Understanding Proton/Neutron Mixed-Symmetry from Low-Momentum Nucleon-Nucleon Interactions

Jason D. Holt
jholt@triumf.ca

INT Program: Nuclear Many-Body Approaches for the 21st Century

October 26, 2007 – Seattle, WA

Outline

- Microscopic Approach: Low-Momentum Interactions
  - Advantages for Nuclear Structure
- Proton/Neutron Mixed-Symmetry
  - Properties and Signatures
  - Experimental Landscape

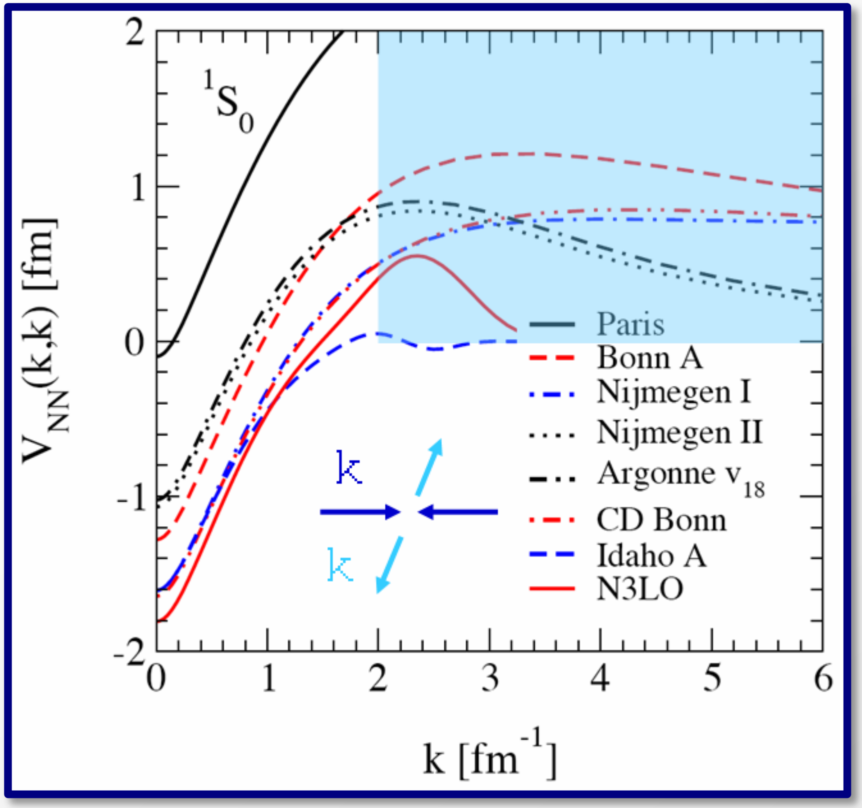
First Results

- Manifestation in **odd-mass nearly-spherical nuclei**
- Microscopic Mechanism for Formation/Evolution
  - Observables: g factors
  - Driven by energy of proton/neutron quadrupole excitations

Internucleon Interactions

$$H(\Lambda) = T + V_{\rm NN}(\Lambda) + V_{\rm 3N}(\Lambda) + V_{\rm 4N}(\Lambda) + \ldots$$

Hierarchy: $V_{\rm NN} > V_{\rm 3N} > \ldots$ all are **effective theories**



- Fit all low-energy NN data
- Details unconstrained for higher momenta
- High momentum modes complicate many-body calculations
- Desire low-momentum interactions for nuclear structure calculations

3N forces: current frontier in many-body calculations for medium-mass nuclei

Low-Momentum Interactions

Generate low-momentum interactions for low-energy problems of interest

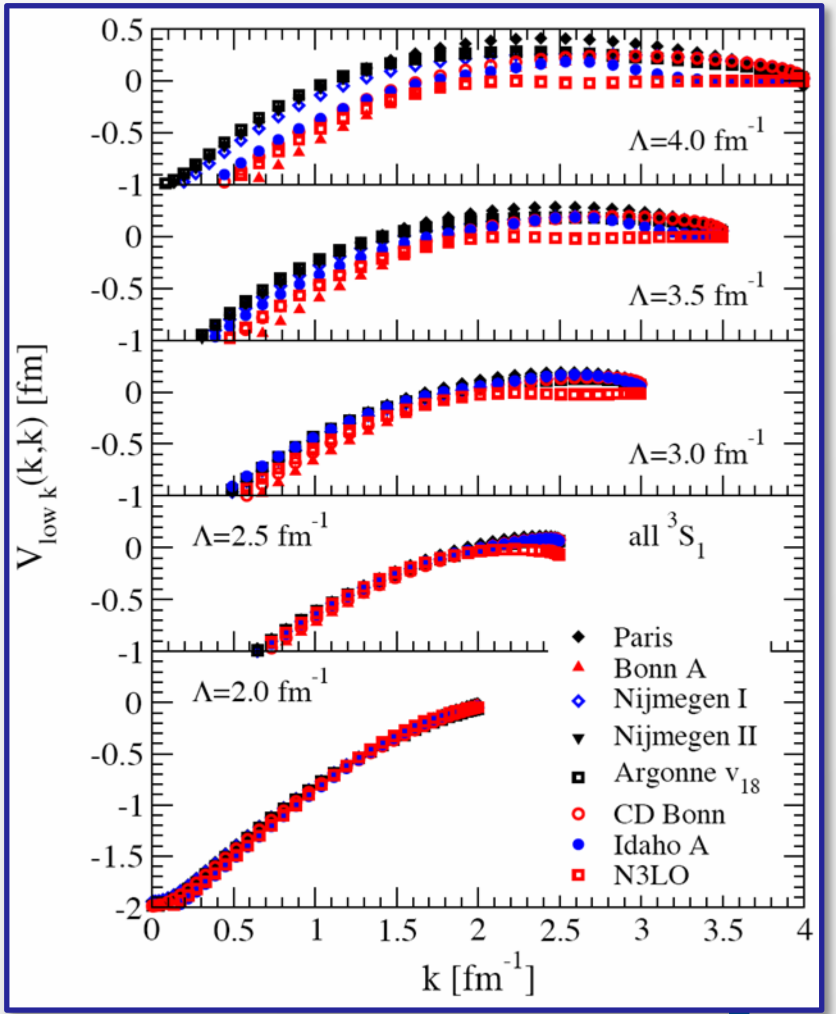
Evolve cutoff to desired resolution scale using exact RG equation

$$\text{Require}: \frac{\mathrm{d}}{\mathrm{d}\Lambda} T = 0$$

High-k modes integrated out as Λ lowered

Collapse to similar potentials as $\Lambda \to 2.0 \text{fm}^{-1}$

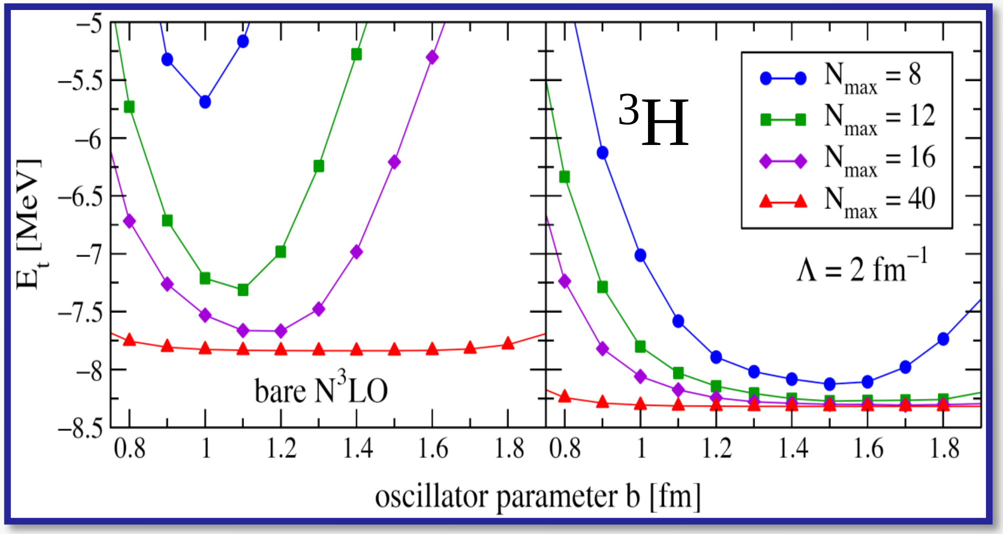
$V_{\text{low } k}(\Lambda)$: class of energy-independent low-momentum interactions which exactly reproduce known NN data below Λ



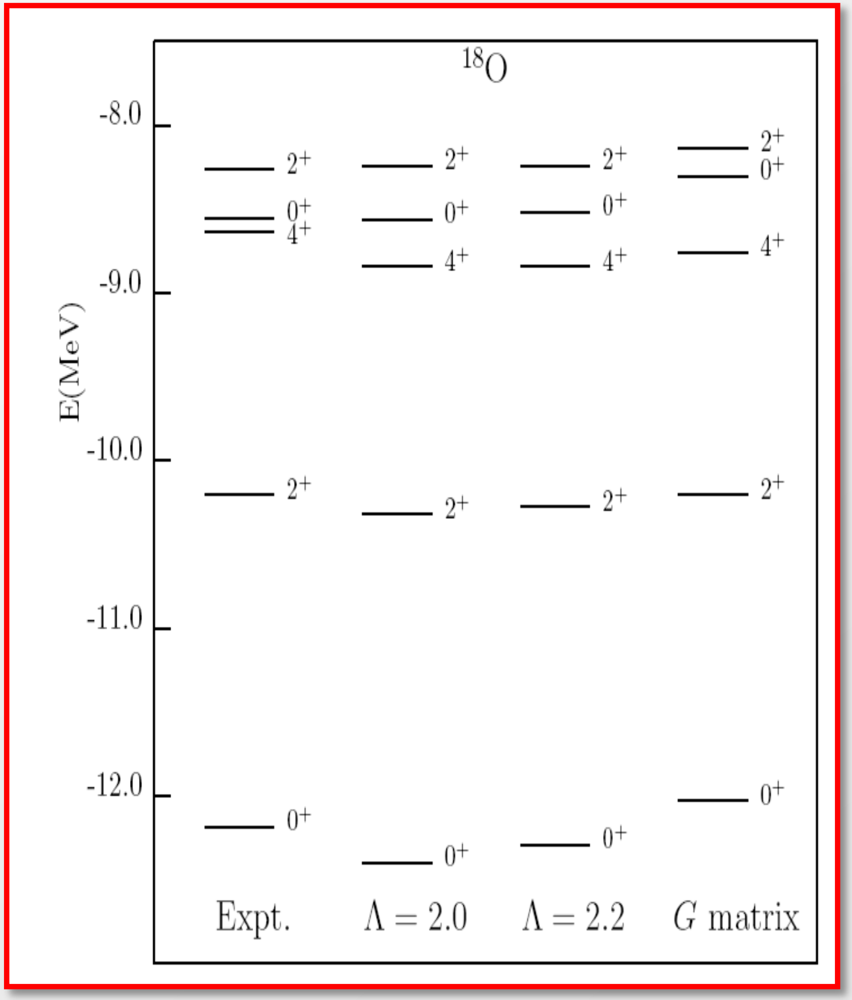
Advantages for Nuclear Structure

Using lower cutoffs:

Improved convergence for structure calculations



Energy independence useful for nuclear structure

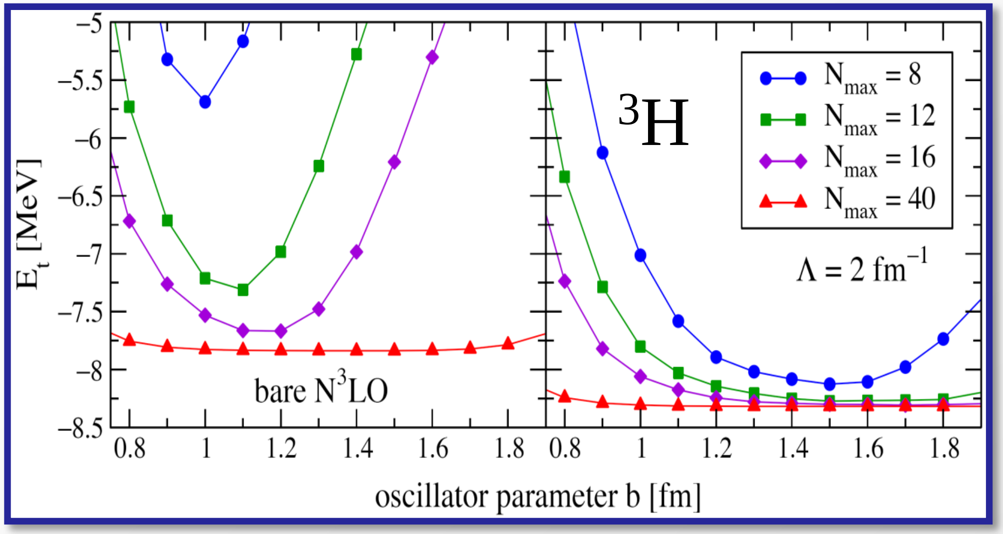


Variation of observables with cutoff **probes error** due to neglected physics.

Advantages for Nuclear Structure

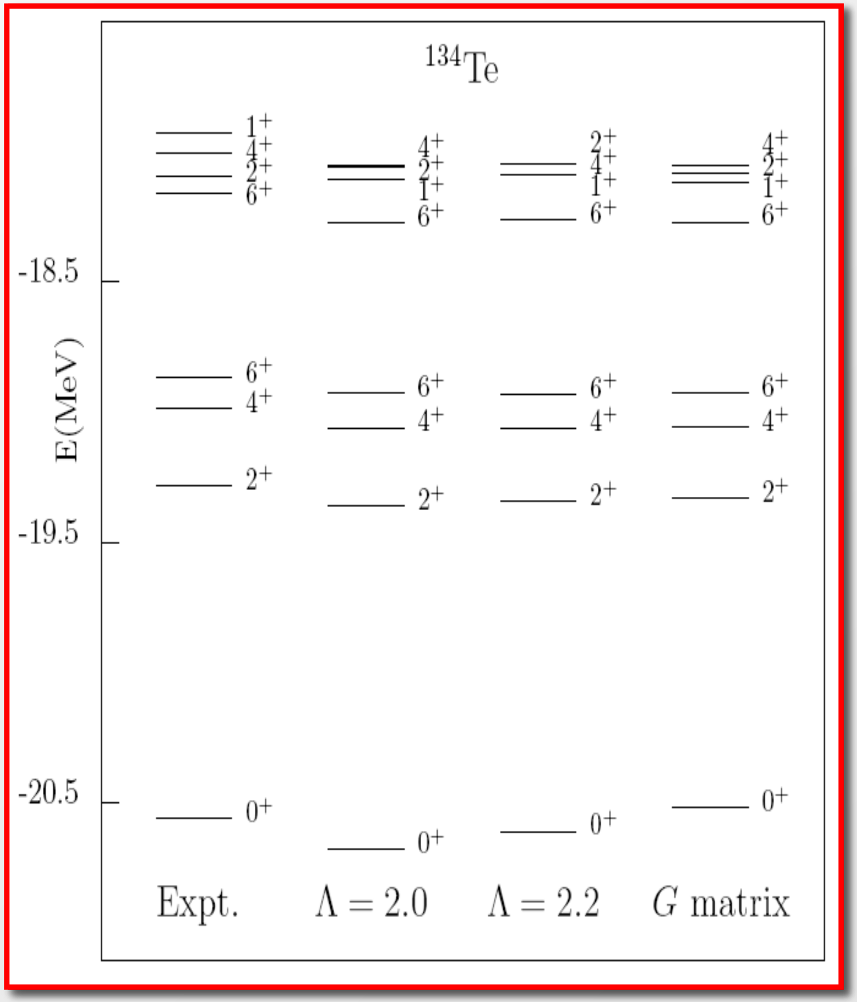
Using lower cutoffs:

Improved convergence for structure calculations



Variation of observables with cutoff **probes error** due to neglected physics.

Energy independence useful for nuclear structure

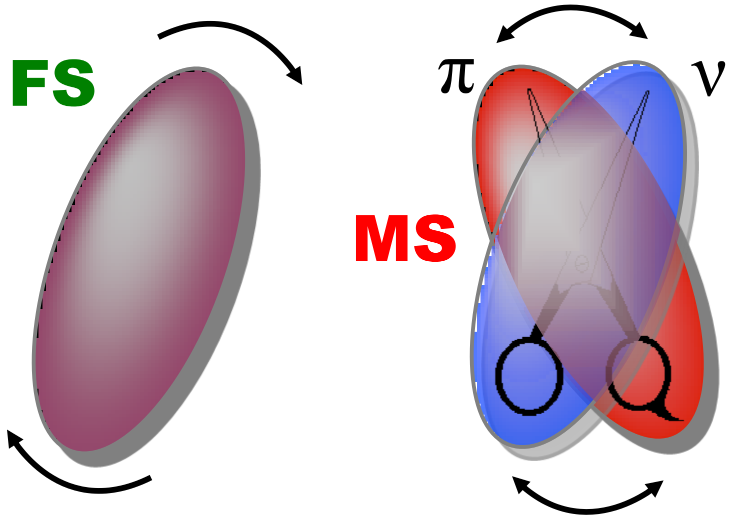


What is a "Mixed-Symmetry" State?

Collective Excitations which are p/n asymmetric

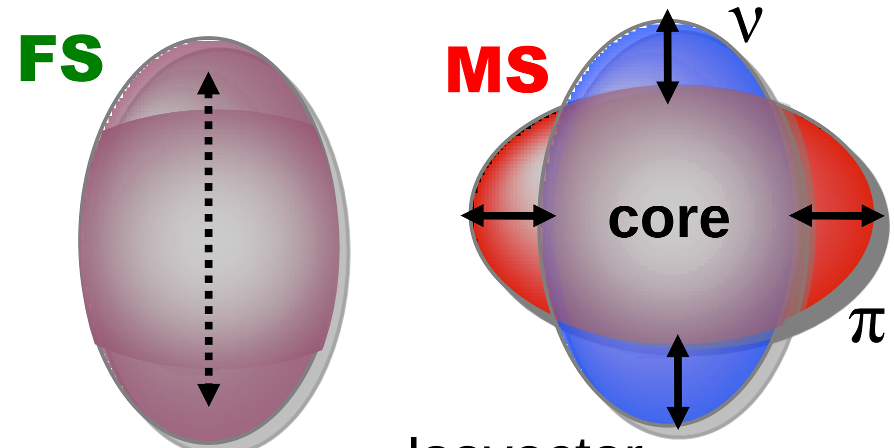
N. Pietralla et al.

Deformed Nuclei (A. Richter et al)



Rotor "Scissor" mode

Nearly-Spherical Nuclei



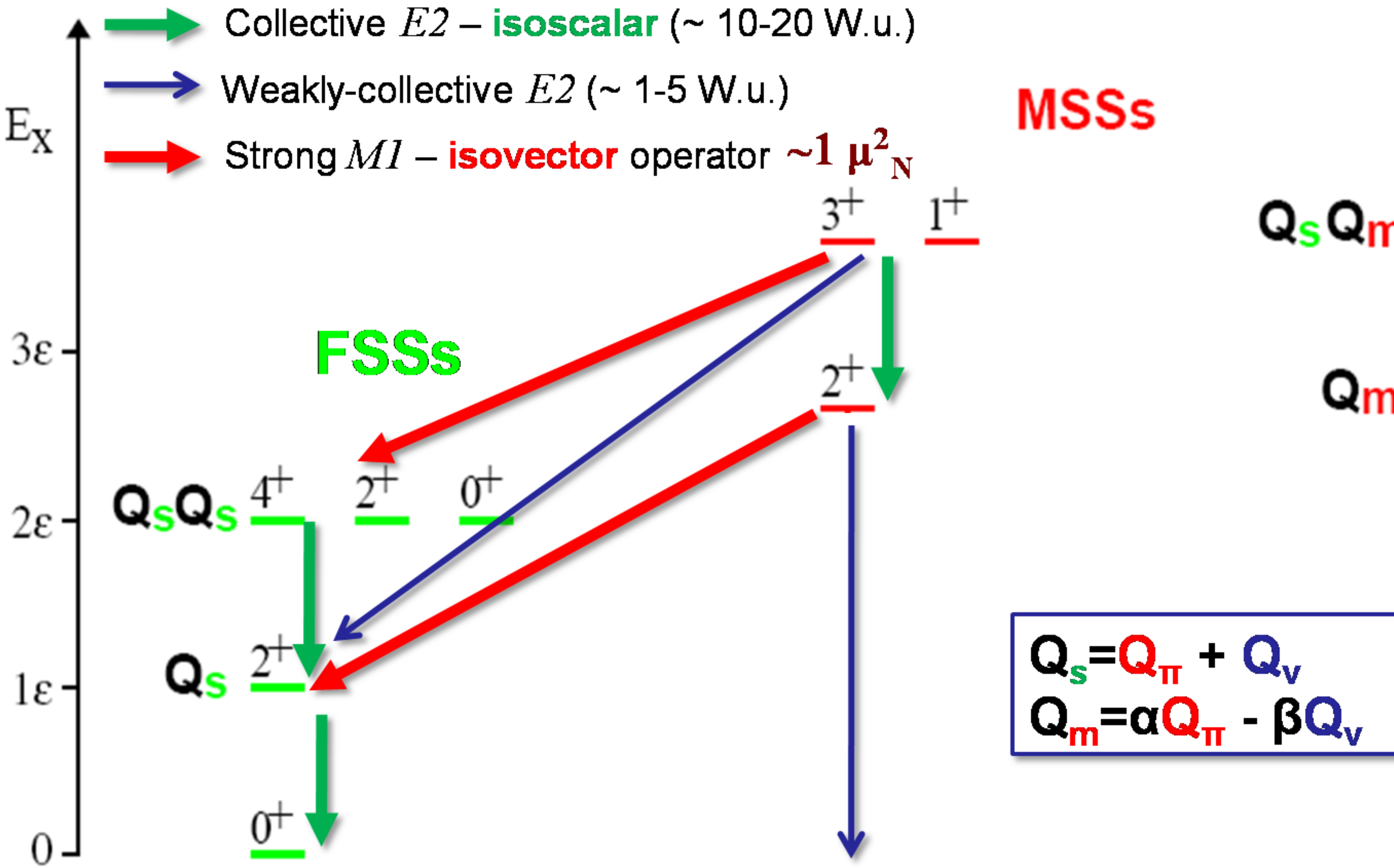
Isoscalar Quadrupole Isovector Quadrupole

Focus: Isovector quadrupole excitations of ***valence*** nucleons

- Understand collective coupling of proton-neutron (p/n) subsystems
  - Sensitive to: shell structures, p/n part of valence shell interaction

Goal: Understand properties microscopically w/ $V_{\mathrm{low}\,k}$

Experimental Spectra/Signatures

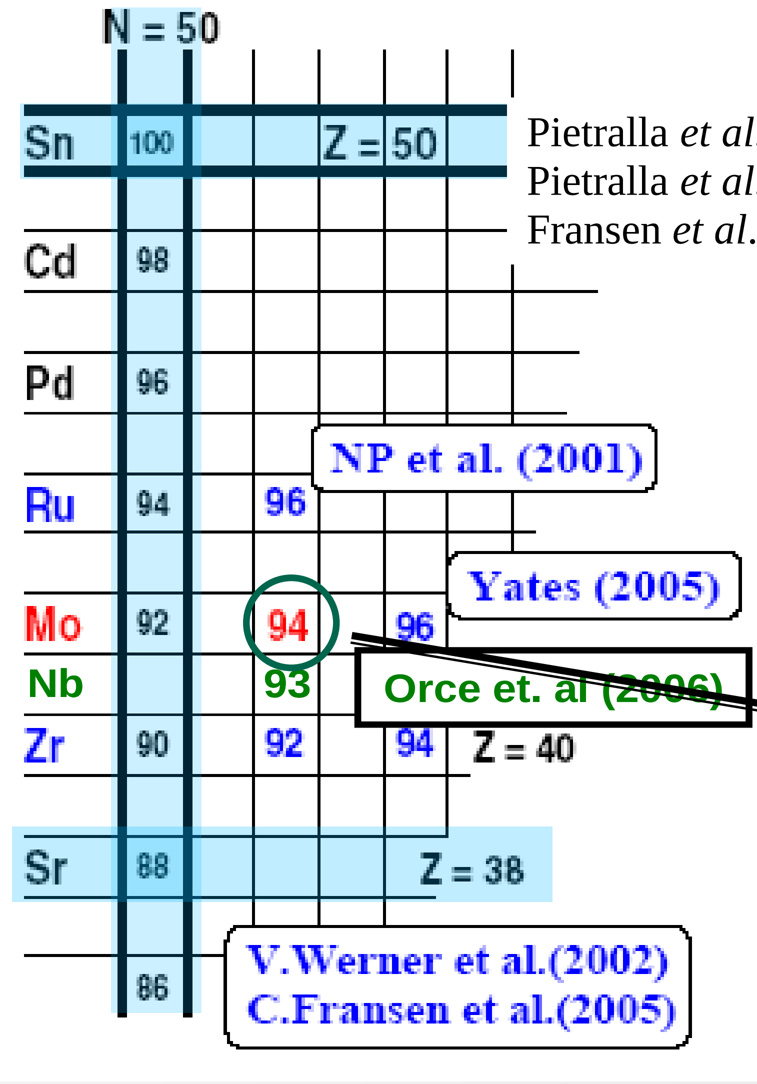


$Q_s = Q_\pi + Q_\nu$

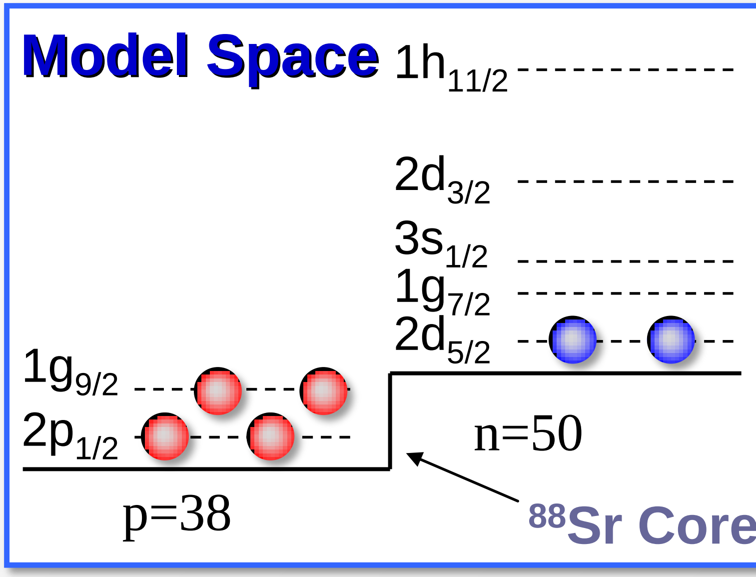
$Q_m = \alpha Q_\pi - \beta Q_\nu$

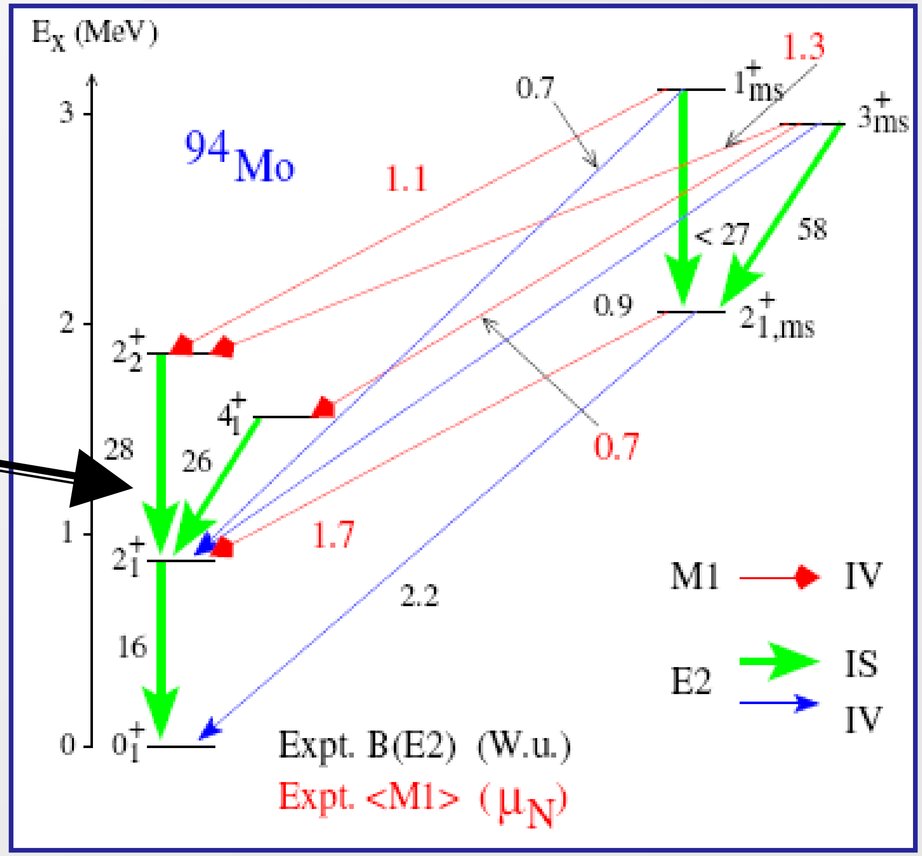
MSSs in A≈90 Nuclei

Experimental Landscape



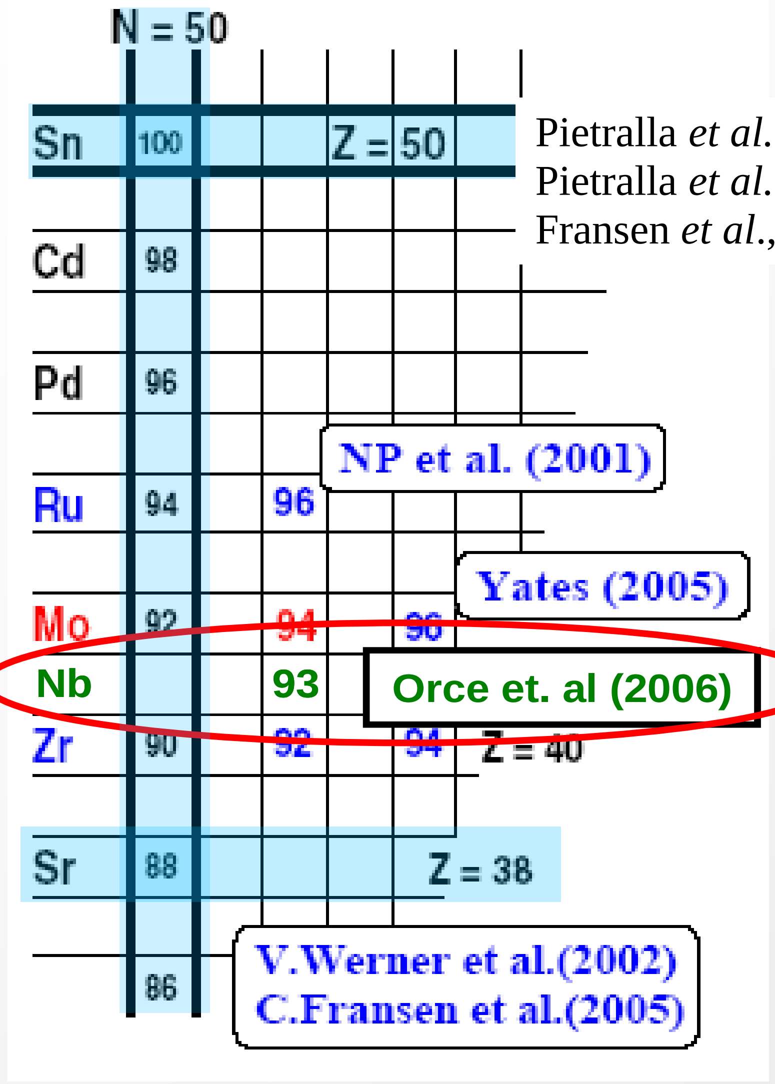
Pietralla *et al.*, PRL **83** (1999)
Pietralla *et al.*, PRL **84** (2000)
Fransen *et al.*, PRC **67** (2003)



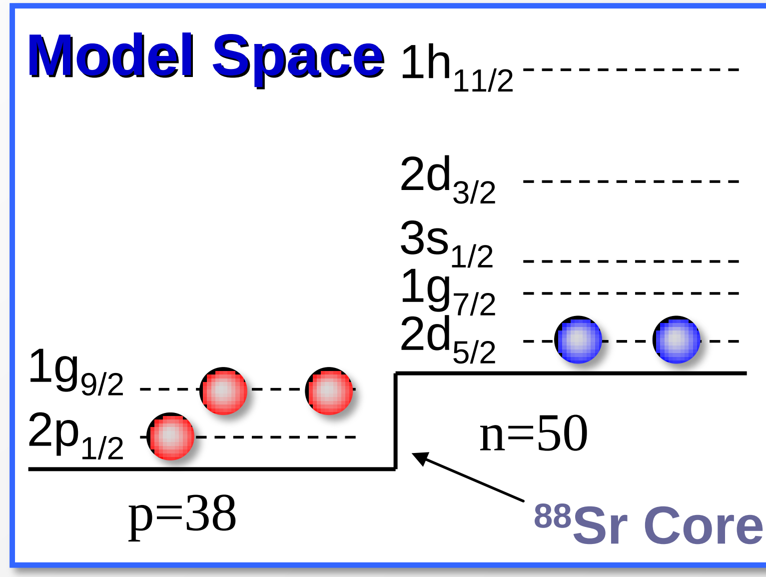


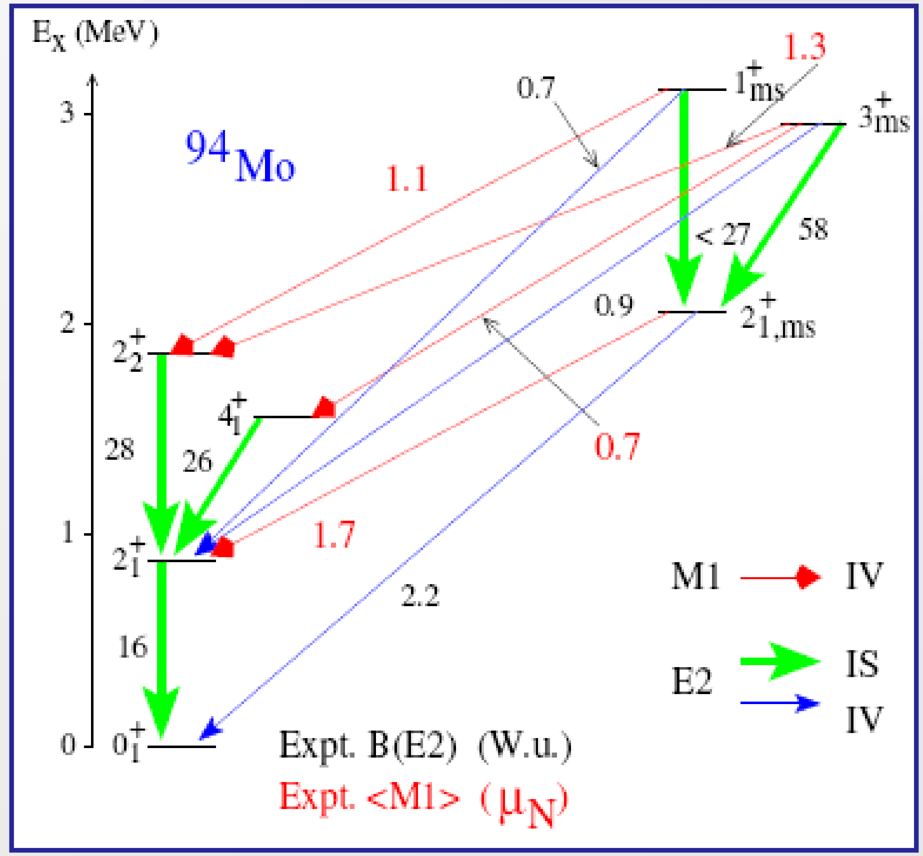
MSSs in A≈90 Nuclei

Experimental Landscape



Pietralla *et al.*, PRL **83** (1999)
Pietralla *et al.*, PRL **84** (2000)
Fransen *et al.*, PRC **67** (2003)

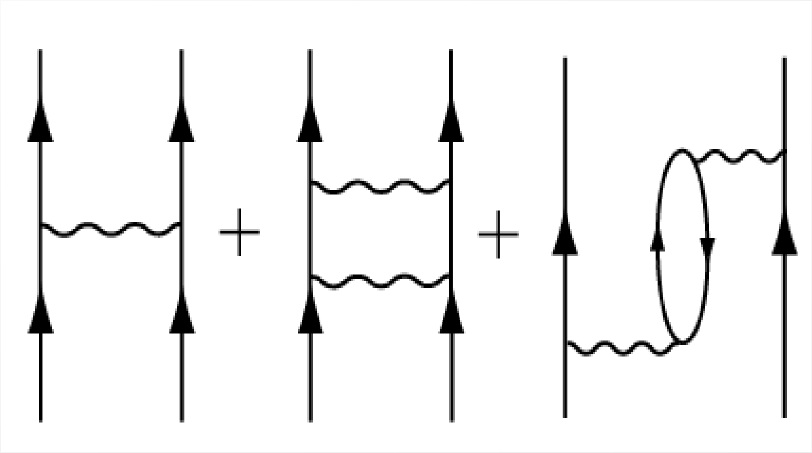




Calculation Methods

Generate **valence shell effective interaction** from microscopic Many body theory:

$V_{\mathrm{low}\,k}$ + 2nd order terms



Future: Validate against exact many-body theories (NCSM, CC,...)

Intermediate states:
taken two oscillator shells above/below model space

OXBASH code for diagonalization

Experimental s.p. energies from: ^{89}Y and ^{89}Sr

EM Transition Operators:

$$O(E2) = e_{\pi} \sum_{i=1}^{Z} r_i^{2} Y_{\mu}^{(2)}(\hat{r}_i) + e_{\nu} \sum_{i=1}^{N} r_i^{2} Y_{\mu}^{(2)}(\hat{r}_i)$$

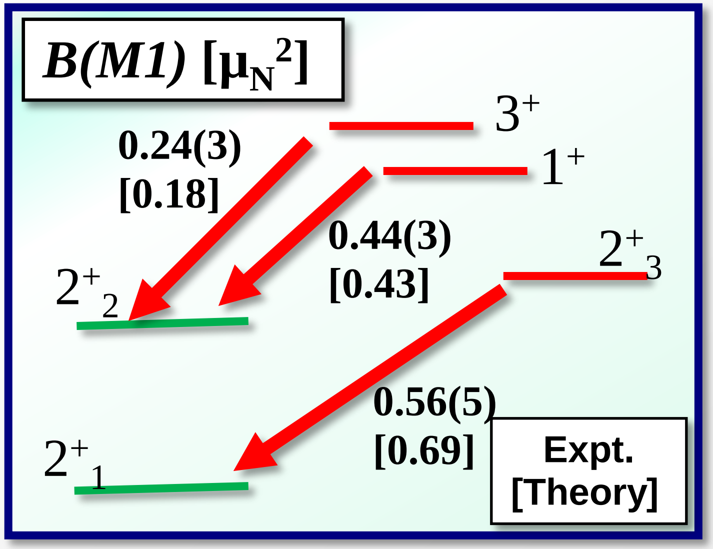
$$O(M1) = \sqrt{3/4\pi}\left(\sum_{i=1}^{Z} \left[g_{\pi}^{l} \vec{\ell}_i^{\,\pi} + g_{\pi}^{s} \vec{s}_i^{\,\pi} \right] + \sum_{i=1}^{N} \left[g_{\nu}^{l} \vec{\ell}_i^{\,\nu} + g_{\nu}^{s} \vec{s}_i^{\,\nu} \right] \right)$$

First Applications

Parameters

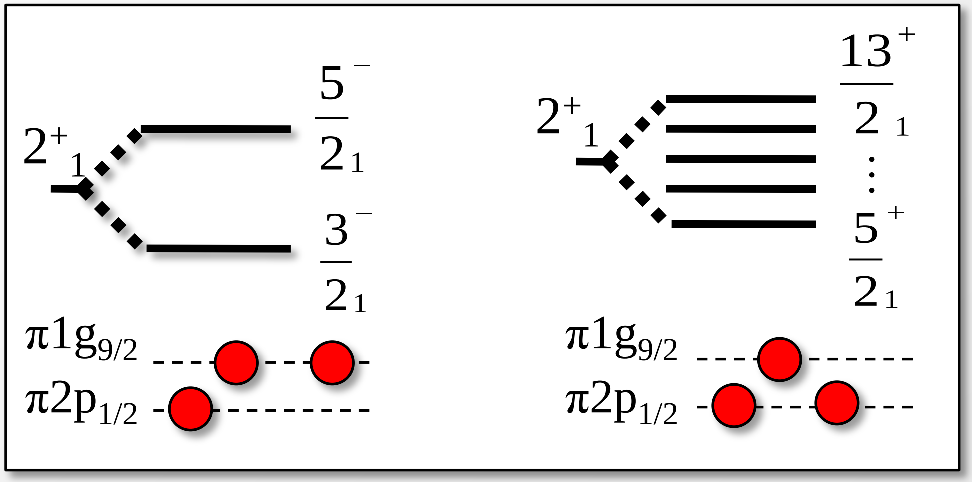
e_p=2.1e, e_n=1.2e
g^s_p =3.18, g^s_n=-2.18
g^l_p=1, g^l_n=0

Simple test: **^{94}Mo**



Also: **^{92}Zr, ^{96}Ru**

First Real Test: **^{93}Nb**

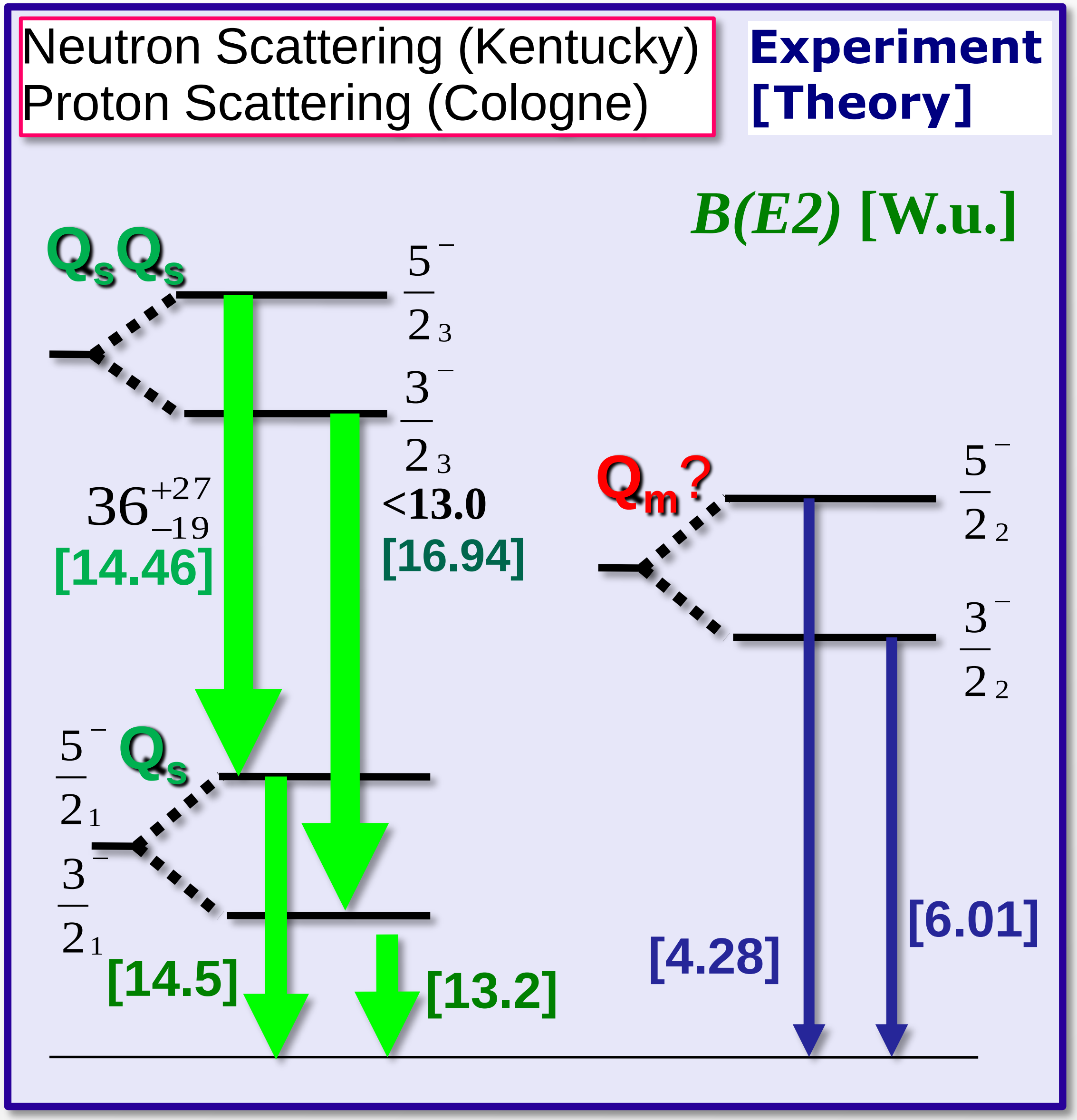


Can we identify MSSs here?

- Will EM transitions be preserved?
- **Concern**: Large *M1* strength could arise from spin-flip of unpaired proton

Quantify spin/orbital *M1* contributions and check IS/IV character of excitations

MS in the Odd-Mass Nucleus ^{93}Nb



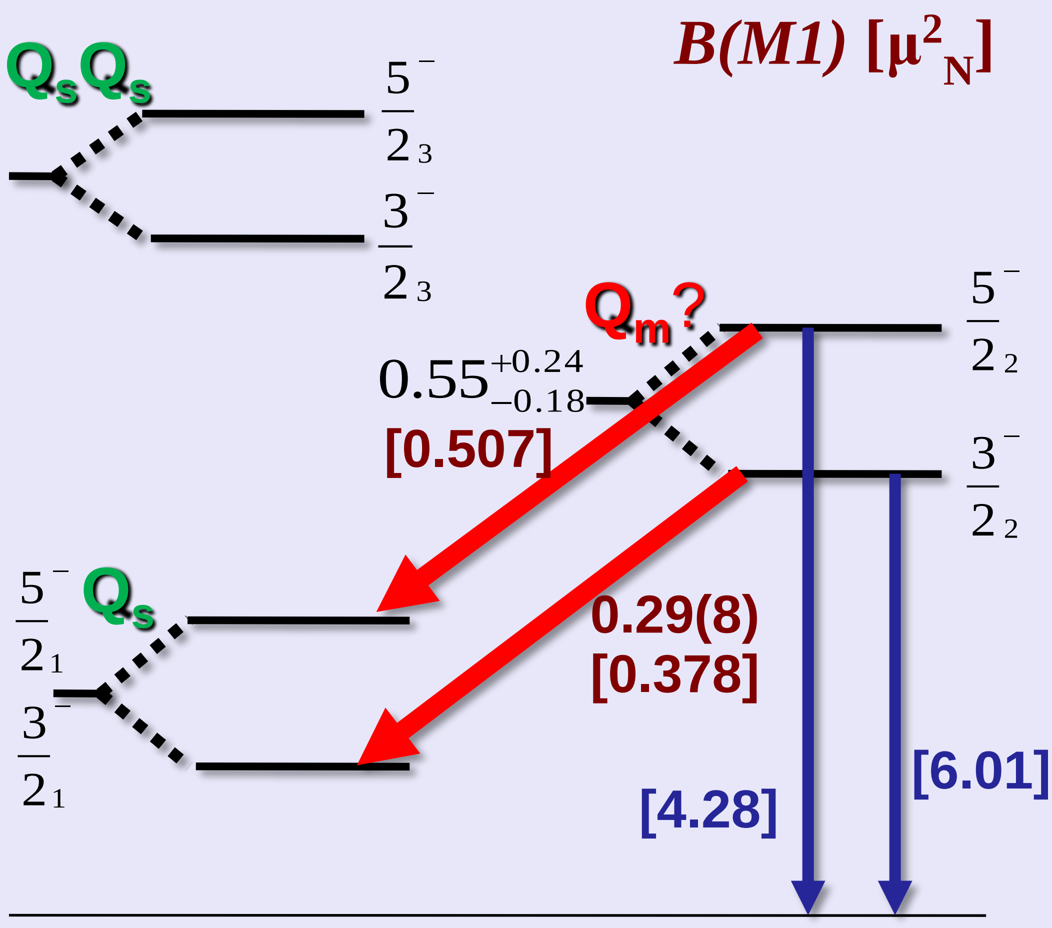
Collective (measured and calculated) *E2* transitions:
One- and two-phonon FSSs

- Weakly-collective *E2* to ground state

MS in the Odd-Mass Nucleus ^{93}Nb

Neutron Scattering (Kentucky)
Proton Scattering (Cologne)

Experiment
[Theory]



Collective (measured and calculated) *E2* transitions:
One- and two-phonon FSSs

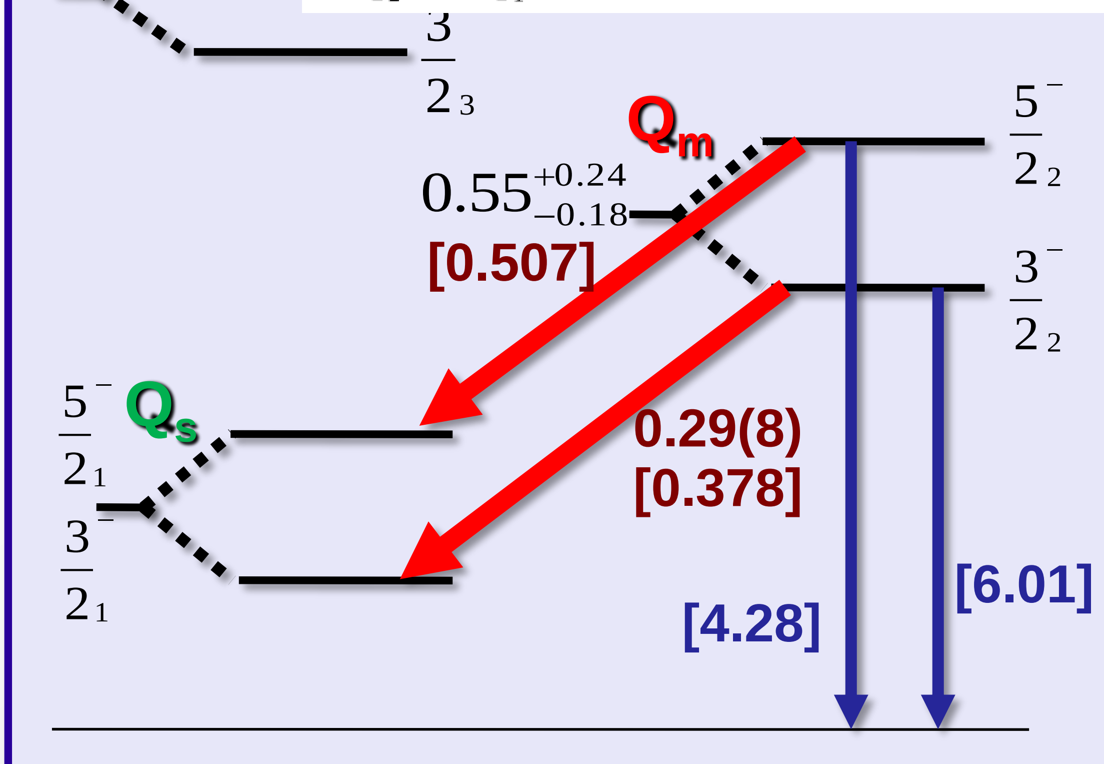
- Weakly-collective *E2* to ground state
- Strong *M1* to symmetric states (Agrees w/ experiment)

MS in the Odd-Mass Nucleus ^{93}Nb

Neutron Scattering (Kentucky)
Proton Scattering (Cologne)

Experiment
[Theory]

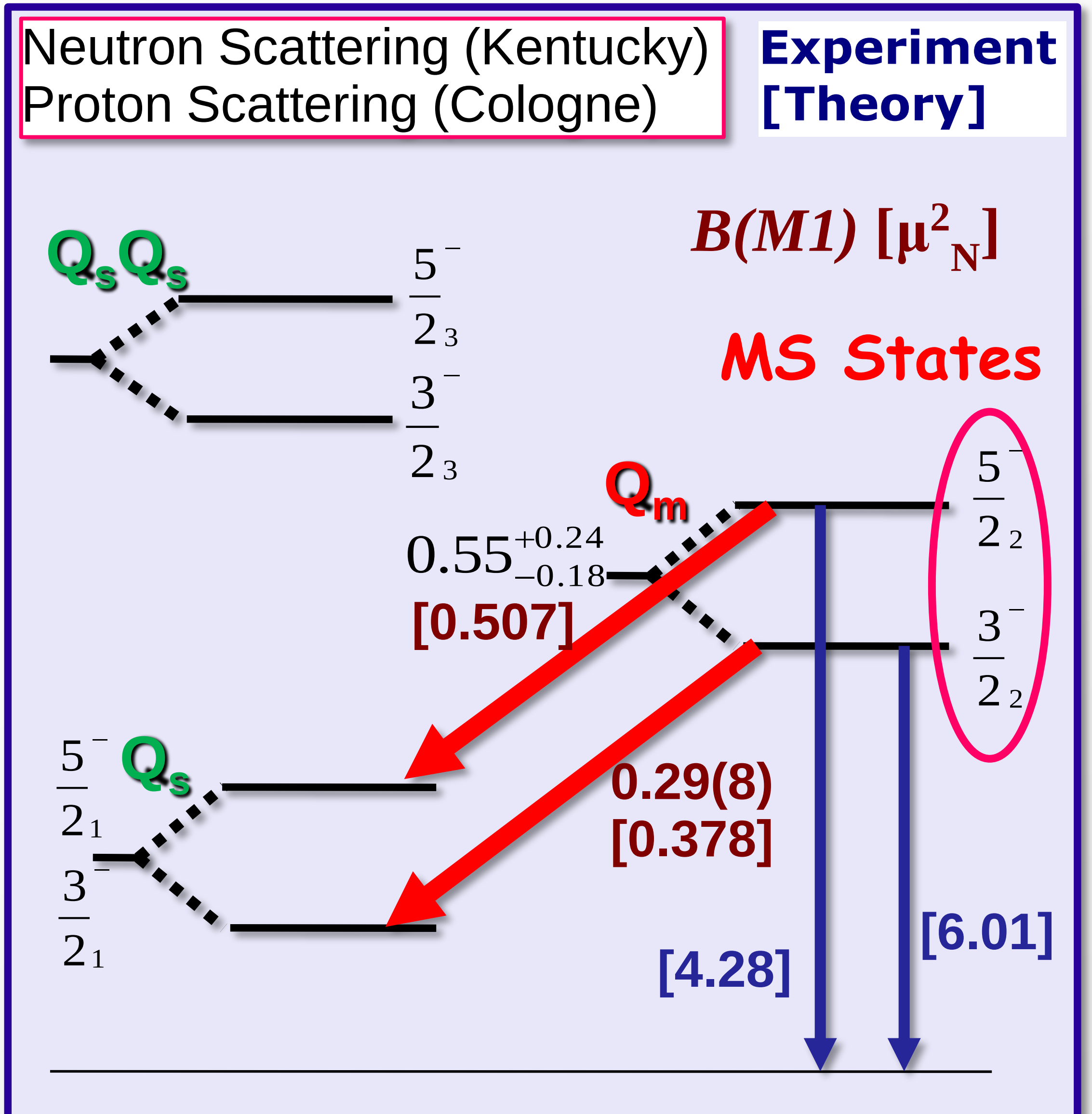
$J_i \to J_f$	Spin $B(M1)$	Orbital $B(M1)$
$\frac{3}{2}^-_2 \to \frac{3}{2}^-_1$	0.110	0.121
$\frac{5}{2}^-_2 \to \frac{5}{2}^-_1$	0.155	0.153



Collective (measured and calculated) $E2$ transitions:
One- and two-phonon FSSs

- Weakly-collective $E2$ to ground state
- Strong $M1$ to symmetric states (Agrees w/ experiment)
- $B(M1)_l \approx B(M1)_s$ **- just as in ^{94}Mo**
  $\Rightarrow$ **One-phonon MS**

MS in the Odd-Mass Nucleus ^{93}Nb



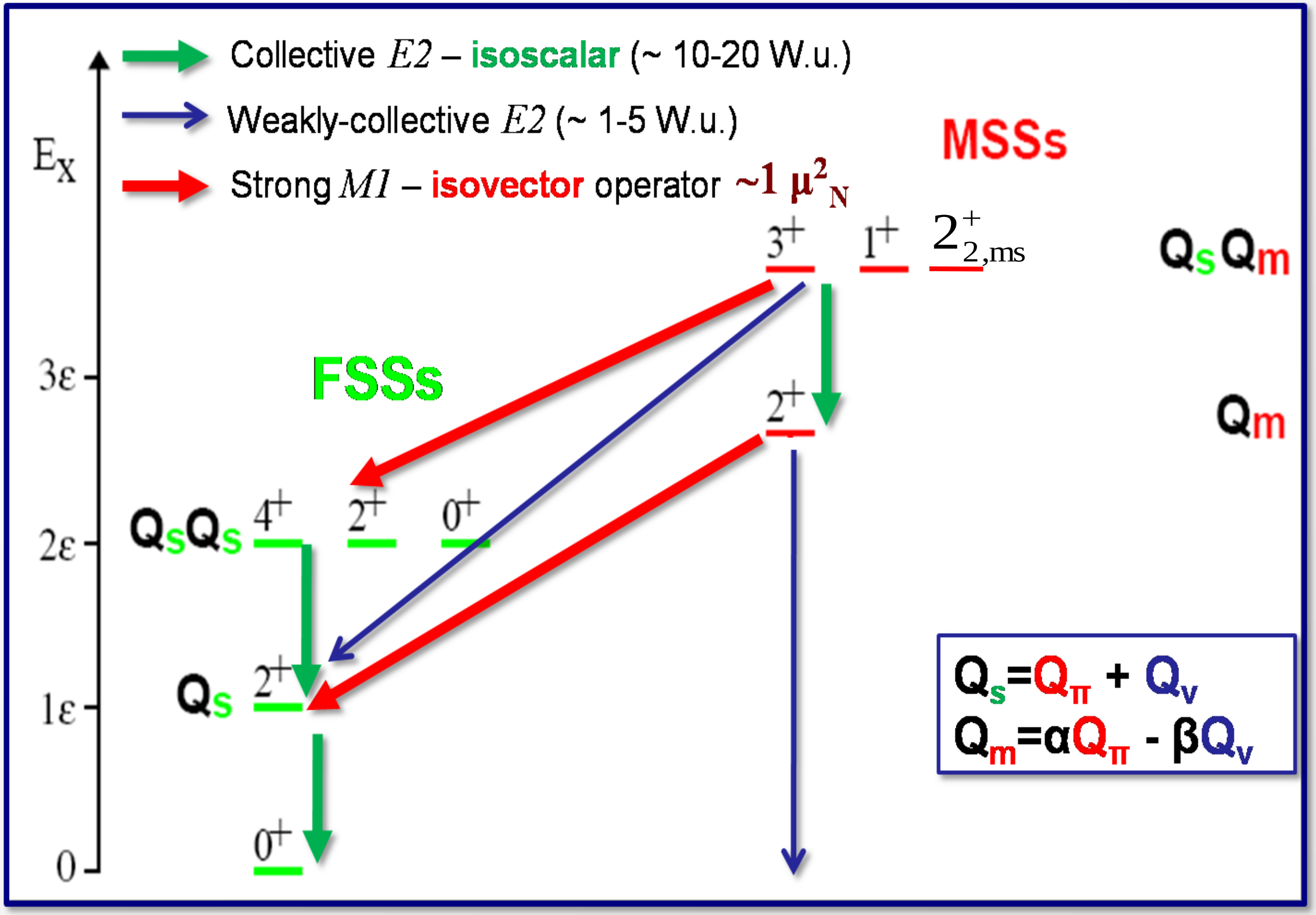
Collective (measured and calculated) $E2$ transitions:
One- and two-phonon FSSs

- Weakly-collective $E2$ to ground state
- Strong $M1$ to symmetric states (Agrees w/ experiment)
- $B(M1)_l \approx B(M1)_s$ - just as in ^{94}Mo $\Rightarrow$ **One-phonon MS**

First identification of MSSs in an odd-mass nearly-spherical nucleus.

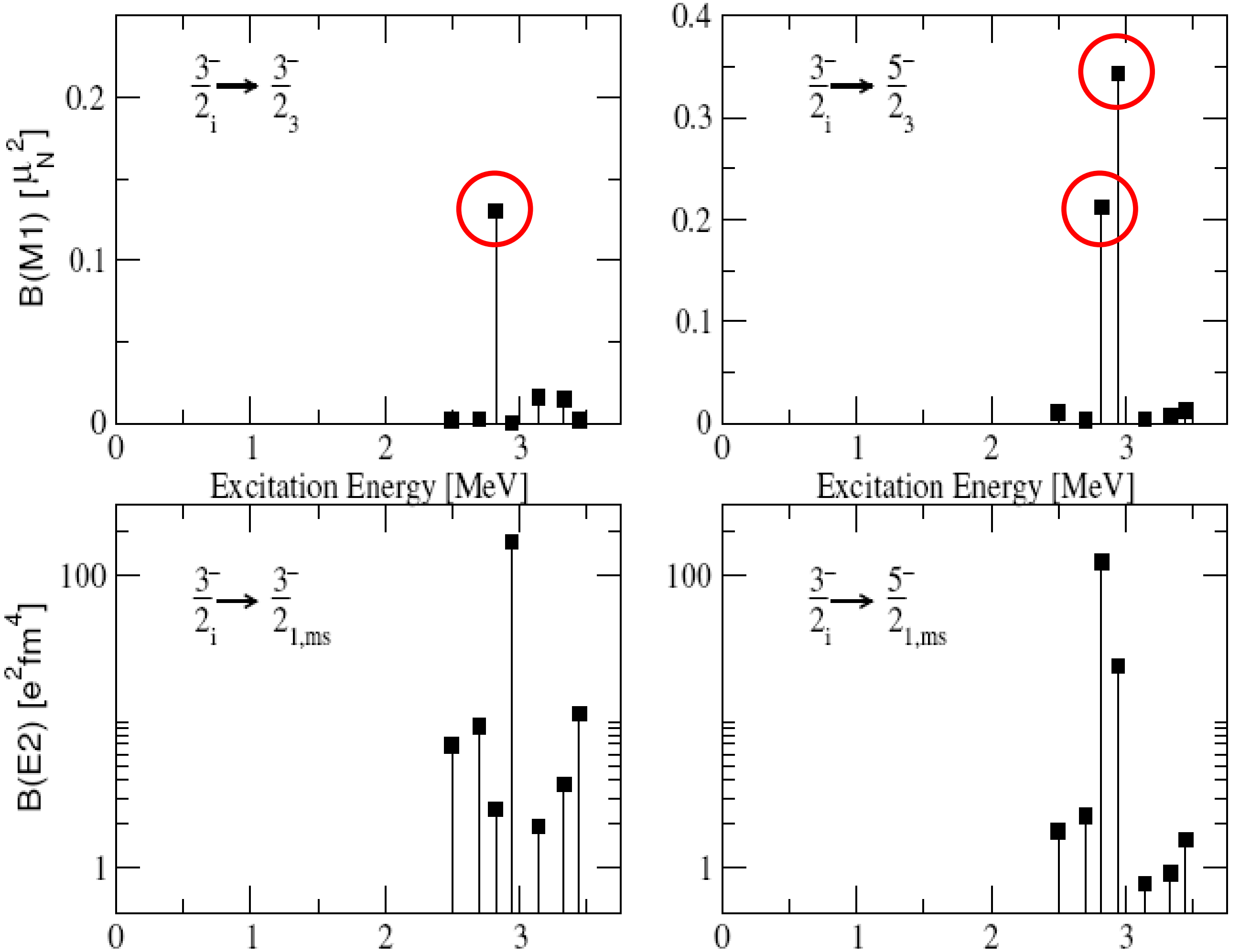
Two-Phonon MS States in ^{93}Nb

- Much more complicated situation: e.g., $\frac{3}{2}^-_{2,ms}$ **two** two-phonon states



Two-Phonon MS States in ^{93}Nb

- Much more complicated situation: e.g., $\frac{3}{2}^-_{2,ms}$ **two** two-phonon states

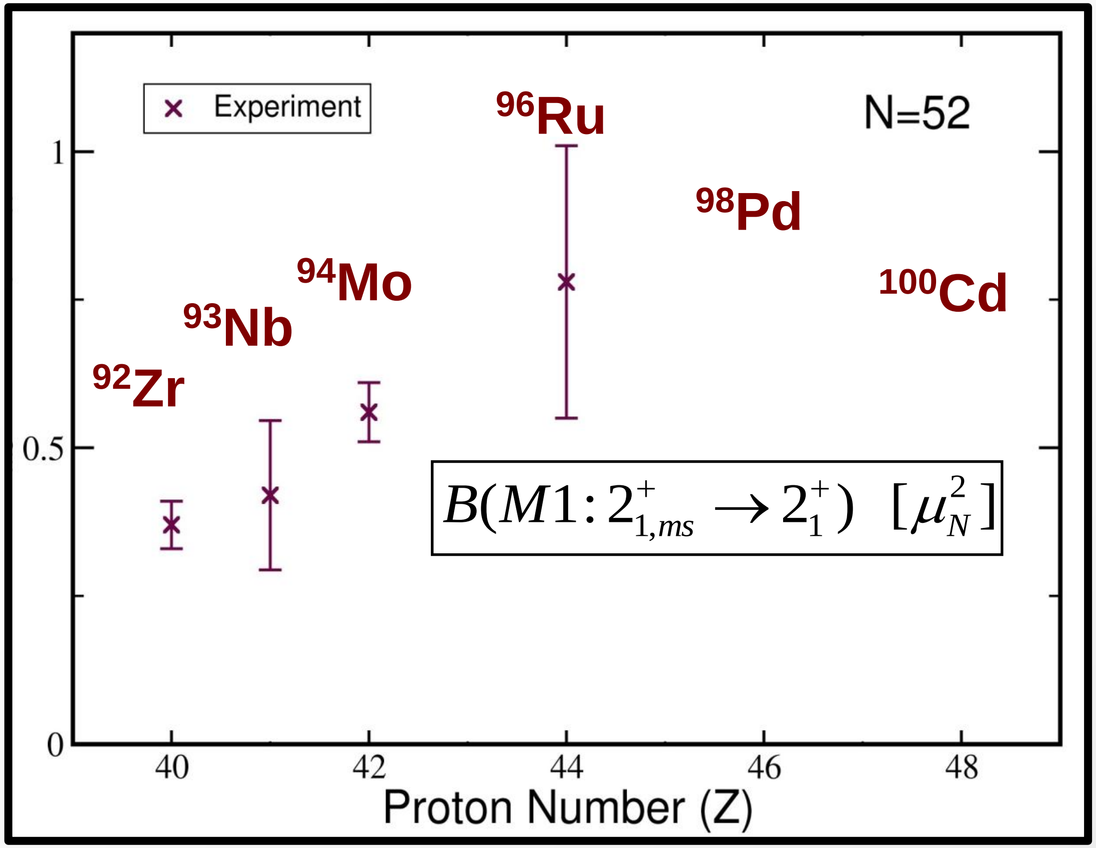


- Two candidates from M1 transition
- Confirmed by E2 transitions
- Identified and predicted properties of two-phonon MSSs in ^{93}Nb:

$$\frac{1}{2}^-_{II,\,ms} \quad \frac{3}{2}^-_{II,\,ms}$$

$$\frac{5}{2}^-_{II,\,ms} \quad \frac{7}{2}^-_{II,\,ms}$$

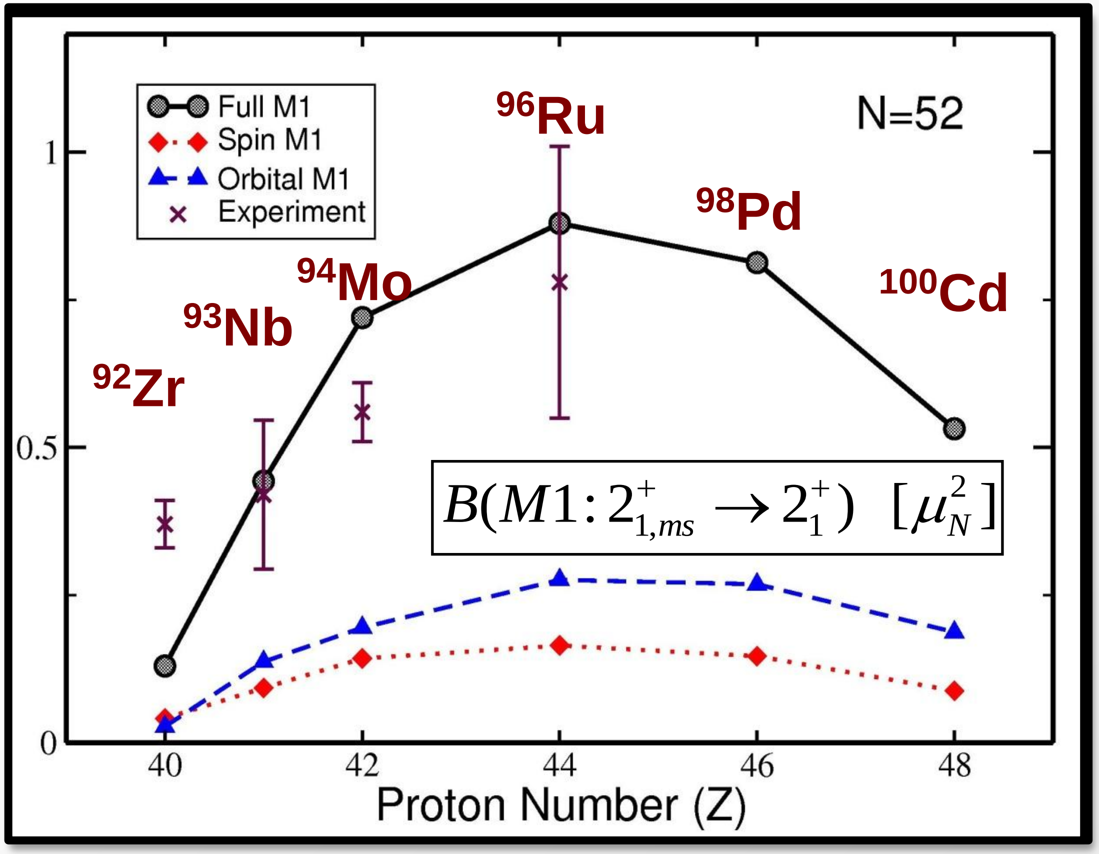
Evolution of Key Signatures of MS



How do MS structures evolve towards Z=50 shell closure?

Predict evolution of MS properties in experimentally-unstudied nuclei...

Evolution of Key Signatures of MS



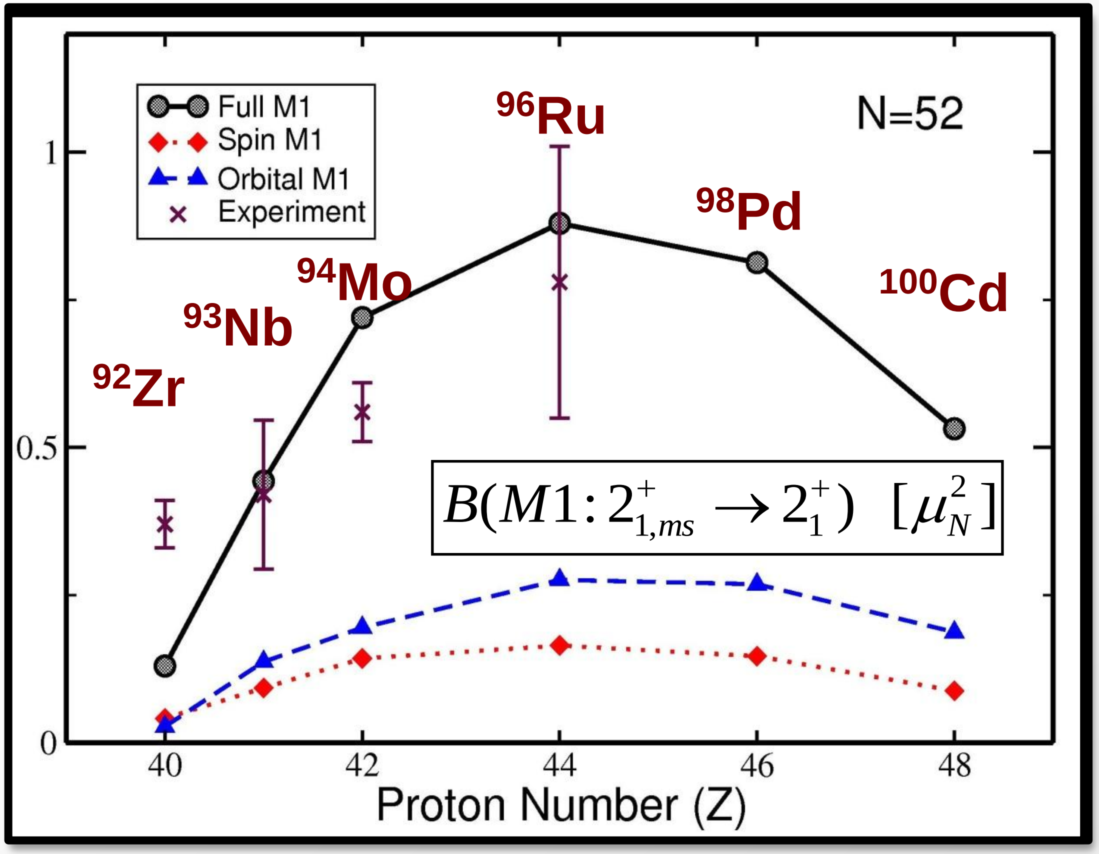
How do MS structures evolve towards Z=50 shell closure?

Predict evolution of MS properties in experimentally-unstudied nuclei...

Qualitative agreement with available data: parabolic behavior peaks at mid-shell

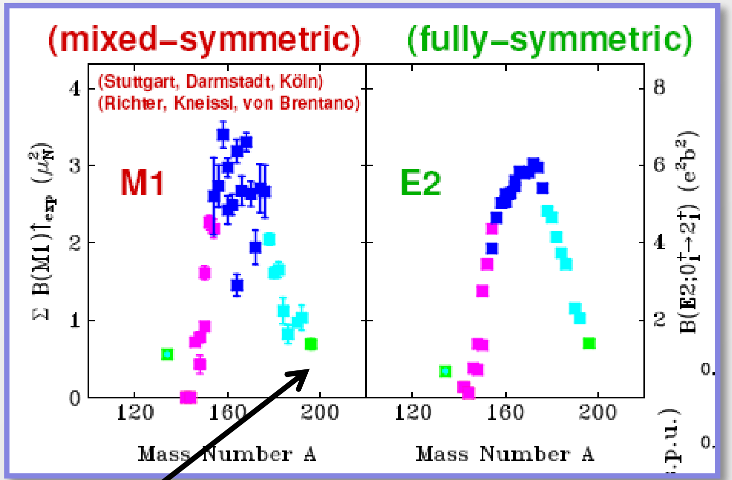
JDH, Pietralla, Kuo, Holt, and Rainovski, Phys. Rev. C **76**, 034326 (2007).

Evolution of Key Signatures of MS



How do MS structures evolve towards Z=50 shell closure?

Predict evolution of MS properties in experimentally-unstudied nuclei...



Pietralla et al., PRC (1998).

Qualitative agreement with available data: parabolic behavior peaks at mid-shell

Collectivity strongest at mid-shell? Nothing new

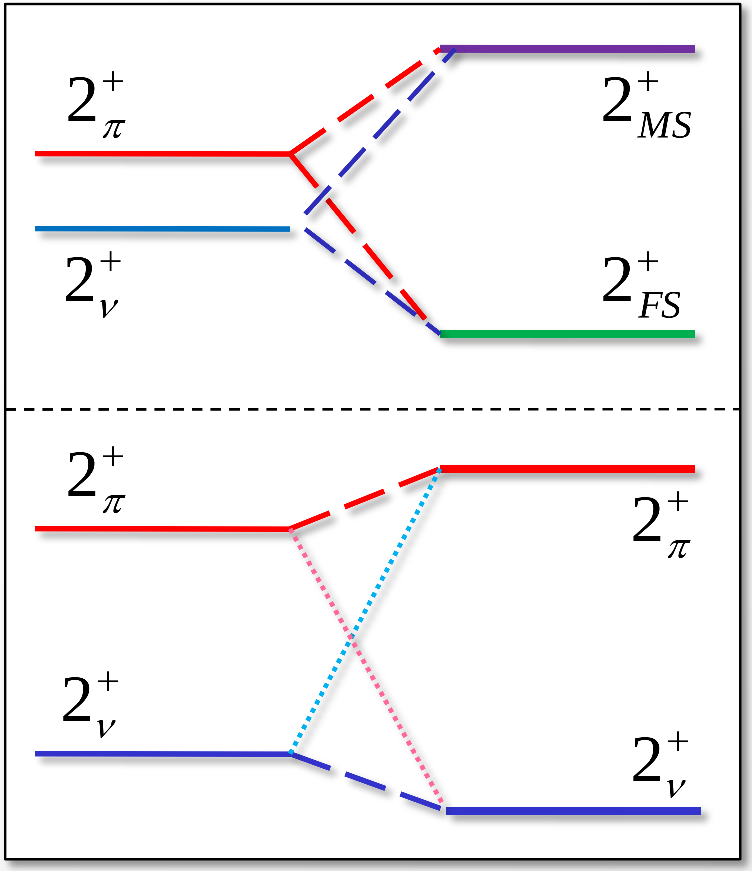
What else can we learn? Why does it happen in this region?

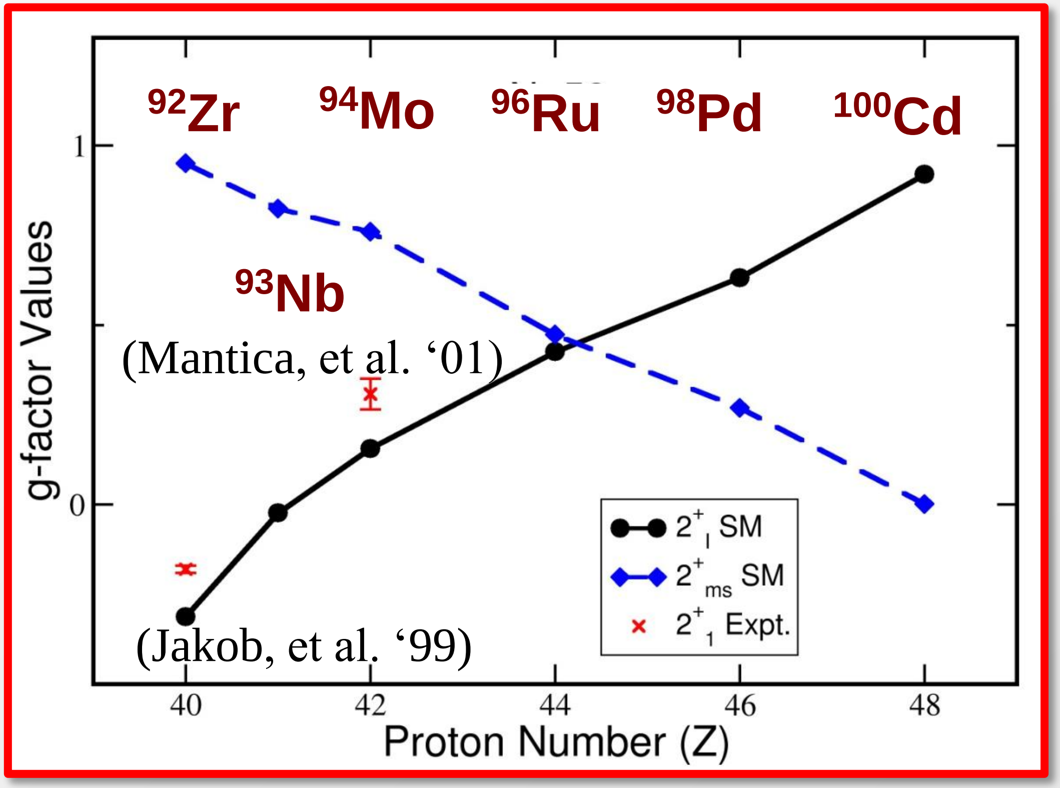
Revealing p/n character: g factors

Configuration mixing:

Energy of p/n excitations crucial

g-factors: sensitive to p/n content





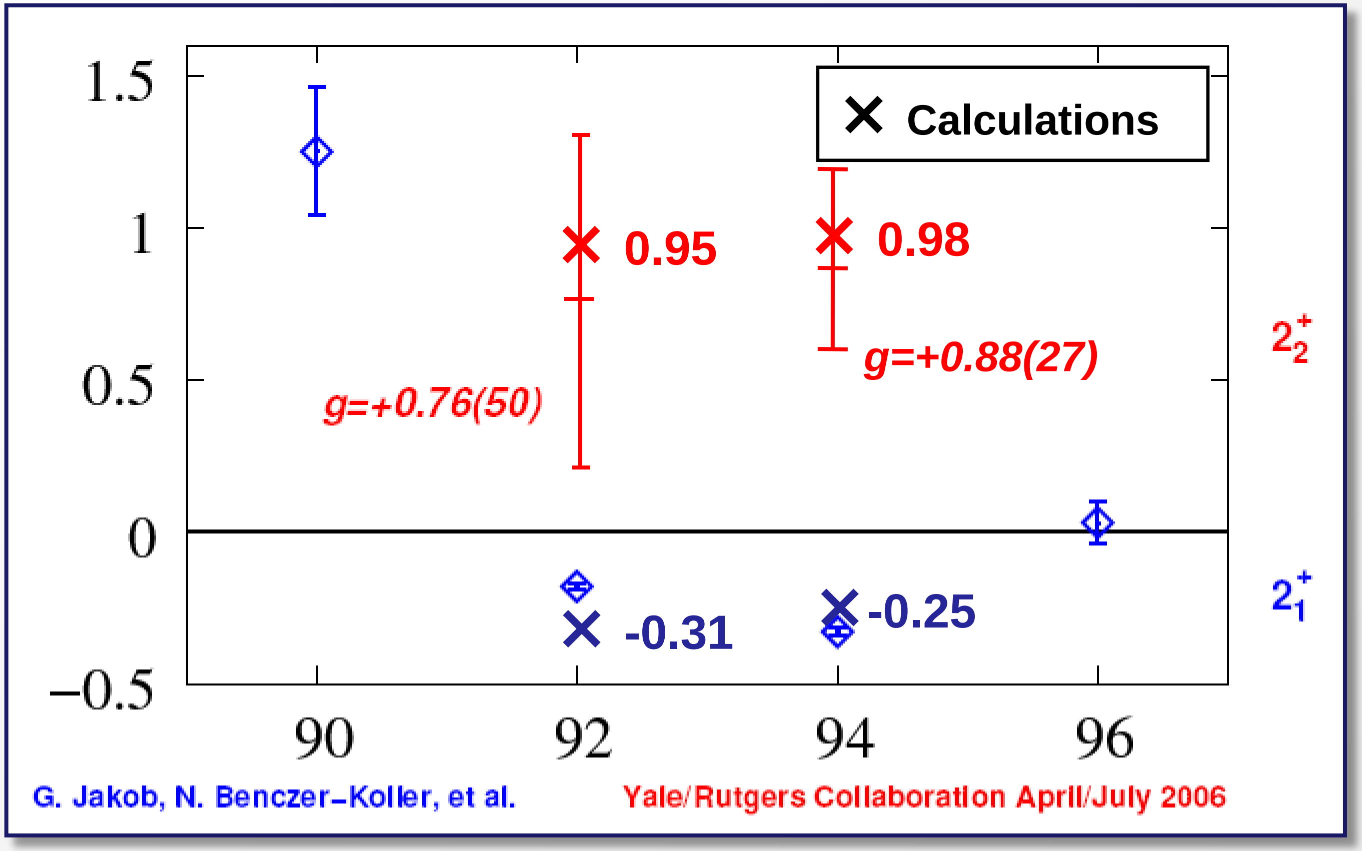
Can we reveal p/n content of the states we're interested in?

- Shell closures: dissimilar p/n content
- Mid-shell: nearly identical (≈ Z/A)
  ⇒ "purest"

g factor Measurements in Zr Isotopes

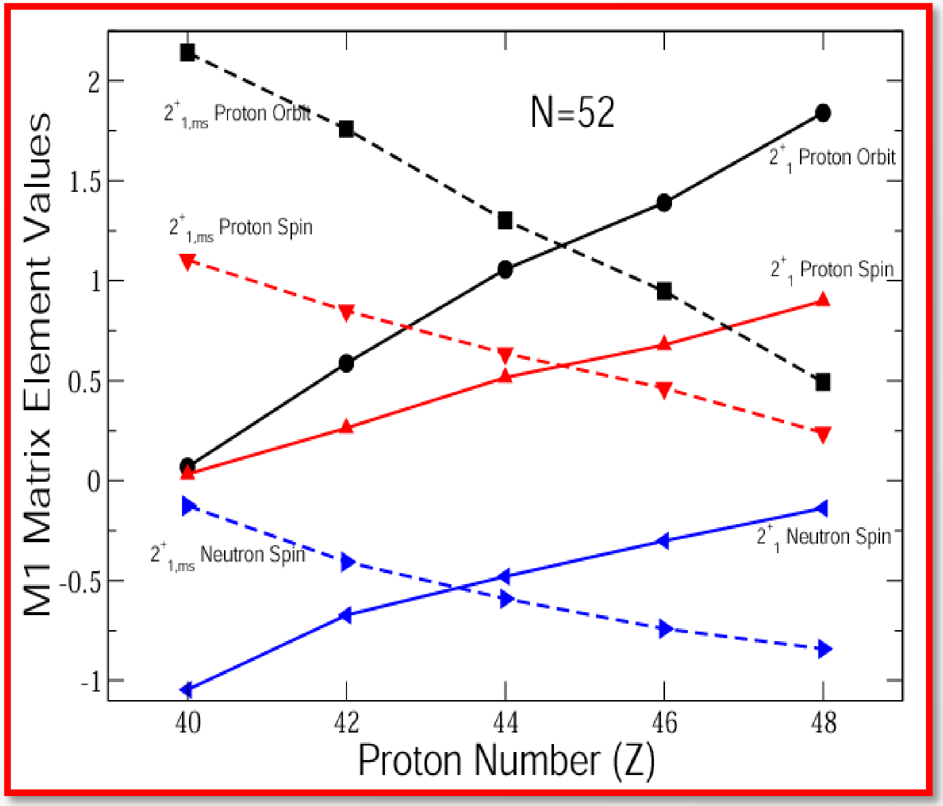
Can this predicted *g* factor trend be seen experimentally?

Compare with **first measurements of magnetic moments of MSSs**



M1 Matrix Elements and SM Wavefunctions

Components of *M1* matrix elements:



Nuc.	SM Wfs	$2^+{}_1$	$2^+{}_{1,ms}$
^{92}Zr	$\|2^+_\nu\rangle$	0.462	-0.129
	$\|2^+_\pi\rangle$	0.078	0.725
^{94}Mo	$\|2^+_\nu\rangle$	0.682	-0.461
	$\|2^+_\pi\rangle$	0.426	0.652
^{96}Ru	$\|2^+_\nu\rangle$	0.586	-0.584
	$\|2^+_\pi\rangle$	0.512	0.548
^{98}Pd	$\|2^+_\nu\rangle$	0.510	-0.681
	$\|2^+_\pi\rangle$	0.576	0.448
^{100}Cd	$\|2^+_\nu\rangle$	0.376	-0.787
	$\|2^+_\pi\rangle$	0.638	0.305

Evolution driven by orbital proton part

Approximations ~60%-70% of total wf

Show clear evolution in p/n character

Mechanism for Evolution of MS

- Wavefunctions can be approximated in terms of fractional-filling:

$$\left|2_1^+\right\rangle \approx \sqrt{f}\left|2_\pi^+\right\rangle + \sqrt{1-f}\left|2_\nu^+\right\rangle$$

$$\left|2_{1,ms}^+\right\rangle \approx \sqrt{1-f}\left|2_\pi^+\right\rangle - \sqrt{f}\left|2_\nu^+\right\rangle$$

$$f = (Z-40)/10$$

- Observables then expressed simply:

$$g\left(2_1^+\right) = \sqrt{\frac{2\pi}{45}}\left[\mu_\nu + f\left(\mu_\pi - \mu_\nu\right)\right]$$

$$g\left(2_{1,ms}^+\right) = \sqrt{\frac{2\pi}{45}}\left[\mu_\pi - f\left(\mu_\pi - \mu_\nu\right)\right]$$

$$B\left(M1; 2_{1,ms}^+ \rightarrow 2_1^+\right) = \frac{1}{5} f\left(1-f\right)\left(\mu_\pi - \mu_\nu\right)^2$$

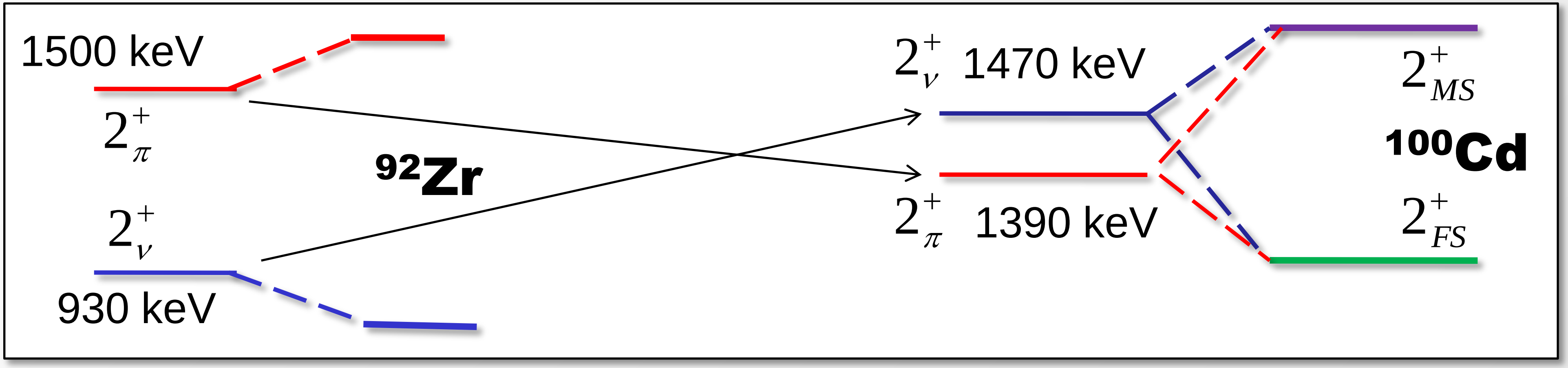
$$\mu_\rho = \left\langle 2_\rho^+ \left\| M1 \right\| 2_\rho^+ \right\rangle$$

$$\mu_\pi > 0, \quad \mu_\nu < 0$$

- Immediately see behavior of *M1* strength and *g* factors

Microscopic Restoration of p/n Symmetry

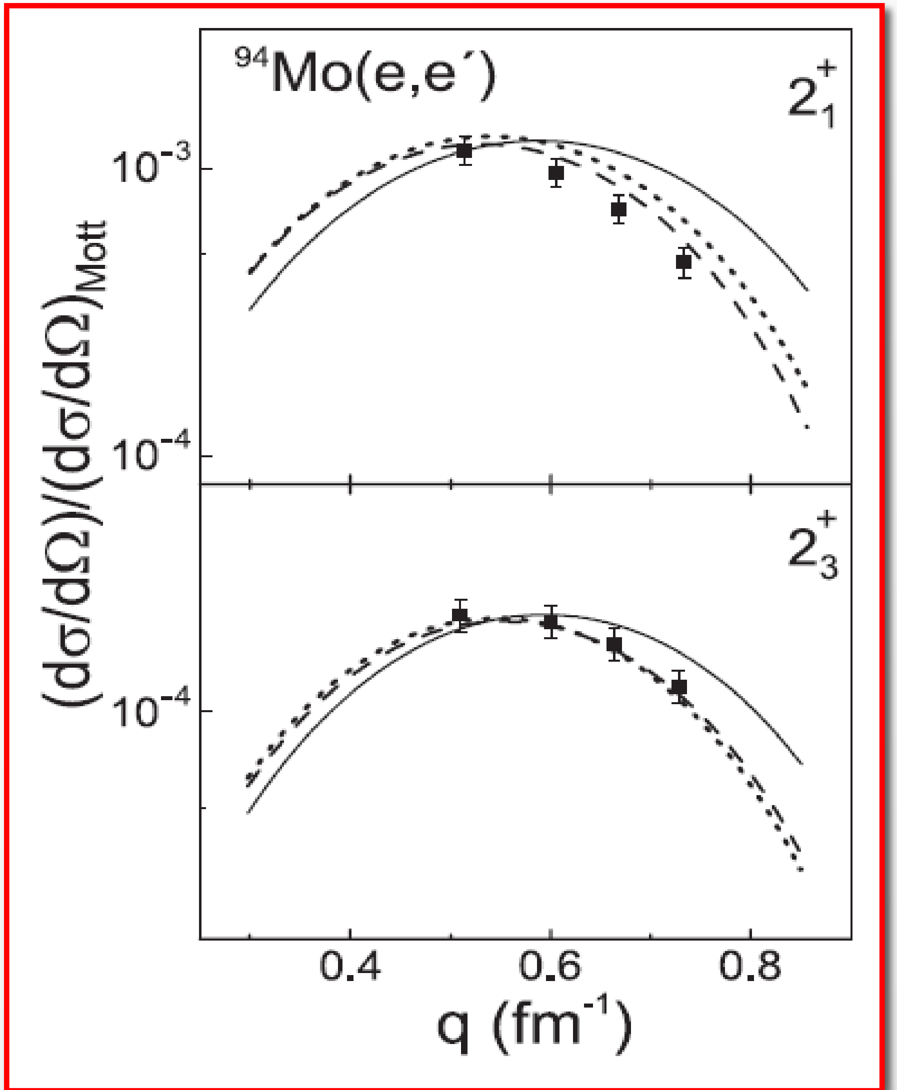
- Can this evolution be explained microscopically?
- Energies of **2^+_π**, **2^+_ν** excitations vary with addition of protons (fill $g_{9/2}$):
  - 2^+_1 energies of N=50 isotones indicates evolution of **2^+_π** energy
  - 2^+_1 energies of ^{92}Sr and ^{102}Sn indicate **2^+_ν** energies



- Degeneracy expected near mid-shell: "purest" collective excitations
- Microscopic mechanism which explains existence, formation, and evolutionary properties of MSSs in this nuclear region

^{94}Mo(e,e´) Form Factors vs. Theory

Electron scattering cross sections: **differential** data

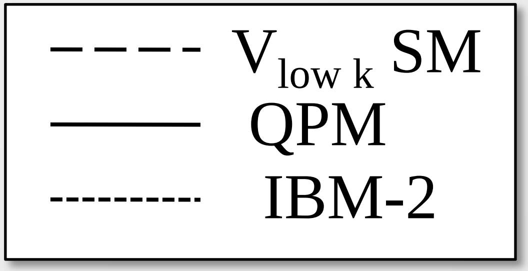


S-DALINAC (Darmstadt) for (e,e')
iThemba Labs (S. Africa) for (p,p')

Provides new test of phonon character of 2^+_{ms}

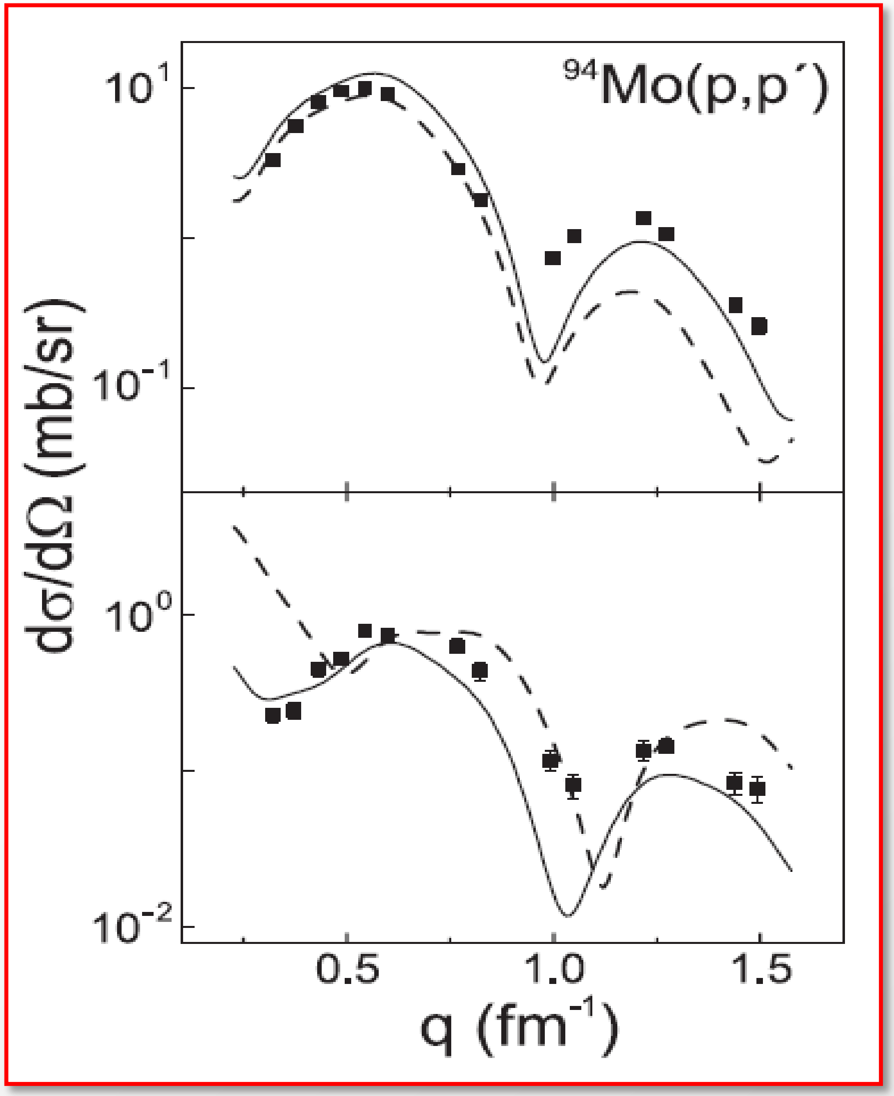
Calculated cross sections from DWBA

SM ***$V_{low\ k}$*** reasonably predicted measured cross-sections.



^{94}Mo(e,e´) Form Factors vs. Theory

Electron scattering cross sections: **differential** data



S-DALINAC (Darmstadt) for (e,e’)
iThemba Labs (S. Africa) for (p,p’)

Provides new test of phonon character of 2^+_{ms}

Calculated cross sections from DWBA

SM $V_{low\ k}$ reasonably predicted measured cross-sections.

- - - -	$V_{low\ k}$ SM
——	QPM

Conclusions

- Use microscopic low-momentum $V_{\mathrm{low}\,k}$ for nuclear structure in nearly-spherical nuclei: focus on MSSs in vibrational nuclei
- First description of MS in odd-mass, nearly spherical ^{93}Nb
- With experiment, showed first evidence for existence in ^{93}Nb
- Microscopic mechanism addressing evolution of MSS experimental signatures
- Predicted electron/proton scattering cross sections in ^{94}Mo
- Future work:
  - Incorporate missing 3N forces into SM calculations

Collaborators

T.T.S. Kuo
G.E. Brown
J.W. Holt

N. Pietralla
J. N. Orce
V. Werner
N. Benczer-Koller

O. Burda