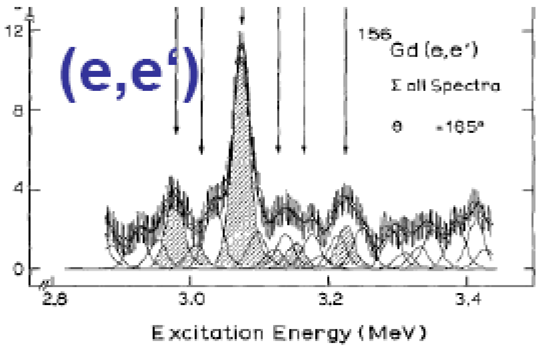
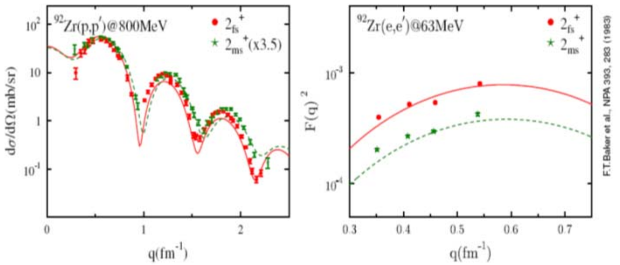
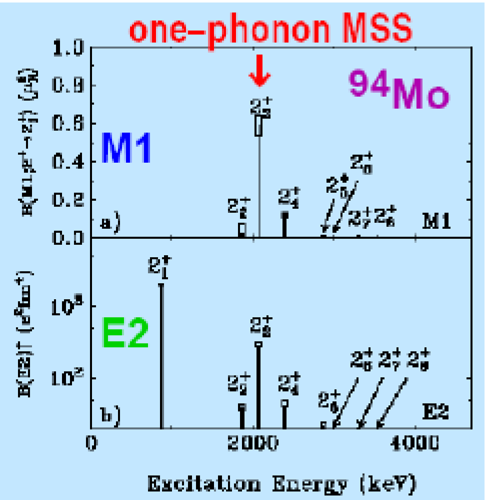
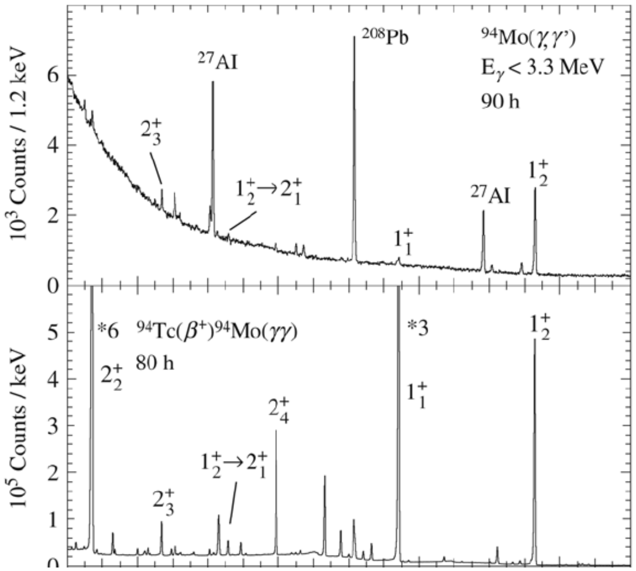
The Beauty of Good Data:
Unveiling the Traces of Mixed Symmetry

Norbert Pietralla, TU Darmstadt
+ his group and collaborators…









Deutsche Forschungsgemeinschaft DFG
SFB634
DAAD
HIC for FAIR Helmholtz International Center
Bundesministerium für Bildung und Forschung BMBF

On March 16th, 1976, Franco Iachello…

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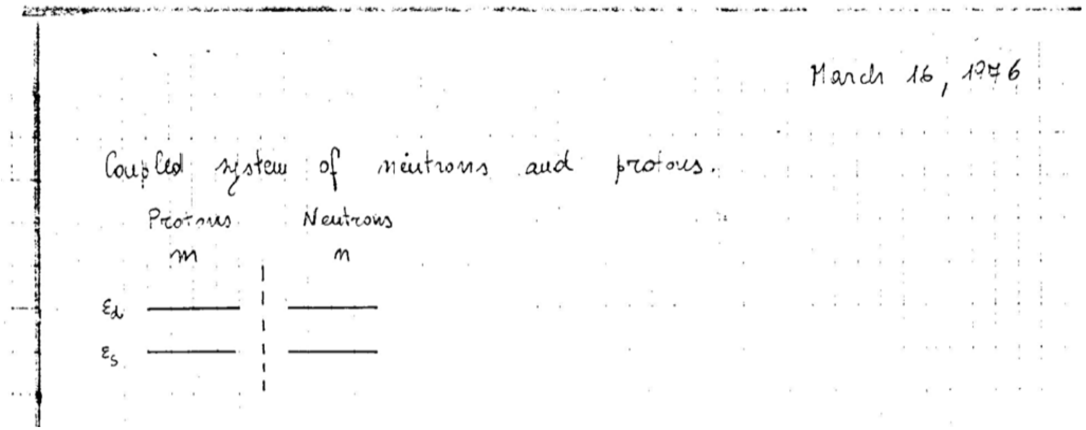
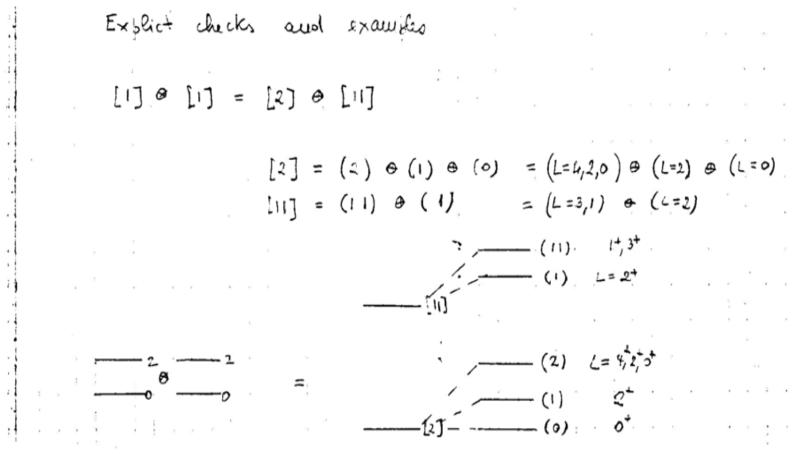


Xerox-copy of Franco‘s log-book



…invented the IBM-2

Arima, Ohtsuka, Iachello, Talmi, PLB 66 (1977) 205.

Outline

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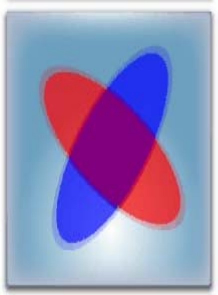
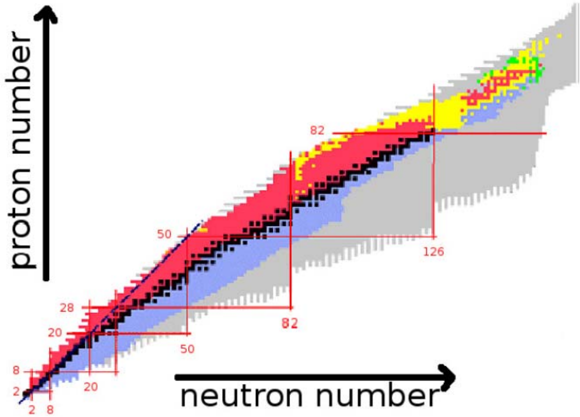
IBM-2: Inspiration & Challenge for Experimentalists

- **Reminder at main features**
  - Focus: Mixed-Symmetry States (MSSs)
- **Some historical milestones**
  - Scissors Mode: ^{156}Gd and Systematics
  - Vibrational MSSs
  - „Complete“ spectroscopy from Projectile-COULEX
- **Recent Developments**
  - First solid ID of MSS in RIB-experiment
  - Systematics in A=130 mass region
  - Quadrupole Transition Radii
- **Summary**





Quadrupole Vibrations with Mixed Symmetry

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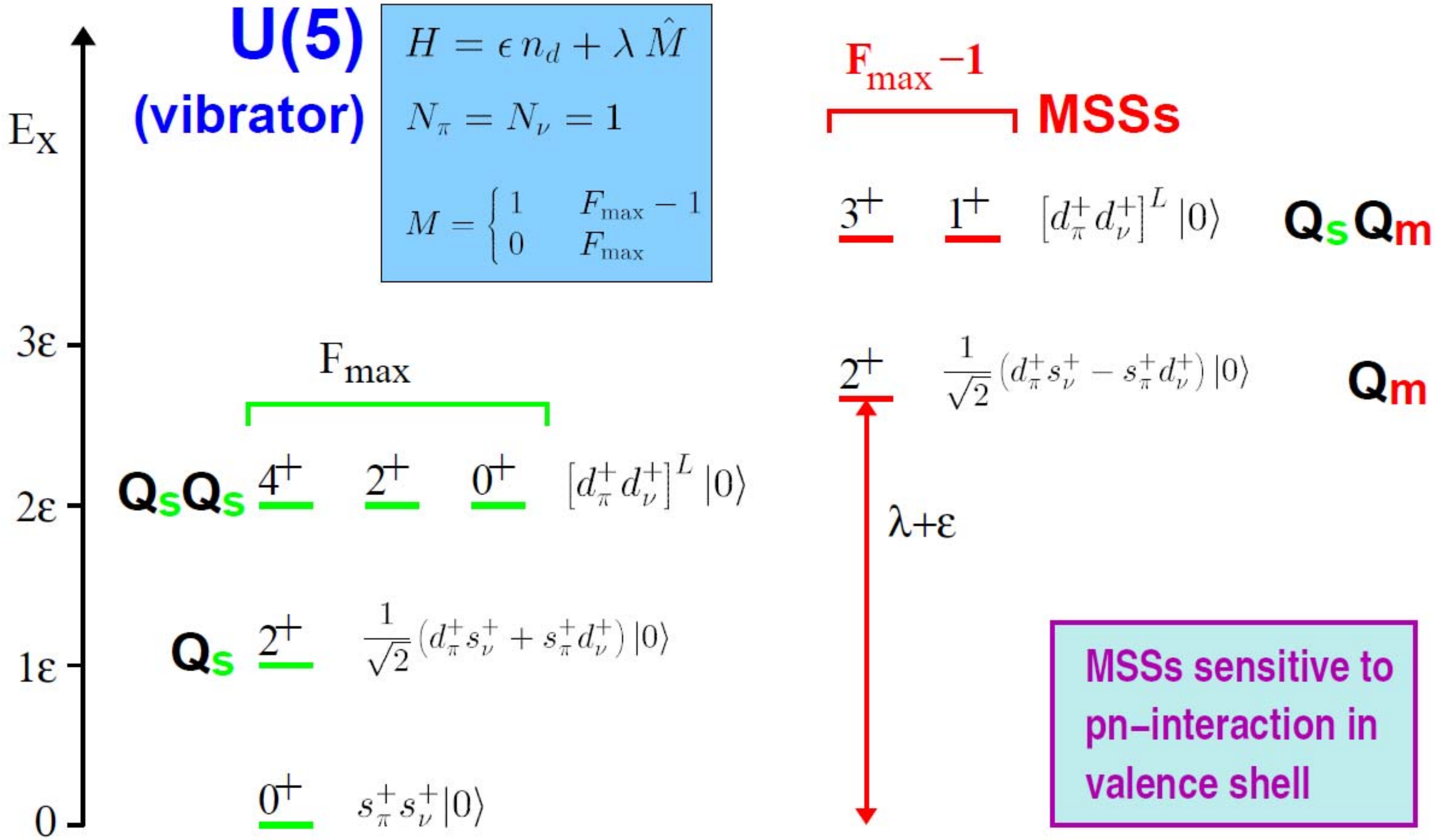

Mixed-Symmetry States at the Analytical Limits

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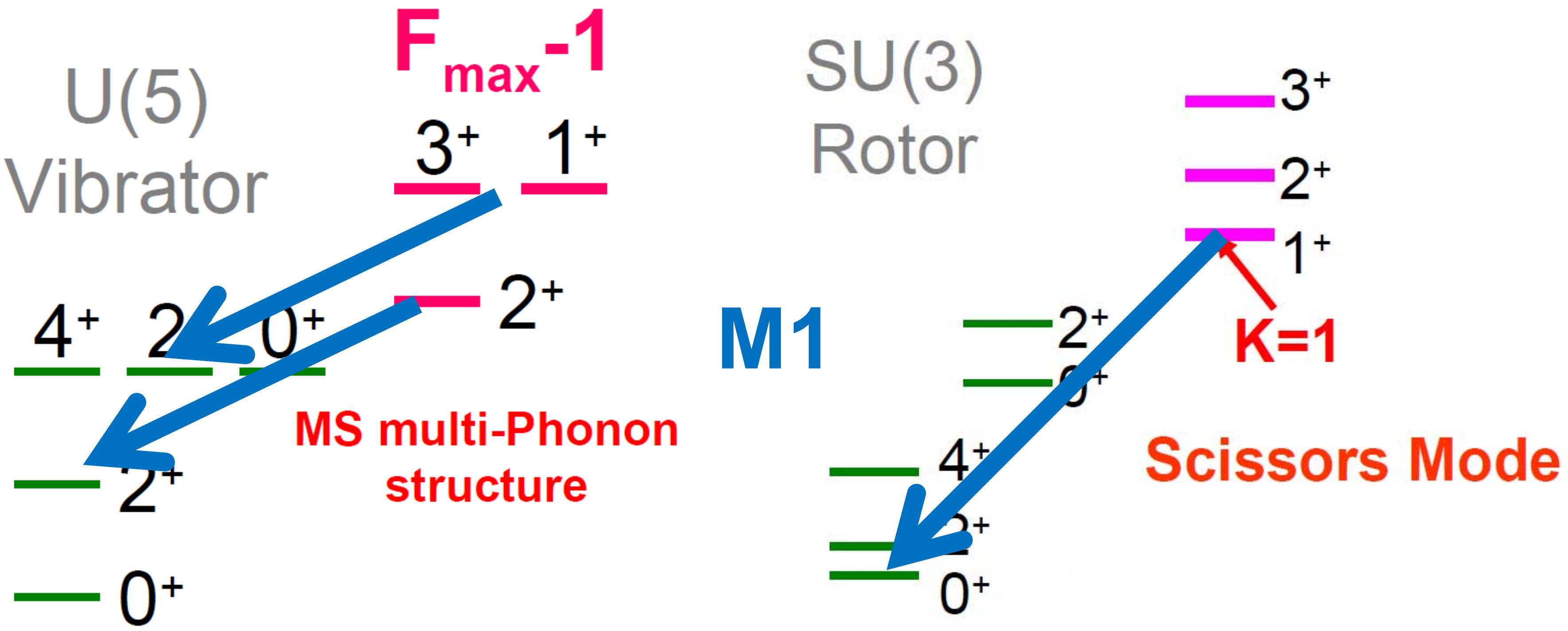


M1 to „phonon partner“

signature ≠ excitation path

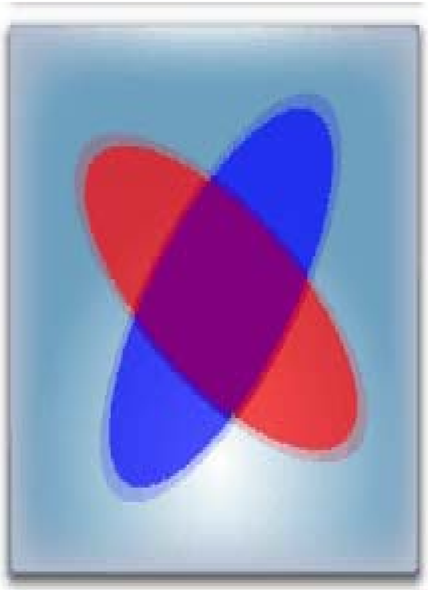
M1 to 0^+ ground state

signature = excitation path

Discovery of Scissors mode: deformed nuclei

Darmstadt, 1983

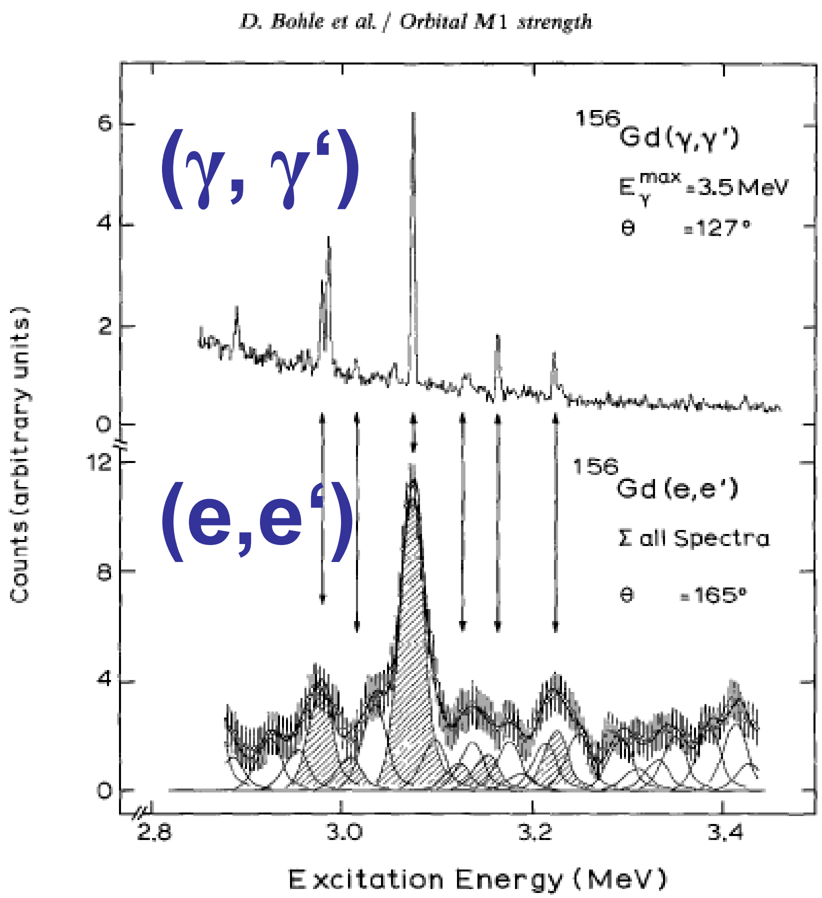
Achim Richter



Predicted by

Lo Iudice & Palumbo, 1978

@ 3 MeV: Iachello, 1981 in IBM-2



Bohle *et al*., NPA 458, 205 (1986).

DALINAC data

Collectivity of the Scissors Mode

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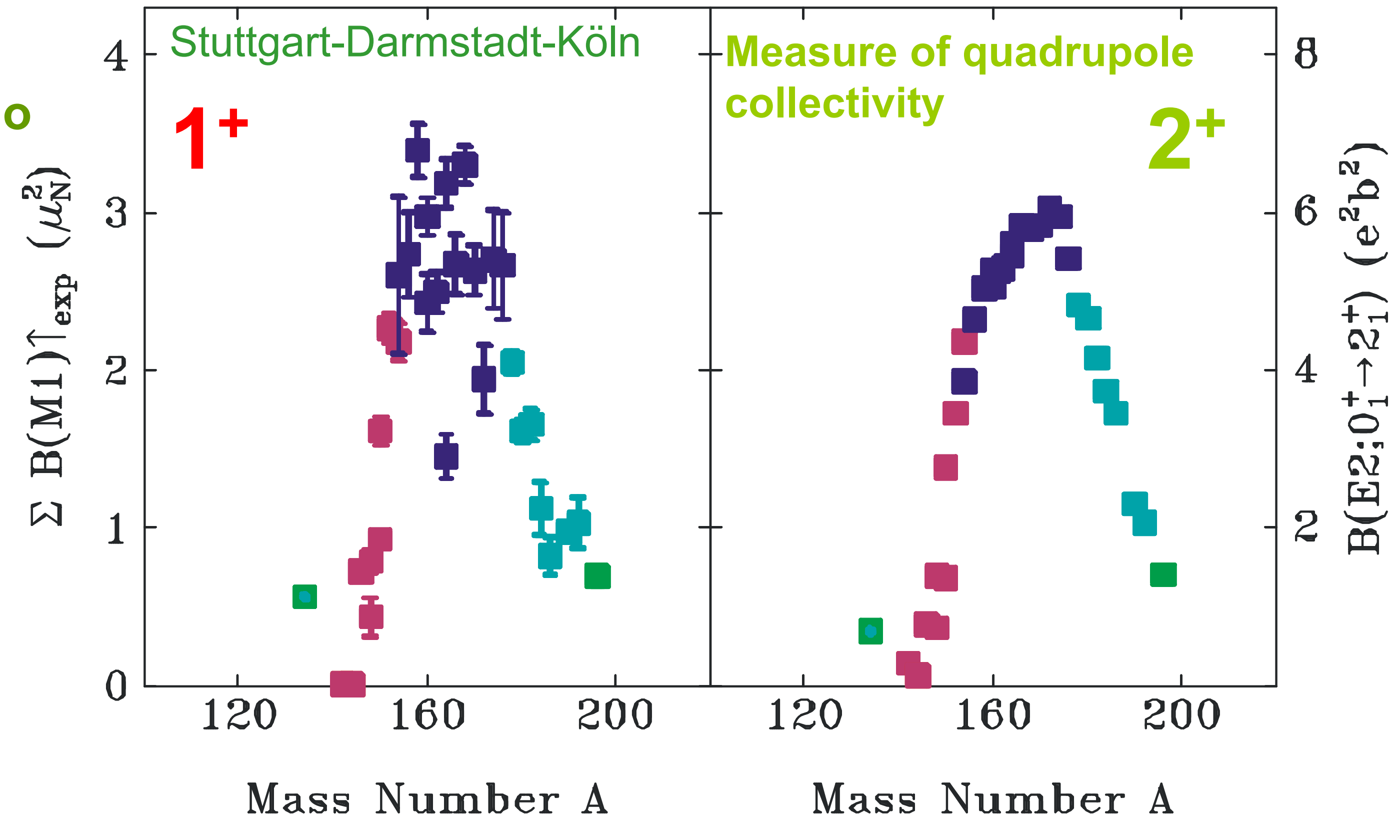
Richter, Kneissl, von Brentano et al.

M1



E2

N. Pietralla et al., PRC **58**, 184 (1998)

^{94}Mo: the „hydrogen atom“ for MS structure

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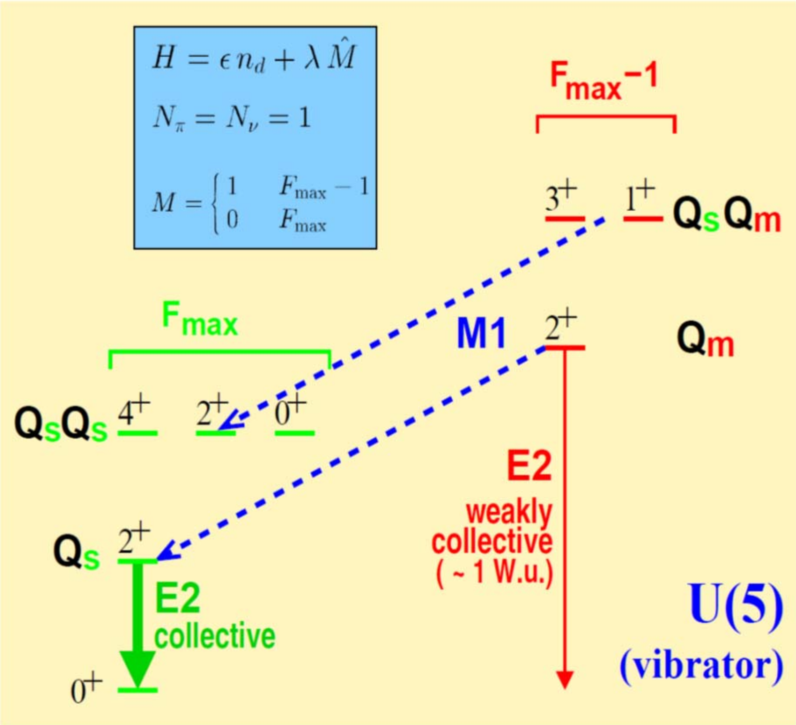
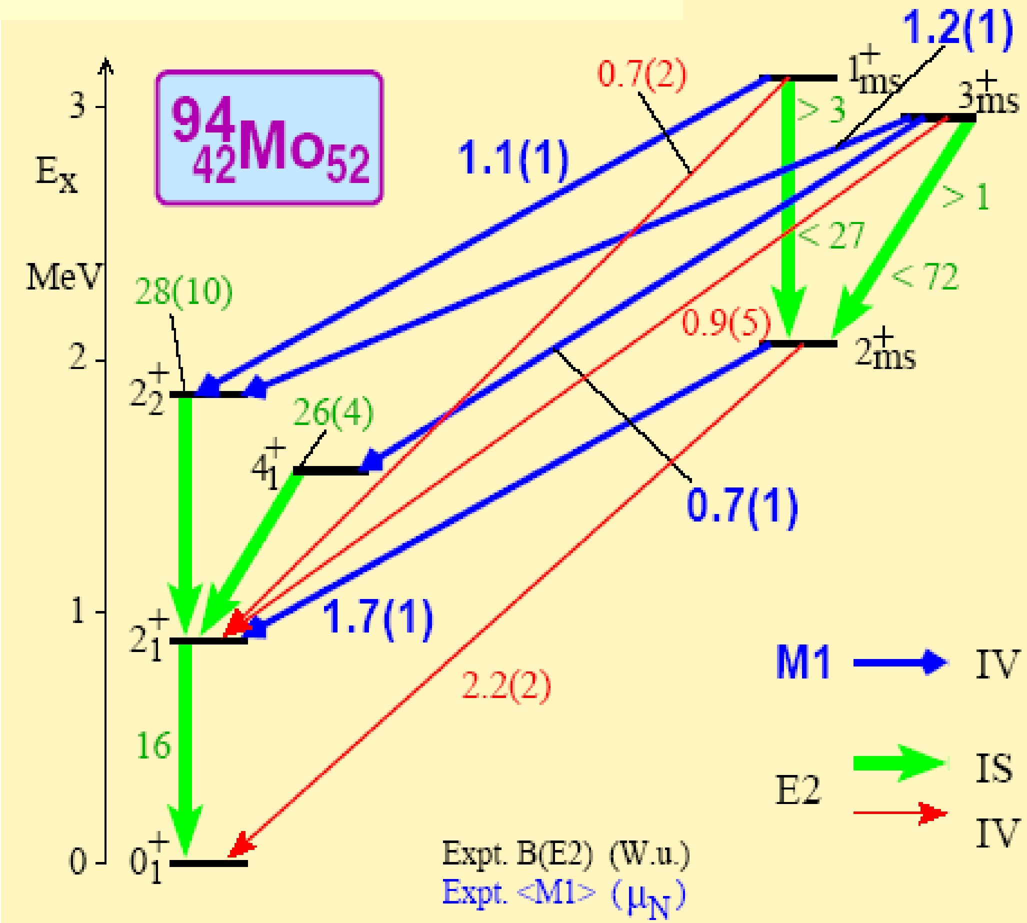
M1 as unique signature for MS states





N.Pietralla, C.Fransen et al., Phys.Rev.Lett. 83, 1303 (1999).
N.Pietralla, C.Fransen et al., Phys.Rev.Lett. 84, 3775 (2000).
C.Fransen, N.Pietralla et al., Phys.Rev.C 67, 024307 (2003).

Identification of One- and Two-phonon MSSs

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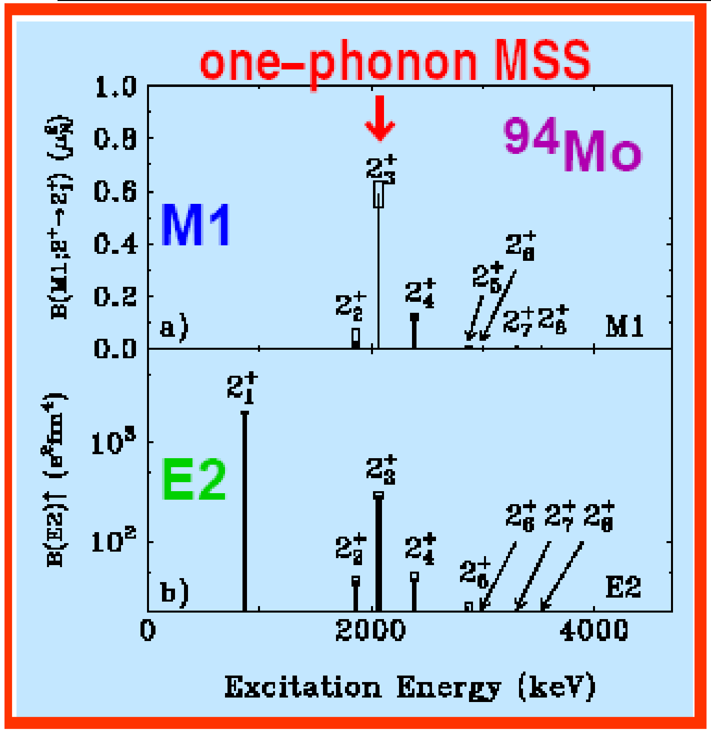
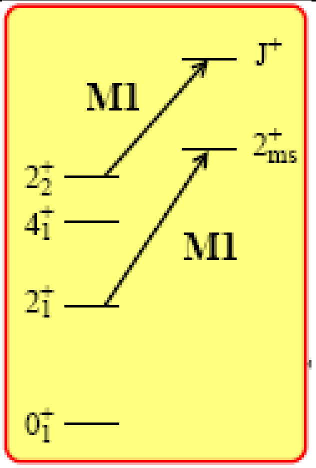
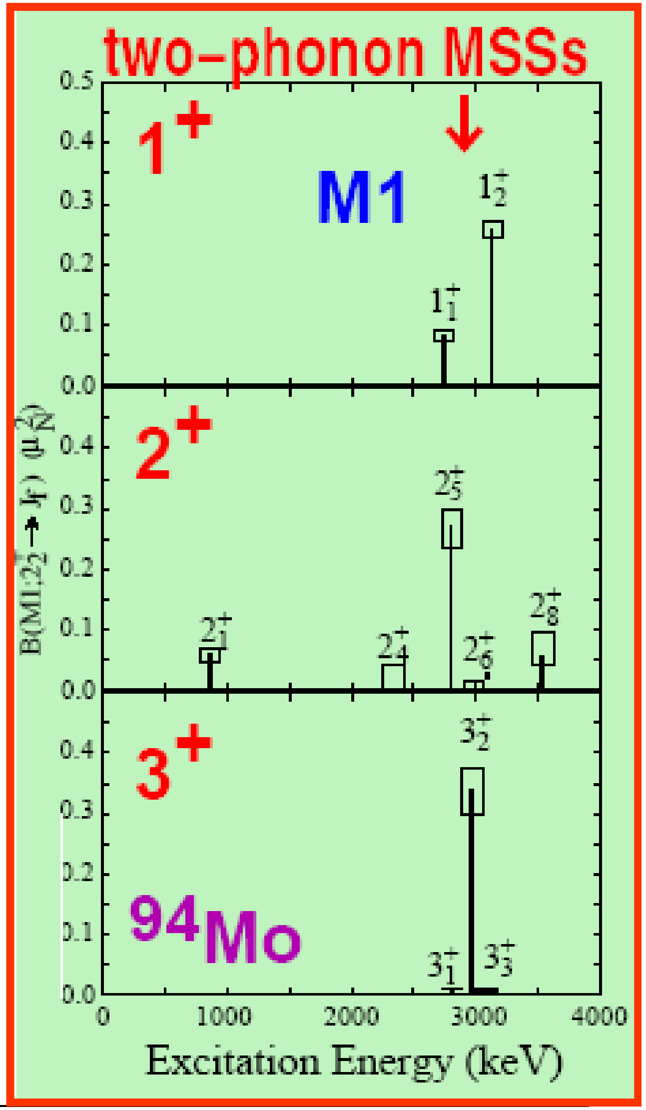






photon scattering
beta-decay
light-ion fusion
neutron scattering

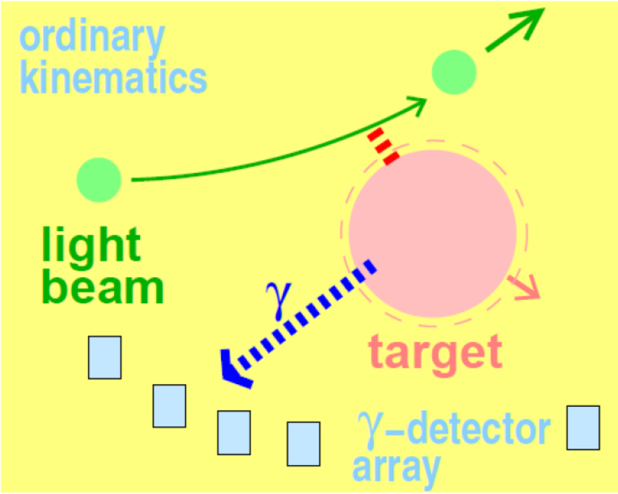
measure all

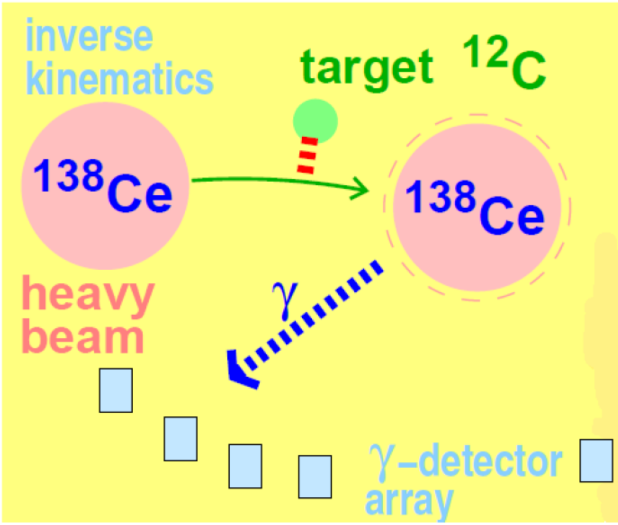
E_x, J^π, τ
BR, δ

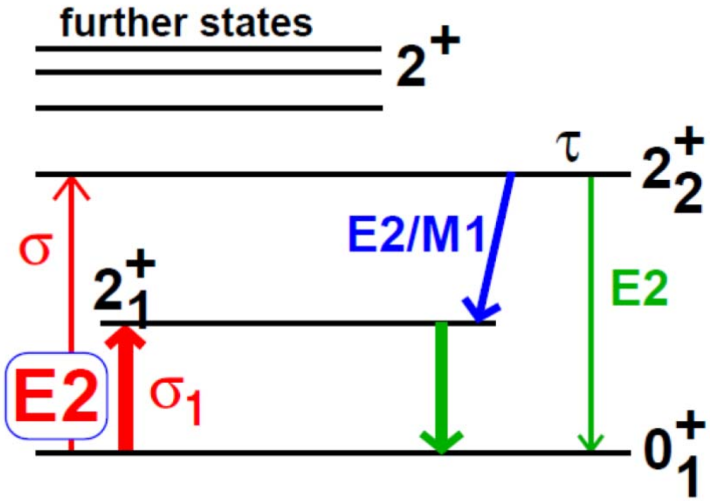
warning !
5 yrs work

N.Pietralla, C.Fransen et al., Phys.Rev.Lett.83, 1303 (1999).
N.Pietralla, C.Fransen et al., Phys.Rev.Lett.84, 3775 (2000).
C.Fransen, N.Pietralla et al., Phys.Lett.B 508, 219 (2001).
C.Fransen, N.Pietralla et al., Phys.Rev.C 67, 024307 (2003).

Projectile-Coulomb Excitation



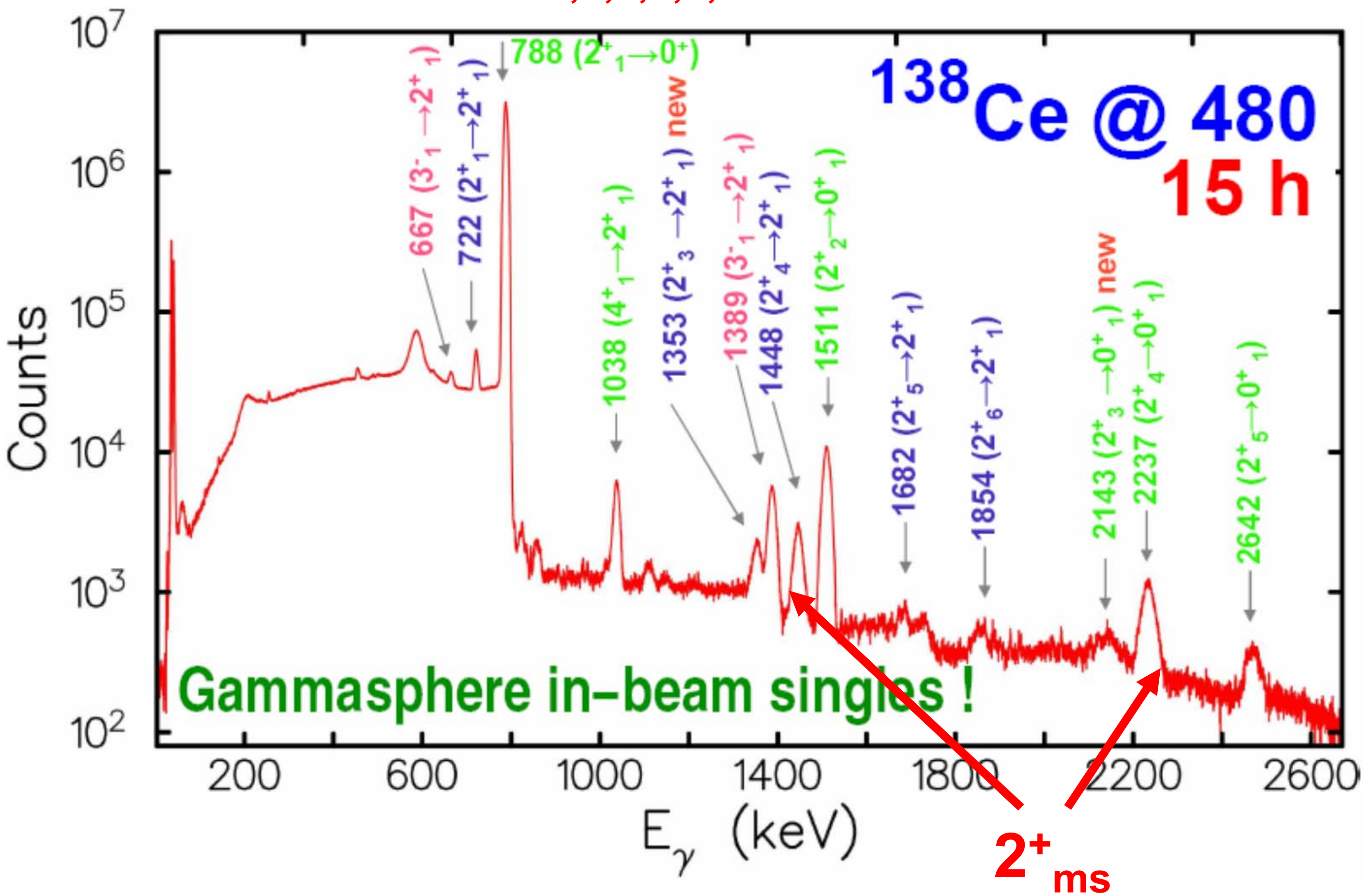




- **Gamma-ray angular distribution**
  - gamma-ray multipolarities
  - spin quantum numbers
- **Gamma intensity**
  - Decay branching ratios
  - Total population of levels
  - Excitation cross section σ
  - Absolute transition rates

CoulEx of Mixed-Symmetry States

Observe $2+_{1,2,3,4,5,6}$ up to 2.7 MeV



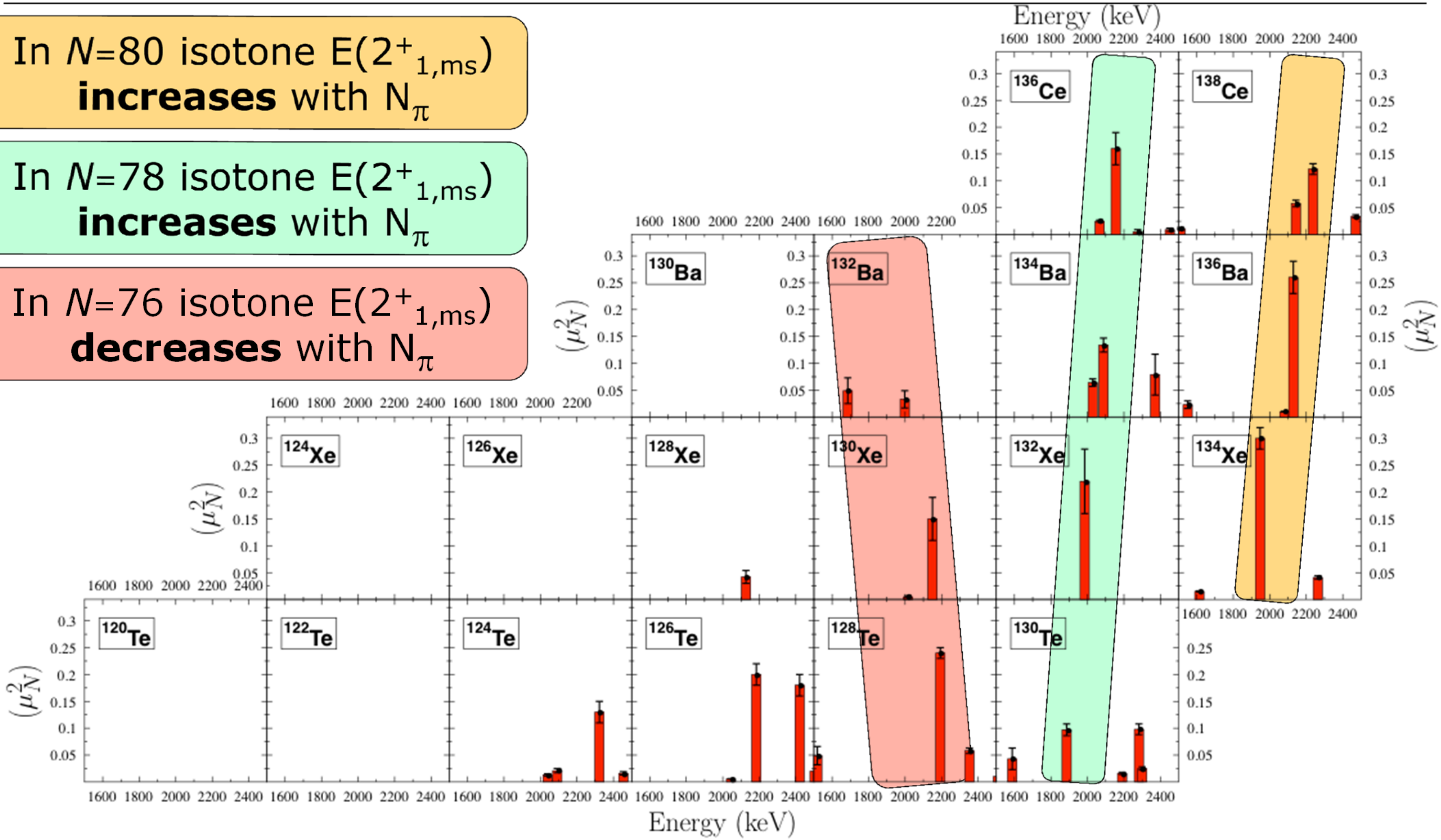
G.Rainovski, NP et al., Phys. Rev. Lett. **96** 122501 (2006).

Systematics of $B(M1;2^+_i \rightarrow 2^+_1)$ on proton number

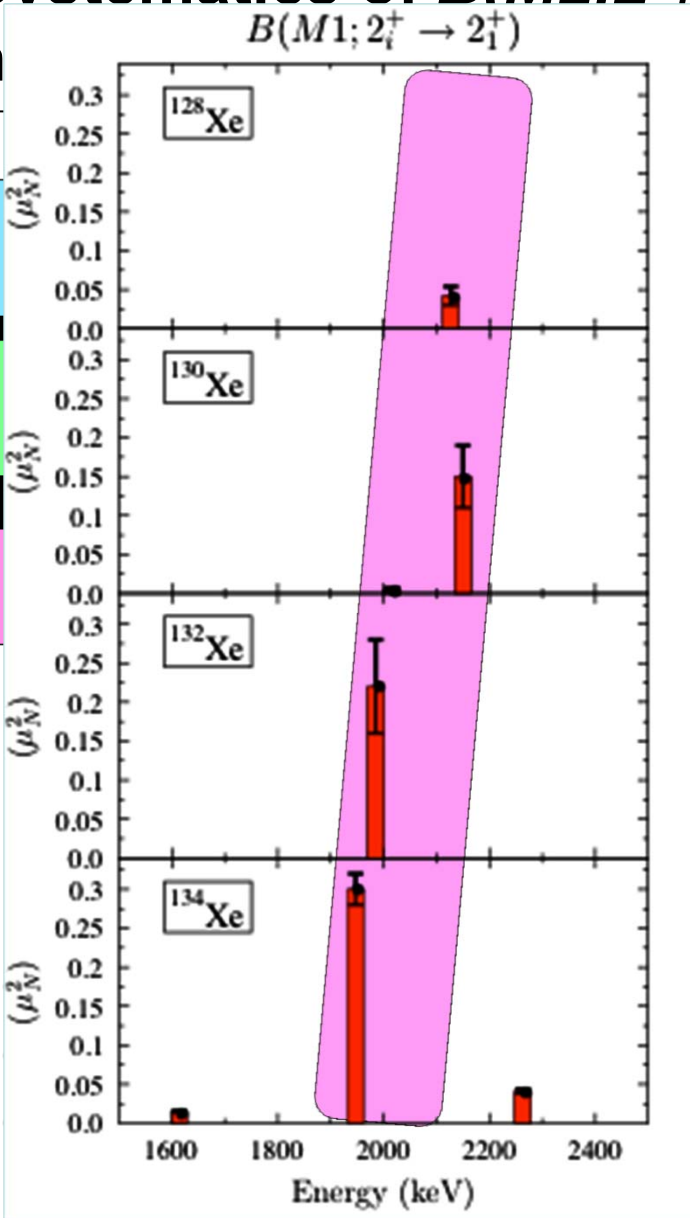
In N=80 isotone $E(2^+_{1,ms})$ **increases** with N_π

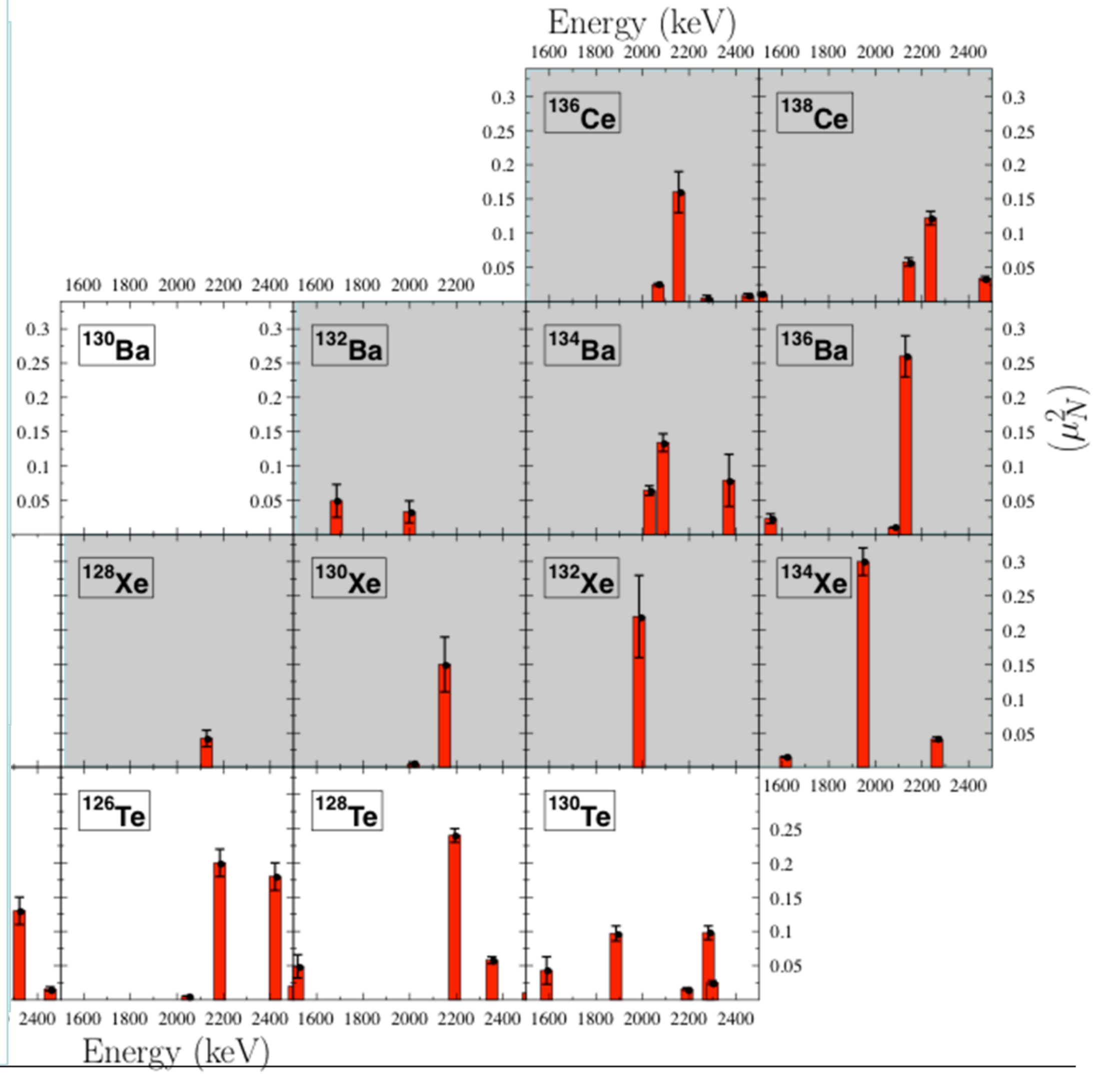
In N=78 isotone $E(2^+_{1,ms})$ **increases** with N_π

In N=76 isotone $E(2^+_{1,ms})$ **decreases** with N_π



Systematics of $B(M1;2^+_i \rightarrow 2^+_1)$ on neutron n





d
d
E

Firm Observation of MSS in an Unstable Nucleus

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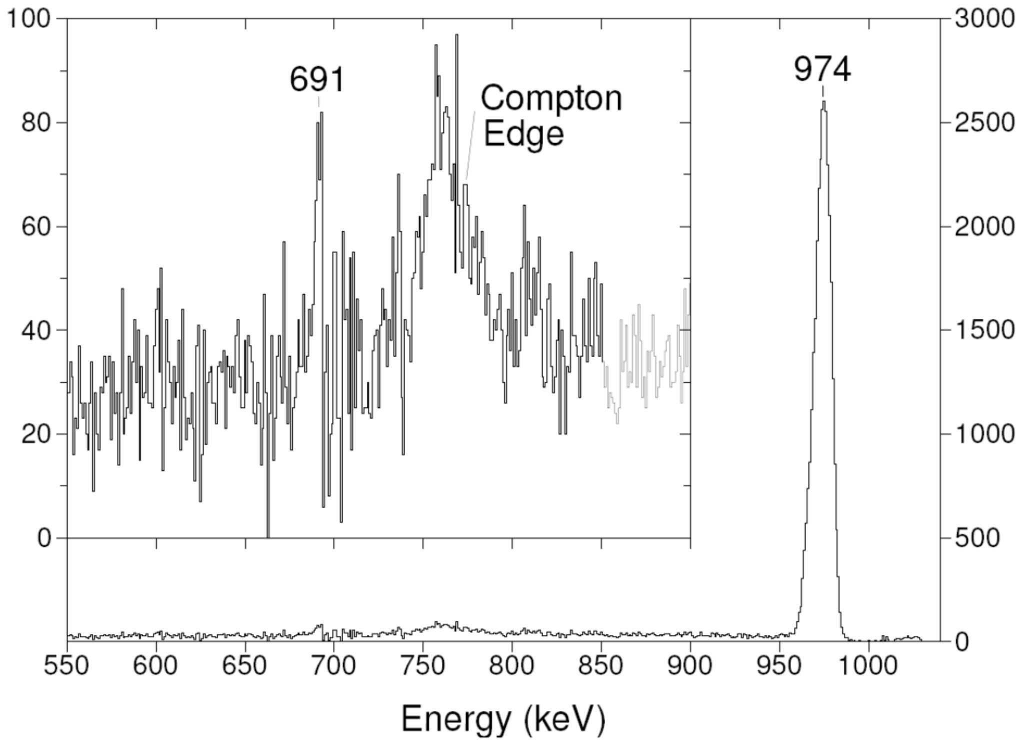
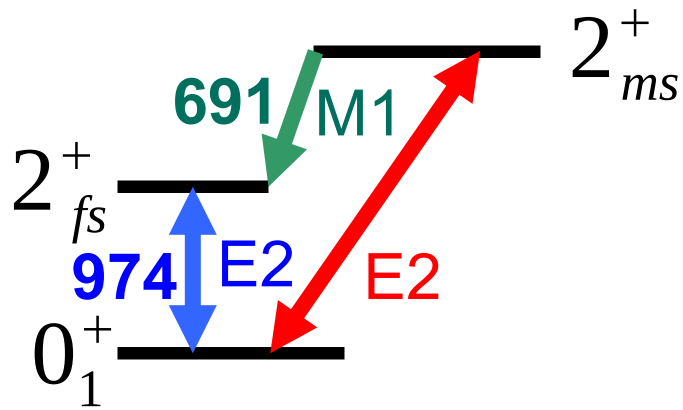
M.Danchev, G.Rainovski, NP et al., PRC 84, 061306(R) (2011)

Oak Ridge - Data

^{132}Te





$^{132}_{52}Te_{80} = {}^{132}_{50}Sn_{82} + 2p + 2n^{-1}$

$B(\mathbf{M1};2^+_{ms} \rightarrow 2^+_{fs}) > 0.2\ \mu_N^2$

$B(\mathbf{E2};2^+_{ms} \rightarrow 0^+_{fs}) = 0.4$ W.u.

^{132}Te: 2 valence protons and neutrons = key nucleus for testing shell model

Systematics along the N=80 Isotopic Chain

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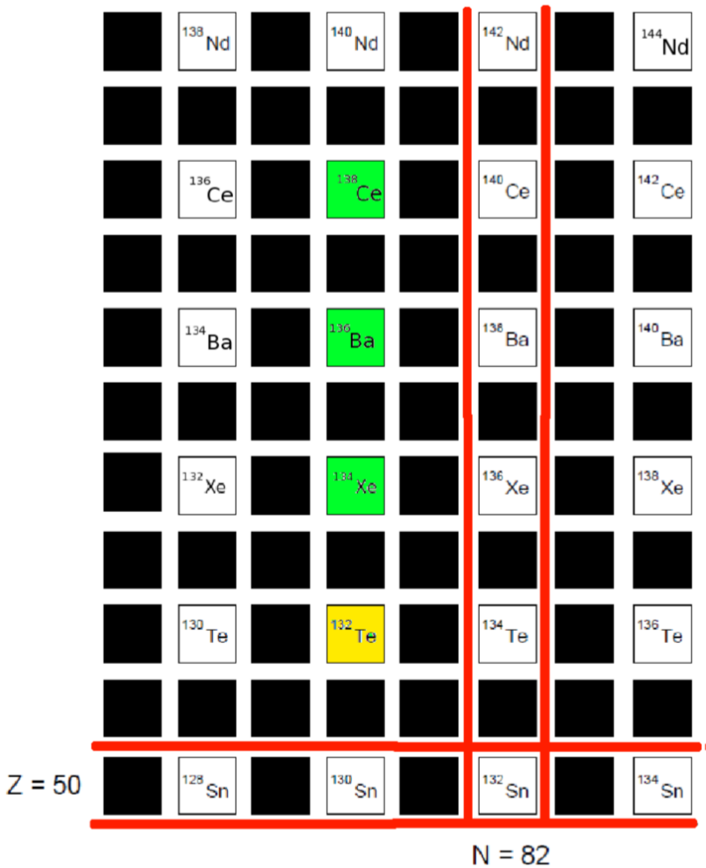
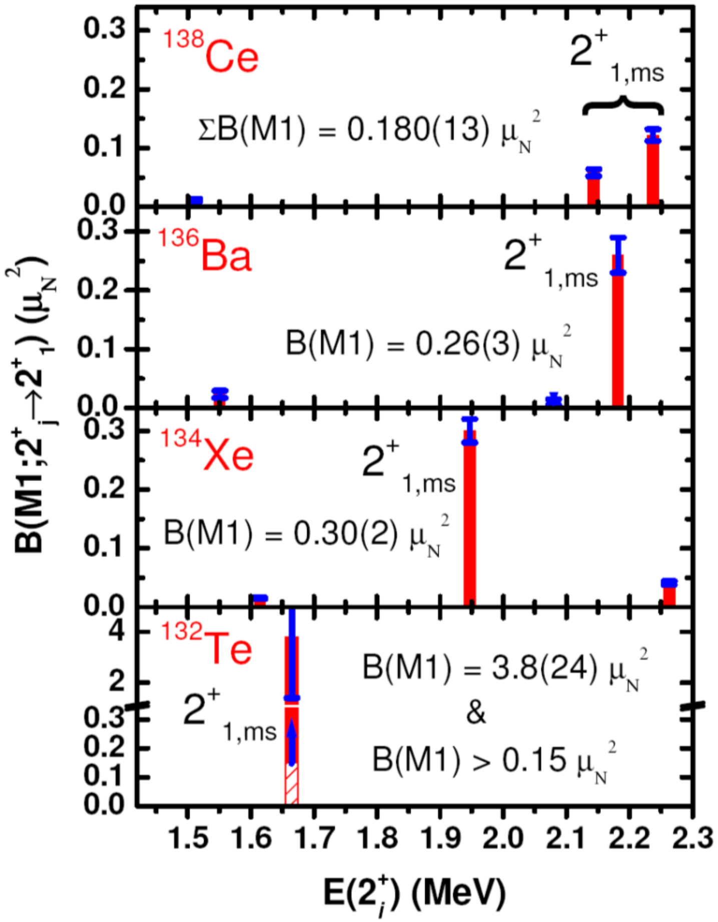
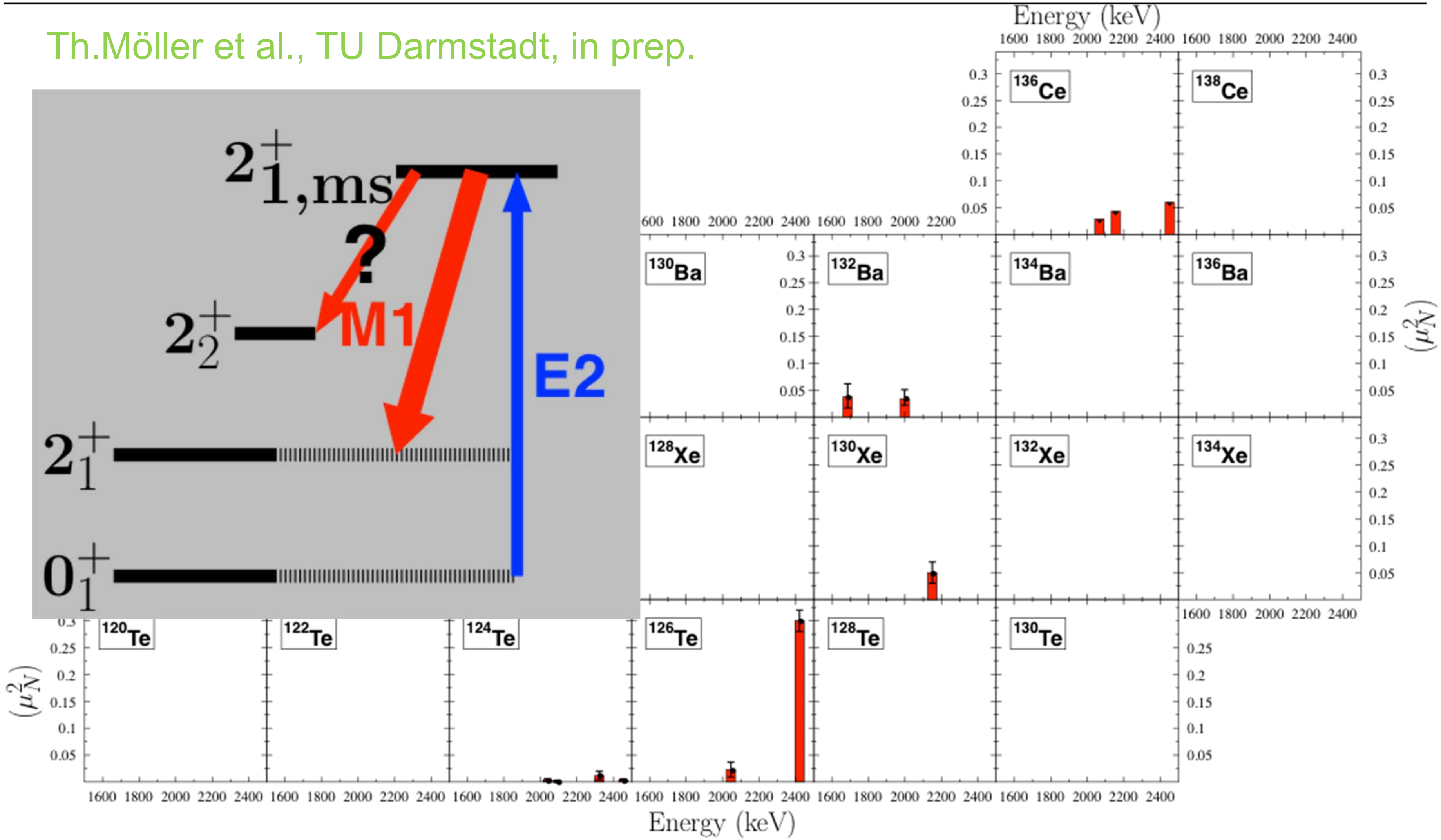




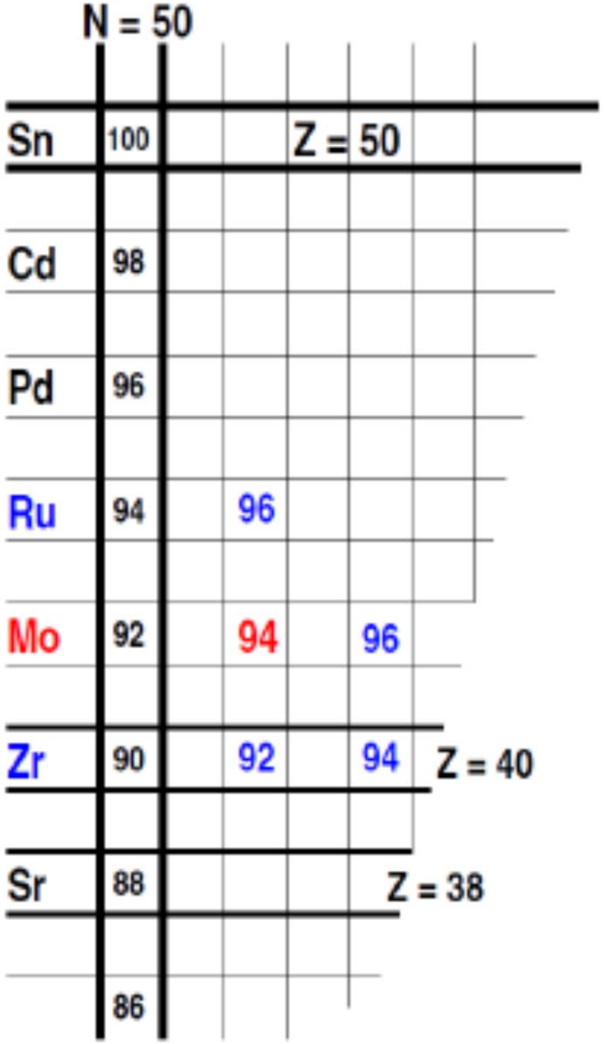
- ^{132}Te is radioactive

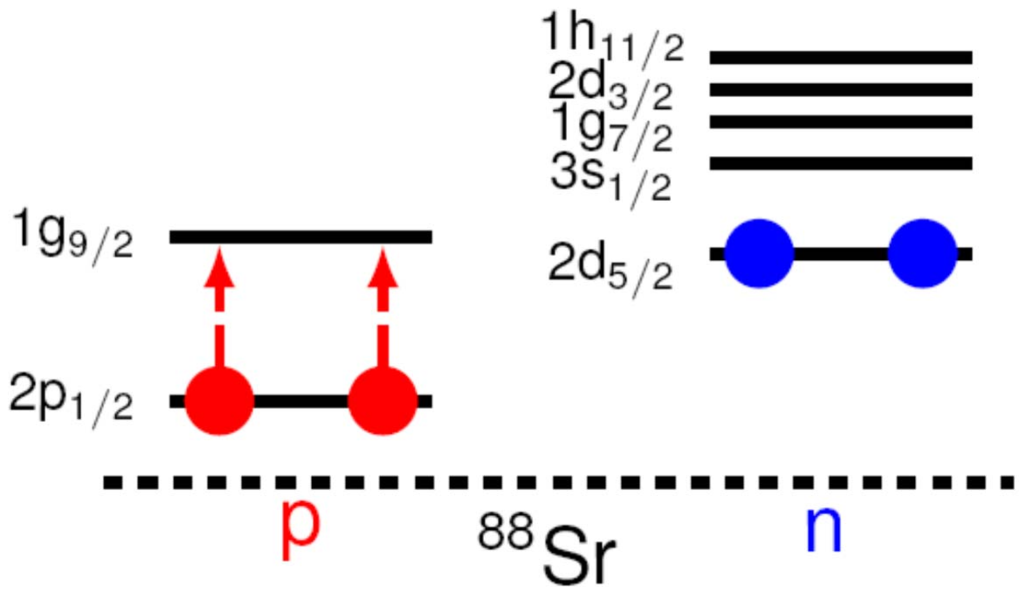
Emerging information on *B(M1;$2^+_i \rightarrow 2^+_2$)*

Th.Möller et al., TU Darmstadt, in prep.



Shell Structure of ^{92}Zr





- 2 valence protons and 2 valence neutrons
- Low-energy structures dominated by $\nu(2d_{5/2})$ and $\pi(1g_{9/2})$ orbitals
- Neutron excitations slightly favored

Electron and Proton Scattering on A = 90

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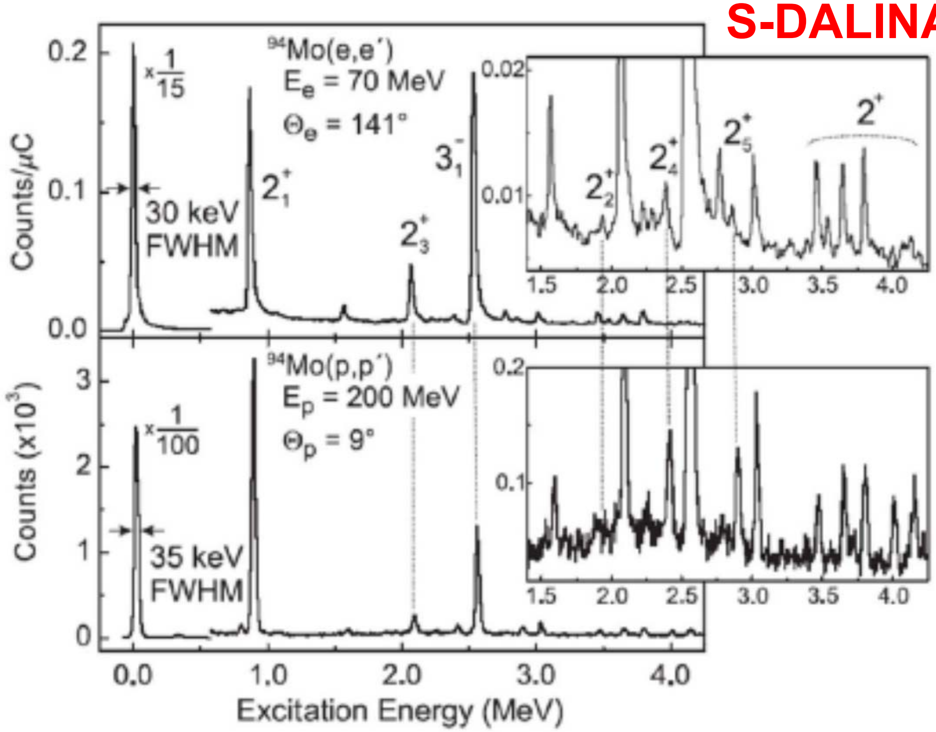
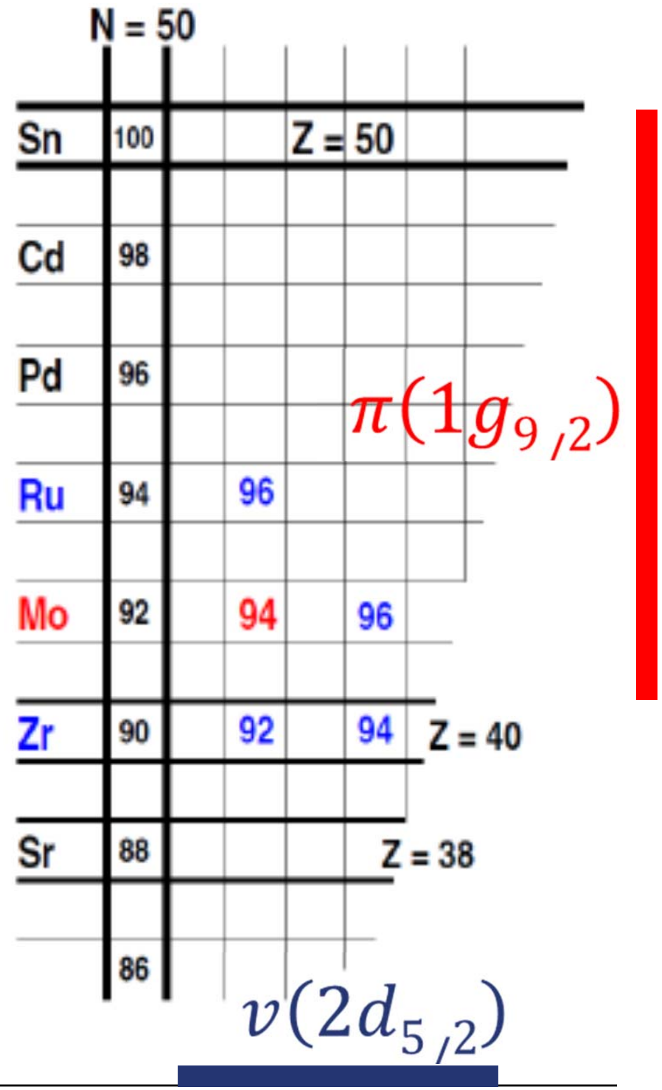
S-DALINAC data



O.Burda et al., Phys.Rev.Lett. 99, 093502 (2007)



- One-phonon states are strongly excited in (e,e') and (p,p') scattering experiments

Superconducting-DArmstadt LINear electron ACcelerator (S-DALINAC)

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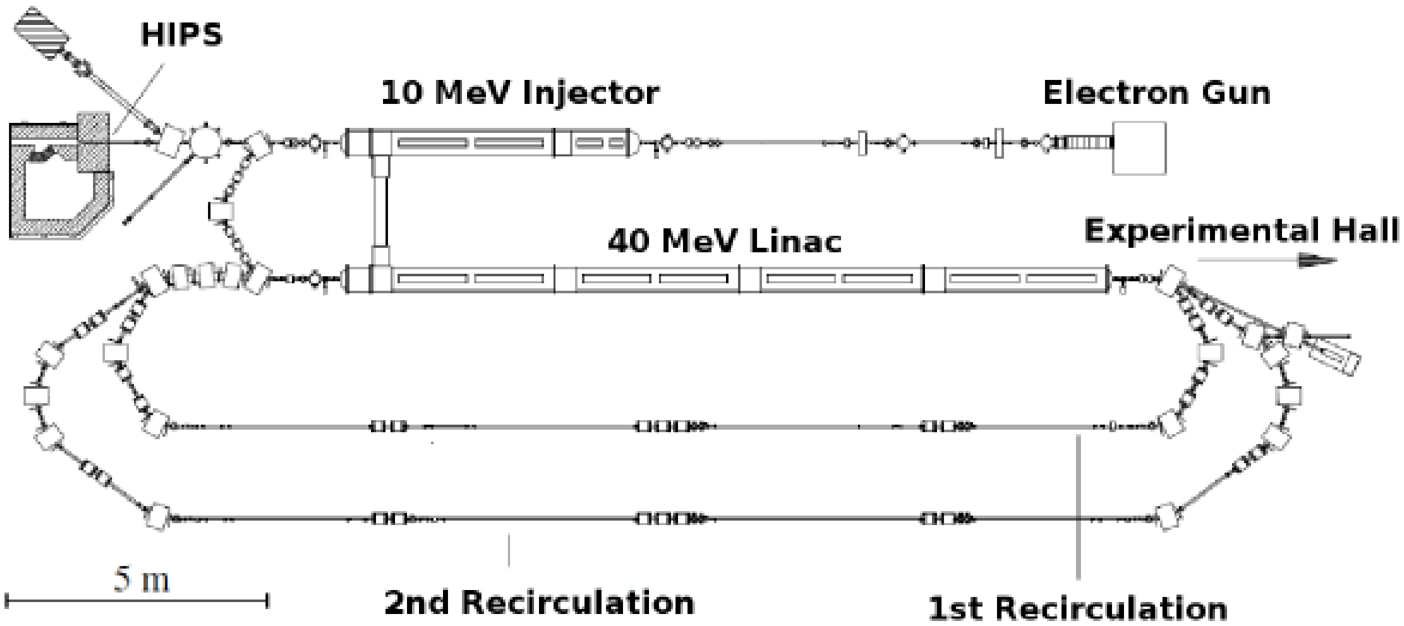


- 130 MeV in-house electron linac
- TM_{010} π-mode acceleration
- „cw“ beam at 3 GHz („S“-band)
- **Ideal for nuclear structure studies**

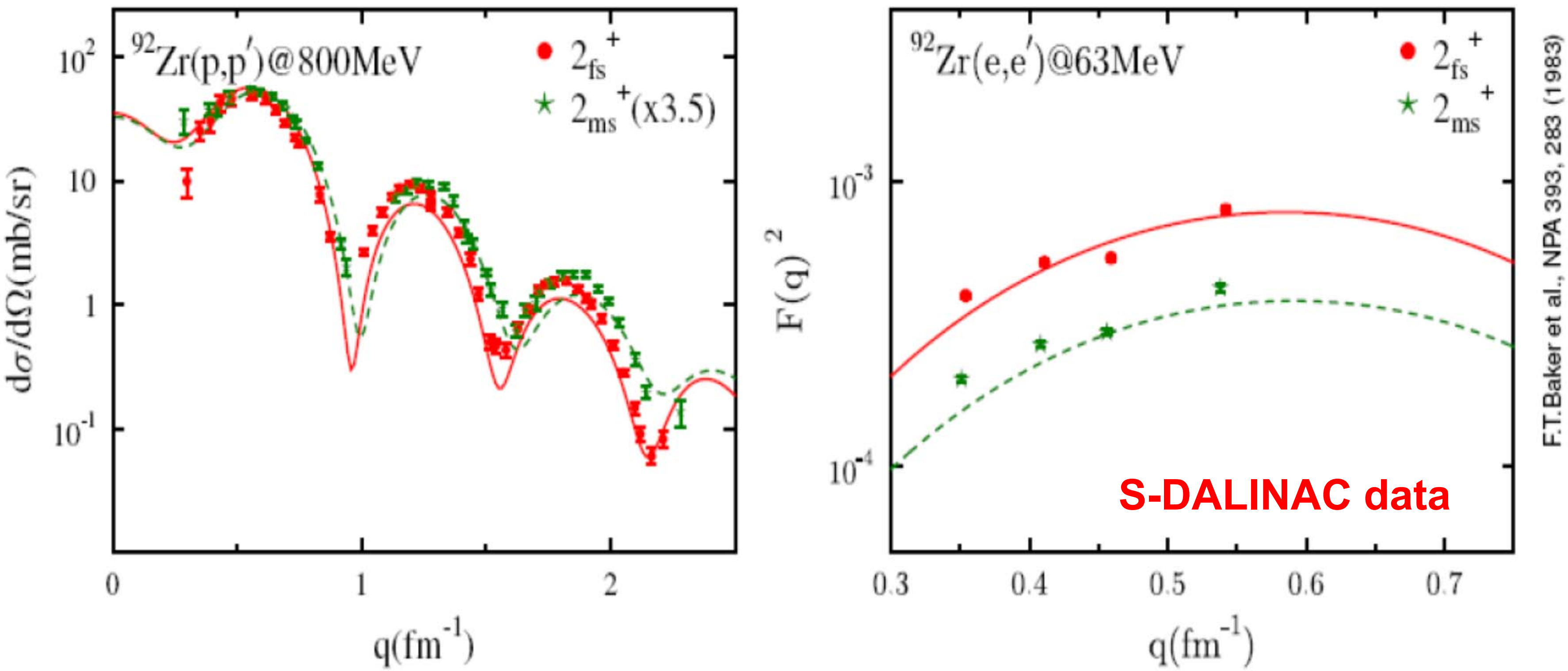
Thanks to

✓ State of Hesse

✓ TU Darmstadt

✓ DFG

Transition Form Factors for ^{92}Zr



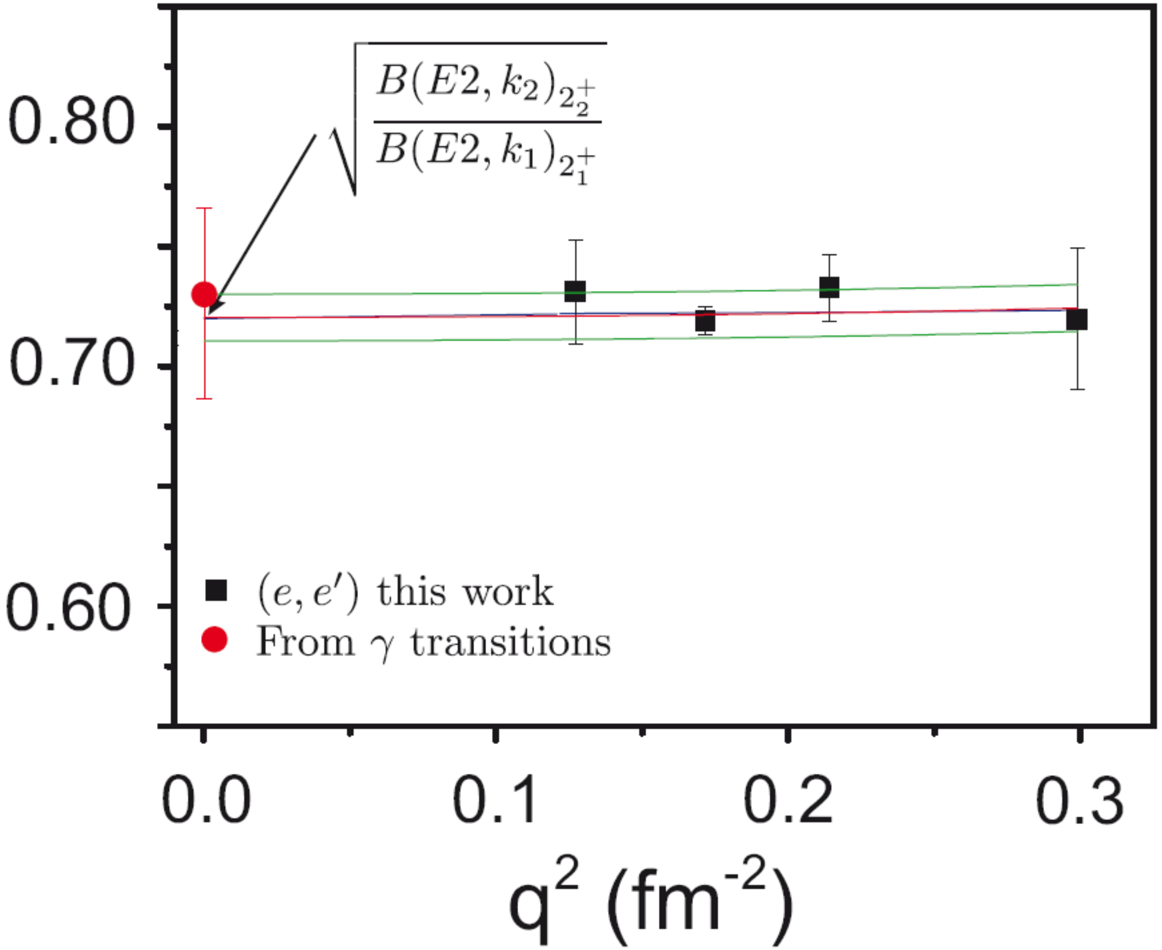
- Diffraction pattern in (p,p‘) shifted to higher momentum transfers for MSS

➢MSS has smaller matter transition radius than FSS! p-n-phase?

C.Walz *et al.*, Phys. Rev. Lett. **106**, 062501 (2011)

E2 Charge Transition Radii for ^{92}Zr

$F(2^+_2)/F(2^+_1)$ from (e,e')



- Ratio of form factors
- = ratio of B(E2) at photon point
- Flat curve as a function of q^2
- Identical E2 charge transition radii within uncertainties
- $R_{ch,tr}(2^+_2) \approx R_{ch,tr}(2^+_1)$

Transition Form Factors for ^{92}Zr

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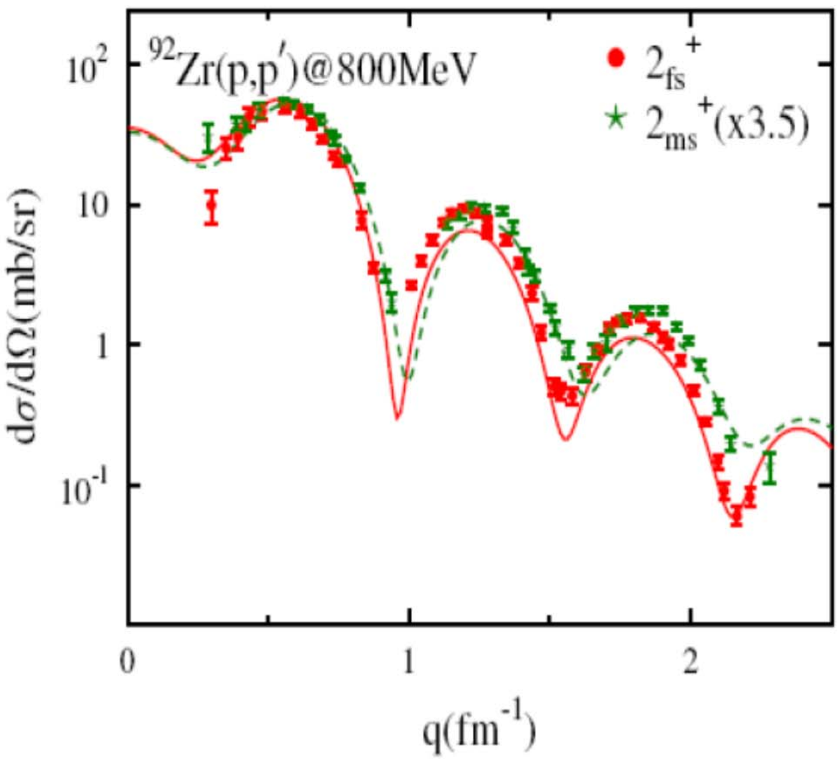

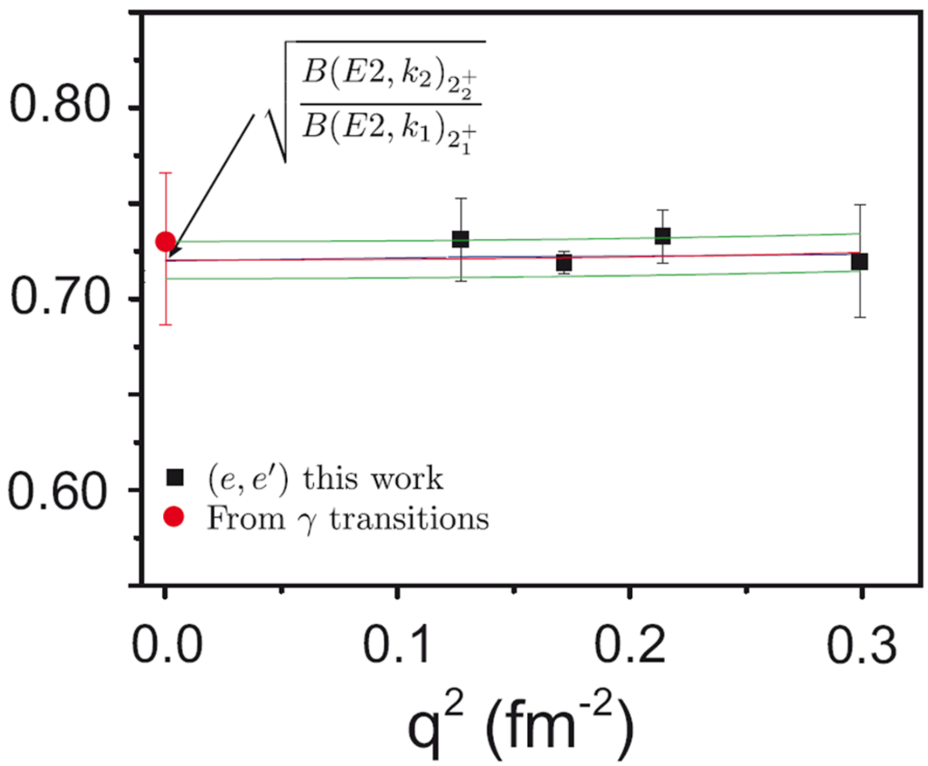

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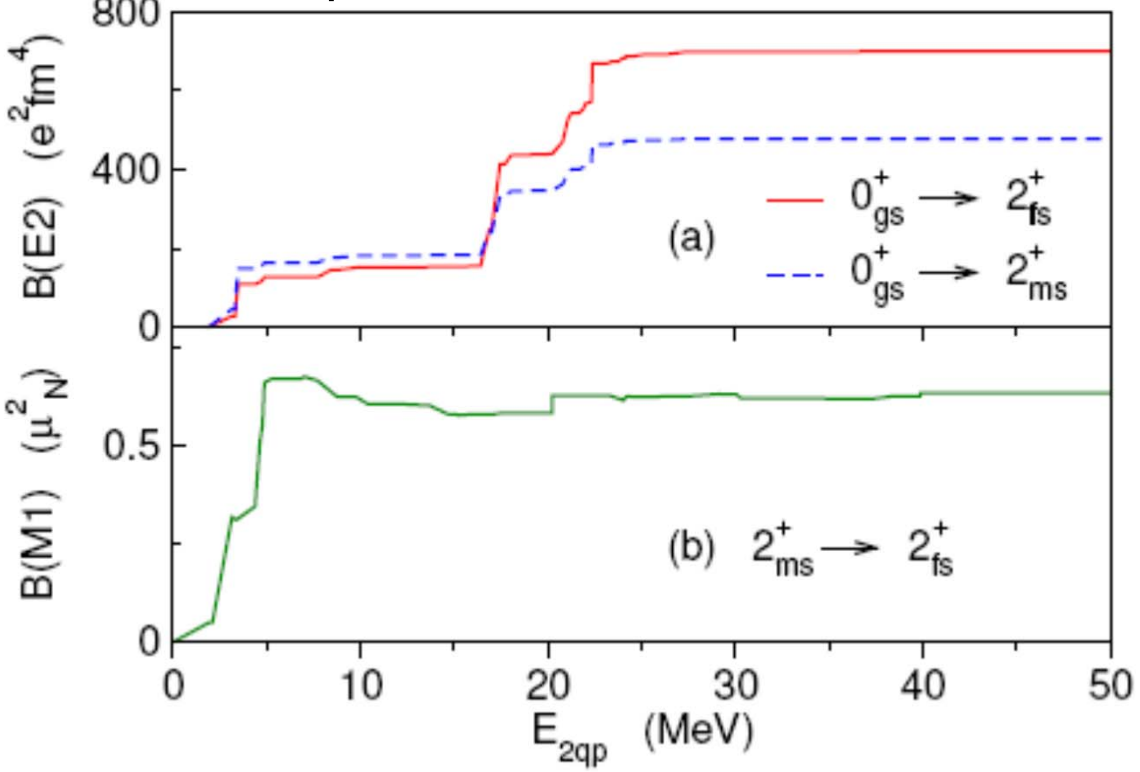
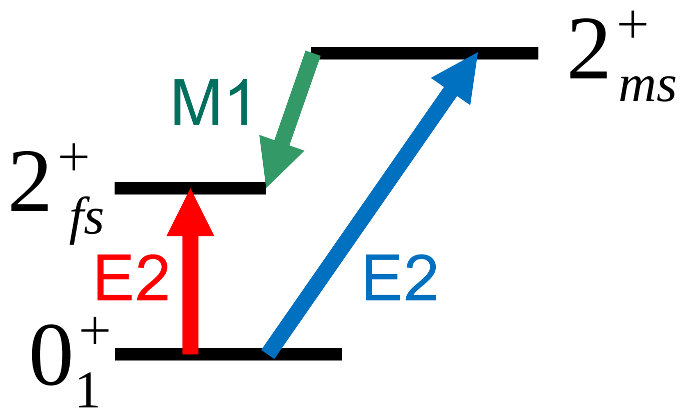
C.Walz *et al.*, Phys. Rev. Lett. **106**, 062501 (2011)

Microscopic analysis of the one-phonon vibrations: transition strengths

Quasiparticle Phonon Model



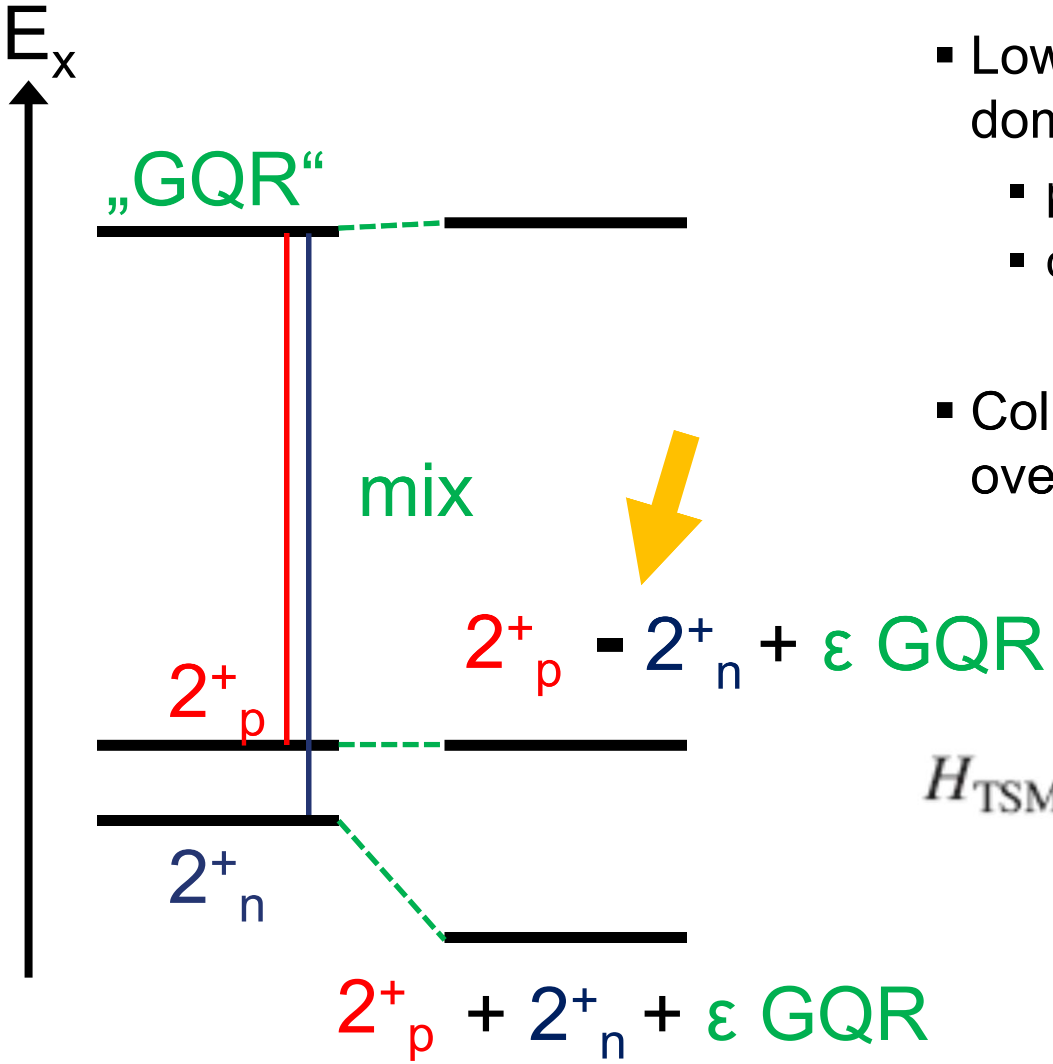


	Full QPM	
	2^+_{fs}	2^+_{ms}
$\nu(2d_{5/2})^2$	0.85	−0.54
$\pi(1g_{9/2})^2$	0.36	0.57

C.Walz *et al.*
PRL **106**, 062501 (2011)

- M1 strength dominated by p and n valence-shell components
- E2 strength dominated by cross-shell components (coupling to GQR)

Simplify to Three-State-Model (TSM)

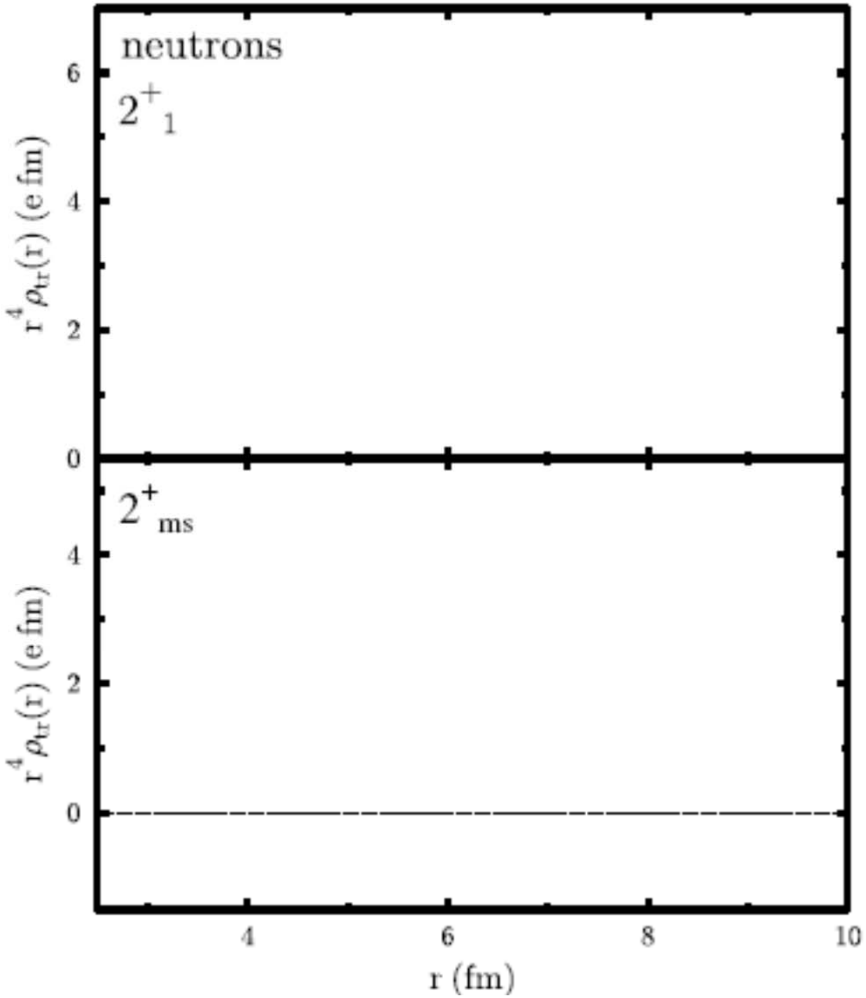


- Low-energy 1-phonon states dominantly contain 3 ingredients:
  - p & n valence-shell component
  - collective component („GQR“)
- Collective interaction dominates over valence-shell interaction

$$H_{\mathrm{TSM}} = \begin{pmatrix} E_{\mathrm{GQR}} & -V_\pi & -V_\nu \\ -V_\pi & \epsilon_\pi & 0 \\ -V_\nu & 0 & \epsilon_\nu \end{pmatrix};$$

$$V_\alpha = g\langle\alpha|\delta(\vec{r}-\vec{r}\,')|\mathrm{GQR}\rangle$$

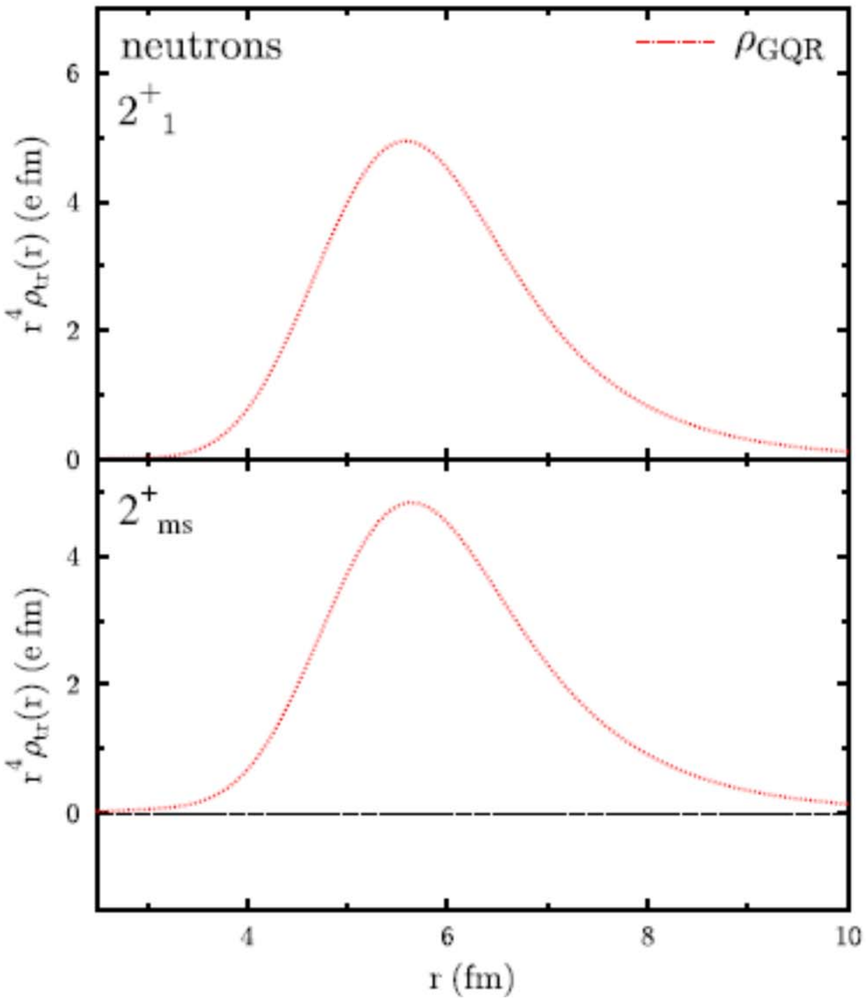
Consequences for the Transition Densities



- $|2^+_1\rangle = 0.33\ |1g^2_{9/2}\rangle_p\ +$
  $0.84\ |2d^2_{5/2}\rangle_n\ +\ 0.42\ |GQR\rangle$

- $|2^+_{ms}\rangle = 0.56\ |1g^2_{9/2}\rangle_p\ -$
  $0.53\ |2d^2_{5/2}\rangle_n\ +\ 0.64\ |GQR\rangle$

Transition Densities from the Collective Part



- $|2^+_1\rangle = 0.33\ |1g^2_{9/2}\rangle_p + 0.84\ |2d^2_{5/2}\rangle_n + 0.42\ |GQR\rangle$
- $|2^+_{ms}\rangle = 0.56\ |1g^2_{9/2}\rangle_p - 0.53\ |2d^2_{5/2}\rangle_n + 0.64\ |GQR\rangle$

Inclusion of Valence Shell Component

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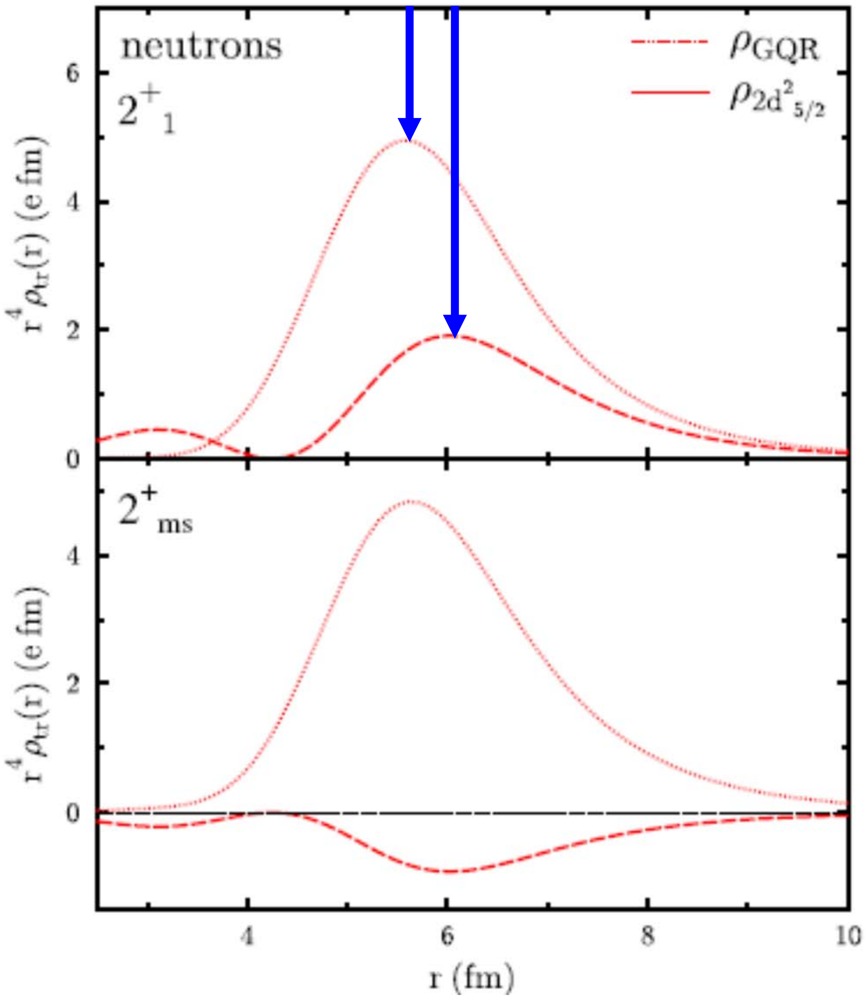

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Total Neutron Transition Densities

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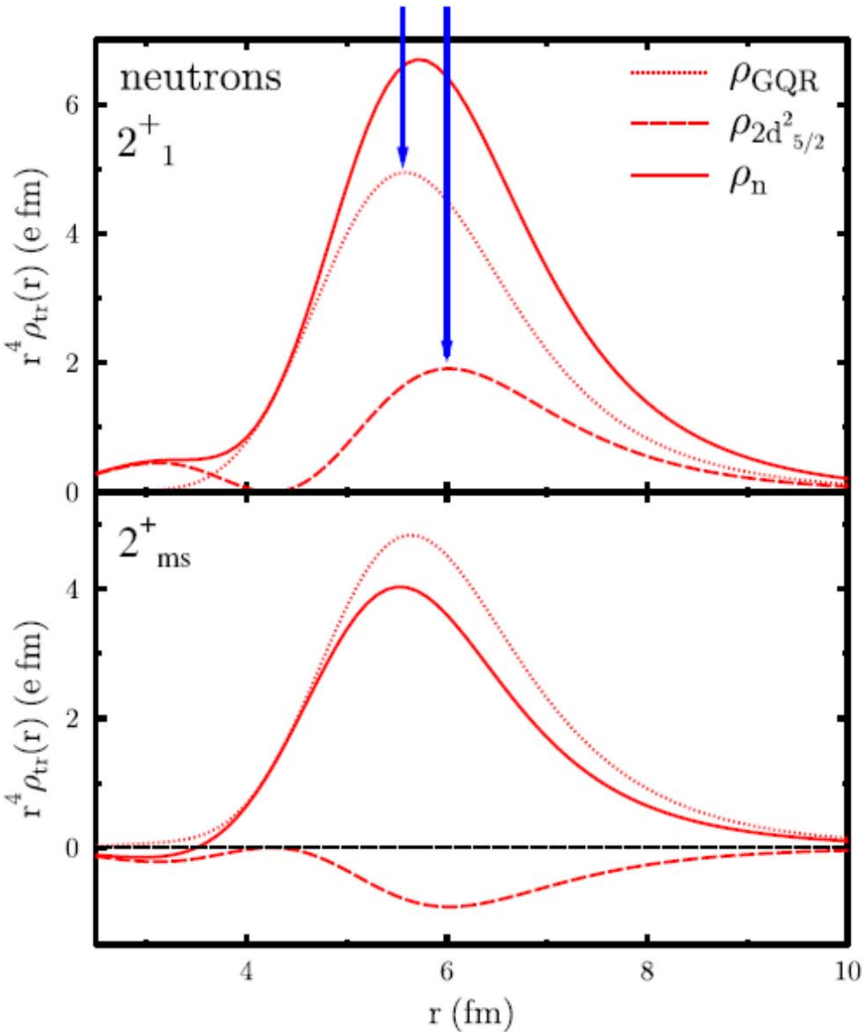

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Total Neutron Transition Densities

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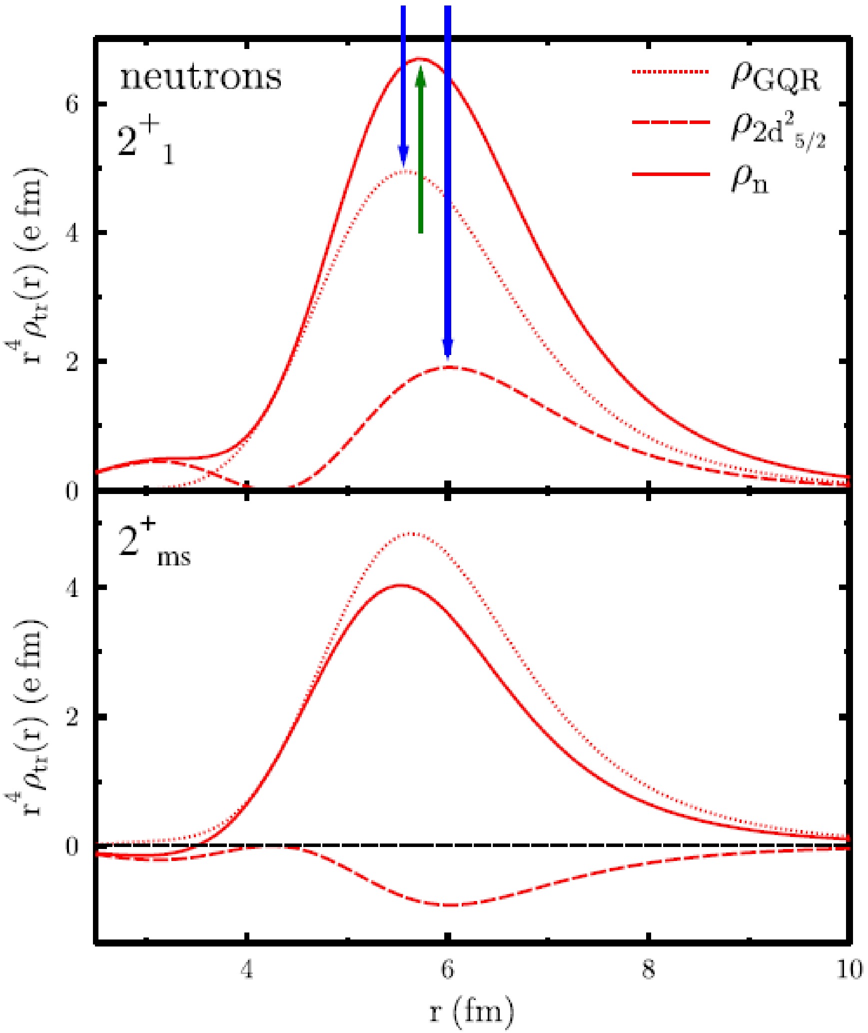

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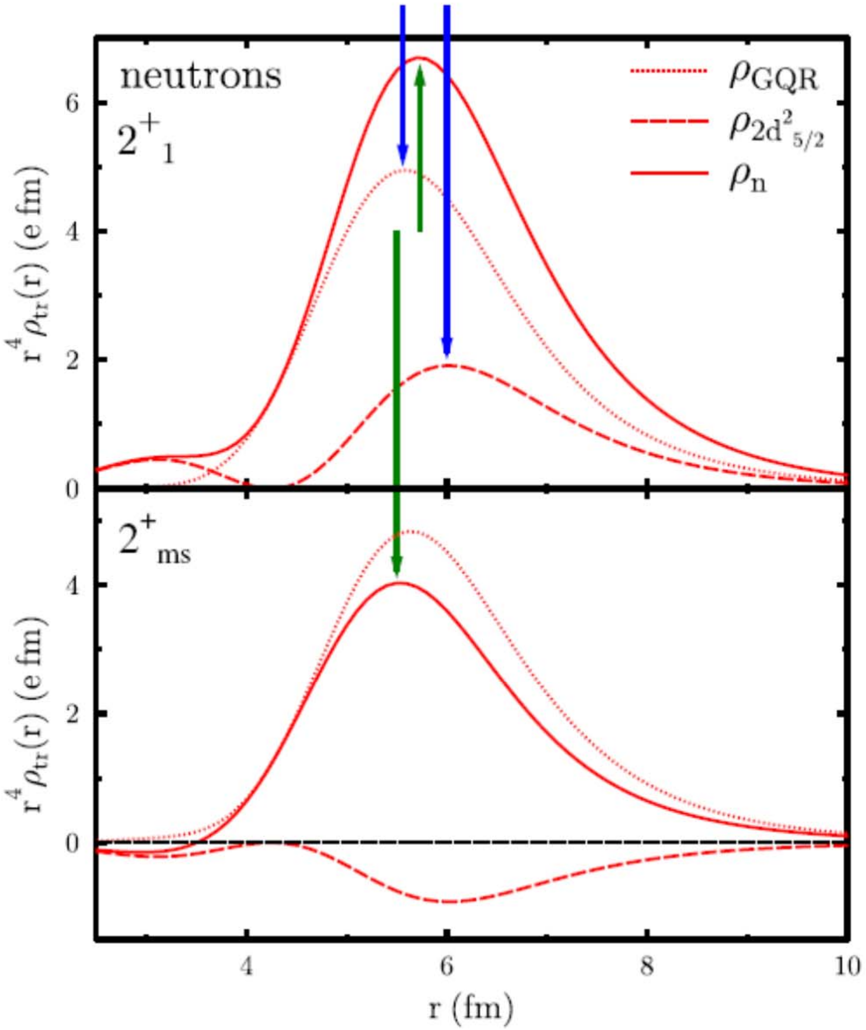
Total Neutron Transition Densities



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Total Neutron Transition Densities

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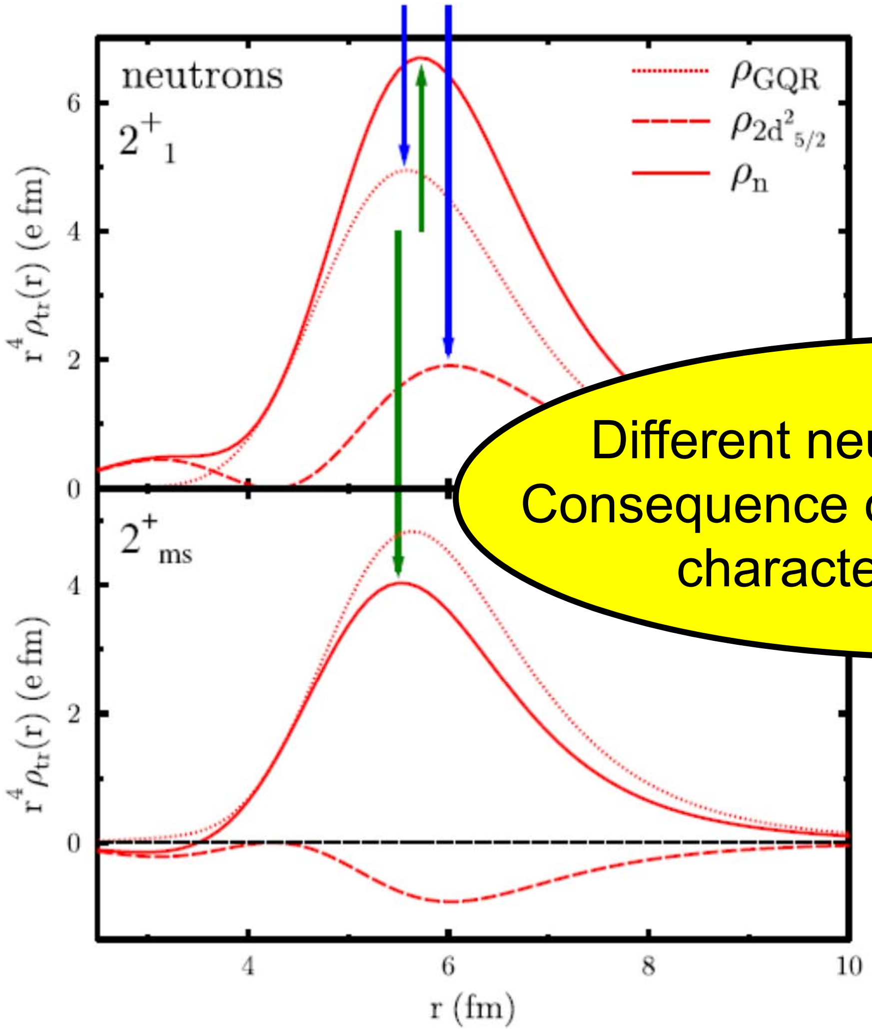
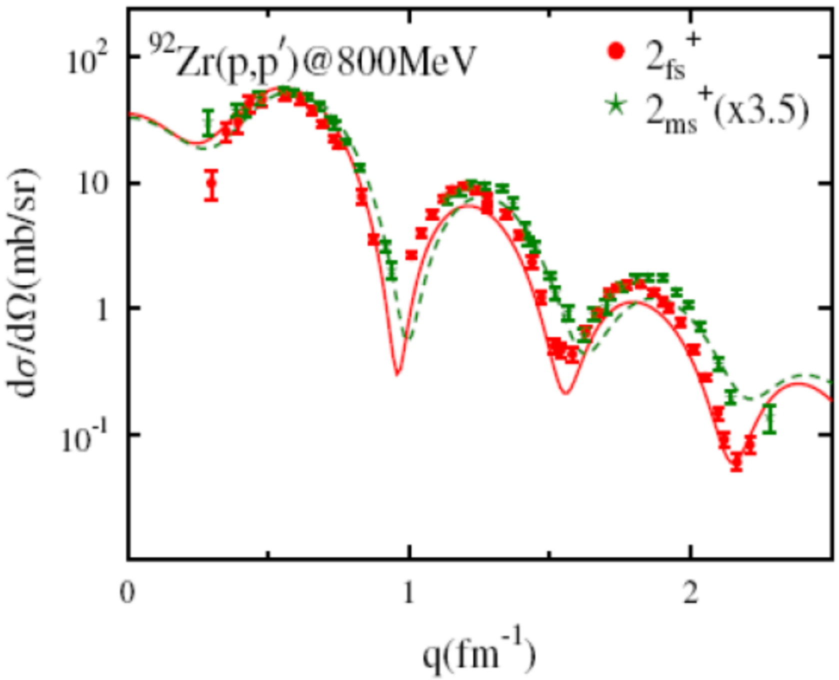


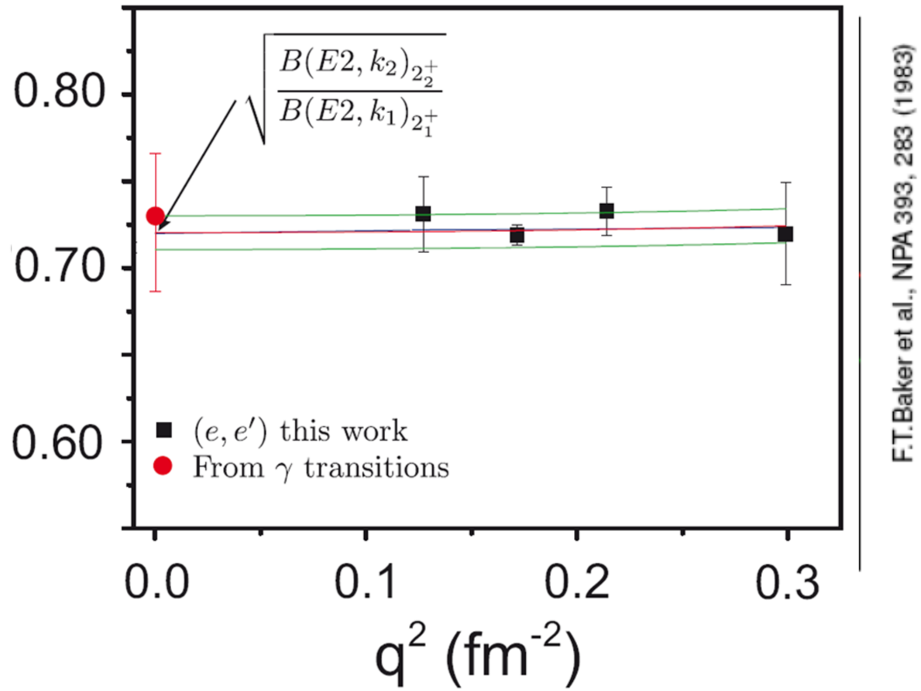
- $|2^+_1\rangle = 0.33\,|1g^2_{9/2}\rangle_p + 0.84\,|2d^2_{5/2}\rangle_n + 0.42\,|GQR\rangle$

Different neutron transition radii:
Consequence of the mixed-symmetry character of the 2^+_2 state

- $|2^+_{ms}\rangle = 0.56\,|1g^2_{9/2}\rangle_p - 0.53\,|2d^2_{5/2}\rangle_n + 0.64\,|GQR\rangle$

Transition Form Factors for ^{92}Zr





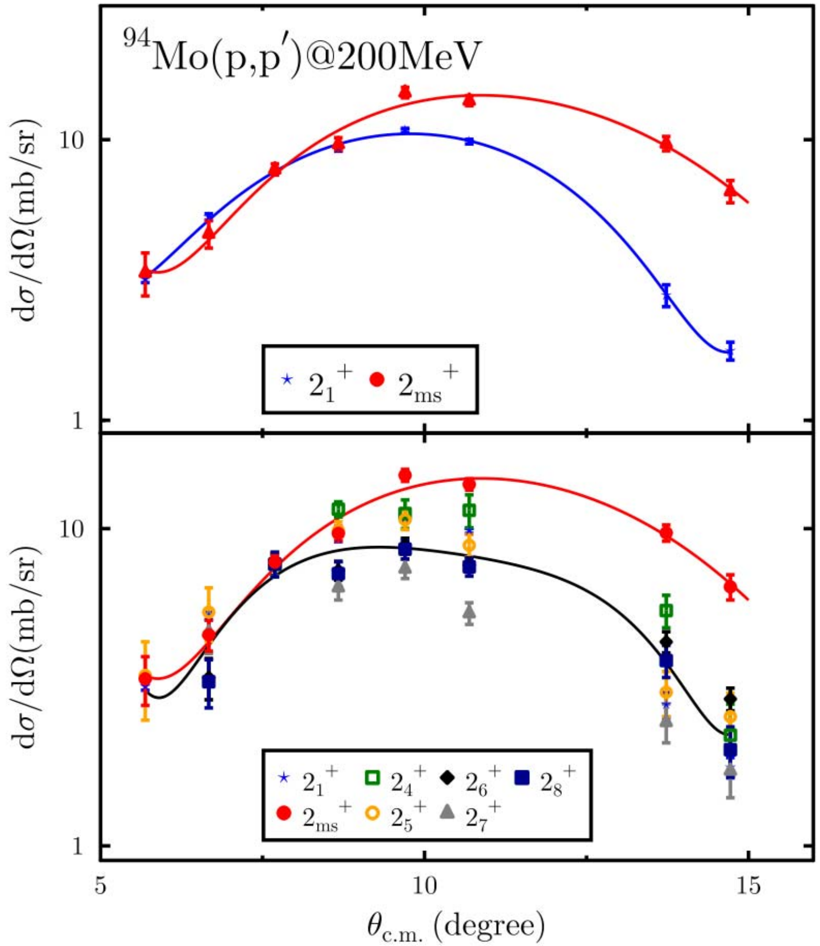
- Pattern-shift to higher momentum transfers for MSS in (p,p')

➢Consequence of the negative sign of the neutron valence-shell component (with a node! Because of n=2)

➢The quantum mechanical phases have been accessible !

C.Walz *et al.*, Phys. Rev. Lett. **106**, 062501 (2011)

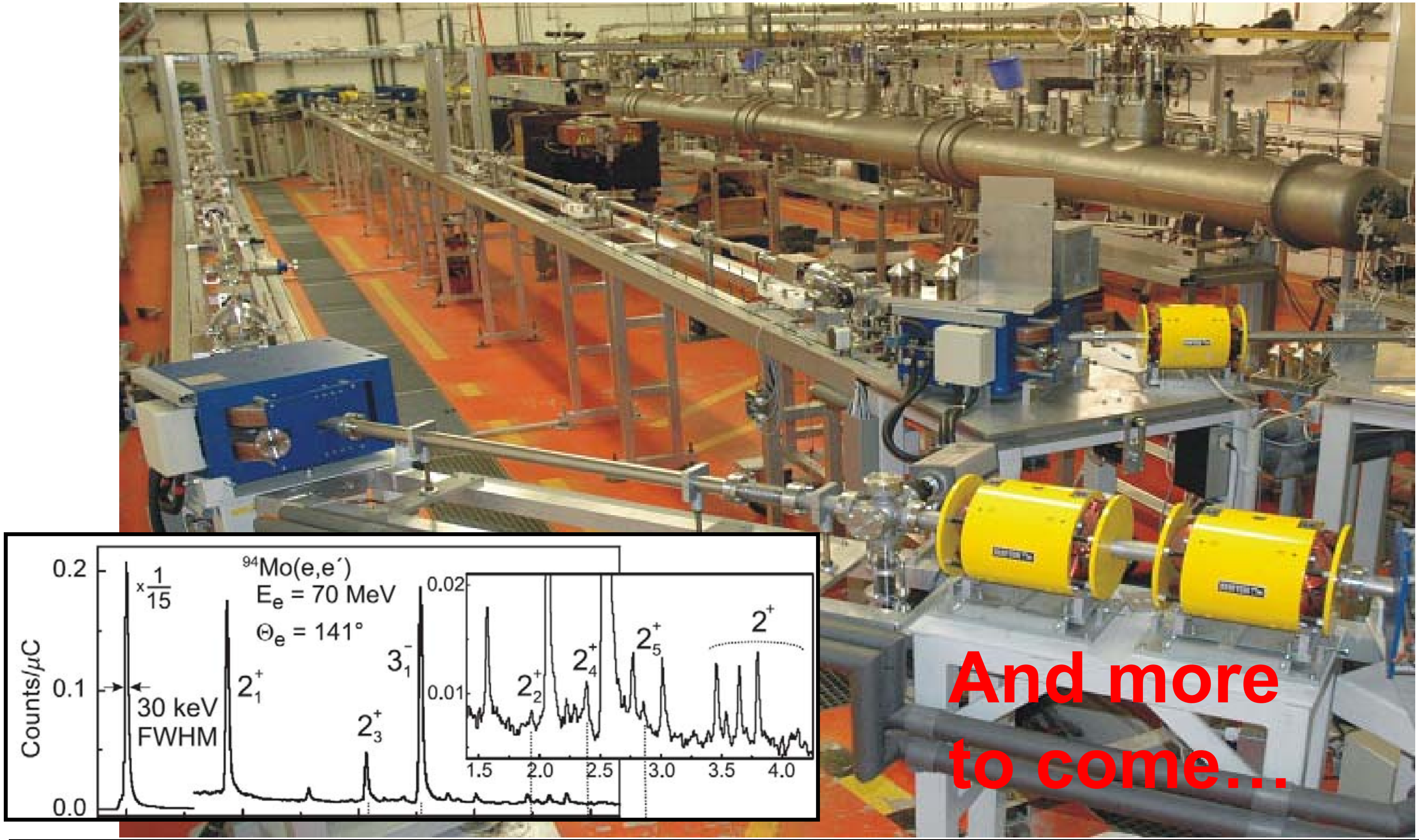
Evidence for relative quantum phase from inelastic proton scattering



C.Walz *et al.*, PRL **106**, 062501 (2011)

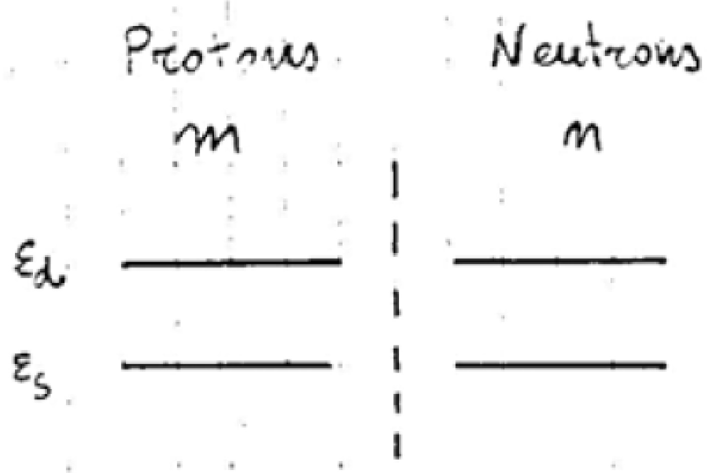
- MSS has smallest matter transition radius of all observed 2^+ states (here for ^{94}Mo).
- This is consequence of the out-of-phase coupling of proton and neutron contributions to the mixed-symmetry wave function.
- New signature for the 2^+_{ms} state.
- Formation of MSS itself is a consequence of the emerging of nuclear collectivity.

S-DALINAC: Beauty in Technology



SFB 634

Conclusions



- IBM-2 still a constant source of inspiration
- MSSs remain a challenge
  - How access multi-phonon MSSs?
  - Evolution with N,Z (energy, strength)
- Transition radii can show relative phase for valence protons and neutron contributions

- **Thank you for years of inspiration!**

- **Happy Birthday, Franco**

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Deutsche Forschungsgemeinschaft DFG

SFB634

DAAD

HIC for FAIR Helmholtz International Center

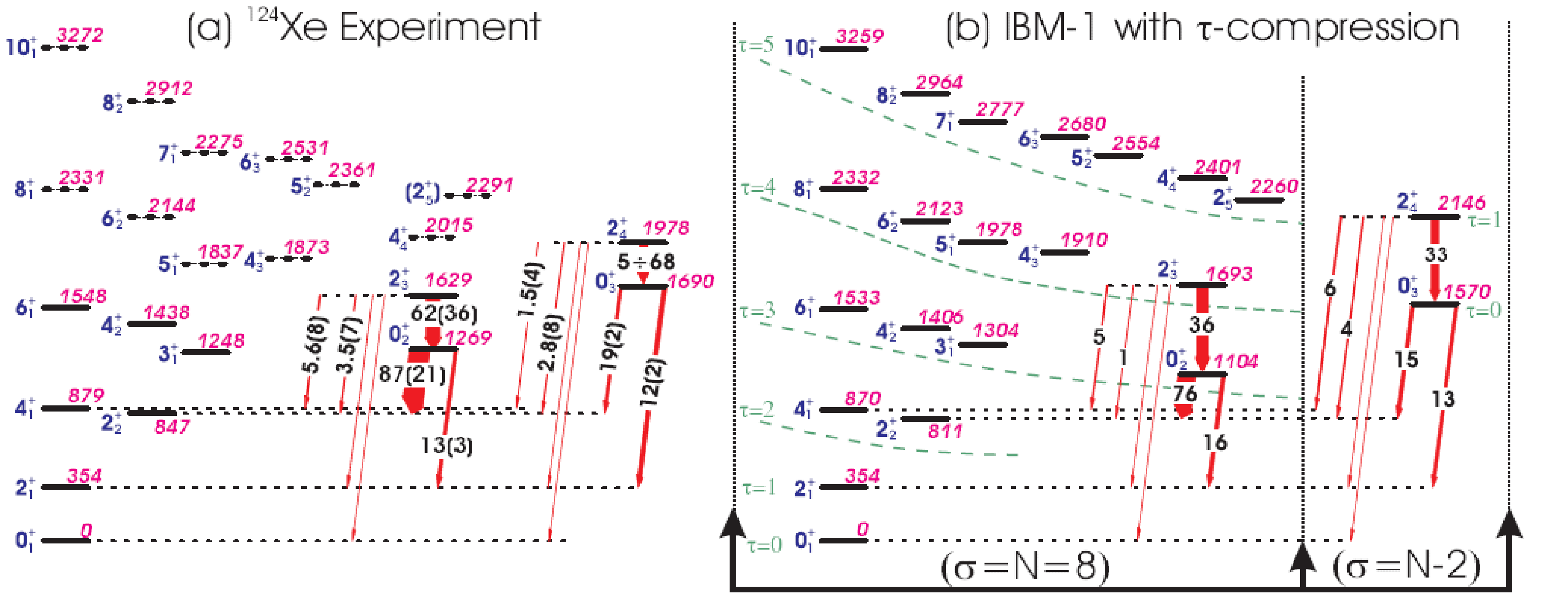
Bundesministerium für Bildung und Forschung

BMBF

sd-IBM 1 Fit: ^{124}Xe

$$H_{\tau\text{-}ECQF} = \varepsilon\, n_d + \lambda\, LL + \kappa\, Q^\chi Q^\chi + \beta\, C_2(O(5))$$

$\lambda/\kappa \rightarrow E(8^+_1)-E(5^+_1)=533$ keV
$\beta/\kappa \rightarrow$ Energy distance GS band
$\varepsilon/\kappa,\ \chi \rightarrow R_0=B(E2;0^+_2\rightarrow 2^+_1)/B(E2;0^+_2\rightarrow 2^+_2)$;
$R_\gamma=B(E2;2^+_2\rightarrow 0^+_1)/B(E2;2^+_2\rightarrow 2^+_1)$;
$\kappa,\ e_B \rightarrow E(2^+_1)$; $B(E2;2^+_1\rightarrow 0^+_1)$



	ϵ/κ	χ	β/κ	λ/κ	κ [keV]	e_B [e^2b^2]
^{126}Xe	-17.0	-0.180	0.55	-0.322	-41.9	0.12246
^{124}Xe	-20.9	-0.257	0.563	-0.284	-34.91	0.14224

^{124}Xe from V. Werner et al, Nucl. Phys. A 692, 451 (2001)

Model pn-symmetry in valence shell:

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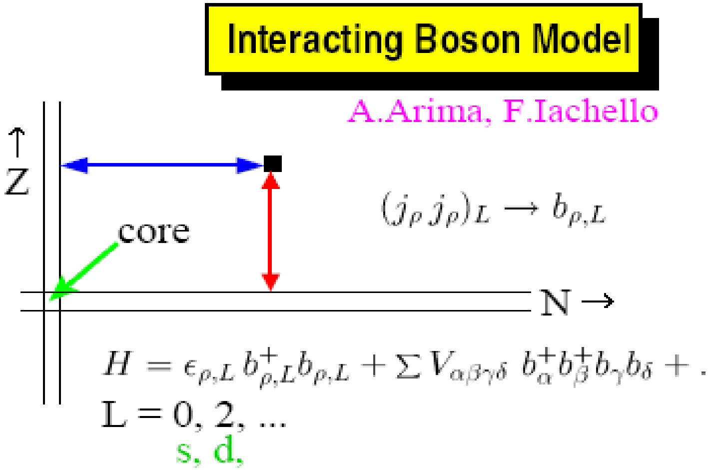
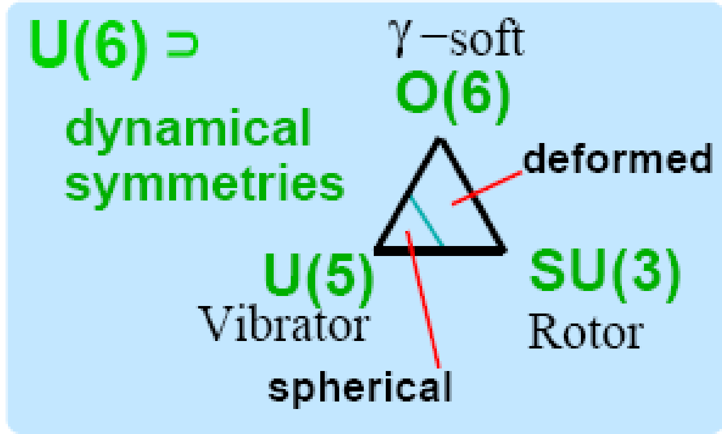
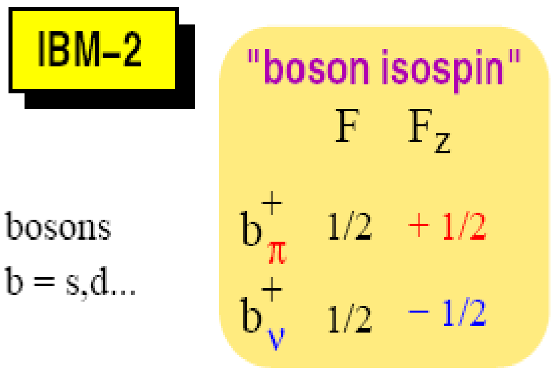
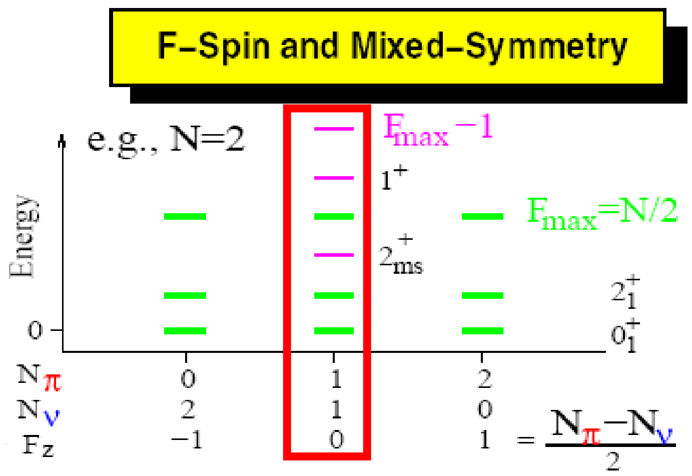






T.Otsuka et al, Nucl.Phys. A 309, 1 (1978).



contain pn antisymmetric pairs

[redacted]

M1 Transitions as Experimental Signatures for Mixed-Symmetry States

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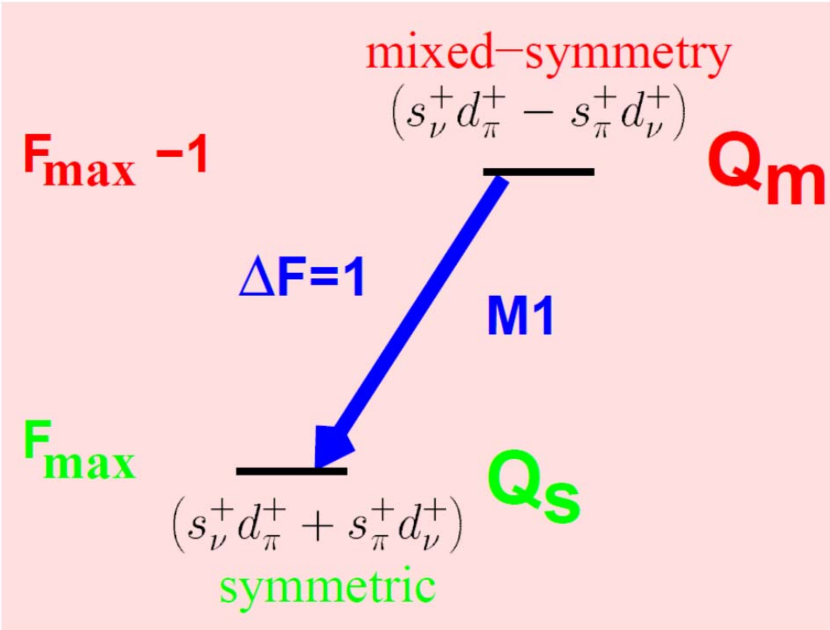
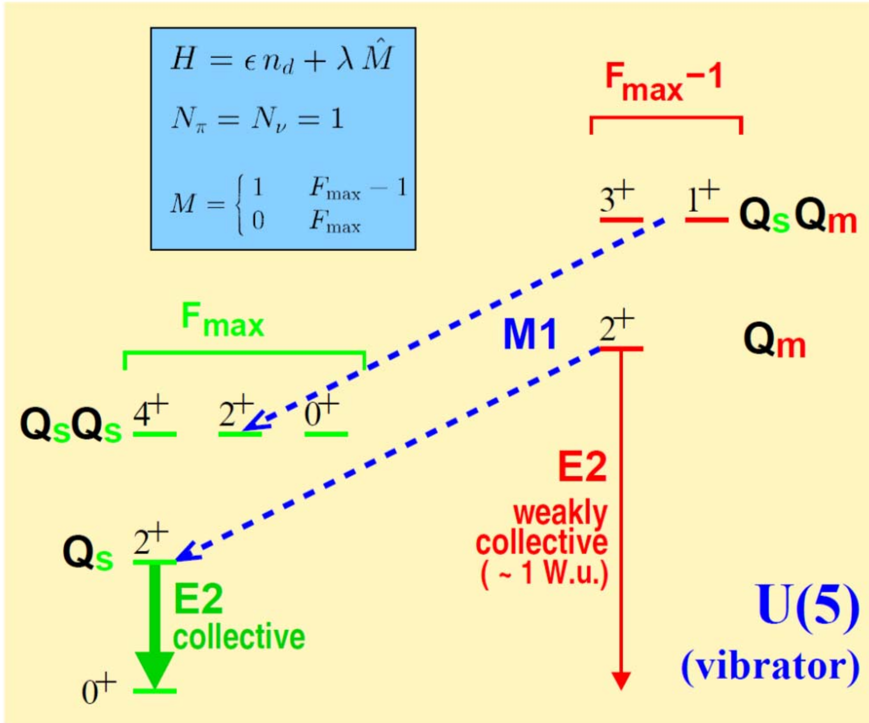
$$T(M1) \propto (g_\pi - g_\nu)\left([d_\pi^+\tilde{d}_\pi]^{(1)} - [d_\nu^+\tilde{d}_\nu]^{(1)}\right) \quad + L_{tot}$$

$$g_\pi \approx 1\ \mu_N\ , \qquad g_\nu \approx 0\ \mu_N$$

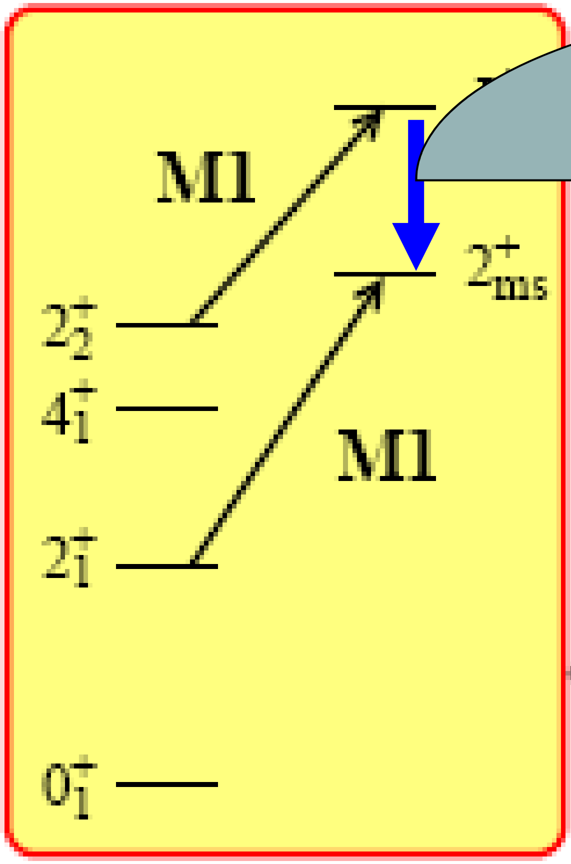
New information on mixed-symmetry states will be the topic for the remaining part of this talk.

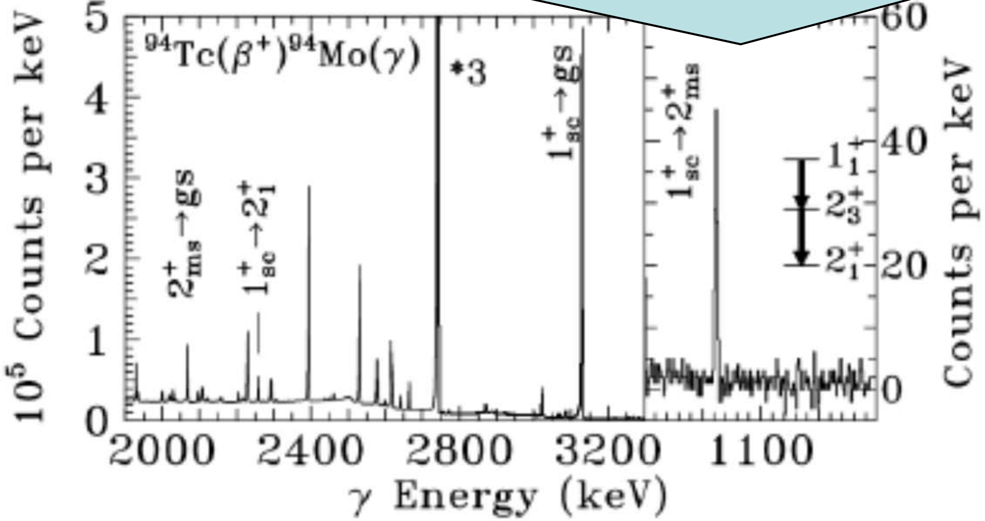




$$\langle F_{max} \,||\, M1 \,||\, F_{max} - 1 \rangle \approx 1\ \mu_N$$

Evidence for common structure of MSSs





N. Pietralla et al., Phys. Rev. Lett. 83 1303 (1999)