M1-excitations in deformed nuclei

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Introduction

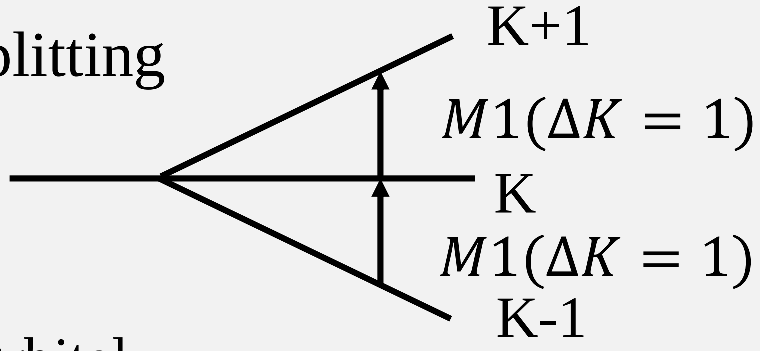
- Magnetic dipole excitations in nuclei provide important information on the nuclear spin and orbital magnetism
- These excitations were mainly represented by M1(K = 1) spin-flip giant resonance (SFR) and low-energy M1 orbital scissor resonance (OSR).
- Balbutsev, Molodtsova, and Schuck have predicted [within the Wigner function moments (WFM) method] that OSR should be supplemented by a low-energy spin-scissor mode (SSR)

E.B. Balbutsev, I. V. Molodtsova, and P. Schuck, Nucl. Phys. A 872, 42 (2011).
E.B. Balbutsev, I. V. Molodtsova, and P. Schuck, Phys. Rev. C 97, 044316 (2018).
E.B. Balbutsev, I.V. Molodtsova, A.V. Sushkov, N.Yu. Shirikova, Phys. of Atom. Nucl., 2019.
E.B. Balbutsev, I. V. Molodtsova, and P. Schuck, Phys. Atom. Nucl. 83, 212 (2020).

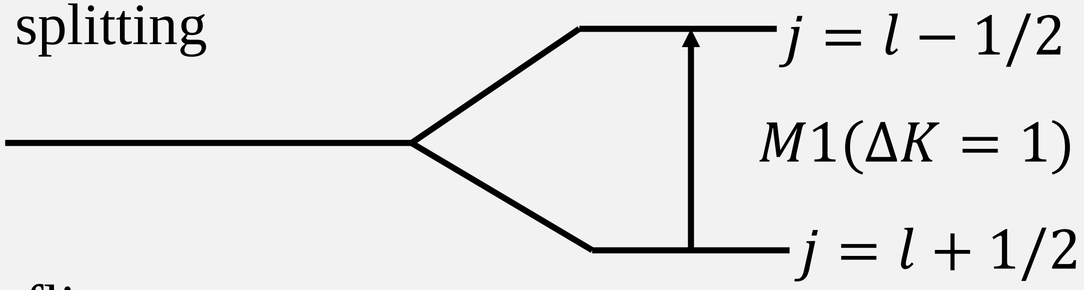
- We analyzed the prediction in the framework of a microscopic self-consistent quasiparticle random phase approximation (QRPA).
- Deformed ^{160,162,164}Dy and ^{232}Th were considered in which the WFM predicted the existence of a spin scissor resonance.

Magnetic excitations

Deformation splitting

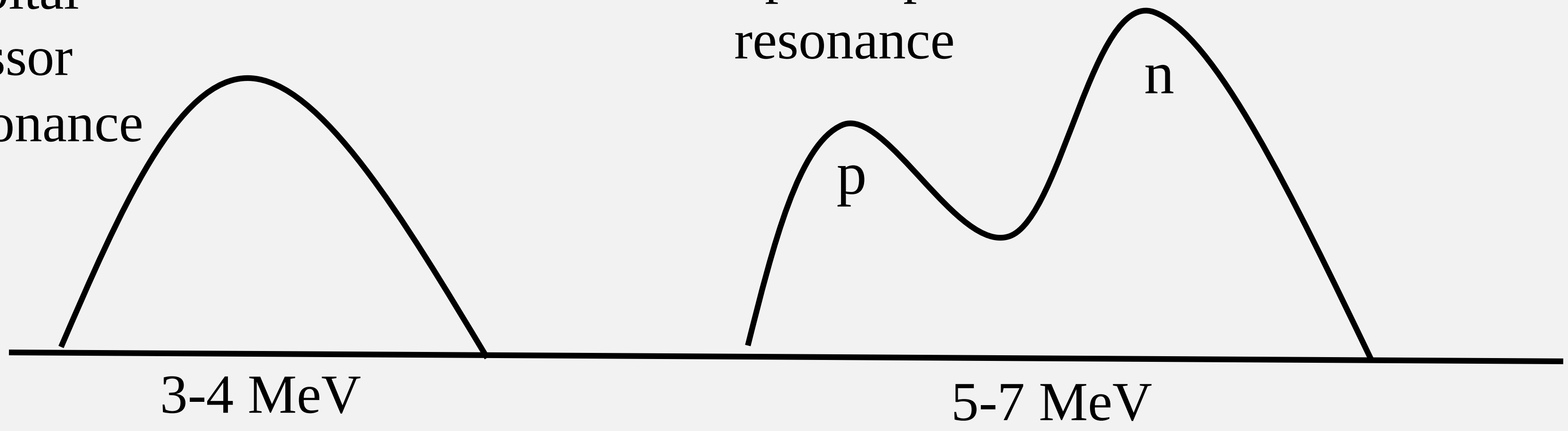


Spin-orbital splitting

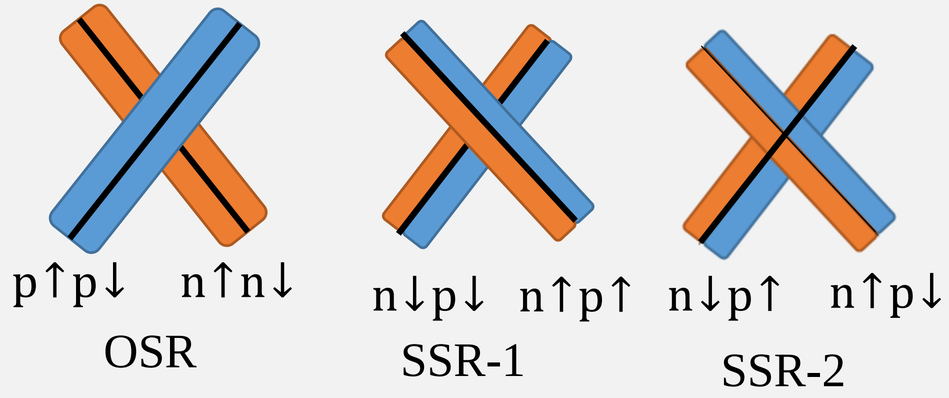


Orbital scissor resonance

Spin-flip resonance



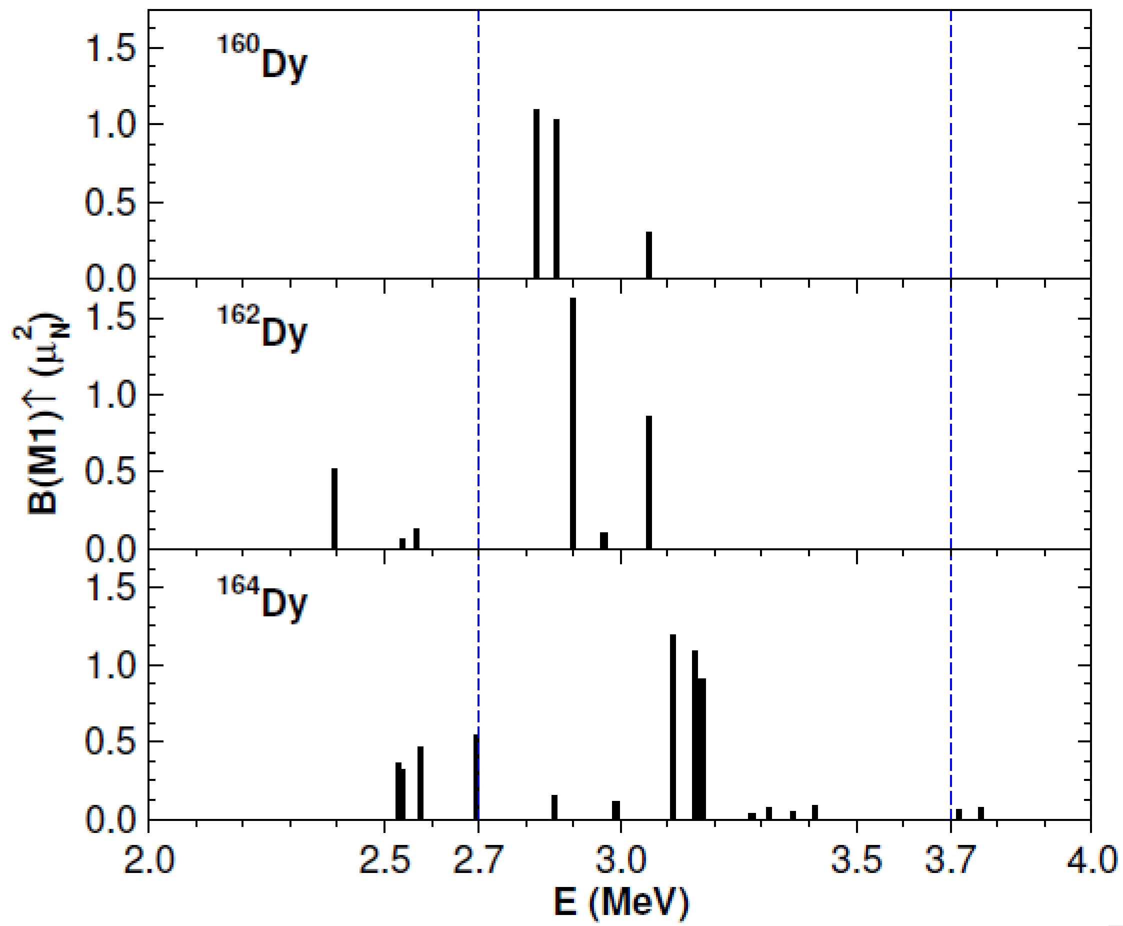
E.B. Balbutsev, I.V. Molodtsova, A.V. Sushkov, N.Yu. Shirikova, Phys. of Atom. Nucl., 2019.

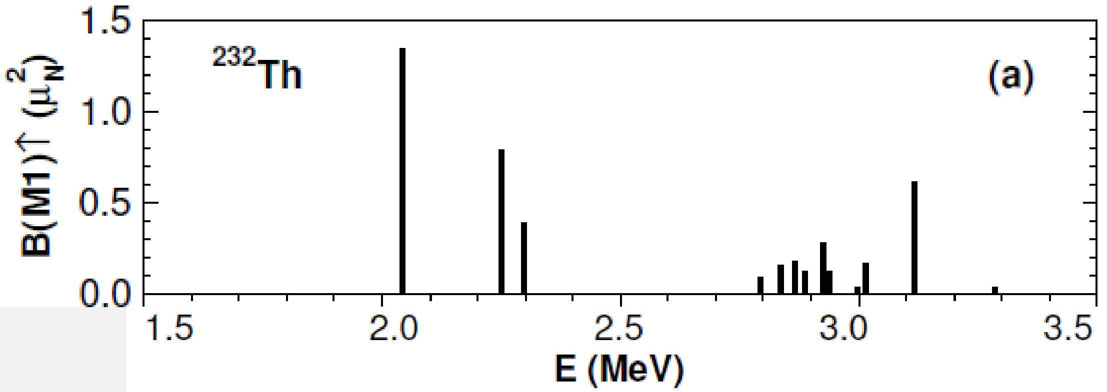


Triple structure of SSR predicted in WFM

NRF experiments

WFM:
The IV M1 states below 2.7 MeV are spin scissor states!





E.B. Balbutsev, I.V. Molodtsova, A.V. Sushkov, N.Yu. Shirikova, Phys. of Atom. Nucl., 2019.
J. Margraf, T. Eckert et al., PRC, 1995.
A.S. Adekola et al., PRC, 2011.

Model

- The QRPA code (Repko) and SKYAX (Reinhard) is used.
- Fully self-consistent QRPA (mean field and residual interaction are derived from the initial Skyrme functional, p-p and p-h channels, residual interaction takes into account all terms from the initial functional).
- For example, 2qp basis includes 5270 proton and 9257 neutron pairs for SG2.
- Spurious admixture are removed.

A. Repko, J. Kvasil, and V. O. Nesterenko, PRC 99, 044307 (2019).

- 3 Skyrme forces (SkM*, SVbas, SG2)
- Volume (SkM* and SG2) and surface (SVbas) pairings.

A. Repko, J. Kvasil, V. O. Nesterenko, and P.-G. Reinhard, EPJA 53, 221 (2017).

	Spin-orbital parameters	
	b4	b4’ [MeV fm^5]
SkM* : J. Bartel et al, NPA 386, 79 (1982).	65.0	65.0
SVbas: P. Klupfel, P.-G. Reinhard et al, PRC 79 034310 (2009).	62.3	34.1
SG2: N. Van Giai and H. Sagawa, Phys. Lett. B 106, 379 (1981).	52.5	52.5

Calculation details

nucl.	SkM*	SVbas	SG2	exp.
^{160}Dy	0.339	0.331	0.339	0.334
^{162}Dy	0.351	0.345	0.346	0.341
^{164}Dy	0.354	0.348	0.352	0.349
^{232}Th	0.256	0.247	0.238	0.248

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type of tran.	g_l^p	g_l^n	η
orbital	1.0	0.0	0.0
spin	0.0	0.0	0.7
total	1.0	0.0	0.7

M. N. Harakeh and A. van der Woude, *Giant resonances*, v.24 (2001)

The calculated deformation for these Skyrme forces is consistent with experimental data.

M11 transition operator:

$$\hat{\Gamma}(M11) = \mu_N \sqrt{\frac{3}{4\pi}} \sum_{q\epsilon p,n} [g_s^q \hat{s}(\mu = 1) + g_l^q \hat{l}(\mu = 1)]$$

transition probabilities:

$$B_\nu(M1) = 2|\langle\nu|\,\hat{\Gamma}(M11)\,|0\rangle|^2$$

bare currents:

$$\hat{\mathbf{j}}_{\mathrm{b}}(\mathbf{r}) = \hat{\mathbf{j}}_{\mathrm{c}}(\mathbf{r}) + \hat{\mathbf{j}}_{\mathrm{m}}(\mathbf{r}) = \frac{e\hbar}{m} \sum_{q=n,p} (\hat{\mathbf{j}}^q_{\mathrm{c}}(\mathbf{r}) + \hat{\mathbf{j}}^q_{\mathrm{m}}(\mathbf{r}))$$

where

$$\begin{aligned}
\hat{\mathbf{j}}^q_{\mathrm{c}}(\mathbf{r}) &= -i\frac{e^q_{\mathrm{eff}}}{2} \sum_{k\epsilon q} (\delta(\mathbf{r}-\mathbf{r}_k)\nabla_k + \nabla_k\delta(\mathbf{r}-\mathbf{r}_k)) \\
\hat{\mathbf{j}}^q_{\mathrm{m}}(\mathbf{r}) &= \frac{\bar{g}^q_s}{2} \sum_{k\epsilon q} (\nabla_k \times \hat{\mathbf{s}}_{qk})\delta(\mathbf{r}-\mathbf{r}_k).
\end{aligned}$$

$\bar{g}_s^q = \eta g_s^q$, η is the quenching.

Spin-flip M1-giant resonance

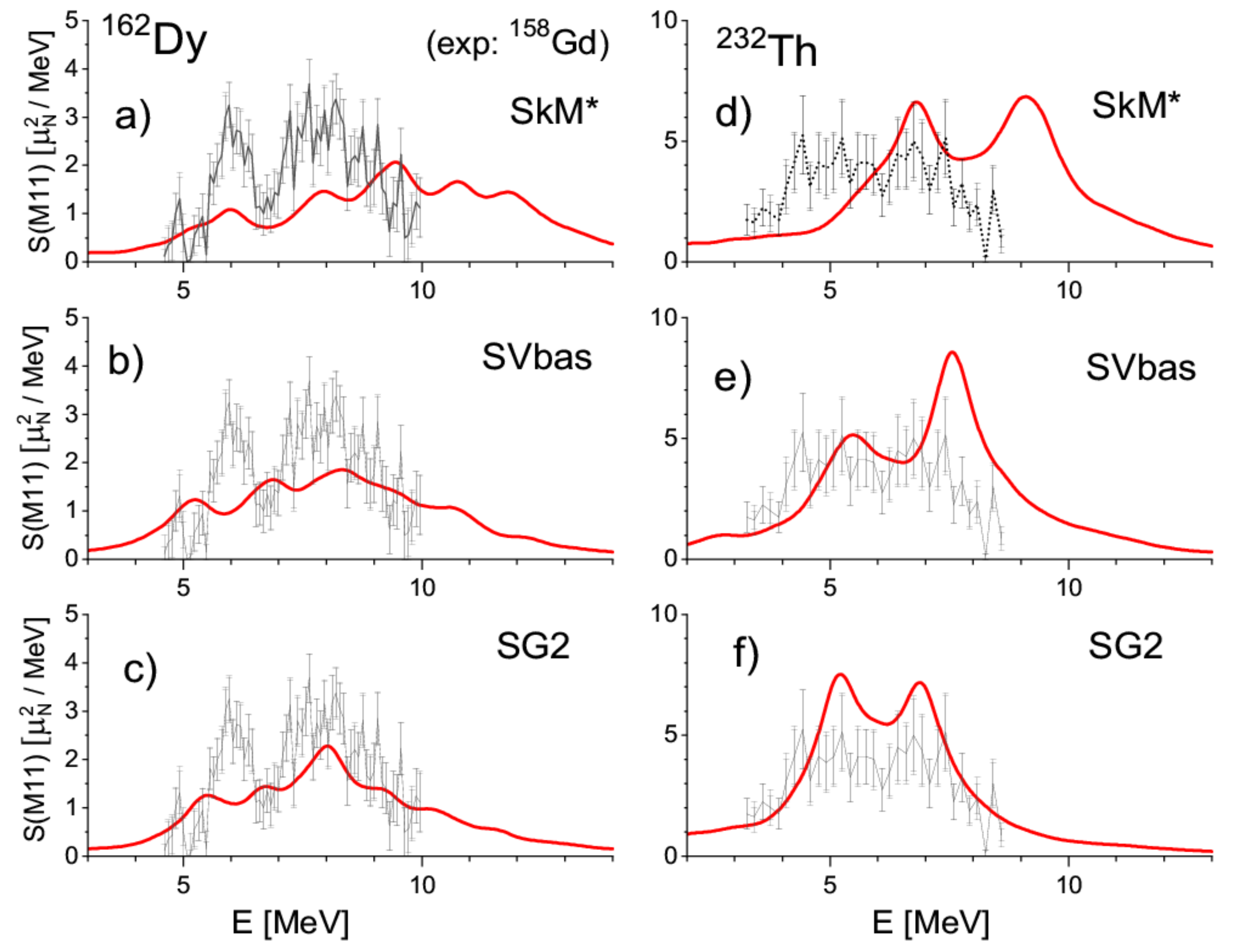
Experiments (p,p'):
158Gd: D. Frekers et al., PLB'1990.
232Th: H.L. Wortche, Ph.D. thesis, 1994.

- good agreement with the experiment for SG2.
- strong dependence of resonance on spin-orbital parameters.

- good agreement with Sarriguren's calculations for SVbas and SG2 forces.

P. Sarriguren et al, PRC 54, 690 (1996).

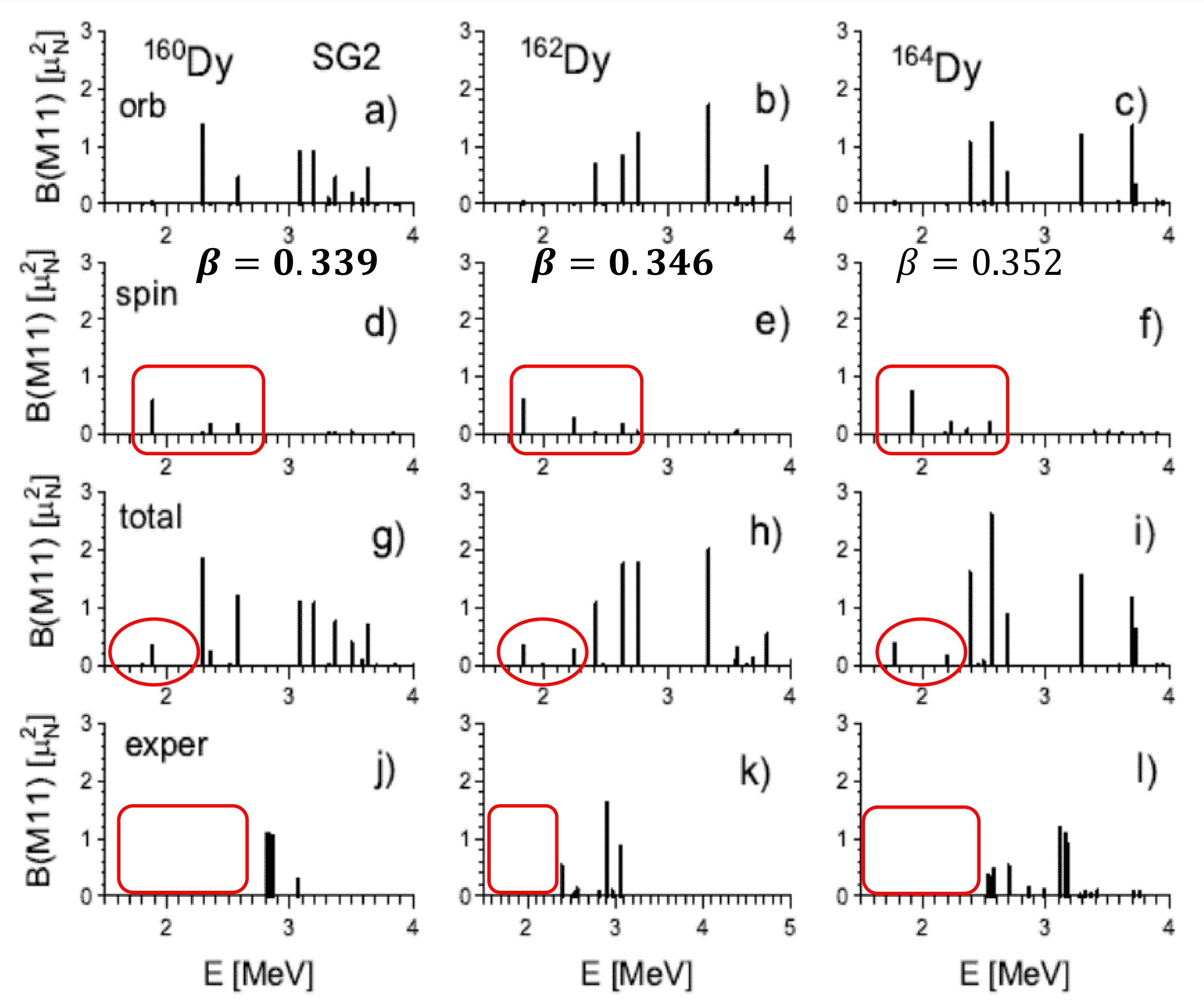
nucl.	$\sum B(M11)_s, \mu_N^2$ [0-12 MeV]			
	SkM*	SVbas	SG2	Sarr.
^{160}Dy	14.5	13.2	12.9	11.4
^{162}Dy	14.7	13.4	13.1	12.2
^{164}Dy	14.7	13.6	13.3	12.2
^{232}Th	17.3	15.6	14.9	14.9



Spin-orbital parameters

b4	b4' [MeV fm^5]
65.0	65.0
62.3	34.1
52.5	52.5

Results for Dy



$\boldsymbol{\beta = 0.339}$ $\boldsymbol{\beta = 0.346}$ $\beta = 0.352$

- in agreement with the WFM, there are low-energy states with a dominant spin part.
- strong interference of spin and orbital contributions.
- the presence of an orbital force in states with a dominant spin component.

Experiments:
160Dy: C. Wesselborg et al, PLB’1988.
162,164Dy: J. Margraf et al, PRC’1995.

Results for Dy

nucl.	force	0-2.4 MeV				2.4-4 MeV				0-4 MeV				
		$\sum B(M11)$			R	$\sum B(M11)$			R	$\sum B(M11)$				R
		orb	spin	total		orb	spin	total		orb	spin	total	exp	
^{160}Dy	SkM*	0.52	0.96	1.32	0.89	2.79	0.55	4.85	1.45	3.31	1.51	6.16		1.28
	SVbas	0.05	0.49	0.23	0.43	2.15	0.51	3.80	1.43	2.20	1.00	4.03	2.42	1.26
	SG2	0.03	0.46	0.28	0.57	2.69	0.54	4.53	1.40	2.72	1.00	4.81		1.29
^{162}Dy	SkM*	0.80	1.09	1.80	0.95	2.69	0.51	4.63	1.45	3.49	1.60	6.44		1.27
	SVbas	0.06	0.73	0.45	0.57	2.35	0.40	4.04	1.47	2.41	1.14	4.49	3.45	1.26
	SG2	0.03	0.72	0.55	0.73	2.85	0.35	4.54	1.42	2.88	1.07	5.09		1.29
^{164}Dy	SkM*	0.96	1.09	2.11	1.03	2.18	0.40	3.94	1.53	3.14	1.49	6.05		1.31
	SVbas	0.06	0.63	0.32	0.47	2.52	0.50	4.37	1.45	2.57	1.13	4.69	6.17	1.27
	SG2	0.03	0.68	0.45	0.63	3.20	0.35	5.05	1.42	3.23	1.03	5.50		1.29

spin force:

- non-collective
- spin-flip partial-hole transitions
- the result is reproduced for 3 forces

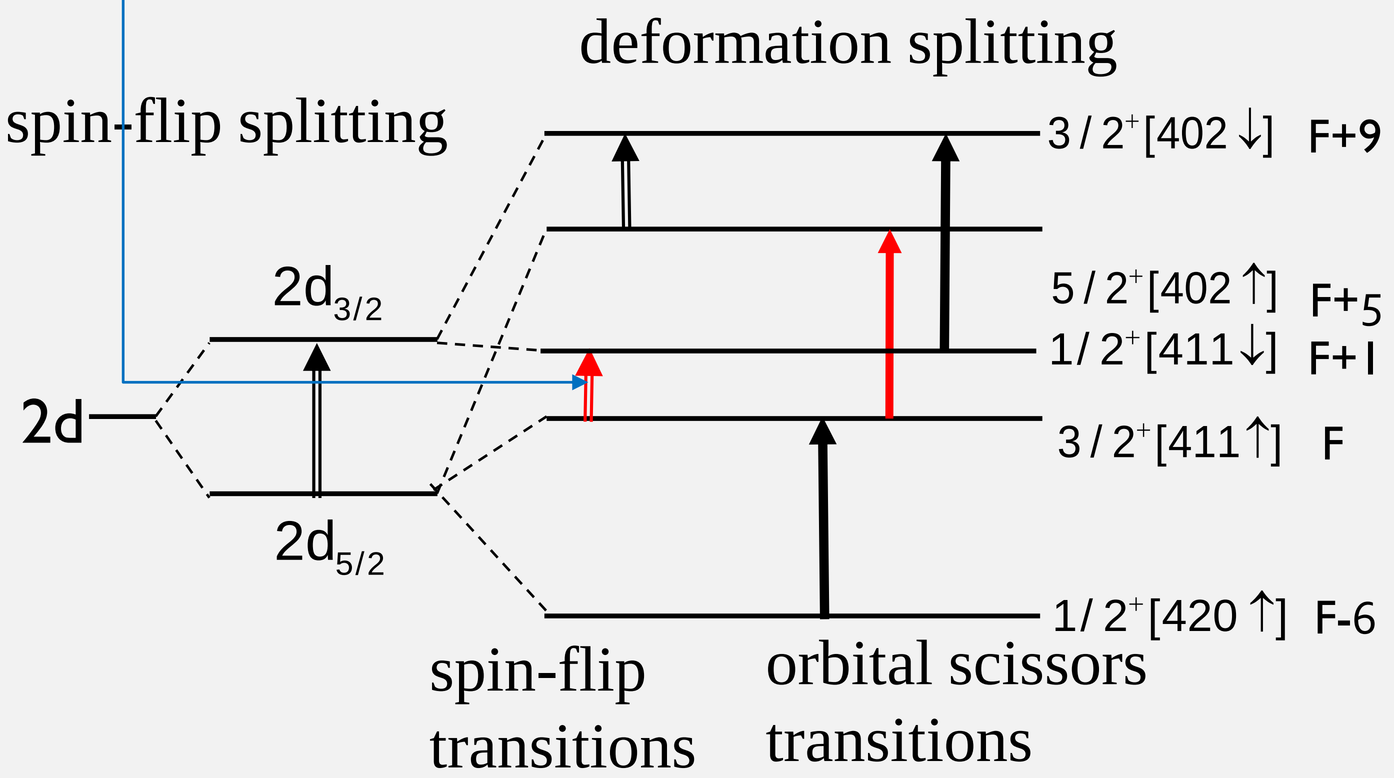
$$R = \frac{\sum B(M11)_t}{\sum B(M11)_o + \sum B(M11)_s}$$

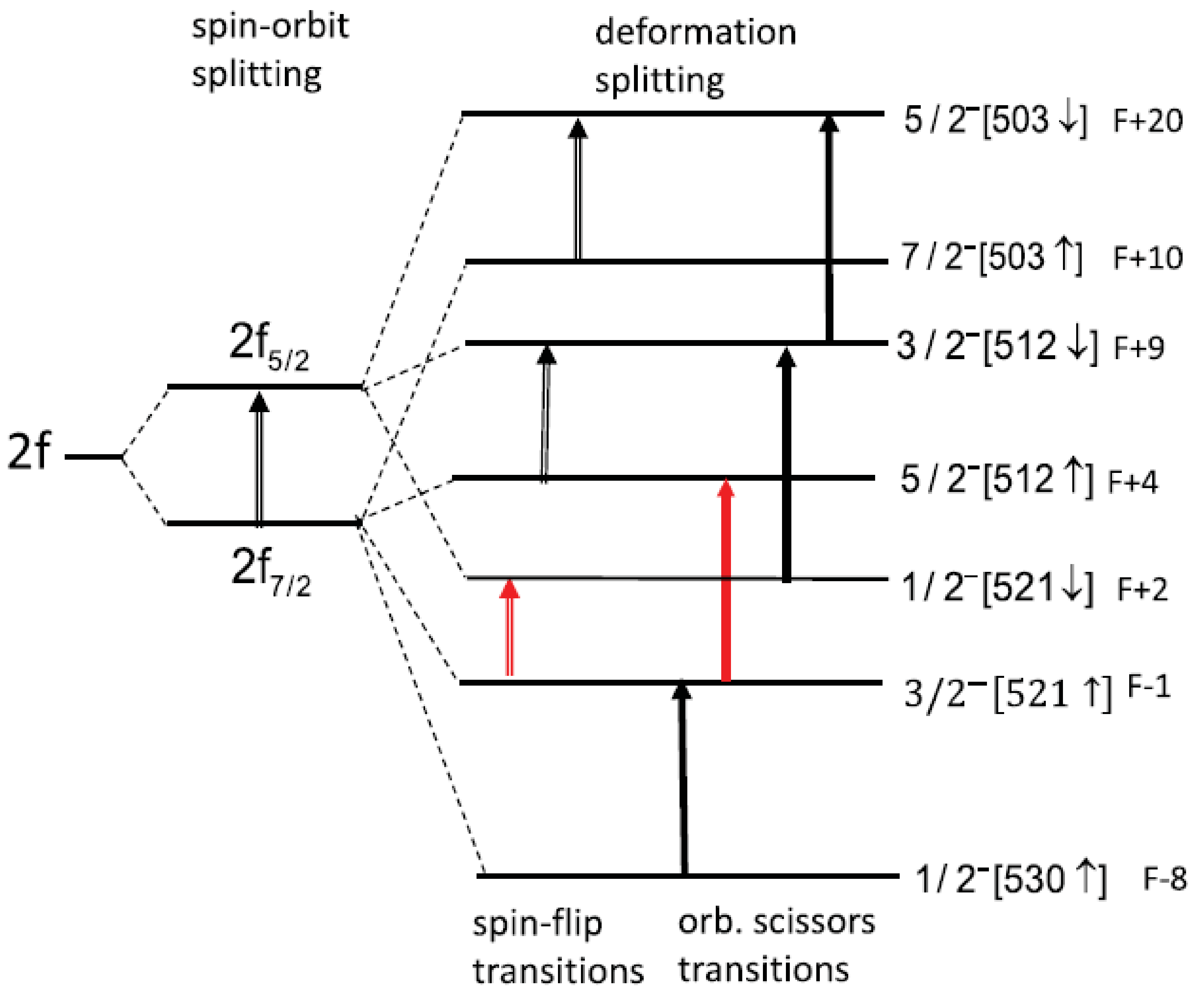
	E, МэВ	main 2qp components			
		%	$[N, n_z, \Lambda]$	Fermi level	sph. limit
SG2	2.06	99	pp [411↑,411↓]	F, F+1	$2d_{5/2}, 2d_{3/2}$
	2.36	99	nn [521↑,521↓]	F-1, F+2	$2f_{7/2}, 2f_{5/2}$
	3.44	57	nn [521↑,512↑]	F-1, F+4	$2f_{7/2}, 1h_{9/2}$

Spin-flip transitions:

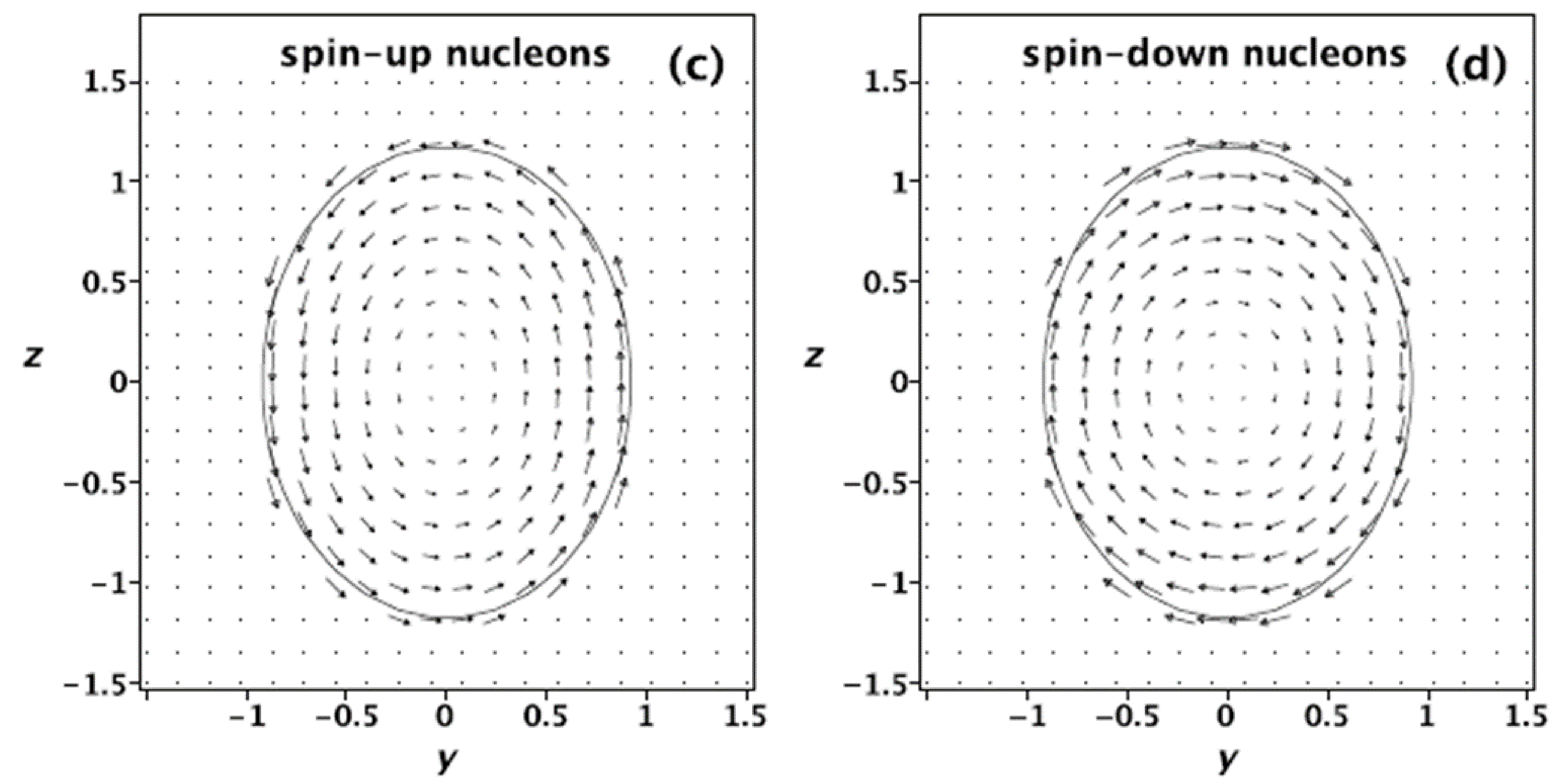
pp[411] ↑→ [411] ↓   nn[521]↑→[521]↓

Deformation is not the main reason for the appearance of spin states

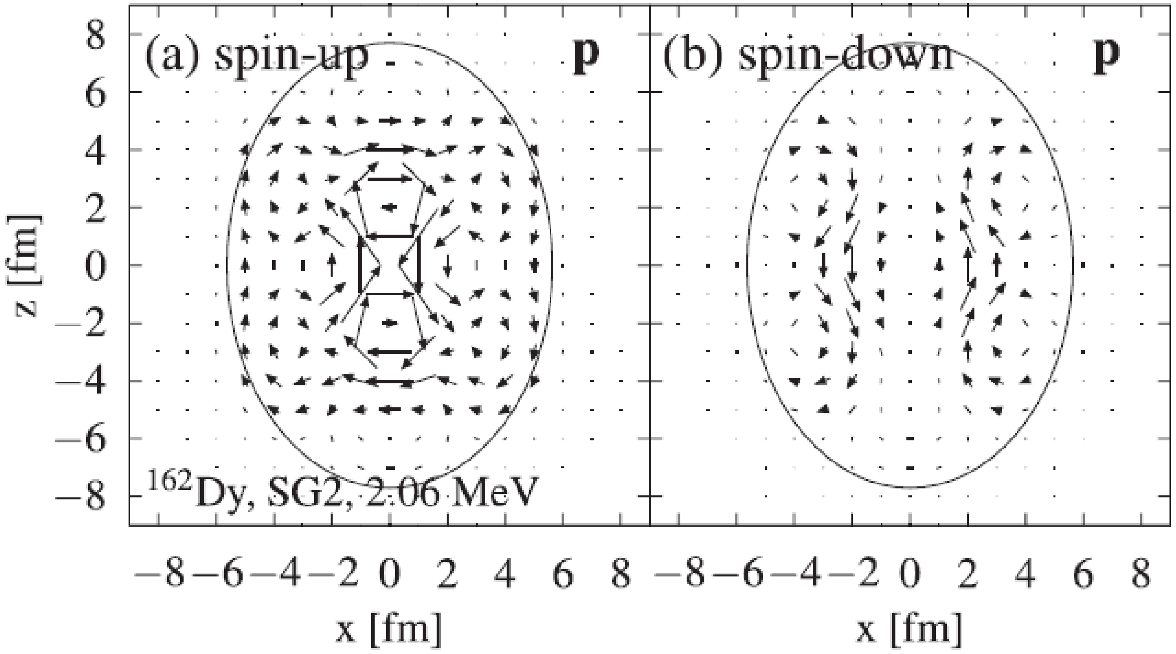


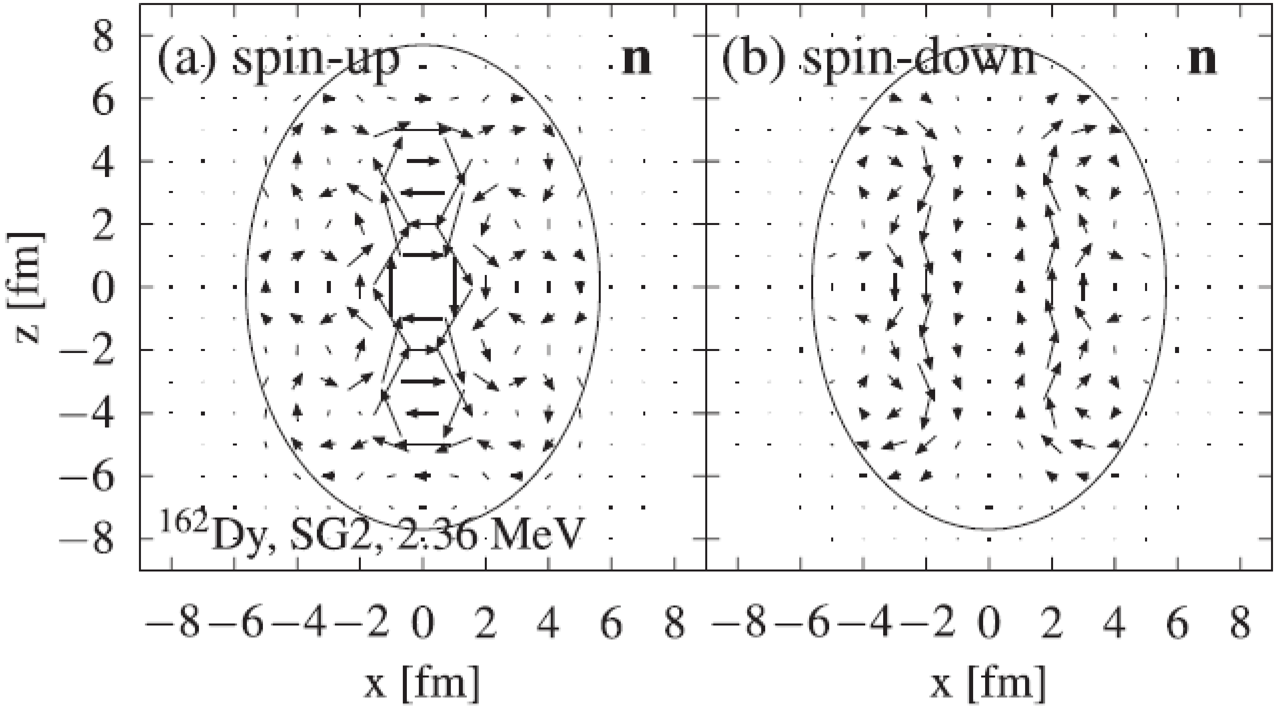

spin-orbit splitting
deformation splitting
2f
$2f_{5/2}$
$2f_{7/2}$
$5/2^-[503\downarrow]$ F+20
$7/2^-[503\uparrow]$ F+10
$3/2^-[512\downarrow]$ F+9
$5/2^-[512\uparrow]$ F+4
$1/2^-[521\downarrow]$ F+2
$3/2^-[521\uparrow]$ F-1
$1/2^-[530\uparrow]$ F-8
spin-flip transitions
orb. scissors transitions

WFM currents



QRPA Currents

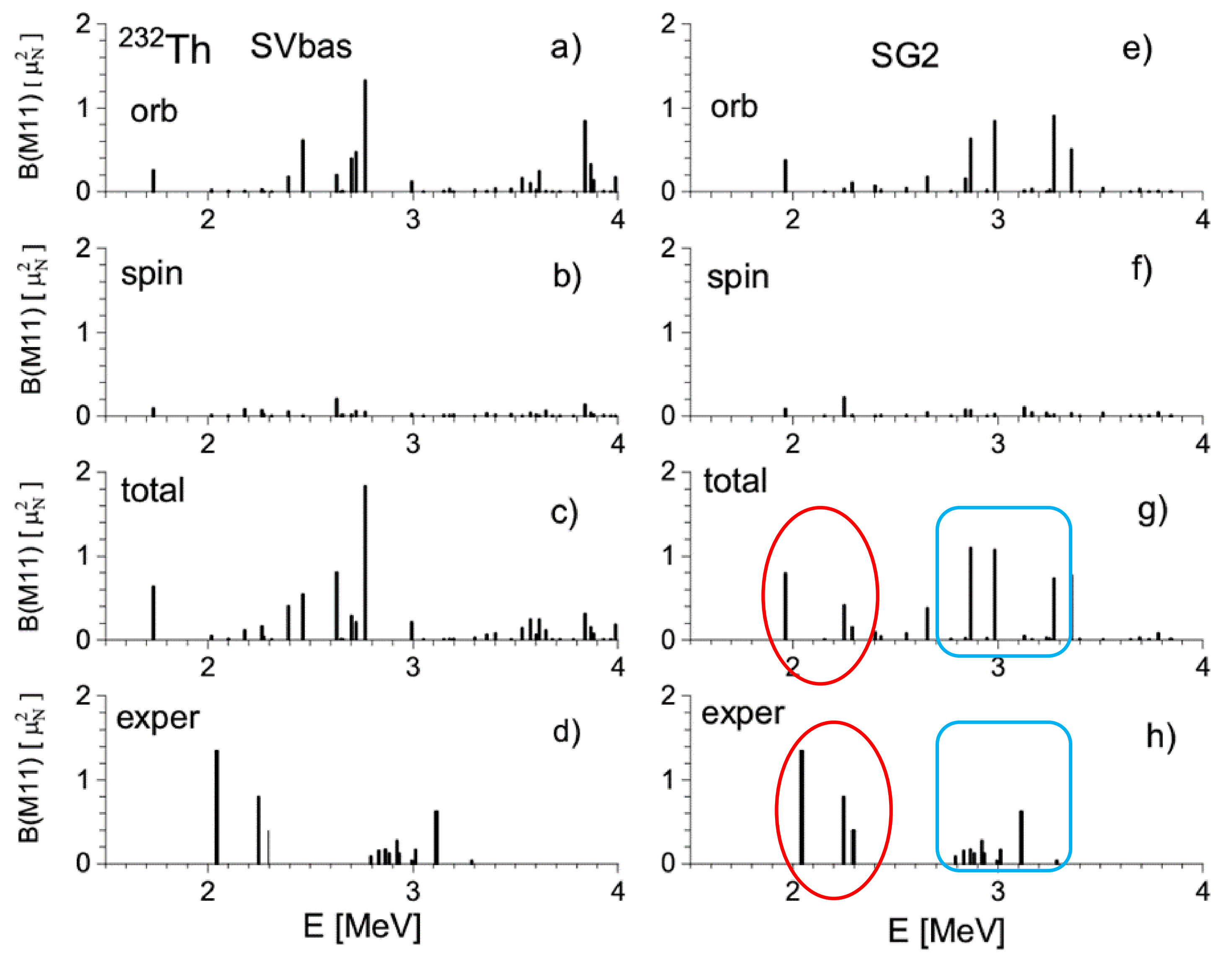




SG2, 2.06 MeV

SG2, 2.36 MeV

Results for Th



- In a weakly deformed ^{232}Th orbital force dominates even at E<2.4 MeV
- Unlike the WFM's predictions, both groups of levels are explained by the fragmentation of the orbital force

Experiment:

A.S. Adekola et al., PRC' 2011.

Conclusions

1) QRPA calculations confirm the existence of spin states in strongly deformed ^{160,162,164}Dy below orbital resonances. These states are low-energy non collective spin-flip excitations.
2) Deformation is not the causes of these excitations, but has a strong influence on their properties.
3) Strong interference of spin and orbital excitations
4) In a weakly deformed ^{232}Th spin-flip excitations were not found
5) The presence of two groups of levels in the experiment can be explained by fragmentation of orbital excitations under the influence of deformation.
6) In general, the presence of a low-energy spin scissor resonance is only partially confirmed for strongly deformed ^{160,162,164}Dy

Thanks for your attention!