E1 and M1 excitations in ^{54}Fe and low-energy M1 strength in open-shell Fe isotopes

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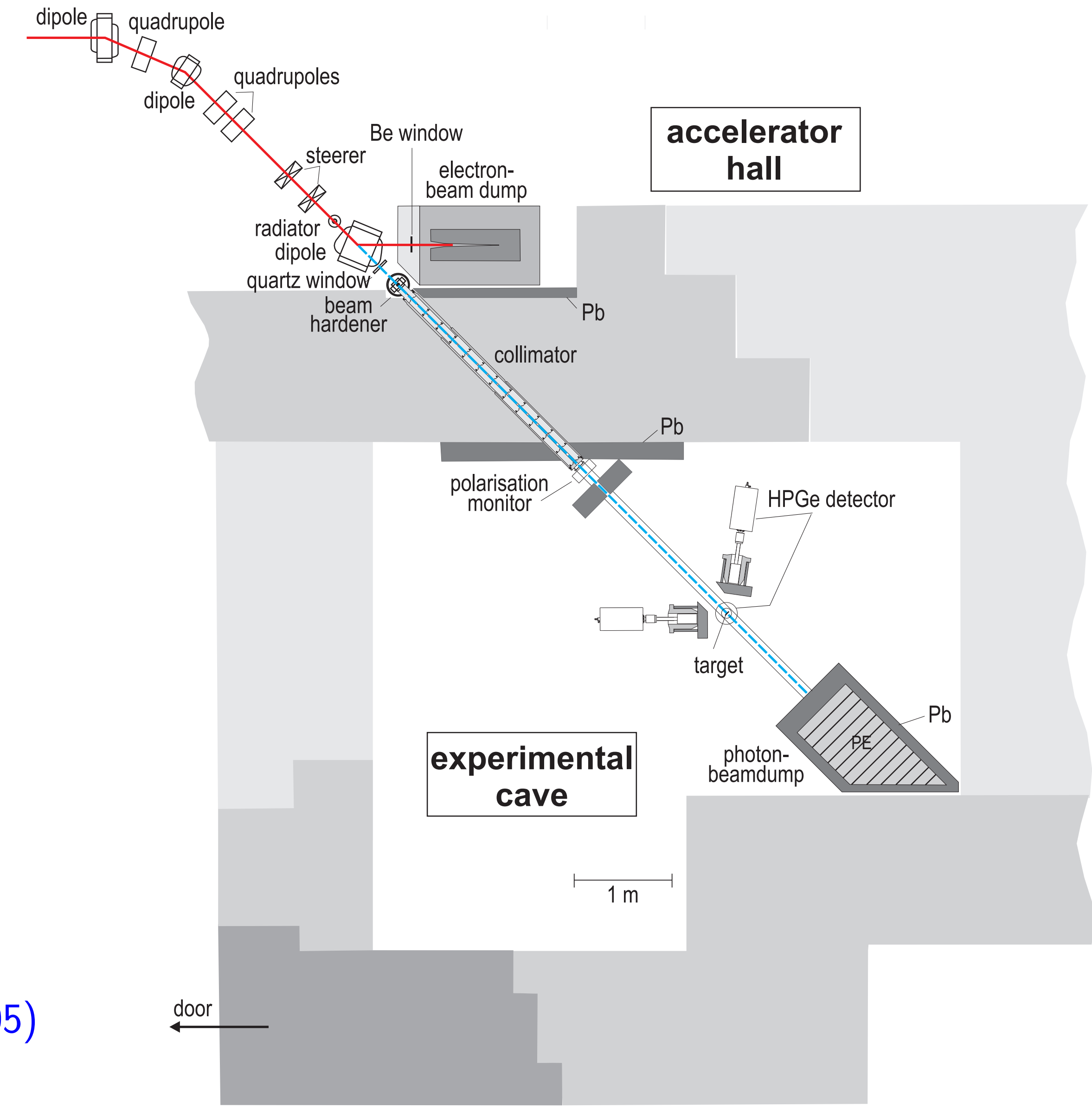
The bremsstrahlung facility at the electron accelerator ELBE

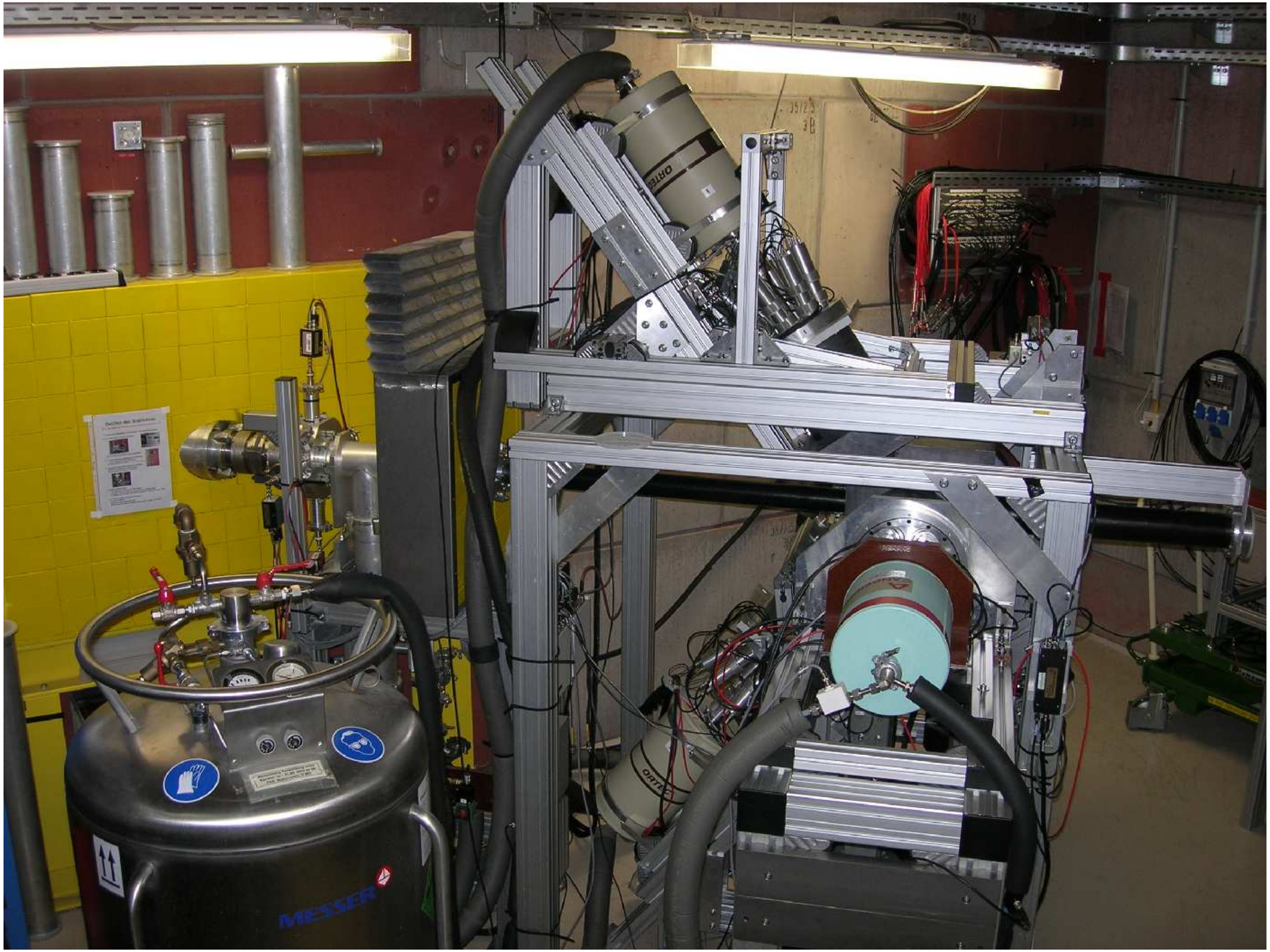
Accelerator parameters:

- Maximum electron energy: $\approx$ 18 MeV
- Maximum average current: $\approx$ 0.8 mA
- Micro-pulse rate: 13 MHz
- Micro-pulse length: $\approx$ 5 ps

R.S. et al., NIM A 555, 211 (2005)

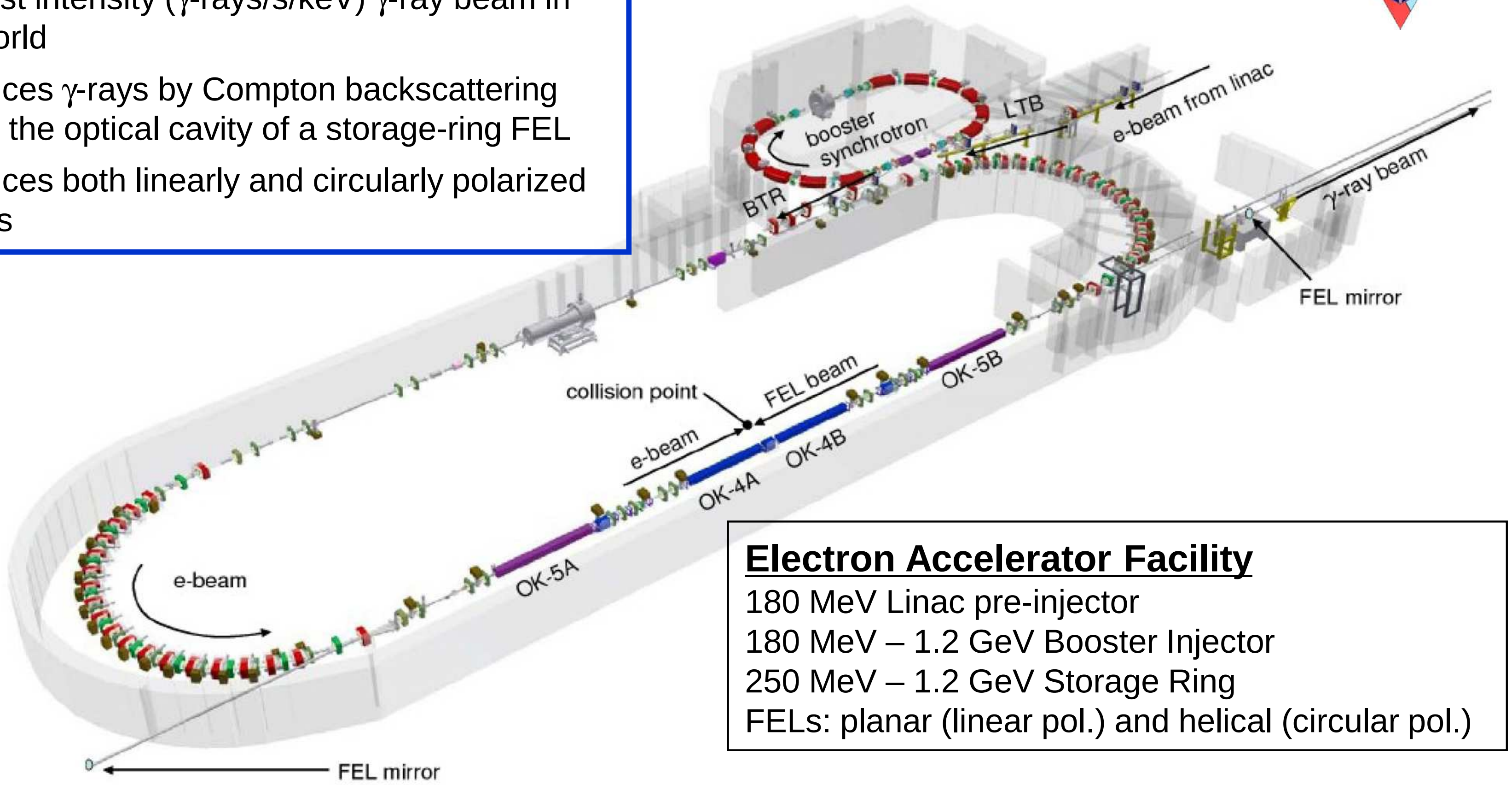


Detector setup at γELBE



High Intensity Gamma-ray Source (HIGS) at TUNL

- Highest intensity (γ-rays/s/keV) γ-ray beam in the world
- Produces γ-rays by Compton backscattering inside the optical cavity of a storage-ring FEL
- Produces both linearly and circularly polarized beams



Electron Accelerator Facility

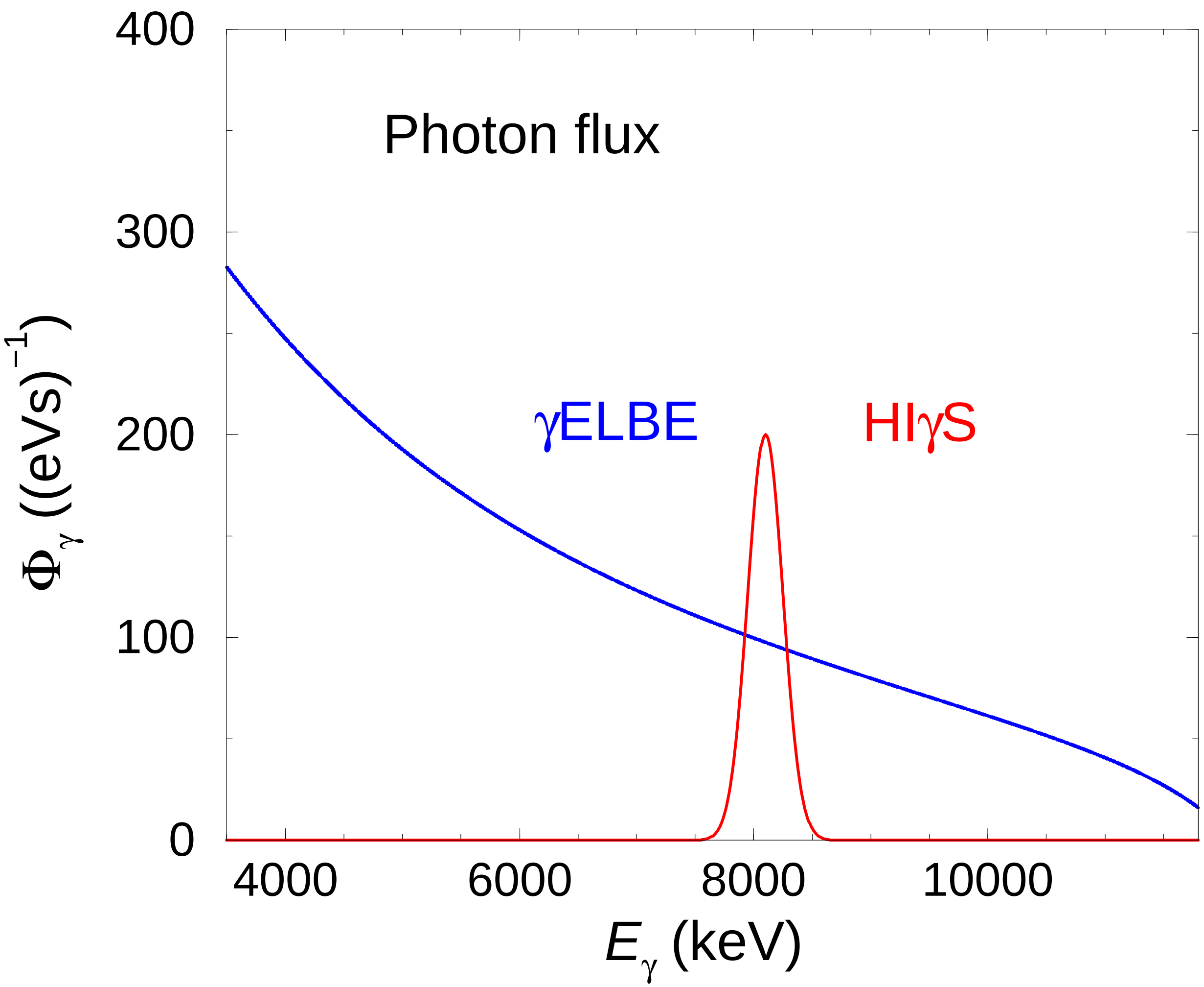
180 MeV Linac pre-injector
180 MeV – 1.2 GeV Booster Injector
250 MeV – 1.2 GeV Storage Ring
FELs: planar (linear pol.) and helical (circular pol.)

γ-ray beam parameters	Values
Energy	1 – 100 MeV
Linear & circular polarization	> 95%
Intensity with 5% $\Delta E_\gamma/E_\gamma$	> 10^7 γ/s

For more details see:
http://www.tunl.duke.edu/higs/

Courtesy of C. Howell (TUNL)

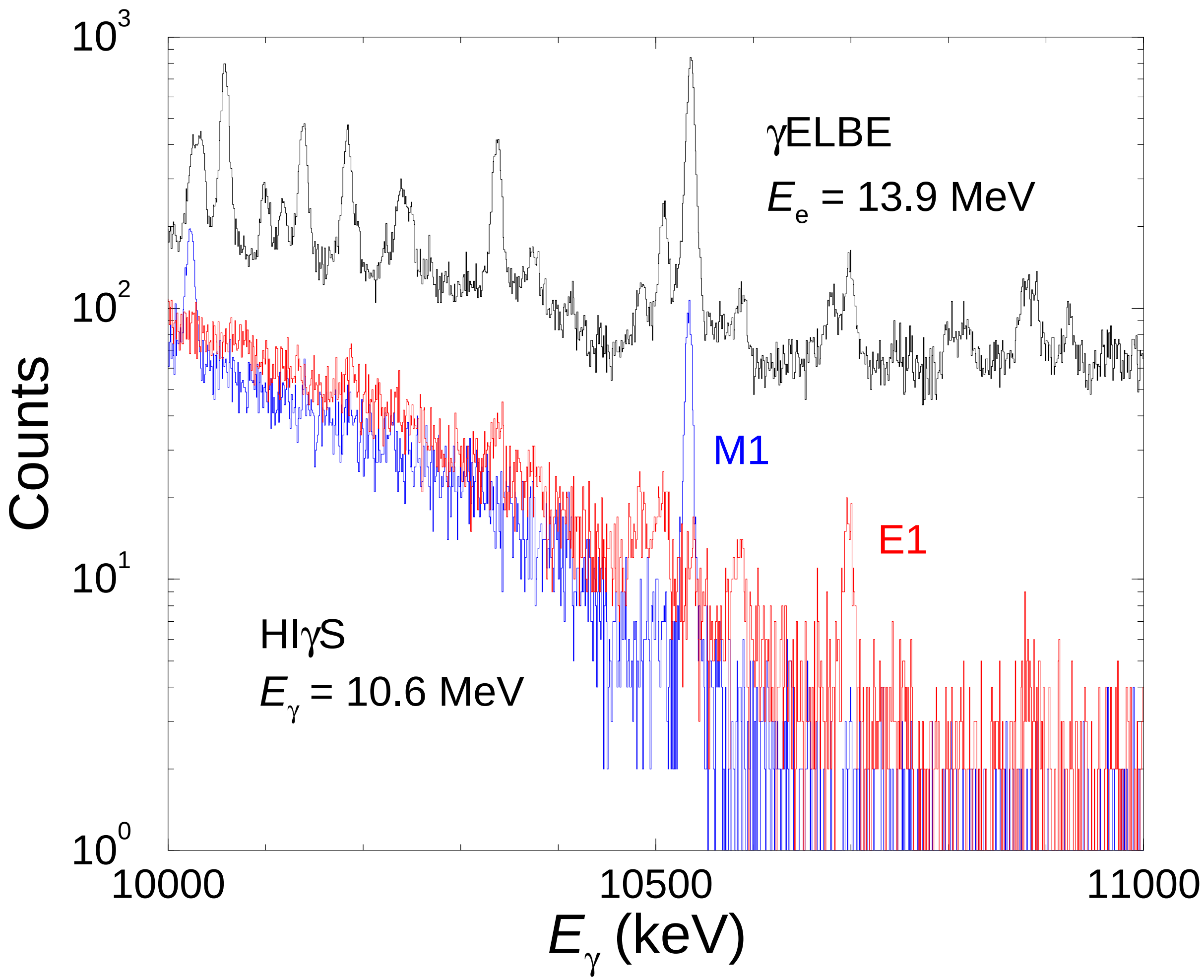
Flux spectra at γELBE and HIγS



γELBE: bremsstrahlung

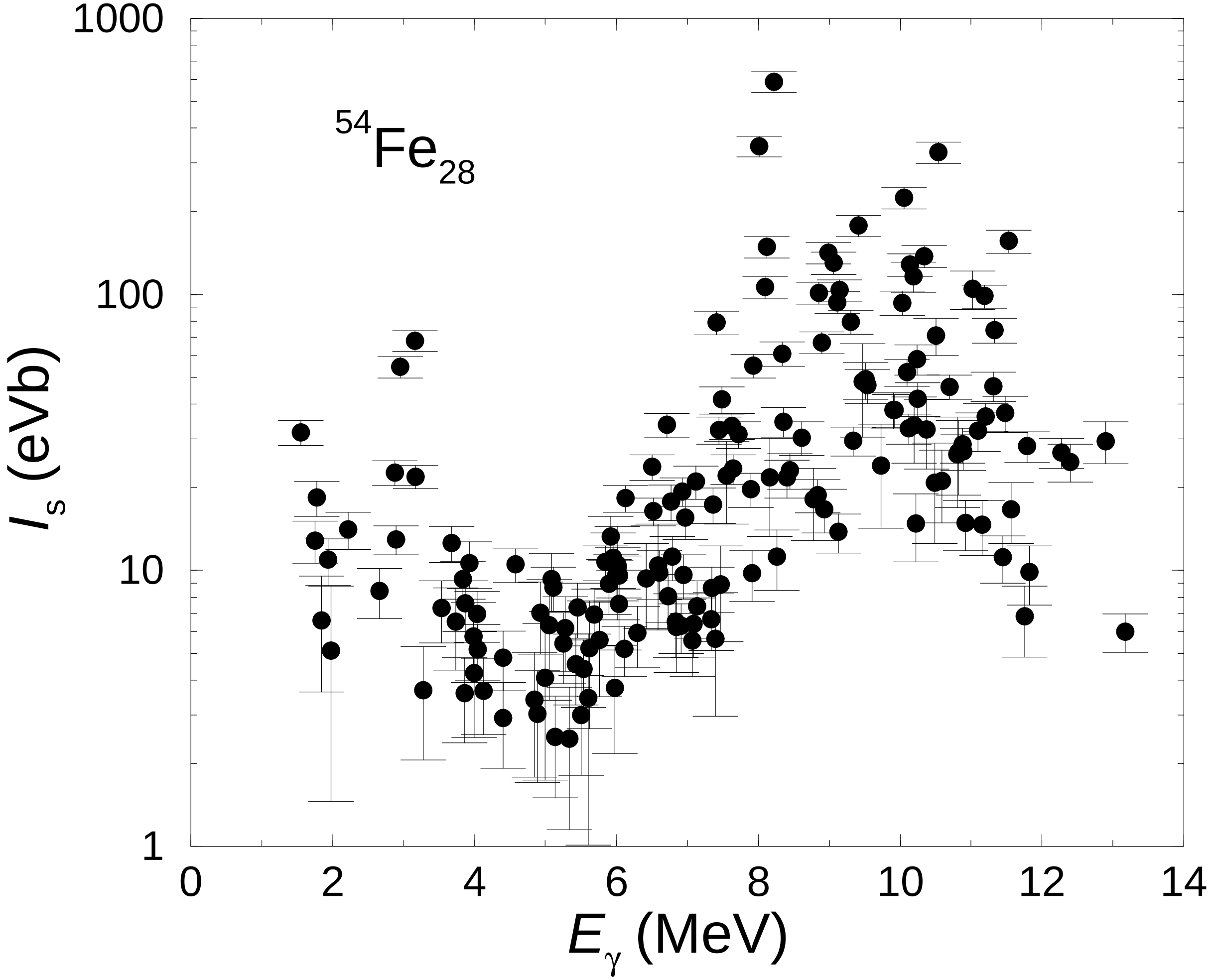
HIγS: quasimononergetic, polarized γ beams

Measurements at γELBE and HIγS



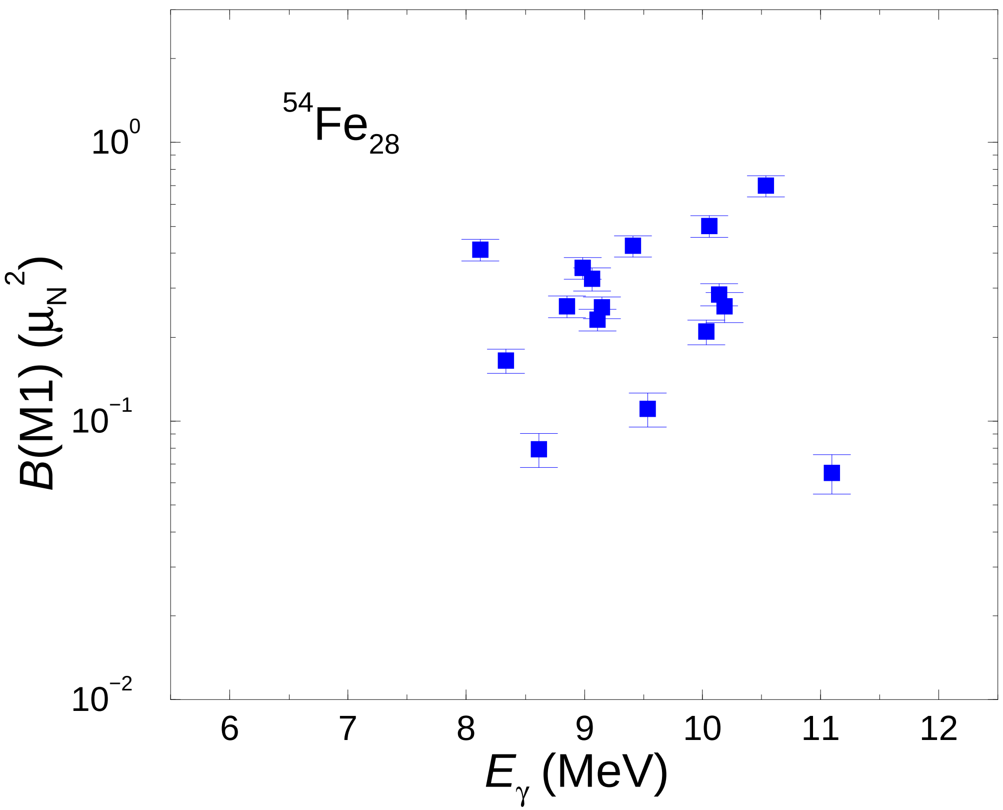
Identification of multipolarities from scattering of polarized γ radiation at HIγS.
E1 radiation in vertical detectors and M1 radiation in horizontal detectors.

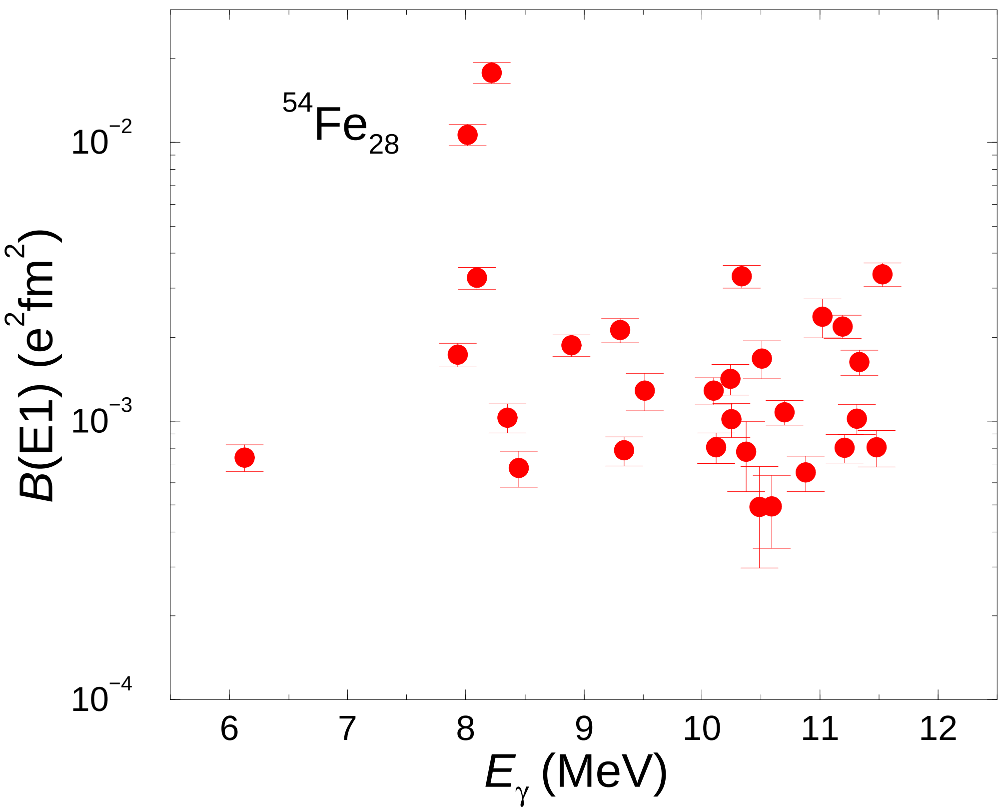
Measurement at γELBE



Energy-integrated scattering cross sections of levels in ^{54}Fe ($J = 1$ assumed)

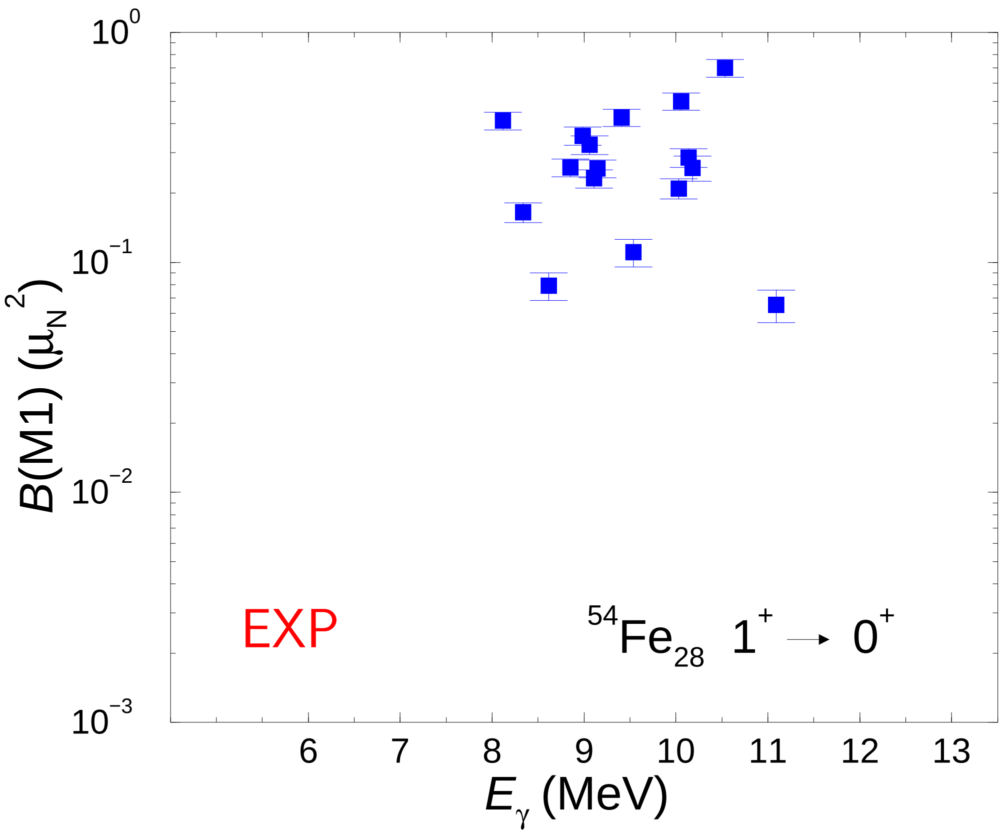
Measurements at γELBE and HIγS

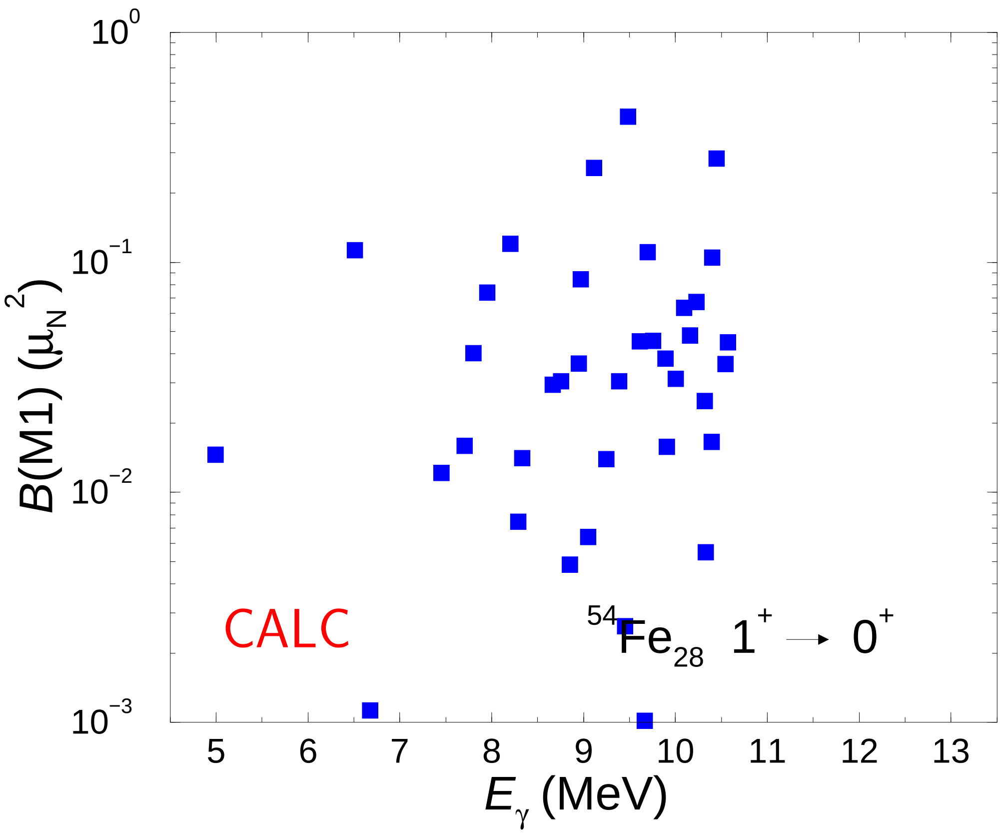




Transitions with clear M1 or E1 assignments from the experiments at HIγS.

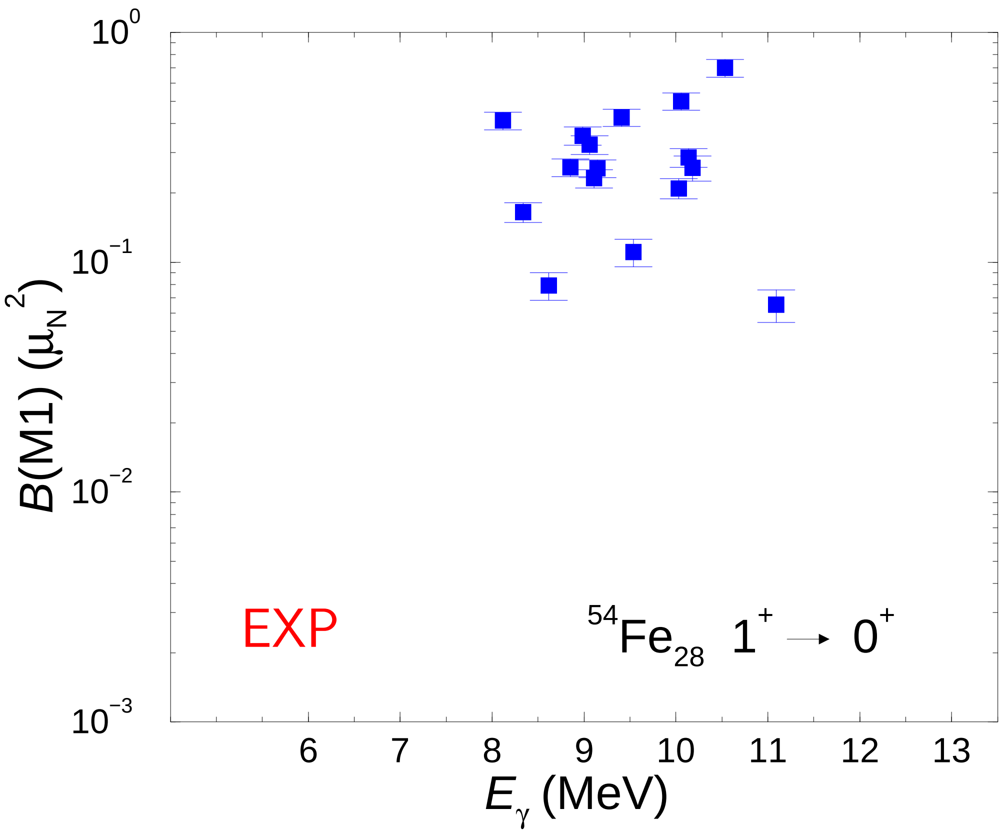
Experimental and calculated B(M1) values in ^{54}Fe

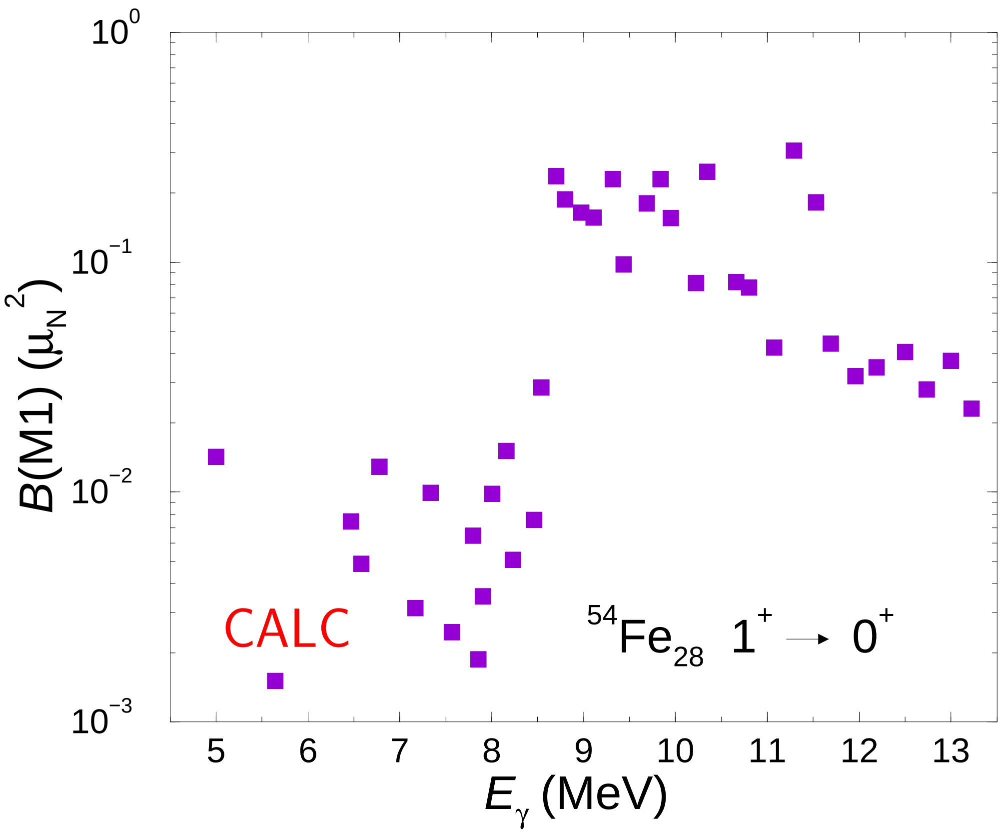




Calculations using NuShellX.

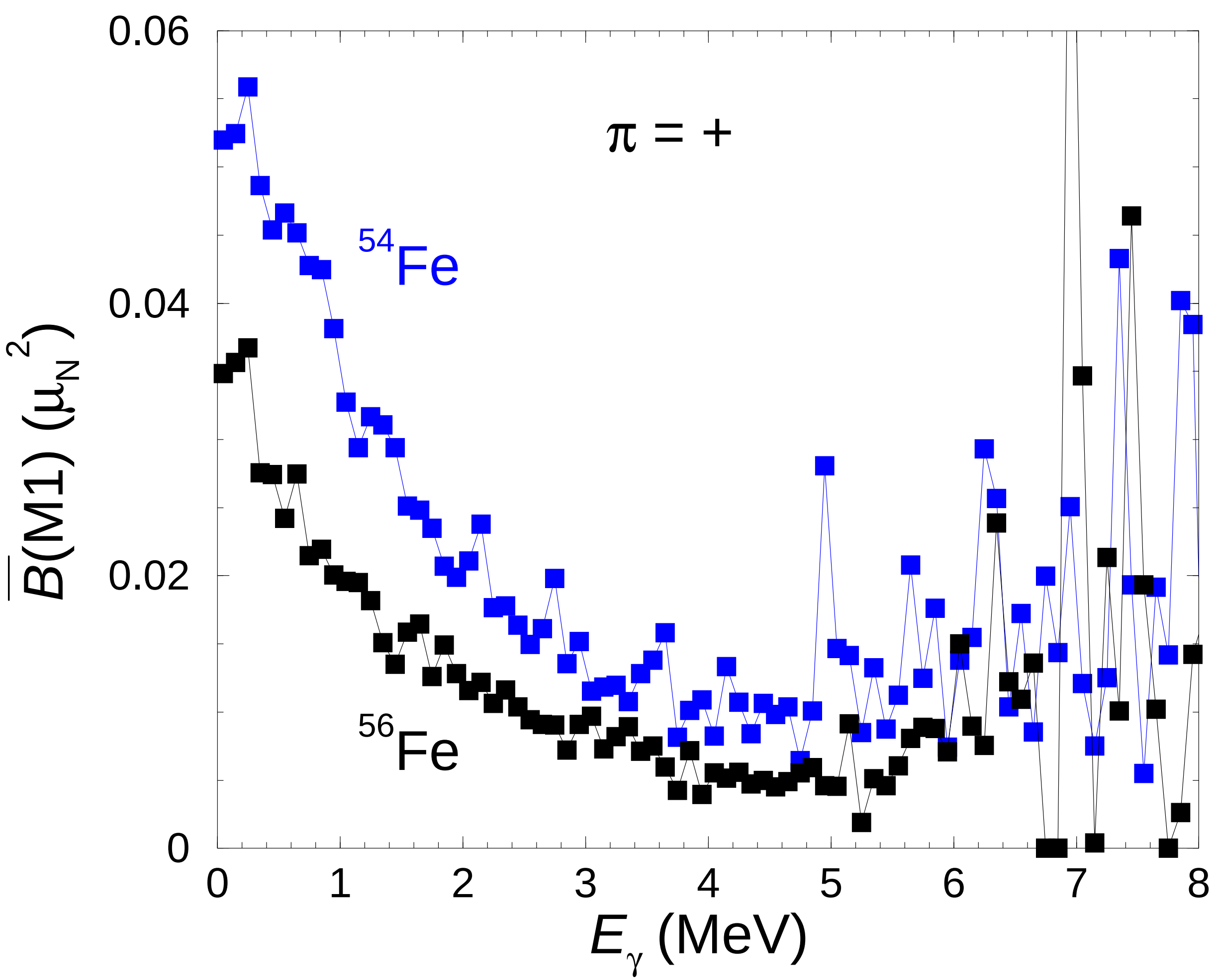
Experimental and calculated B(M1) values in ^{54}Fe





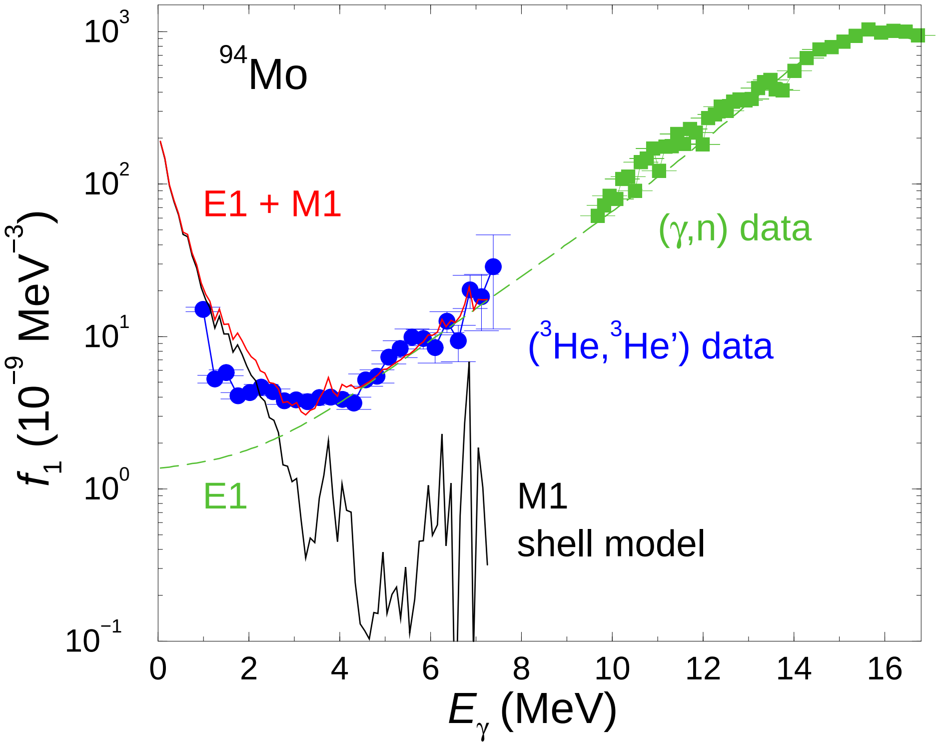
Calculations by K. Sieja.

Low-energy enhancement in $^{54}Fe_{28}$



Values in ^{56}Fe as in PRL 113, 252502 (2014), but without lower limits of B(M1) and without gates in E_x.

Shell-model calculations of M1 strength functions



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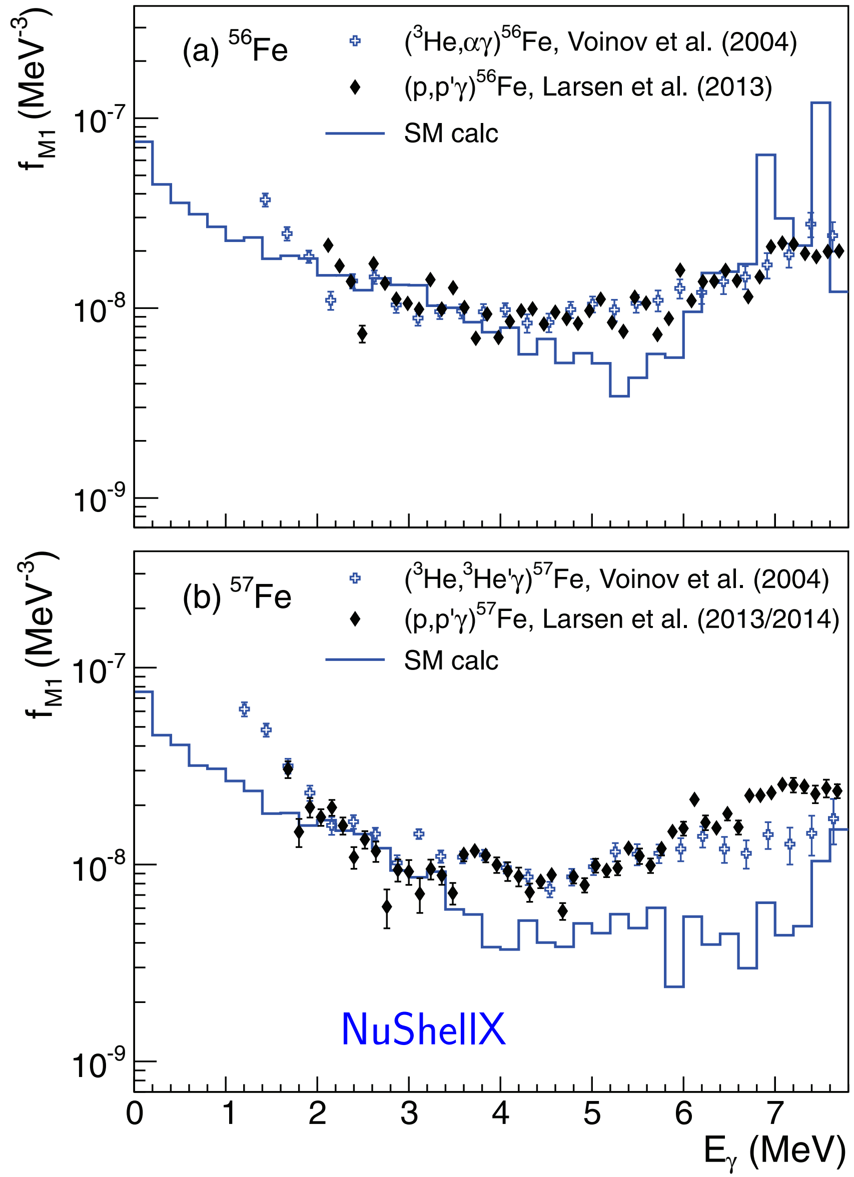


NuShellX

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

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

Shell-model calculations for $^{60}Fe_{34}$, $^{64}Fe_{38}$, $^{68}Fe_{42}$

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)]

Orbits: $\pi(0f_{7/2}^{(6-t)}, 0f_{5/2}^{t}, 1p_{3/2}^{t}, 1p_{1/2}^{t}) \quad \nu(0f_{5/2}^{f5}, 1p_{3/2}^{p3}, 1p_{1/2}^{p1}, 0g_{9/2}^{g9})$

Limitations of occupation numbers:

- $t = 0$ to 2.
- $f5 = 2$ to 6.
- $p3 = 0$ to 4 for ^{60}Fe and 2 to 4 for ^{64,68}Fe.
- $p1 = 0$ to 2 for all.
- $g9 = 0$ to 2, 4, 6 for ^{60,64,68}Fe, respectively.

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

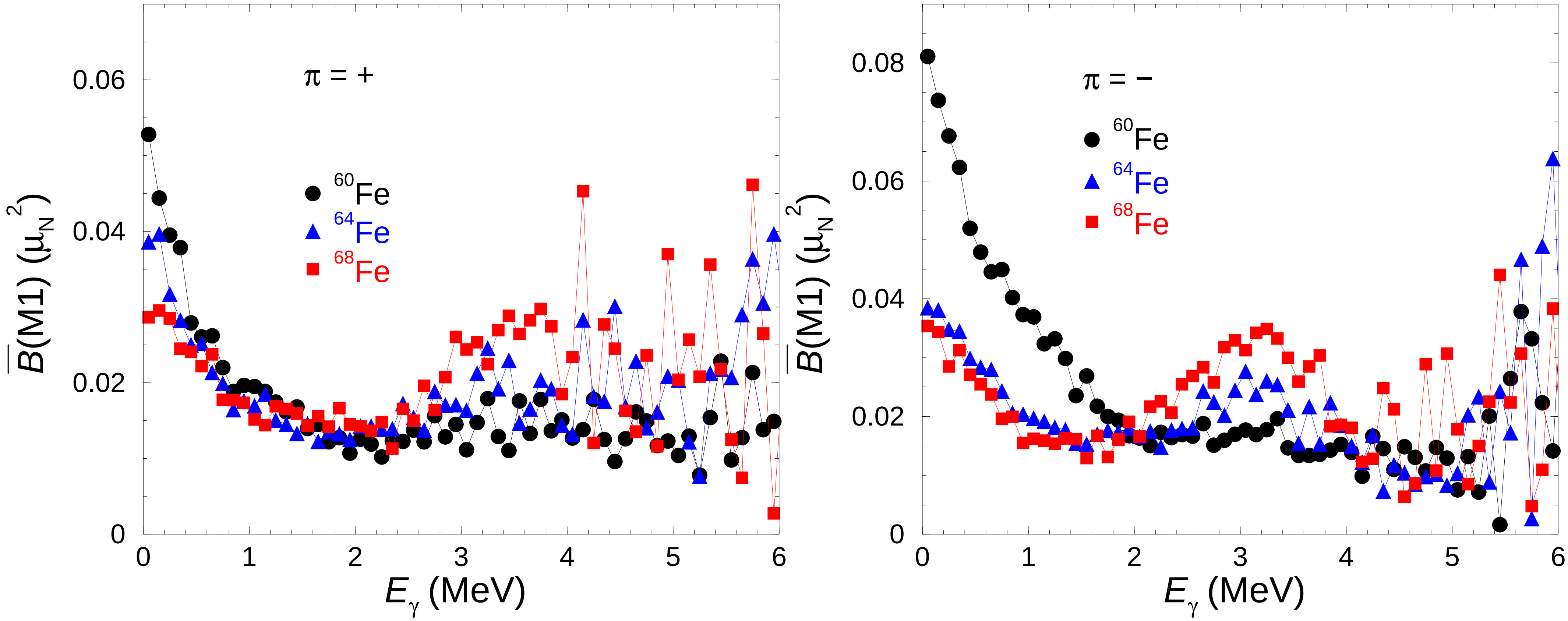
Transition strengths: $e_\pi = 1.5\ e$, $e_\nu = 0.5\ e$; $\quad g_s = 0.9\ g_s^{\text{free}}$

B(E2) values in Fe isotopes

Experimental and calculated reduced E2 transition strengths of the $2_1^+ \rightarrow 0_1^+$ transitions in ^{60,62,64,66,68}Fe.

	$E(2_1^+)$ (keV)		$B(\mathrm{E2}, 2_1^+ \rightarrow 0_1^+)$ (W.u.)			β_2
	EXP	CALC	EXP	GLOB	CALC	CALC
$^{60}Fe_{34}$	824	772	13.6(14)	19.6	26.2	0.31
$^{62}Fe_{36}$	877	544	14.7(18)	17.3	27.8	0.32
			13.6(17)			
$^{64}Fe_{38}$	746	595	$30.9^{+13.8}_{-7.2}$	19.1	26.8	0.32
			22.6(22)			
$^{66}Fe_{40}$	574	568	21.0(21)	23.4	27.8	0.32
$^{68}Fe_{42}$	522	616		24.2	25.4	0.31

Average M1 strengths in Fe isotopes

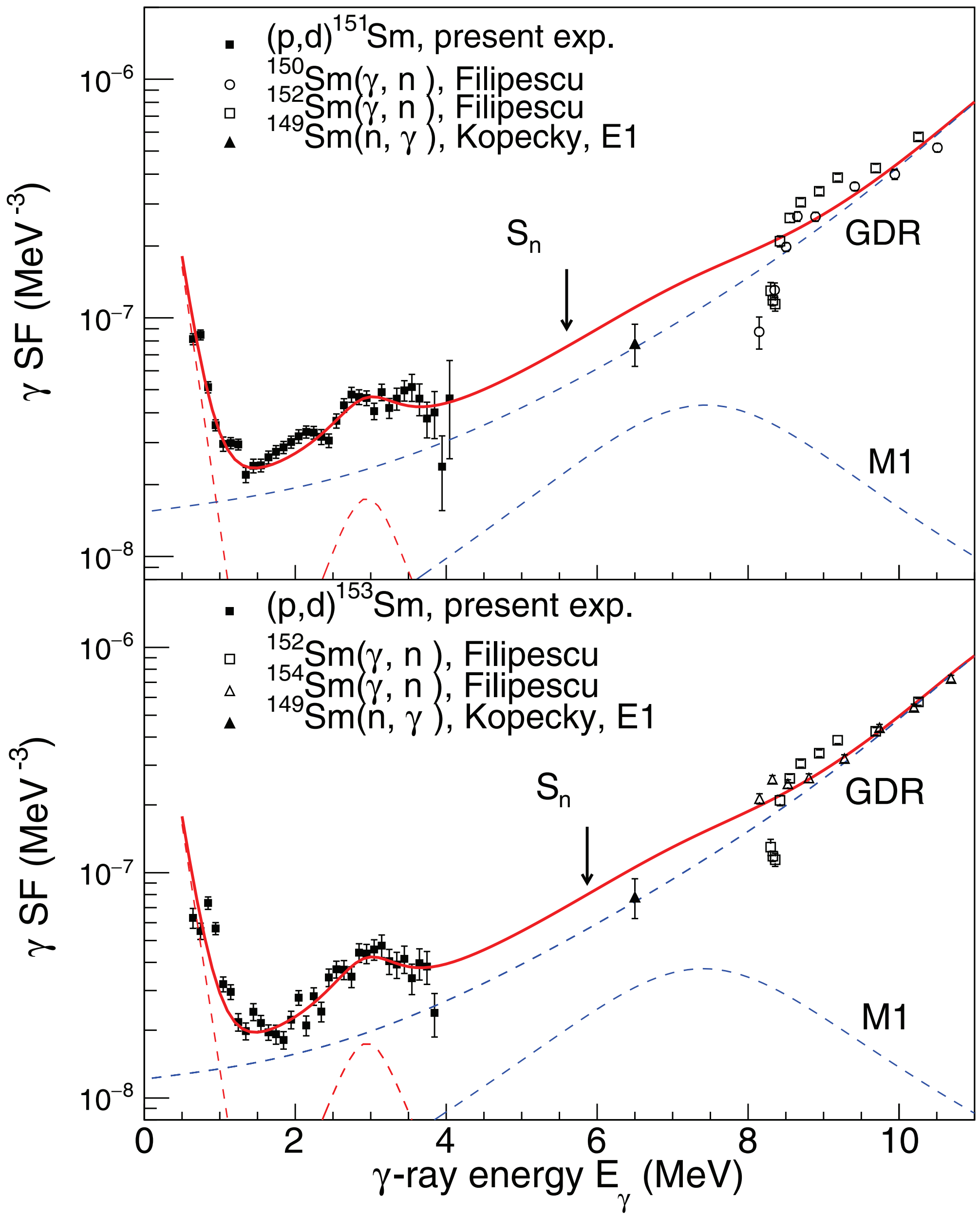


⇒ Enhancement of M1 strength toward very low transition energy.

⇒ Development of a bump around 3 MeV with increasing neutron number.

PRL 118, 092502 (2017)

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



(p,d) data:

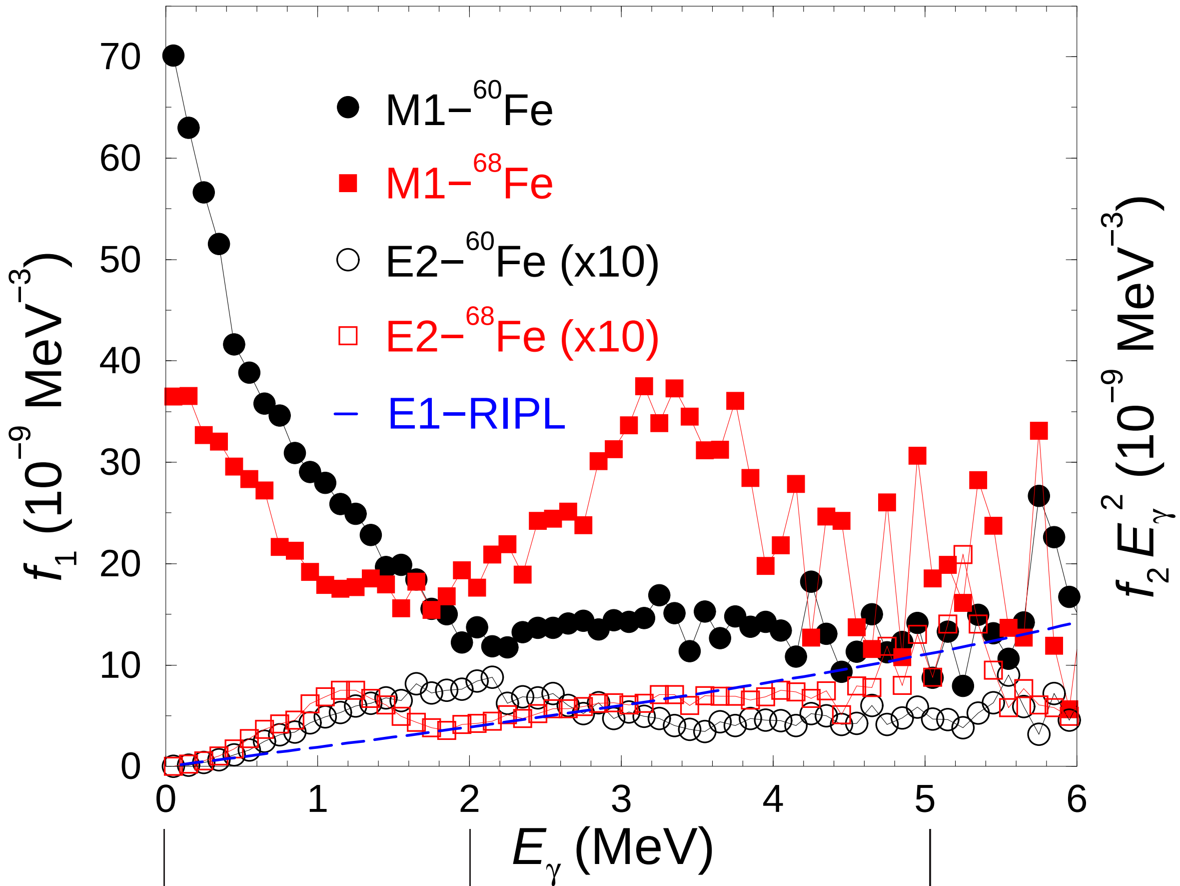
A. Simon et al.

PRC 93, 034303 (2016)

⇒ First observation of upbend and scissors resonance in one nuclide

⇒ Strength in the scissors region about twice of that found in (γ,γ) experiments

Strength functions in ^{60}Fe and ^{68}Fe



	$E_\gamma < 2$ MeV	$2 \leq E_\gamma \leq 5$ MeV	Sum
$^{60}Fe_{34}$	5.67	3.52	9.19
$^{64}Fe_{42}$	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

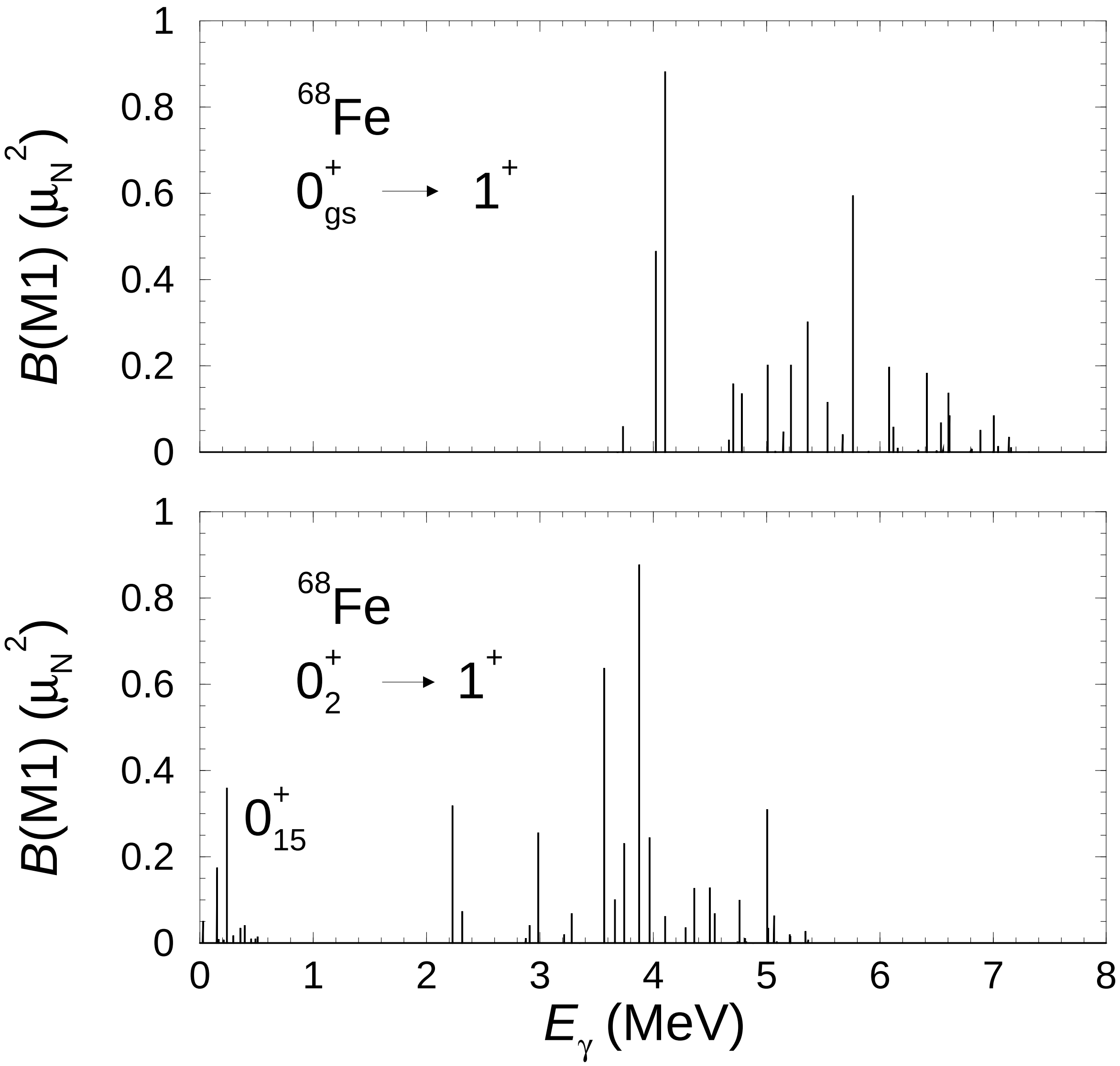
$f_1 = 16\pi/9\ (\hbar c)^{-3}\ \overline{B}(\mathrm{M1})\ \rho(E_x, J)$

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

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

PRL 118, 092502 (2017)

Absorption strength in ^{68}Fe

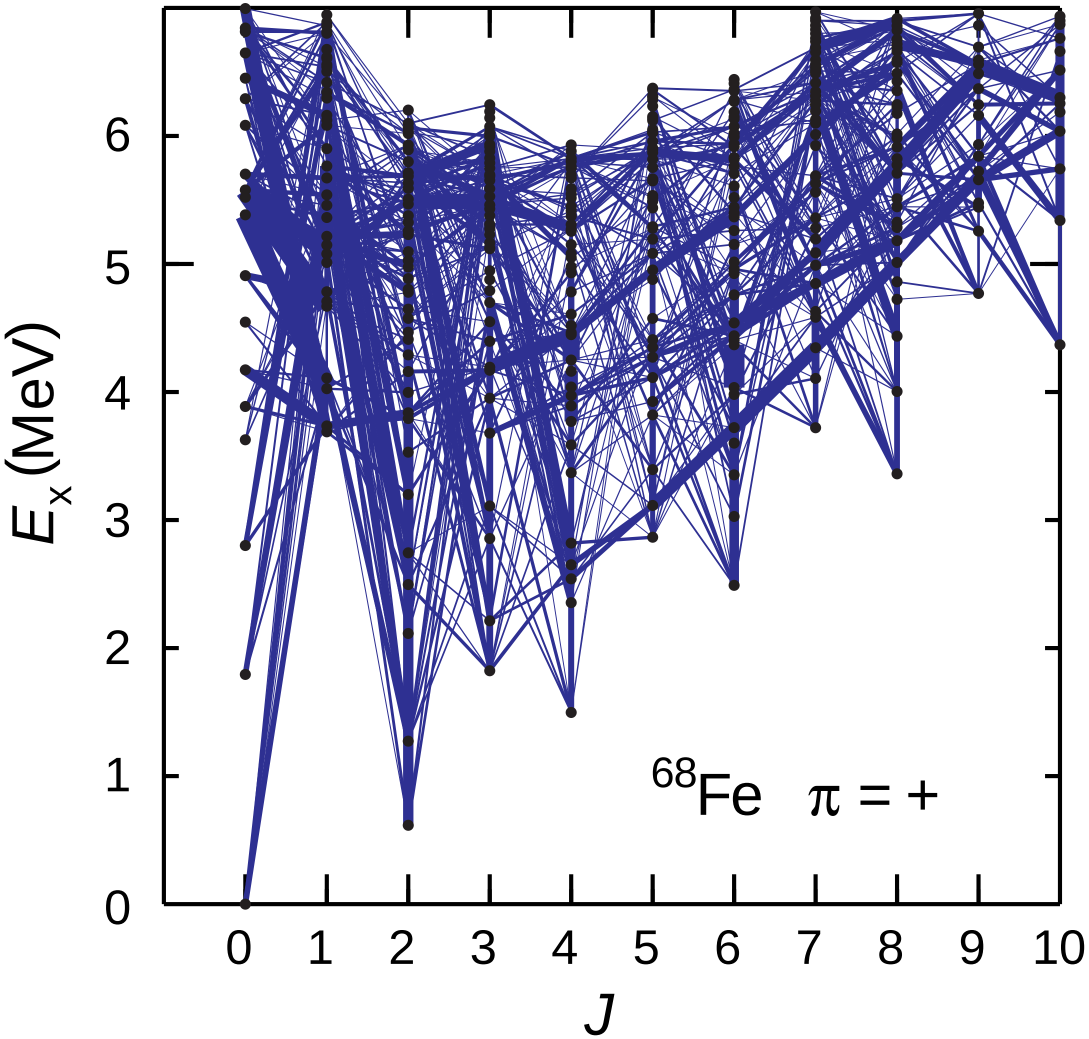


$\sum B(\mathrm{M1})$ (μ_N^2) $(2\leq E_\gamma \leq 5$ MeV$)$	$0_1^+ \rightarrow 1^+$	$0_2^+ \rightarrow 1^+$
$^{60}\mathrm{Fe}_{34}$	0.66	1.98
$^{64}\mathrm{Fe}_{42}$	1.65	2.59
$^{68}\mathrm{Fe}_{42}$	1.74	3.45

$\Rightarrow$ Strength from excited states about two times that found in (γ,γ) experiments because of more strong M1 transitions in the scissors region.

PRL 118, 092502 (2017)

M1 transitions in ^{68}Fe



Transitions with $B(\mathrm{M1}) > 0.1\mu_N^2$.
Line widths $\sim B(\mathrm{M1})$ values.

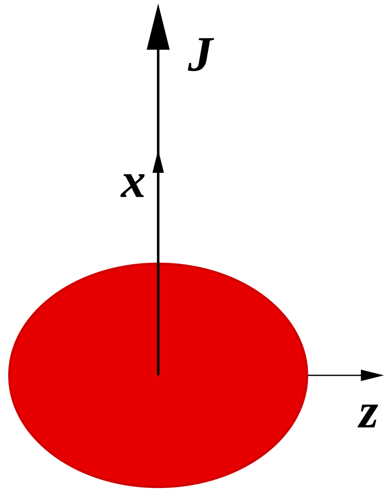
$J_i = J_f, J_f \pm 1$, $E_\gamma < 2$ MeV:
low-energy upbend

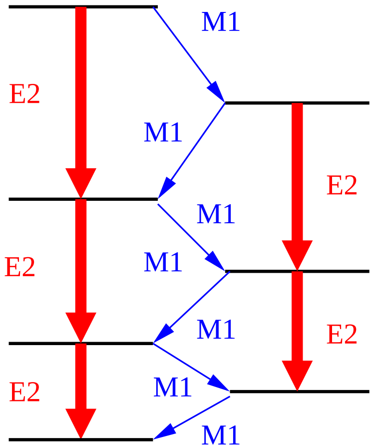
$J_i = J_f \pm 1$, $E_\gamma \approx 3$ MeV:
scissors region

$J_i = J_f + 1$, $E_x \sim J(J+1)$:
shears bands

Nuclear rotation

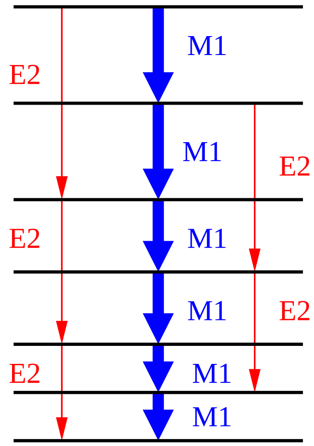
electric (collective) rotation

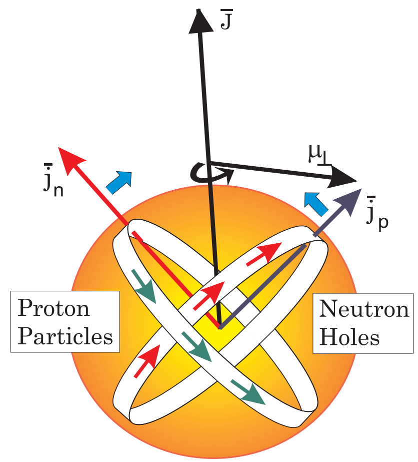




$B(\mathrm{E2}) \sim Q_0^2$

magnetic rotation

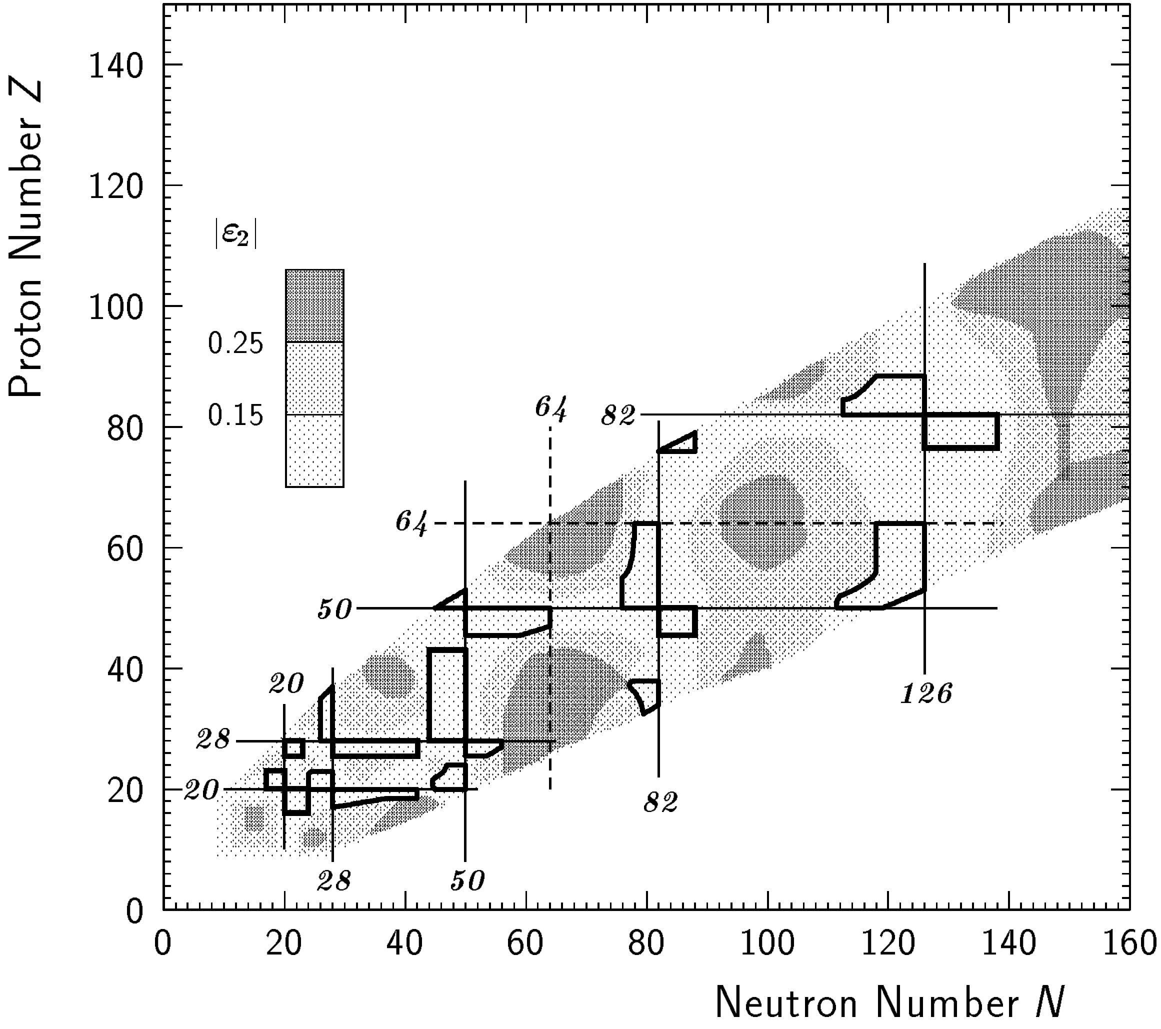




$B(\mathrm{M1}) \sim \mu_\perp^2$

$$E_x = \frac{\hbar^2}{2\Theta} J(J+1); \quad E_\gamma \sim J$$

Predicted Appearance of magnetic rotation



Magnetic rotation - "Shears bands"

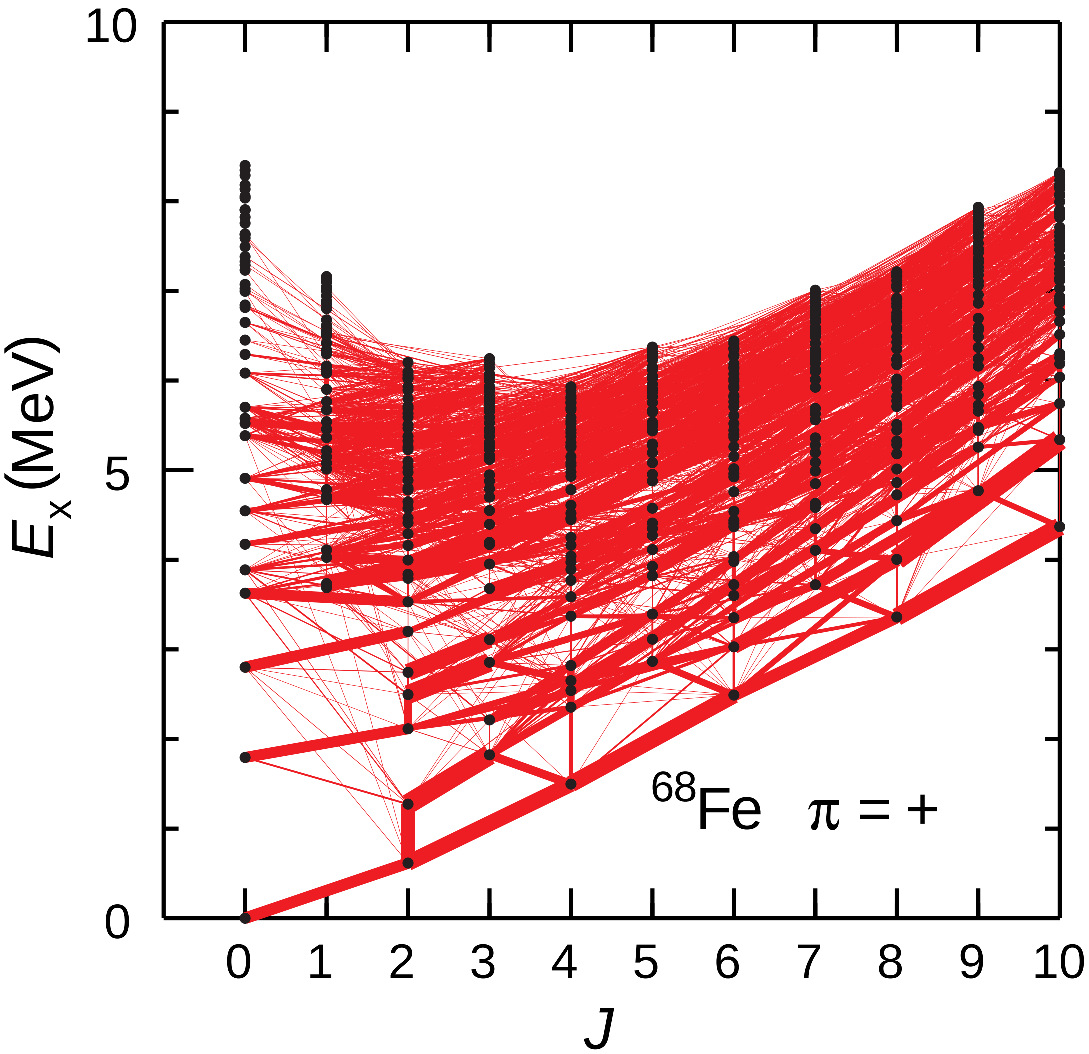
S. Frauendorf, Rev. Mod. Phys. 73, 463 (2001).

Examples near $N = 50$: ^{82}Rb, ^{84}Rb

H. Schnare et al., PRL 82, 4408 (1999).

R.S. et al., PRC 66, 024310 (2002).

E2 transitions in ^{68}Fe

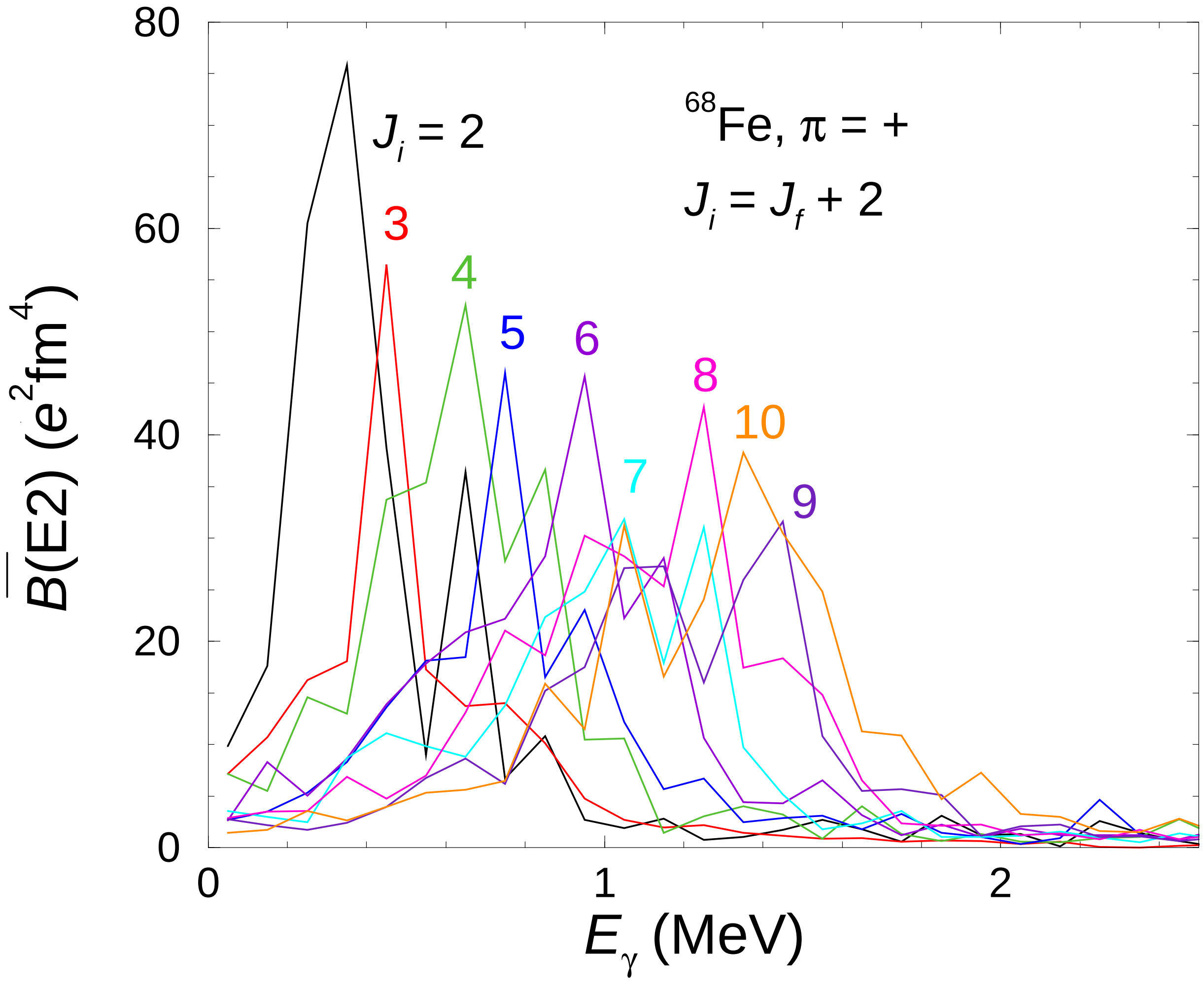


Line widths $\sim B(\mathrm{E2})$ values.

$J_i = J_f, J_f \pm 1$:
admixtures to dipole transitions

$J_i = J_f + 2$, $E_x \approx J(J+1)/(2\mathcal{J})$:
collective bands

Average E2 strengths in ^{68}Fe



Largest B(E2) values in rotational-like sequences:

$$E_x \approx J(J+1)/(2\mathcal{J})$$

$$E_\gamma \approx (2J-1)/\mathcal{J}$$

$$\mathcal{J} \approx 12\ \mathrm{MeV}^{-1}$$

Summary

- Photon-scattering experiments on $^{54}Fe_{28}$ carried out at γELBE and HIγS. 30 prominent E1 and 16 M1 transitions observed up to 11.5 MeV.
- Strength in the quasicontinuum in analysis. Additional experiment with bremsstrahlung up to 7.5 MeV needed.
- Large-scale shell-model calculations performed for $^{60}Fe_{34}$, $^{64}Fe_{38}$, $^{68}Fe_{42}$. Collective properties of yrast states are reproduced in the used model space.
- The low-energy M1 strength decreases with increasing neutron number and a bump in the scissors region develops while the sum of the two stays nearly constant.
- The strength in the scissors region includes many transitions between excited states. This explains the different strengths found in experiments using photoexcitation and light-ion induced reactions.

$\Rightarrow$

Collaborators

Experiments at γELBE (HZDR):	D. Bemmerer, R. Beyer, A.R. Junghans, T. Kögler, A. Wagner *et al.*
Experiments at HIγS (TUNL):	M. Bhike, Krishichayan, W. Tornow, U. Gayer, H. Pai (U Darmstadt), V. Derya (U Köln)
Calculations:	B.A. Brown (NSCL/MSU) S. Frauendorf (U Notre Dame) K. Sieja (IPHC/CNRS)

Gamma-ray strength functions

- Gamma-ray strength functions describe average electromagnetic transition strengths in the quasicontinuum of nuclear states at high excitation energy:

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

- Photoabsorption:

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

- 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.