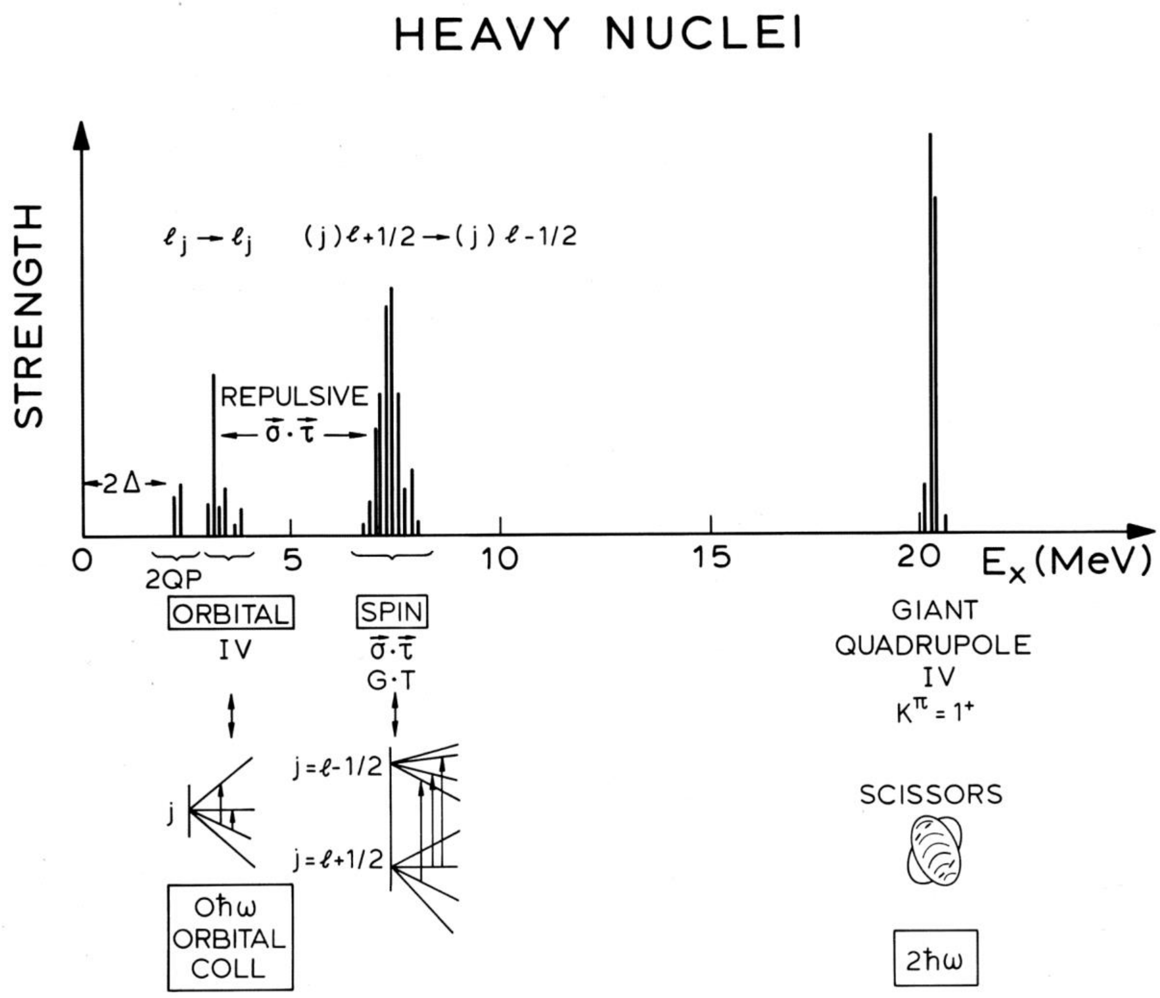
J. Menéndez, D. Gazit, A. Schwenk, Phys. Rev. Lett. 107, 062501 (2011)



Prediction of Chiral Effective Field Theory: Quenching of GT strength significantly modified by two-body currents at finite momentum transfer

Similar effects for spin-M1 strength?

Schematic M1 Response in Heavy Nuclei



only for deformed

only for deformed

Spin M1 Strength in Heavy Nuclei

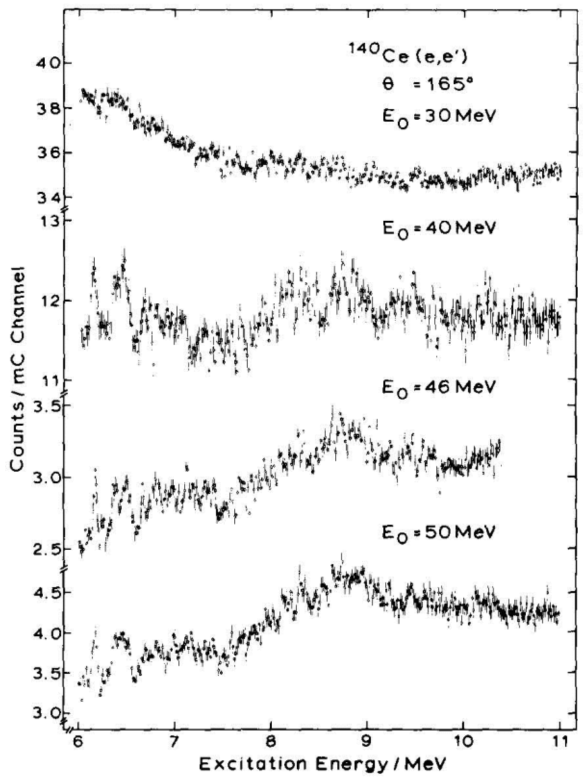
TECHNISCHE UNIVERSITÄT DARMSTADT

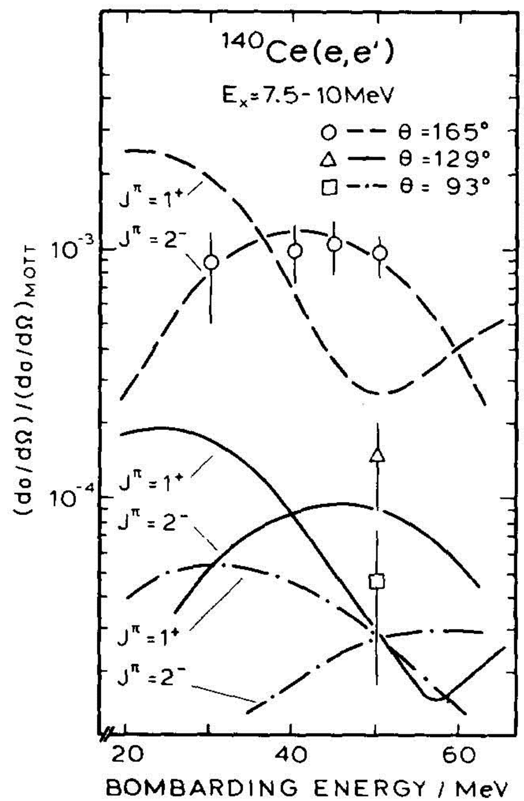
There are little data in heavy nuclei. Why?

Let's have a look at the different experimental methods and their problems.

Spin M1 Strength in Heavy Nuclei: Electron Scattering

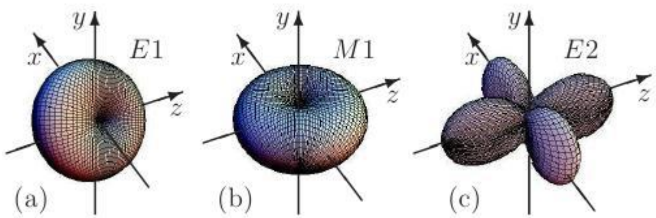
D. Meuer et el., Phys. Lett. B 106, 289 (1981)



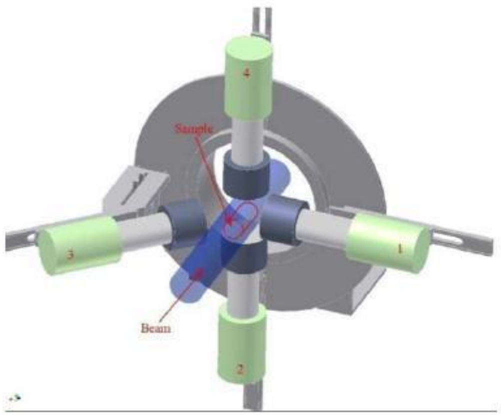


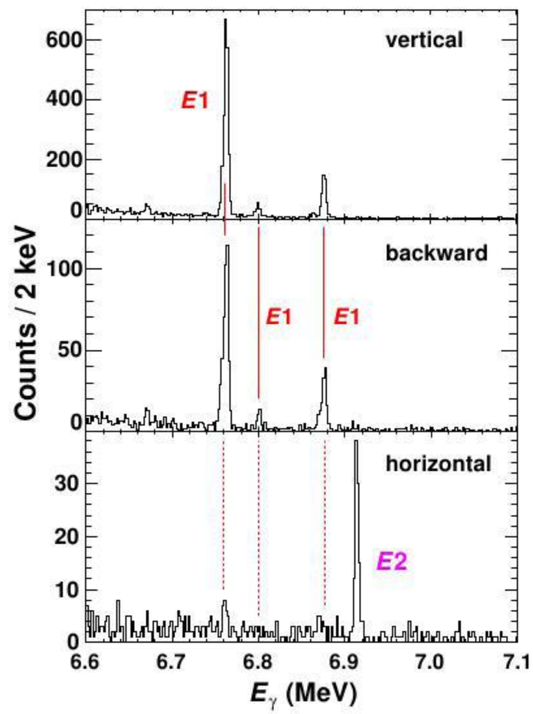
Difficult to distinguish M1 from M2, M2 dominates
Radiative tail prohibitive at low momentum transfer

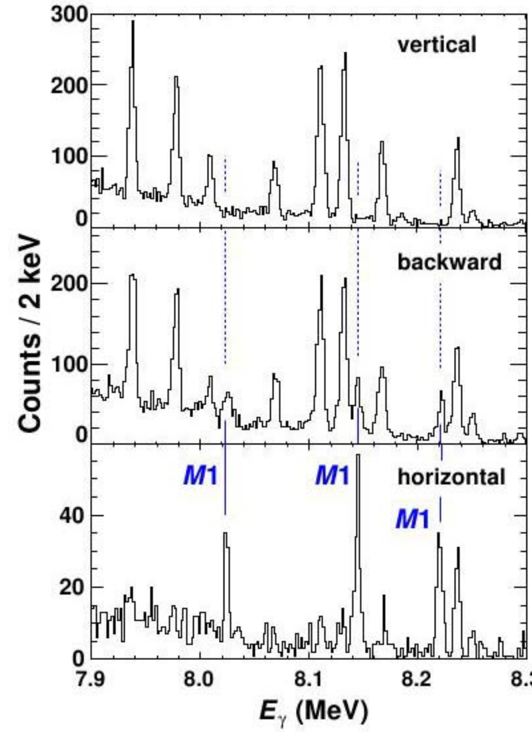
Spin M1 Strength in Heavy Nuclei: Photon Scattering



z axis: beam direction; x axis: vector of polarization







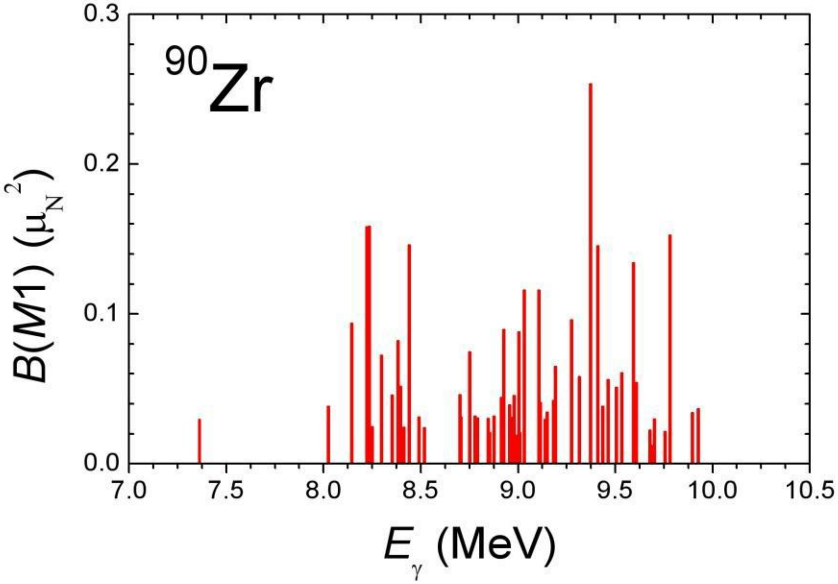
Polarized photon scattering (HIγS) allows distinction of E1 and M1

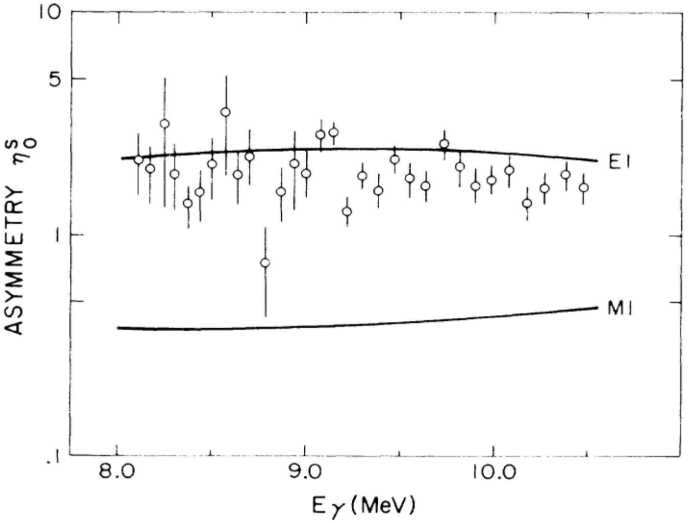
Spin M1 Strength in Heavy Nuclei: Photon Scattering

TECHNISCHE UNIVERSITÄT DARMSTADT

A. Tonchev et al.,
Phys. Rev. Lett. 104, 072501 (2010)

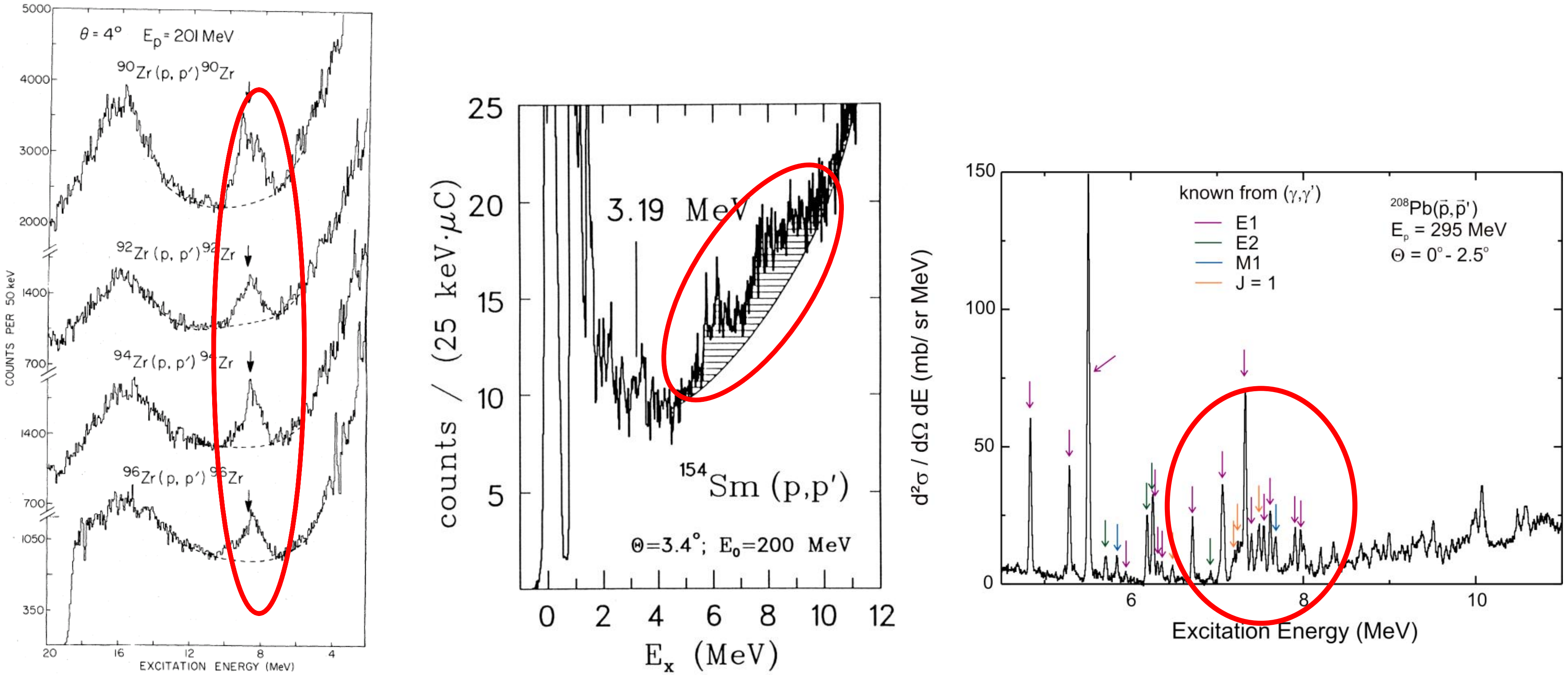
R.M. Laszewski, R. Alarcon, S.D. Hoblit,
Phys. Rev. Lett. 59, 431 (1987)





- Corrections for unobserved branching ratios necessary
- Method works up neutron threshold only
- M1 cross sections always small (few %) with respect to E1

Spin M1 Strength in Heavy Nuclei: Proton Scattering



Orsay 1982 TRIUMF 1990 RCNP Osaka 2006

Heavily mixed with E1 strength (Coulomb excitation of pygmy resonance)
Problem: conversion of cross sections to transition strengths

Spin M1 Strength in Heavy Nuclei: Proton Scattering

TECHNISCHE UNIVERSITÄT DARMSTADT

- Polarized proton scattering at 0°
  - intermediate energy: 300 MeV optimal for spin-isospin excitations
  - strong Coulomb excitation of 1^- states
  - high resolution: ΔE = 25 keV (FWHM)
  - angular distributions: E1 / M1 separation
  - polarization observables: spinflip / non-spinflip separation

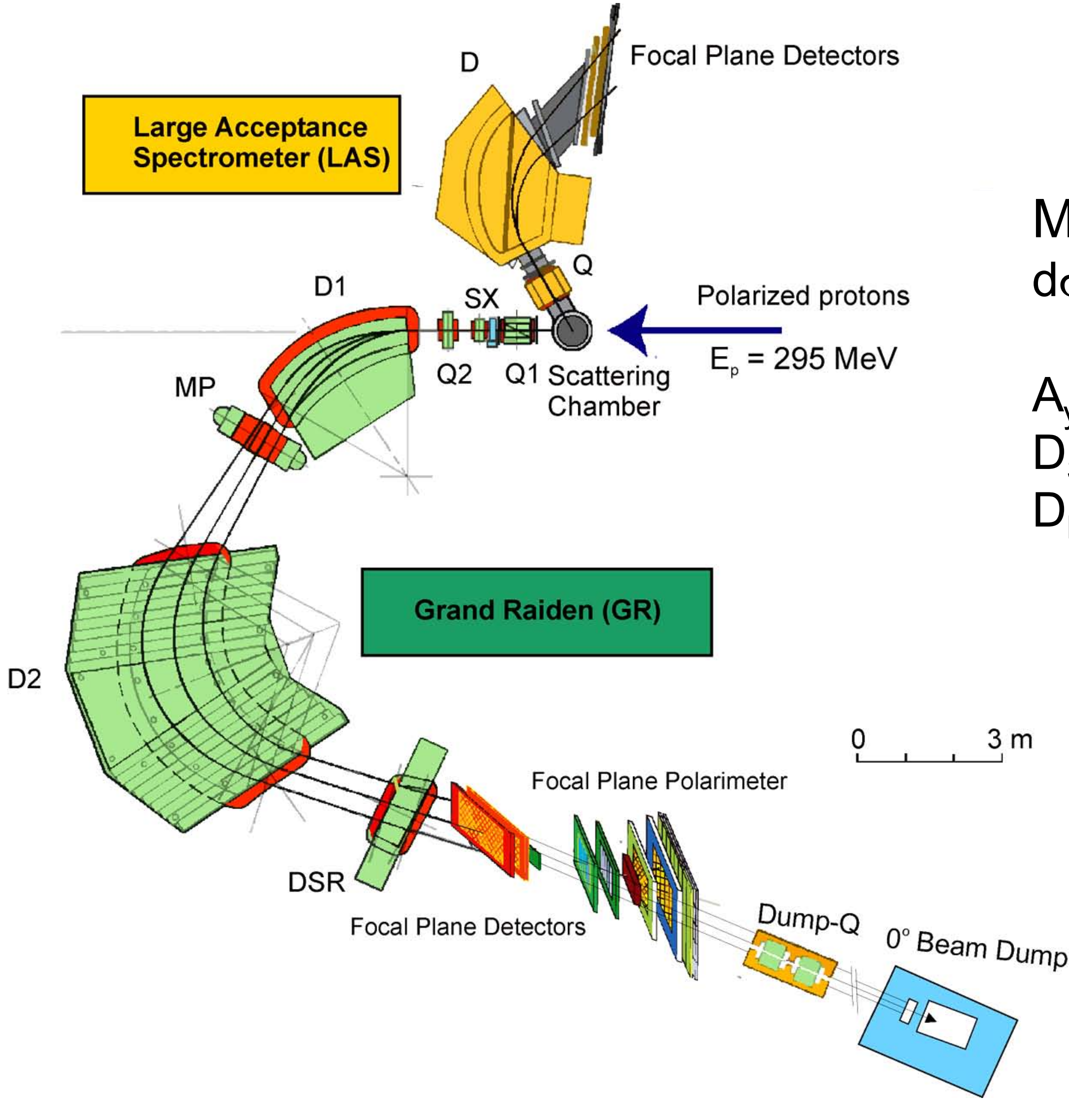
- ^{208}Pb as a reference case

  A. Tamii et al., Phys. Rev. Lett. 107, 062502 (2011)

  I. Poltoratska et al., Phys. Rev. C 85, 041304(R) (2012)

0º Setup at RCNP

TECHNISCHE UNIVERSITÄT DARMSTADT



Measured observables

$d\sigma/d\Omega$ - angular distributions ($0° \leq \Theta \leq 10°$)

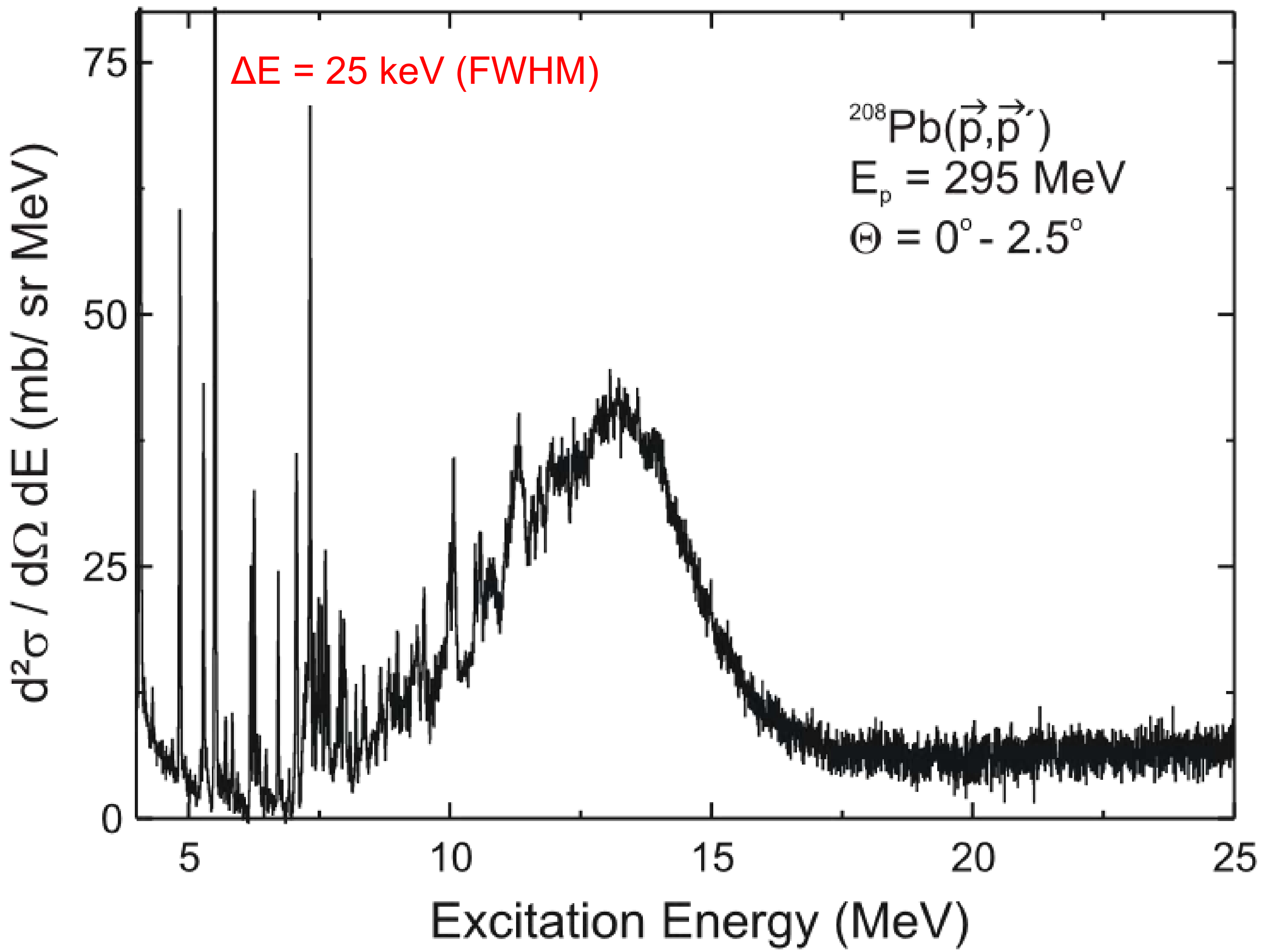
A_y - asymmetry

D_{SS} at 0° - sideways polarization

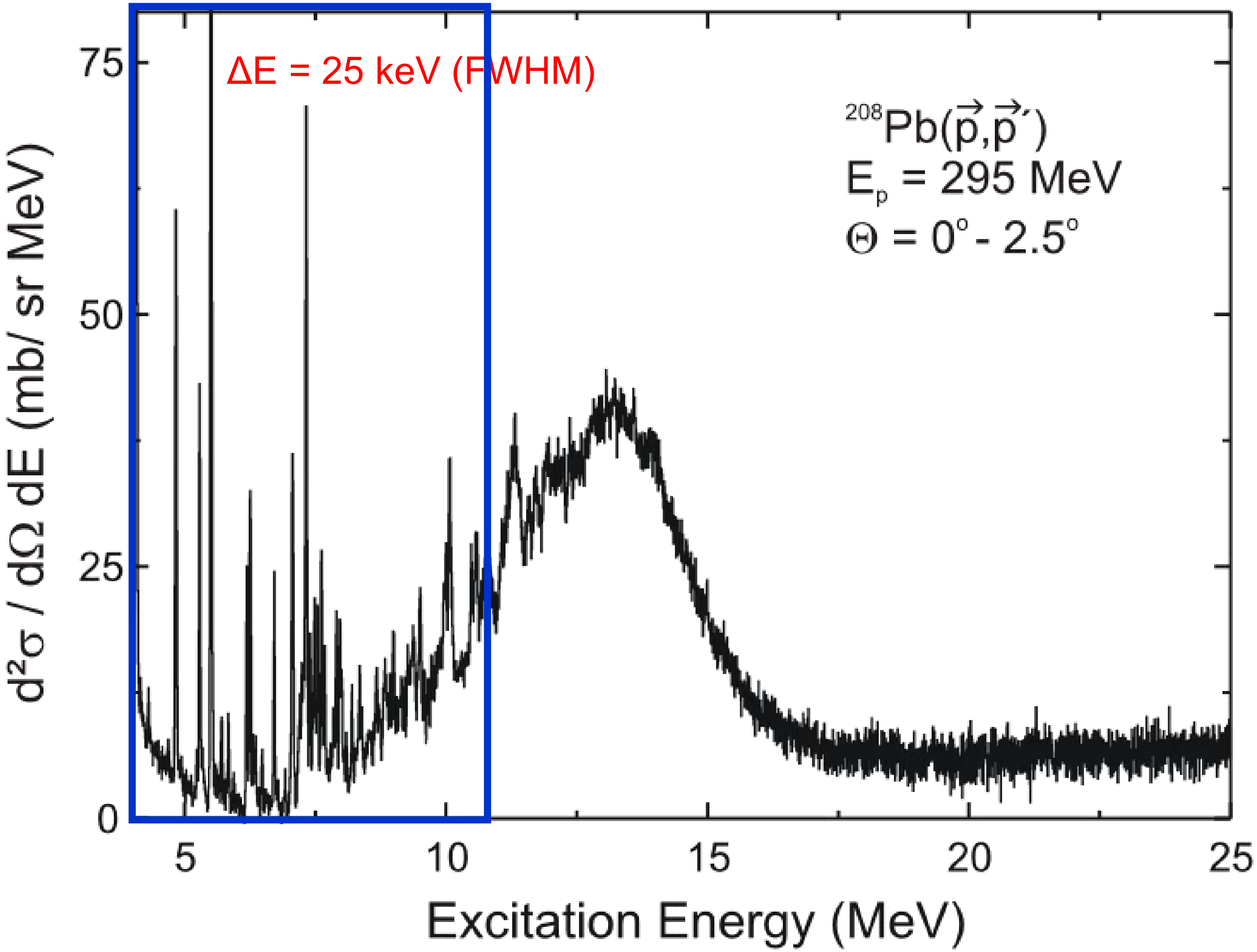
D_{LL} at 0° - longitudinal polarization

A. Tamii et al., Nucl. Instrum.Methods 605, 326 (2009)

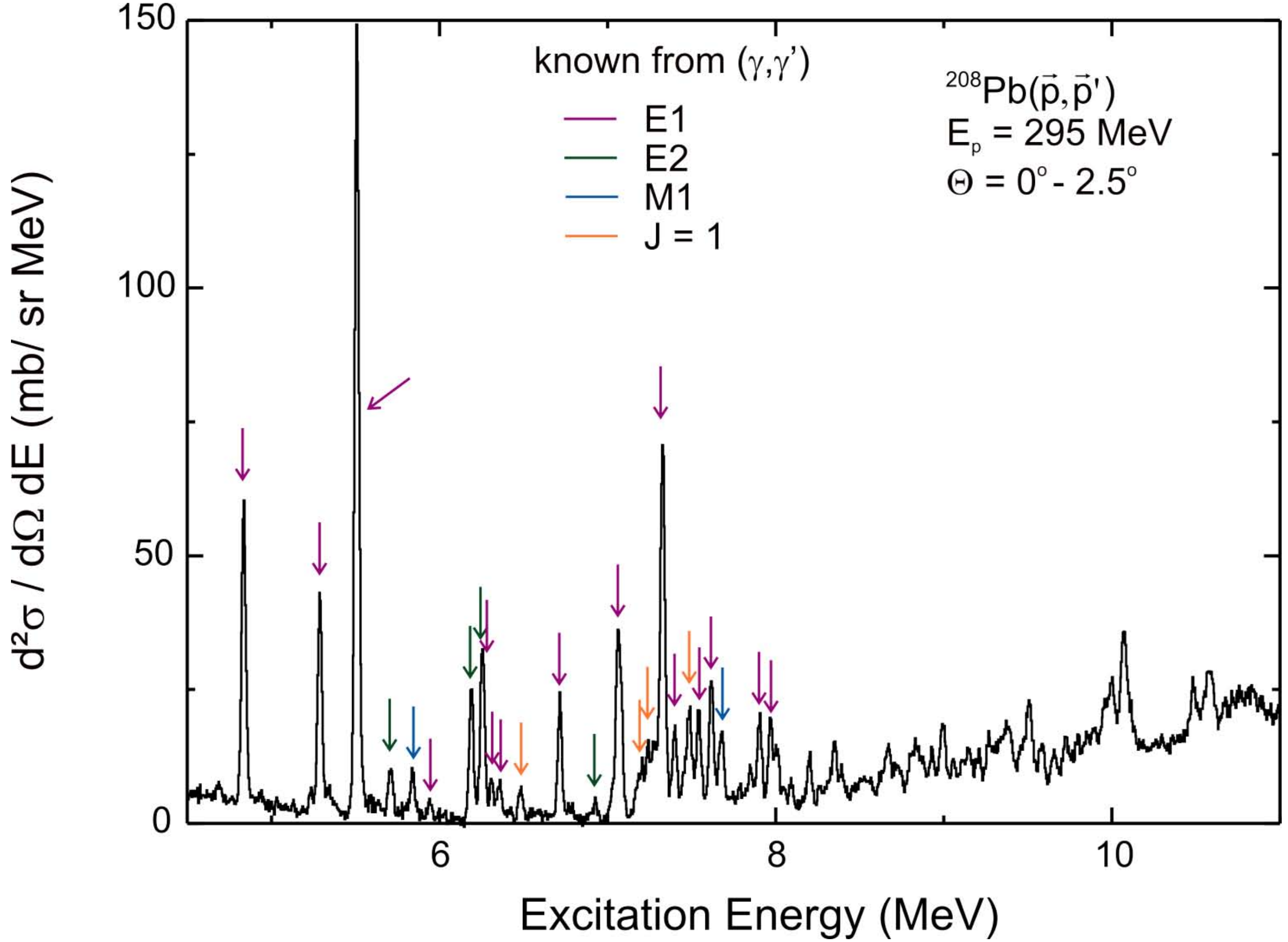
^{208}Pb: Spectrum at 0°



^{208}Pb: Spectrum at 0°

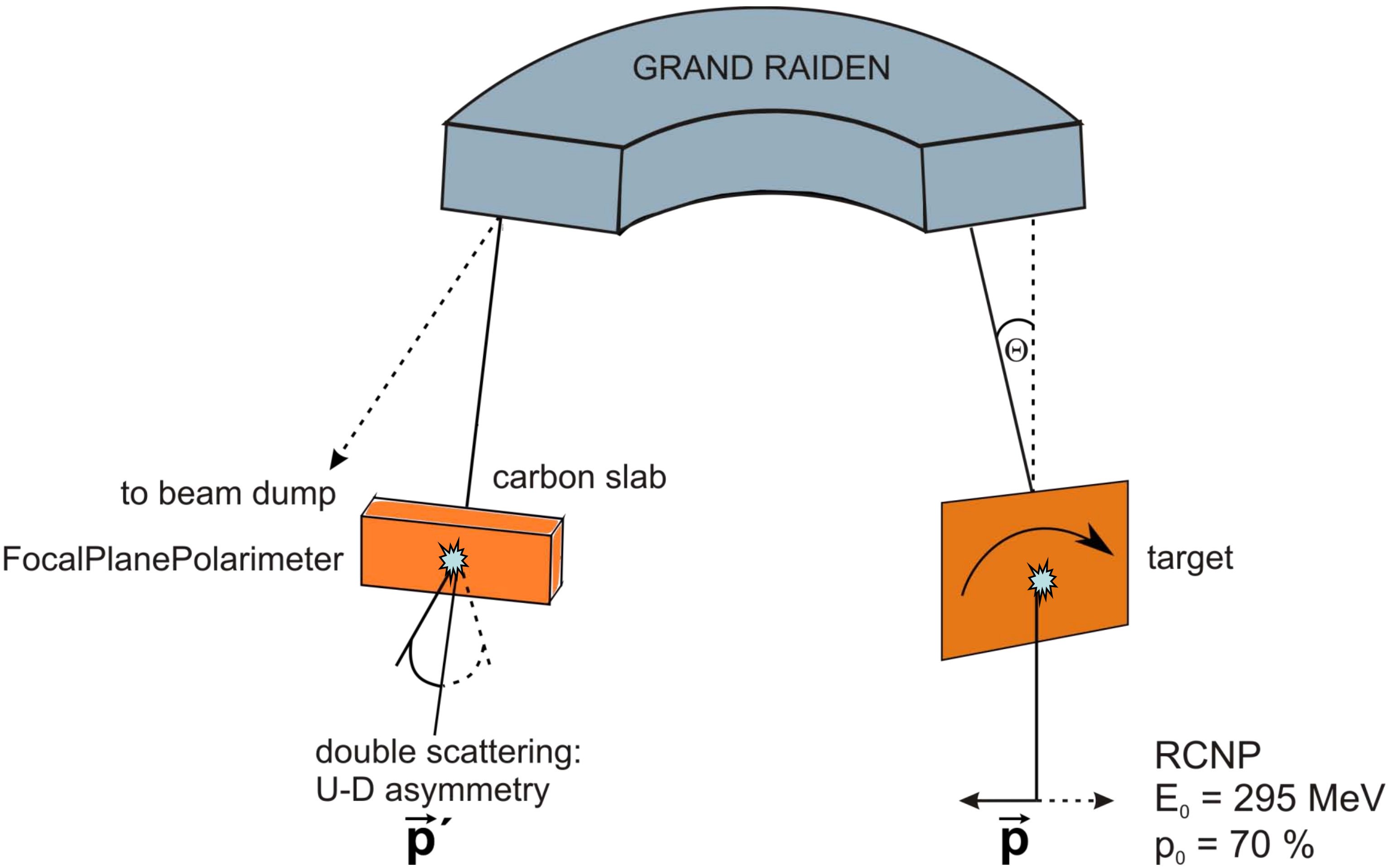


^{208}Pb: Low-Energy Part of the Spectrum



- All dipole transitions known from (γ,γ') are observed

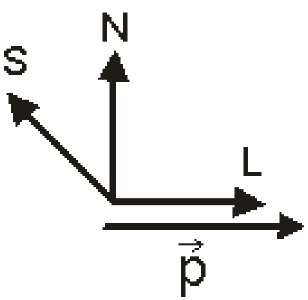
Measurement of Spin Observables



E1/M1 Decomposition by Spin Observables

Polarization observables at 0° ➡ spinflip / non-spinflip separation

(model-independent)



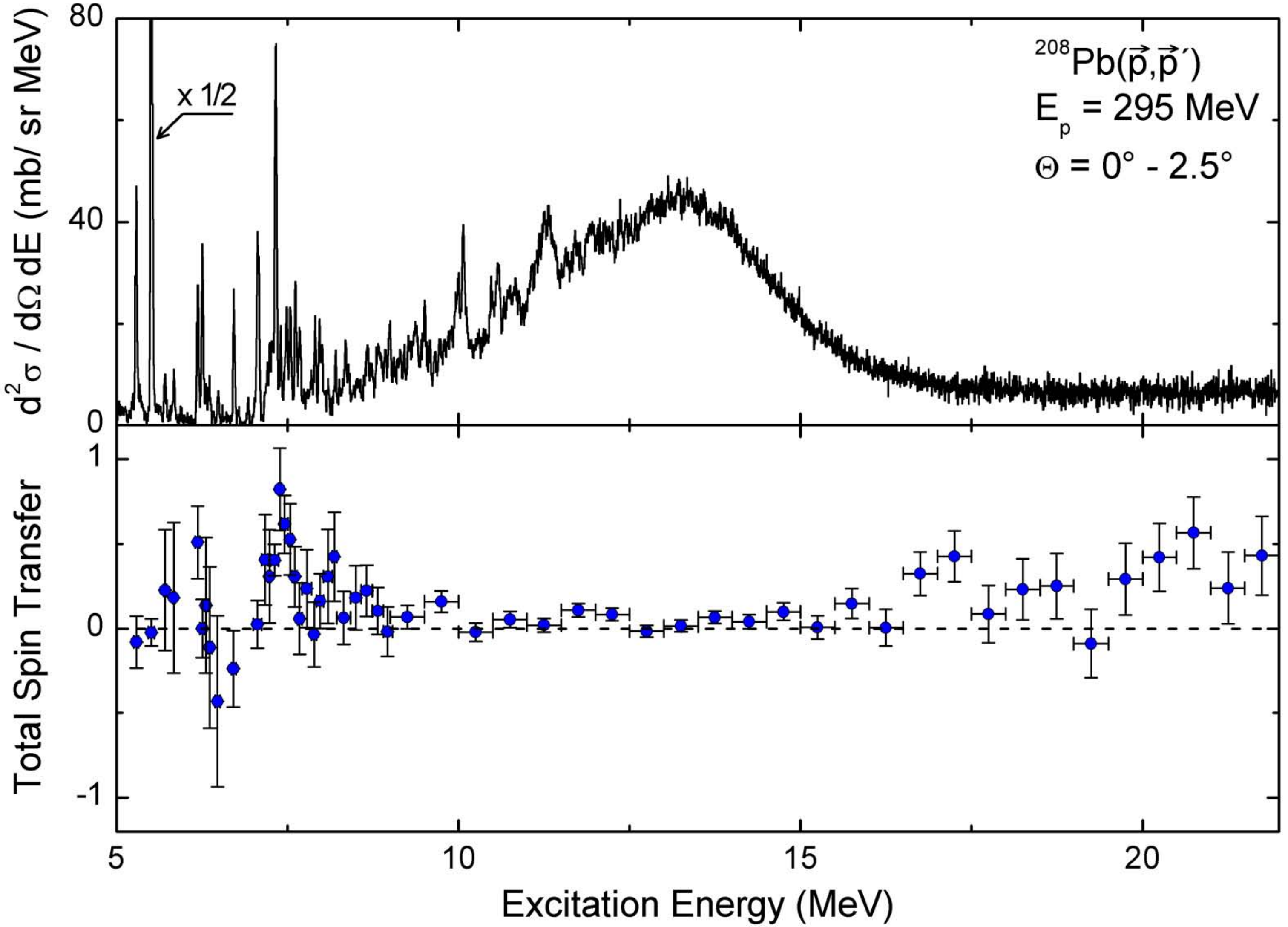
$$D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S=1 \rightarrow 1^+ \\ 3 \text{ for } \Delta S=0 \rightarrow 1^- \end{cases}$$

sideway   normal   longitudinal

At 0° $D_{SS} = D_{NN}$ ➡ $\text{Total Spin Transfer } \Sigma \equiv \dfrac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 \\ 0 \text{ for } \Delta S = 0 \end{cases}$

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

Decomposition into Spinflip / Non-Spinflip Cross Sections

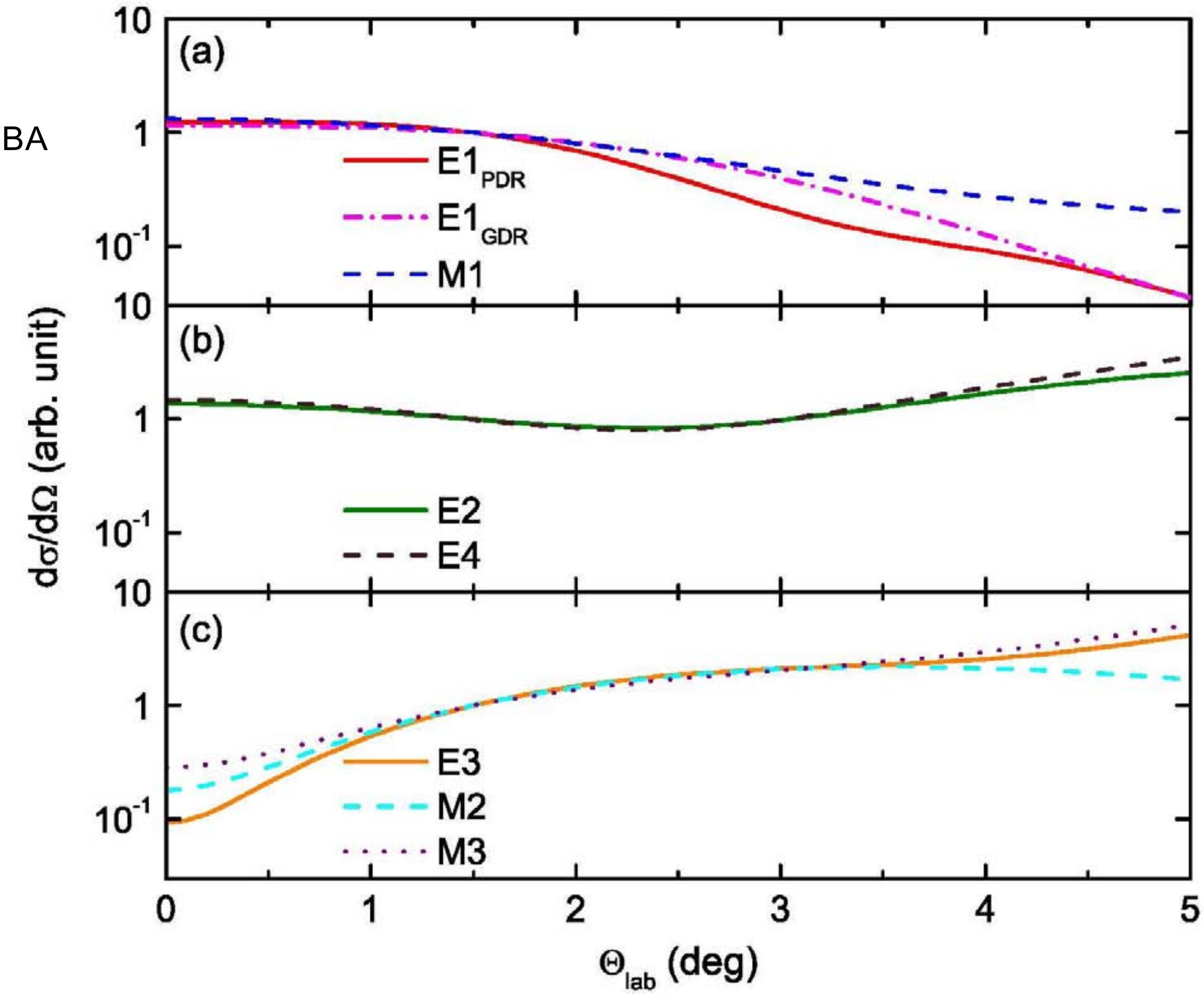


Multipole Decomposition of Cross Section
Angular Distributions

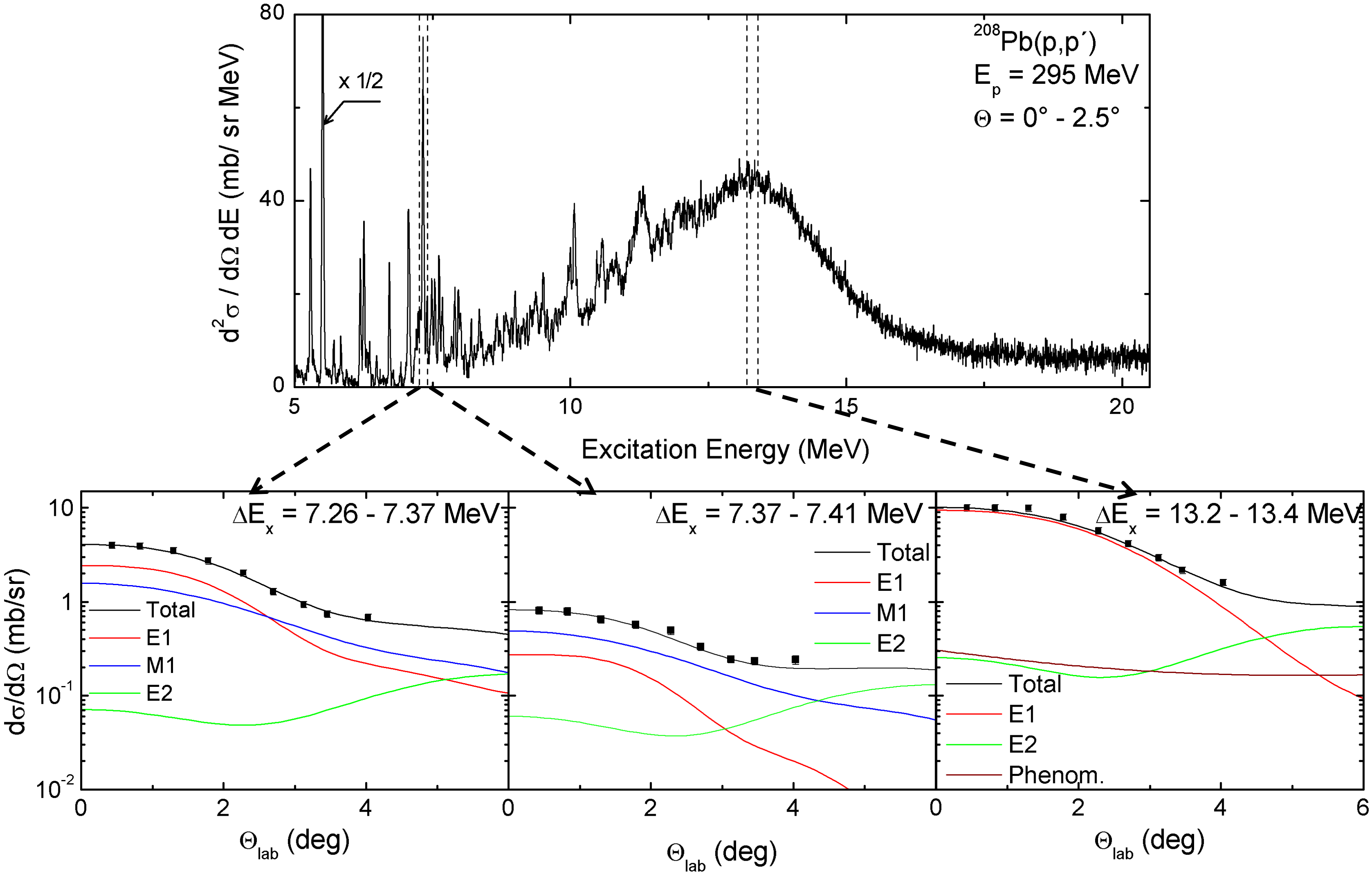
TECHNISCHE UNIVERSITÄT DARMSTADT

$$\left.\frac{d\sigma(\Theta)}{d\Omega}\right|_{\text{data}} = \sum_{\Delta L} a_{\Delta L} \left.\frac{d\sigma(\Theta)}{d\Omega}\right|_{\text{DWBA}}$$

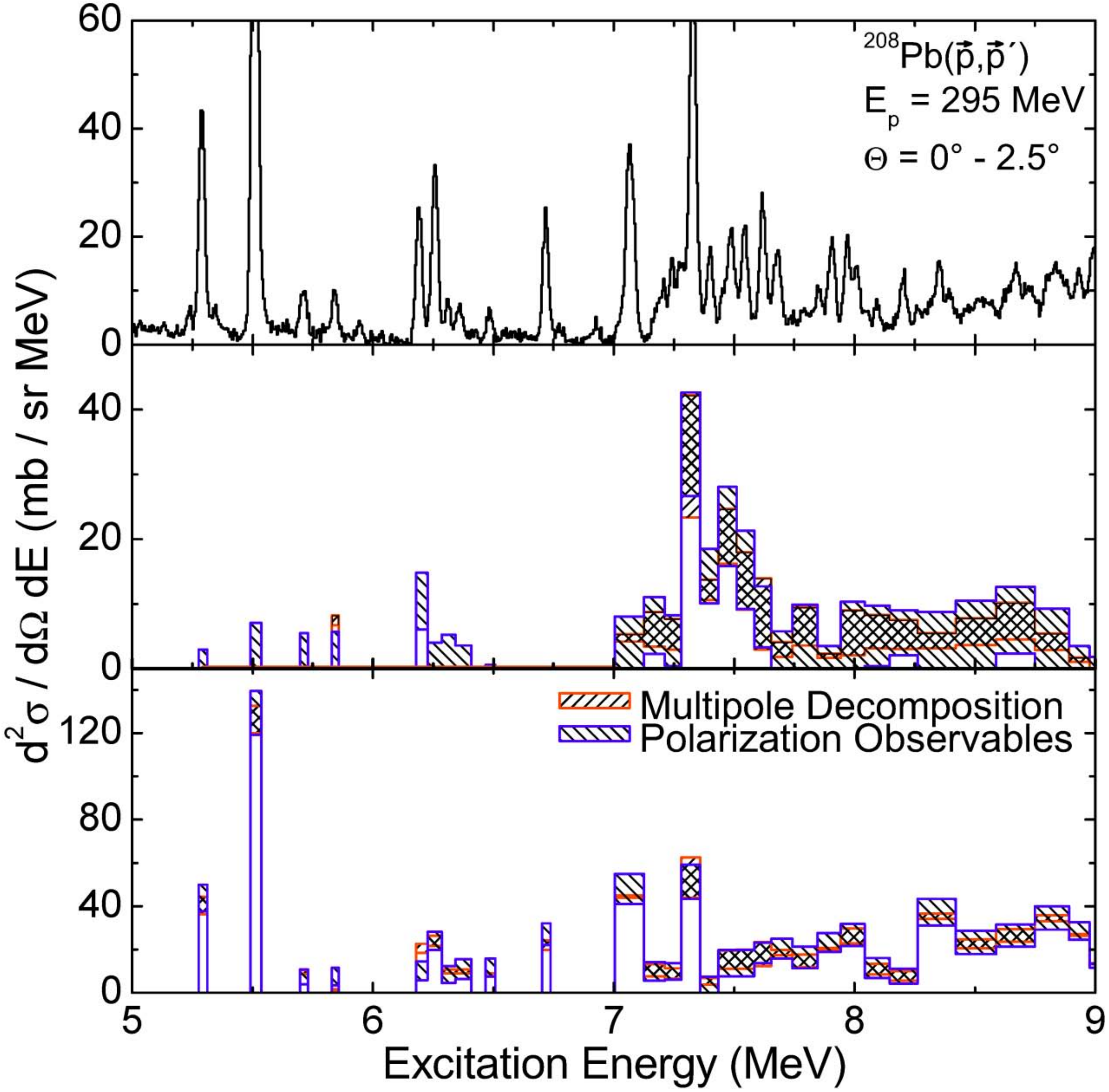
- Restrict data to $\Theta \leq 4°$
- ΔL = 0 → spin M1
- ΔL = 1 → E1 (Coulomb + nuclear)
- ΔL > 1 → only E2 (or E3) considered
- GDR region: ΔL = 0 replaced by phenomenological background



Multipole Decomposition of Angular Distributions



Comparison of Both Methods



Total

$\Delta S = 1$

$\Delta S = 0$

Conversion of Cross Section to Transition Strength

TECHNISCHE UNIVERSITÄT DARMSTADT

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

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

exp. data extrapolated to 0°

unit cross section

kinematical factor

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

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

Conversion of Cross Section to Transition Strength

- Transition strength

$$B(\mathrm{GT},\mathrm{M1}) = \frac{1}{2}\frac{C^2}{2T_\mathrm{f}+1}|\langle f||\sum_k^A \sigma_k \tau_k||i\rangle|^2$$

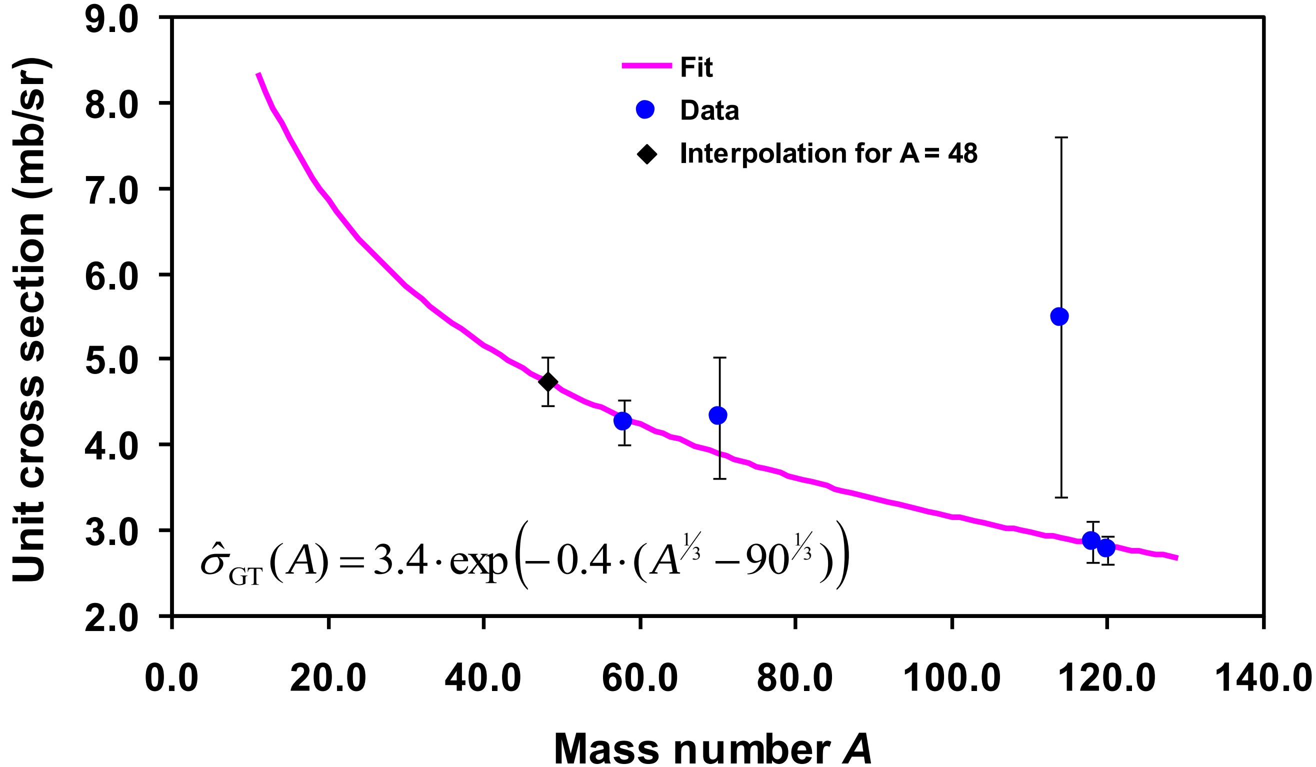
- Relation between B(GT) and M1 can be established by two assumptions
  - analog states have the same matrix elements
  - cross sections of (p,p‘) and (p,n) are analogous

- Equivalent M1 strength

$$B(\mathrm{M1}) \cong B(\mathrm{M1})_{\sigma\tau} = \frac{3}{8\pi}\left(\frac{g_s^{\mathrm{IV}}}{2}\right)^2 B(\mathrm{M1}_{\sigma\tau})\,[\mu_N^2]$$

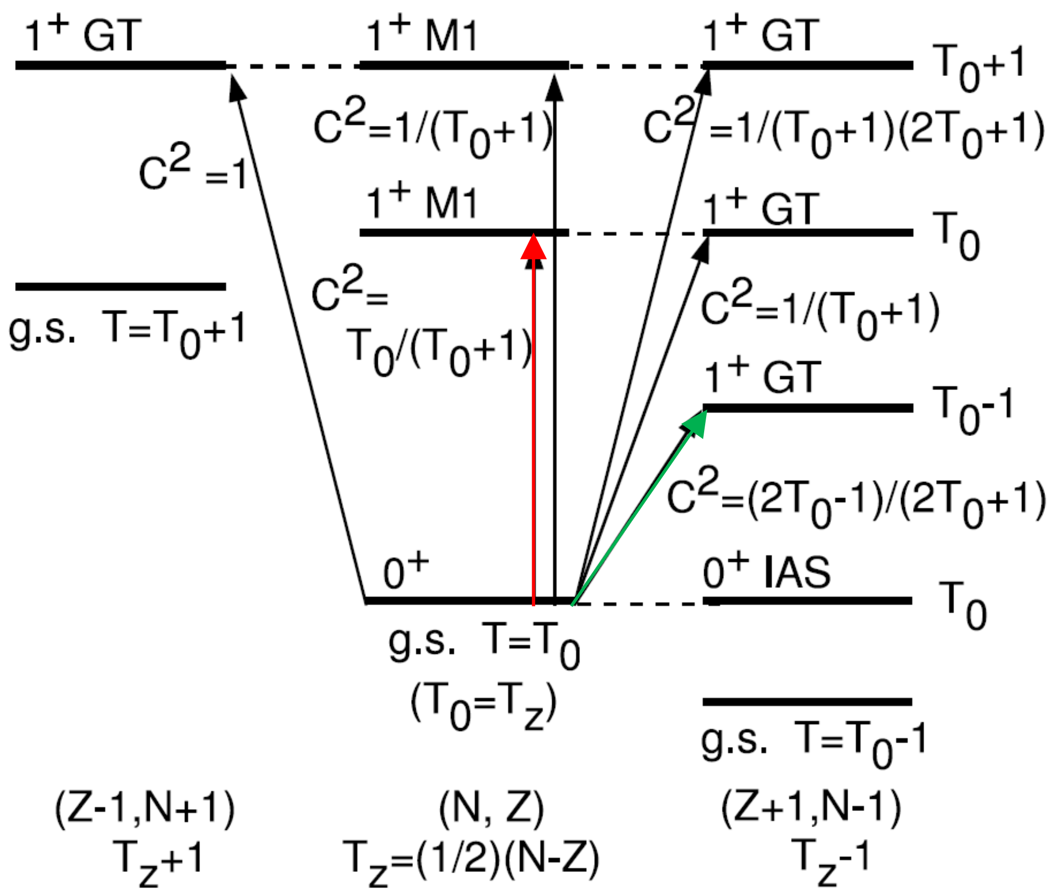
GT Unit Cross Section

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



GT unit cross section for (p,n) reaction at 300 MeV from β decay

Clebsch-Gordan Coefficients



Relation between M1 and GT unit cross section

1. Assume equal matrix elements for the spin-M1 and GT transition

$$\frac{B(\mathrm{M}1_{\sigma\tau})}{B(\mathrm{GT})} = \frac{T_0}{T_0 + 1}$$

2. Difference of (p,p') and (p,n) reaction at $q = 0$

$$\frac{\sigma_{\mathrm{M1}}(q=0)}{\sigma_{\mathrm{GT}}(q=0)} = \frac{1}{2}$$

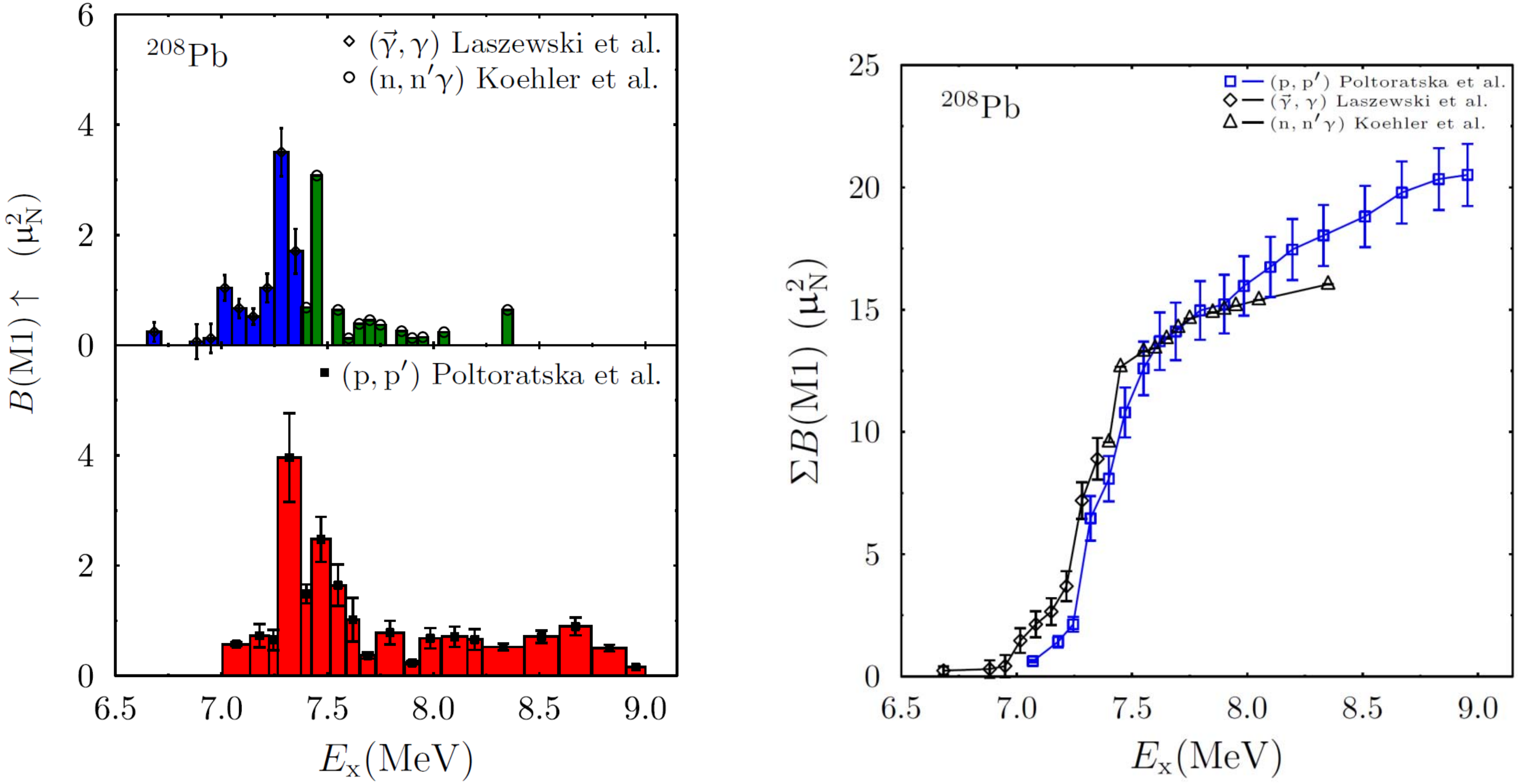
3. Relation between the M1 and GT unit cross section

$$\frac{\sigma_{\mathrm{M1}}(q=0)}{\sigma_{\mathrm{GT}}(q=0)} = \frac{\hat{\sigma}_{\mathrm{M1}}}{\hat{\sigma}_{\mathrm{GT}}} \cdot \frac{B(\mathrm{M}1_{\sigma\tau})}{B(\mathrm{GT})} \Rightarrow \boxed{\frac{\hat{\sigma}_{\mathrm{M1}}}{\hat{\sigma}_{\mathrm{GT}}} = \frac{1}{2}\,\frac{T_0 + 1}{T_0}}$$

Spin-M1 Resonance in ^{208}Pb

TECHNISCHE UNIVERSITÄT DARMSTADT

J. Birkhan et al., to be published



A new tool to study systemativs of the spin-M1 resonance in heavy nuclei!

5. Special topics
   – meson-exchange currents
   – forbidden transitions

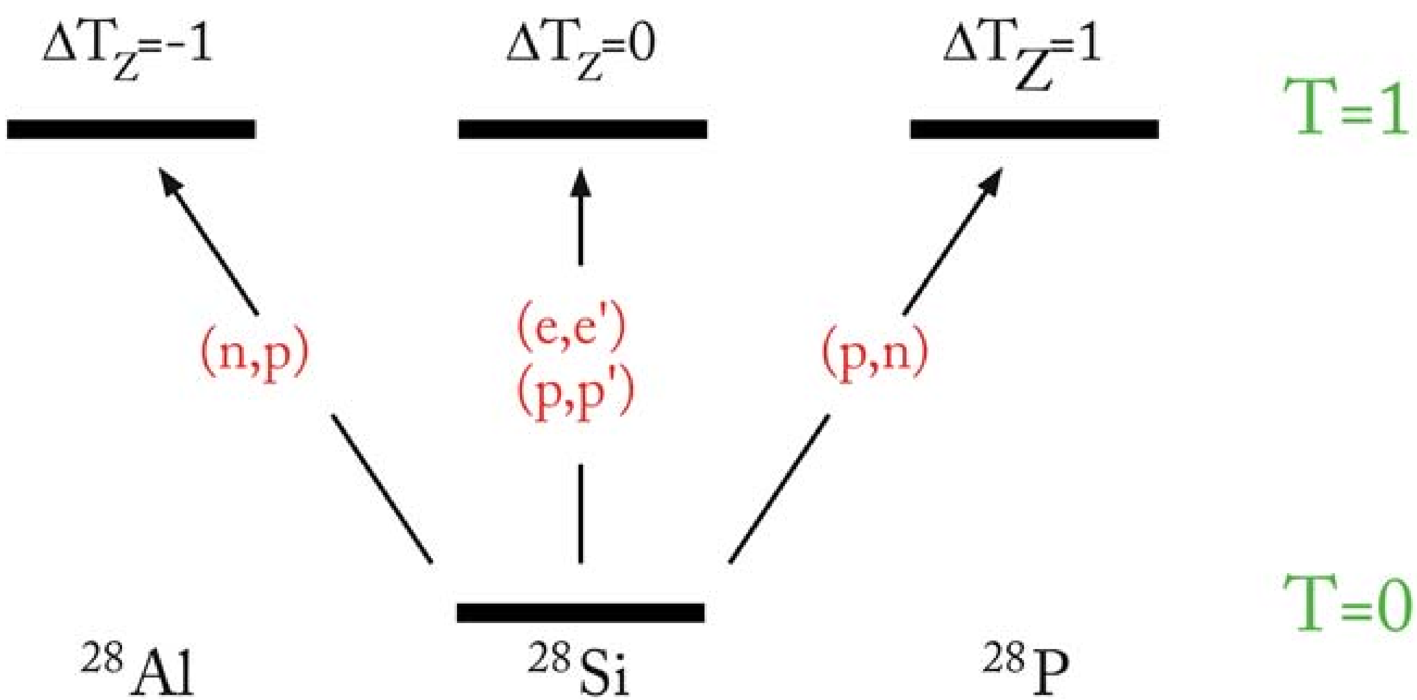
Relation of M1 and Gamow-Teller Strength in Light Nuclei

TECHNISCHE UNIVERSITÄT DARMSTADT

Spin-M1 and GT transitions are mediated by the same (στ) operator

→ excited states are **isospin-analogue states**

Simple example (T_0 = 0)



Relation of B(M1) and GT Strength In Light Nuclei

Different response to electromagnetic and hadronic probes

(e,e') →	$B(M1) = \left[\mathrm{M}(\sigma) + \mathrm{M}(l) + \mathrm{M}_\Delta + \mathrm{M}_V^{MEC}\right]^2 \frac{3(\mu_p - \mu_n)^2}{8\pi}$
(p,p') (n,p) (p,n) →	$B(GT) = \left[\mathrm{M}(\sigma) + \mathrm{M}_\Delta + \mathrm{M}_A^{MEC}\right]^2$

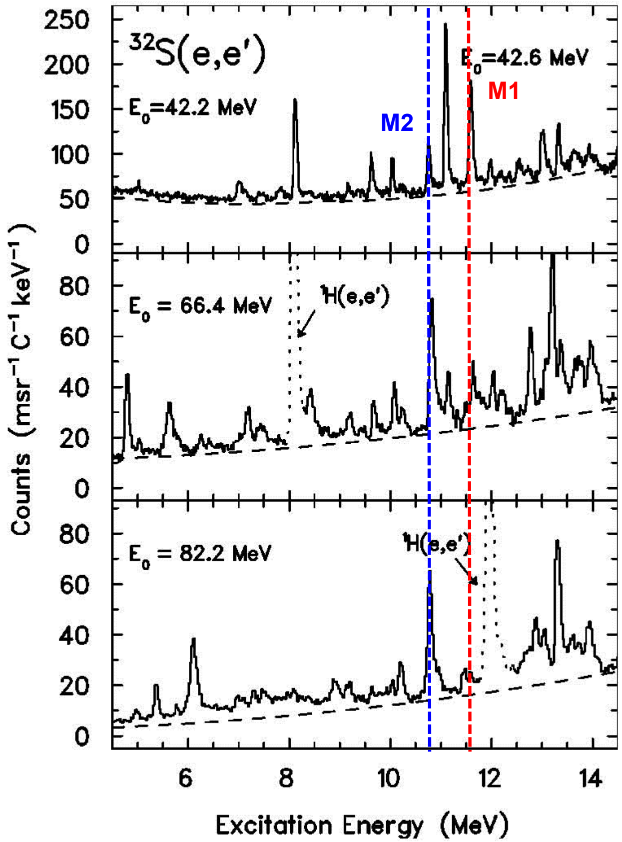
Electromagnetic: spin and orbital matrix elements contribute coherently
→ interference term

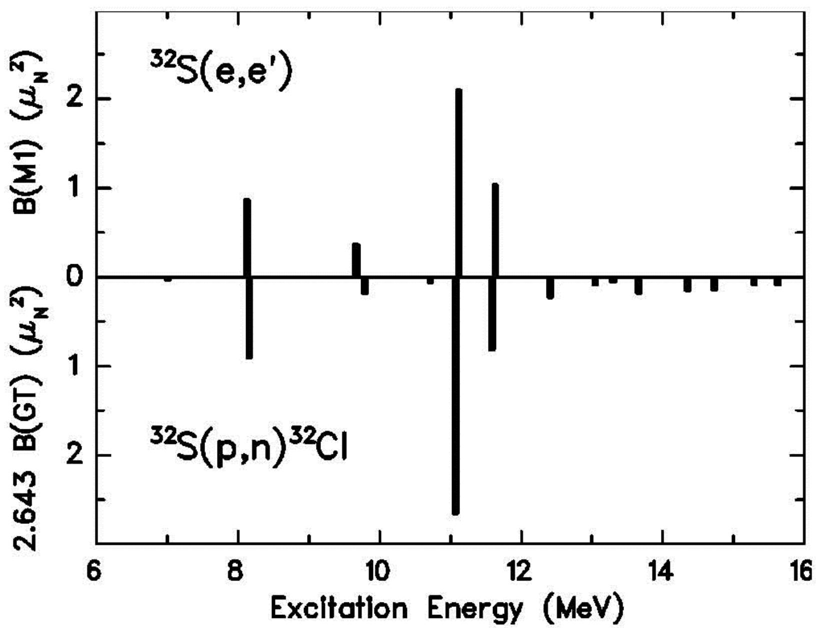
Hadronic: spin matrix element only

M_Δ and M_A^{MEC} contributions are small (in first order)

Spin-Orbital Interference: The Example of ^{32}S

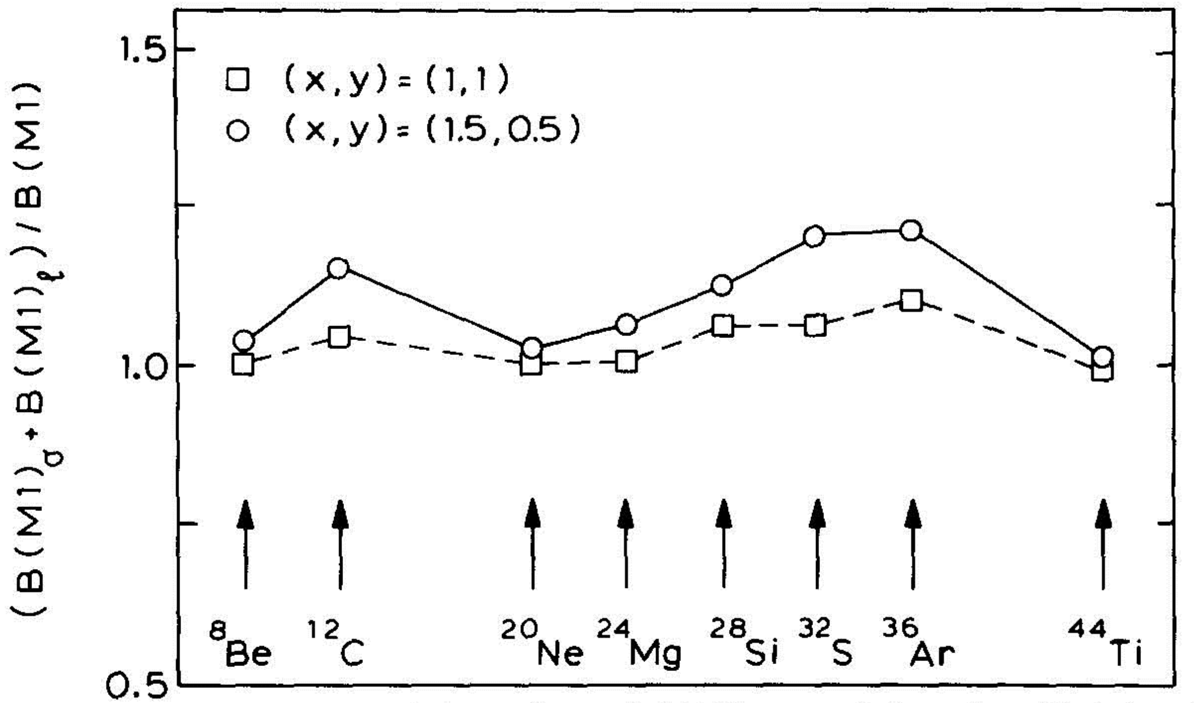
F. Hofmann et al., Phys. Rev. C 65, 024311 (2002)





Spin-Orbital Interference in N = Z Nuclei

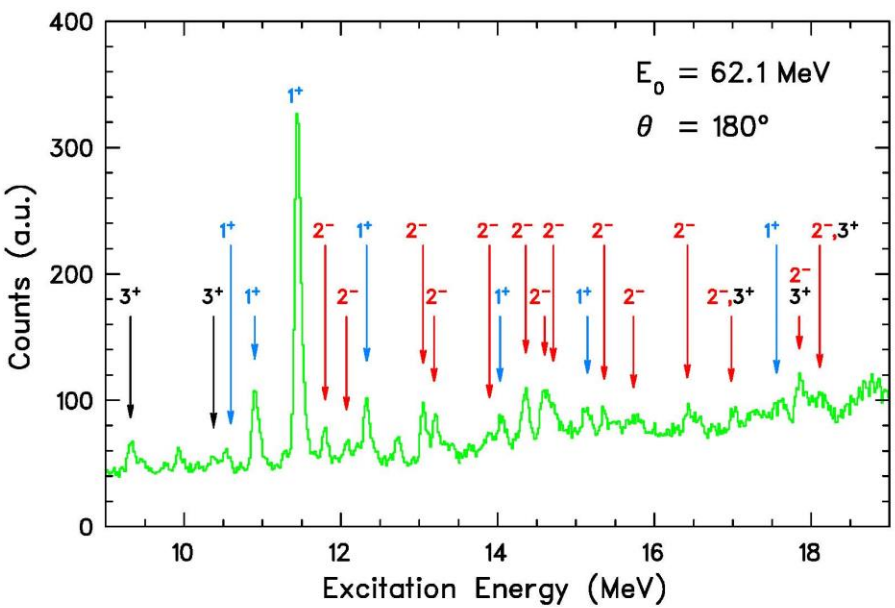
M.S. Fayache, PvNC, A. Richter, Y.Y. Sharon. L. Zamick, Nucl. Phys. A 627, 14 (1997)



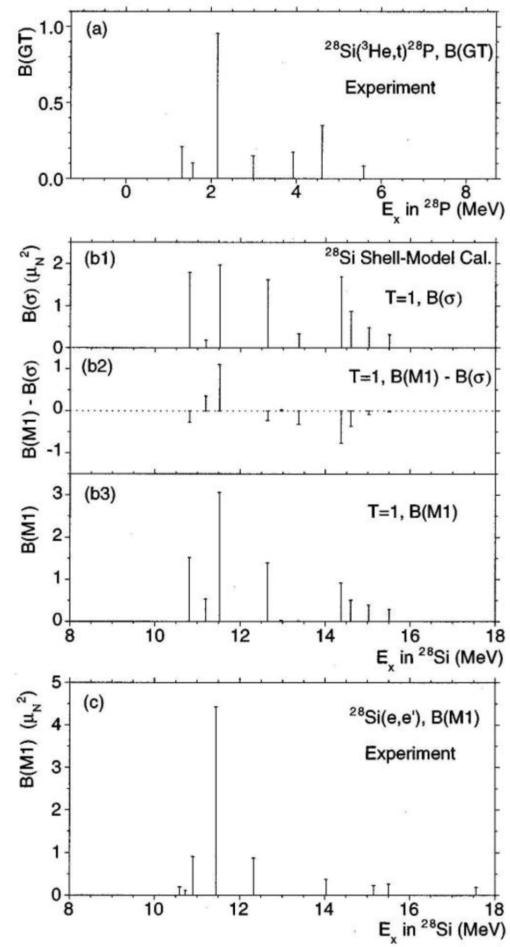
Orbital contribution to ΣB(M1) approximately cancels because of random sign of interference term

M1 and Spin-M1 Strength in ^{28}Si

C. Lüttge et al.,
Phys. Rev. C 53, 127 (1996)

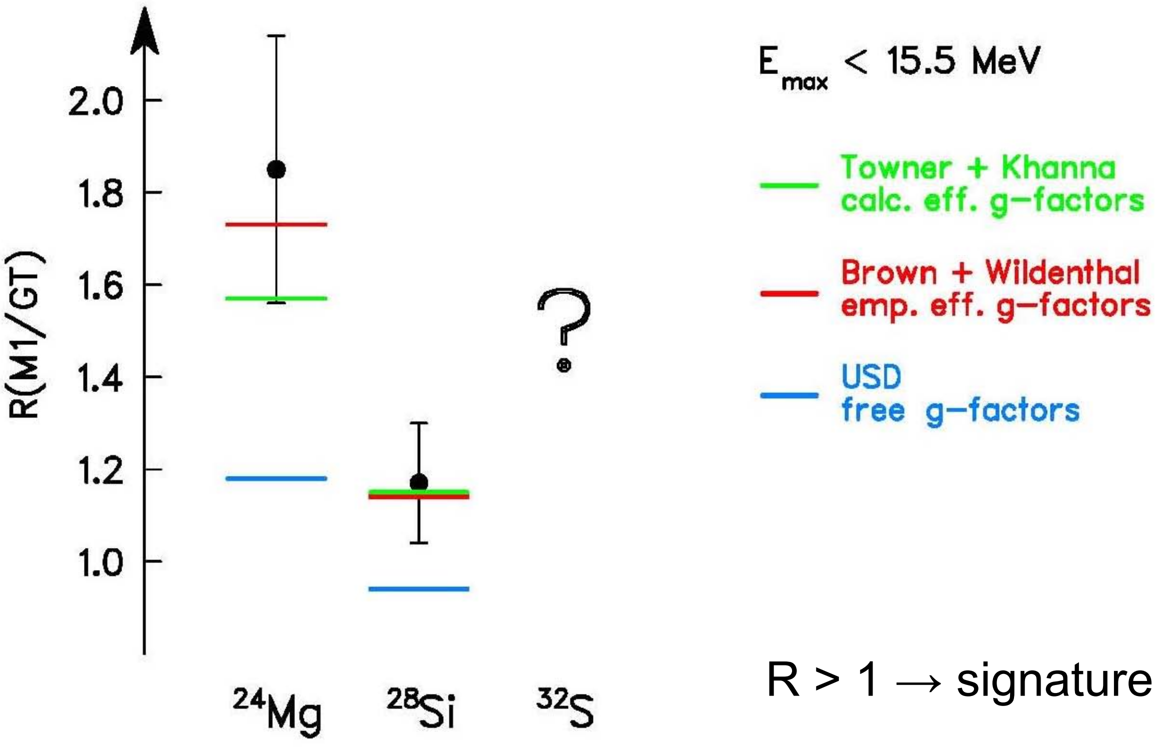


Y. Fujita et al., Phys. Rev. C 55, 1137 (1997)



M1 and Spin-M1 Strength in sd-Shell Nuclei

A. Richter et al., Phys. Rev. Lett. 65, 2519 (1990)
C. Lüttge et al., Phys. Rev. C 53, 127 (1996)
PvNC et al., Phys. Rev. C 55, 532 (1997)



R > 1 → signature of **meson exchange currents**

Pseudospin Symmetry

More than forty years ago a quasidegeneracy was observed (Arima, Hecht) in single-particle spectra with quantum numbers

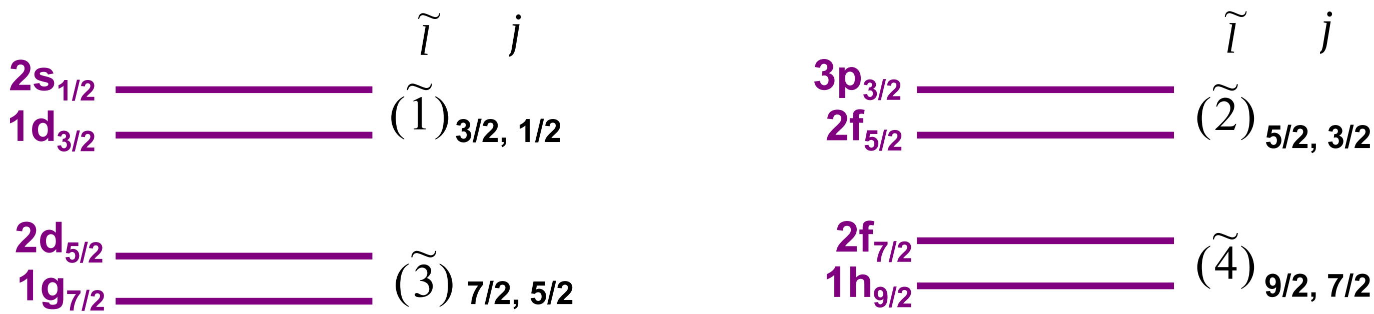
$$[n, l, j = l + 1/2] \qquad [n-1, l+2, j' = (l+3/2)]$$

pseudo orbital angular momentum

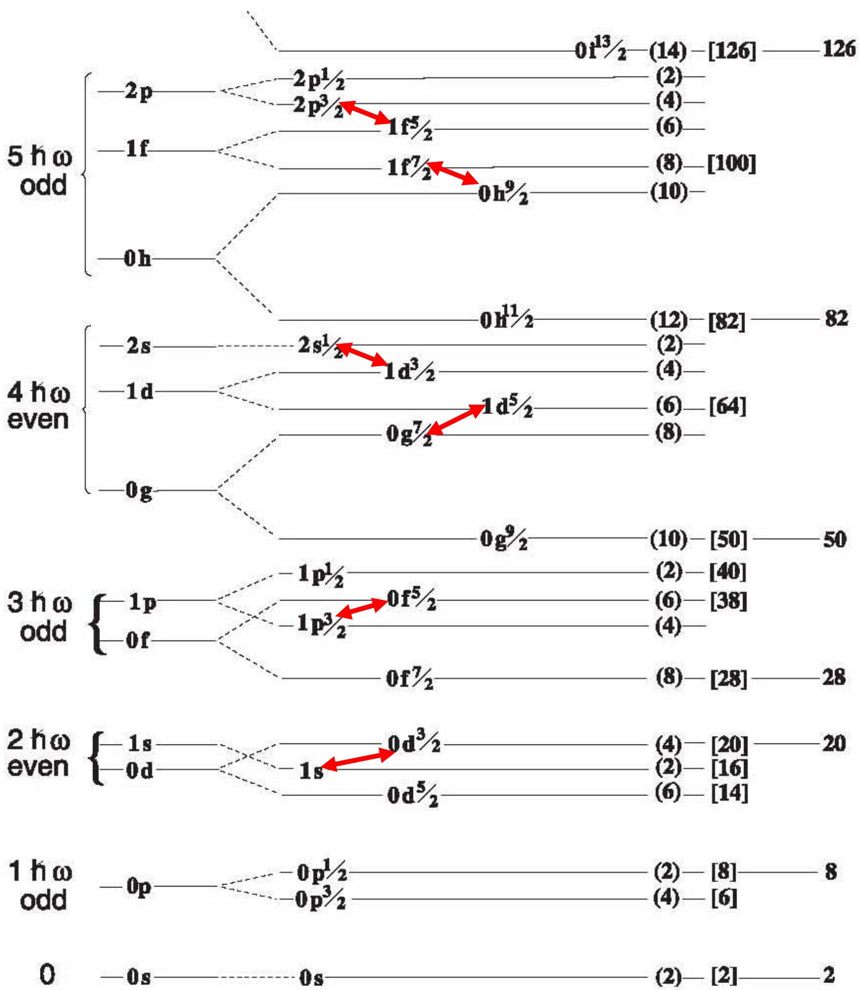
$$\tilde{l} = l + 1$$

pseudo spin

$$\tilde{s} = 1/2$$

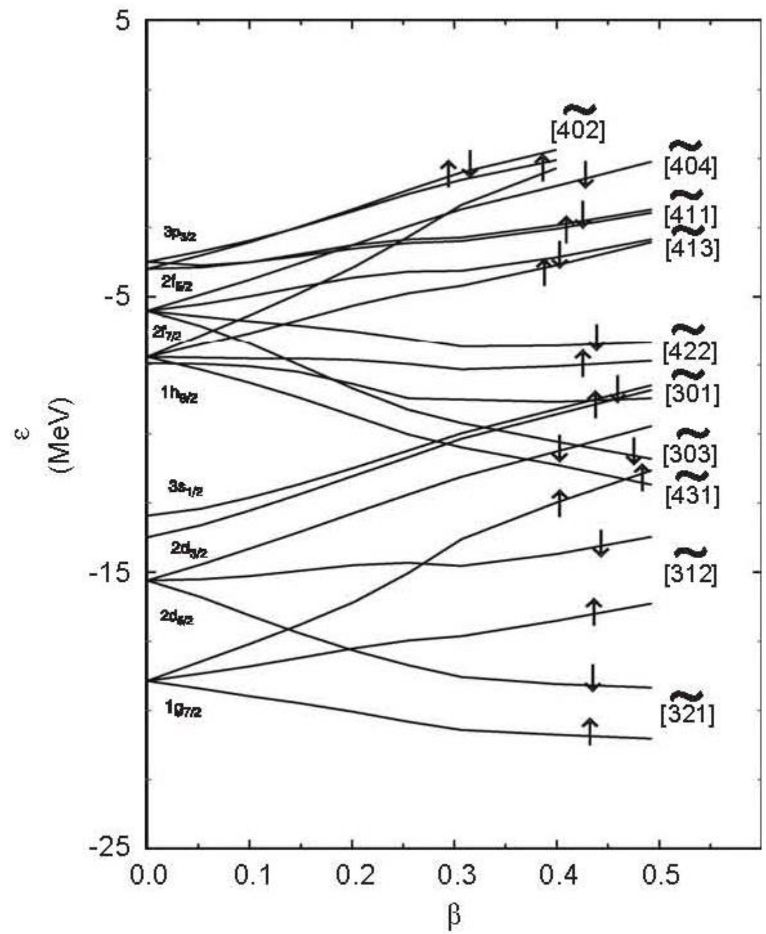


Pseudospin Symmetry



Pseudospin Symmetry

Pseudospin partners appear also in deformed nuclei



Pseudospin Symmetry

The origin of pseudospin symmetry remained a mystery until J.N. Ginocchio realized that it is a relativistic SU(2) symmetry.

For an extensive review see J.N. Ginocchio, Phys. Rep. 414, 165 (2005)

SU(2) Symmetries of the Relativistic Hamiltonian

TECHNISCHE UNIVERSITÄT DARMSTADT

Dirac Hamiltonian has an invariant SU(2) symmetry for two limits

$$H = \left[\vec{\alpha} \cdot \vec{p} + \beta(m + V_S(\vec{r})) + V_V(\vec{r})\right]$$

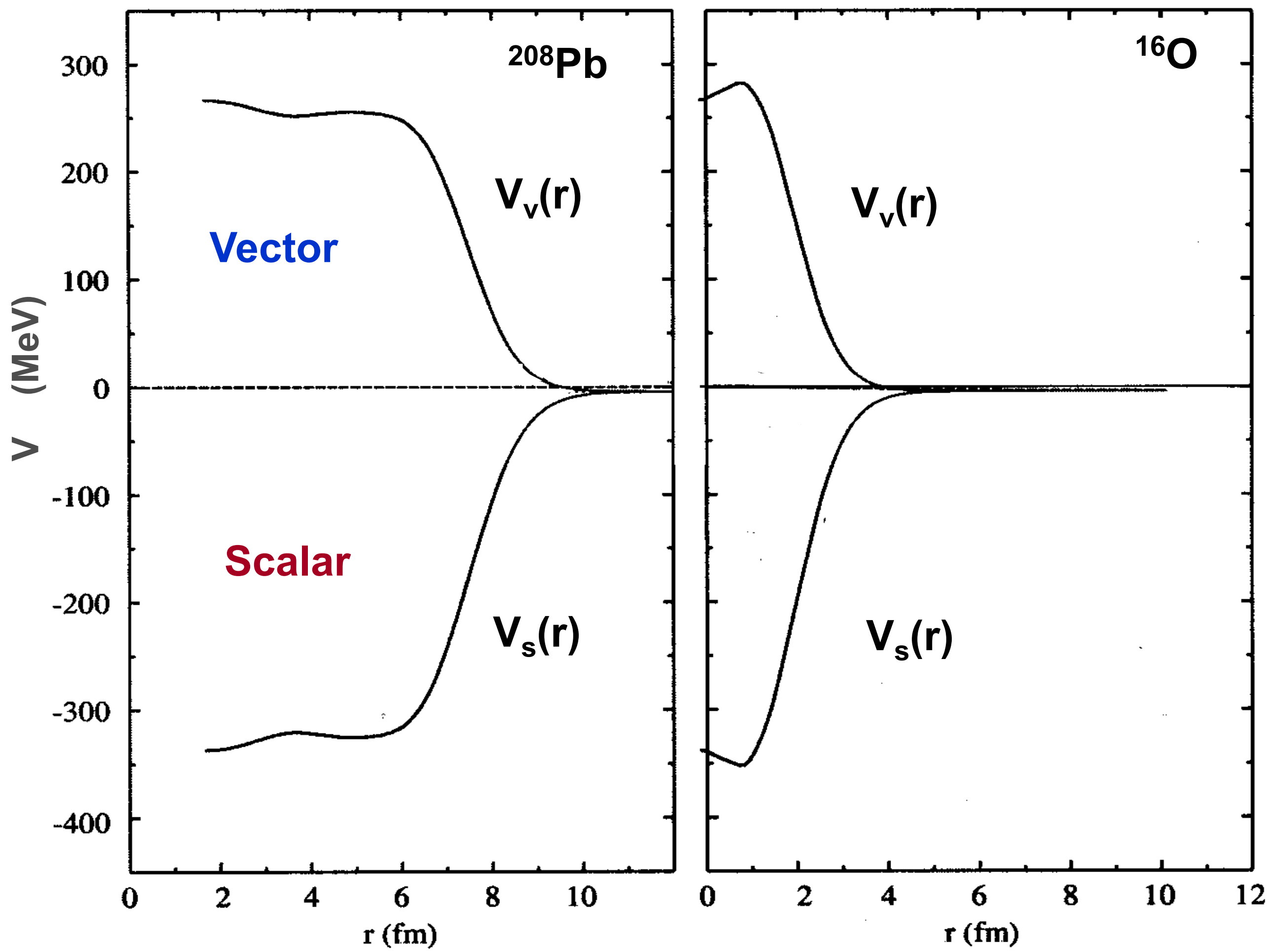
Usual Dirac Matrices $\alpha_i = \begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix}$ $\beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ σ_i = **Pauli Spin Matrices**

Pseudospin Symmetry: $V_S(\vec{r}) + V_V(\vec{r}) = C_{PS}$

Spin Symmetry: $V_S(\vec{r}) - V_V(\vec{r}) = C_S$

PS in nuclei: $V_S(\vec{r}) + V_V(\vec{r}) = 0$

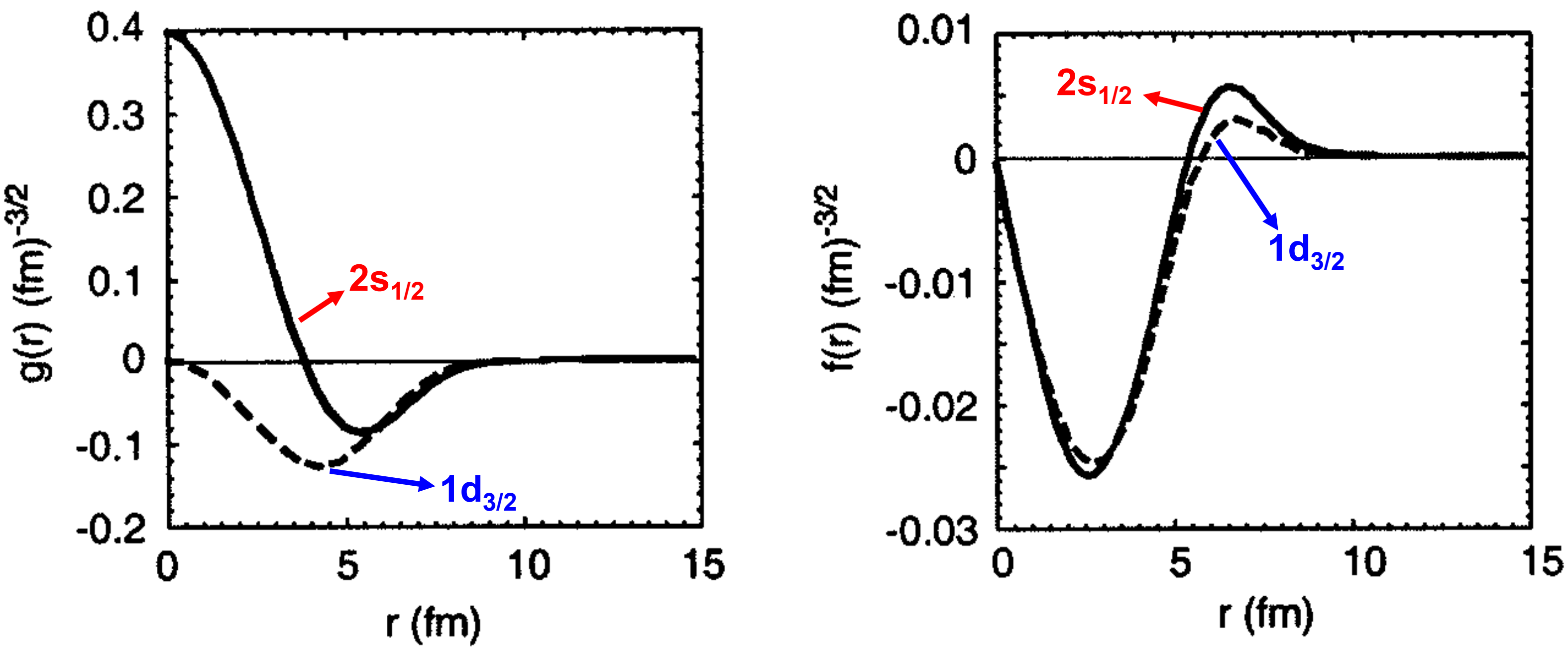
Mean Field Potentials



$V_s > V_v \rightarrow$ only approximate symmetry

Wave functions

Pseudospin symmetry predicts that the lower spatial amplitudes of the two eigenstates in the doublets are equal.



Amplitudes of lower component are always small. How can one test this?

SCIENCE DIRECT
PHYSICS REPORTS
ELSEVIER
Physics Reports 414 (2005) 165–261
www.elsevier.com/locate/physrep

Relativistic symmetries in nuclei and hadrons

Joseph N. Ginocchio

8. Magnetic dipole and Gamow–Teller transitions

…

Since the lower component of the Dirac wavefunction is small [6,81,25,82], the effect of pseudospin symmetry on the relativistic wavefunction is difficult to test empirically except perhaps in certain forbidden transitions, which, like Horton's ears, amplify the effects of the small amplitudes. For example, single-nucleon magnetic dipole and Gamow–Teller transitions between pseudospin doublets are forbidden

…

M1 transition between pseudospin partners: $\Delta L = 2, \Delta S = 1, \Delta J = 1, \Delta\pi = +$

Forbidden because M1 operator cannot not change radial quantum number

Pseudospin Symmetry Prediction for M1 Transition

$$j = \tilde{l} - 1/2 \qquad\qquad j' = \tilde{l} + 1/2$$

π single particle states

$$\frac{B(M1; j' \to j)}{S_j S'_j} = \frac{1}{2(2j+3)\sqrt{(j+1)(2j+1)}} \left[(j+2)(2j+1)\frac{\mu_{j'}^{exp}}{S'_j} - (2j+3)(j+1)\frac{\mu_j^{exp}}{S_j} + 4(j+1)^2 \, \mu_p \right]^2$$

ν single particle states

$$\frac{B(M1; j' \to j)}{S_j S'_j} = \frac{j+1}{2j+1} \left(\frac{\mu_j^{exp}}{S_j} - \mu_n \right)^2 \qquad \frac{B(M1; j' \to j)}{S_j S'_j} = \left(\frac{j+2}{2j+3} \right)^2 \frac{2j+1}{j+1} \left(\frac{\mu_{j'}^{exp}}{S'_j} + \frac{j+1}{j+2} \, \mu_n \right)^2$$

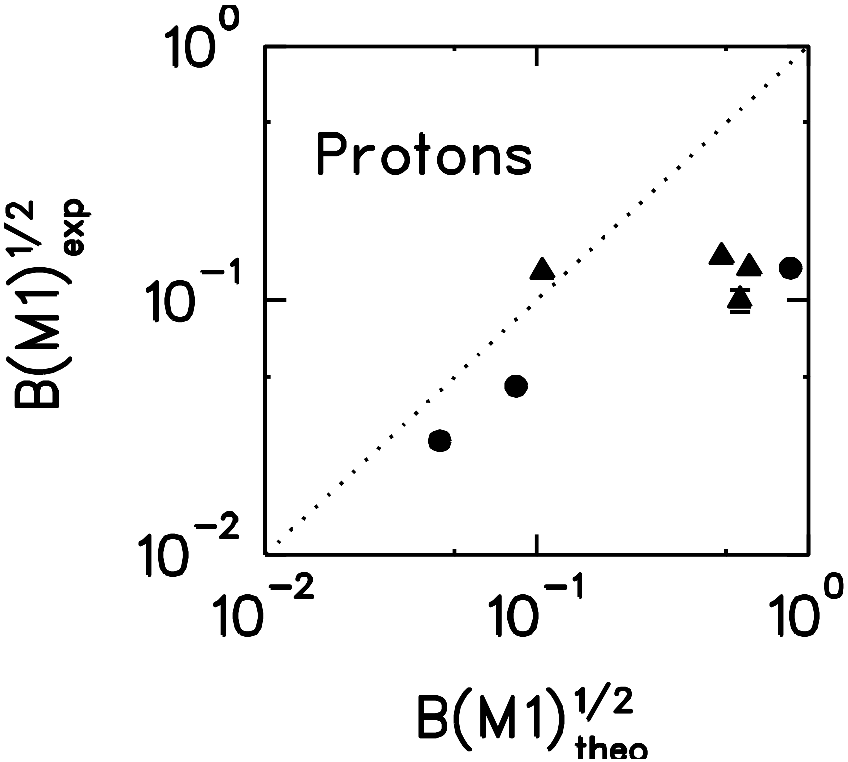
Connection between magnetic moments of initial and finals state and M1 strength

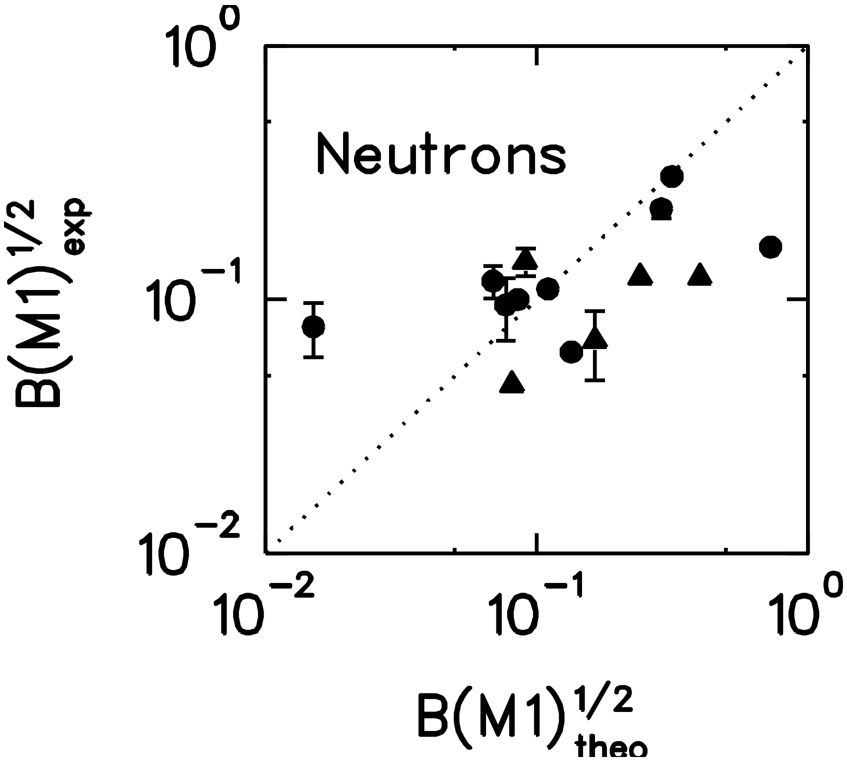
No pure single particle states in nature but approximately fullfilled near shell closures

Correction by spectroscopic factors from single-nucleon transfer reactions

Experimental Test

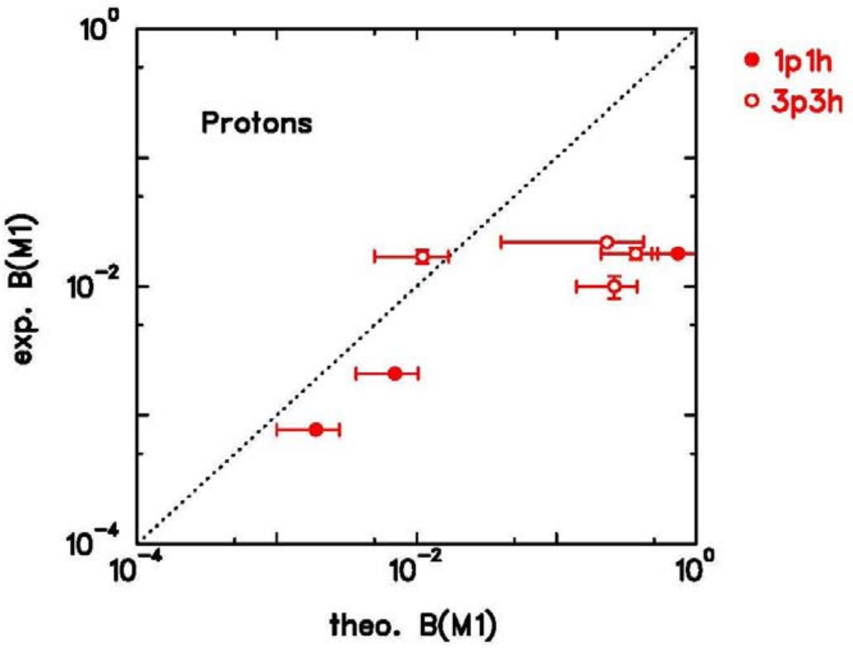
PvNC, J.N. Ginocchio, Phys. Rev. C 62, 014308 (2000)

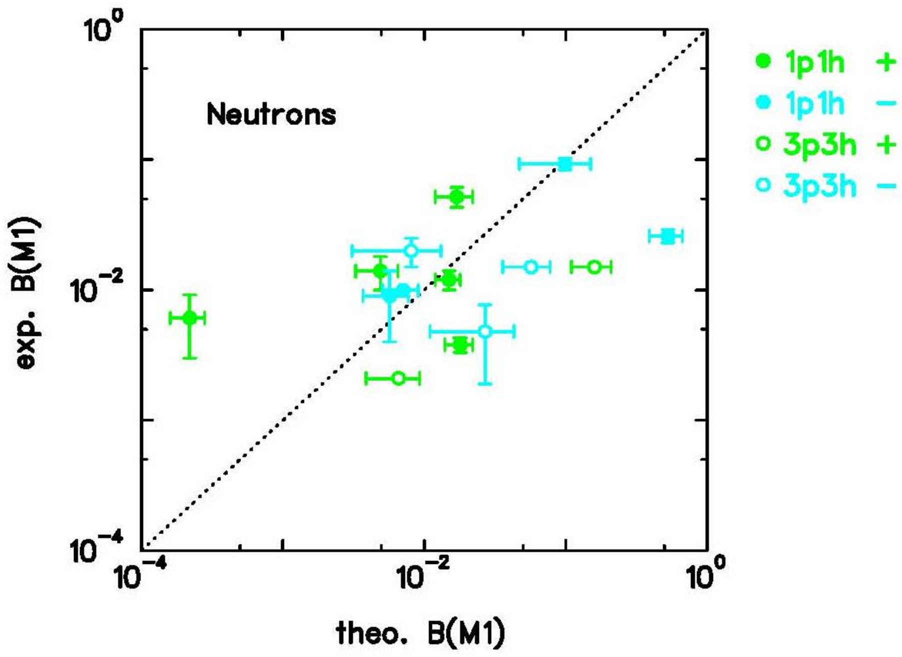




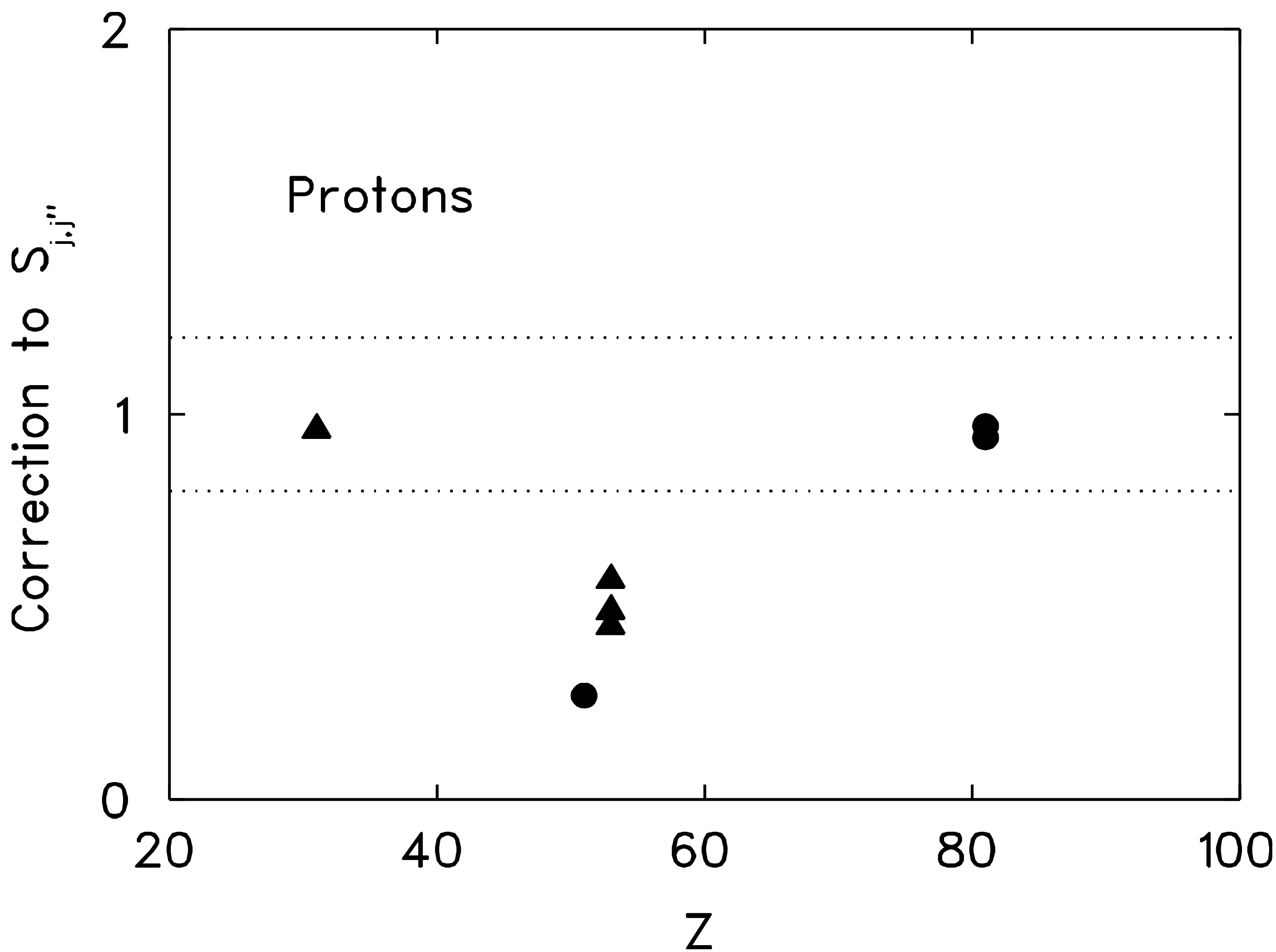
Experimental Test

PvNC, J.N. Ginocchio, Phys. Rev. C 62, 014308 (2000)

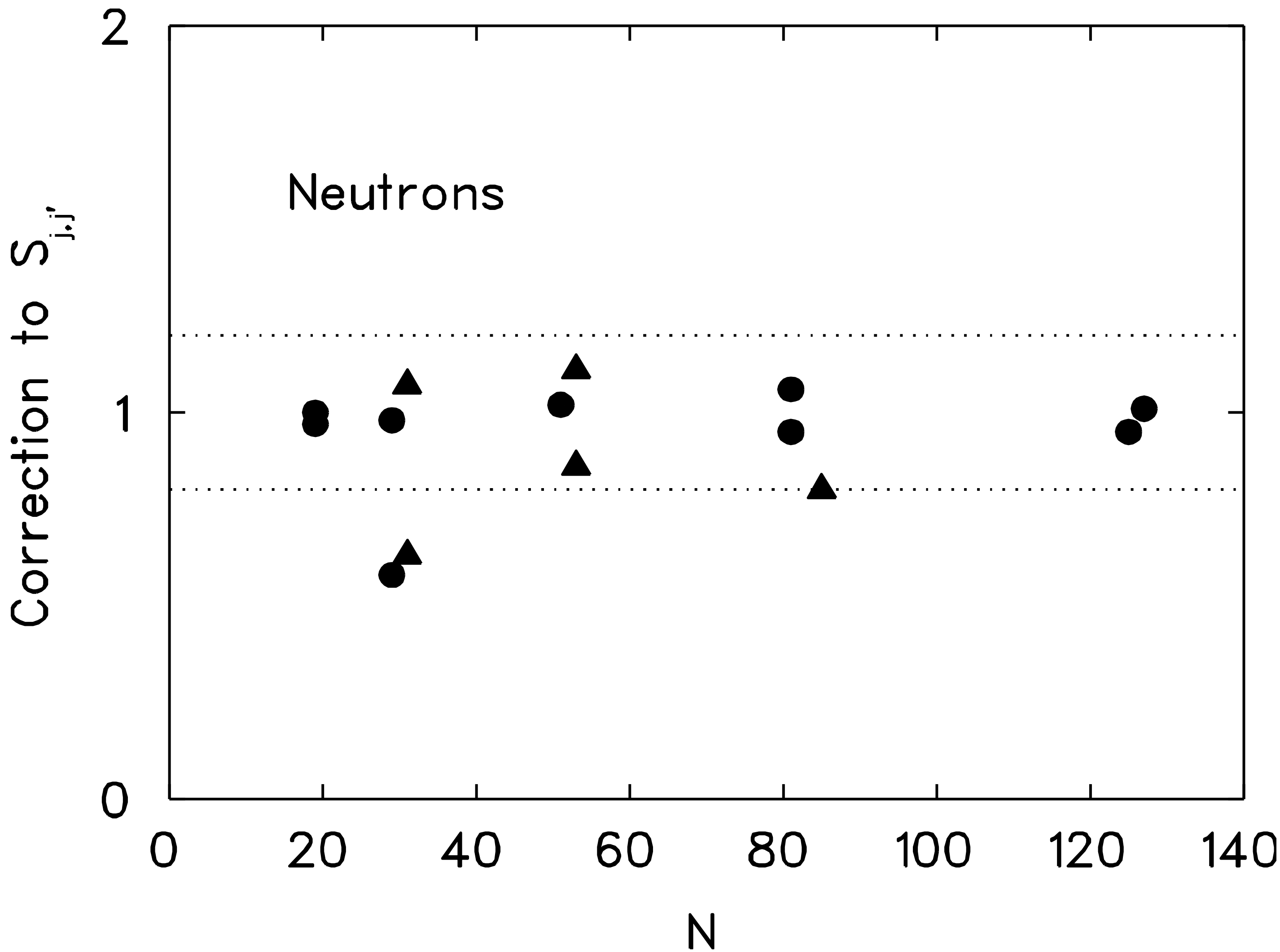




Experimental Test



Experimental Test



Experimental Test: Conclusions

Overall good agreement except for marked deviations at Z = 50 and N = 28 shell closures

Quenching of magnetic moments (Arima-Horie) not included

Similar test of pseudospin symmetry predictions relating allowed and forbidden GT transition fails

6. Higher magnetic multipoles
   – orbital M2 strength (the twist mode)
   – spin-dipole mode
   – M3 strength
   – stretched transitions

M2 Strength

Question:
If you had to measure M2 strength in nuclei, which probe would you choose: photons, electrons, or protons?

M2 Strength

Question:
If you had to measure M2 strength in nuclei, which probe would you choose: photons, electrons, or protons?

Answer:

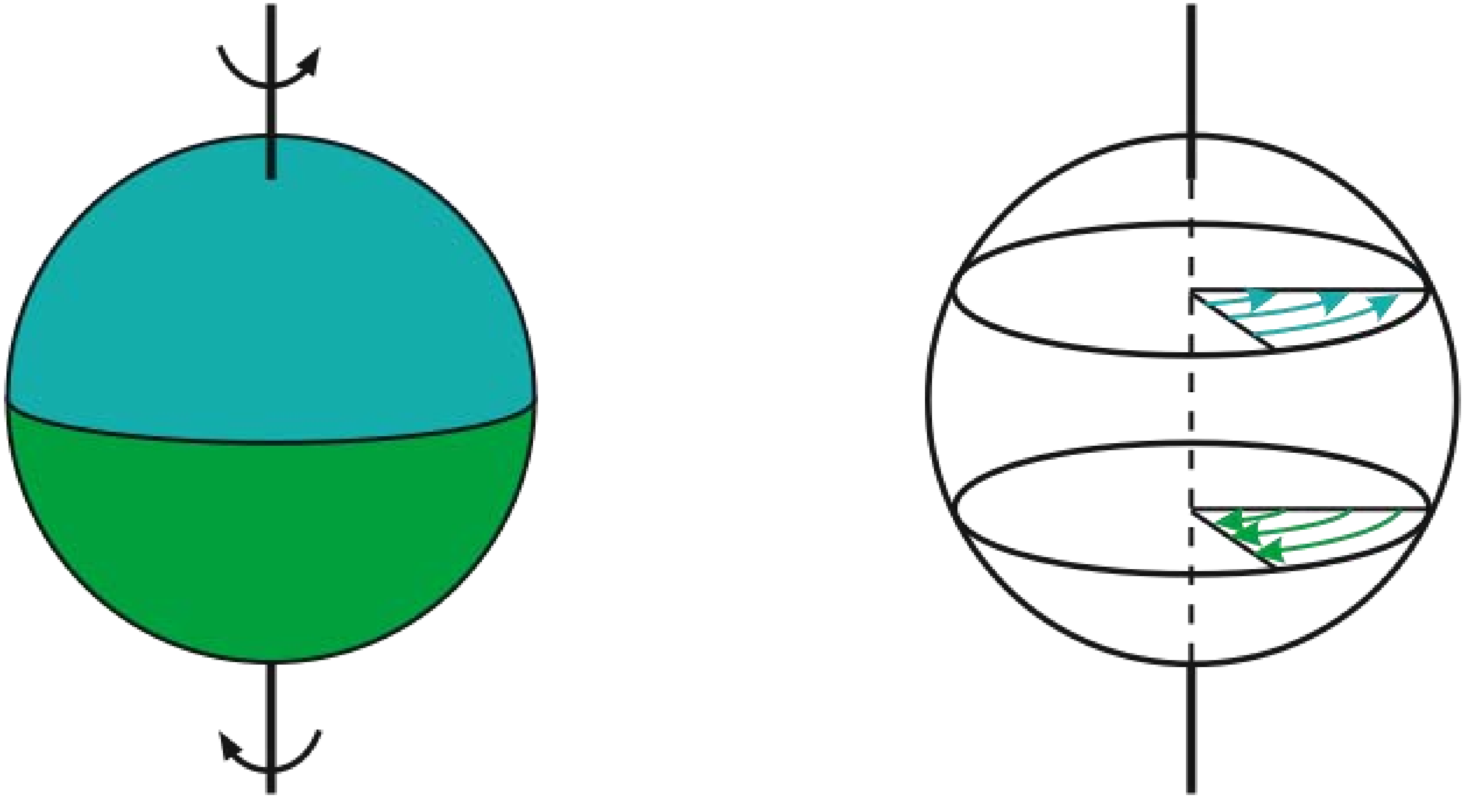
Photon scattering: no, radiative widths of M2 transitions too small

Electron scattering: excellent probe, high resolution needed

Proton scattering: measures spin-dipole strength (ΔL = 1, $J^{\pi} = 0^-, 1^-, 2^-$). The 2^- component is the analog of the spin-M2 strength. Extraction is difficult (different spin components overlap). Proton scattering is a ‘dirty‘ probe, at higher momentum transfers all possible modes are excited with comparable cross sections.

Orbital M2 Resonance: The Twist Mode

Predicted in semiclassical models



Purely transverse

Quantum phenomenon in finite Fermi systems

Implications of the Twist Mode

In simple proton- and neutron-fluid models the twist mode cannot exist (no restoring force).

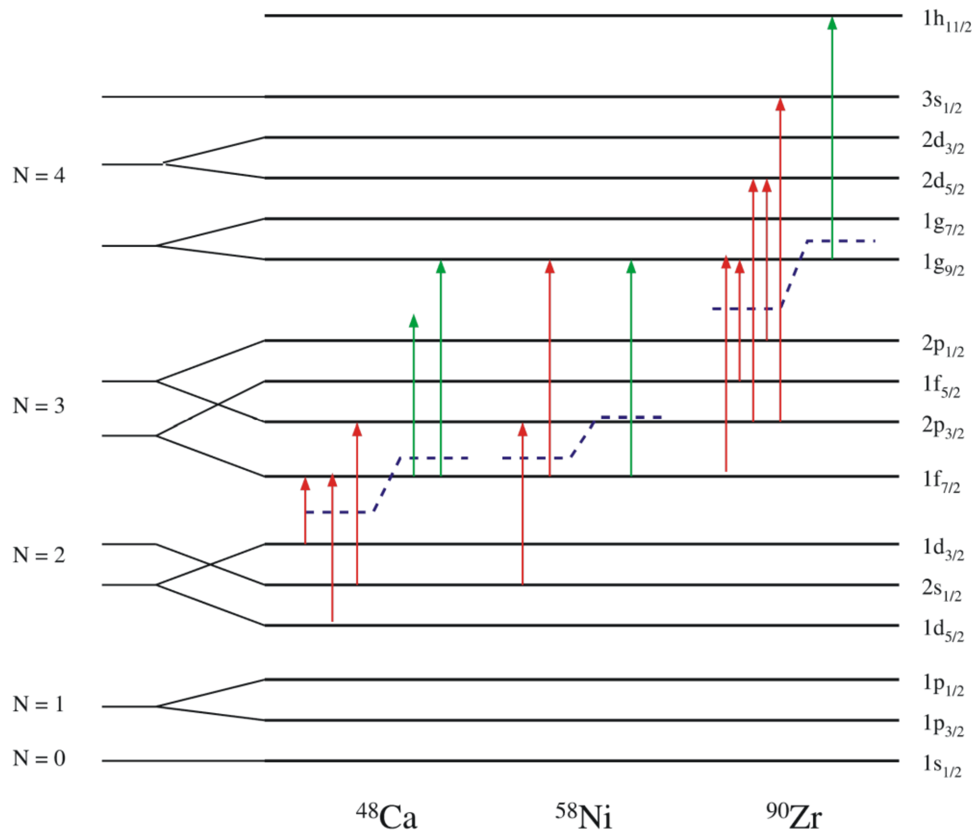
Giant resonances are generally poorly described by two-fluid models (exception GDR).

Theoretically they are predicted to rather behave like an elastic medium. Observation of the twist mode is a direct evidence.

Twist mode measures elasticity of nuclei → relation to bulk properties of nuclear matter (shear module).

M2 Transitions in the Shell Model Picture

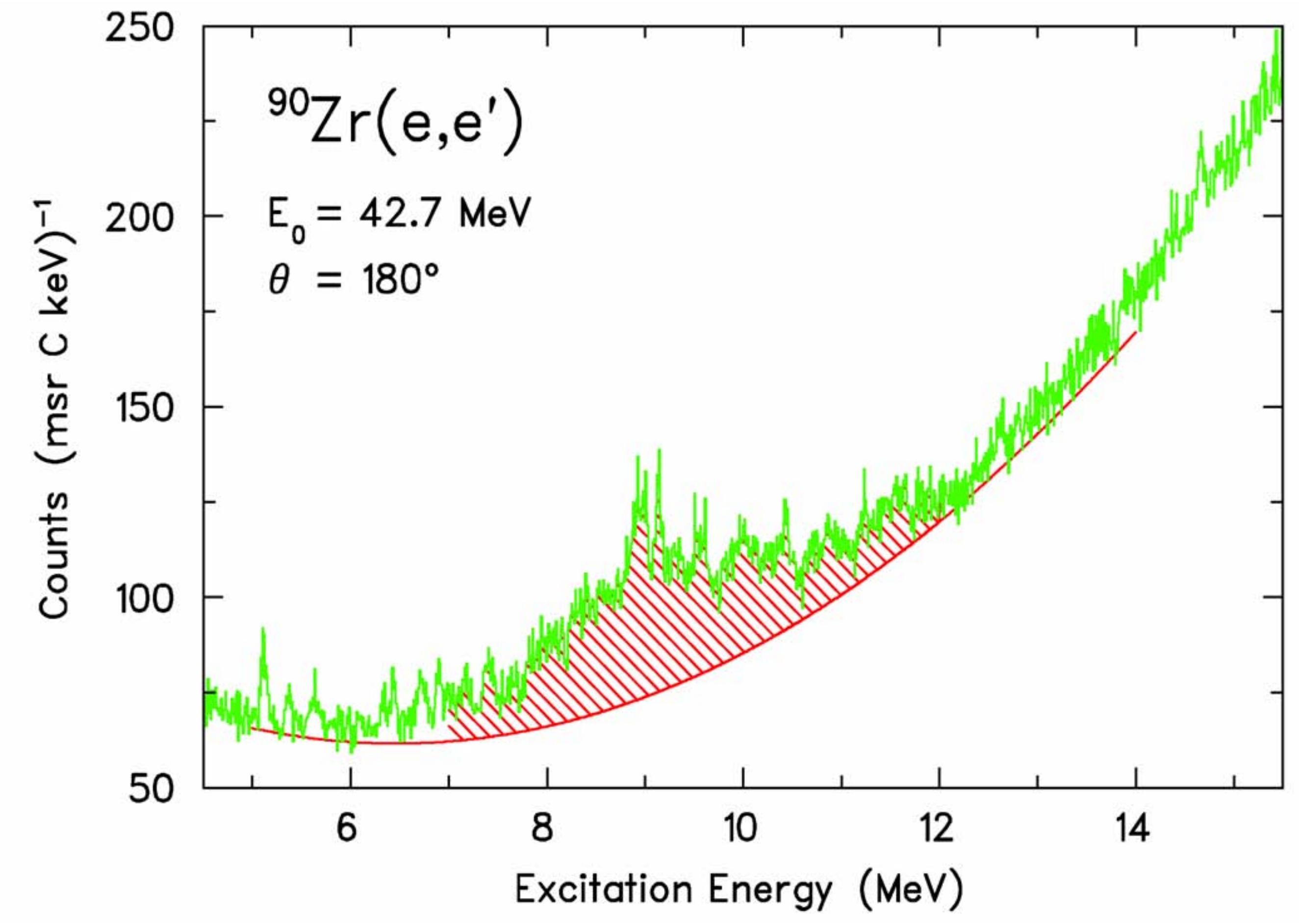
TECHNISCHE UNIVERSITÄT DARMSTADT



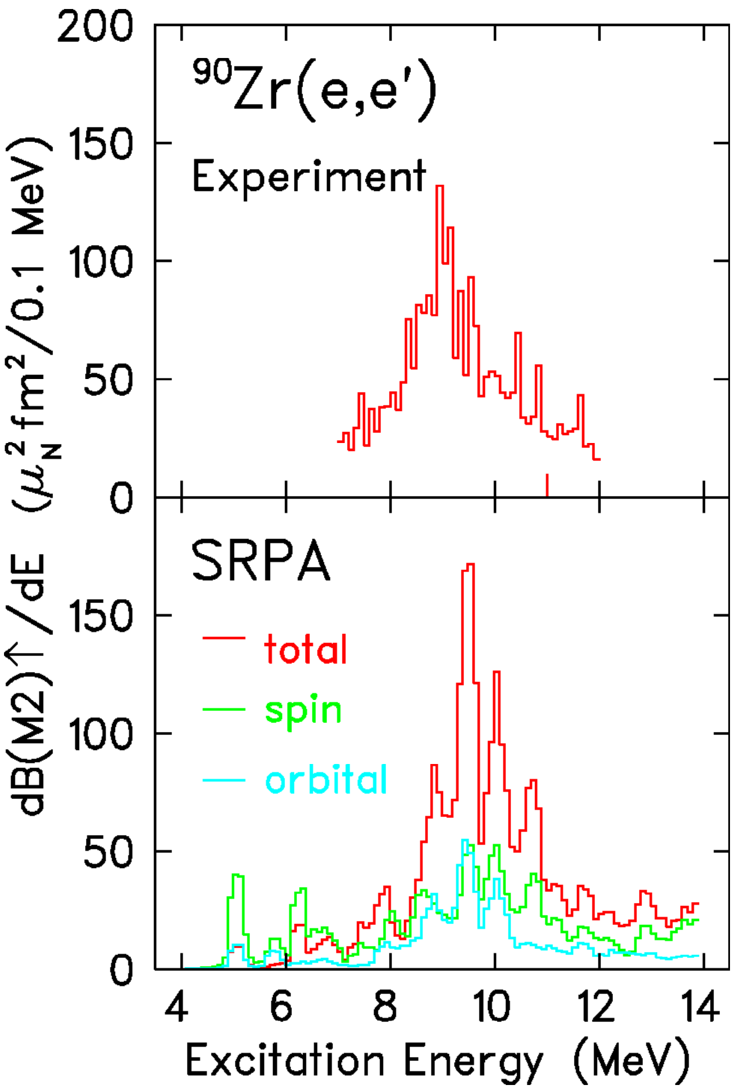
$$\boldsymbol{M}(M2)=\frac{e\hbar}{2Mc}\sum_k\left(g_s(k)s_k+\frac{2}{3}g_l(k)l_k\right)\nabla_k r_k^2 Y_2$$

M2 Resonance in 180° Electron Scattering

PvNC et al., Phys. Rev. Lett. 82, 1105 (1999)



M2 Resonance in ^{90}Zr

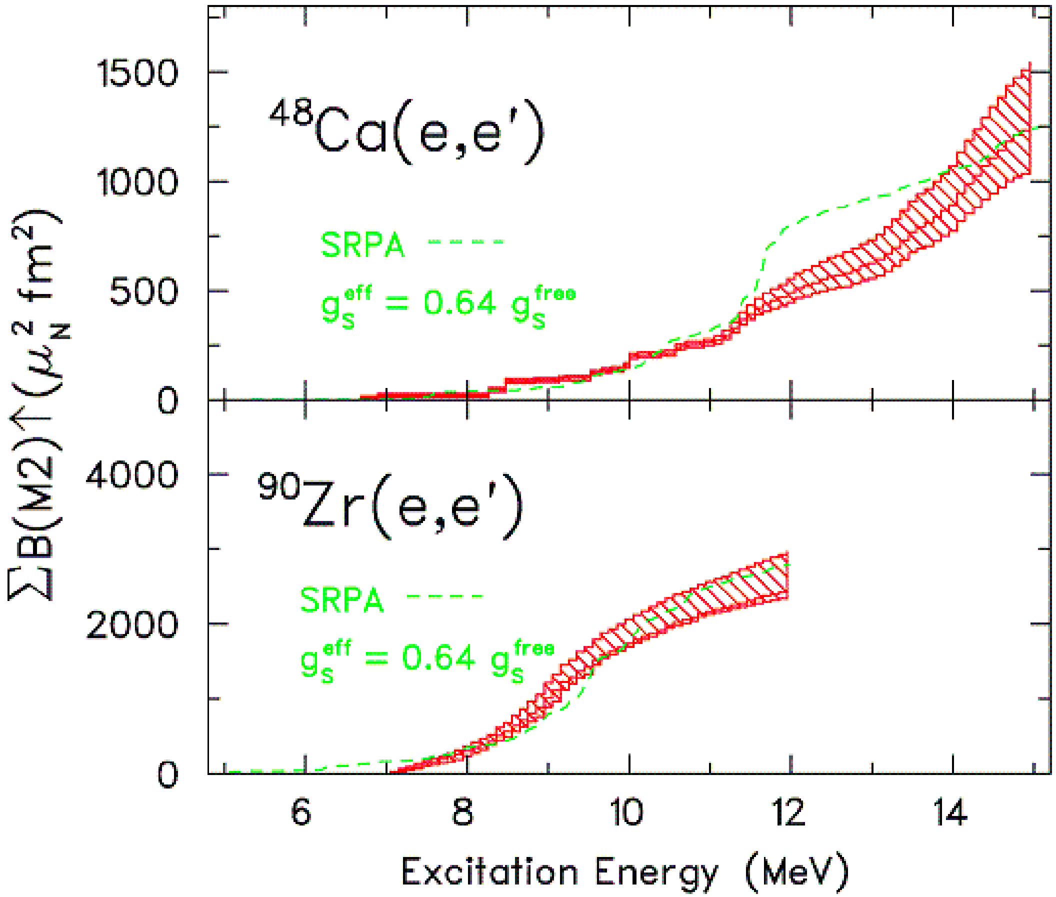


Strong constructive interference

Quantitative description possible

→ indirect evidence for twist mode

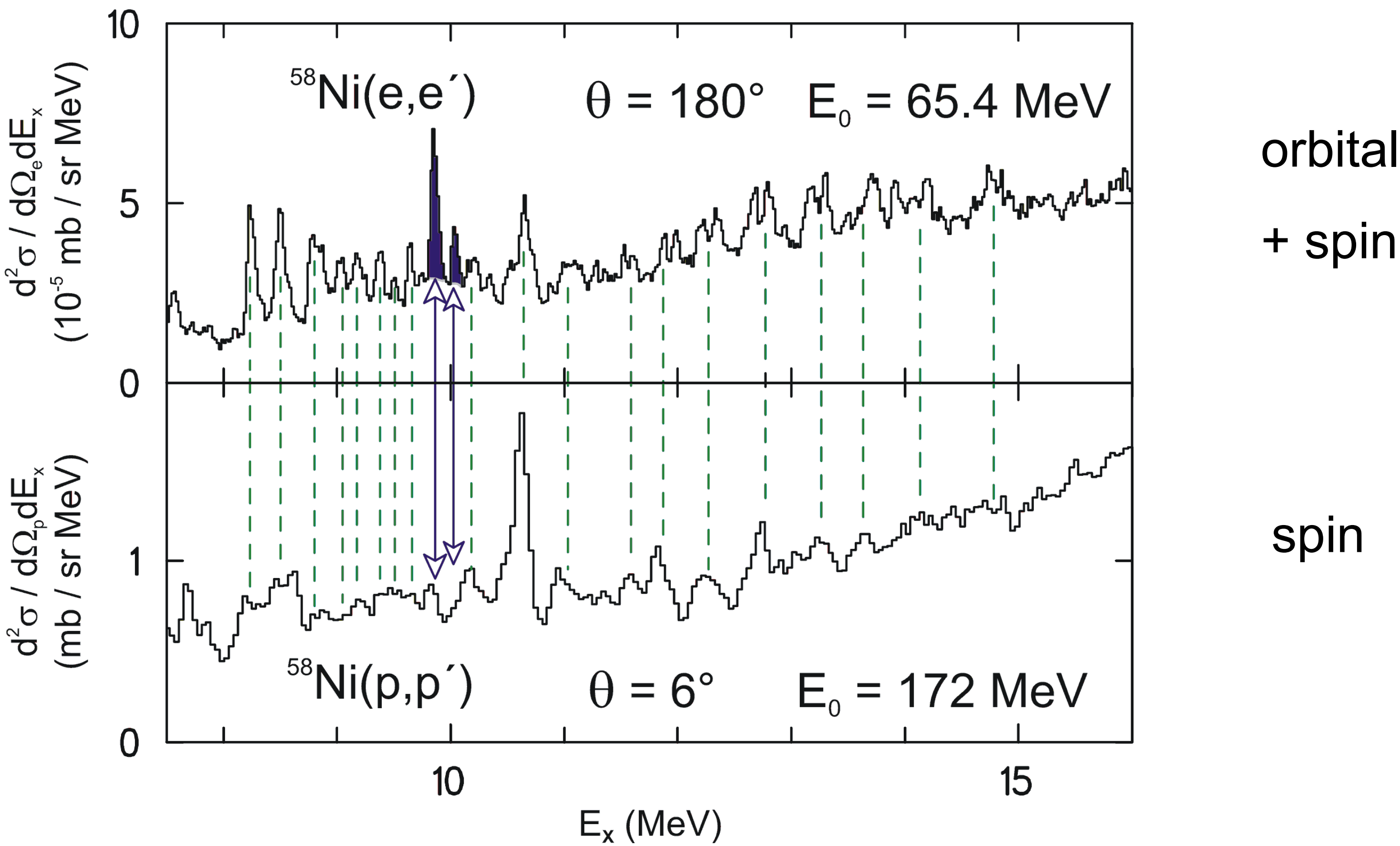
Running Sums



Quenching comparable to M1 case

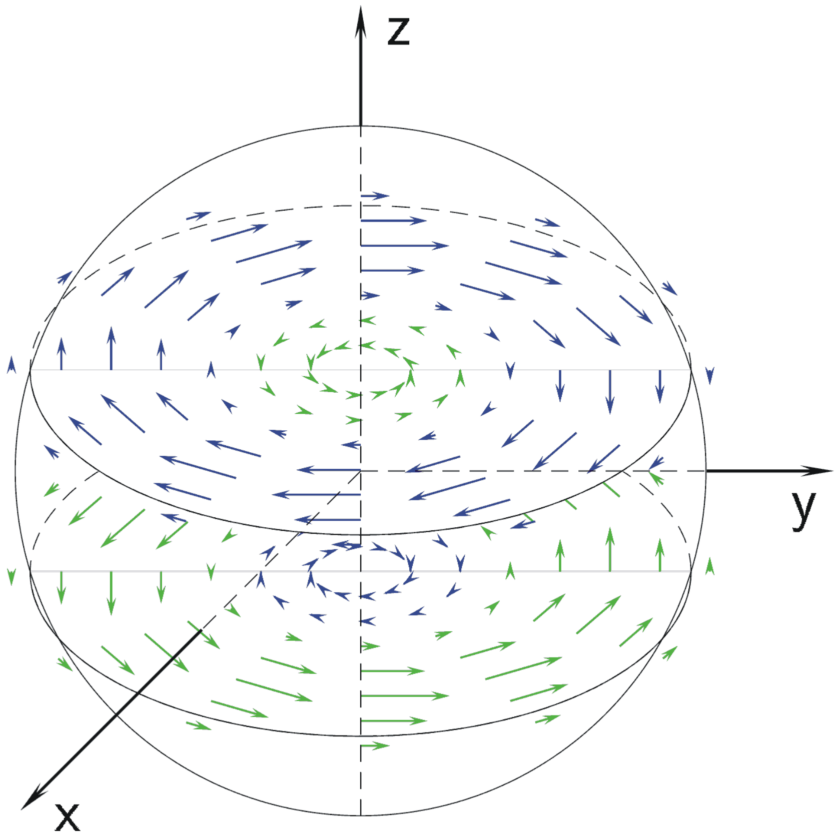
Direct Evidence for Orbital M2 Excitations

B. Reitz et al., Phys. Lett. B 532, 179 (2002)



Prominent M2 transitions around 10 MeV not excited in (p,p‘) → orbital

Microscopic Picture of the Twist Mode

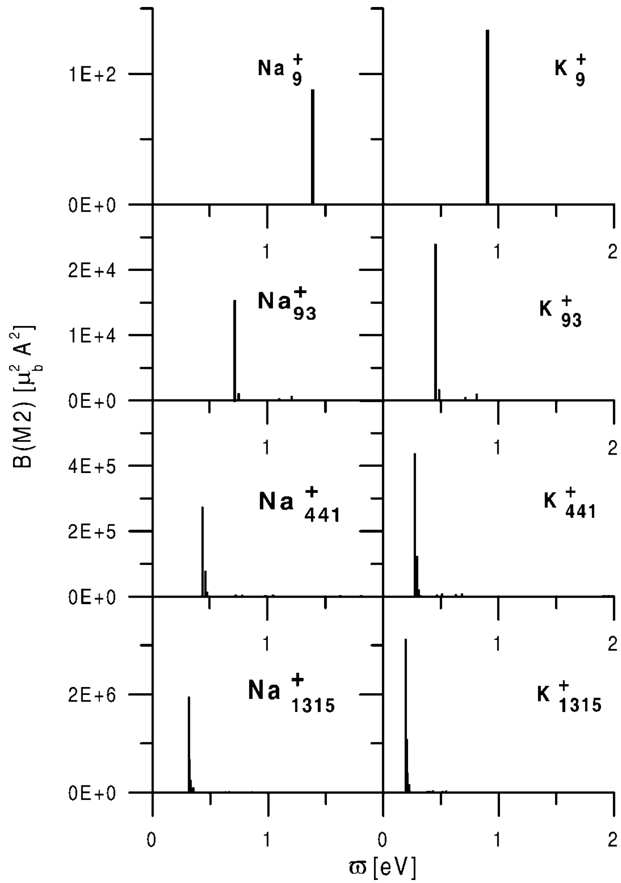


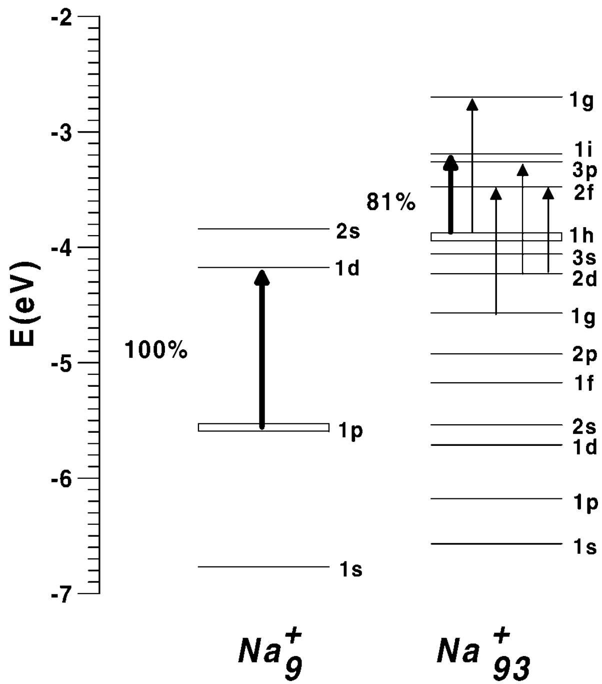
Current

Clockwise - counterclockwise flow in the two hemispheres
Reversal of flow direction in the interior → node in transition density
Semiclassical picture confirmed in microscopic calculations

Twist Mode in Metallic Clusters

V.O. Nesterenko et al., Phys. Rev. Lett. 85, 3141 (2000)

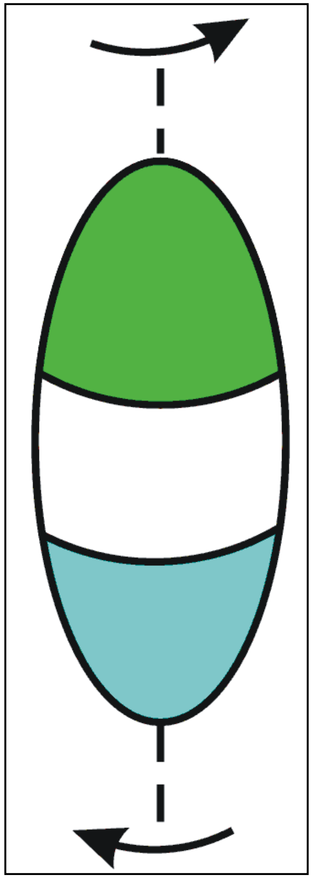




Twist Mode in Ultracold Atomic Fermi Gases

TECHNISCHE UNIVERSITÄT DARMSTADT

X. Viñas, R. Roth, P. Schuck, and J. Wambach, Phys. Rev. A 64, 055601(2001)



Trapped Fermi gas with $T \ll \frac{k_F^2}{2m} = \varepsilon_F$

(e.g. ^{6}Li, ^{40}K at $\cong$ 600 nK)

- Unique mode for degenerate Fermi gases
- Landau theory predicts quadrupole deformation of the Fermi sphere:
  - anisotropic pressure tensor
  - transverse zero sound
  - ”R-Modes” in neutron stars
- Excitation of the Twist Mode in traps difficult

Relation of M2 and Spin-Dipole (SD) Strength

TECHNISCHE UNIVERSITÄT DARMSTADT

Spin-Dipole resonance: $\Delta L = 1, \Delta S = 1\ \Delta T = 1, J^{\pi} = 0^{-}, 1^{-}, 2^{-}$

Similar relation between to the M1/GT case can be derived for the M2 and SD ($J^{\pi} = 2^{-}$) operators.

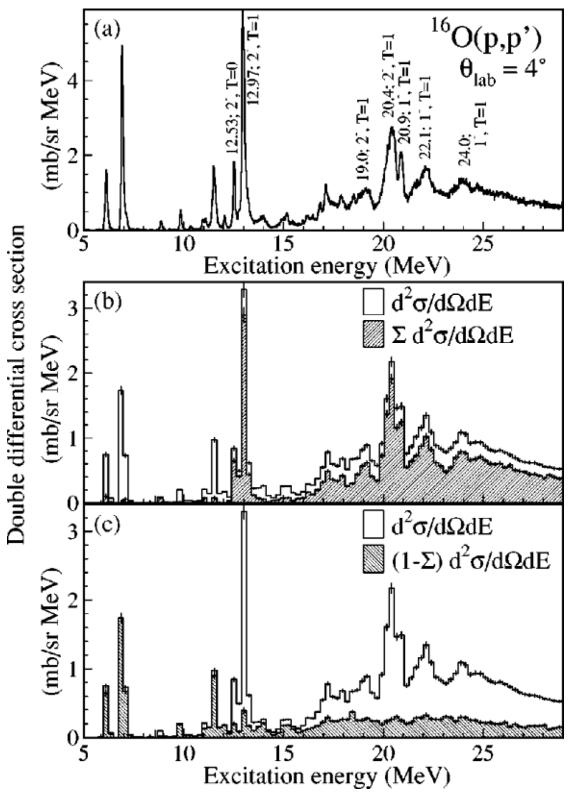
Experimental decomposition of SD components has recently been achieved with charge-exchange reactions.

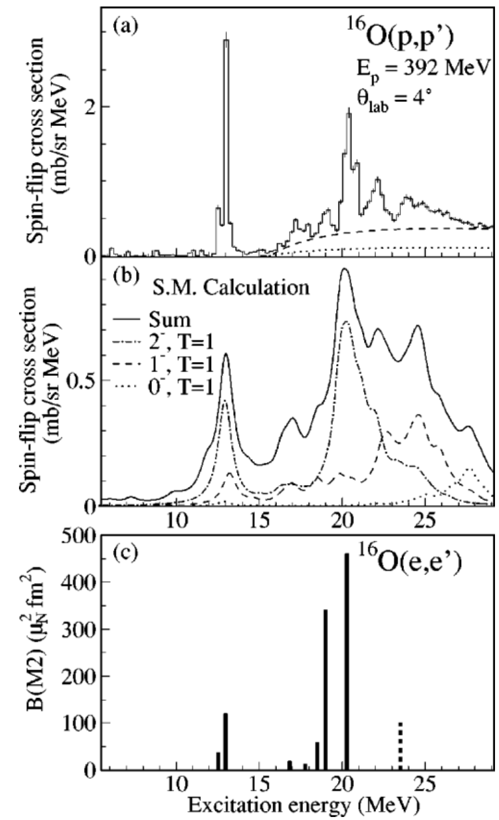
In (p,p') much more complicated because of strong excitation of non-spinflip modes. Additional observables must be measured (spin transfer, coincident particle/gamma decay).

Presently no method available for model-independent conversion of cross sections to matrix elements. Needs detailed comparison to first-forbidden beta decay (only possible for a few nuclei).

Spin-Dipole Strength in ^{16}O

T. Kawabata et al., Phys. Rev. C 65, 064316 (2002)

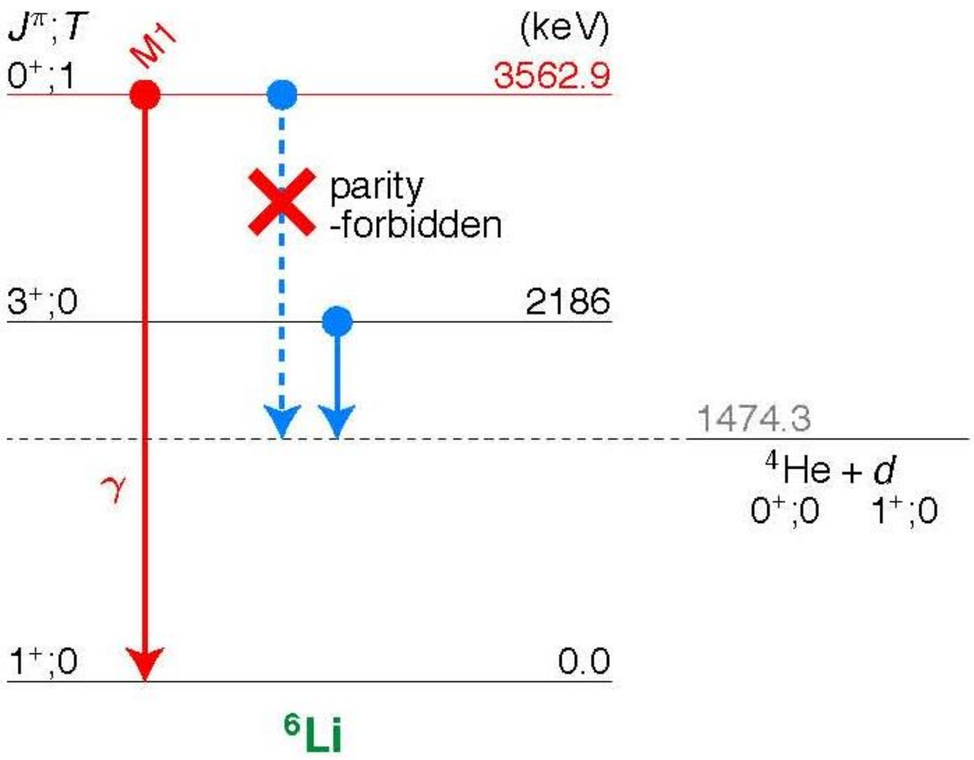




Polarization transfer observables to extract spin-flip part
No separation of spin components but M2 dominates

^{6}Li Scattering - a Tool for Pure Spinflip Response?

S. Noji et al., proposal E441, CAGRA@GRAND RAIDEN

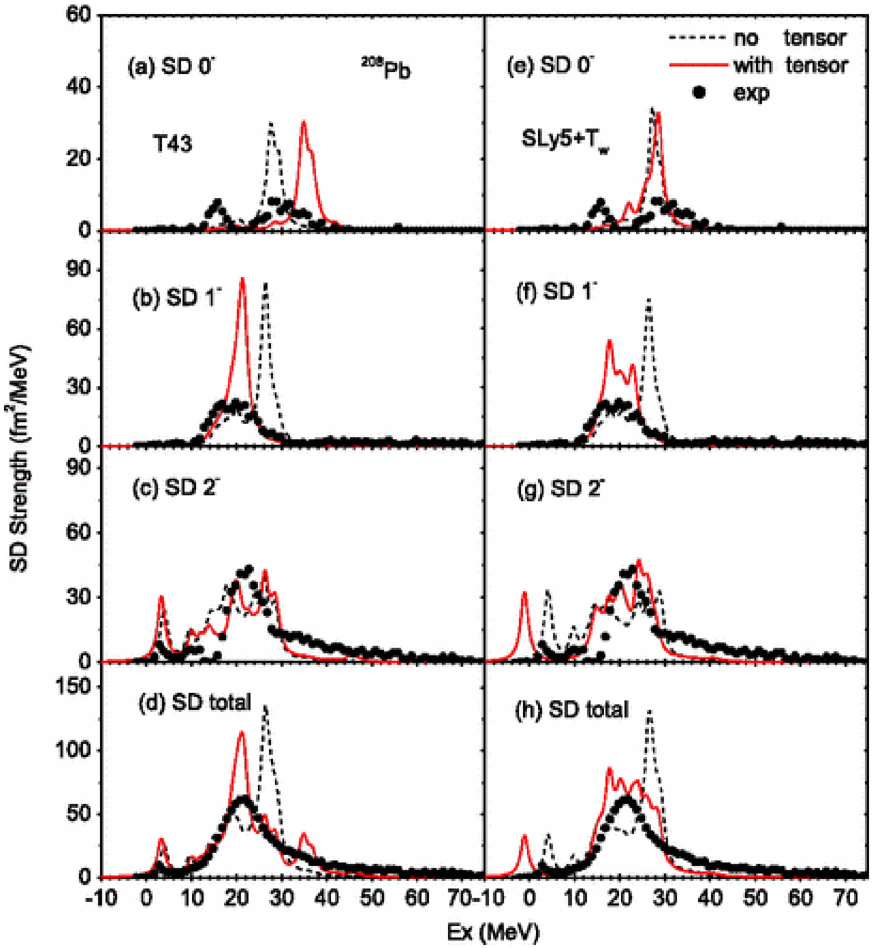


Pure Δ S = 1, ΔT = 1 transition

Mainly for spin-M1 but eventually separation of SD strength possible with multipole decomposition

Spin Components of Spin-Dipole Resonance and Tensor Interaction

C.L. Bai et al., Phys. Rev. Lett. 105, 072501 (2010)



RPA calculation with Skyrme interaction

Inclusion of tensor force modifies energy centroid of spin components

$J^\pi = 0^- \rightarrow$ upward shift

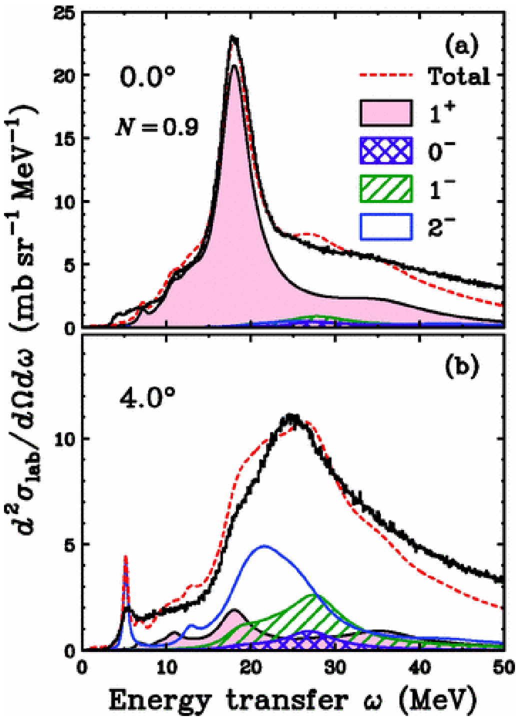
$J^\pi = 1^- \rightarrow$ downward shift

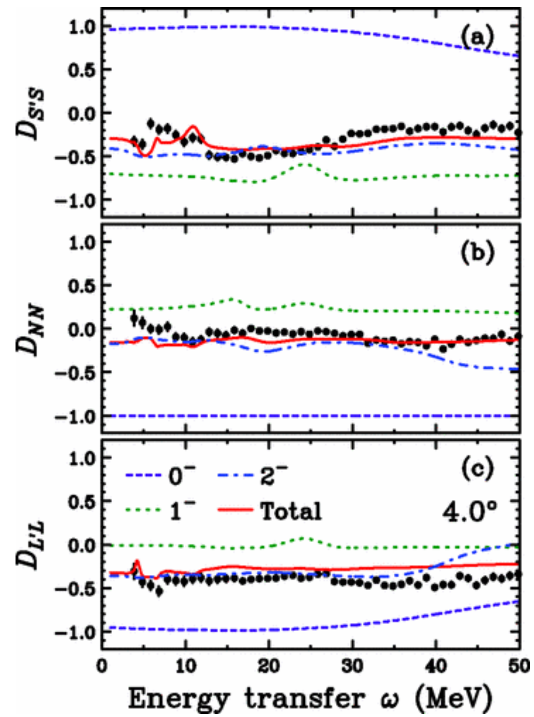
$J^\pi = 2^- \rightarrow$ no shift

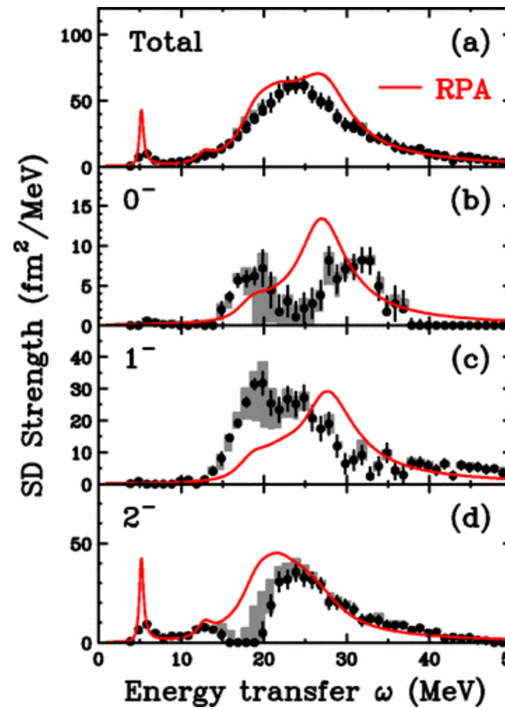
Separation of Spin-Dipole Components in the ^{208}Pb(pol p, pol n) Reaction

TECHNISCHE UNIVERSITÄT DARMSTADT

T. Wakasa et al., Phys. Rev. C 85, 064606 (2012)



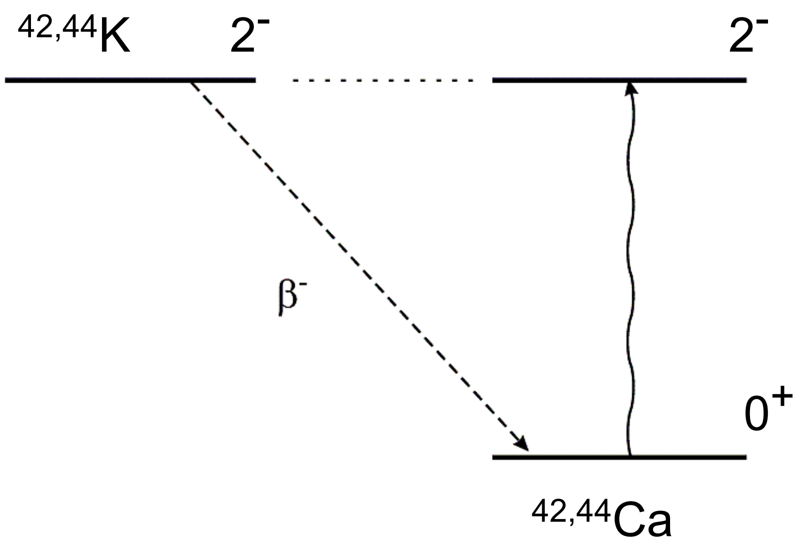


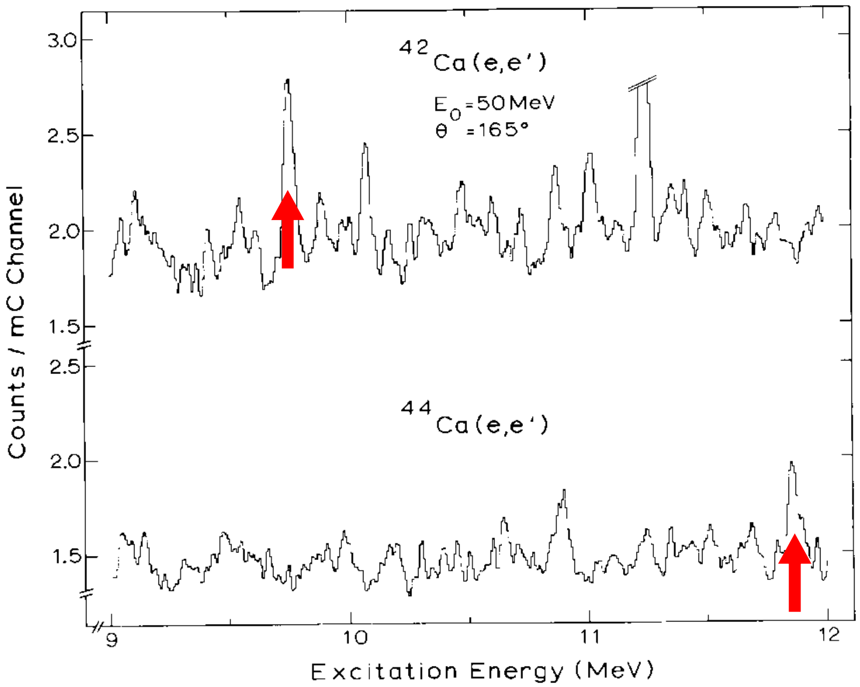


MDA for extraction of SD cross sections
Polarization transfer observables for separation of spin components
Polarization measurement of outgoing neutron

Spin-M2 Strength and First-Forbidden Matrix Elements

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





Orbital matrix elements zero within error bars

Quenching of g_A and g_V similar

M3 and Spin-Quadrupole Strength

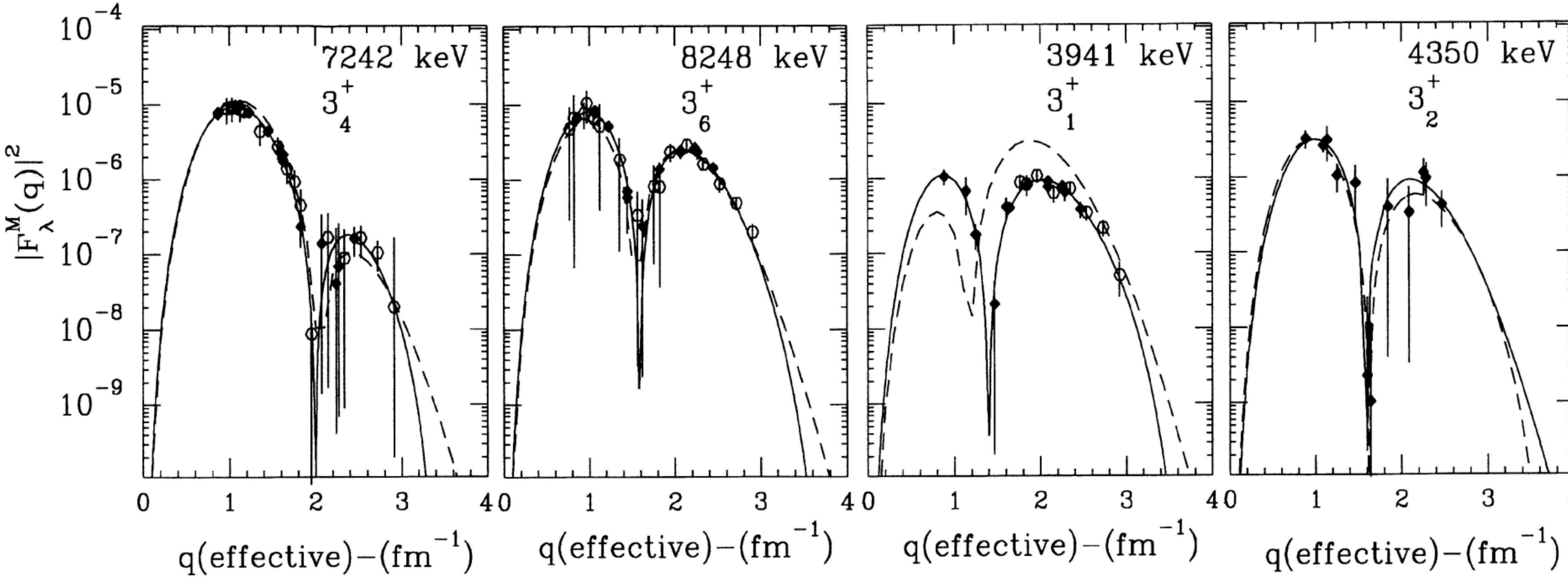
Almost ‘Terra Incognita’.

No sytematic data on spin-quadrupole (ΔL = 2, J^π = ,1^+,2^+,3^+) strength. No method for conversion of cross sections to matrix elements available.

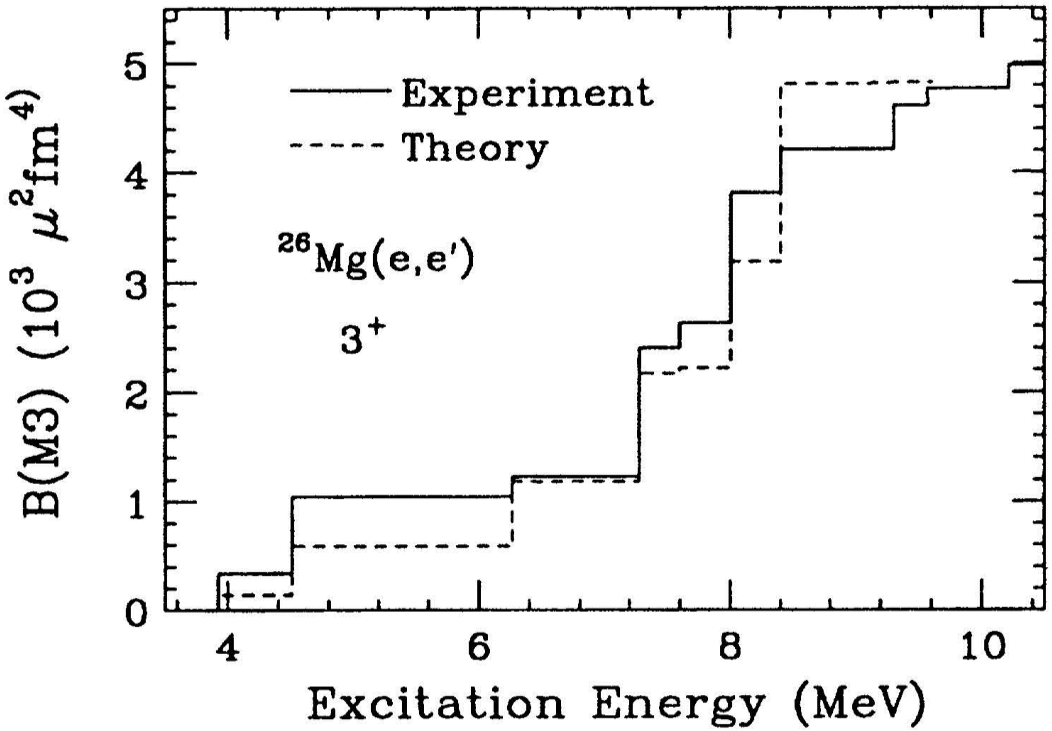
I am aware only of one systematic measurement of a M3 strength distribution.

M3 Strength in ^{26}Mg: Form Factors

K.K. Seth et al., Phys. Rev. Lett. 74, 642 (1995)



M3 Strength in ^{26}Mg: Running Sum



Comparison to USD shell model calculations: no quenching!?

Stretched Particle-Hole States

Coupling of j = l + ½ orbits with highest possible j value to maximum J across an oscillator shell

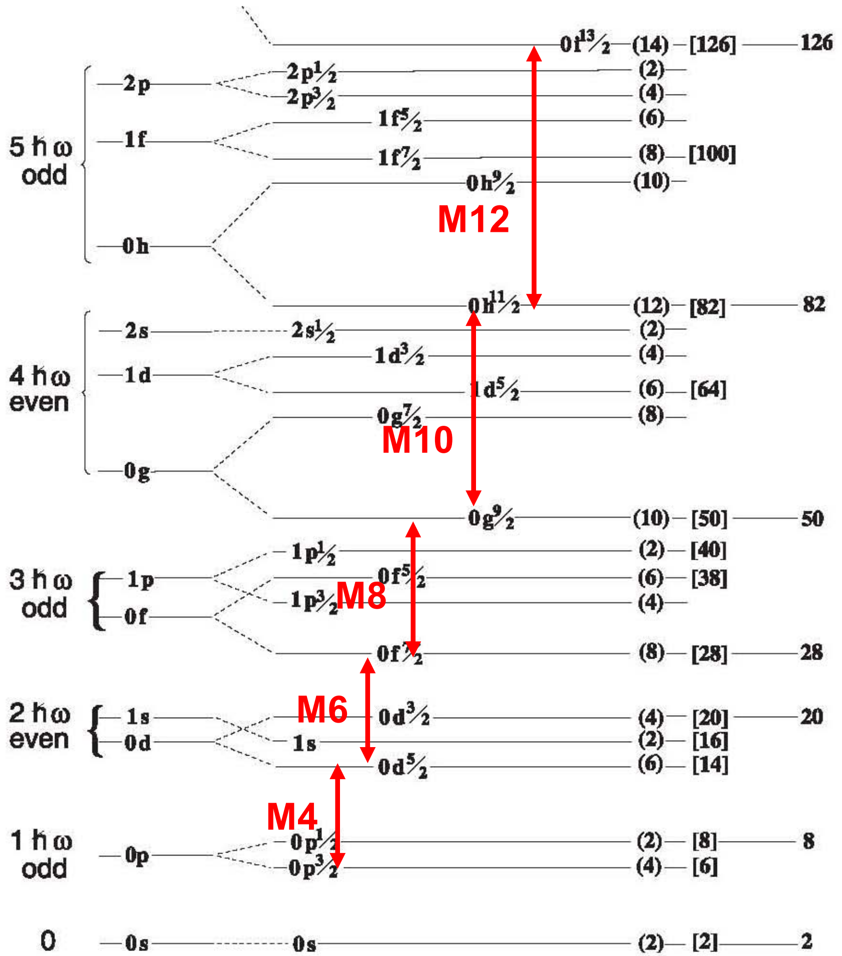
$$|j_1 - j_2| \le J \le j_1 + j_2 = J_{max} = l_1 + {}^1\!/_2 + l_2 + {}^1\!/_2 = l_1 + l_2 + 1$$

Spinflip transition
Simple particle-hole structure
Highest spin at a given excitation energy → little mixing

Test of tensor part of the NN interaction

Test of medium effects: Is there a difference between free NN scattering and scattering within a nucleus?

Magnetic Transitions to Stretched States



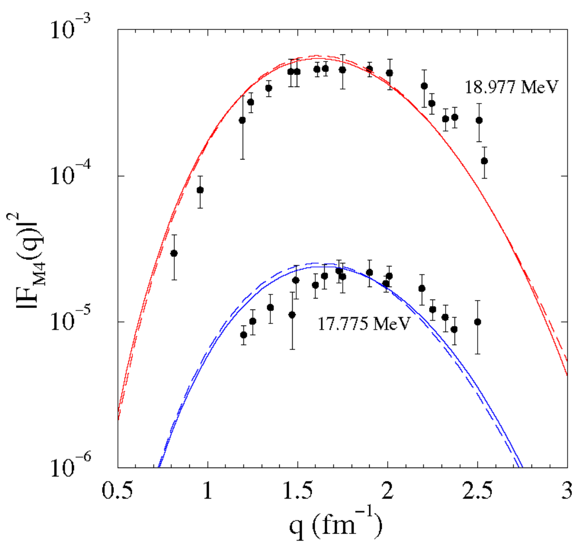
Electron Scattering Form factors

C.E. Hyde-Wright et al., Phys. Rev. C 35, 880 (1987)

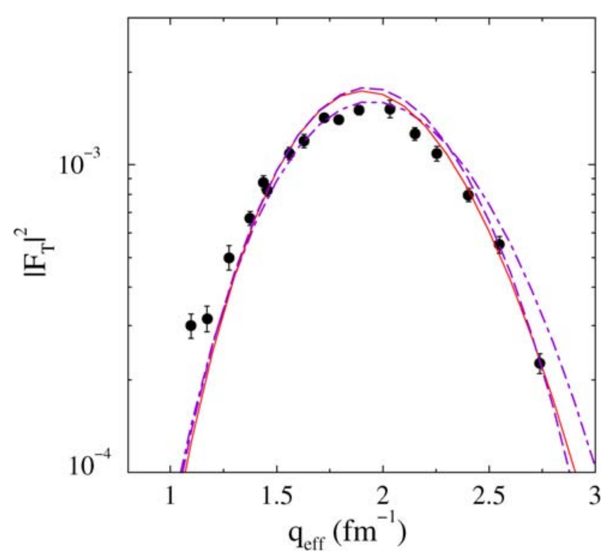
S. Yen et al., Phys. Lett. B 93, 250 (1980)

J.E. Wise et al., Phys. Rev. C31, 1699 (1984)

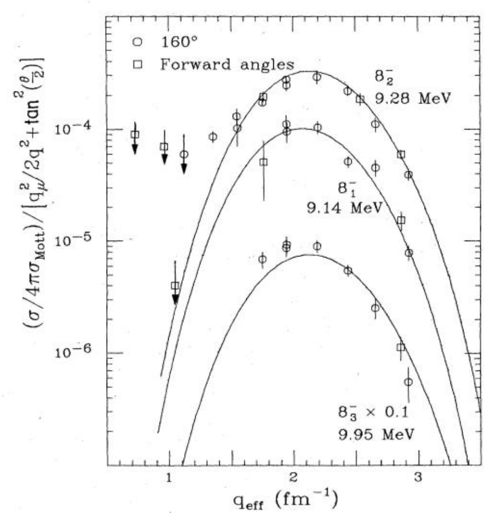
^{16}O M4



^{28}Si M6



^{48}Ca M8



Matrix elements fixed

Strongly quenched with respect to shell-model results

Proton Scattering

Same levels oberved in ^{16}O and ^{28}Si

Discrepancies in the assignment of 8^- states in ^{48}Ca

Quenching factors from (e,e‘) and (p,p‘) show large differences in some cases

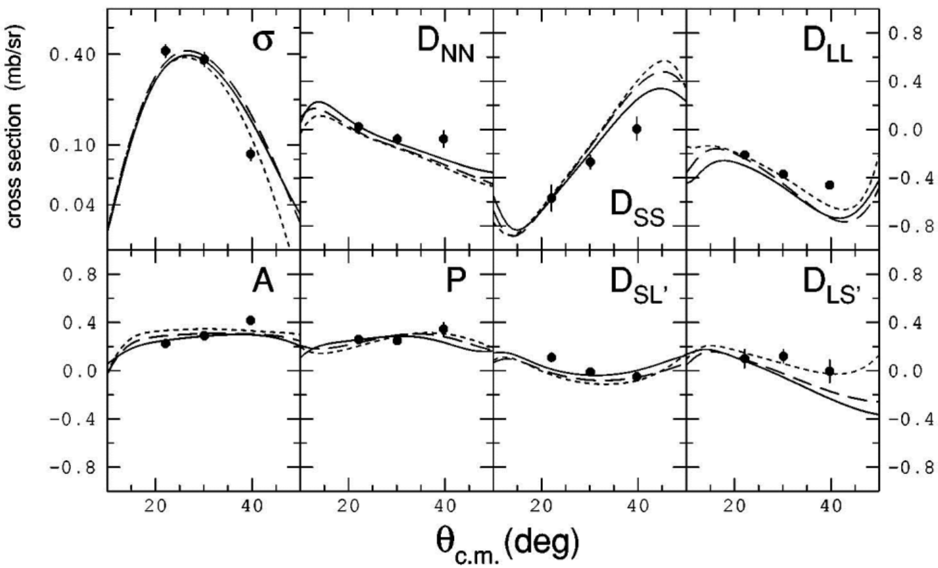
Quenching factors from (p,p‘) experiments at different incident energies show large differences in some cases

^{16}O: Test of Medium Effects

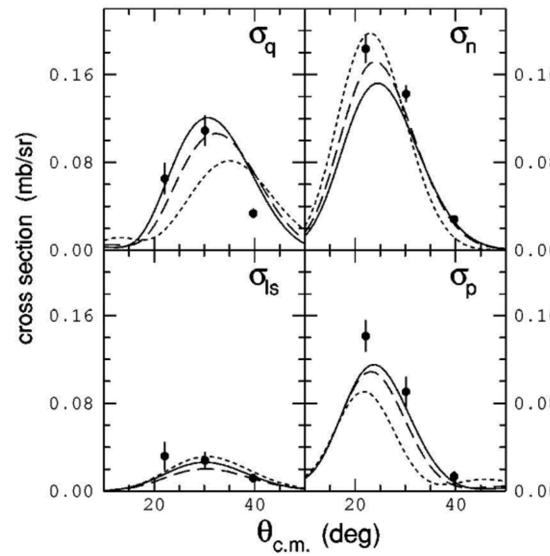
TECHNISCHE
UNIVERSITÄT
DARMSTADT

F. Sammaruca et al., Phys. Rev. C 61, 014309 (1999)

4^-, T = 1 state 18.98 MeV



Parts of the effective NN interaction



Reduction of ρ-meson mass predicted in the medium (Brown-Rho scaling)
DWIA description of reaction mechanism to poor to draw conclusions