Evolution of low-lying M1 modes in germanium isotopes

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Gamma-ray strength functions

- Gamma-ray strength functions describe average electromagnetic transition strengths at high excitation energy and high level density of nuclear states:

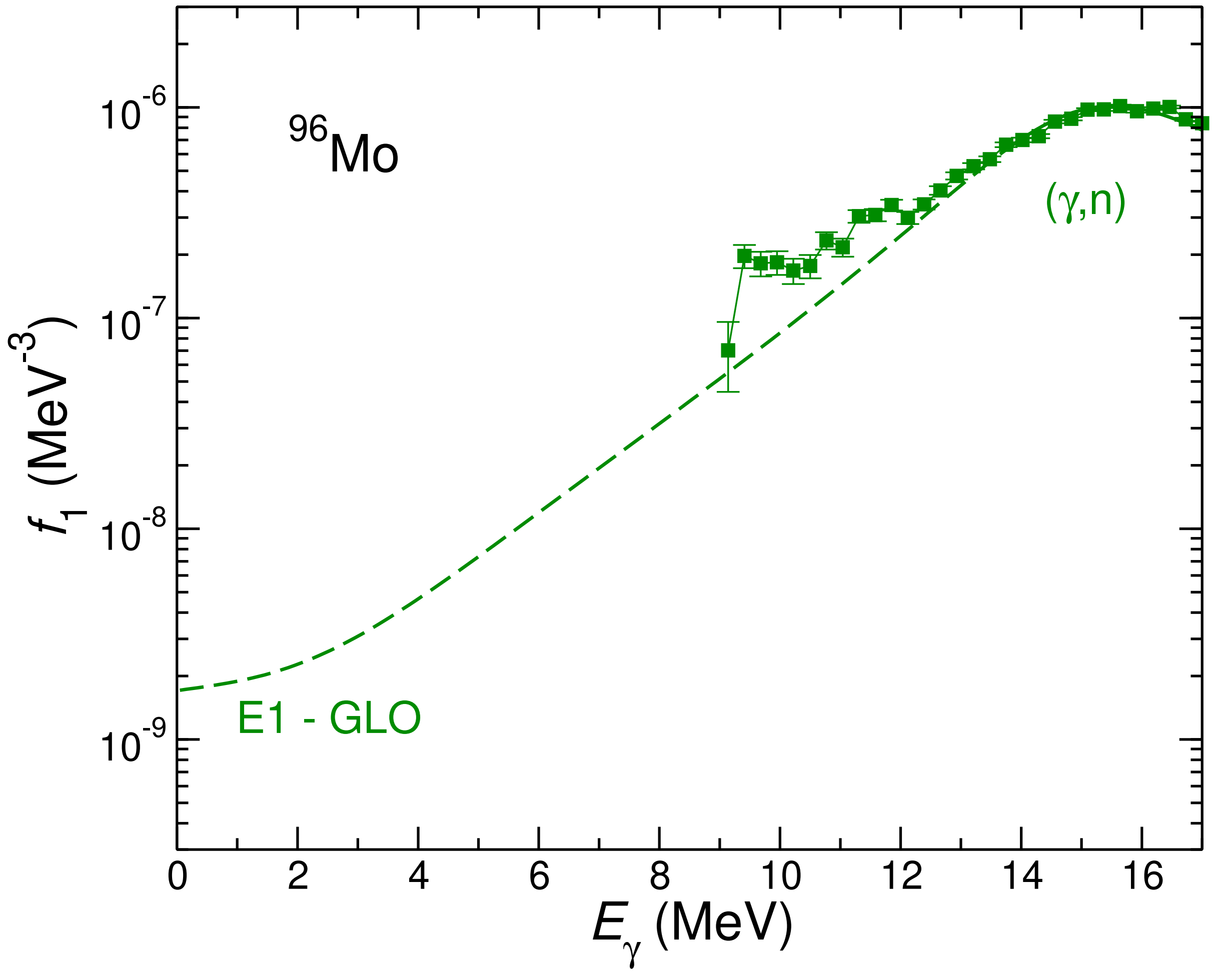
$f_{fiL}(E_\gamma) = \overline{\Gamma_{fiL}}\ \rho(E_i, J_i)\ /\ E_\gamma^{2L+1}$ $E_\gamma = E_i - E_f$ $J_i = 0, \ldots, J_\mathrm{max}$

- Photoabsorption:

$f_L = \sigma_\gamma\ /\ [(2J_i+1)/(2J_0+1)\ (\pi\hbar c)^2\ E_\gamma^{2L-1}]$ $E_\gamma = E_i$ $J_i = 1, (2)$

- Brink-Axel hypothesis:
  The strength function does not depend on the excitation energy.
  The strength function for excitation is identical with the one for deexcitation.

Dipole strength functions in ^{96}Mo



(γ,n) data:

H. Beil et al., NPA 227, 427 (1974).

GLO: RIPL data base.

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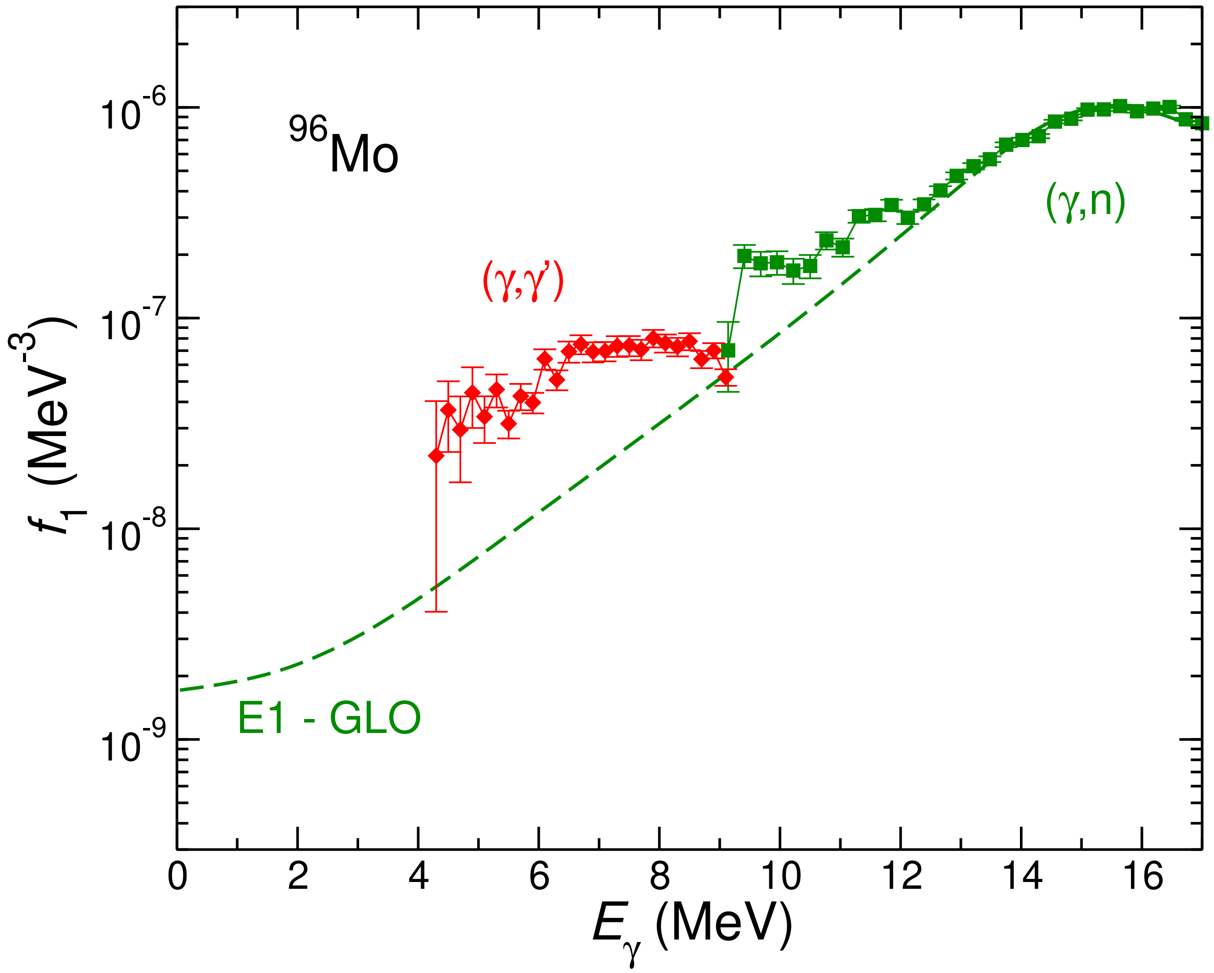

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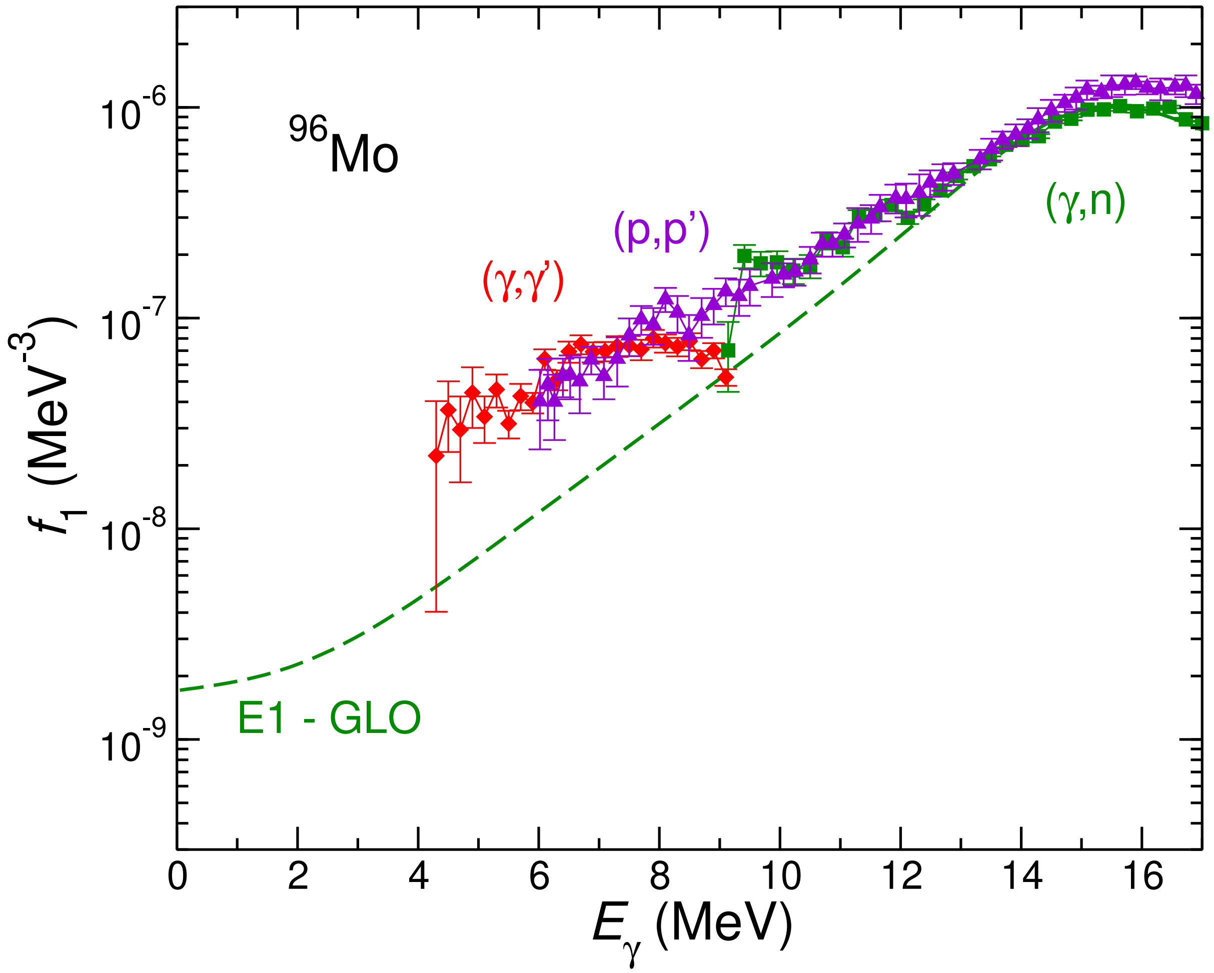

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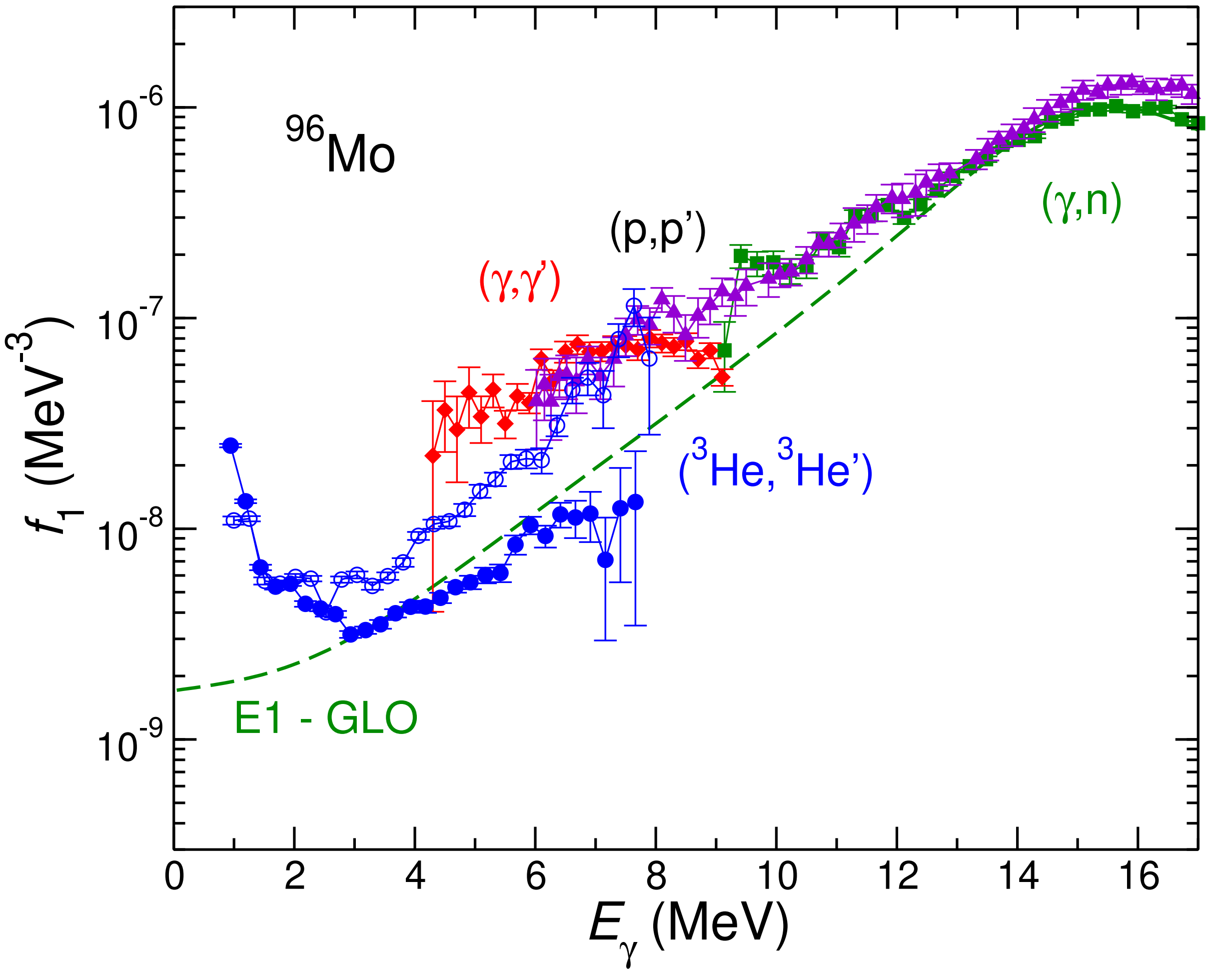

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D. Martin et al., PRL 119, 182503 (2017).

(^{3}He,^{3}He') data from OCL (Oslo):

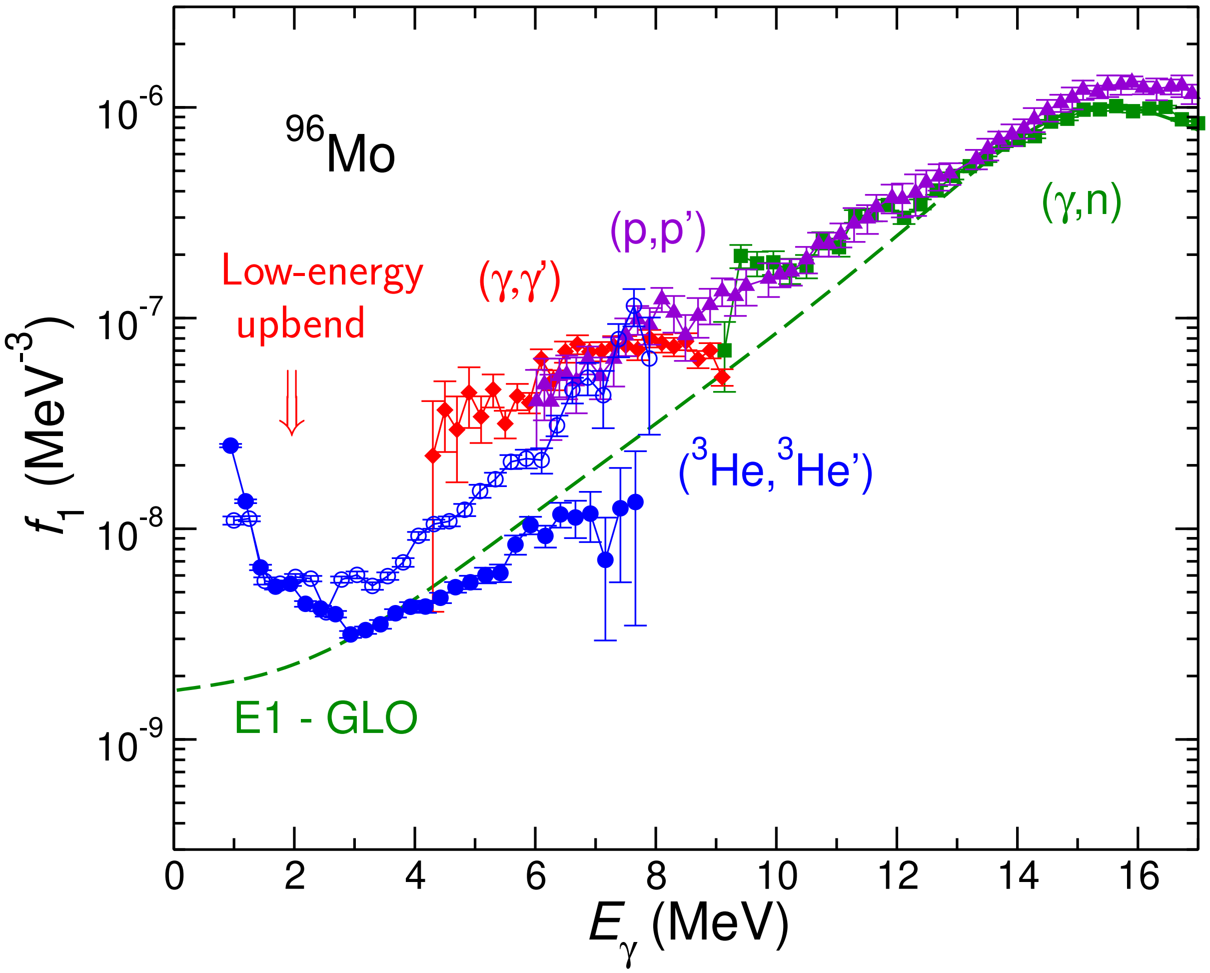
M. Guttormsen et al.,

PRC 71, 044307 (2005).

H. Utsunomiya et al.,

PRC 88, 015805 (2013).

Dipole strength functions in ^{96}Mo



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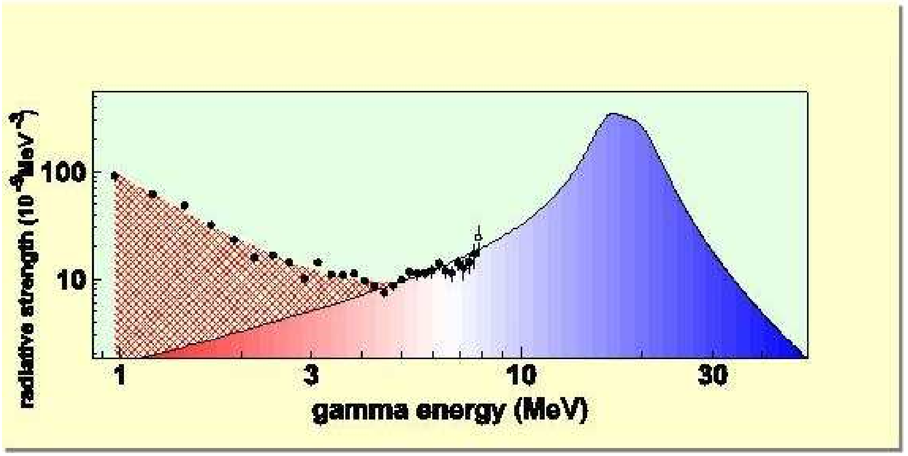
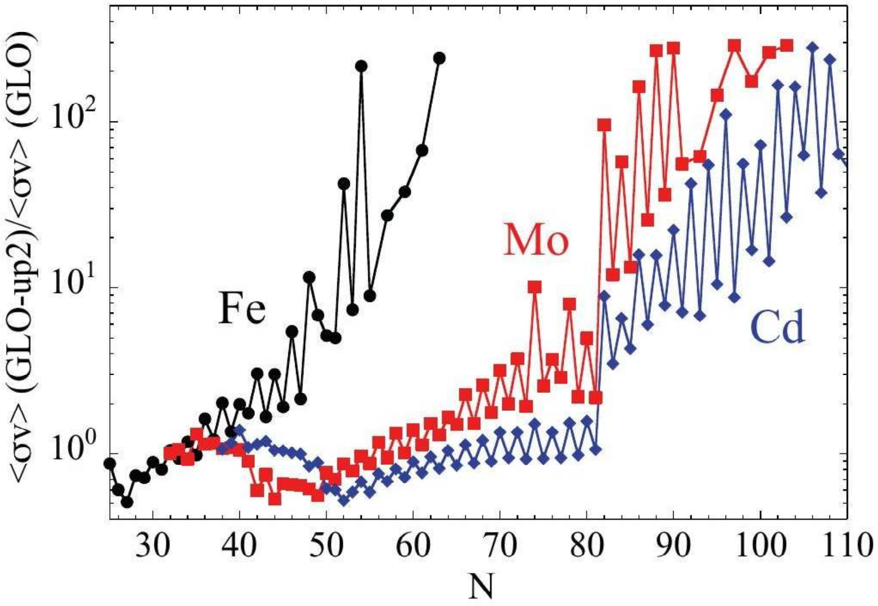
What are origin and consequences of the upbend?

Effect of enhanced low-energy dipole strength in the r-process





"The nucleus goes red."
Unexpected upbend of dipole strength toward low energy observed in Fe, Mo, Cd isotopes.

Courtesy of M. Guttormsen.

Ratios of Maxwellian-averaged (n,γ) reaction rates at $T = 10^9$ K for isotopic chains up to the neutron drip line using strength functions with and without low-energy upbend of dipole strength.

A.C. Larsen, S. Goriely, PRC 82, 014318 (2010)

⇒ Big influence of low-energy strength on neutron-capture rates of very neutron-rich nuclei in the astrophysical r-process.

Shell-model calculations of M1 strength functions

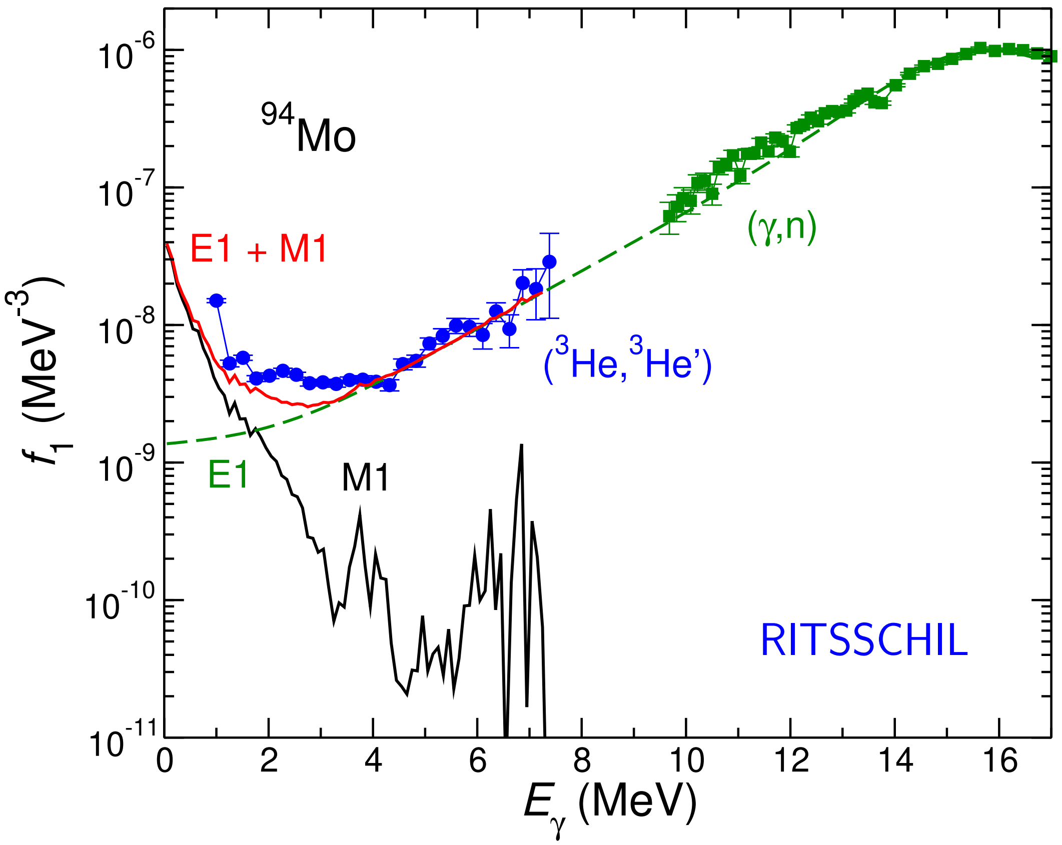
Determination of average quantities:

- 40 levels of each spin from 0 to 10 for each parity.
- All possible transitions between these 440 states - about 24000 M1 transitions.
- Average $B(\mathrm{M1})$ values in bins of $E_\gamma = E_i - E_f$.
- M1 strength function:
  $f_{\mathrm{M1}}(E_\gamma, E_i, J_i,\pi) = 16\pi/9\ (\hbar c)^{-3}\ \overline{B}(\mathrm{M1}, E_i \rightarrow E_f, J_i,\pi)\ \rho(E_i, J_i,\pi)$.
  $f_{\mathrm{M1}}(E_\gamma)$ obtained by averaging over E_i, J_i, and π.

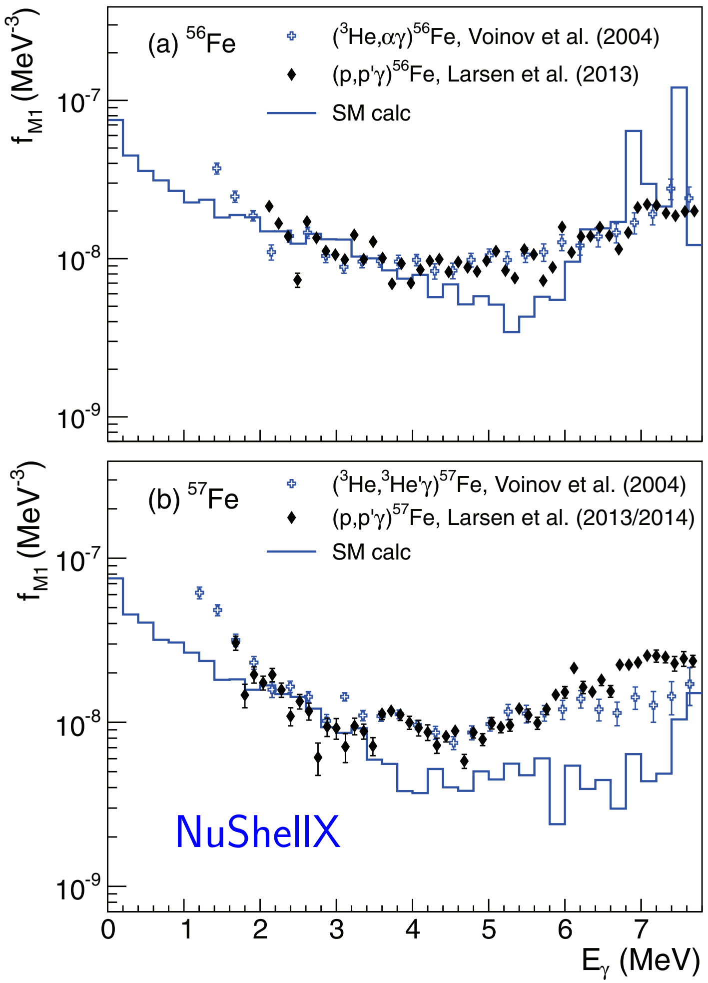
Codes:

- NuShellX@MSU
  B.A. Brown and W.D.M. Rae, Nucl. Data Sheets 120, 115 (2014).
- RITSSCHIL
  D. Zwarts, Comput. Phys. Commun. 38, 365 (1985).

Shell-model calculations of M1 strength functions



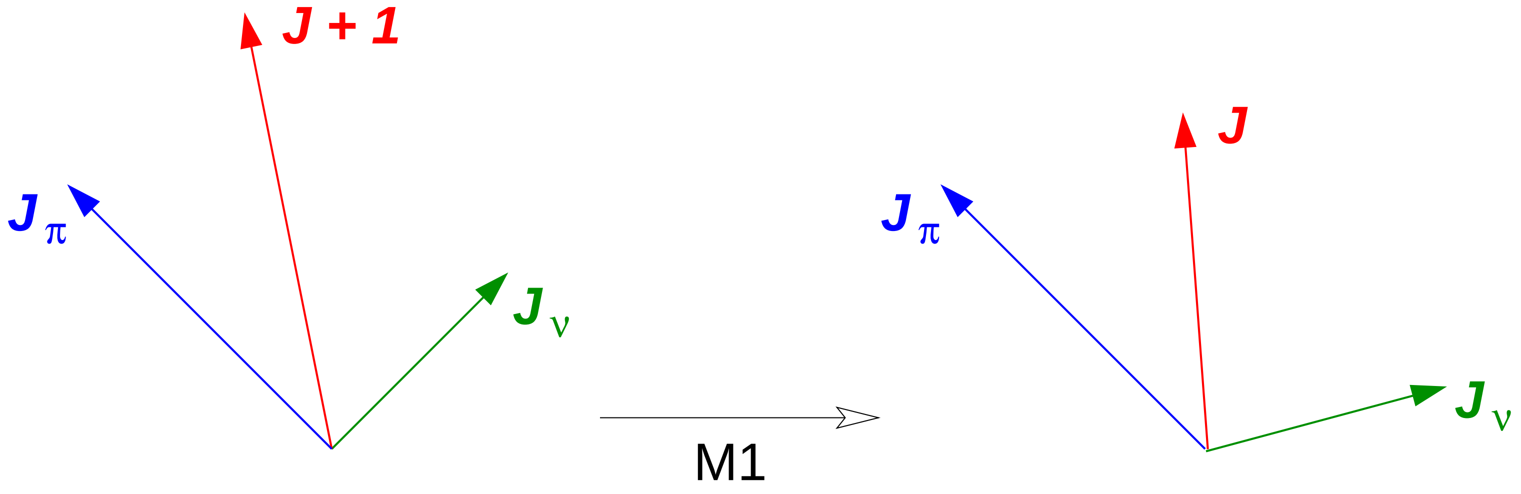
Low-energy enhancement of M1 radiation



R. Schwengner, S. Frauendorf, A.C. Larsen
PRL 111, 232504 (2013)

B.A. Brown, A.C. Larsen
PRL 113, 252502 (2014)

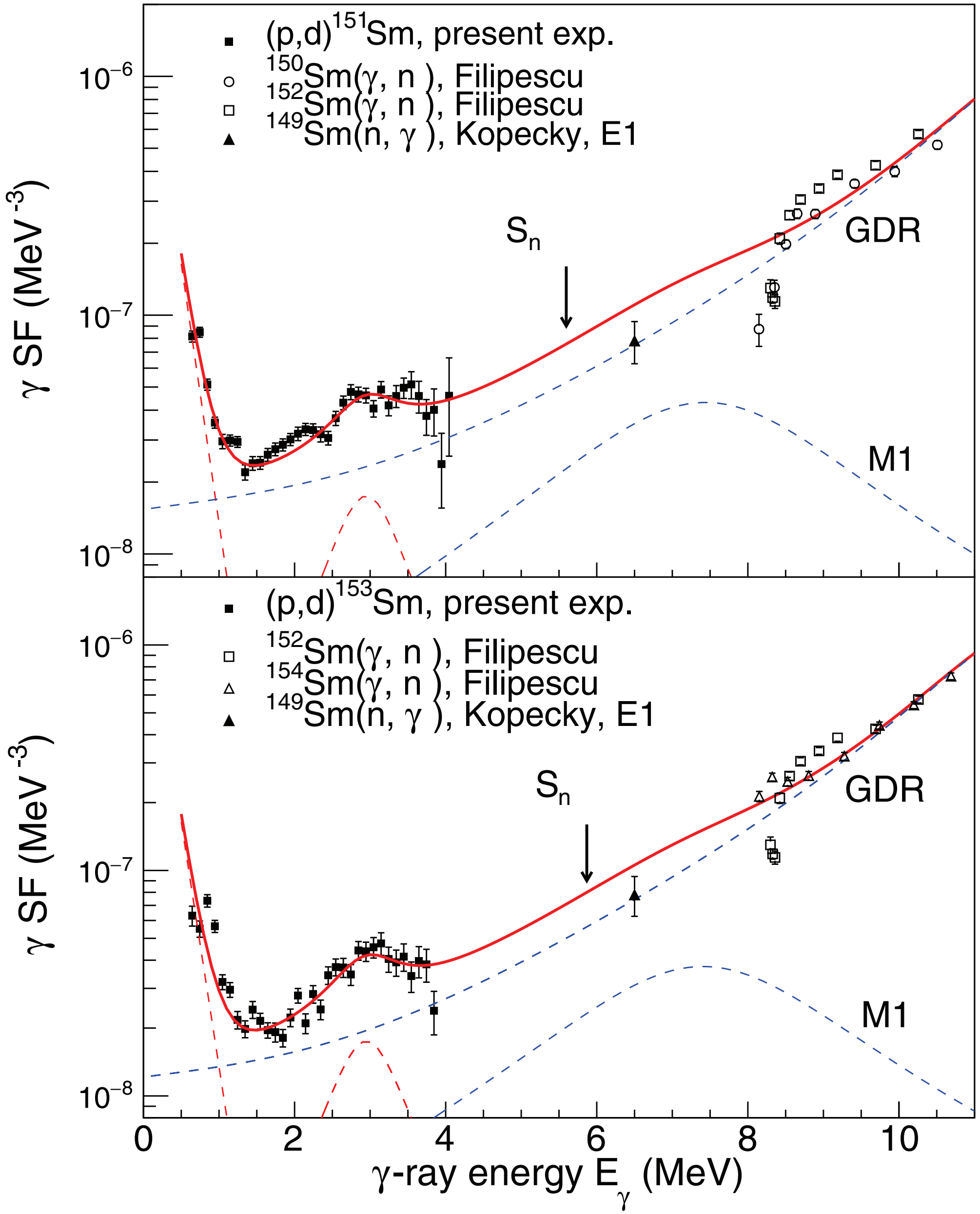
Generation of large M1 strengths



⇒ Large M1 strengths appear between close-lying states with equal configurations (multiplets) by a reorientation of proton and neutron spins.

⇒ Important role of configurations including protons and neutrons in specific high-*j* orbitals (e.g. $f_{7/2}$, $g_{9/2}$, $h_{11/2}$).

Dipole strength functions in ^{151}Sm and ^{153}Sm



(p,d) data:

A. Simon et al.

PRC 93, 034303 (2016)

⇒ First observation of upbend and scissors resonance in one nuclide.

⇒ Strength in the scissors region about three times that found in (γ,γ) experiments.

Shell-model calculations for $^{60}\mathrm{Fe}_{34}$, $^{64}\mathrm{Fe}_{38}$, $^{68}\mathrm{Fe}_{42}$

Code: NuShellX@MSU

[B.A. Brown and W.D.M. Rae, Nucl. Data Sheets 120, 115 (2014)]

Model space: CA48PN with CA48MH1 Hamiltonian (^{48}Ca core)

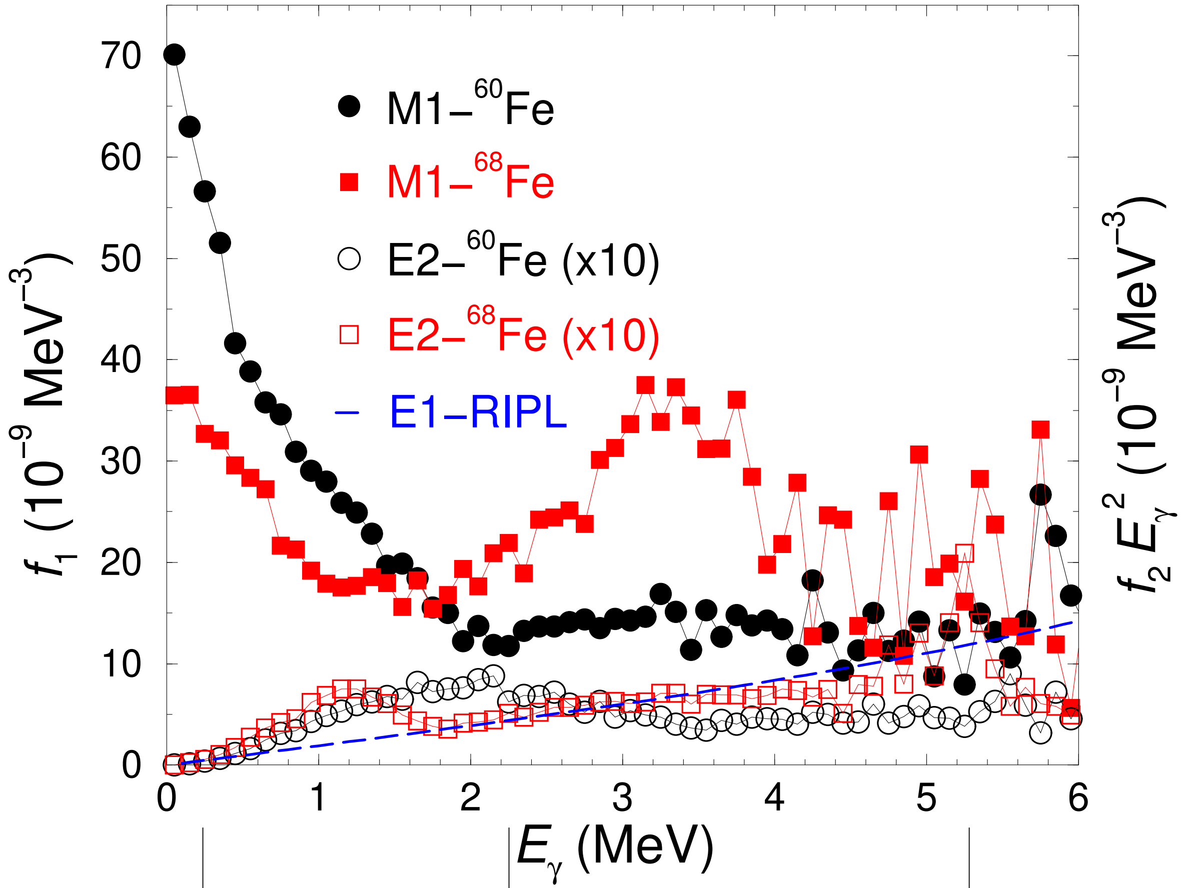
[M. Hjorth-Jensen, T.T.S. Kuo, and E. Osnes, Phys. Rep. 261, 125 (1995)]

Orbitals: $\pi(0f_{7/2}, 0f_{5/2}, 1p_{3/2}, 1p_{1/2}) \quad \nu(0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2})$

Calculations: 40 levels of each spin from 0 to 10 and of each parity.

Transition strengths: $e_\pi = 1.5\ e$, $e_\nu = 0.5\ e$; $\quad g_s = 0.9\ g_s^{\mathrm{free}}$

Strength functions from shell-model calculations



	$E_\gamma < 2$ MeV	$2 \leq E_\gamma \leq 5$ MeV	Sum
^{60}Fe$_{34}$	5.67	3.52	9.19
^{64}Fe$_{38}$	4.46	5.13	9.59
^{68}Fe$_{42}$	3.98	6.63	10.61

$B(\mathrm{M1})_{\mathrm{tot}}(\mu_N^2)$

Dipole strength function

$f_1 = 16\pi/9\ (\hbar c)^{-3}\ \overline{B}(\mathrm{M1})\ \rho(E_x, J)$

$\rho(E_x, J)$ - level density
of the shell-model states,
includes $\pi = +$, $\pi = -$,
all spins from 0 to 10.

R. Schwengner, S. Frauendorf, B.A. Brown
PRL 118, 092502 (2017)

$\Rightarrow$ Sum of strengths at low energy
and in the scissors region
stays nearly constant.

Evolution of M1 strength functions from open to closed shells

- Occurrence of low-lying M1 modes:

  - Enhanced strength near zero transition energy.
  → decreases from ^{60}Fe to ^{68}Fe.

  - Strength in the scissors region.
  → develops toward the midshell nucleus ^{68}Fe.

- Is this correlated evolution of the two M1 modes a general feature in nuclei?

⇒ Calculations in another mass region using another Hamiltonian.

Shell-model calculations for ^{62}Ge$_{30}$, ^{64}Ge$_{32}$, ^{66}Ge$_{34}$, ^{70}Ge$_{38}$, ^{74}Ge$_{42}$, ^{78}Ge$_{46}$, ^{80}Ge$_{48}$

Code: NuShellX@MSU

[B.A. Brown and W.D.M. Rae, Nucl. Data Sheets 120, 115 (2014)]

Model space: jj44pn with the jj44bpn Hamiltonian (^{56}Ni core)

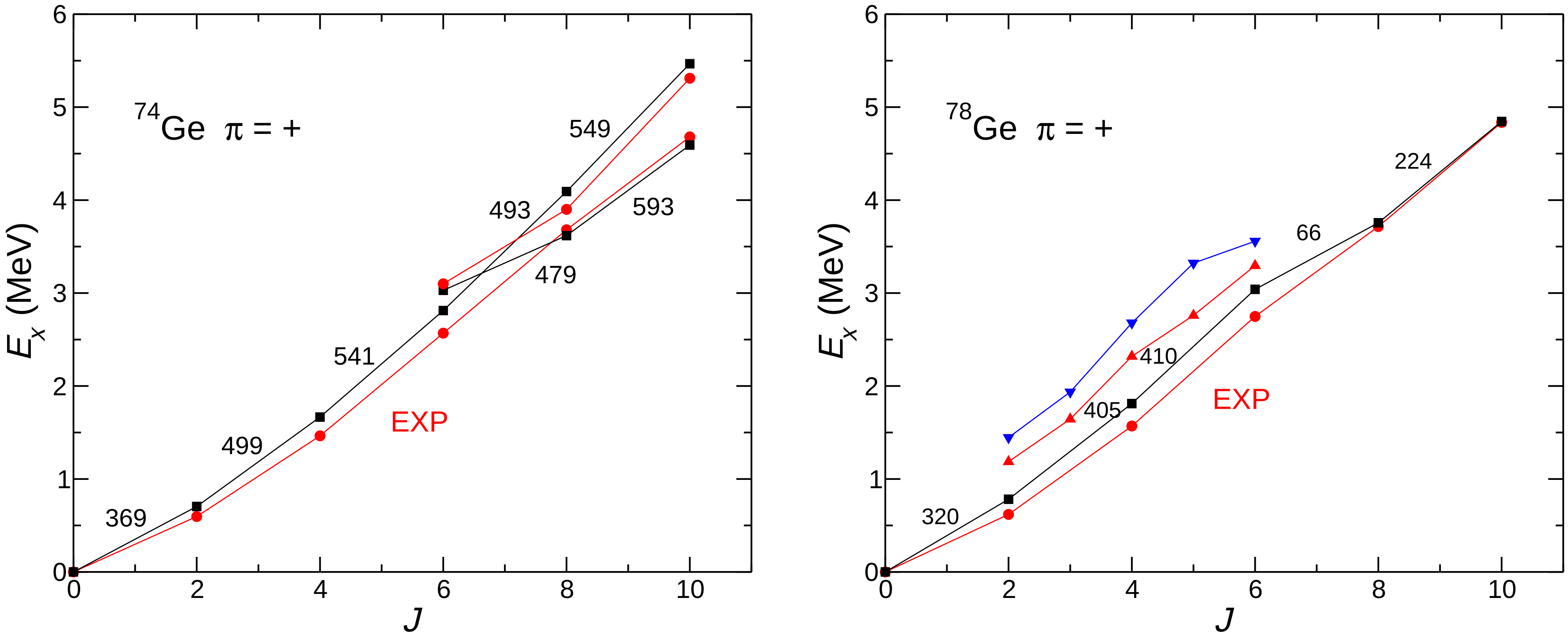
[M. Honma, T. Otsuka, T. Mizusaki, and M. Hjorth-Jensen, Phys. Rev. C **80**, 064323 (2009).]
[B. A. Brown and A. F. Lisetskiy, unpublished.]
[A. F. Lisetskiy, B. A. Brown, M. Horoi, and H. Grawe, Phys. Rev. C **70**, 044314 (2004).]

Orbitals: $\pi(0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2})$ $\nu(0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2})$

Calculations: 40 levels of each spin from 0 to 10 and of each parity.

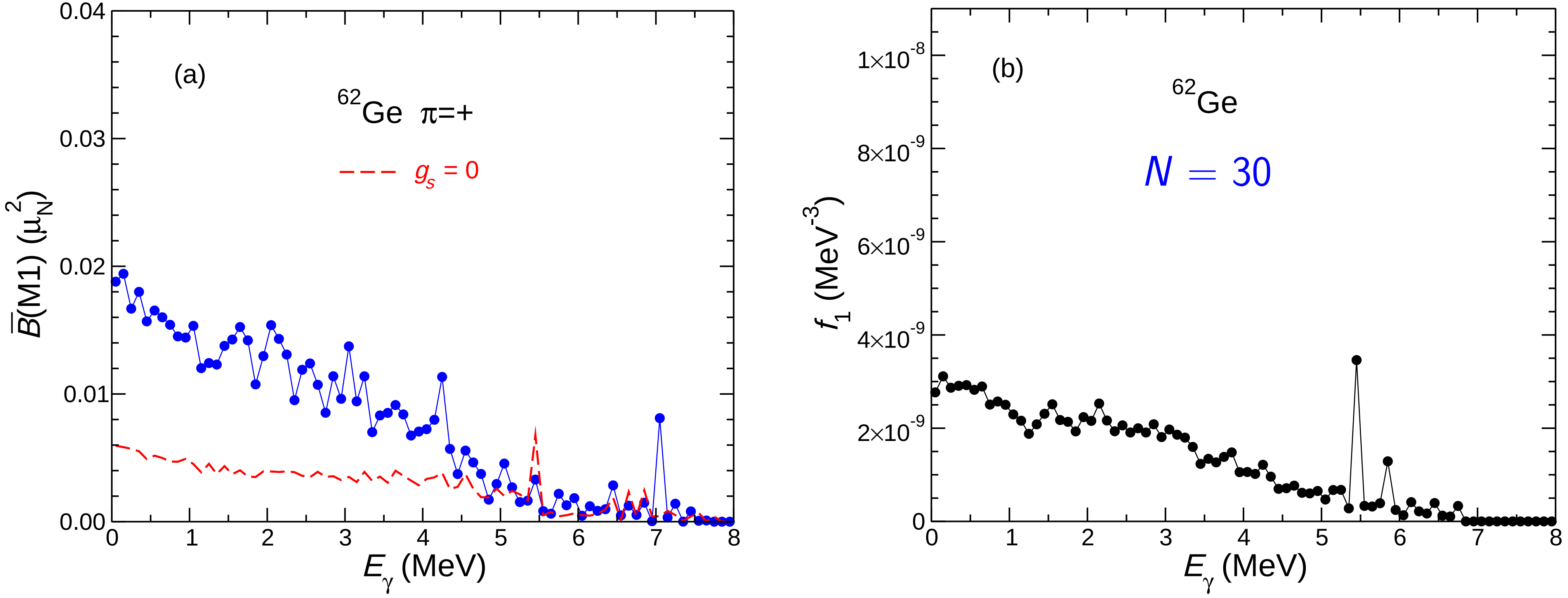
Transition strengths: $e_\pi = 1.5\ e$, $e_\nu = 0.5\ e$; $g_s = 0.7\ g_s^{\mathrm{free}}$

Level sequences in the yrast region



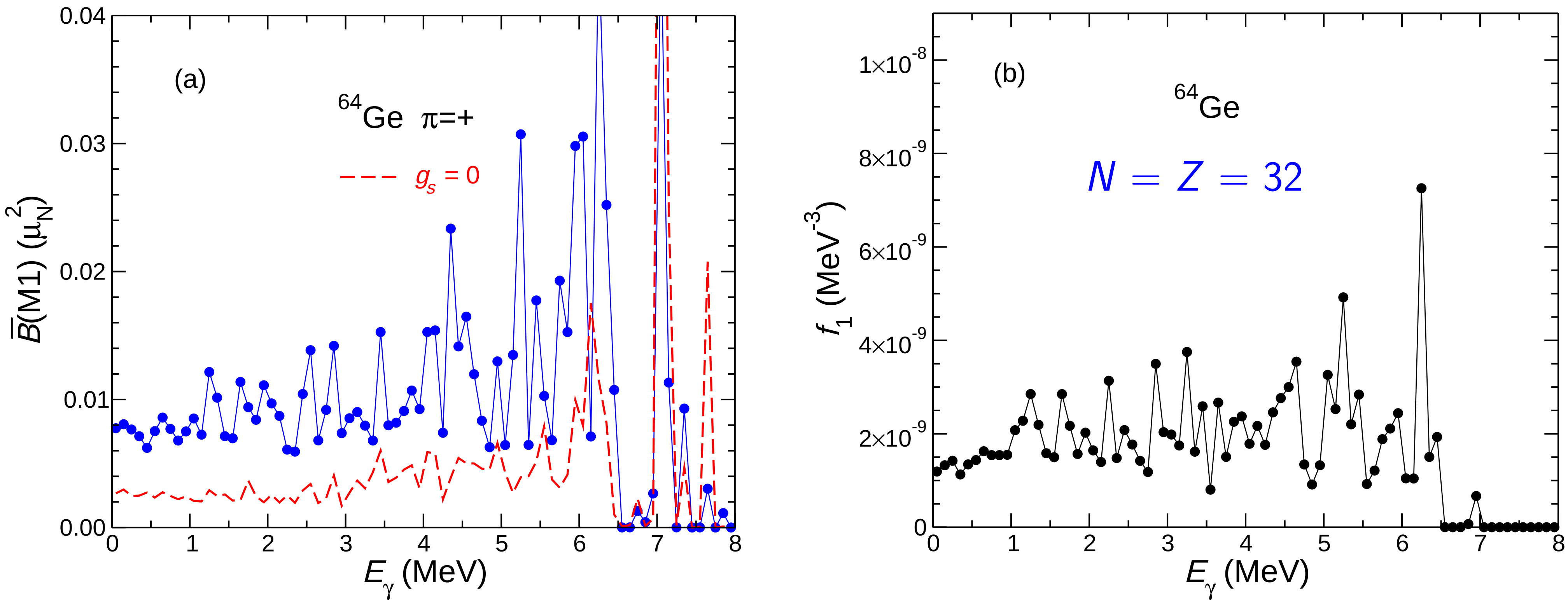
Black numbers: Calculated $B(E2)$ in e^2fm^4.

M1 strength functions in Ge isotopes with N = 30 to 48



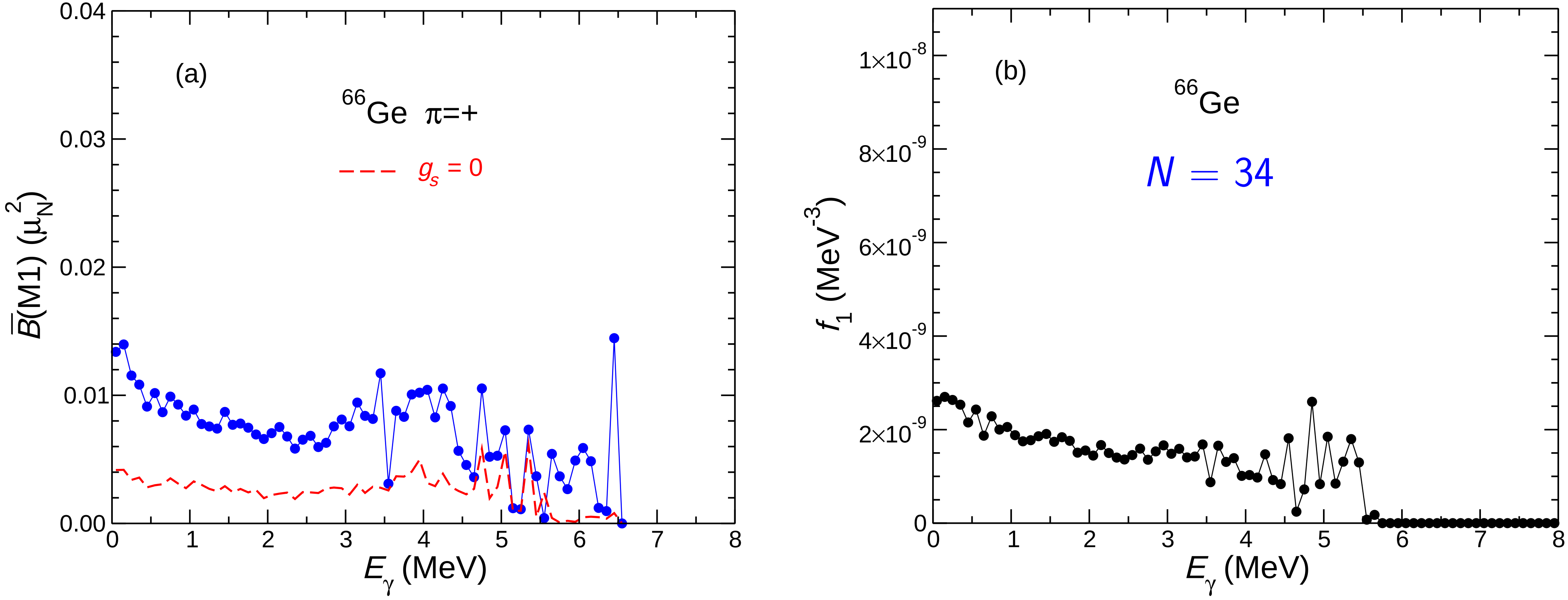
⇒ Steady increase of M1 strength toward low transition energy.

M1 strength functions in Ge isotopes with N = 30 to 48



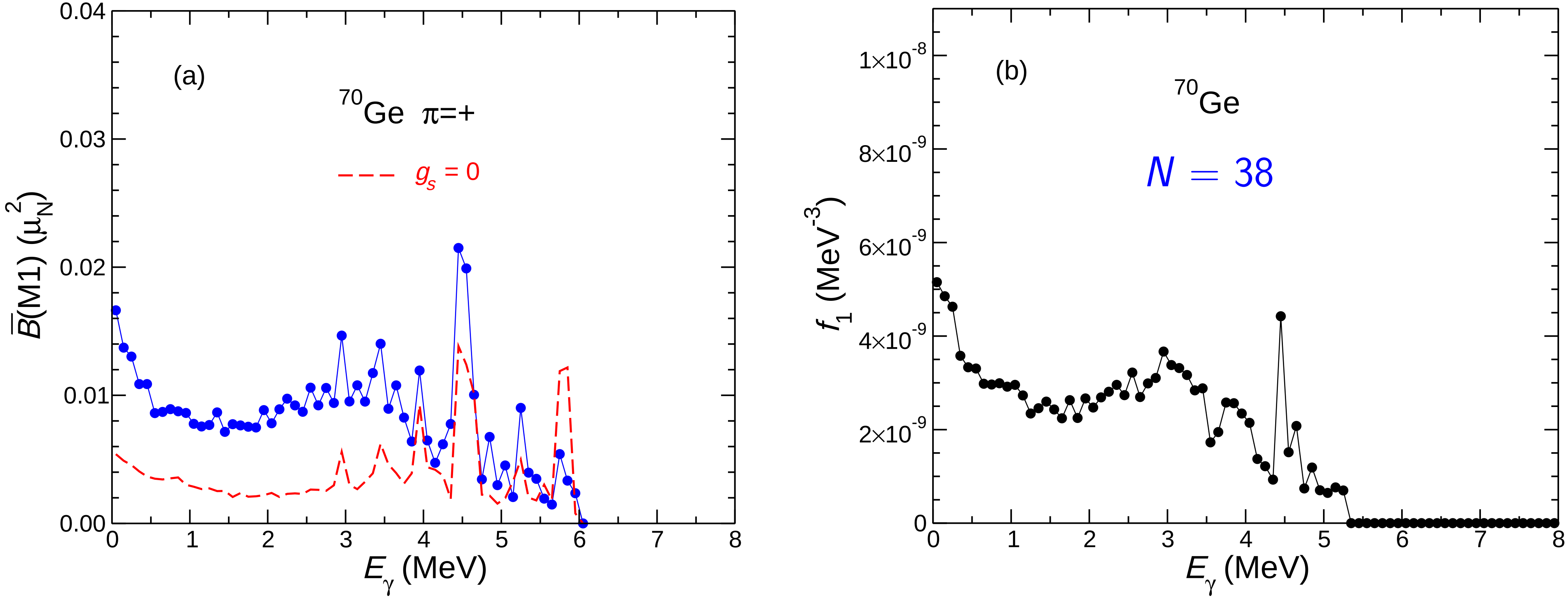
⇒ No enhancement of M1 strength toward low transition energy.
Suppressed M1 strength between $T = 0$ states may weaken the average M1 strength.

M1 strength functions in Ge isotopes with N = 30 to 48



⇒ Moderate increase of M1 strength toward low transition energy.

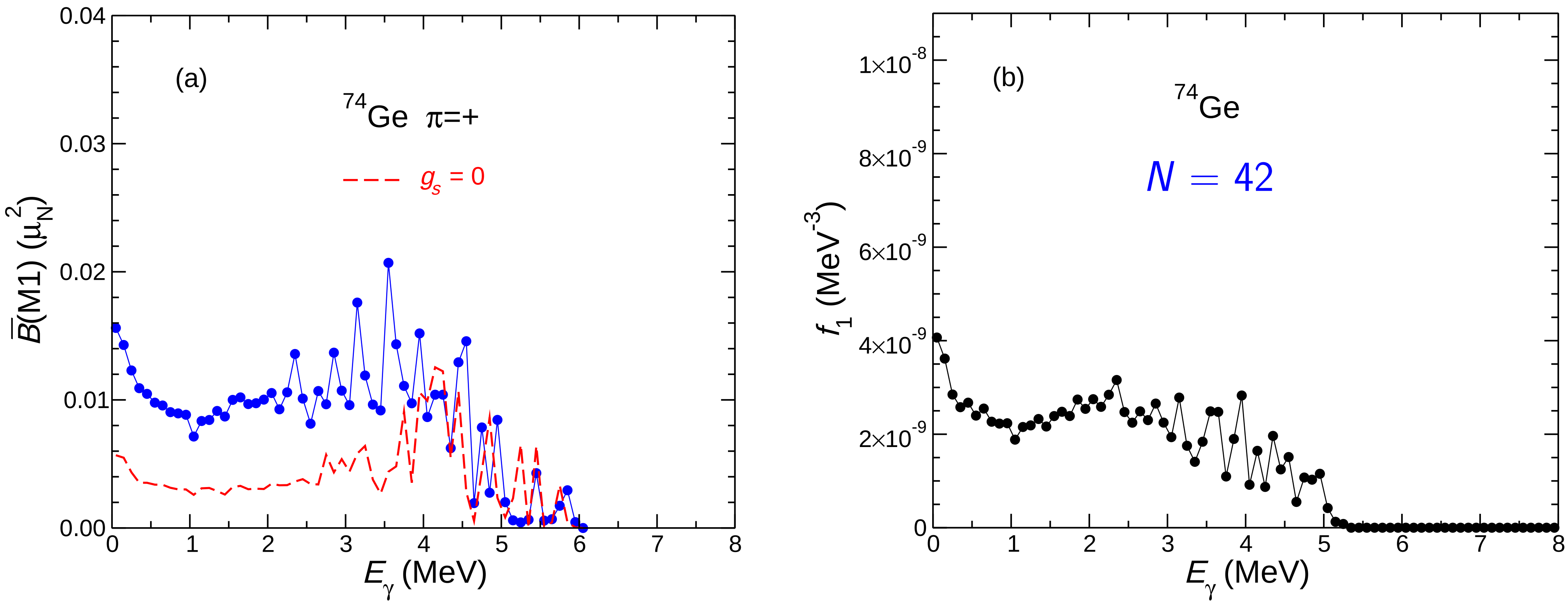
M1 strength functions in Ge isotopes with N = 30 to 48



⇒ Low-energy enhancement of M1 strength.

⇒ Development of a bump in the scissors region around 3 MeV.

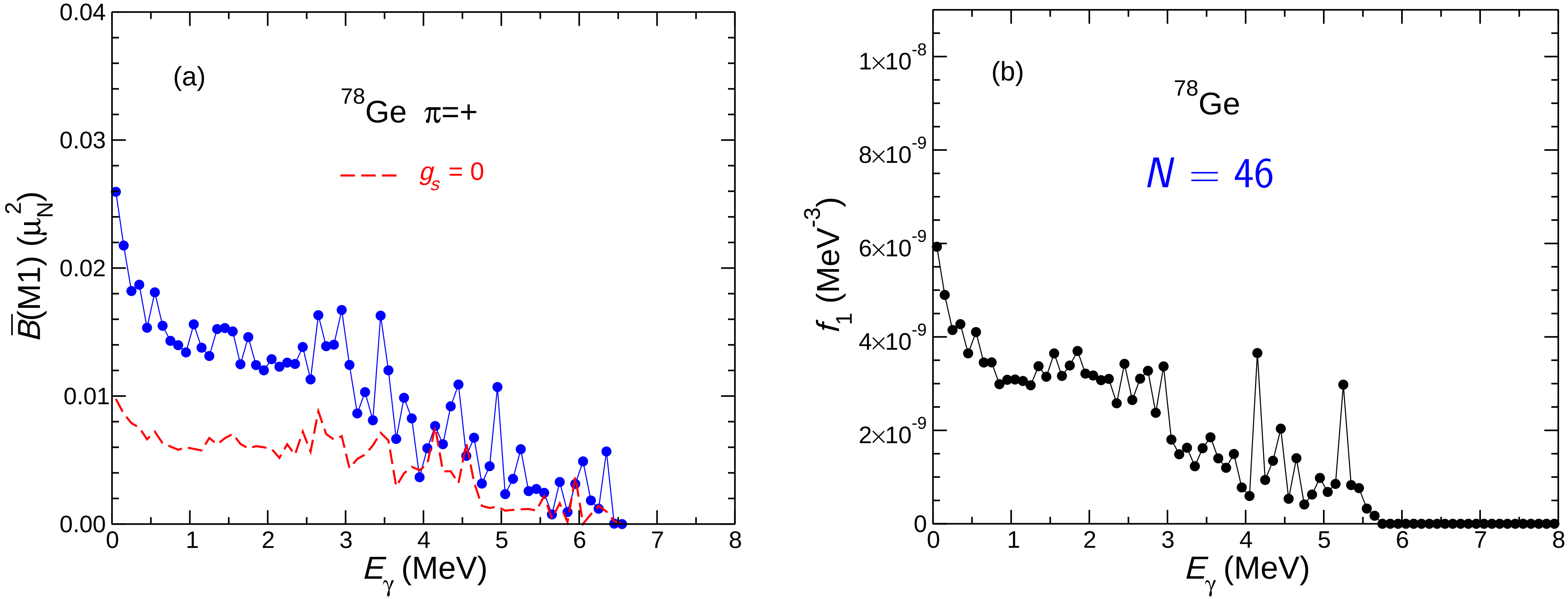
M1 strength functions in Ge isotopes with N = 30 to 48



⇒ Low-energy enhancement of M1 strength.

⇒ Broad bump in the scissors region around 3 MeV.

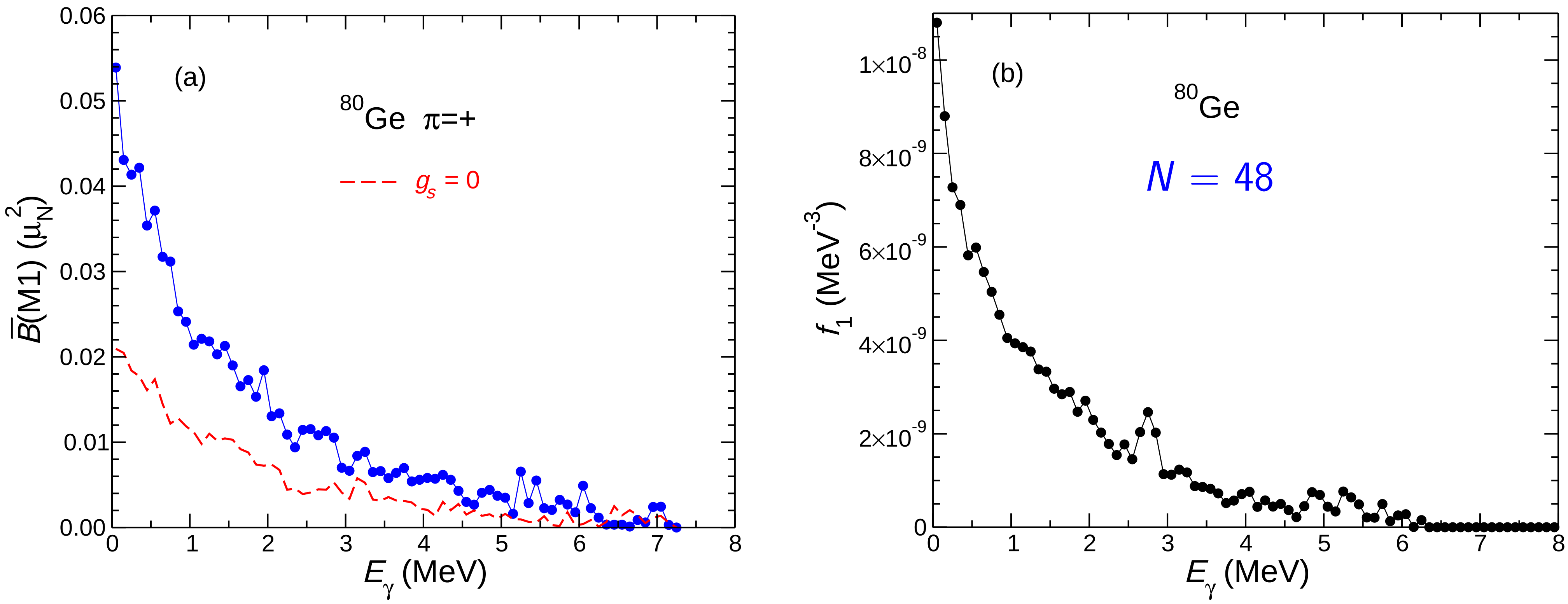
M1 strength functions in Ge isotopes with N = 30 to 48



⇒ Increase of the low-energy enhancement of M1 strength.

⇒ Decrease of the bump in the scissors region around 3 MeV.

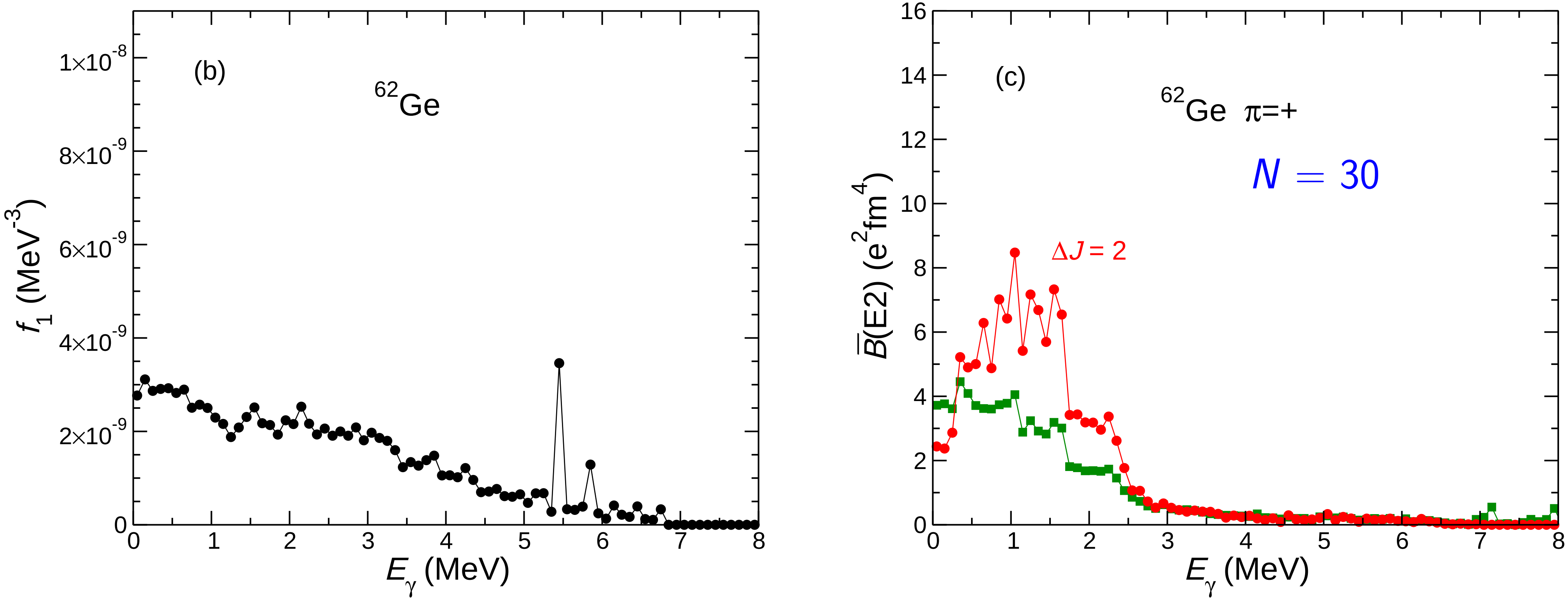
M1 strength functions in Ge isotopes with N = 30 to 48



⇒ Steep increase of the low-energy enhancement of M1 strength.

⇒ Vanishing bump in the scissors region around 3 MeV.

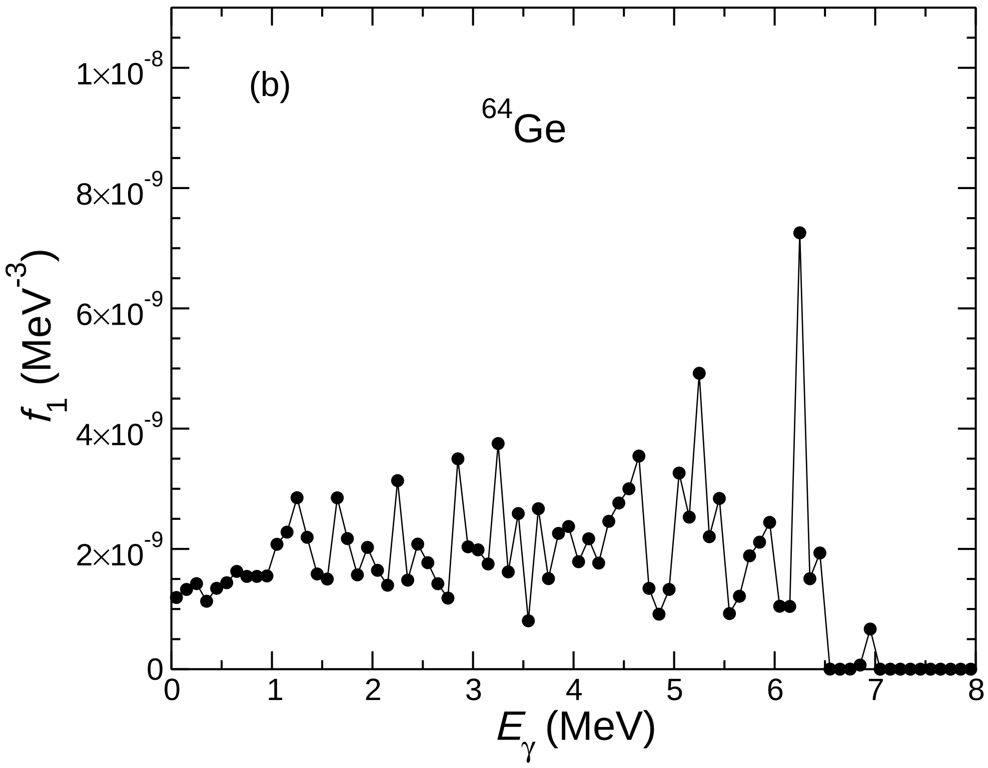
M1 strength functions in Ge isotopes with N = 30 to 48

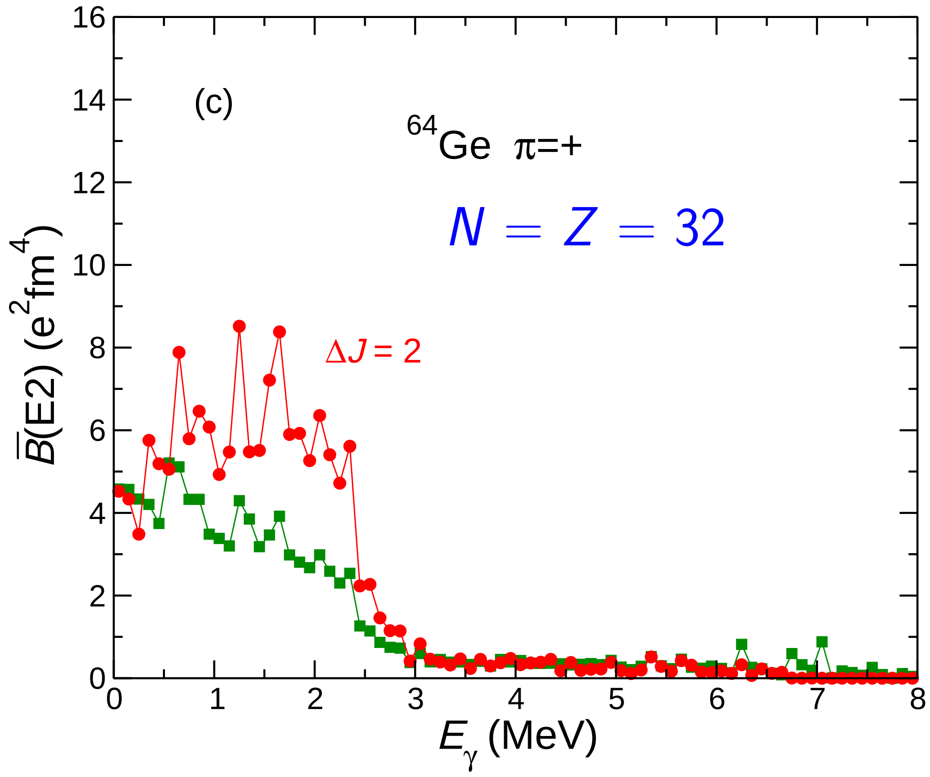


⇒ Steady increase of M1 strength toward low transition energy.

⇒ Moderate strength of stretched E2 transitions.

M1 strength functions in Ge isotopes with N = 32 to 48

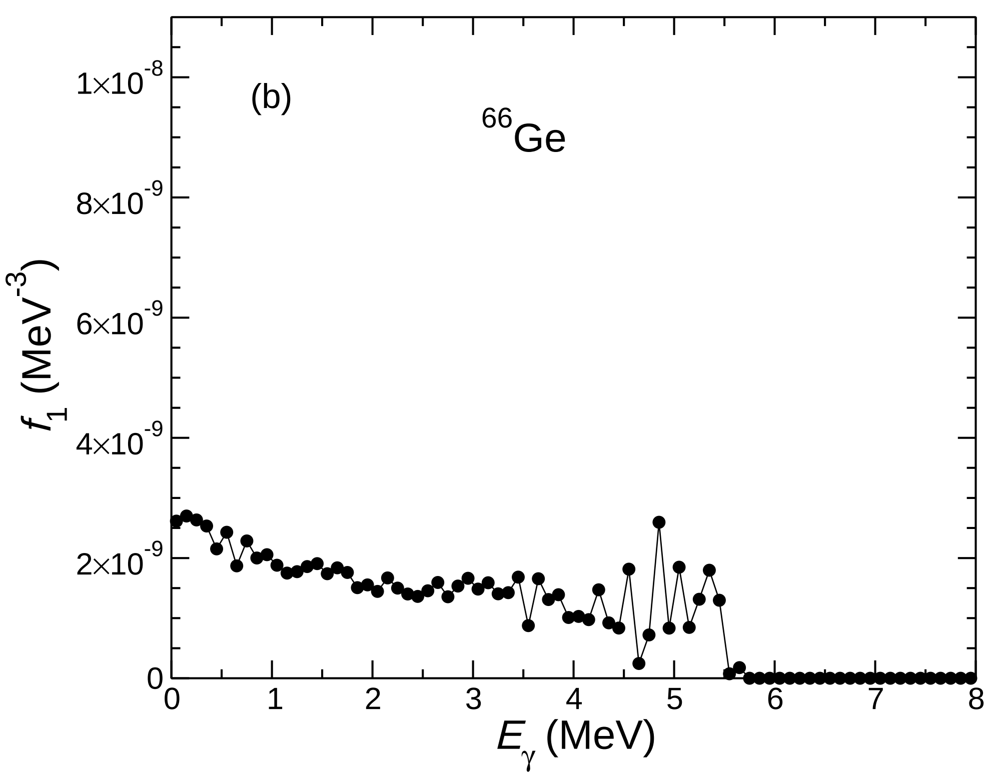


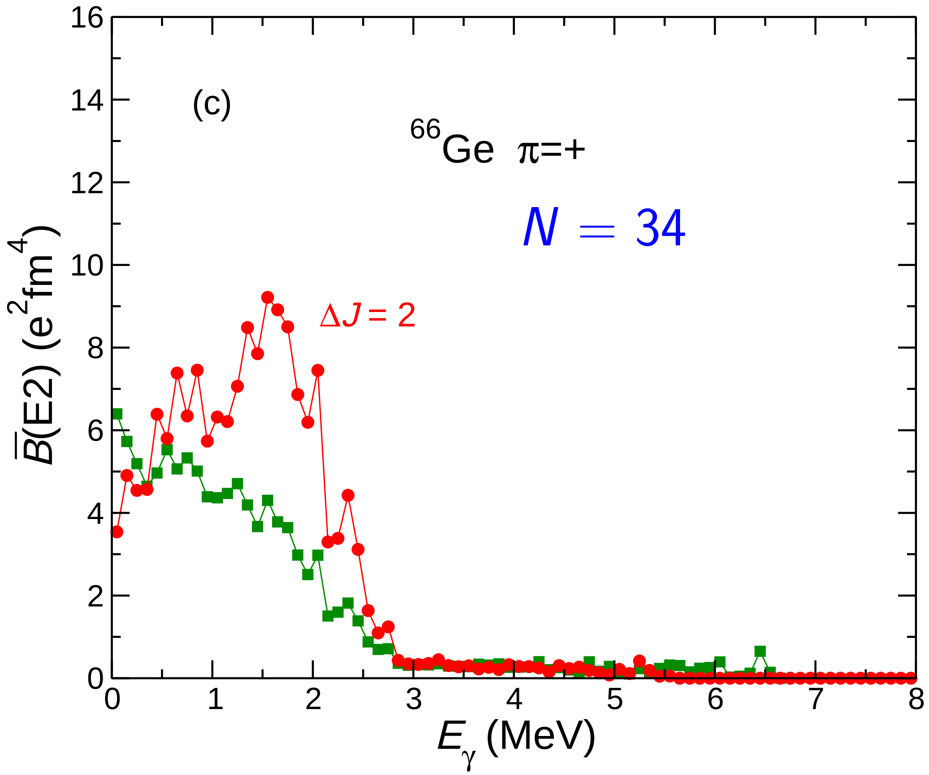


⇒ No enhancement of M1 strength toward low transition energy.

⇒ Moderate strength of stretched E2 transitions.

M1 strength functions in Ge isotopes with N = 30 to 48

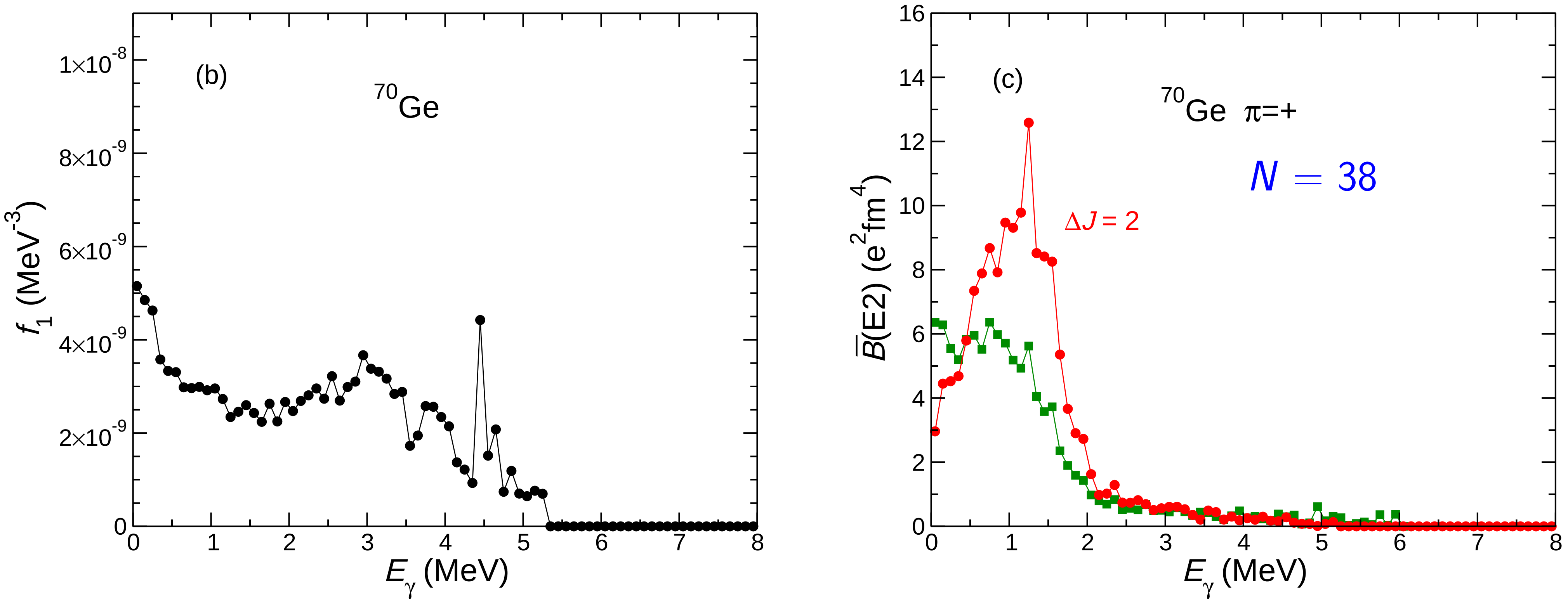




⇒ Steady increase of M1 strength toward low transition energy.

⇒ Moderate strength of stretched E2 transitions.

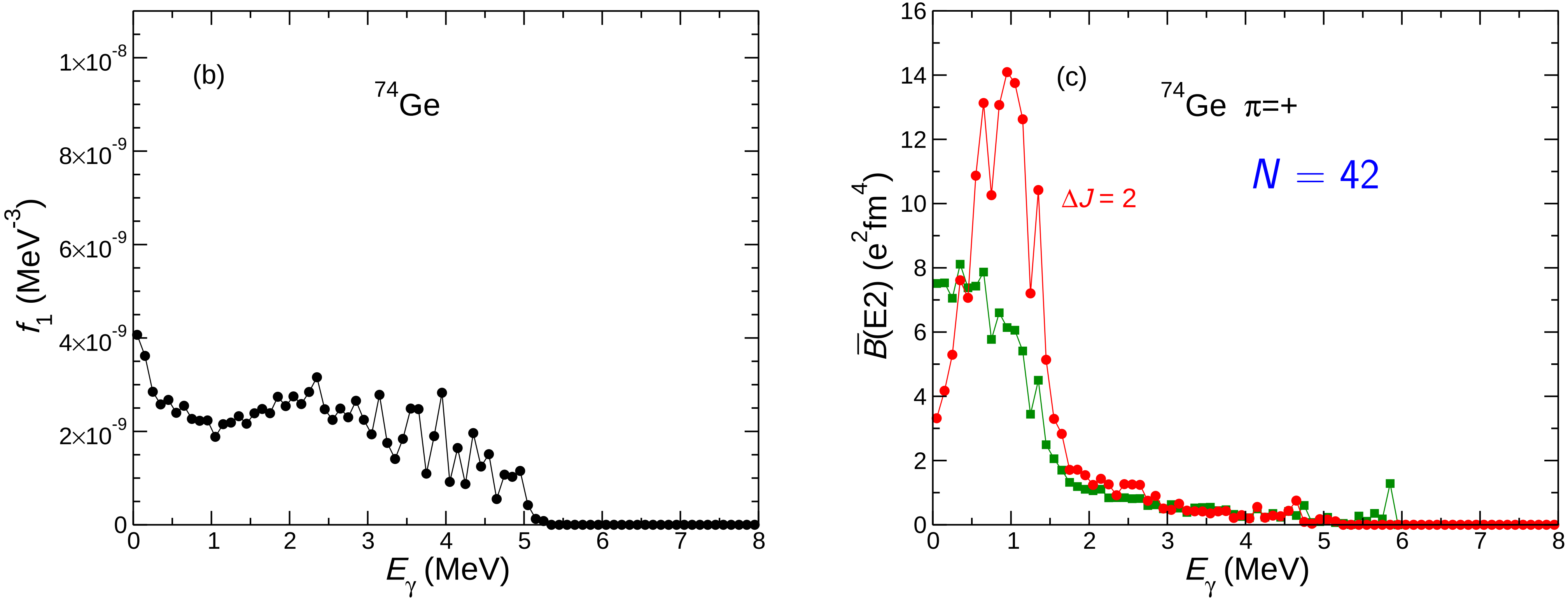
M1 strength functions in Ge isotopes with N = 30 to 48



⇒ Development of a bump in the scissors region around 3 MeV.

⇒ Increase of E2 strength of stretched transitions.

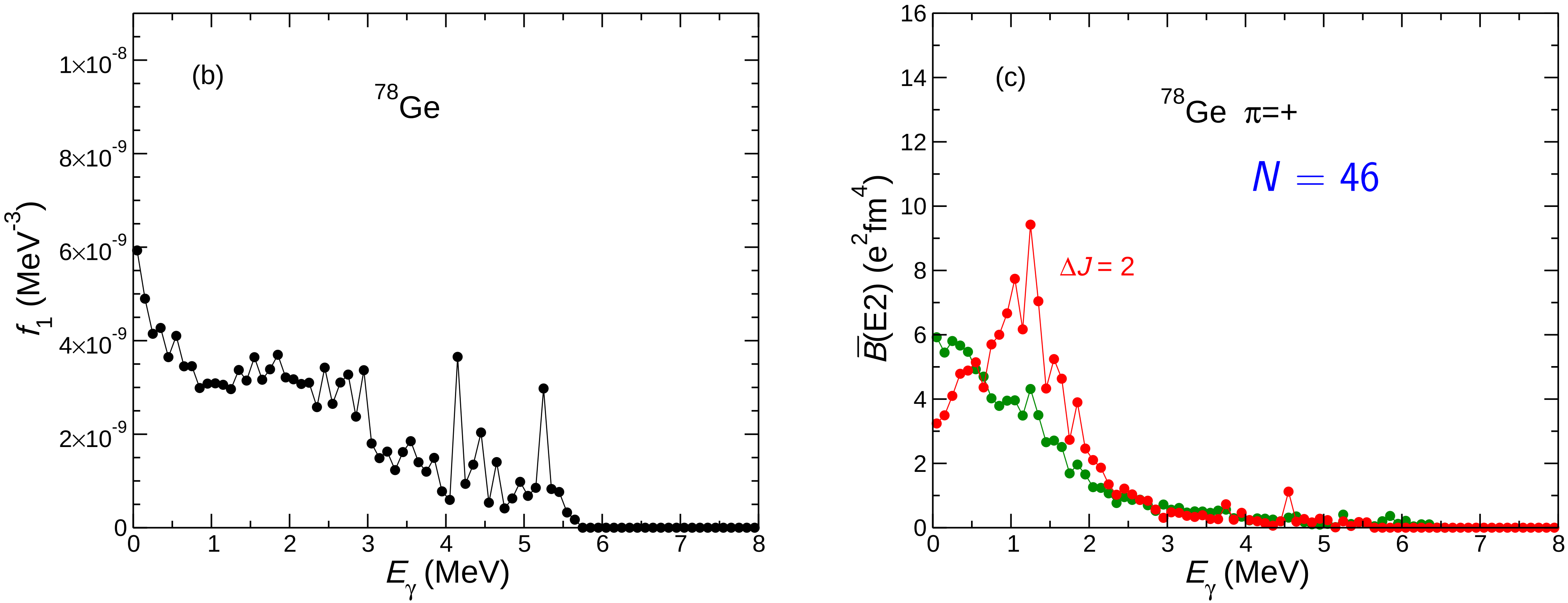
M1 strength functions in Ge isotopes with N = 30 to 48



⇒ Broad bump in the scissors region around 3 MeV.

⇒ Increased E2 strength of stretched transitions.

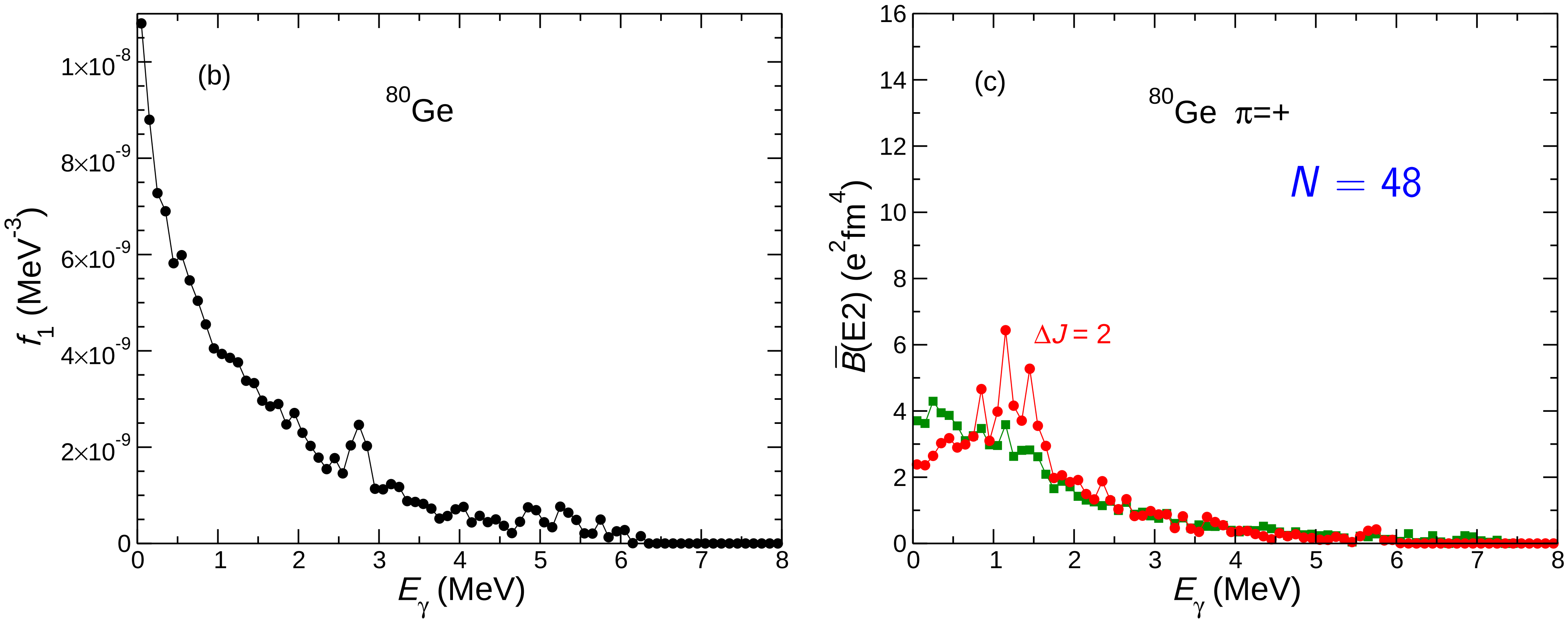
M1 strength functions in Ge isotopes with N = 30 to 48



⇒ Decrease of the bump in the scissors region around 3 MeV.

⇒ Decrease of E2 strength.

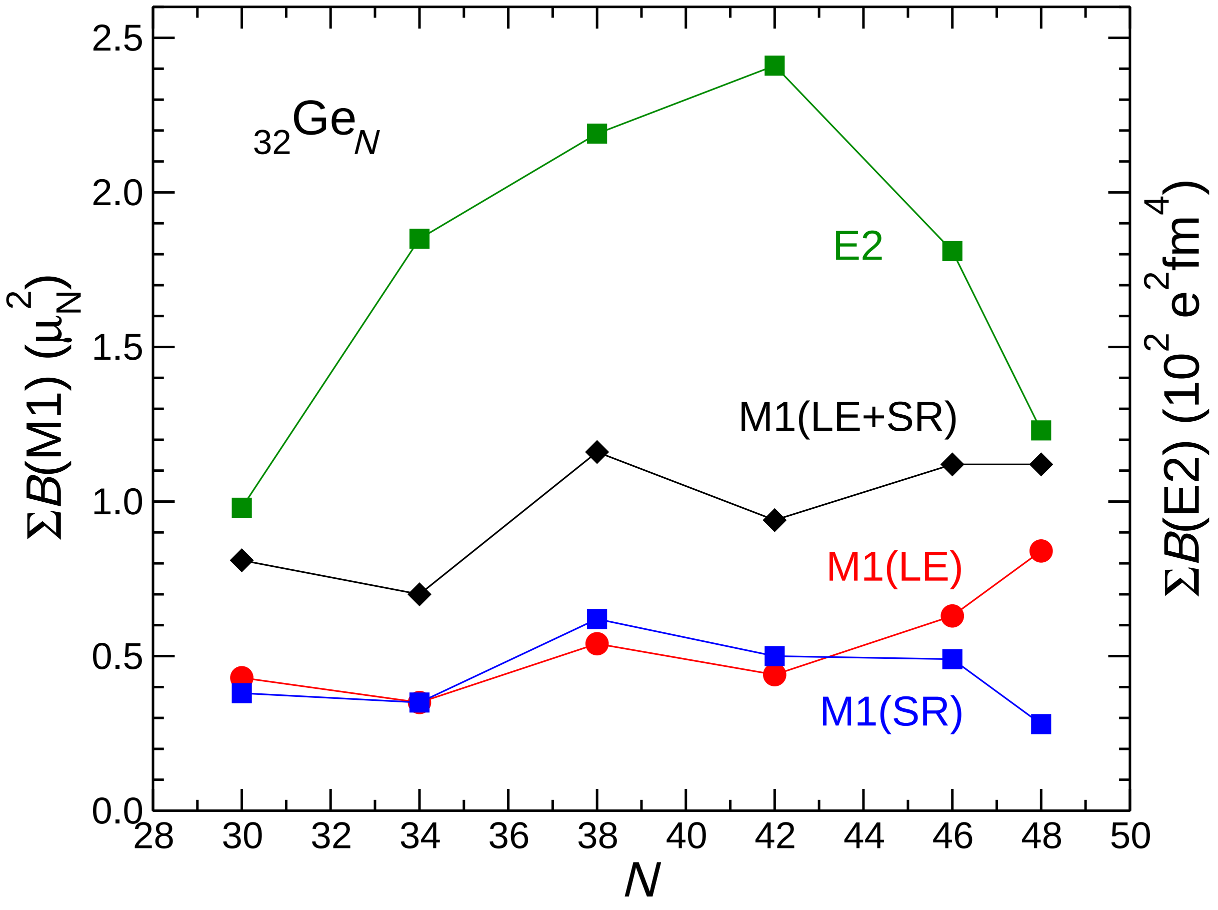
M1 strength functions in Ge isotopes with N = 30 to 48



⇒ Vanishing bump in the scissors region around 3 MeV.

⇒ Little E2 strength.

Summed strengths in Ge isotopes with N = 30 to 48



⇒ Low-energy M1 strength increases with filling the $g_{9/2}$ orbital toward the shell closure.

⇒ M1 strength in the scissors region correlates with collectivity.

Summary

- Shell-model calculations of a large number of M1 and E2 transition strengths in the series of germanium isotopes with $N = 30$ to 48.
- Derivation of average quantities $\Rightarrow$ γ-ray strength functions.
- Occurrence of low-lying M1 modes:
  - Enhanced strength near zero transition energy develops with filling neutrons into the $g_{9/2}$ orbital and becomes strongest near the shell closure at $N = 50$.
  - Strength in the scissors region appears in the midshell nuclei and correlates with the quadrupole collectivity.
- These characteristics are consistent with those earlier found in calculations for iron isotopes and with experimental observations in samarium isotopes.
- The present study of low-lying M1 strength in a relatively long isotopic series demonstrates that the appearance of the two correlated M1 modes is a global phenomenon across various mass regions.
- Published in Phys. Rev. C **105**, 034335 (2022).