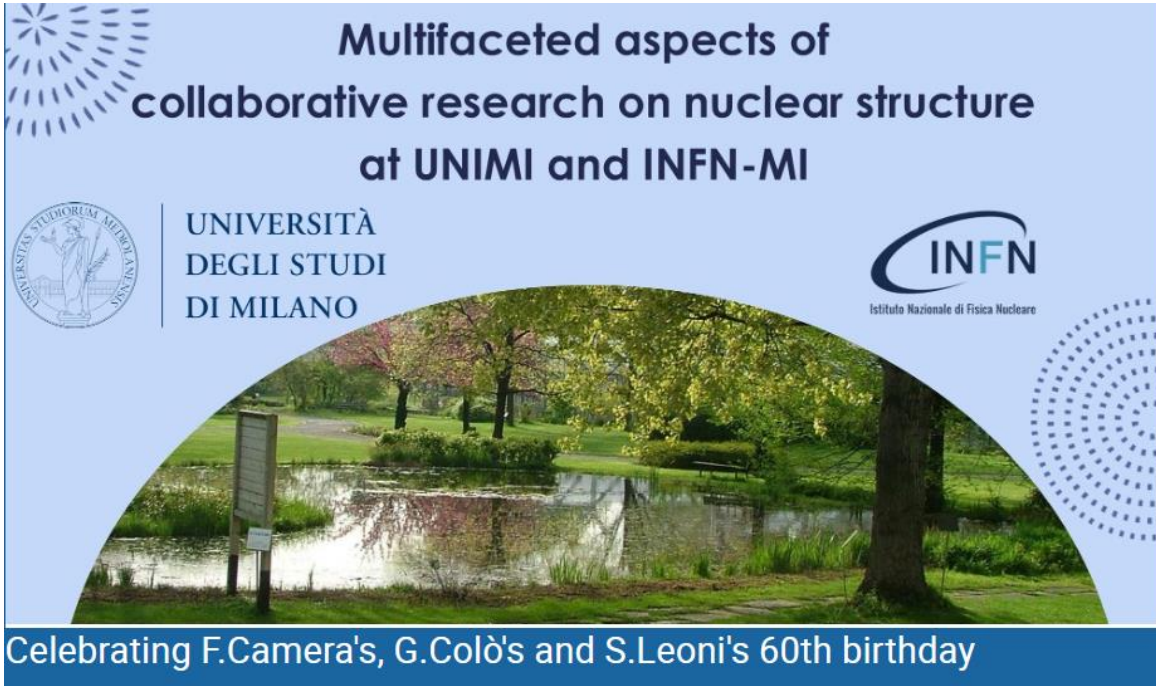
Tensor force, Equation of states and Particle-vibration coupling

Ligang Cao
Beijing Normal University



Te… Equation of states and Particle-vibration coupling

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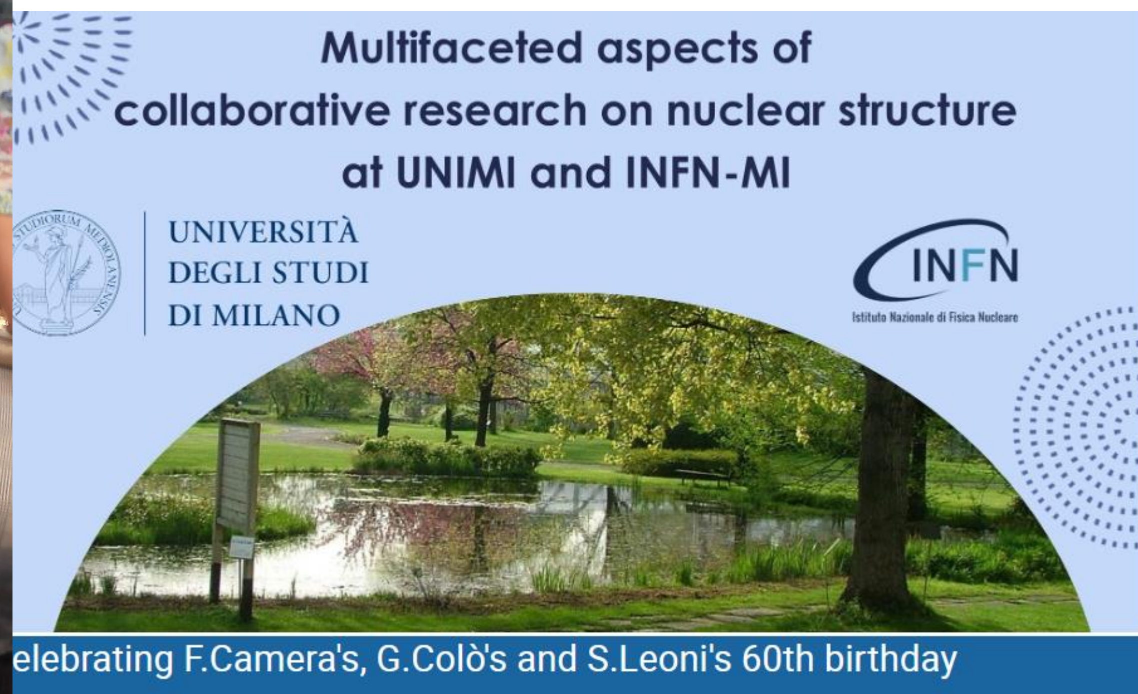


Gets to know (2004) and meet (2007) Gianluca

LNS Skyrme effective interaction

Euro-Asian Link

Exoct 07 at Catania

As postdoc, works with Gianluca 2008

1. Skyrme tensor force and its applications

2. Equation of states of nuclear matter

3. Single-particle states from particle-vibration coupling

Totally published 18 papers, 14 papers in the journals and 4 papers contributed the proceedings of the conferences.

2017!

1 Skyrme Tensor force and its applications

$$V_{tensor} = \frac{T}{2}\{[(\sigma_1 \cdot k')(\sigma_2 \cdot k') - \frac{1}{3}(\sigma_1 \cdot \sigma_2)k'^2]\delta(r_1 - r_2)$$
$$+\delta(r_1 - r_2)[(\sigma_1 \cdot k)(\sigma_2 \cdot k) - \frac{1}{3}(\sigma_1 \cdot \sigma_2)k^2]\}$$
$$+U[(\sigma_1 \cdot k')\delta(r_1 - r_2)(\sigma_2 \cdot k) - \frac{1}{3}(\sigma_1 \cdot \sigma_2)\delta(r_1 - r_2)(k' \cdot k)]$$

The energy density founctional for centeral exchange and tensor part:

$$H_{sg} = -\frac{1}{16}(t_1 x_1 + t_2 x_2)J^2 + \frac{1}{16}(t_1 - t_2)[J_p^2 + J_n^2]$$

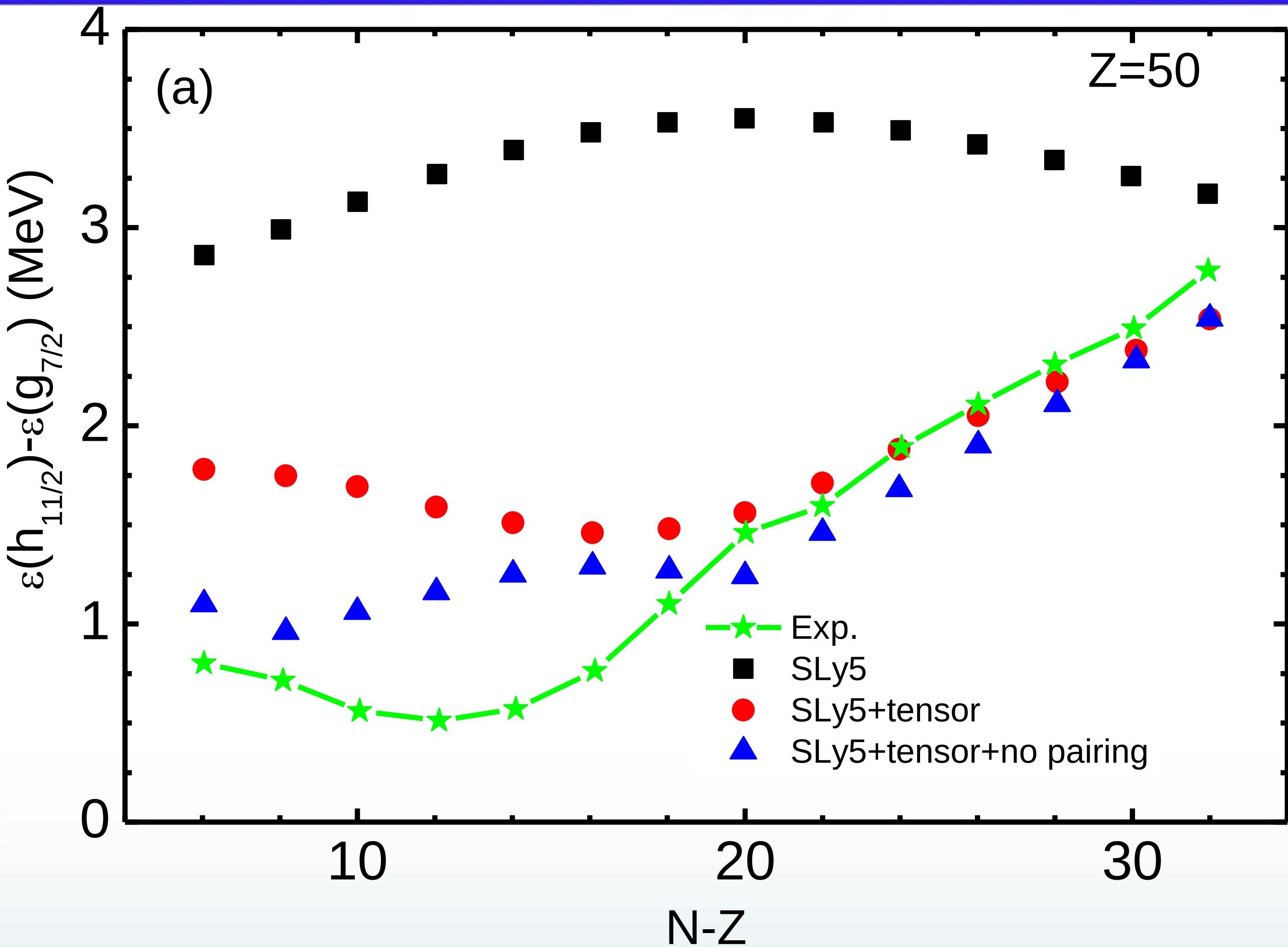
$$H_{tensor} = \frac{5}{24}(T+U)J_n J_p + \frac{5}{24}U(J_n^2 + J_p^2)$$

$J_q(r)$ is the spin density

$$\Delta H = \frac{1}{2}\alpha(J_n^2 + J_p^2) + \beta J_n J_p$$

$$\alpha = \alpha_c + \alpha_T, \beta = \beta_c + \beta_T$$

$$\alpha_c = \frac{1}{8}(t_1 - t_2) - \frac{1}{8}(t_1 x_1 + t_2 x_2); \beta_c = -\frac{1}{8}(t_1 x_1 + t_2 x_2)$$
$$\alpha_T = \frac{5}{12}U; \beta_T = \frac{5}{24}(T+U)$$



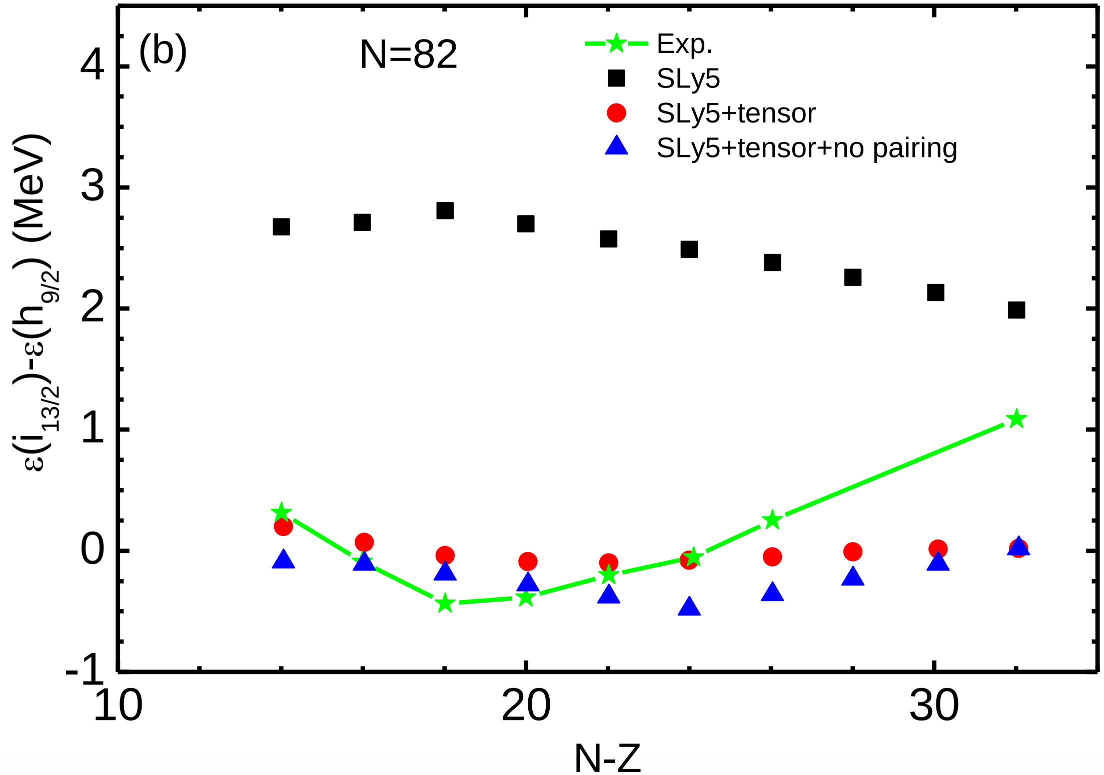
SLy5
G. Colo, et. al.
PLB646(2007)227

$$\alpha_c = 80.2 MeVfm^5$$
$$\beta_c = -48.9 MeVfm^5$$
$$\alpha_T = -170 MeVfm^5$$
$$\beta_T = 100 MeVfm^5$$
$$\alpha = -89.8 MeVfm^5$$
$$\beta = 51.1 MeVfm^5$$
$$T = 888.0 MeVfm^5$$
$$U = -408.0 MeVfm^5$$

$$U^p_{s.o.} = \frac{W_0}{2r}\left(2\frac{d\rho_p}{dr} + \frac{d\rho_n}{dr}\right) + \left(\alpha\frac{J_p}{r} + \beta\frac{J_n}{r}\right)$$

^{120}Sn neutron spin-saturated state
$J_n=0$

$$\alpha = -89.8 MeVfm^5 < 0 \qquad J_p > 0 \qquad U^p_{s.o.} \uparrow \qquad \varepsilon_{h11/2} \downarrow \qquad \varepsilon_{g7/2} \uparrow$$



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^{132}Sn

$$\alpha = -89.8 MeVfm^5 < 0 \qquad J_n > 0 \qquad \alpha\frac{J_n}{r} < 0$$

$$\beta = 51.1 MeVfm^5 > 0 \qquad J_p > 0 \qquad \beta\frac{J_p}{r} > 0 \qquad U^n_{s.o.} \uparrow \qquad \varepsilon_{i13/2} \downarrow \qquad \varepsilon_{h9/2} \uparrow$$

We included Skyrme tensor force into RPA to investigate its effects on excited states

PHYSICAL REVIEW C **80**, 064304 (2009)

Effects of the tensor force on the multipole response in finite nuclei

PHYSICAL REVIEW C **81**, 044302 (2010)

Spin and spin-isospin instabilities and Landau parameters of Skyrme interactions with tensor correlations

Li-Gang Cao (曹李刚),[1,2,3,4] Gianluca Colò,[3,4] and Hiroyuki Sagawa[5]
[1]*Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, People's Republic of China*

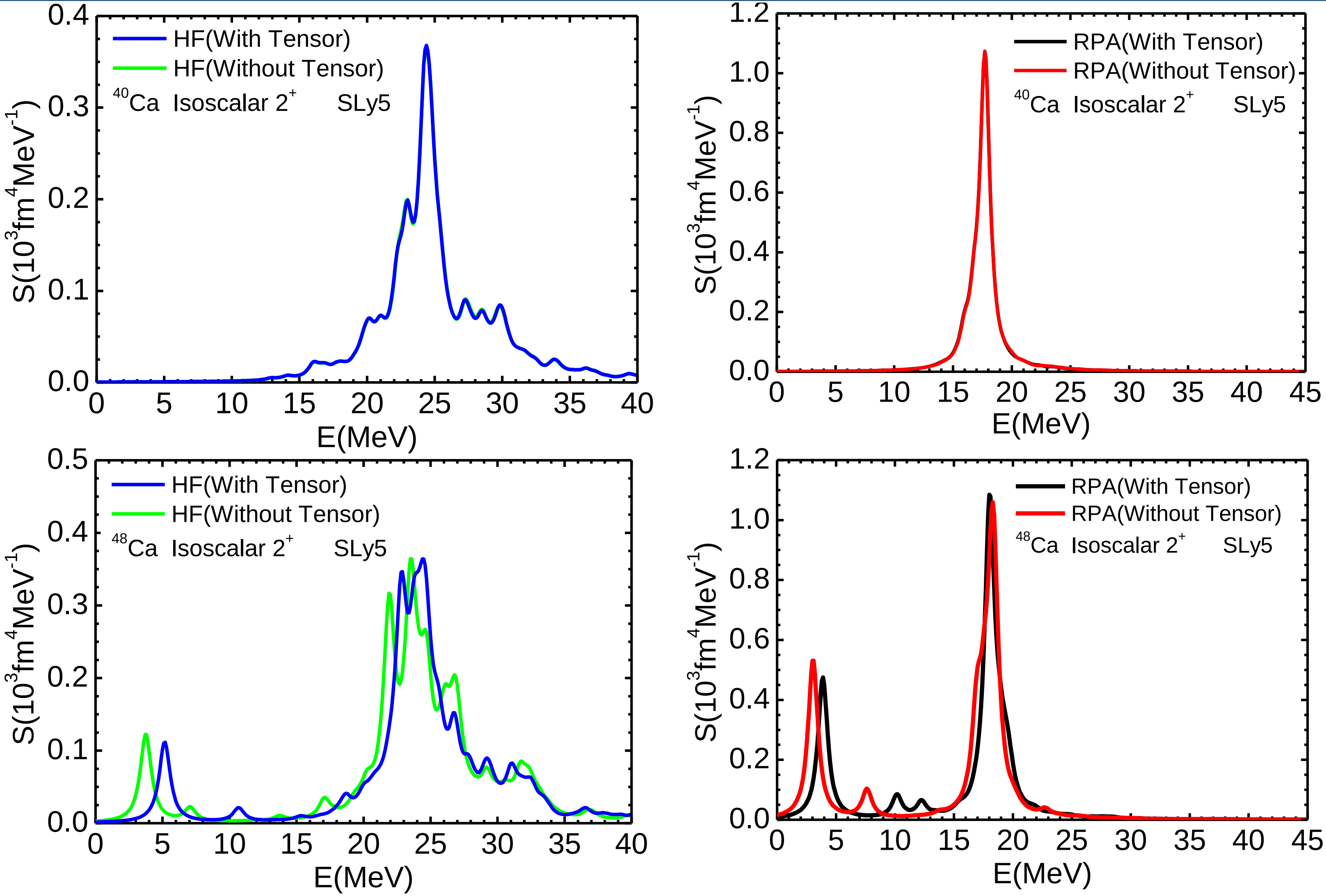
PHYSICAL REVIEW C **83**, 034324 (2011)

Effects of tensor correlations on low-lying collective states in finite nuclei

Li-Gang Cao (曹李刚),[1,2,3] H. Sagawa,[2] and G. Colò[4,5]
[1]*Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, People's Republic of China*
[2]*Center for Mathematics and Physics, University of Aizu, Aizu-Wakamatsu, Fukushima 965-8560, Japan*
[3]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, People's Republic of China*
[4]*Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, I-20133 Milano, Italy*
[5]*Istituto Nazionale di Fisica Nucleare (INFN), Sez. di Milano, via Celoria 16, I-20133 Milano, Italy*
(Received 4 January 2011; revised manuscript received 17 February 2011; published 29 March 2011)

We present a systematic analysis of the effects induced by tensor correlations on low-lying collective states of magic nuclei, by using the fully self-consistent random phase approximation (RPA) model with Skyrme interactions. The role of the tensor correlations is analyzed in detail in the case of quadrupole (2^+) and octupole (3^-) low-lying collective states in ^{208}Pb. The example of ^{40}Ca is also discussed, as well as the case of magnetic dipole states (1^+).

ISGQR: Cao L. G. et.al.,PRC 80, 064304(2009)



$$\Delta E_{RPA} \approx \Delta E_{HF} + \langle V_{tensor} \rangle$$

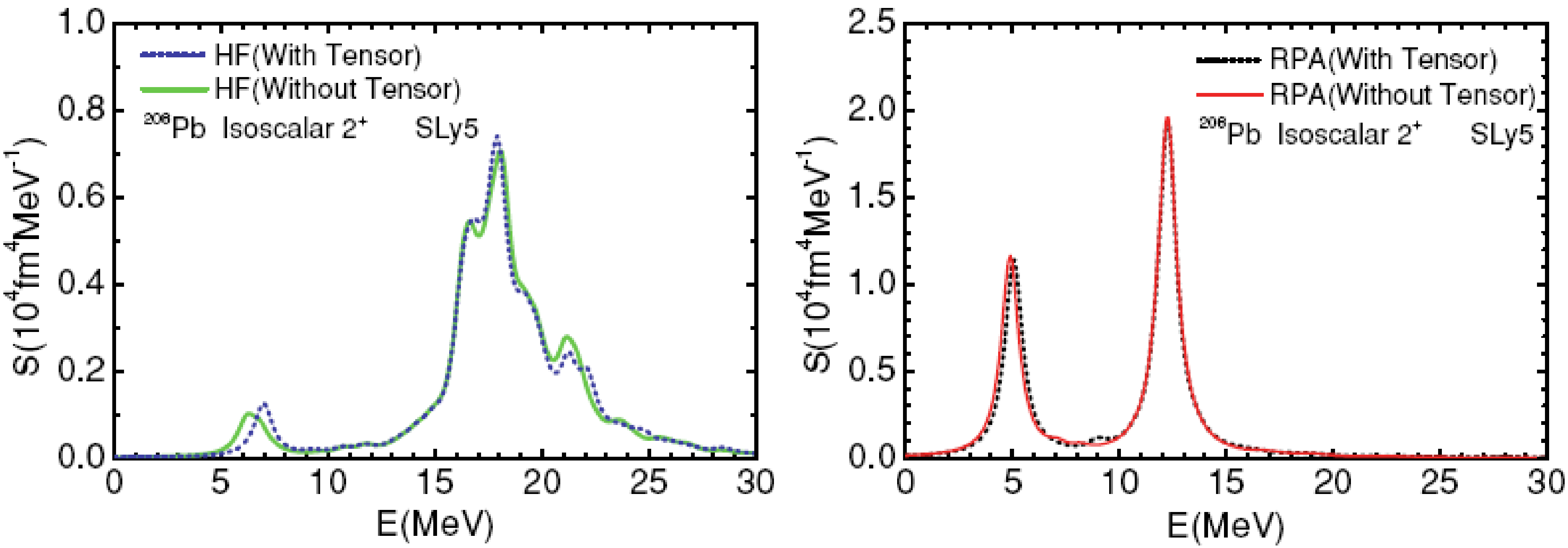
neutron $f_{7/2} \rightarrow p_{3/2}$

$$\Delta E_{HF} = 1.41MeV$$

$$\Delta E_{RPA} = 0.83MeV$$

$$\langle V_{tensor} \rangle = -0.58MeV$$

ISGQR: Cao L. G. et.al.,PRC 80, 064304(2009)



$(2f_{7/2}1h_{11/2}^{-1})_{\pi}$

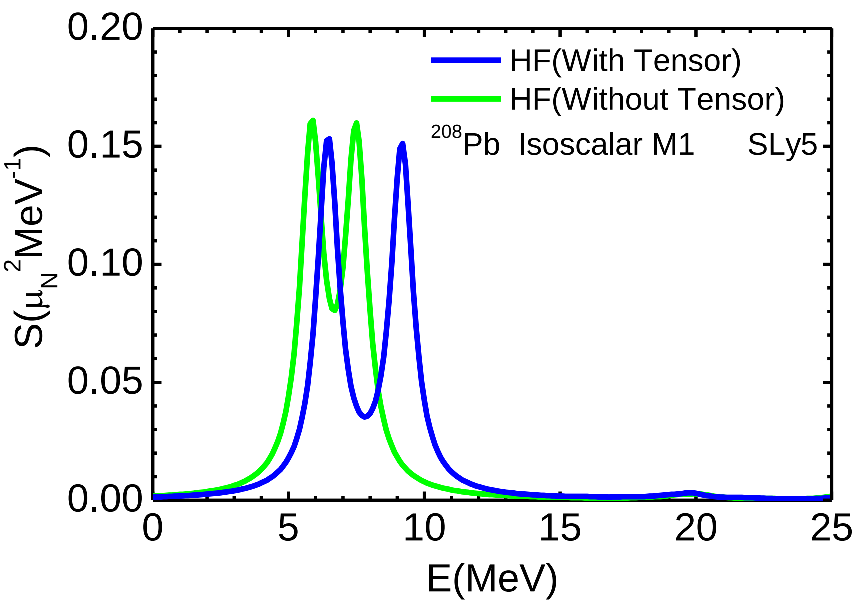
$(2g_{9/2}1i_{13/2}^{-1})_{\upsilon}$

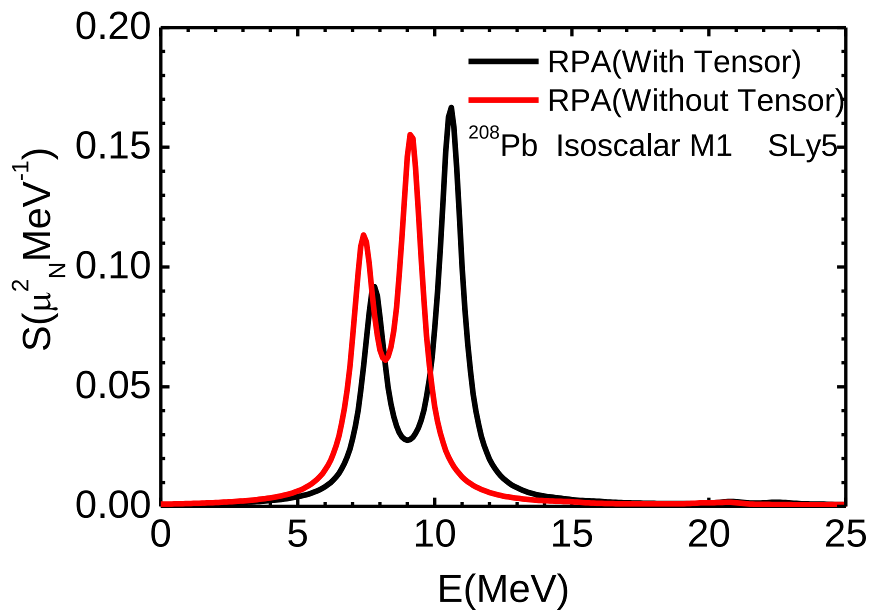
$$\Delta E_{RPA} \approx \Delta E_{HF} + \langle V_{tensor} \rangle$$

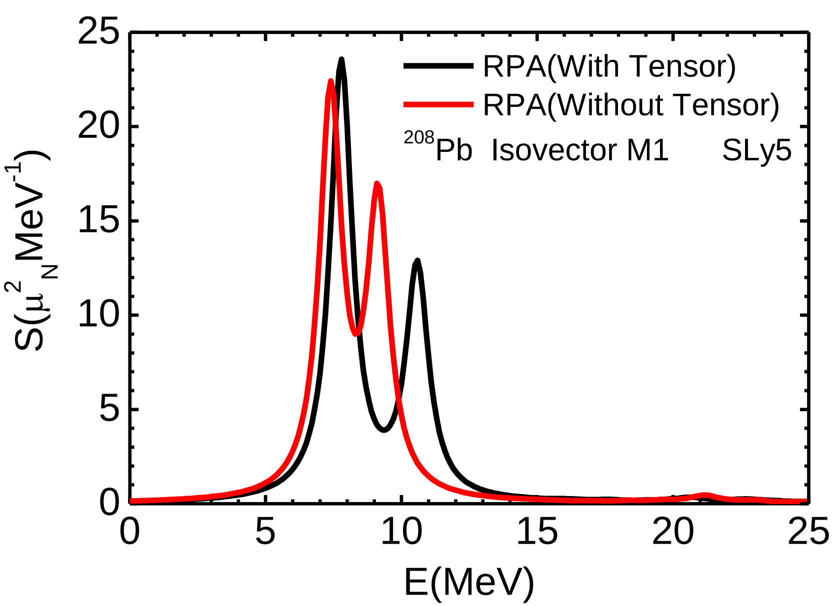
$$\Delta E_{HF} = 0.60MeV$$

$$\Delta E_{RPA} = 0.17MeV$$
$$\langle V_{tensor} \rangle = -0.43MeV$$

M1 states: Cao L. G. et.al.,PRC 80, 064304(2009)







$$\Delta E_{RPA} \approx \Delta E_{HF} + \langle V_{tensor} \rangle$$

proton $h_{11/2} \rightarrow h_{9/2}$	neutron $i_{13/2} \rightarrow i_{11/2}$
$5.85MeV \rightarrow 6.46MeV$	$7.49MeV \rightarrow 9.17MeV$
$\Delta E_{HF} = 0.61MeV$	$\Delta E_{HF} = 1.68MeV$
$7.39MeV \rightarrow 7.79MeV$	$9.14MeV \rightarrow 10.57MeV$
$\Delta E_{RPA} = 0.40MeV$	$\Delta E_{RPA} = 1.43MeV$
$\langle V_{tensor} \rangle = -0.21MeV$	$\langle V_{tensor} \rangle = -0.25MeV$

M1 states in Sn isotopes:

PHYSICAL REVIEW C **102**, 034327 (2020)

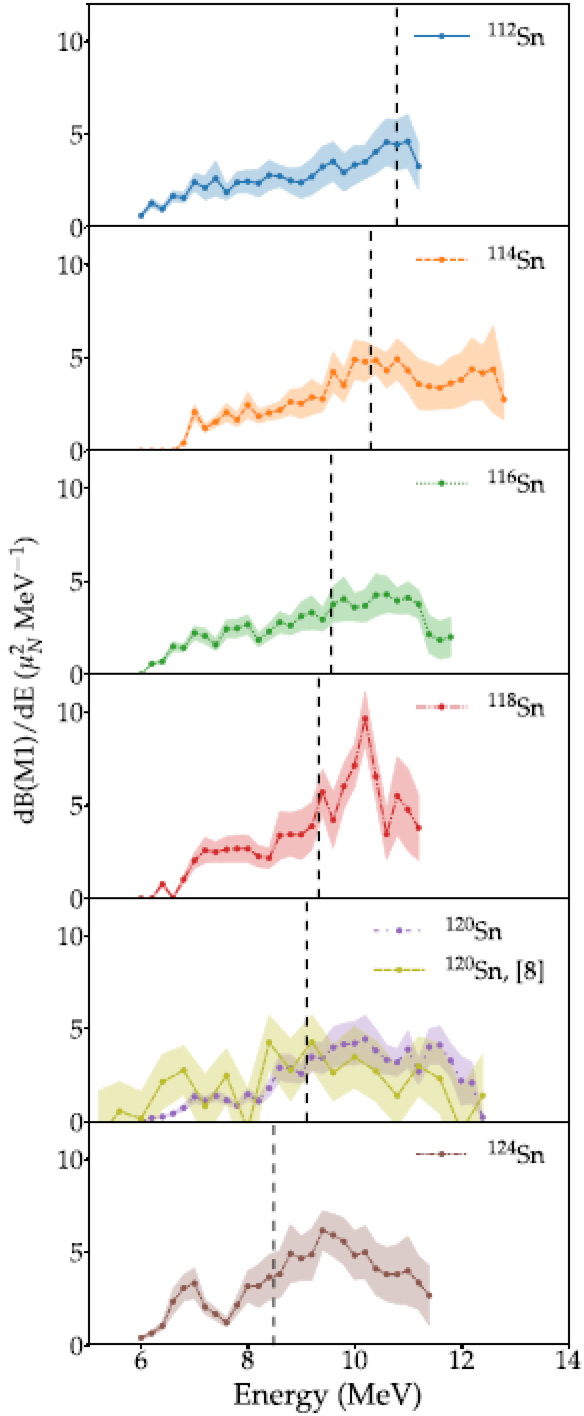
Electric and magnetic dipole strength in ^{112,114,116,118,120,124}Sn

S. Bassauer,[1,*] P. von Neumann-Cosel,[1,†] P.-G. Reinhard,[2] A. Tamii,[3] S. Adachi,[3] C. A. Bertulani,[4] P. Y. Chan,[3] A. D'Alessio,[1] H. Fujioka,[5] H. Fujita,[3] Y. Fujita,[3] G. Gey,[3] M. Hilcker,[1] T. H. Hoang,[3] A. Inoue,[3] J. Isaak,[1,3] C. Iwamoto,[6] T. Klaus,[1] N. Kobayashi,[3] Y. Maeda,[7] M. Matsuda,[8] N. Nakatsuka,[1] S. Noji,[9] H. J. Ong,[10,3] I. Ou,[11] N. Pietralla,[1] V. Yu. Ponomarev,[1] M. S. Reen,[12] A. Richter,[1] M. Singer,[1] G. Steinhilber,[1] T. Sudo,[3] Y. Togano,[13] M. Tsumura,[14] Y. Watanabe,[15] and V. Werner[1]

[1] *Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
[2] *Institut für Theoretische Physik II, Universität Erlangen, D-91058 Erlangen, Germany*
[3] *Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[4] *Department of Physics and Astronomy, Texas A&M University–Commerce, Commerce, Texas 75429, USA*
[5] *Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan*
[6] *RIKEN, Nishina Center for Accelerator-Based Science, 2-1 Hirosawa, Wako 351-0198, Saitama, Japan*
[7] *Department of Applied Physics, Miyazaki University, Miyazaki 889-2192, Japan*

PHY ... 2020)

Electric and ... 16,118,120,124Sn



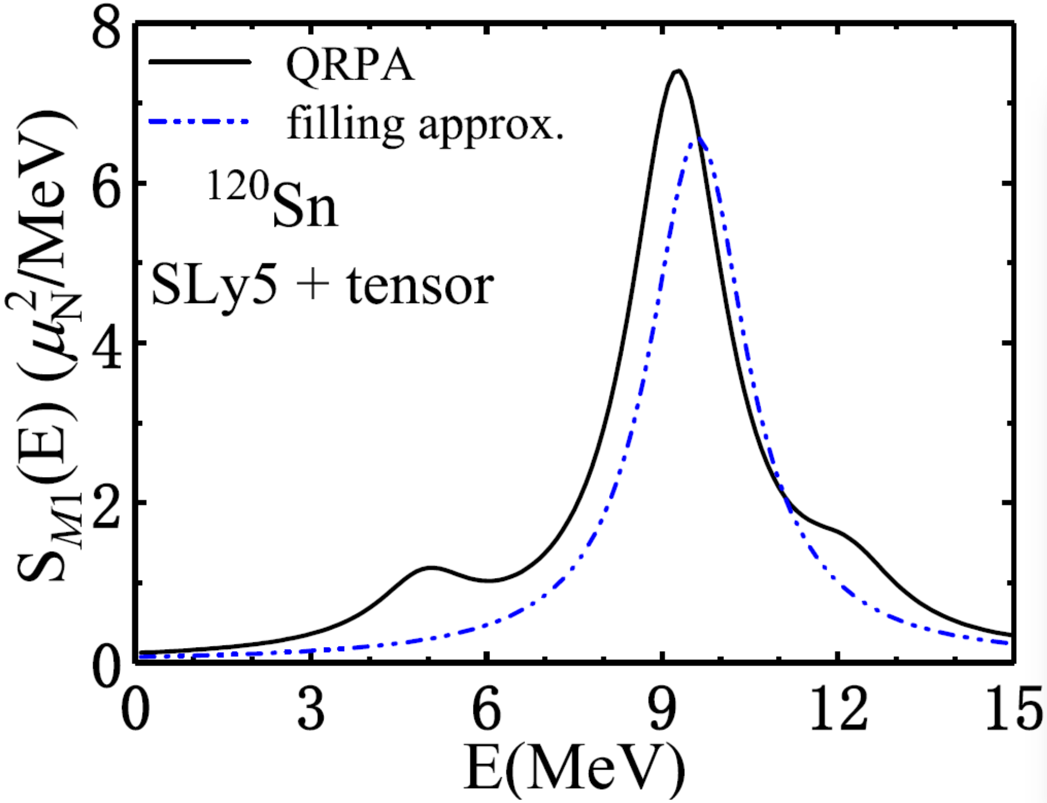
S. Bassauer,[1,*] P. von Neumann-Co ... chi,[3] C. A. Bertulani,[4] P. Y. Chan,[3]
A. D'Alessio,[1] H. Fujioka,[5] H. Fujita,[3] ... g,[3] A. Inoue,[3] J. Isaak,[1,3] C. Iwamoto,[6]
T. Klaus,[1] N. Kobayashi,[3] Y. Maed ... I. J. Ong,[10,3] I. Ou,[11] N. Pietralla,[1]
V. Yu. Ponomarev,[1] M. S. R ... er,[1] T. Sudo,[3] Y. Togano,[13]
M ... 1

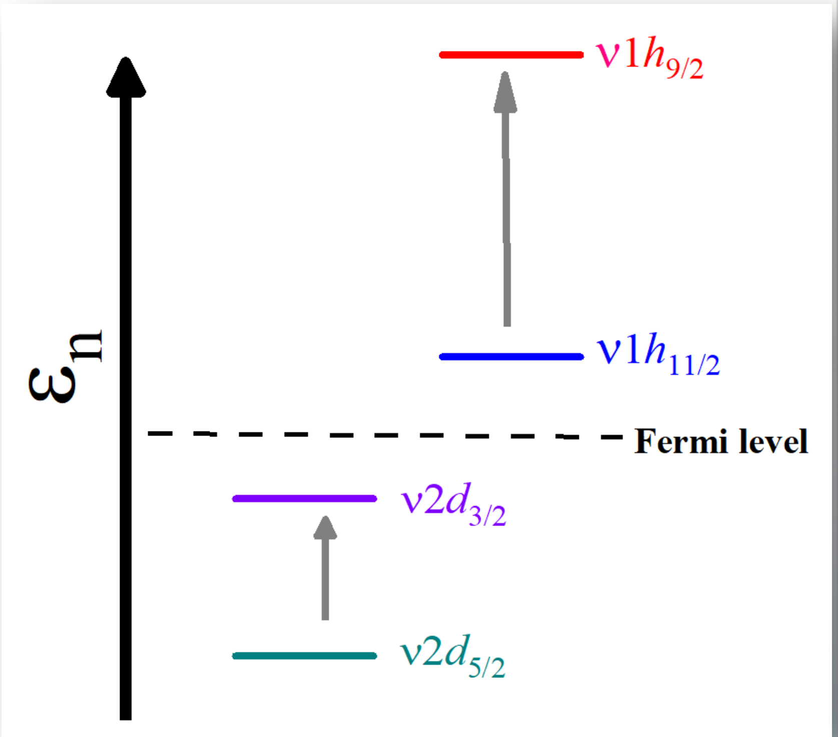
[1]*Institut für Kernphys ... Darmstadt, Germany*
[2]*Institut für Theore ... Erlangen, Germany*
[3]*Research Center for ... ka 567-0047, Japan*
[4]*Department of Physics and ... ommerce, Texas 75429, USA*
[5]*Department o ... 2-8551, Japan*
[6]*RIKEN, Nishina Center for ... 351-0198, Saitama, Japan*
[7]*Department of ... 89-2192, Japan*

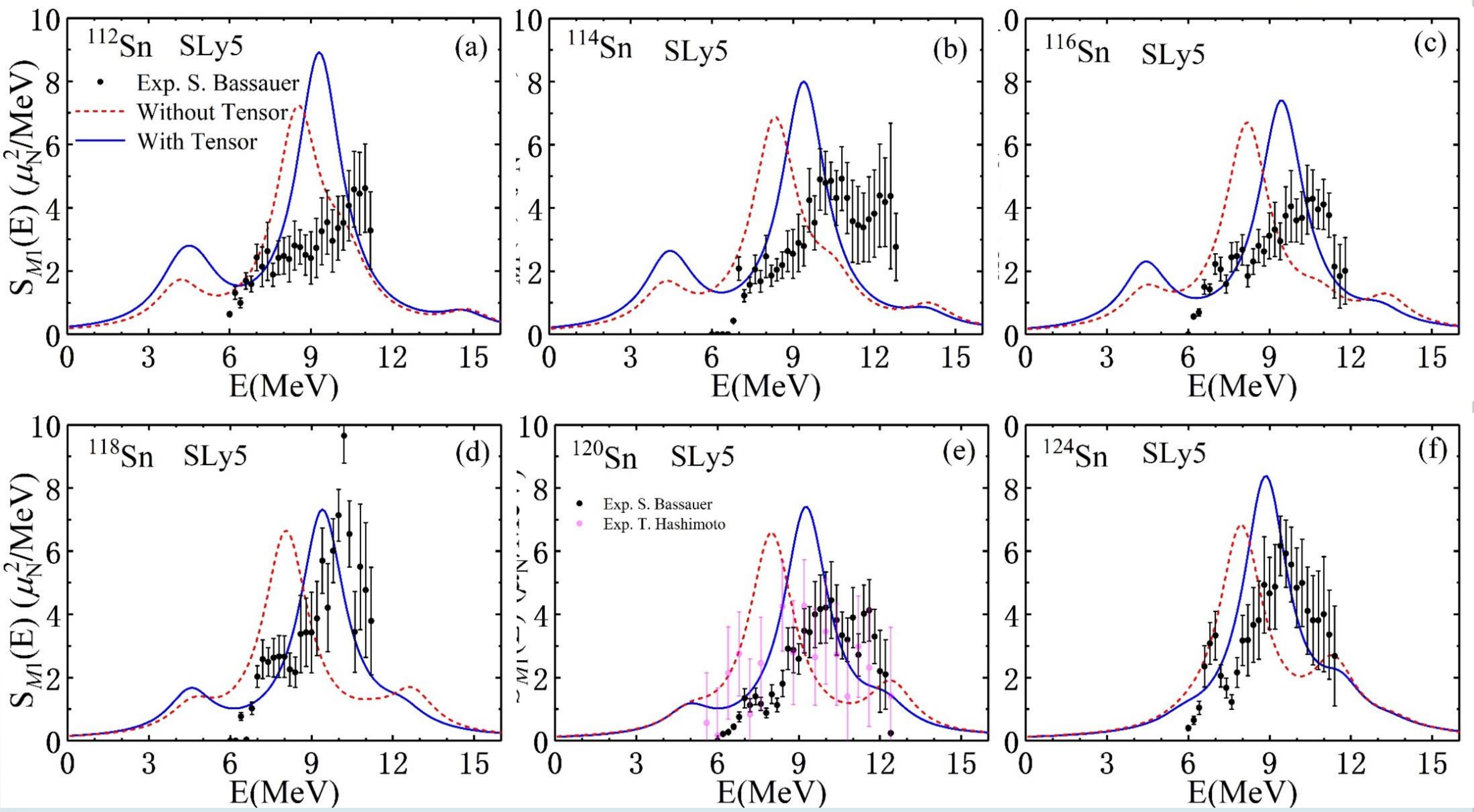
M1 states:

Sun S. et.al.,PRC 109, 014312(2024)

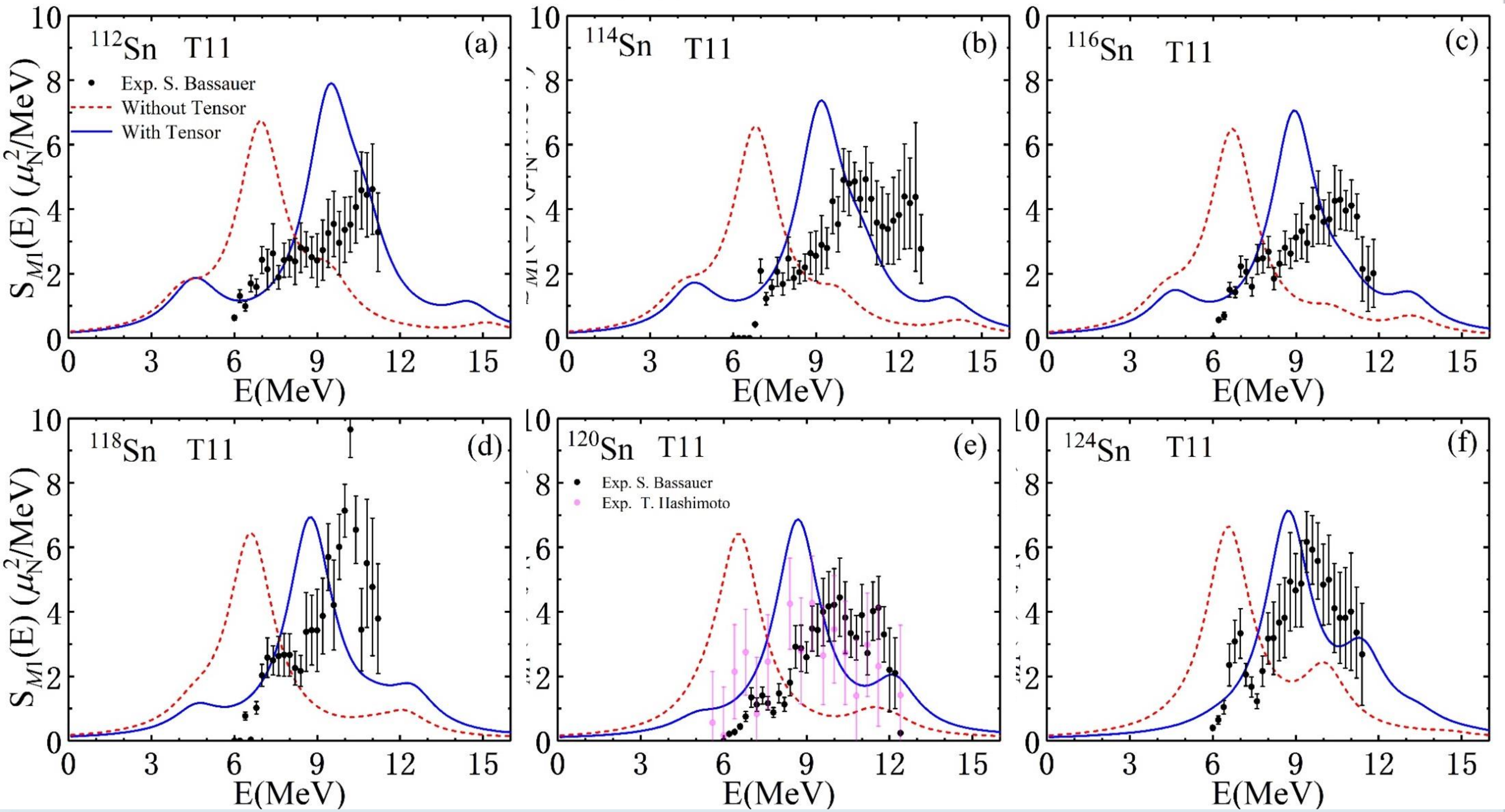
Pairing effect:







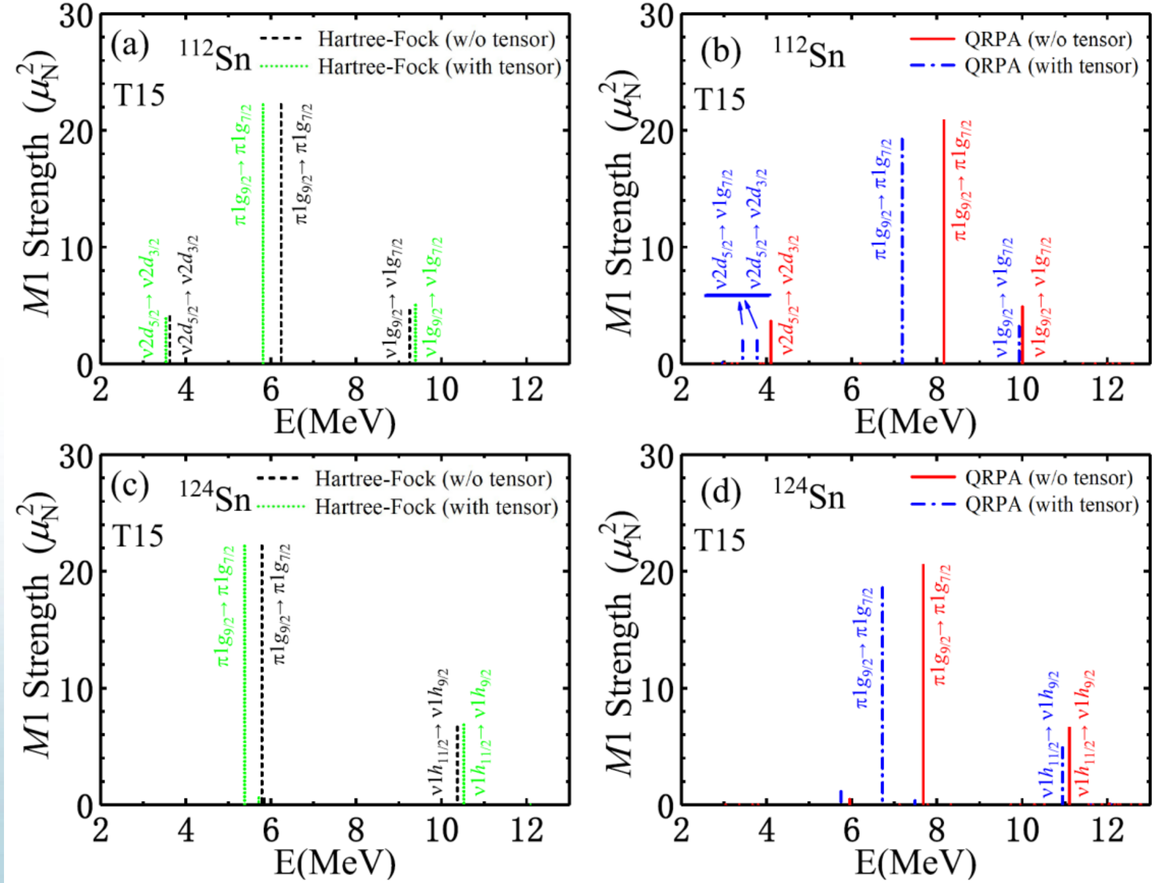
M1 states: Sun S. et.al.,PRC 109, 014312(2024)



M1 states：

Sun S. et.al.,PRC 109, 014312(2024)

	T	U	α	β	α_C	β_C	α_T	β_T
SLy5	888.0	−408.0	−89.8	51.1	80.2	-48.9	-170.0	100.0
T11	258.9	−342.8	−60.0	−60.0	82.8	-42.5	-142.8	-17.5
T15	−500.9	173.3	180.0	−60.0	107.8	8.3	72.2	-68.3



2. Equation of states of nuclear matter

$$\frac{E}{A}(\rho, I) \approx E_{SNM}(\rho) + S_2(\rho) I^2$$

$$E_{SNM}(\rho) = E_0 + \frac{K_0}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{Q_0}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + O(4)$$

$$S_2(\rho) = E_{sym} + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{sym}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{Q_{sym}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + O(4)$$

$$K_0 = 9\rho_0^2 \frac{\partial^2 E_{SNM}(\rho)}{\partial \rho^2}\bigg|_{\rho=\rho_0}$$

$$L = 3\rho_0 \frac{\partial S_2(\rho)}{\partial \rho}\bigg|_{\rho=\rho_0}$$

↔

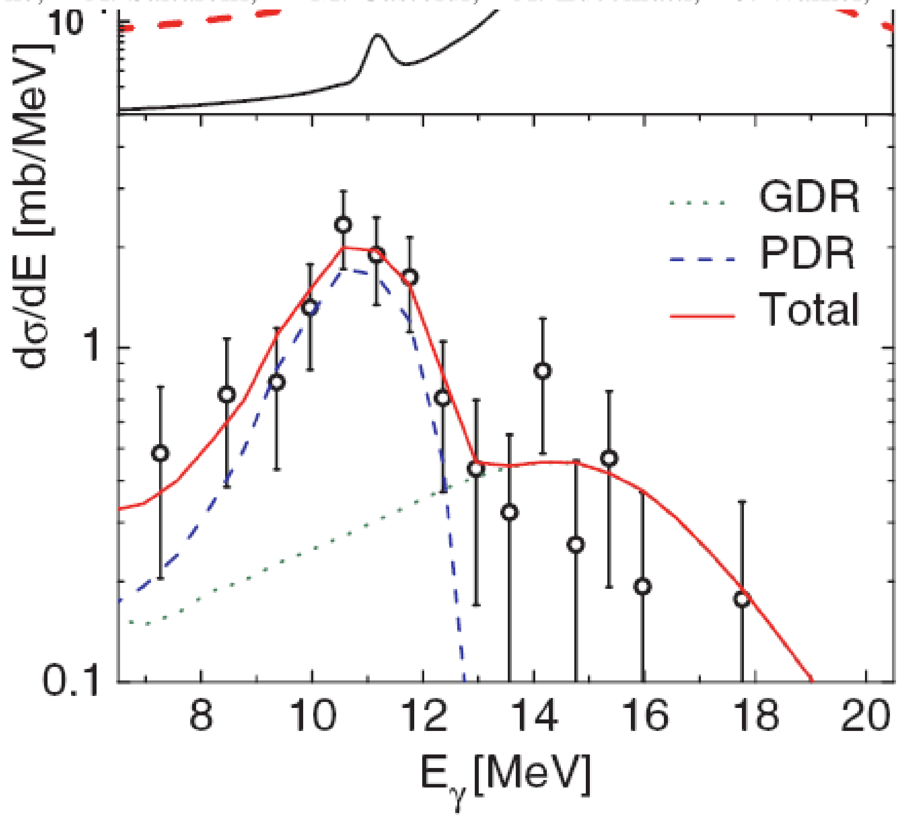
Nuclear structure
Heavy ion collision
Physics of neutron star

Constrains symmetry energy from PDR

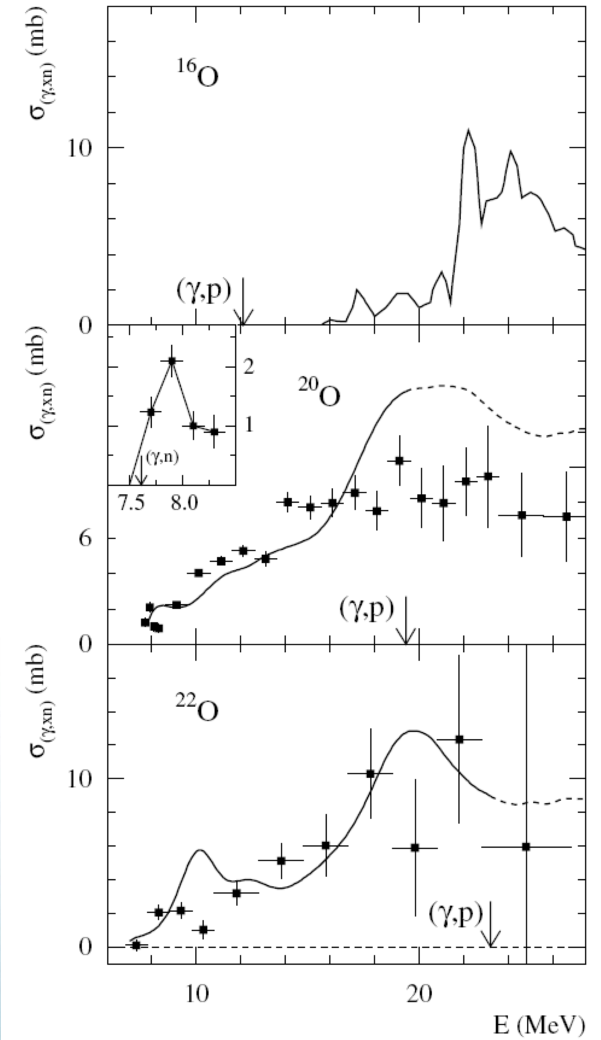
PRL **102,** 092502 (2009) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2009

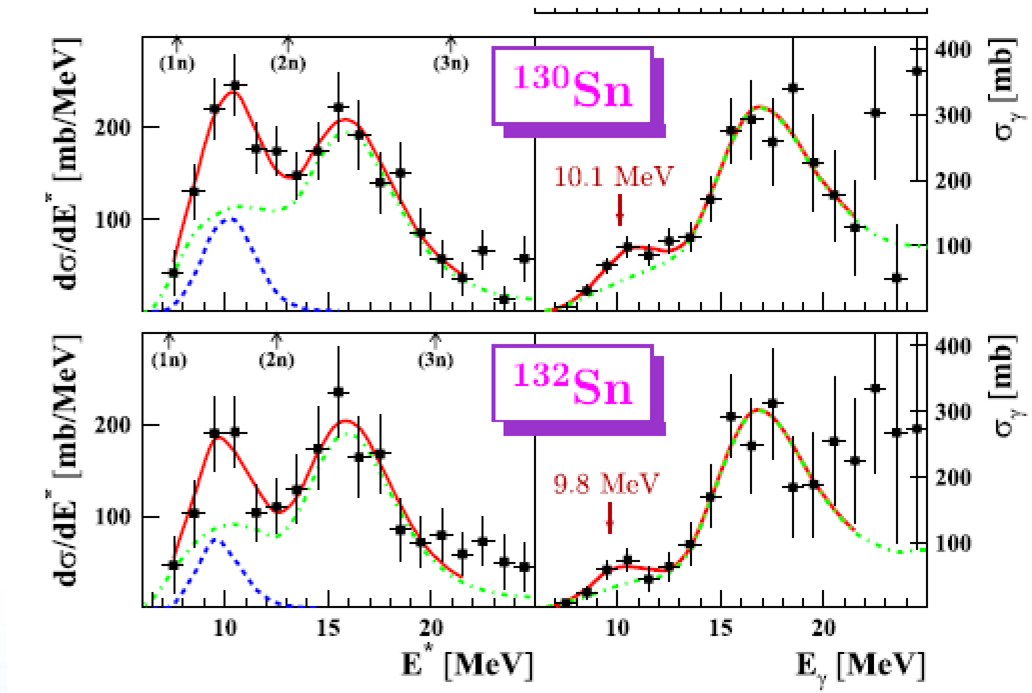
Search for the Pygmy Dipole Resonance in ^{68}Ni at 600 MeV/nucleon

O. Wieland,[1] A. Bracco,[1,2] F. Camera,[1,2] G. Benzoni,[1] N. Blasi,[1] S. Brambilla,[1] F. C. L. Crespi,[1,2] S. Leoni,[1,2] B. Million,[1] R. Nicolini,[1,2] A. Maj,[3] P. Bednarczyk,[3] J. Grebosz,[3] M. Kmiecik,[3] W. Meczynski,[3] J. Styczen,[3] T. Aumann,[4] A. Banu,[4] T. Beck,[4] F. Becker,[4] L. Caceres,[4,*] P. Doornenbal,[4,†] H. Emling,[4] J. Gerl,[4] H. Geissel,[4] M. Gorska,[4] O. Kavatsyuk,[4] M. Kavatsyuk,[4] I. Kojouharov,[4] N. Kurz,[4] R. Lozeva,[4] N. Saito,[4] T. Saito,[4] H. Schaffner,[4] H. J. Wollersheim,[3] J. Jolie,[5] P. Reiter,[5] N. Warr,[5] G. deAngelis,[6] A. Gadea,[6] D. Napoli,[6] S. Lenzi,[7,8] S. Lunardi,[7,8] D. Balabanski,[9,10] G. LoBianco,[9,10] C. Petrache,[9,‡] A. Saltarelli,[9,10] M. Castoldi,[11] A. Zucchiatti,[11] J. Walker,[12] and A. Bürger[13,§]



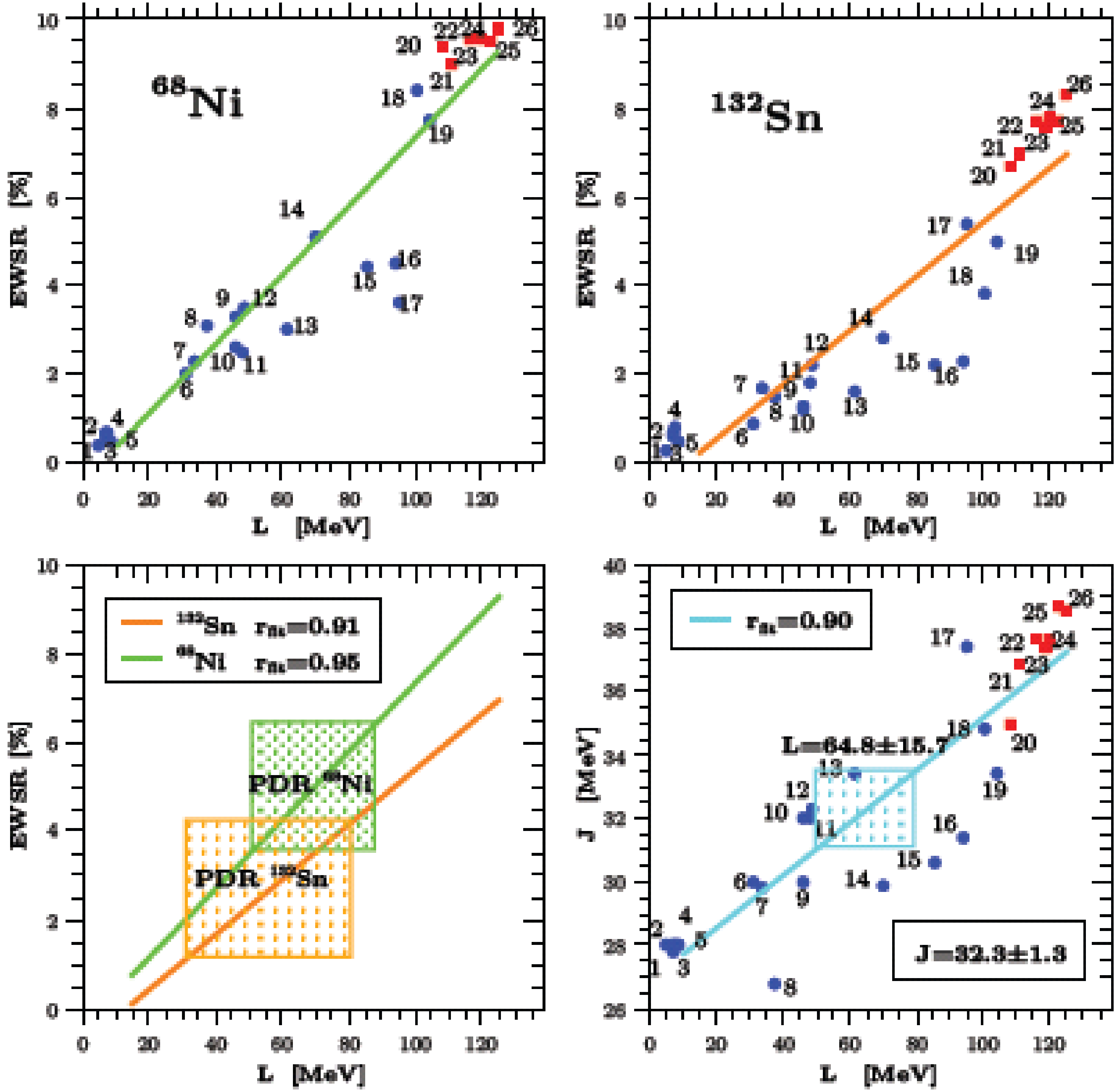
The Pygmy dipole states were also found in 20,22O and 130,132Sn





A. Leistenschneider, et al., Phys. Rev. Lett. 86, 5442 (2001)
P. Adrich, et al., Phys. Rev. Lett. 95, 132501 (2005).

A. Carbone, et. al., Phys. Rev. C 81, 041301(R) (2010).

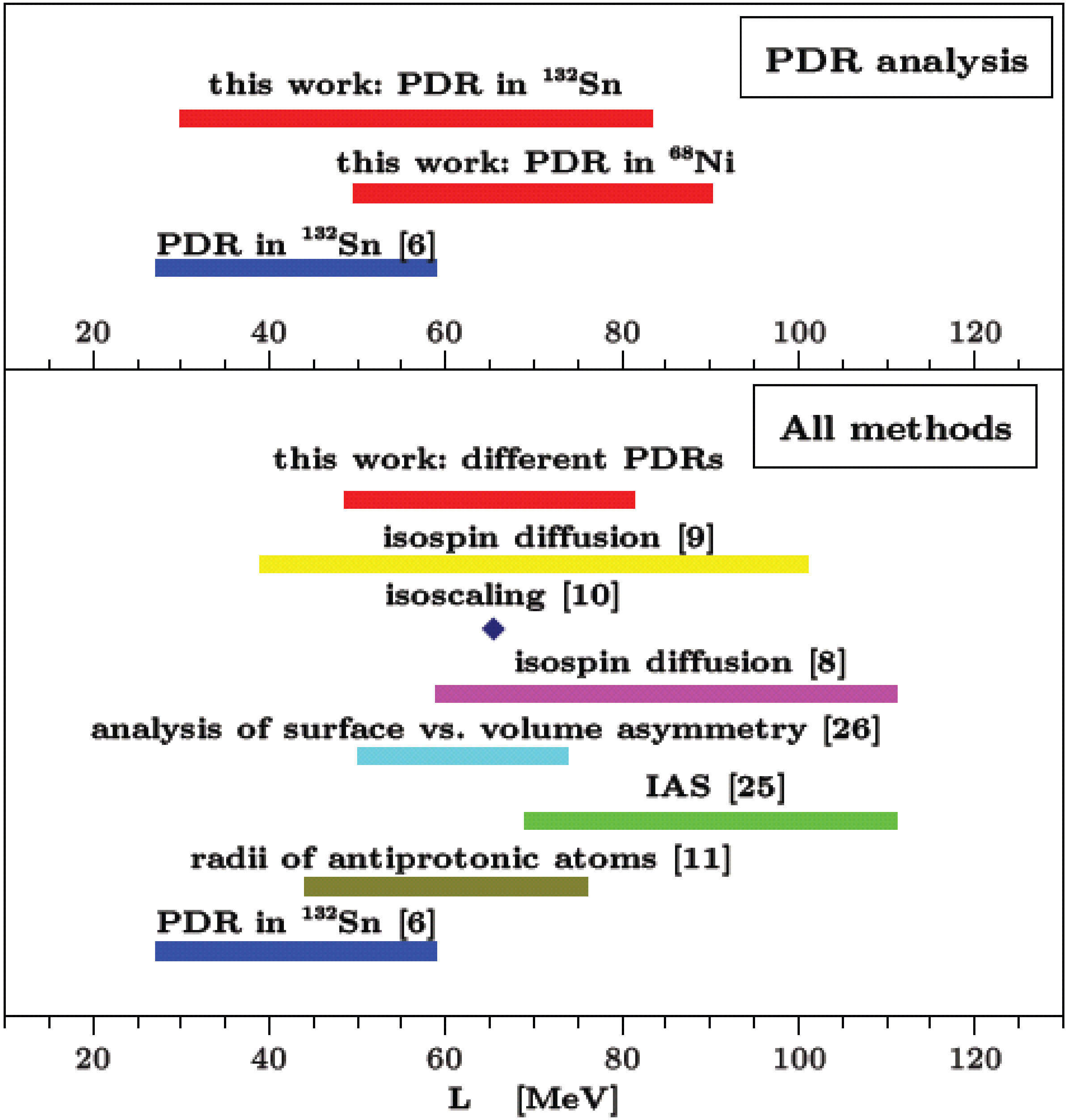


Ni68
50.3-89.4 MeV

Sn132
29.0-82.0 MeV

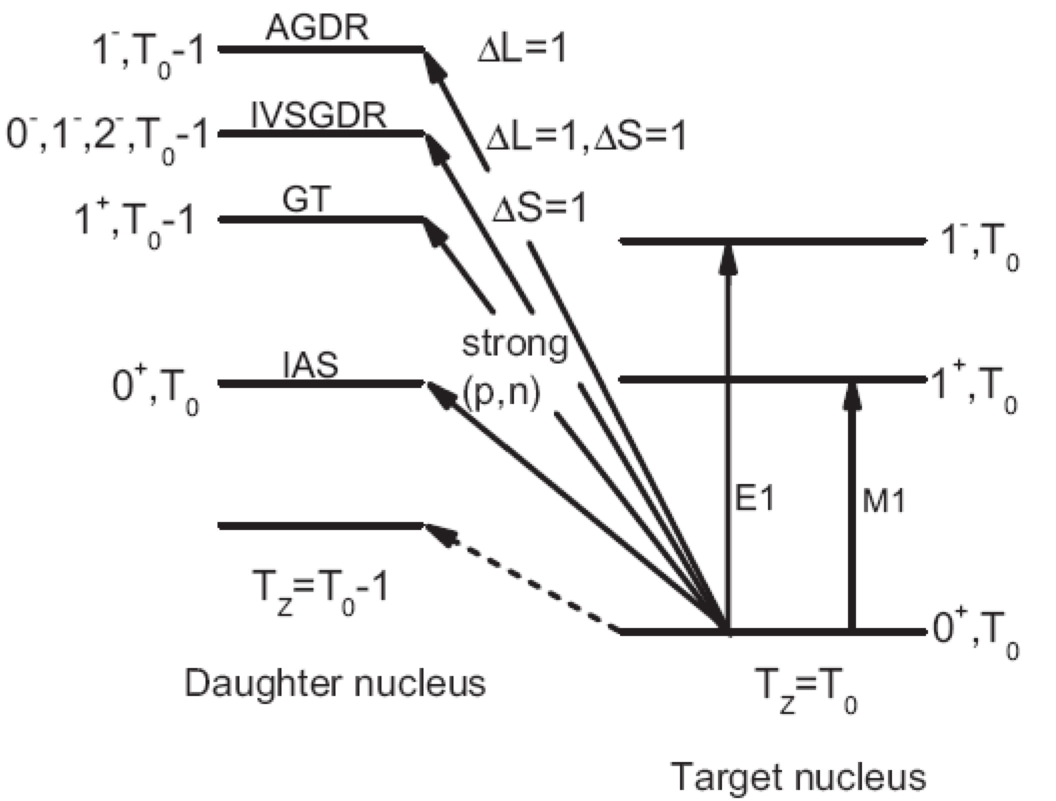
$$L(\rho_0) = 64.8 \pm 15.7 MeV$$

$$S(\rho_0) = 32.3 \pm 1.3 MeV$$



Andrea Carbone Gianluca Colo, Angela Bracco, Li-Gang Cao, Pier Francesco Bortignon, Franco Camera, and Oliver Wieland, Phys. Rev. C 81, 041301(R) (2010).

Anti-analog giant dipole resonance and the symmetry energy



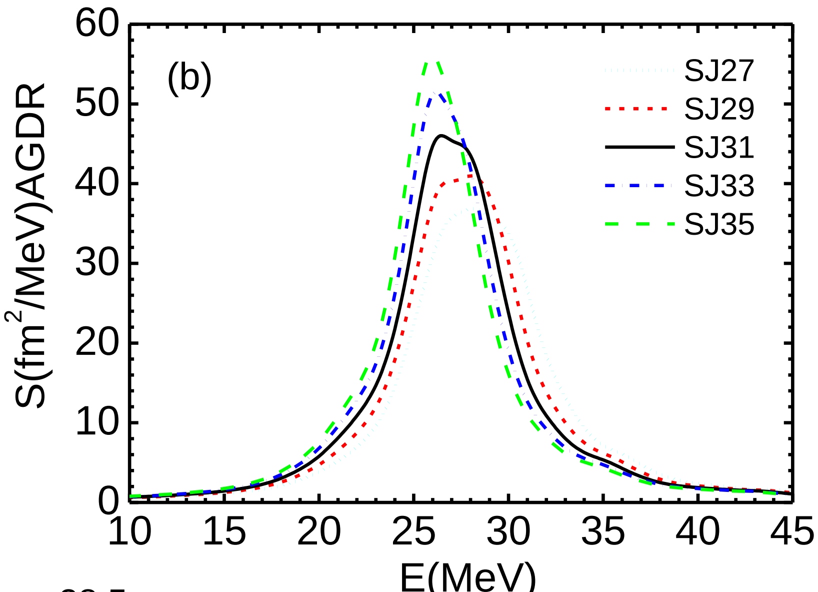
Spin-isospin GRs

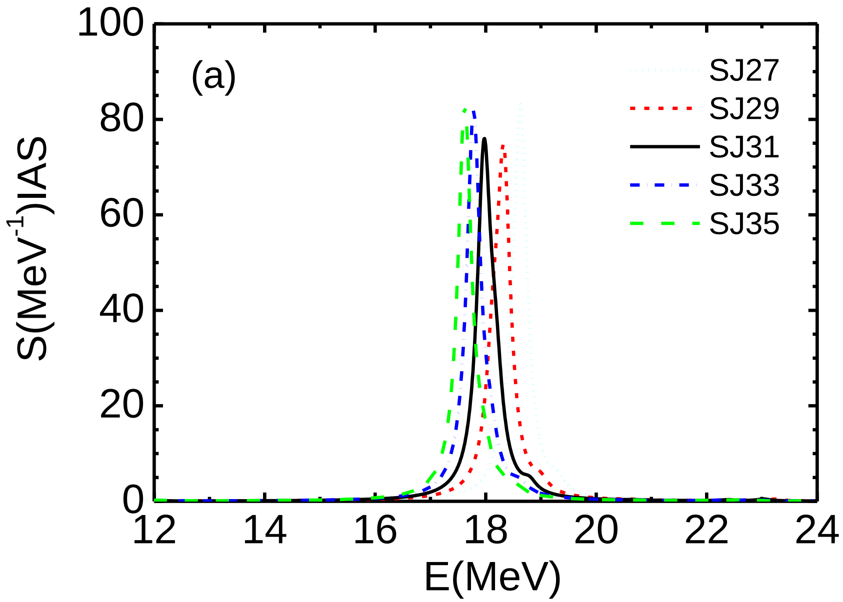
1) Spin dipole, Yako, PRC74, 051303(R) (2006)

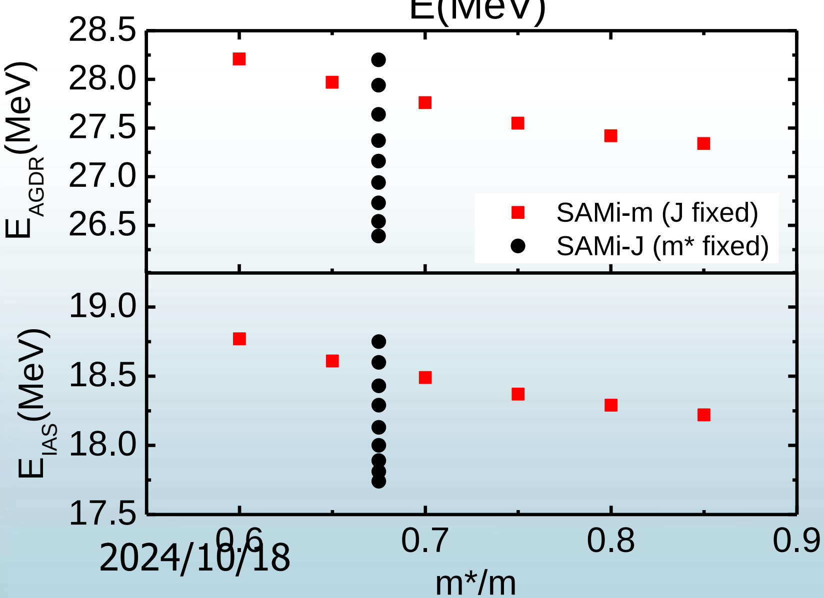
$$S_- - S_+ = \frac{9}{4\pi}(N\langle r^2\rangle_n - Z\langle r^2\rangle_p),$$

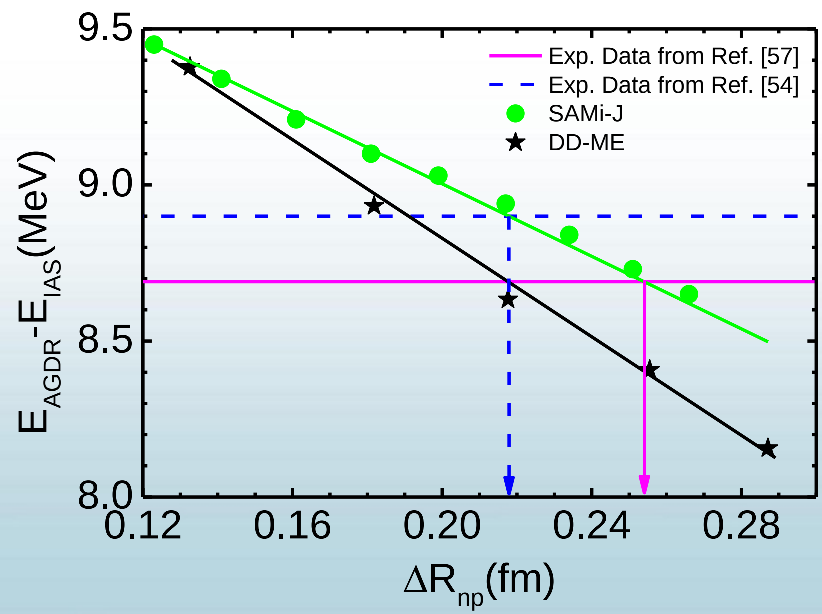
2) In Krmpotic's work, they claimed that the excitation energy of the AGDR is sensitive to the neutron skin thickness.

F. Krmpotic, K. Nakayama, and A. Pio Galeao, Nucl. Phys. A 399, 478 (1983).


(b)
S(fm²/MeV)AGDR
E(MeV)
SJ27
SJ29
SJ31
SJ33
SJ35

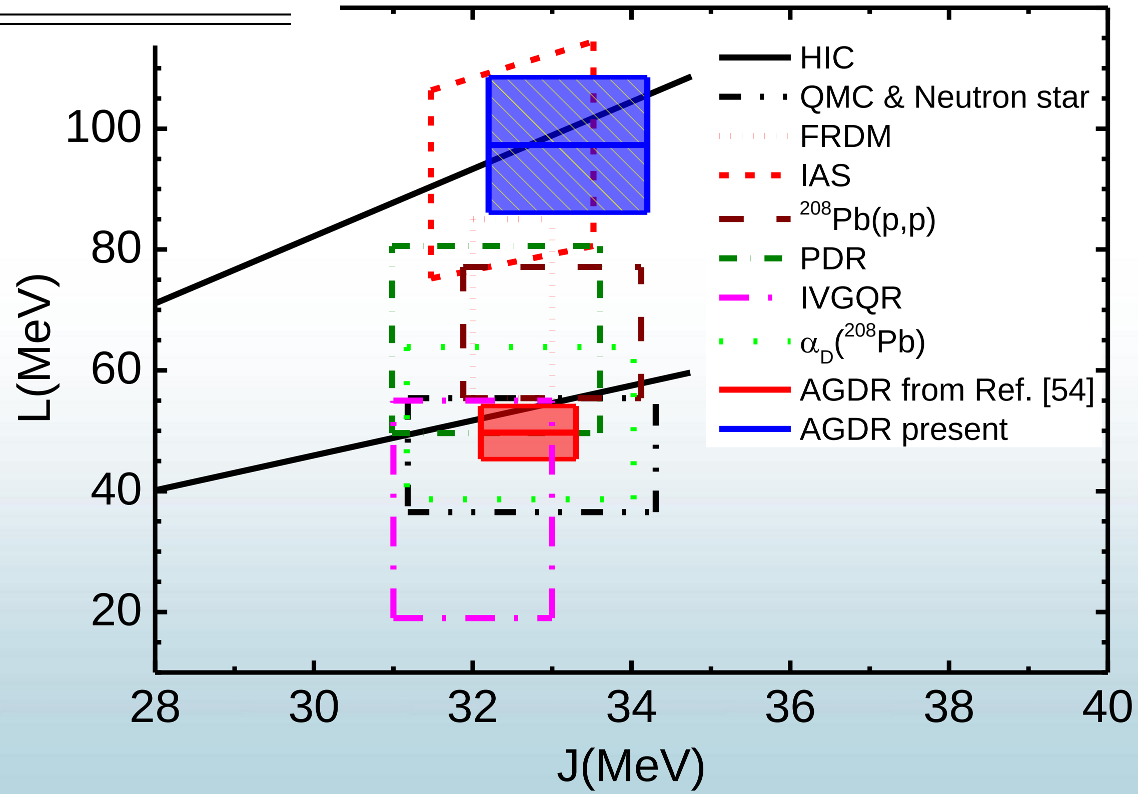

(a)
S(MeV⁻¹)IAS
E(MeV)
SJ27
SJ29
SJ31
SJ33
SJ35


E_AGDR(MeV)
E_IAS(MeV)
m*/m
SAMi-m (J fixed)
SAMi-J (m* fixed)


E_AGDR-E_IAS(MeV)
ΔR_np(fm)
Exp. Data from Ref. [57]
Exp. Data from Ref. [54]
SAMi-J
DD-ME

Method	Ref.	Date	ΔR_{np}(fm)
antiproton absorption	[31]	2001	0.180 ± 0.030
(α,α') IVGDR	[69]	2004	0.120 ± 0.070
PDR	[43]	2010	0.194 ± 0.024
$(\vec{p},\vec{p}')$	[35]	2011	0.156 ± 0.025
α_D	[41]	2012	0.168 ± 0.022
parity violation	[29]	2012	0.330 ± 0.170
AGDR from Exp1	[57]	2013	0.216 ± 0.048
AGDR from Exp2	[54]	2013	0.190 ± 0.028
(γ,π^0)	[1]	2014	0.150 ± 0.030
AGDR from Exp1	present	2015	0.254 ± 0.062
AGDR from Exp2	present	2015	0.218 ± 0.015

$R_np = 0.236 \pm 0.018$fm
$J = 33.2 \pm 1.0$ MeV
$L = 97.3 \pm 11.2$ MeV



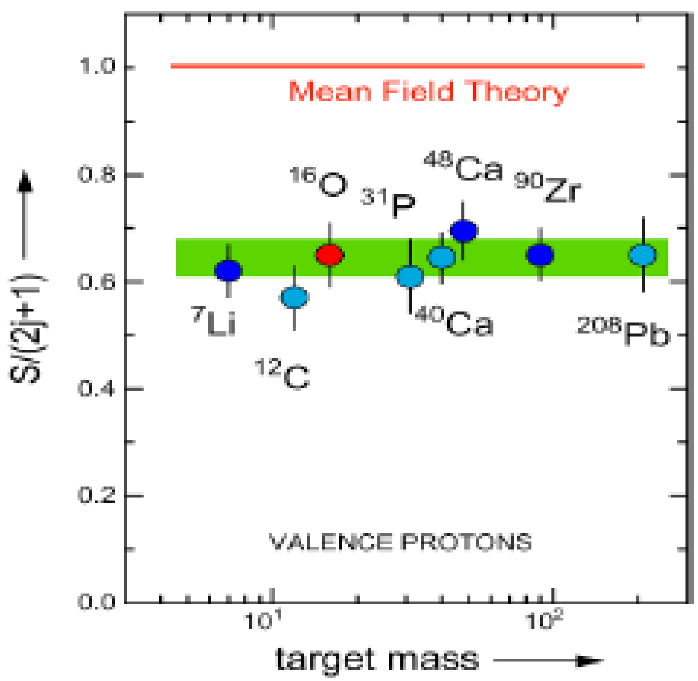
3. Single-particle states from particle-vibration coupling

limitations of EDFT

- Widths of GRs.
- Single-particle states and their spectroscopic factors

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp} = S^2 \left(\frac{d\sigma}{d\Omega}\right)_{\rm DWBA}$$

NIKHEF   NPA 553, 297c (1993)



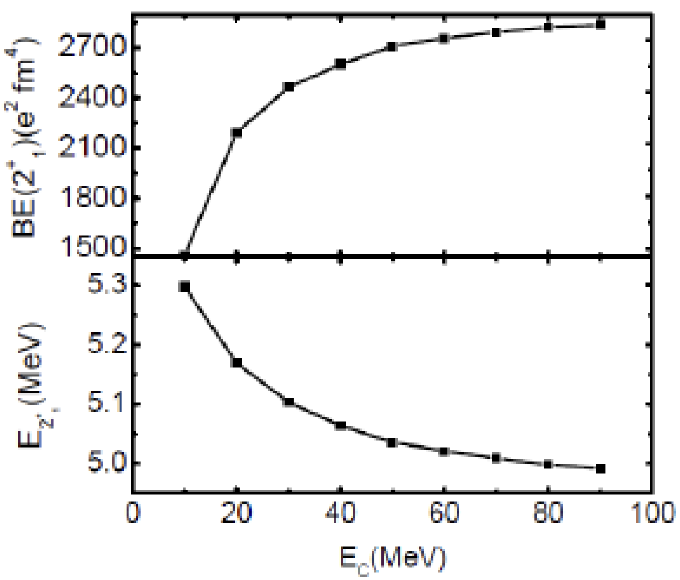
Our fully self-consistent implementation

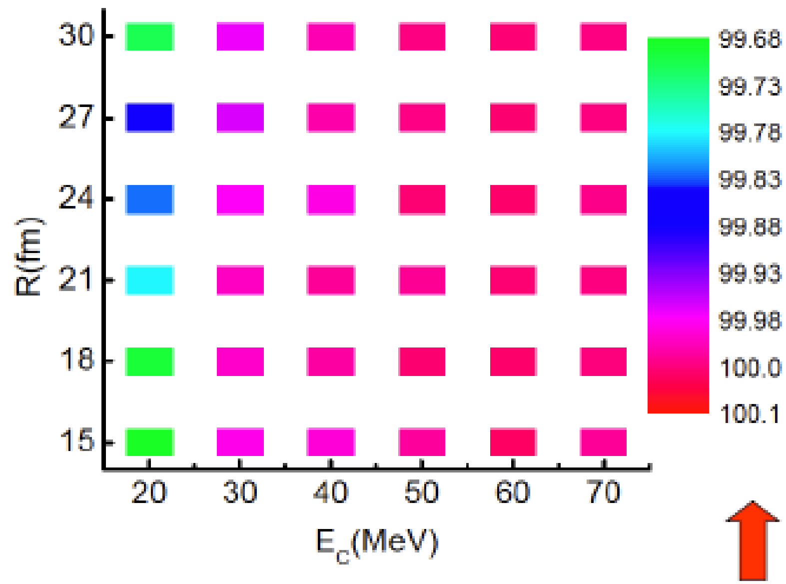
The continuum is discretized. The basis must be large due to the zero-range character of the force. Parameters: R, E_C.

The energy-weighted sum rule should be equal to the double-commutator value: well fulfilled !

$$m_1(\hat{O}) = \sum_\nu E_\nu |\langle \nu|\hat{O}|\tilde{0}\rangle|^2 = \frac{1}{2}\langle 0|[\hat{O},[H,\hat{O}]]|0\rangle$$

^{208}Pb - SGII





G. Colò, L. Cao, N. Van Giai, L. Capelli Comp. Phys. Comm. 184, 142 (2013).

Percentages $m_1(RPA)/m_1(DC)$ [%]

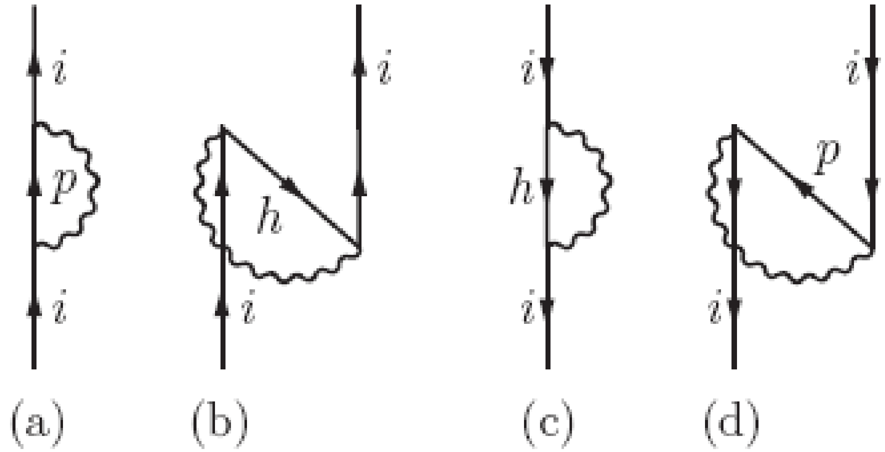
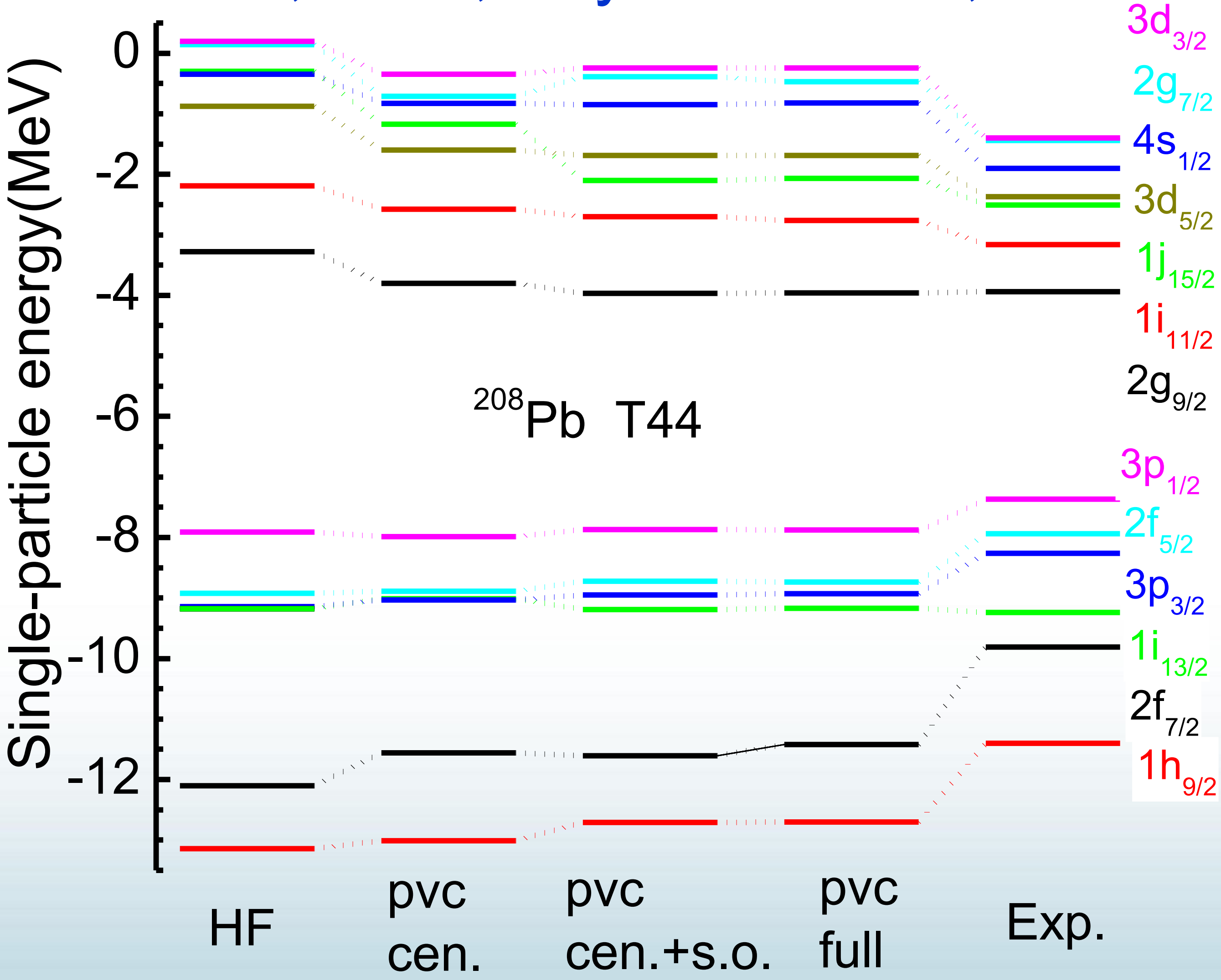


FIG. 1. The four diagrams associated with the single-nucleon self-energy. See the text for details.

$$\Sigma_i(\omega) = \frac{1}{2j_i+1}\left(\sum_{nL,\ p>F}\frac{|\langle i||V||p,nL\rangle|^2}{\omega-\varepsilon_p-\omega_{nL}+i\eta} + \sum_{nL,\ h<F}\frac{|\langle i||V||h,nL\rangle|^2}{\omega-\varepsilon_h+\omega_{nL}-i\eta}\right),$$

Cao LG, et.al., Phys.Rev. C89, 044314 (2014)



The values of σ are 1.421, 1.002, 0.907, 0.873 for T44 .

Spectroscopic factor

$$S_\alpha^\lambda = \left(1 - \frac{\partial \Sigma_\alpha}{\partial \varepsilon}\right)^{-1}_{\varepsilon=\varepsilon_\alpha^\lambda}.$$

TABLE IV: The energies and spectroscopic factors of the single-particle states in ^{208}Pb in various approximations. The results are obtained by using SLy5 and T44 parameter sets. The experimental data are taken from Ref.[31, 32].

		HF	pvc central		pvc central+S.O.		pvc full			Spectroscopic factors	
		$\varepsilon^{(0)}$	$\Delta\varepsilon_i$	ε_i	$\Delta\varepsilon_i$	ε_i	$\Delta\varepsilon_i$	ε_i	ε_i^{exp}	S_i^{th}	S_i^{exp}
T44	$3d_{3/2}$	0.20	-0.55	-0.35	-0.44	-0.24	-0.44	-0.24	-1.40	0.895	1.09
	$2g_{7/2}$	0.14	-0.85	-0.71	-0.53	-0.39	-0.61	-0.47	-1.44	0.832	1.05
	$4s_{1/2}$	-0.35	-0.48	-0.83	-0.50	-0.85	-0.47	-0.82	-1.90	0.896	0.98
	$3d_{5/2}$	-0.88	-0.72	-1.60	-0.81	-1.69	-0.81	-1.69	-2.37	0.855	0.98
	$1j_{15/2}$	-0.30	-0.87	-1.17	-1.80	-2.10	-1.77	-2.07	-2.51	0.583	0.58
	$1i_{11/2}$	-2.19	-0.39	-2.58	-0.51	-2.70	-0.57	-2.76	-3.16	0.884	0.86
	$2g_{9/2}$	-3.28	-0.52	-3.80	-0.69	-3.97	-0.68	-3.96	-3.94	0.877	0.83
	$3p_{1/2}$	-7.91	-0.08	-7.99	0.04	-7.87	0.03	-7.88	-7.37	0.905	0.90
	$2f_{5/2}$	-8.92	0.03	-8.89	0.19	-8.72	0.18	-8.74	-7.94	0.888	0.60
	$3p_{3/2}$	-9.14	0.11	-9.03	0.19	-8.95	0.21	-8.93	-8.26	0.844	0.88
	$1i_{13/2}$	-9.18	0.17	-9.01	-0.01	-9.19	0.01	-9.17	-9.24	0.903	0.91
	$2f_{7/2}$	-12.10	0.54	-11.56	0.49	-11.61	0.68	-11.42	-9.81	0.580	0.95
	$1h_{9/2}$	-13.14	0.13	-13.01	0.43	-12.71	0.44	-12.70	-11.40	0.831	0.98

Cao LG, et.al., Phys.Rev. C89, 044314 (2014)

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