大規模殻模型計算によるE1応答

E1 responses calculated with large-scale shell-model calculations

原子力機構先端基礎研究センター　宇都野 穣

Yutaka Utsuno

Advanced Science Research Center, Japan Atomic Energy Agency

共同研究者　清水 則孝（東大CNS）

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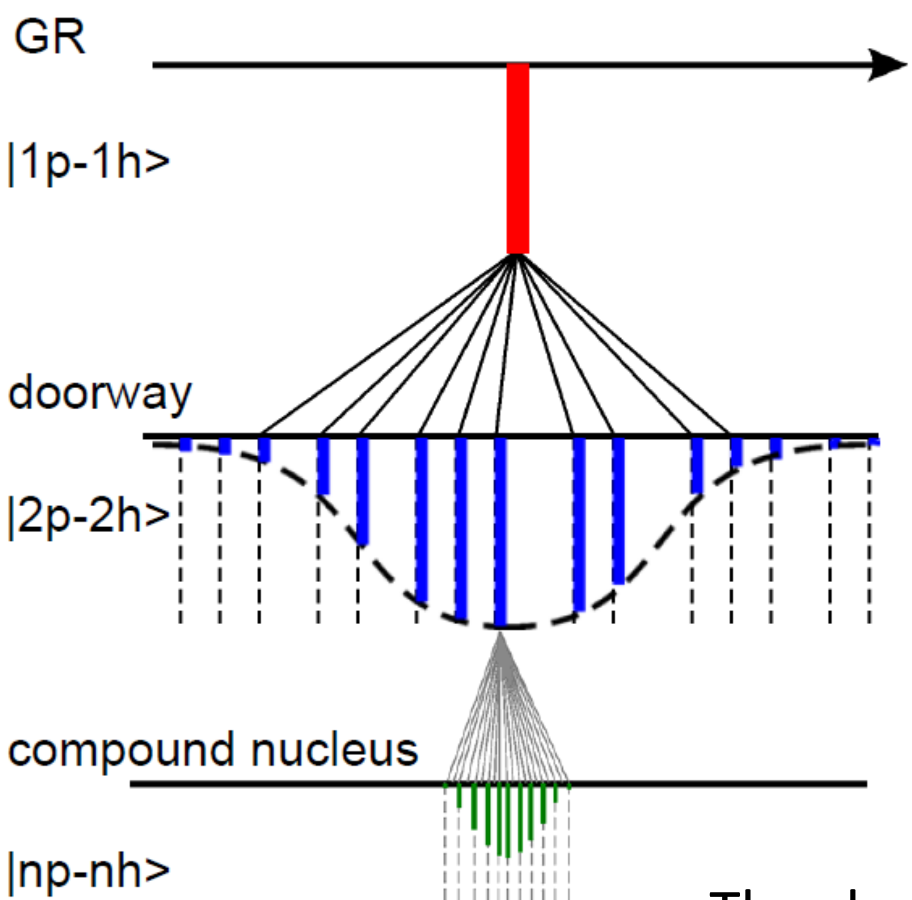
Describing giant resonances



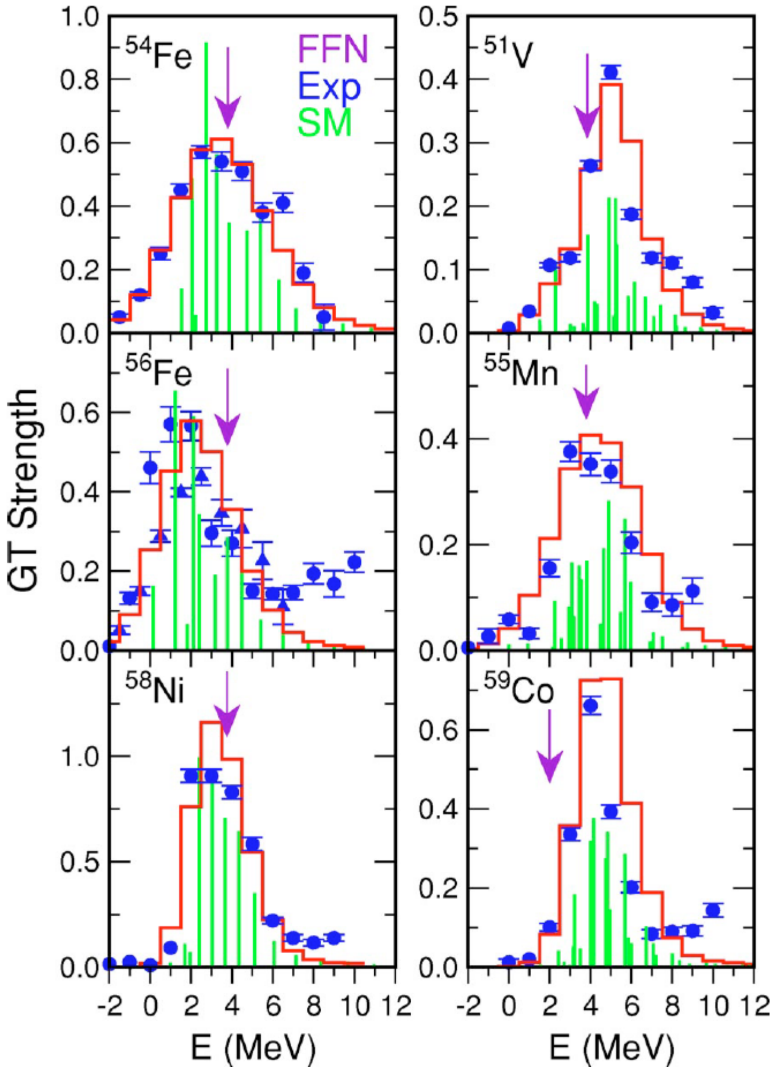
- Requirement for microscopic theory
  - Single-particle space: large enough to satisfy the sum rule
  - Non-collective states: needed to get the damping of giant resonances

→ The shell-model calculation is a good choice from these viewpoints, if the model space is taken to be large.

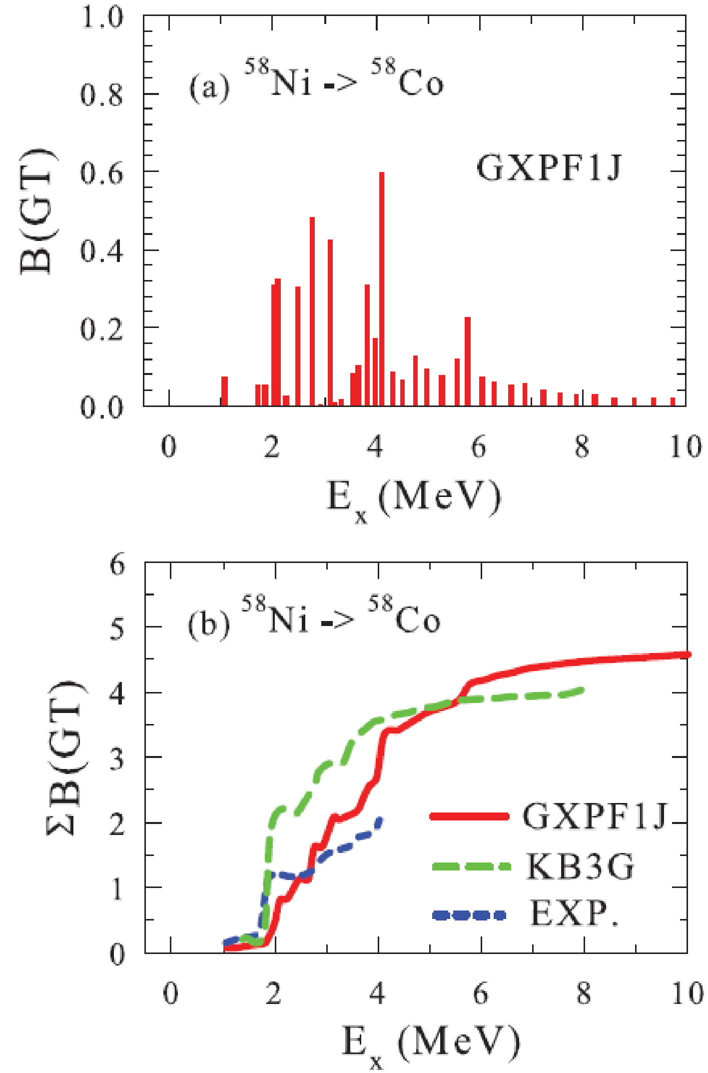
illustrated by A. Richter

Success in M1/GT responses

GT+ distribution (electron capture)

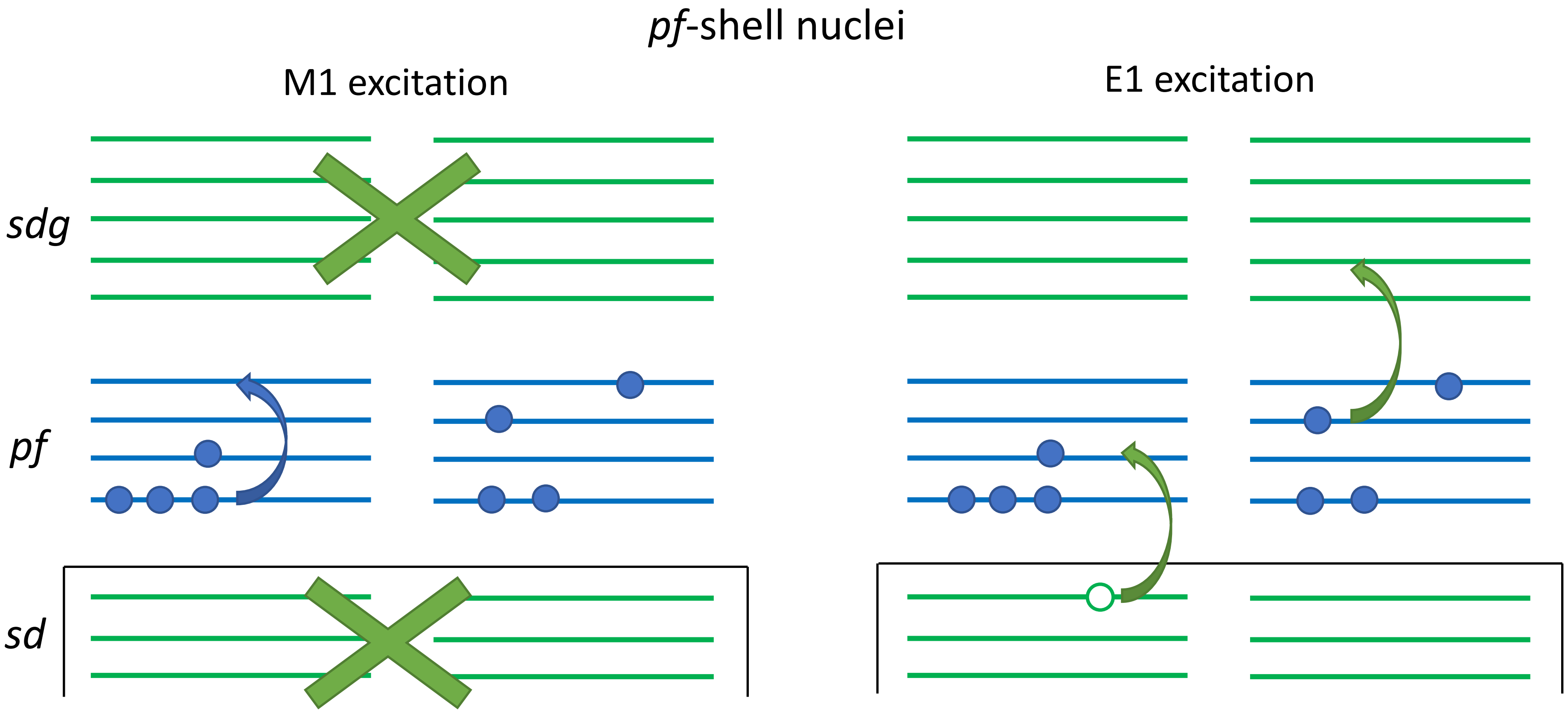


K. Langanke and G. Martínez-Pinedo, Rev. Mod. Phys. 75, 819 (2003).



T. Suzuki et al., Phys. Rev. C 83, 044619 (2011).

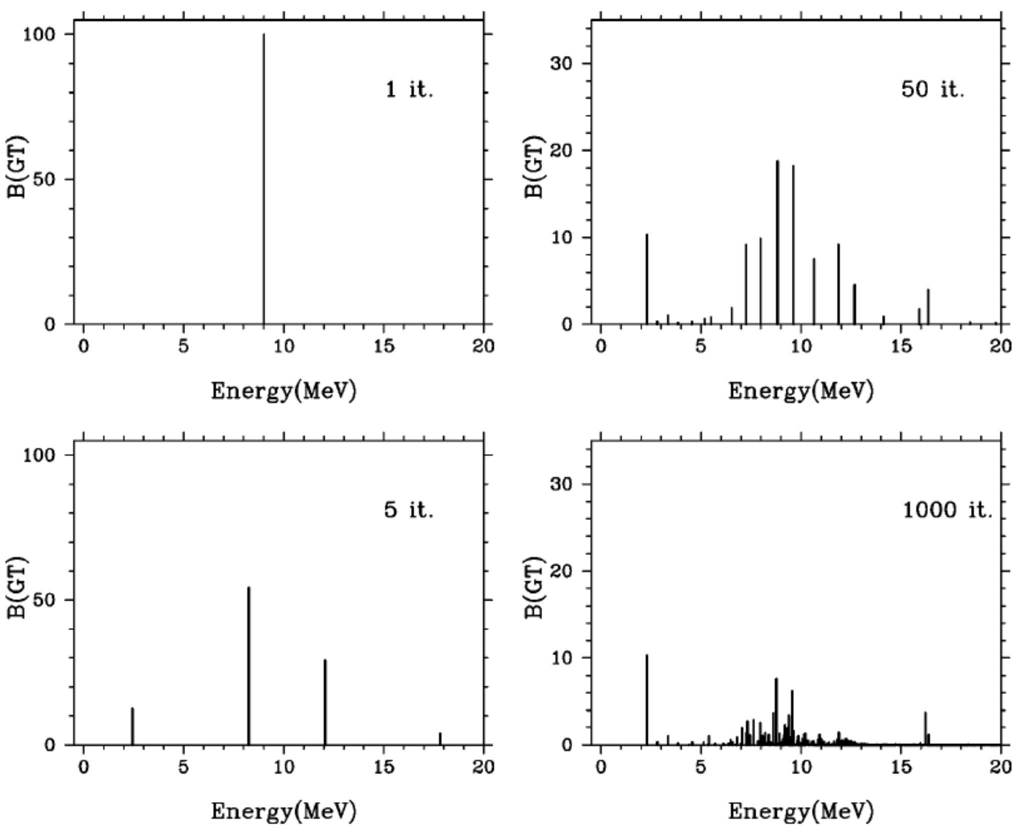
E1 responses: much more demanding task

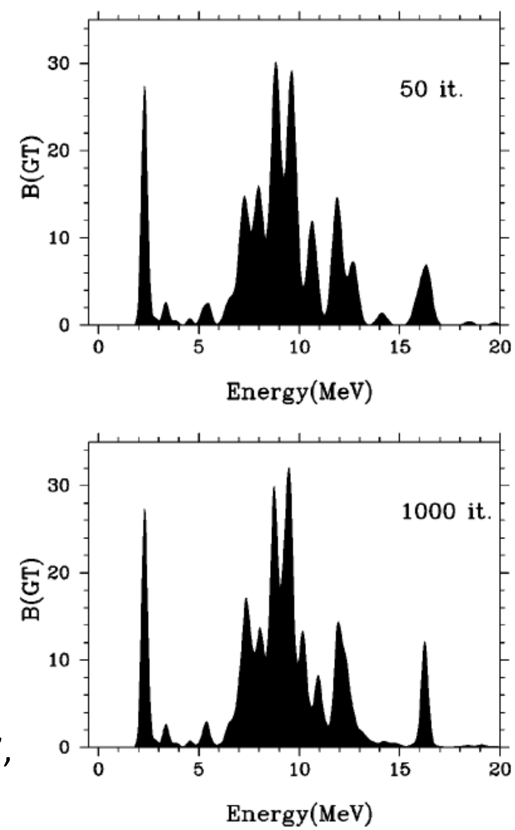


- M-scheme dimension for ^{56}Ni
  - 1^+ in $0\hbar\omega$ space (M1): 1.1×10^{9}
  - 1^- in $1\hbar\omega$ space (E1): 7.1×10^{10}
- Current limit: 10^{10}-10^{11} (for calculating near yrast states)

Some computational aspects

- Lanczos strength function
  - Economical and efficient method to calculate strength distributions
    - Use the initial state $\hat{O}|g.s.\rangle$ and carry out the usual Lanczos iterations
    - Provide the exact $(2n-1)$th moment after *n* iterations

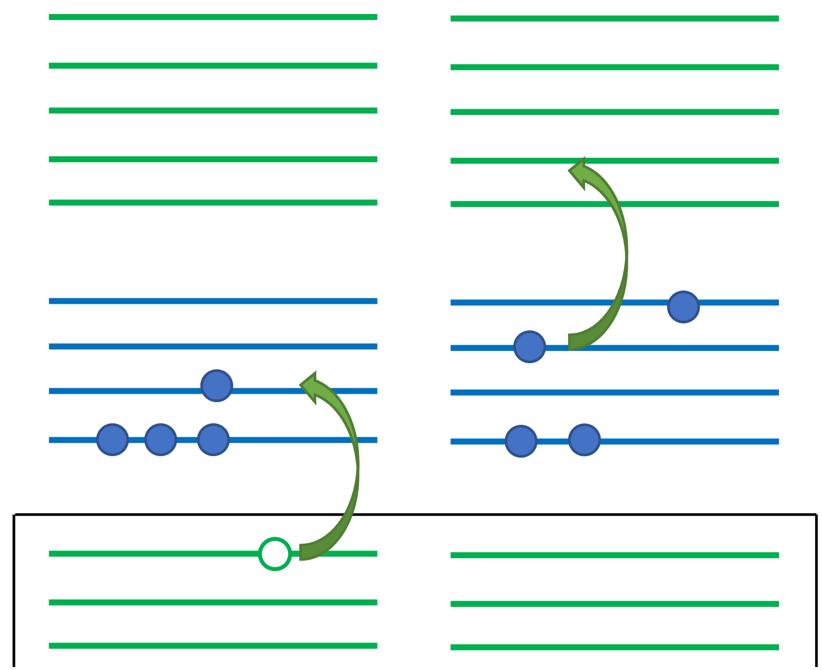




E. Caurier et al., Rev. Mod. Phys. 77, 427 (2005).

Our study on E1 responses

- Target: *pf*-shell nuclei (^{40}Ca to Ni and Zn region)
- Valence shell: *sd-pf-sdg* shell
  - Conserving the B(E1) sum
    - Ground state: $0\hbar\omega$ state
    - 1^- states: $1\hbar\omega$ state
  - Validity checked later

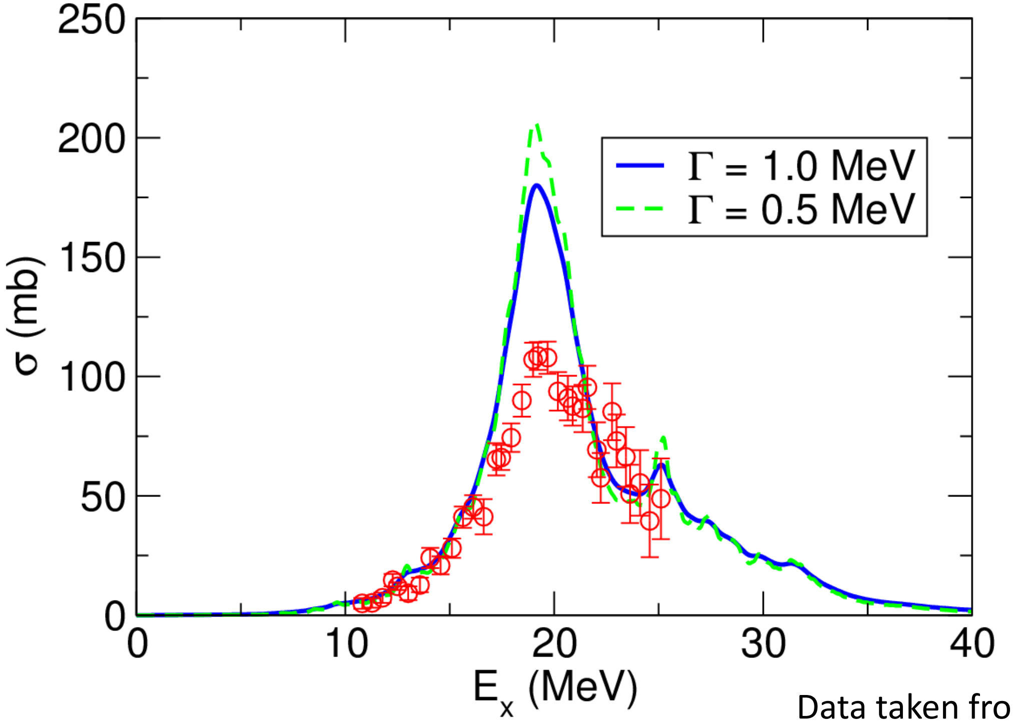


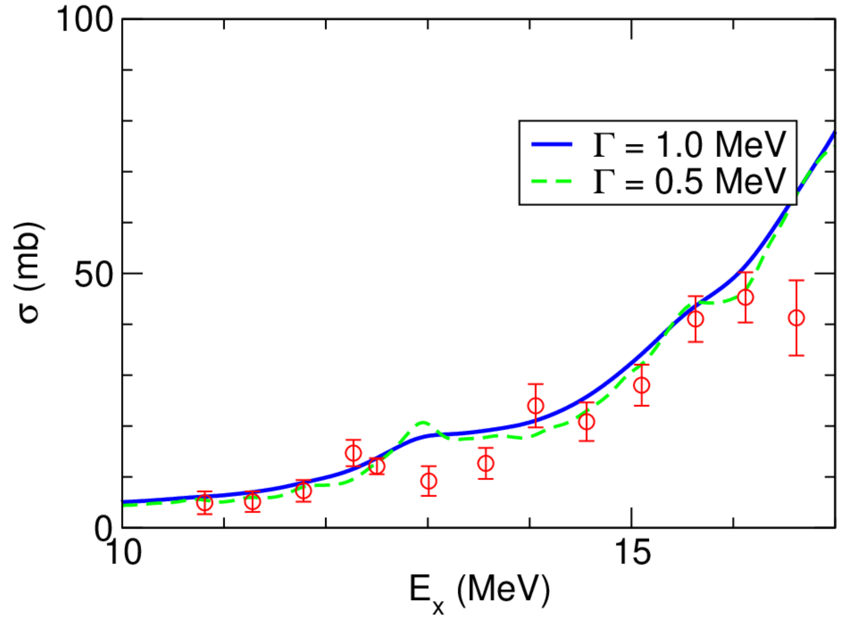
- Effective interaction
  - SDPF-MU extended to *sd-pf-sdg*
  - Empirical (USD+GXPF1B) + phenomenological (V_{MU}: Gaussian central + spin-orbit + tensor)

^{48}Ca: feasibility test

- Why ^{48}Ca?
  - Reliable data available including recent (*p*,*p*') measurement performed at RCNP (J. Birkhan et al., Phys. Rev. Lett. 118, 252501 (2017))
  - Ca isotopes: relatively small shell-model dimension because of no valence protons in the *pf* shell (for g.s.)
    - It is possible to examine the effect of ground-state correlation beyond the $0\hbar\omega$ space.
  - Ground state: well described with the *pf*-shell space
    - Lighter Ca isotopes: considerable particle-hole correlation beyond the Z=N=20 shell gap

Comparison to the data



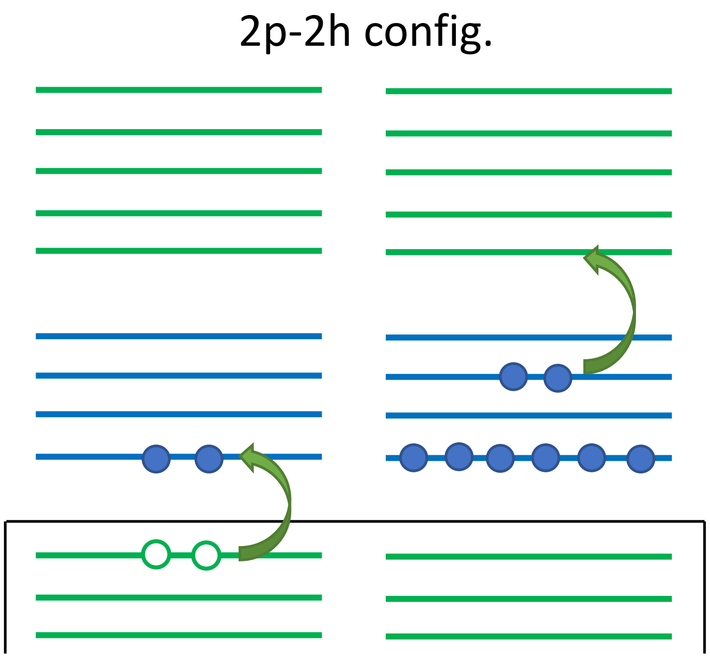


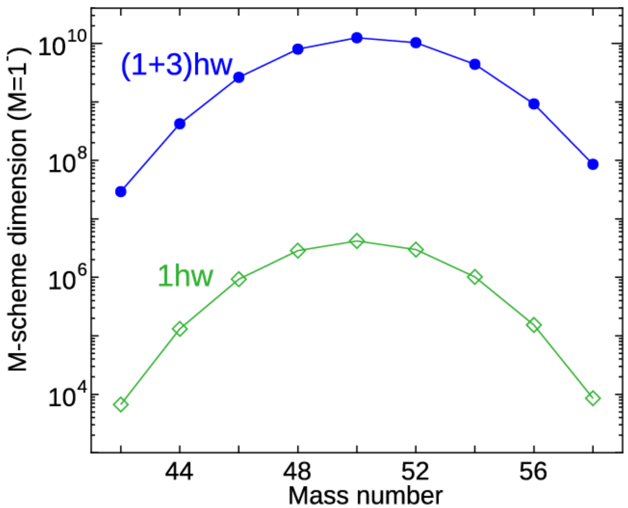
Data taken from CDFE (Russia); http://cdfe.sinp.msu.ru

- Fair agreement with the experimental data
  - GDR peak overestimated
  - Low-energy slope: good
  - Almost no sensitivity to Γ: spreading width caused by the coupling to non-collective states

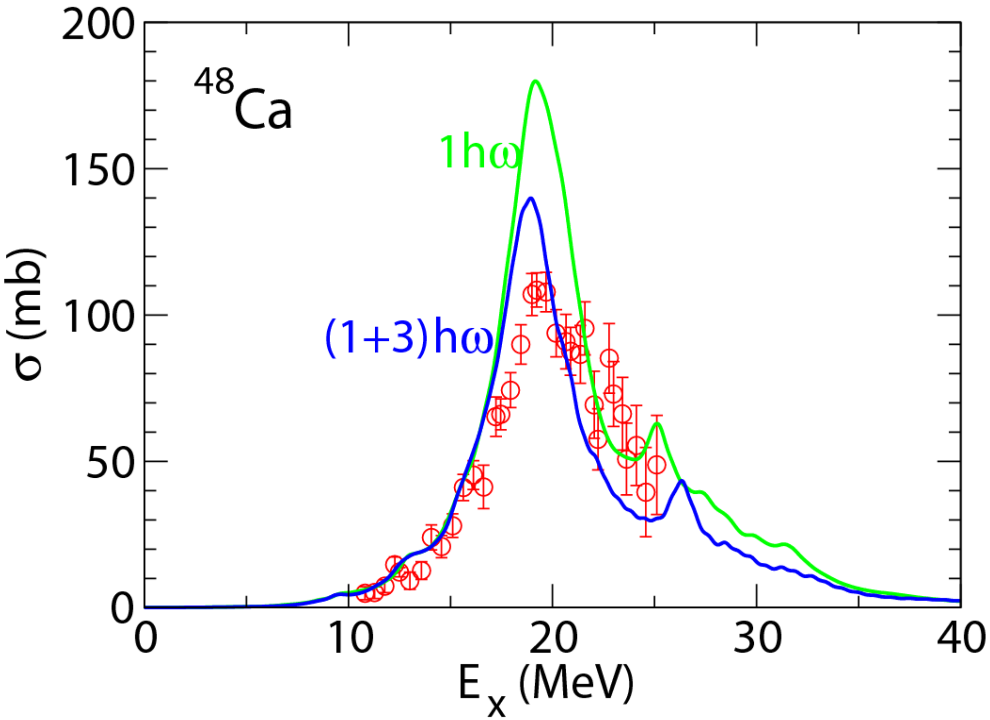
More correlation included

- How about including the 2p-2h excitation across the Z=N=20 shell?
- Same valence shell, but including 2p-2h excitation: $(0+2)\hbar\omega$ ground state
- 1^- states: up to 3p-3h excitation from the lowest configuration: $(1+3)\hbar\omega$ 1^- states





$1\hbar\omega$ vs. $(1+3)\hbar\omega$ calculation



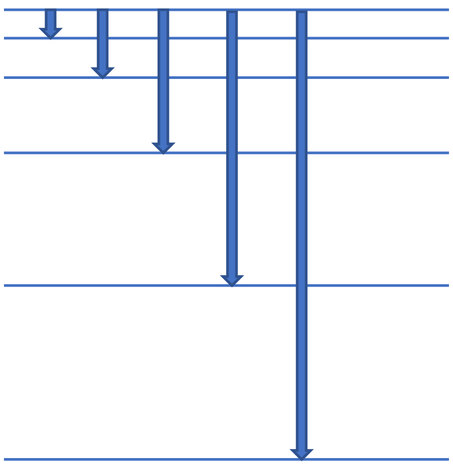
$$\sum_k B(E1; g.s. \to 1_k^-) \quad (e^2 fm^2)$$

g.s.	1⁻	sum
$0\hbar\omega$	$1\hbar\omega$ (= full space)	16.5
$(0+2)\hbar\omega$	$(1+3)\hbar\omega$ in *sd-pf-sdg*	13.6
$(0+2)\hbar\omega$	full space	13.9

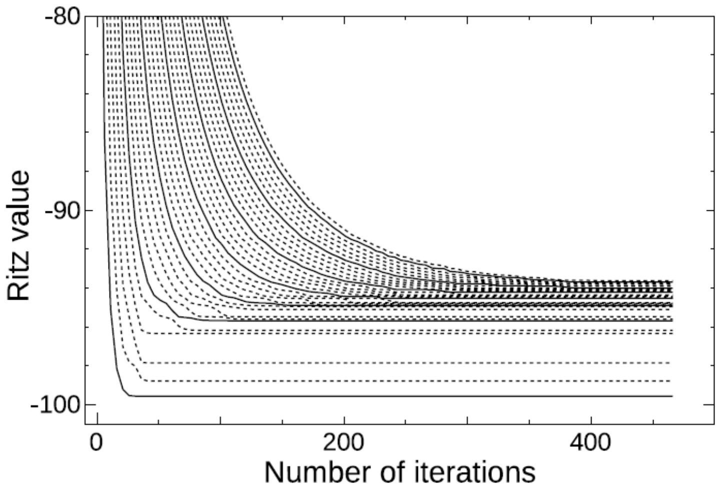
- Decrease of the B(E1) sum
  - GDR peak lowered
- Low-energy tail of GDR: almost unchanged

Towards describing decay process

- *In principle*, any gamma decays can be calculated with the shell model, whether the initial state is the ground state or an excited state.
- *In practice*, calculating eigenstates at high excitation energy is not easy, because the eigenstates are converged in the order of eigenenergy.
- Our first step: check the Brink hypothesis for low-lying levels, which is usually assumed in various analyses.



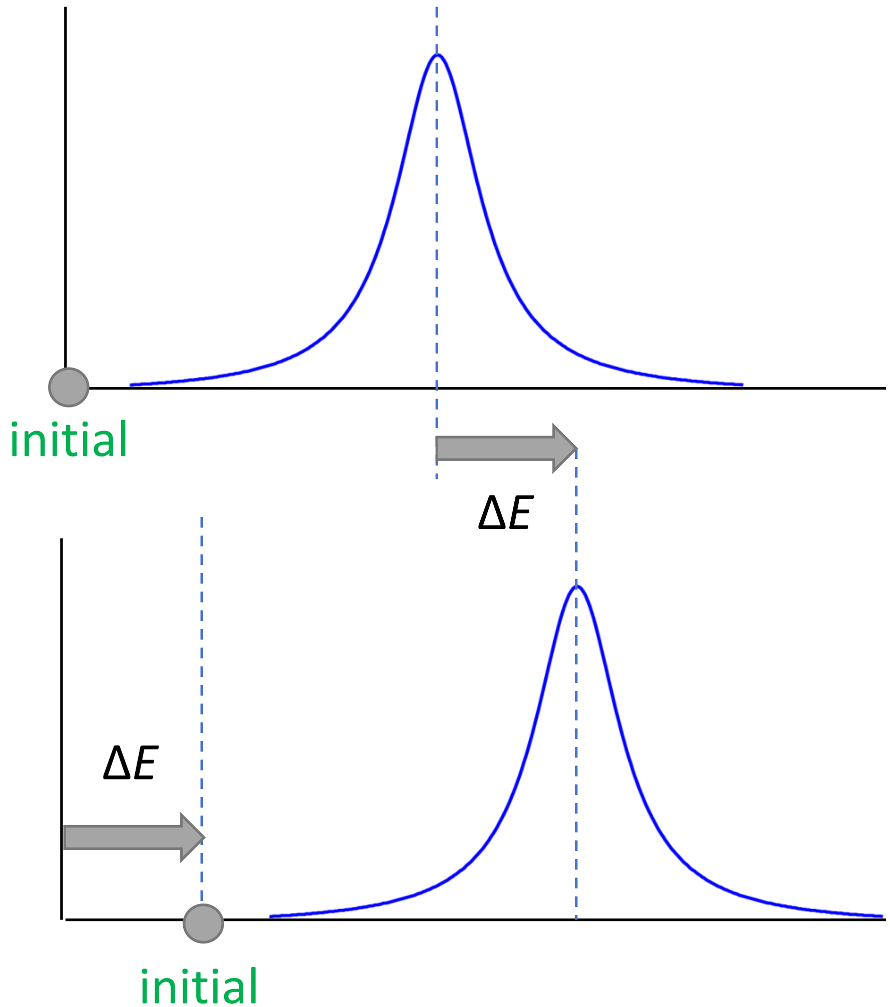
typical convergence pattern



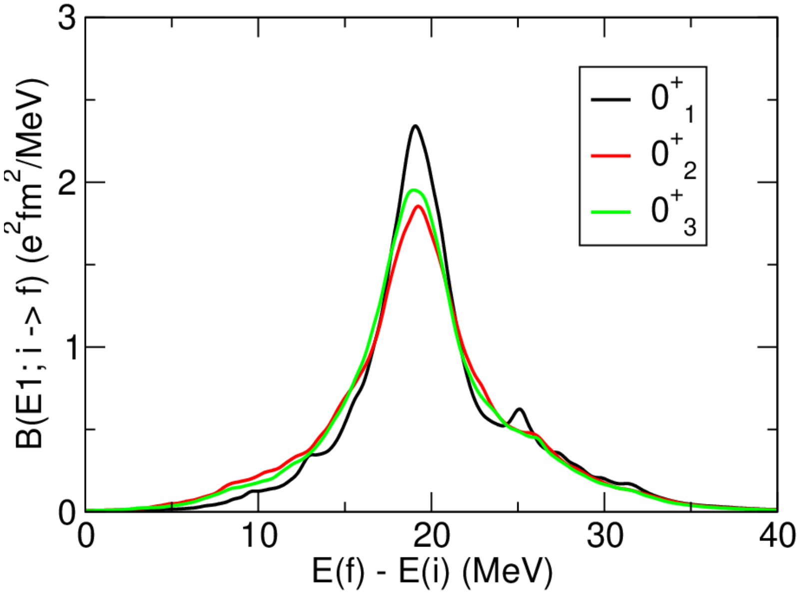
N. Shimizu et al., Comput. Phys. Commun. 244, 372 (2019)

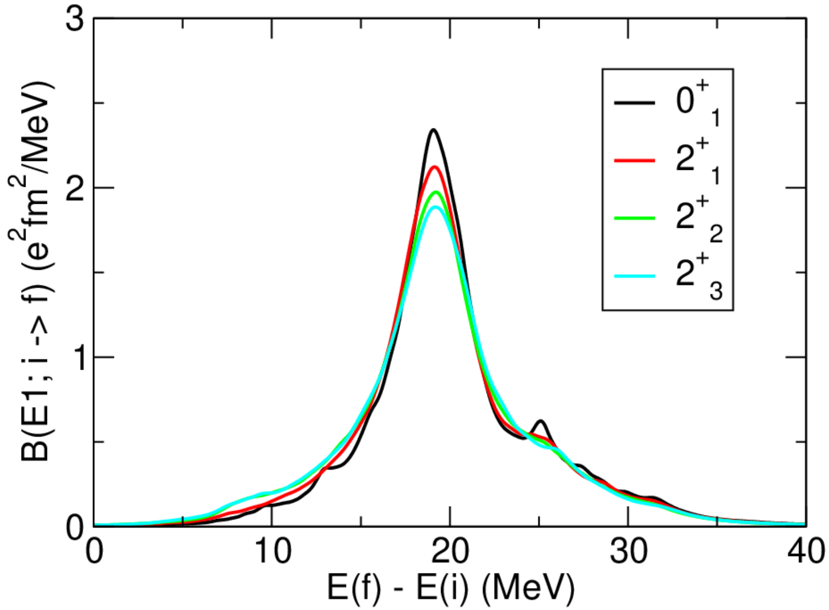
Brink hypothesis

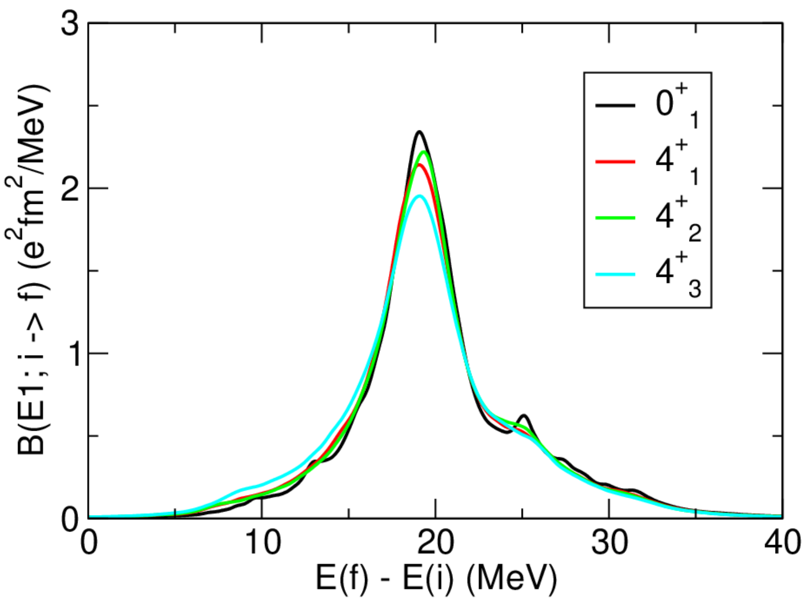
- E1 strength function for excited states: same form as that of the ground state



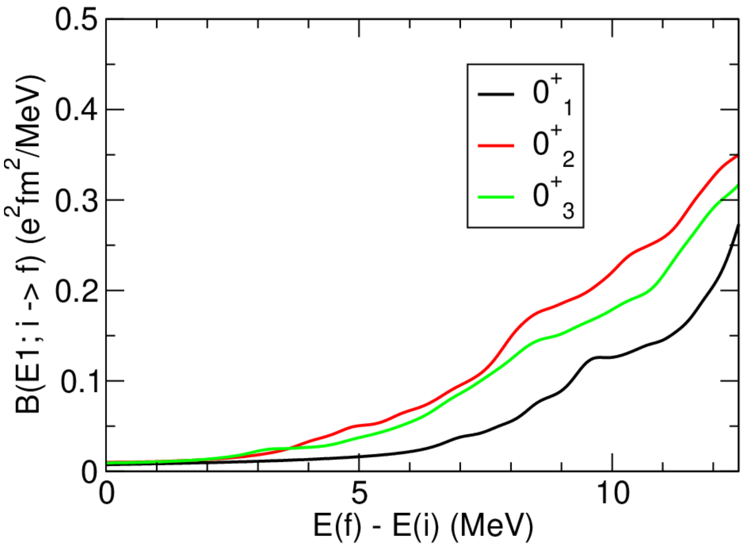
^{48}Ca: GDR region

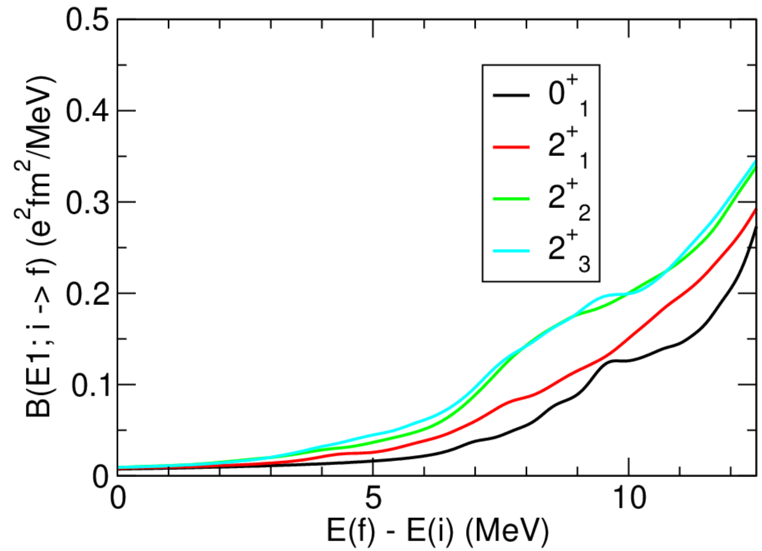


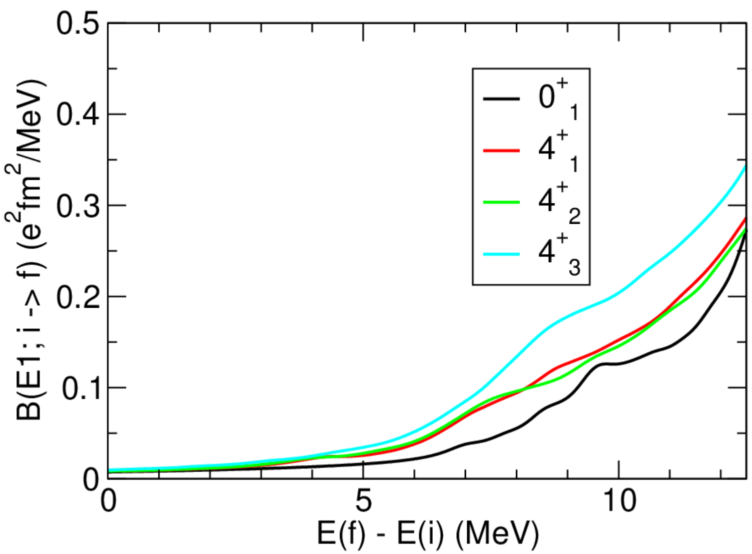




^{48}Ca: focusing on low-energy transitions

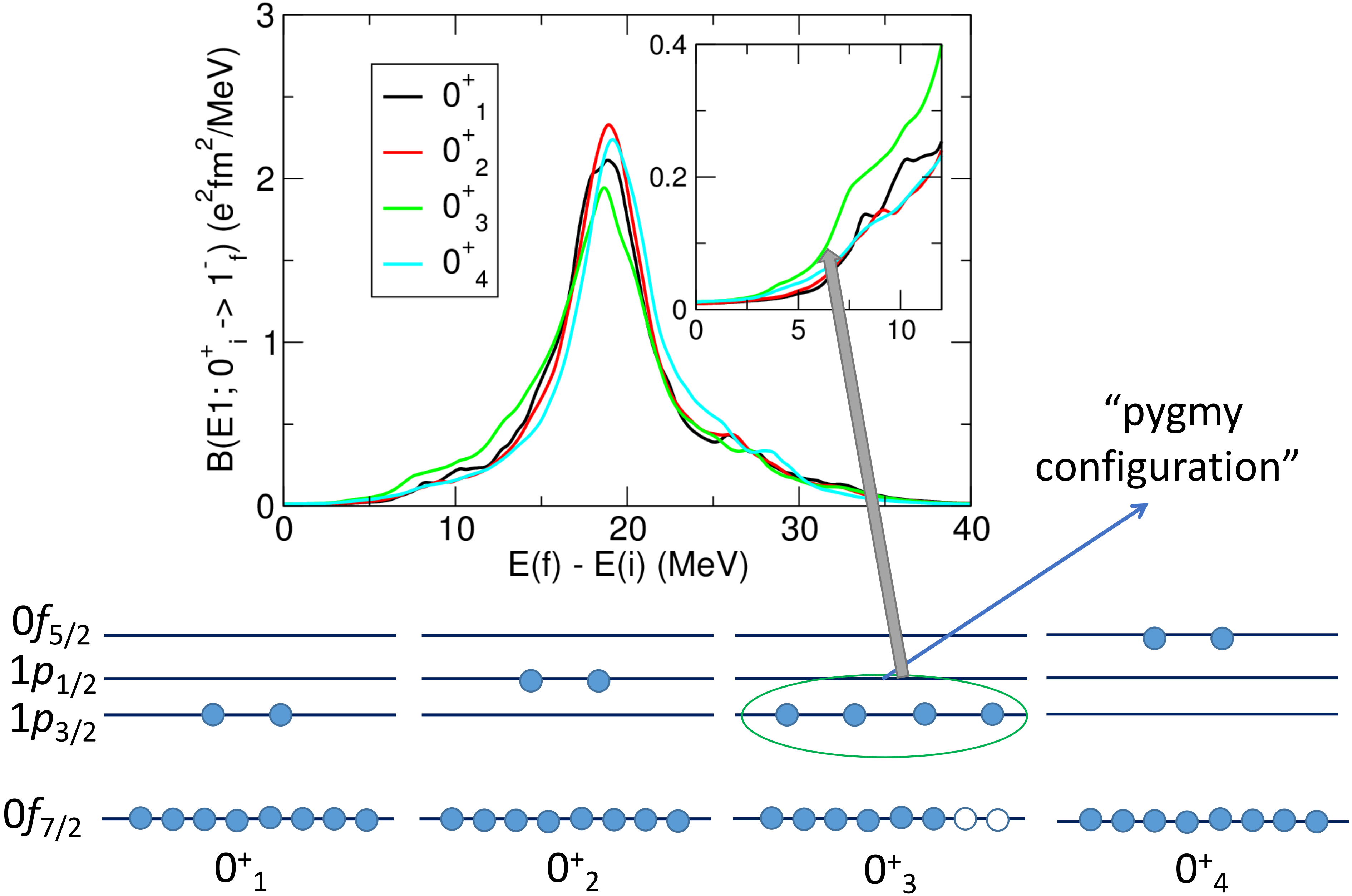




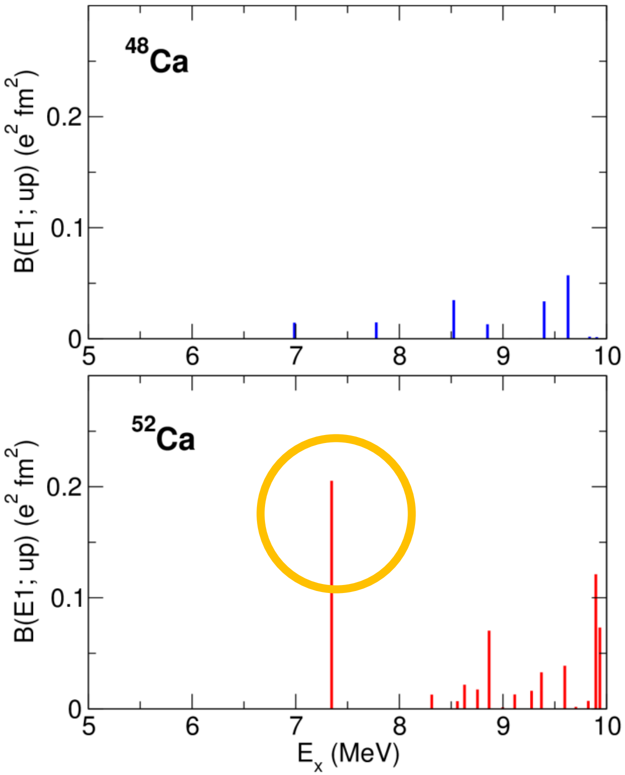


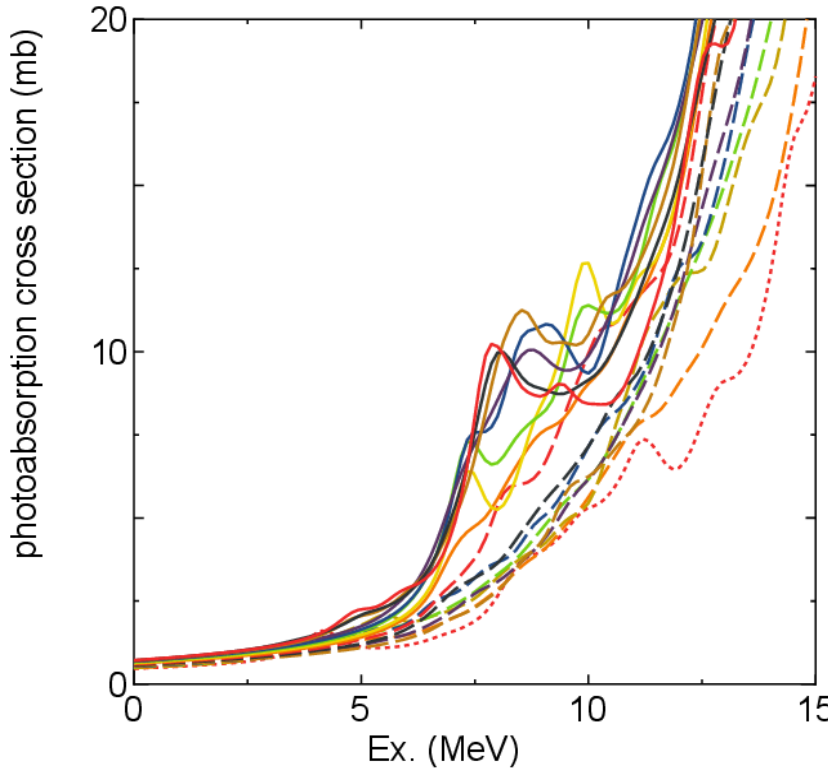
excitation-energy dependence?

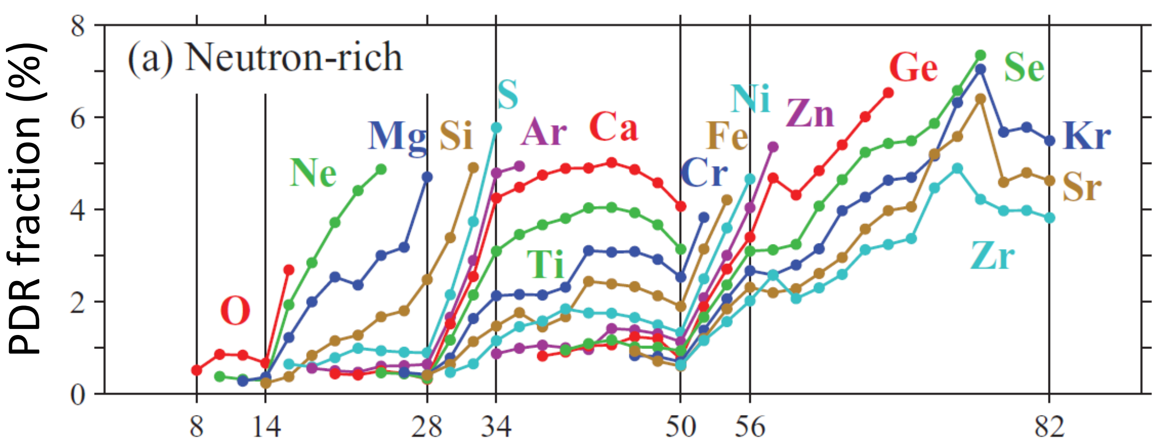
^{50}Ca: suggesting configuration dependence



Development of pygmy dipole resonance





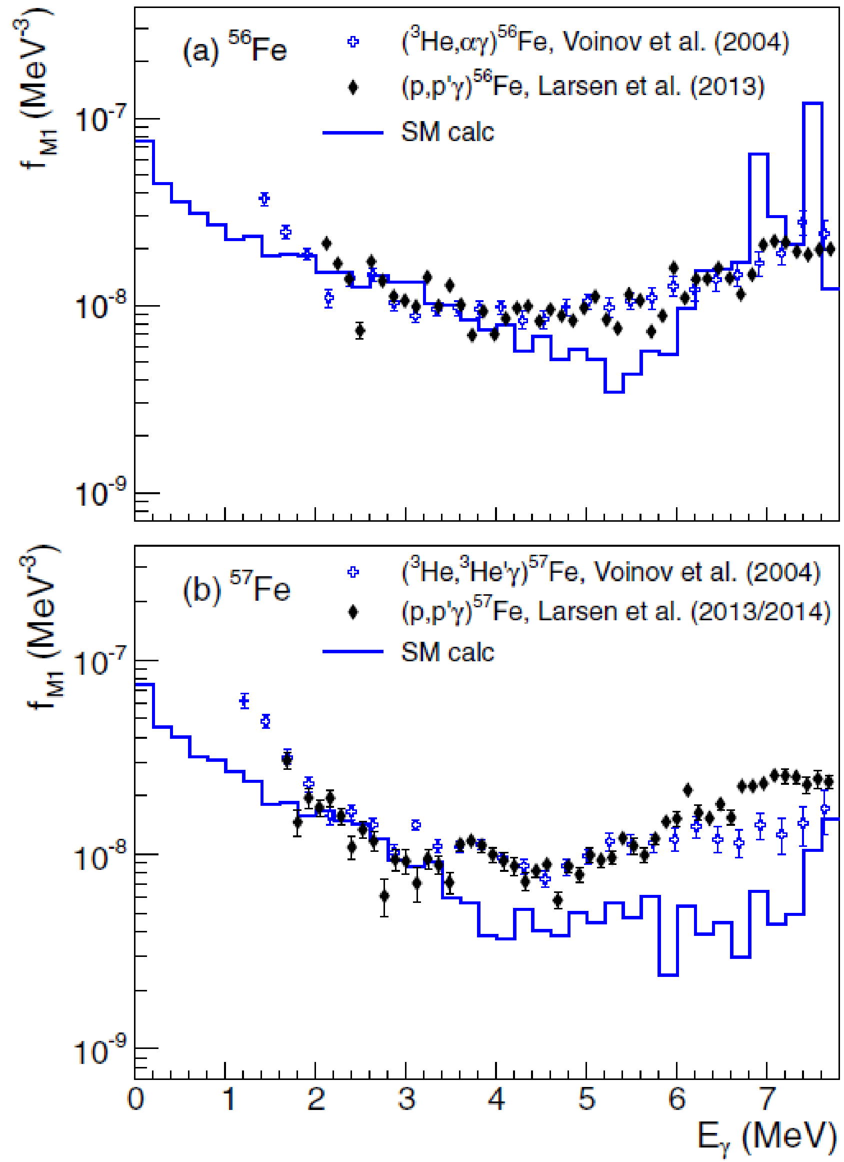


T. Inakura et al., Phys. Rev. C 84, 021302(R) (2011)

strong correlation with the occupation of the *p* orbitals

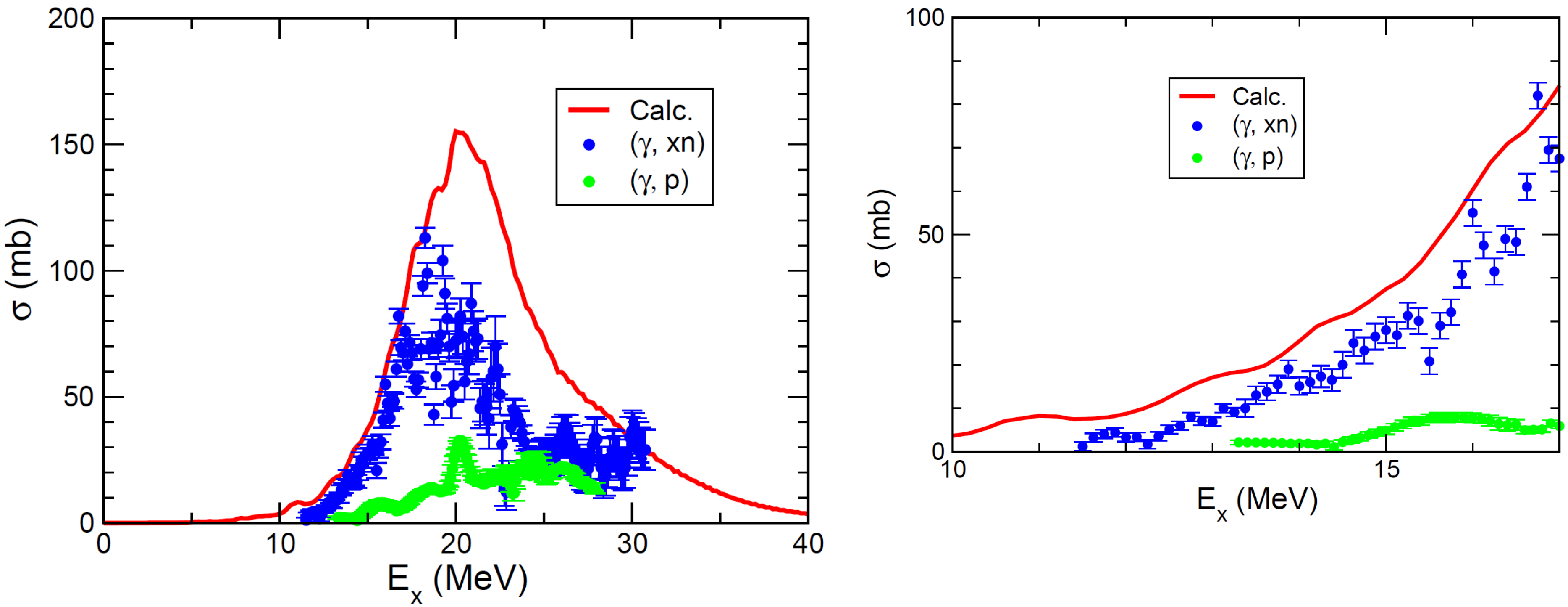
Enhancement of low-energy M1

- γ-ray strength function
  - [mean transition matrix element]×[level density]
  - Measured with the Oslo method
    - Measuring de-excitation γ rays from compound nuclei
    - Simultaneously determining level density and γSF
    - Assuming the Brink hypothesis
- Enhancement of γSF at low energy: due to M1 according to the shell model



B.A. Brown and A.C. Larsen, Phys. Rev. Lett. 113, 252502 (2014).

^{52}Cr: an example beyond Ca



Data taken from CDFE (Russia); http://cdfe.sinp.msu.ru

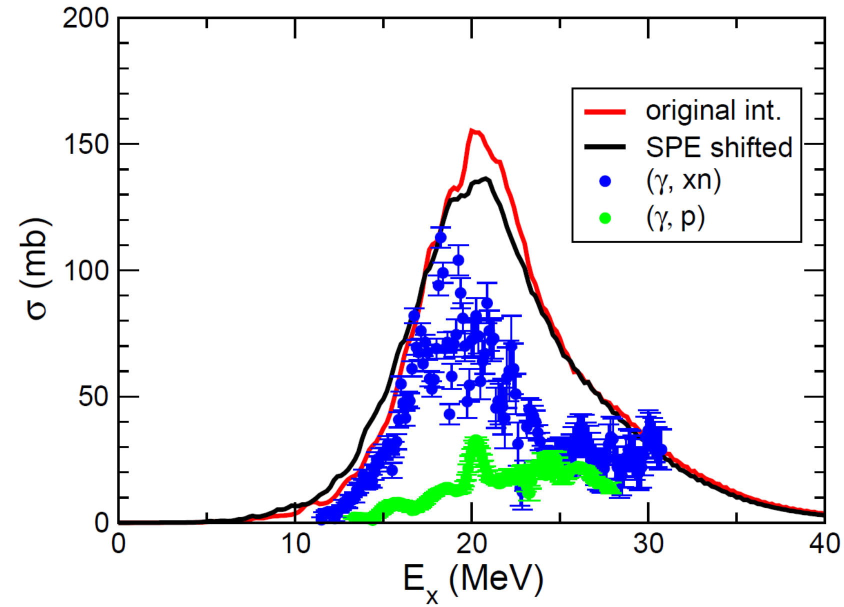
- M-scheme dimension: 3 billion (1$\hbar\omega$ calc.)
- Basic trend: similar to ^{48}Ca
  - GDR peak: overestimated
  - Low-energy tail: good but still overestimated

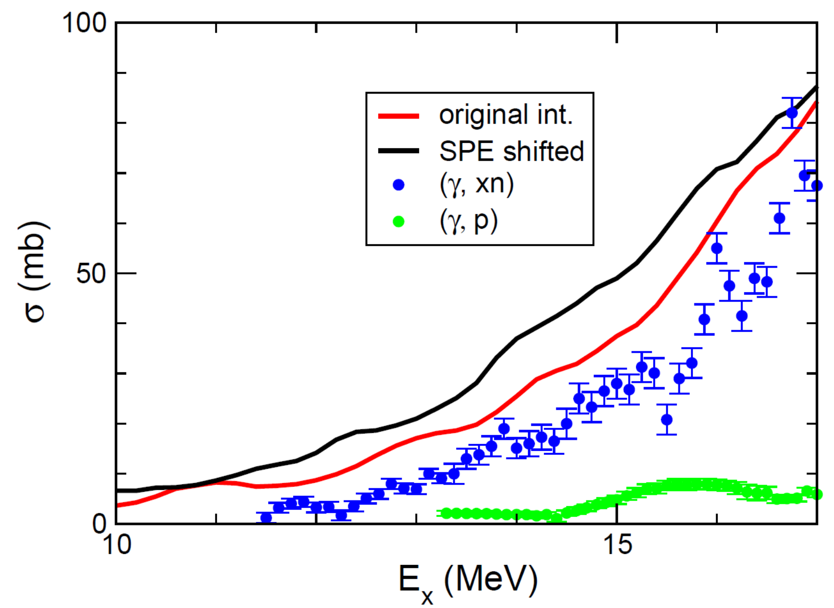
Sensitivity of single-particle energies

- Comparison to modified SPEs
  - SPEs of *sdg* orbitals: lowered by 0.8 MeV to 5.7 MeV so that Ex and C2S of low-lying states in ^{58}Ni can be well reproduced.

Nucl.	J^π	E_x (MeV)		C^2S		
		Cal.	Exp.	j	Cal.	Exp.
^{57}Co	$7/2_1^-$	0	0	$\pi 0f_{7/2}^{-1}$	5.28	4.27, 5.53
	$1/2_1^+$	3.037	2.981	$\pi 1s_{1/2}^{-1}$	0.98	1.05, 1.31
	$3/2_1^+$	3.565	3.560	$\pi 0d_{3/2}^{-1}$	1.70	1.50, 2.33
^{57}Ni	$3/2_1^-$	0	0	$\nu 1p_{3/2}^{-1}$	1.14	1.04, 1.25, 0.96
	$1/2_1^+$	5.581	5.580	$\nu 1s_{1/2}^{-1}$	0.51	0.62, 1.08
	$3/2_1^+$	5.579	4.372	$\nu 0d_{3/2}^{-1}$	0.29	0.01
	$3/2_2^+$	6.093	6.027	$\nu 0d_{3/2}^{-1}$	0.22	0.66, 0.54
^{59}Cu	$3/2_1^-$	0	0	$\pi 1p_{3/2}^{+1}$	0.53	0.46, 0.49, 0.25
	$9/2_1^+$	3.139	3.023	$\pi 0g_{9/2}^{+1}$	0.26	0.24, 0.32, 0.27
^{59}Ni	$3/2_1^-$	0	0	$\nu 1p_{3/2}^{+1}$	0.51	0.82, 0.33
	$9/2_1^+$	3.053	3.054	$\nu 0g_{9/2}^{+1}$	0.63	0.84, 0.39
	$5/2_1^+$	4.088	3.544	$\nu 1d_{5/2}^{+1}$	0.04	0.03
	$5/2_2^+$	4.595	4.506	$\nu 1d_{5/2}^{+1}$	0.30	0.23, 0.14
	$1/2_1^+$	4.399	5.149	$\nu 2s_{1/2}^{+1}$	0.00	0.09
	$1/2_2^+$	5.492	5.569	$\nu 2s_{1/2}^{+1}$	0.18	0.02
	$1/2_3^+$	5.589	5.692	$\nu 2s_{1/2}^{+1}$	0.02	0.13

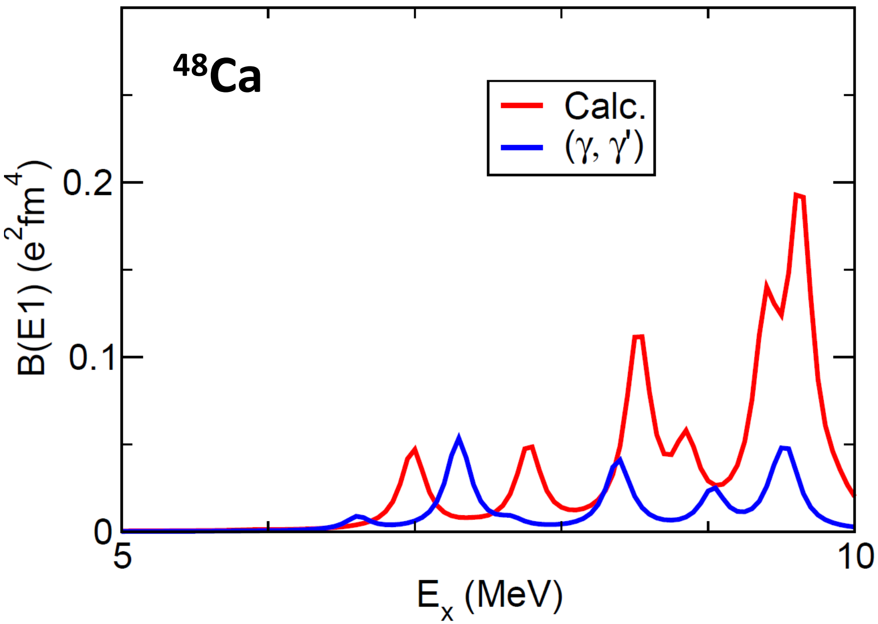
N. Shimizu et al., Phys. Lett. B 753, 17 (2016).



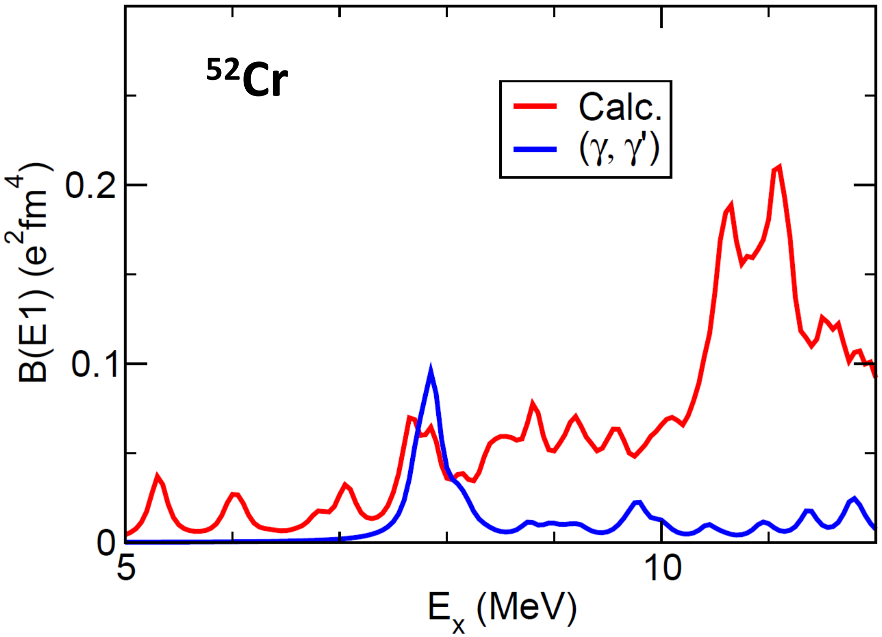


Comparison to (γ, γ′) data

- Below threshold
  - Providing a stringent test of the GDR tail



Data: T. Hartmann et al., Phys. Rev. Lett. 93, 192501 (2004).



Data: T. Shizuma et al., Phys. Rev. C 96, 044316 (2017).

Overestimate for E_x>9 MeV: too long tail in our calculation

Summary and perspectives: Tamii-san's questions

1. Present status of E1 strength distributions for $A \leq 56$
    - It is in principle possible to calculate almost all the nuclei in the $1\hbar\omega$ space as far as the ground state is dominated by $0\hbar\omega$.
    - Reasonable description of the slope of GDR
    - GDR peak overestimated: $(1+3)\hbar\omega$ calculation required
2. What limits the predictive power? Possible to improve?
    - Limited g.s. correlation that causes the overestimate of GDR peak
        - $(1+3)\hbar\omega$ calculation: presently infeasible except Ca isotopes (and some Sc)
    - SPEs: some sensitivity to the low-energy tail of GDR
    - Two-body interaction?
3. What data are needed to improve the model?
    - Systematic and higher-precision data are useful to find "systematic errors" in theory