Микроскопический анализ дипольных электрических и магнитных возбуждений в $^{156}\mathrm{Gd}$

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Introduction

Electric and magnetic dipole excitations represent very important part of nuclear dynamics

These excitations:

i) E1 low-energy pygmy dipole resonance (PDR)
ii) isovector E1 giant dipole resonance (GDR)
iii) isovector M1 low-energy orbital scissors resonance (OSR)
iv) M1 spin-flip giant resonance (SFGR)

M. N. Harakeh and A. van der Woude, Giant Resonances (Clarendon Press, Oxford, 2001).
N. Paar et al, Rep. Prog. Phys. 70, 691 (2007).
D. Savran et al, Prog. Part. Nucl. Phys. 70, 210 (2013).
N. Lo Iudice and F. Palumbo, Phys. Rev. Lett. 41, 1532 (1978).
D. Bohle et al, Phys. Lett. B137, 24 (1984).

The deformed ^{156}Gd is perhaps the most suitable nucleus to investigate all these dipole modes altogether

^{156}Gd:

- large quadrupole deformation - appearance of E1 toroidal mode and low-energy spin-flip excitations
- Experimental data for GDR, OSR, SFGR and NRF (Nuclear resonance fluorescence) data

G.M. Gurevich et al, Nucl. Phys. A 351, 257 (1981).
H.H. Pitz et al, Nucl. Phys. A492, 411 (1989).
A. Richter, Nucl. Phys. A 507, 99c (1990).
A. Richter, Prog. Part. Nucl. Phys. 34, 261 (1995).
H.J. Wortche Ph.D. thesis, Technischen Hochschule Darmstadt, Germany, 1994.

^{156}Gd attractive for a simultaneous investigation of the total family of E1 and M1 modes.

Early studies of the dipole mode in ^{156}Gd:

R. Nojarov and A. Faessler, Z. Phys. A: Atomic Nuclei 336, 151 (1990).
E. Guliyev, H. Quliyev, and A.A. Kuliev, J. Phys. G: Nucl. Part. Phys. 47, 115107 (2010).
P. Sarriguren, E. Moya de Guerra, and R. Nojarov, Phys. Rev. C 54, 690 (1996).
V.G. Soloviev, A.V. Sushkov, N.Yu. Shirikova, and N. Lo Iudice, Nucl. Phys. A 600, 155 (1996).
V.G. Soloviev, A.V. Sushkov and N.Yu. Shirikova, Phys. Part. Nucl. 31, n. 4, 786 (2000).

However all these studies were performed within the models which are not self-consistent.

Model

- The Skyrme QRPA code (Repko).

A. Repko, J. Kvasil, V. O. Nesterenko, and P.-G. Reinhard, arXiv:1510.01248[nucl-th].

- 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).
- Single-particle basis includes 683 proton and 787 neutron levels.
- For example, 2qp basis includes 5158 proton and 9165 neutron pairs for SVbas.
- Spurious admixture are removed.

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

- 3 Skyrme forces (SG2, SVbas, SLy6)

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

Calculation details

force	κ	b_4 MeVfm^5	b_4' MeVfm^5	G_p MeVfm^3	G_n MeVfm^3	pairing
SVbas	0.4	62.3	34.1	674.62	606.90	surface
SLy6	0.25	61.0	61.0	298.76	288.52	volume
SG2	0.53	52.5	52.5	296.76	269.58	volume

$\beta_{\mathrm{exp}} = 0.340$

force	β_2
SVbas	0.327
SLy6	0.333
SG2	0.329

$$V^q_{pair}(\vec{r},\vec{r}') = G_\mathrm{q}\left[1+\eta\frac{\rho(\vec{r})}{\rho_{pair}}\right]\delta(\vec{r}-\vec{r}')$$

M1 and E1 transition operators:

$$\hat{\Gamma}(E1,K) = e\sum_{q\epsilon p,n} e^q_{eff}\sum_k [rY_{1K}(\Omega)]_k$$

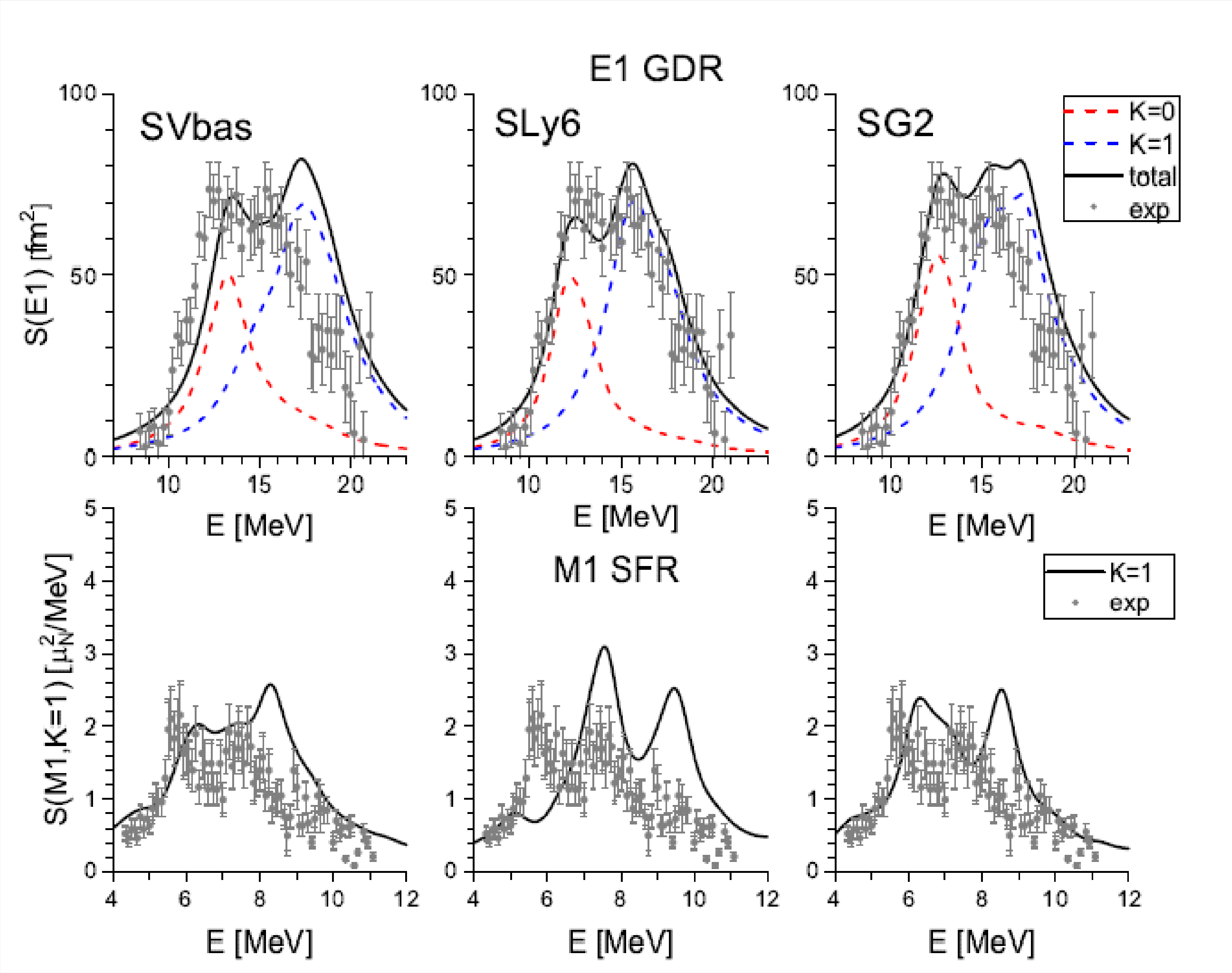
$$\hat{\Gamma}(M1,K) = \mu_N\sqrt{\frac{3}{4\pi}}\sum_{q\epsilon p,n}\sum_k [g^q_s\hat{s}_k + g^q_l\hat{l}_k]$$

transition probabilities:

$$B_\nu(E1,K) = (1+\delta_{K,1})|<\nu|\hat{\Gamma}(E1,K)|0>|^2$$

$$B_\nu(M1,K) = (1+\delta_{K,1})|<\nu|\hat{\Gamma}(M1,K)|0>|^2$$

E1 Giant dipole and M1 Spin-flip giant resonances



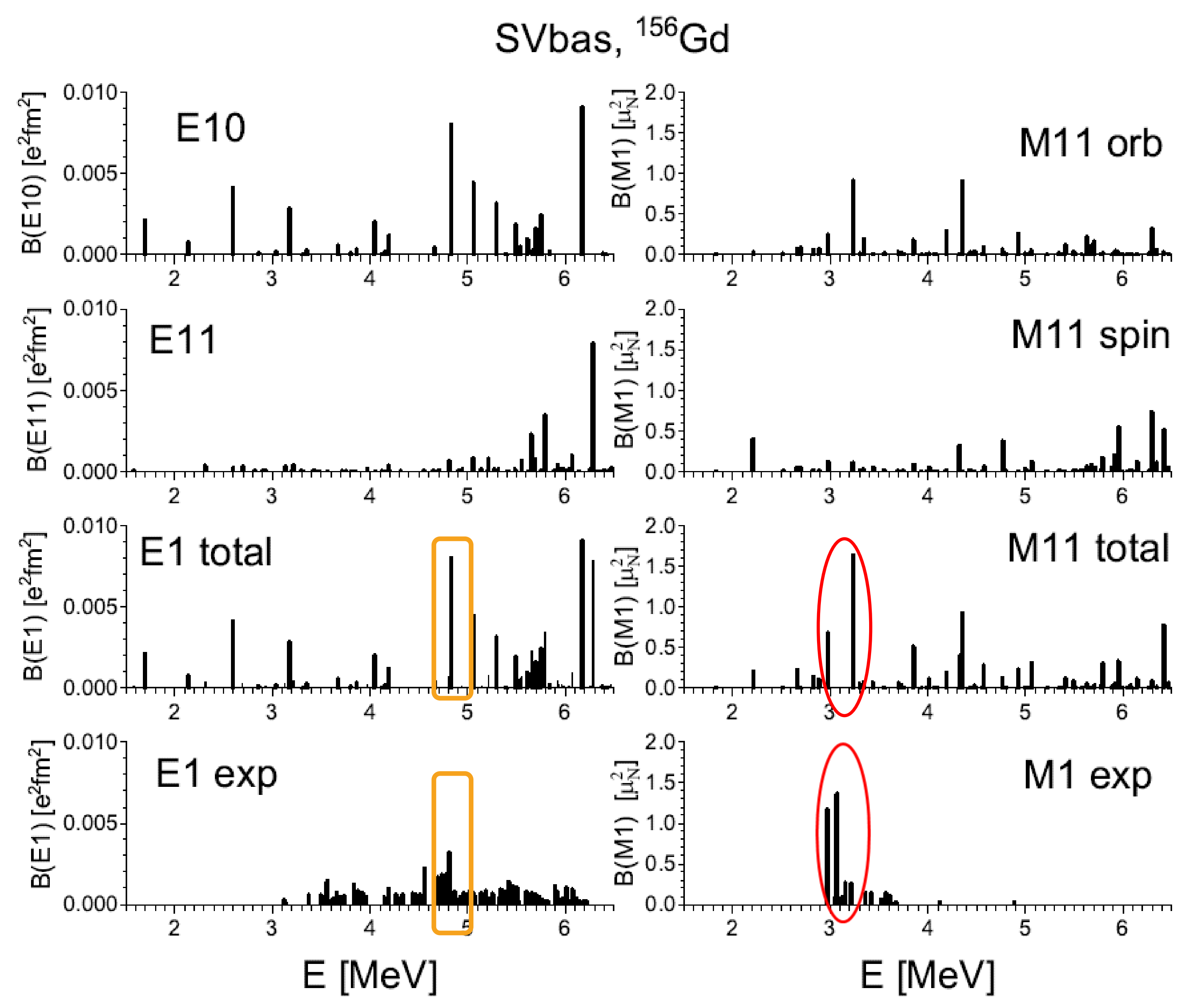
All three Skyrme forces give a nice description of GDR, including its deformation splitting (the best agreement for SLy6)

SFGR is described well by SVbas and SG2, but worse for SLy6.

Exp. data:

G.M. Gurevich et al, Nucl. Phys. A 351, 257 (1981).
H.J. Wortche Ph.D. thesis, Germany, 1994.

B(T1, K) strength



Force	orb	spin	total
SVbas	1.89	0.52	3.57
SLy6	2.31	0.38	5.59
SG2	2.49	0.40	3.91

($\sum B(M1)$ in OSR region [2.5 – 4 MeV])

In the experiment, the states are localized only at 3-3.5 MeV, which is strange.
The location of the B(M1) peak in good agreement with the experimental data.

exp: M. Tamkas et al, Nucl. Phys. A987, 79 (2019).

Force	ν	E	$B(M1)$ $[\mu_N^2]$			main 2qp components			
		[MeV]	orb	spin	total	%	$[N, n_z, \Lambda]$	F-position	spher. limit
SVbas	9	3.23	0.92	0.10	1.63	39	nn $[521\uparrow, 530\uparrow]$	$F+2, F-3$	$2f_{7/2}, 2f_{7/2}$
						15	pp $[402\uparrow, 411\uparrow]$	$F+5, F$	$2d_{5/2}, 2d_{5/2}$
SLy6	10	3.33	1.76	0.20	3.10	41	pp $[532\uparrow, 541\uparrow]$	$F+1, F-2$	$1h_{11/2}, 1h_{11/2}$
						39	nn $[521\uparrow, 530\uparrow]$	$F+2, F-3$	$2f_{7/2}, 2f_{7/2}$
SG2	9	3.35	1.10	0.06	1.64	36	pp $[523\uparrow, 532\uparrow]$	$F+4, F$	$1h_{11/2}, 1h_{11/2}$
						28	nn $[521\uparrow, 530\uparrow]$	$F+1, F-4$	$2f_{7/2}, 2f_{7/2}$

The peak at 3.3-3.4 MeV has an orbital nature

Force	E10	E11	E10+E11	$E1_{exp}$	$M1_o$	$M1_s$	$M1_t$	$M1_{exp}$
SVbas	0.043	0.017	0.060	0.073	4.35	3.53	7.44	3.99
SLy6	0.030	0.028	0.058	0.073	4.51	1.35	7.22	3.99
SG2	0.040	0.014	0.054	0.073	4.21	2.72	6.89	3.99

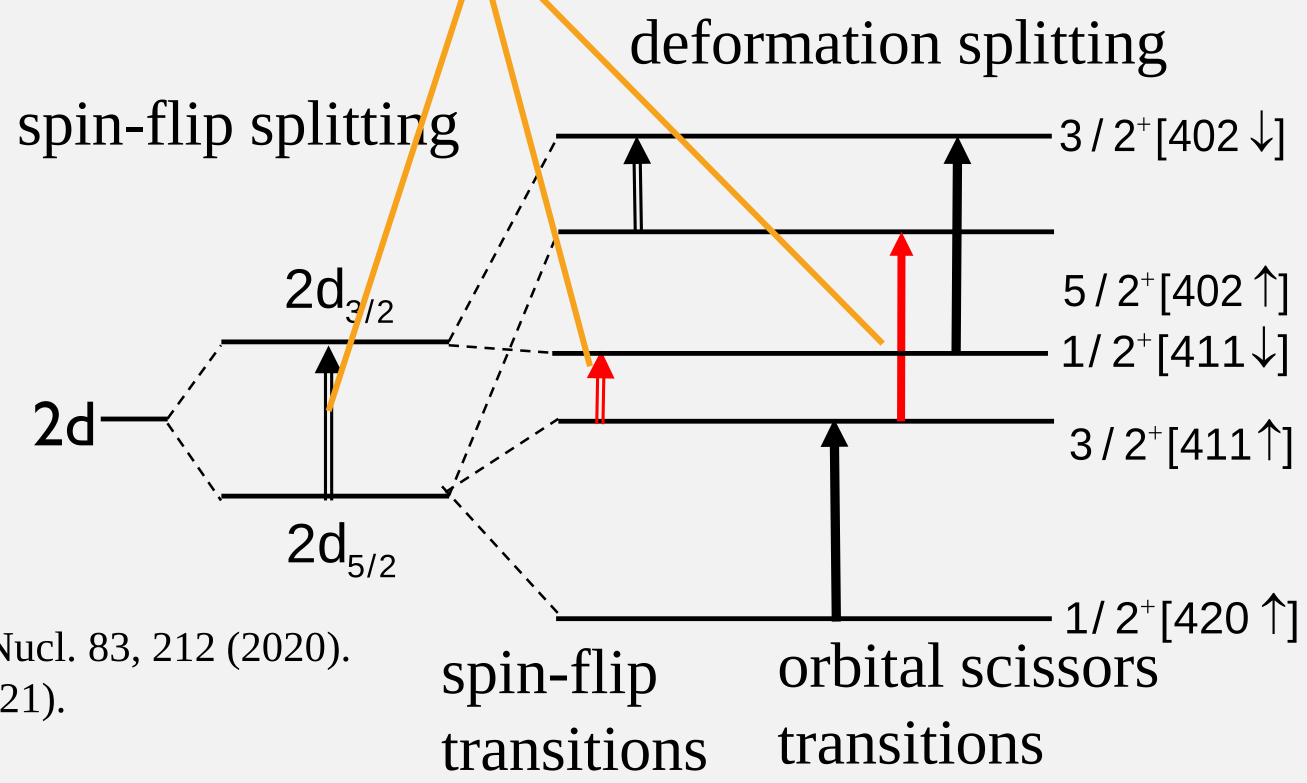
Comparison of B(E1) and B(M1) with experimental data at the interval 2.95 to 6.25 MeV.

- Value of B(E1) for all three forces is slightly less than the experimental one
- In calculations significant low-energy peak at 2.6-2.8 MeV
- The total B (M1) much larger than the experimental one.

Low-energy spin-flip

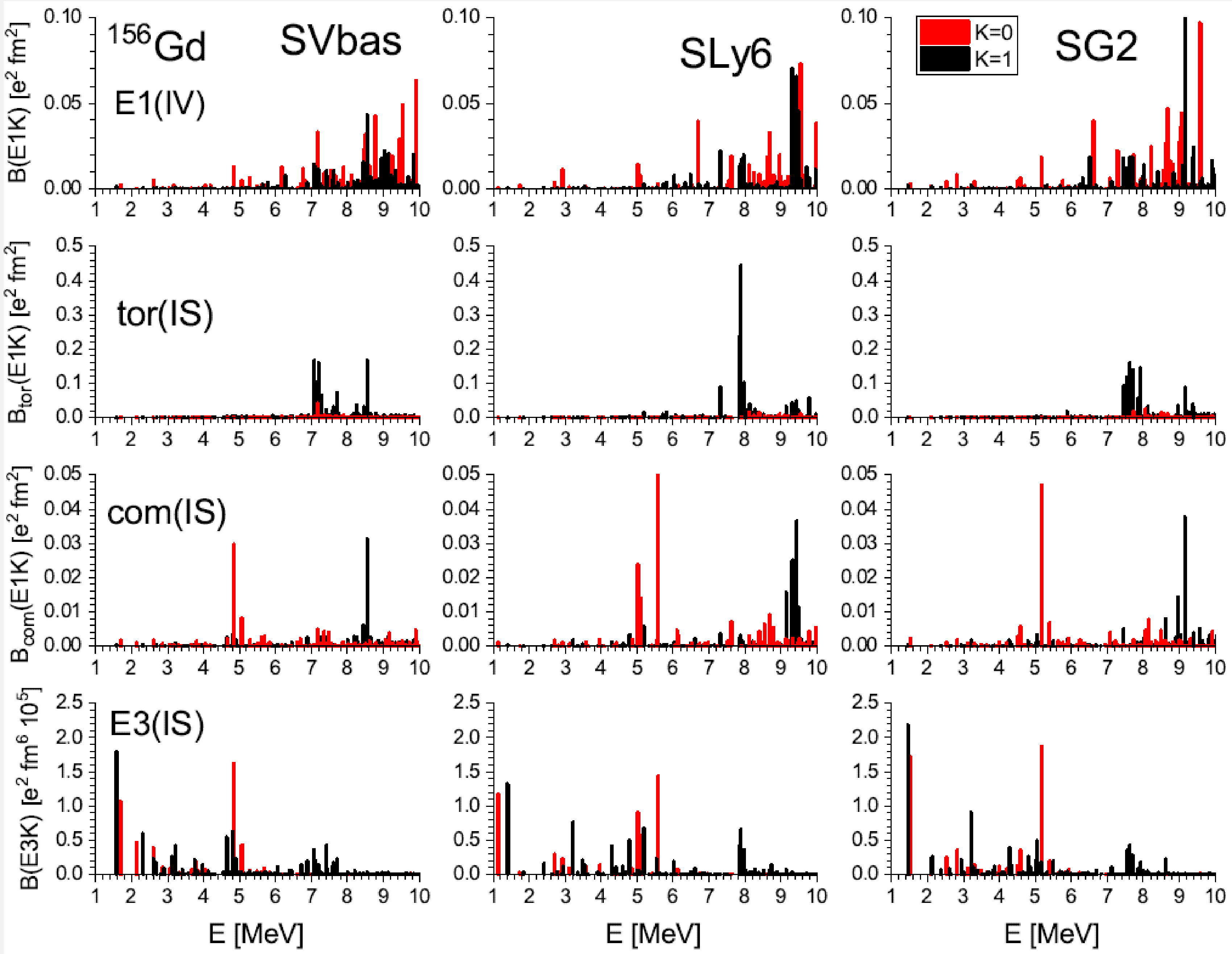
Force	ν	E	$B(M1)[\mu_N^2]$			main 2qp components		
		[MeV]	orb	spin	total	%	$[N, n_z, \Lambda]$	F-position
SVbas	2	2.21	0.03	0.39	0.21	99	$pp[411\downarrow, 411\uparrow]$	$F+2, F$
SLy6	4	2.46	0.07	0.32	0.09	98	$pp[411\downarrow, 411\uparrow]$	$F+2, F+1$
SG2	3	2.43	0.01	0.30	0.22	99	$pp[411\downarrow, 411\uparrow]$	$F+2, F+1$

- low-energy M1 spin states are present for all three Skyrme forces
- these states have a spin-flip character



E.B. Balbutsev, I. V. Molodtsova, and P. Schuck, Phys. Atom. Nucl. 83, 212 (2020).
V. O. Nesterenko, P. I. Vishnevskiy et al, Phys. Rev. C, 103 (2021).

B(E1) strength at 1-10 MeV



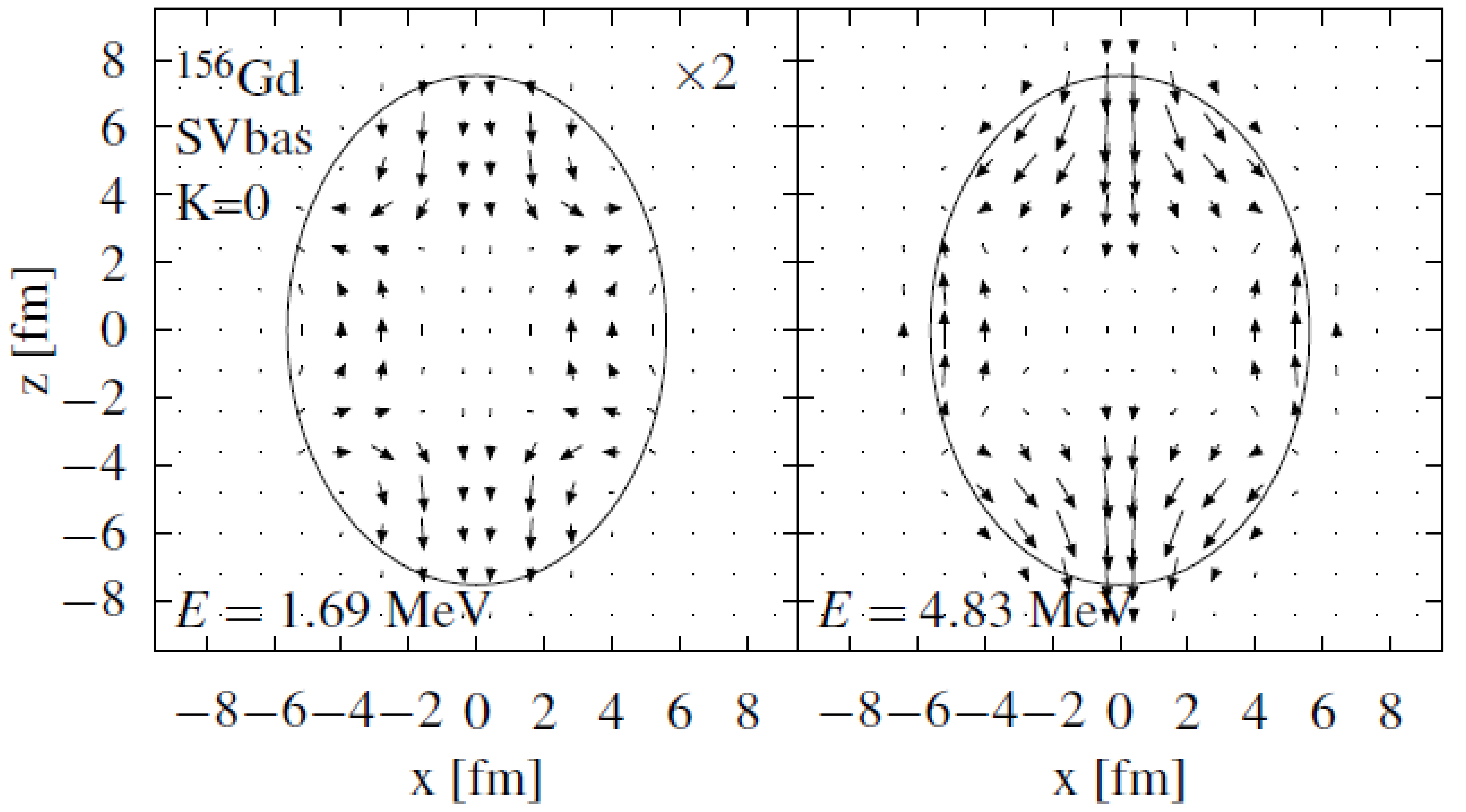
Toroidal states are almost completely described by states with K=1.

Two groups of compression states:

- 5-5.5 MeV for K=0
- 8.5-9.5 MeV for K=1

In general, all three Skyrme forces describe E1(IV), E1tor and E1com in a simillar way.

Octupole character of the maximum compression state



^{156}Gd
SVbas
K=0
×2
E = 1.69 MeV
E = 4.83 MeV
z [fm]
x [fm]
x [fm]
8
6
4
2
0
−2
−4
−6
−8
−8 −6 −4 −2 0 2 4 6 8
−8 −6 −4 −2 0 2 4 6 8

Conclusions

1) ^{156}Gd is well suited for studying the connections of magnetic and electric excitations in nuclei.
2) There are no QRPA forces capable of describing electric and magnetic dipole excitations equally well. Necessary to use several Skyrme forces for simultaneous investigation of magnetic and electric dipole transitions
3) QRPA calculations do not confirm the NRF experimental data (experimental data for M1 after 3.5 MeV is absent). But at the same time, the location of the peaks in the calculations coincides with the experiment.

THANKS FOR YOUR ATTENTION!