Nuclear Pygmy Modes and Astrophysical Reactions

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Agenda

- **The Giessen DFT Approach: Microscopic EDF for HFB and multi-phonon QRPA theory**
- **Sn-isotopes: ground states and pygmy dipole (PDR) modes**
- **Neutron and proton capture cross sections for N≈50 isotone**
- **Cosmo-chronometry: PDR modes in ^{206}Pb**

…credits to N. Tsoneva (now at ELI-NP at Bucharest)

The Giessen EDF Approach
GiEDF

The Giessen EDF Approach:

Density Functional Theory and Multi-Phonon QRPA Theory

Phys.Atom.Nucl. 79 (2016) 885, EPJ A (2019) in print

$$E(\rho,\kappa) \approx E(\rho_0,\kappa_0) + \sum_{q=p,n}\left(\left(T_q + U_q(\rho_0)\right)\delta\rho_q + \Delta_q\delta\kappa_q\right) + \sum_{q,q'=p,n} f_{qq'}(\rho_0)\delta\rho_q\delta\rho_{q'} + \ldots$$

$$\delta\rho_q \sim \varphi_k^\dagger\varphi_n \;\; ; \;\; \delta\kappa_q \sim \varphi_k\varphi_n \;\; \& \text{ h.c.} \;\; ; \;\; \text{q=p,n}$$

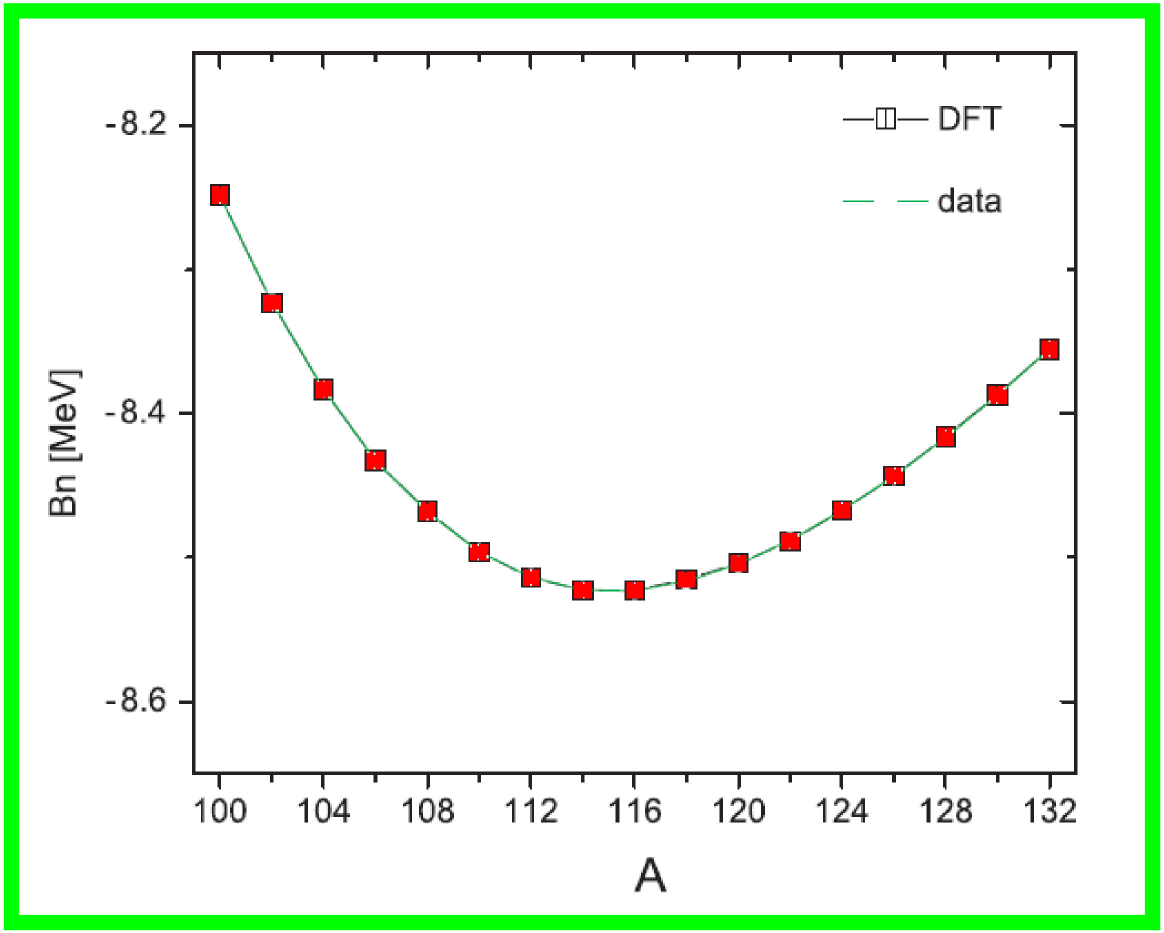
Single Particle Self-Energy:

$$U_q = \frac{\delta}{\delta\rho_q}\frac{1}{2}\langle V\rangle = \sum_{q'} V_{qq'}(\rho)\rho_{q'} + \frac{1}{2}\sum_{q'q''}\rho_{q'}\rho_{q''}\frac{\delta}{\delta\rho_q}V_{q'q''}(\rho)$$

HF Mean-Field
G-Matrix and 3-body interaction

Rearrangement Self-Energy
Static polarization

GiEDF and HFB: Binding Energies of Sn-Isotopes



N. Tsoneva, H.L., Phys.Rev. C78 (2008) 064314

Nuclear Excitations

Residual Two-Quasiparticle Interactions by Fermi-Liquid Theory

Second Variation of the EDF:

(q,q'=p,n and spins)

$$f_{qq'} = V_{qq'}(\rho) + 2\sum_{q''} \rho_{q''} \frac{\delta}{\delta\rho_q} V_{q'q''}(\rho) + \frac{1}{2}\sum_{k'k''} \rho_{k'}\rho_{k''} \frac{\delta^2}{\delta\rho_q \delta\rho_{q'}} V_{k'k''}(\rho)$$

ph-term | **polarization contributions**

Landau-Migdal Residual Interaction

The Multi-Phonon RPA (M*RPA) Approach to Nuclear Spectroscopy

- **Anharmonicities due to coupling to multi-quasiparticle configurations**
- **Core polarization effects**
- **Damping width and energy shifts of ph-/2QP-states**
- **Quenching of interaction vertices and transition strengths („effective charge“)**

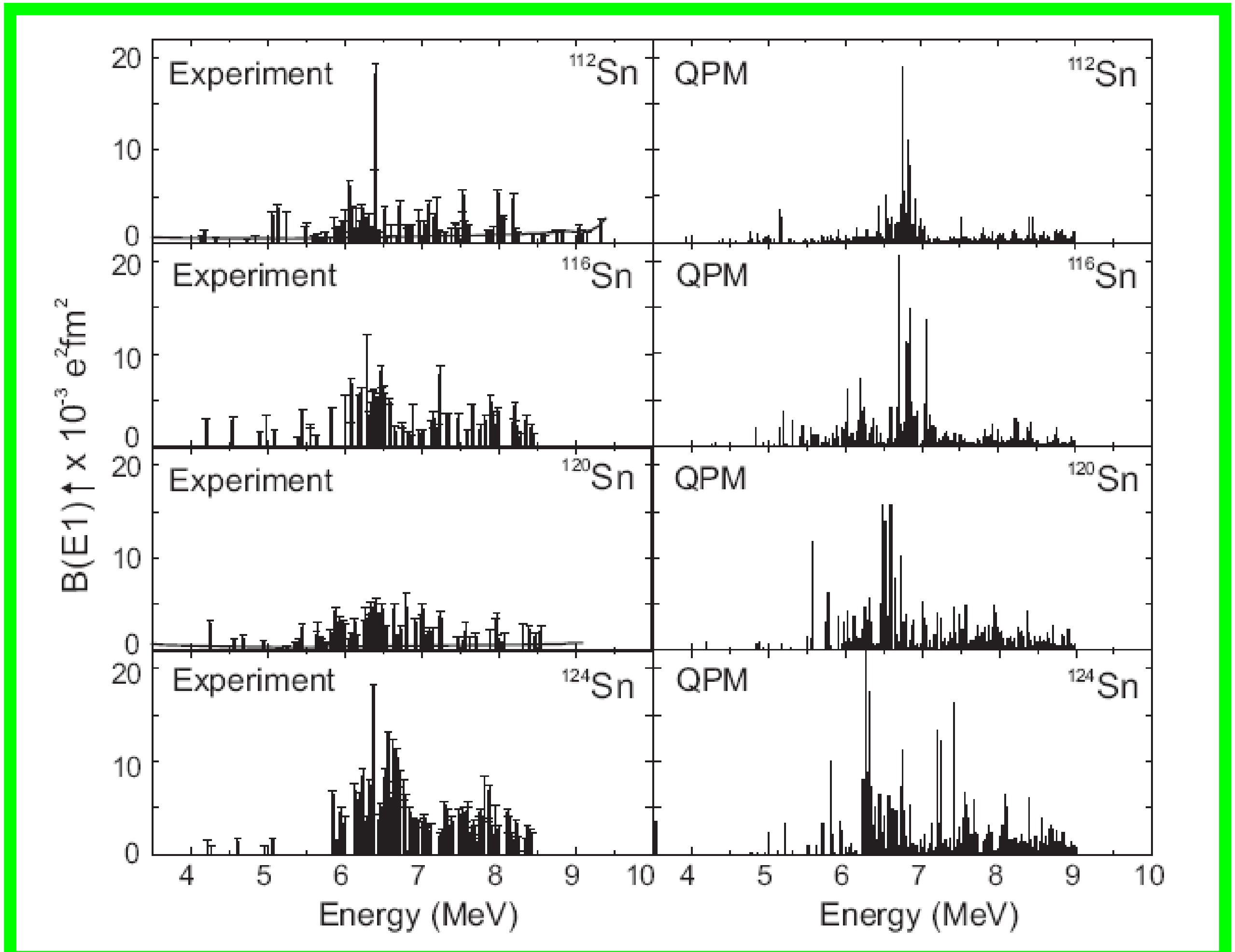
$$\Psi_i^\dagger = \sum_a z_a^{(i)} \Omega_a^\dagger + \sum_{ab} z_{ab}^{(i)} \Omega_a^\dagger \Omega_b^\dagger + \sum_{abc} z_{abc}^{(i)} \Omega_a^\dagger \Omega_b^\dagger \Omega_c^\dagger$$

Multi-Configuration Multi-Quasiparticle Wave Function – up to 3p3h/6QP

Phys.Atom.Nucl. 79 (2016) no.6, 885; EPJA special issue (2019) in print

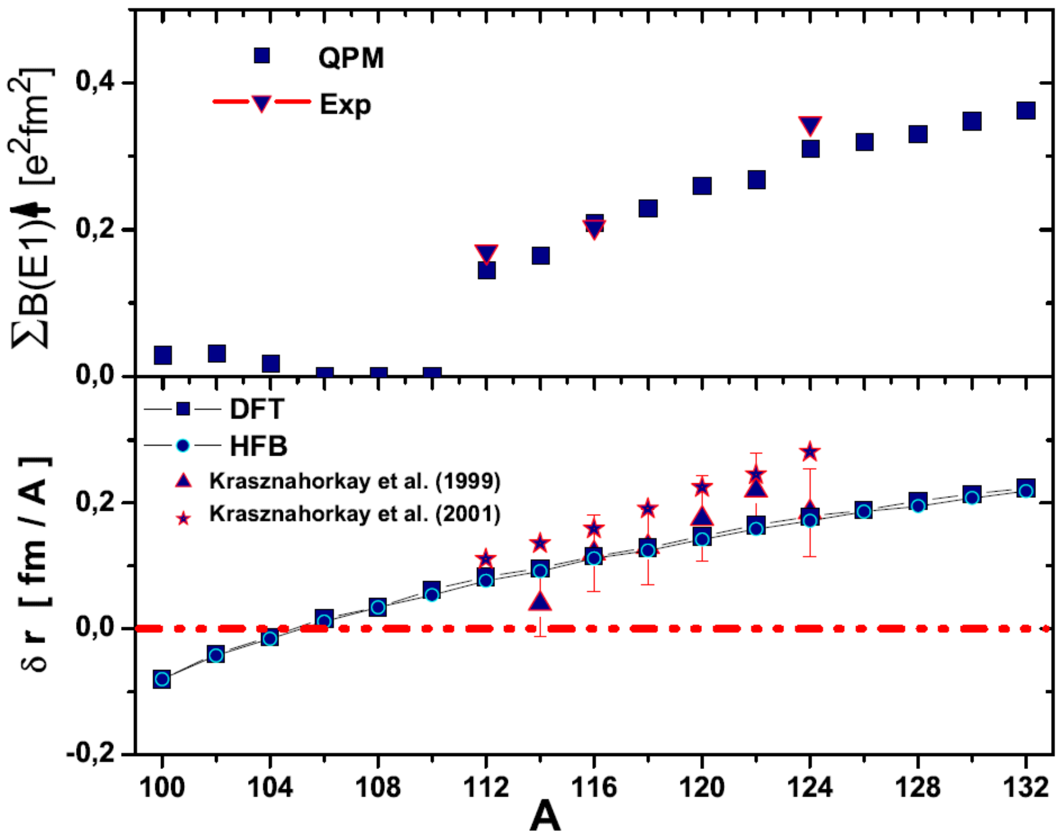
Giessen DFT & Multi-Phonon Approach

Pygmy Dipole Modes in Sn-Isotopes



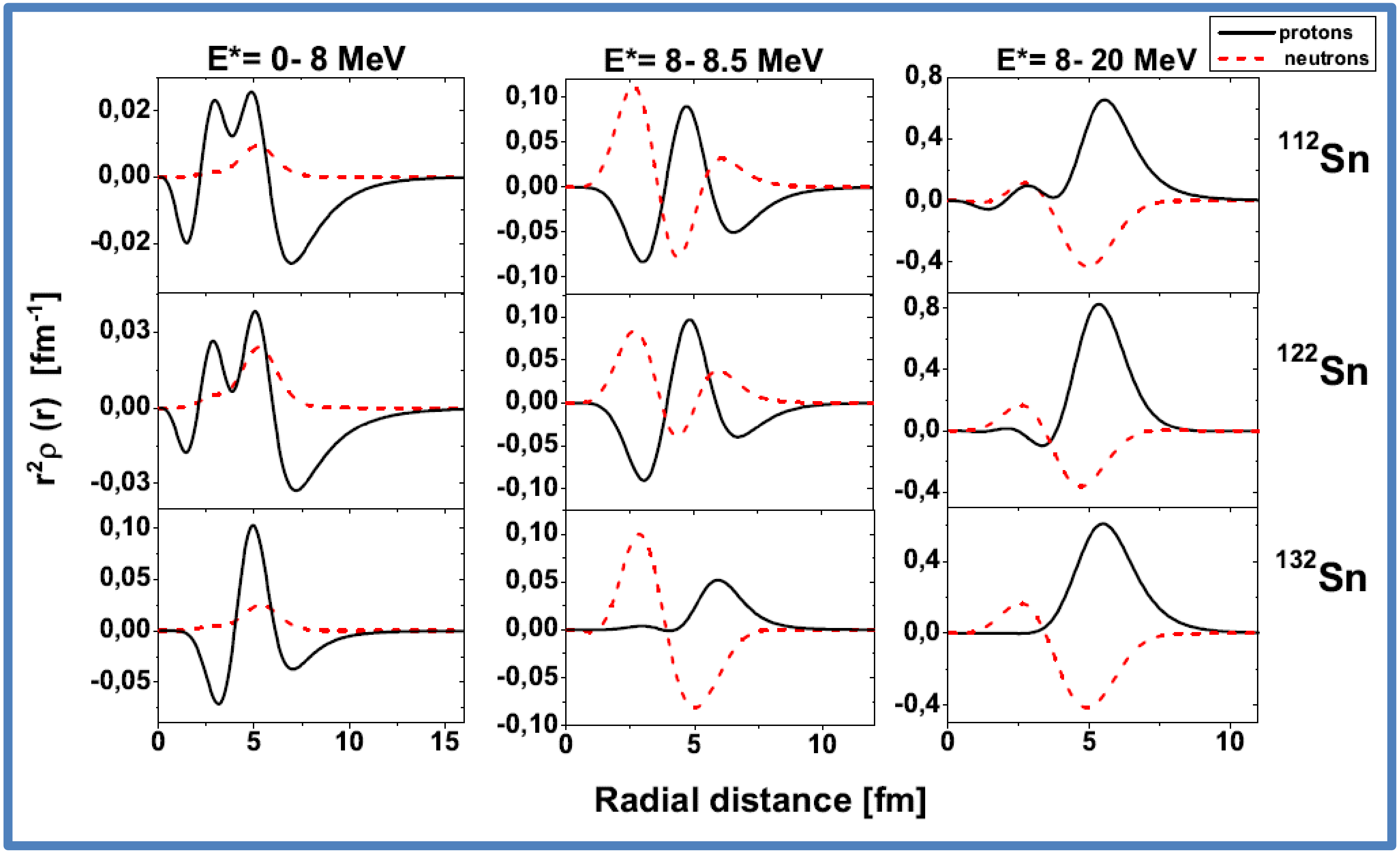
PhysRevC.90.024304(2014)

Pygmy Dipole Modes and Nuclear Skins



N. Tsoneva, H.L., Phys.Rev. C78 (2008) 064314

Dynamics of Pygmy Dipole Modes



N. Tsoneva, H.L., Phys.Rev. C78 (2008) 064314

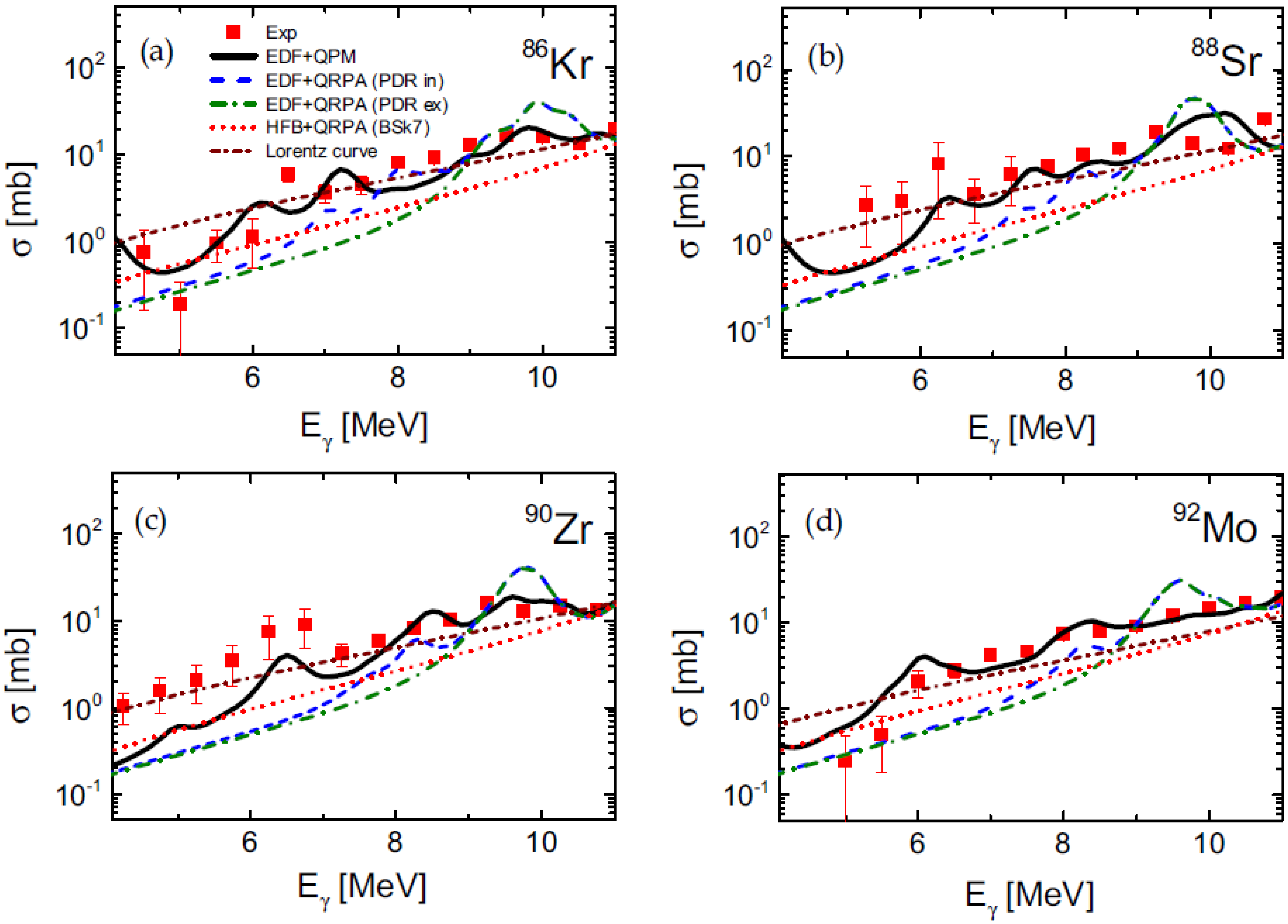
The N=50 Isotones

PHYSICAL REVIEW C **87**, 024306 (2013)

Pygmy dipole strength in ^{86}Kr and systematics of $N = 50$ isotones

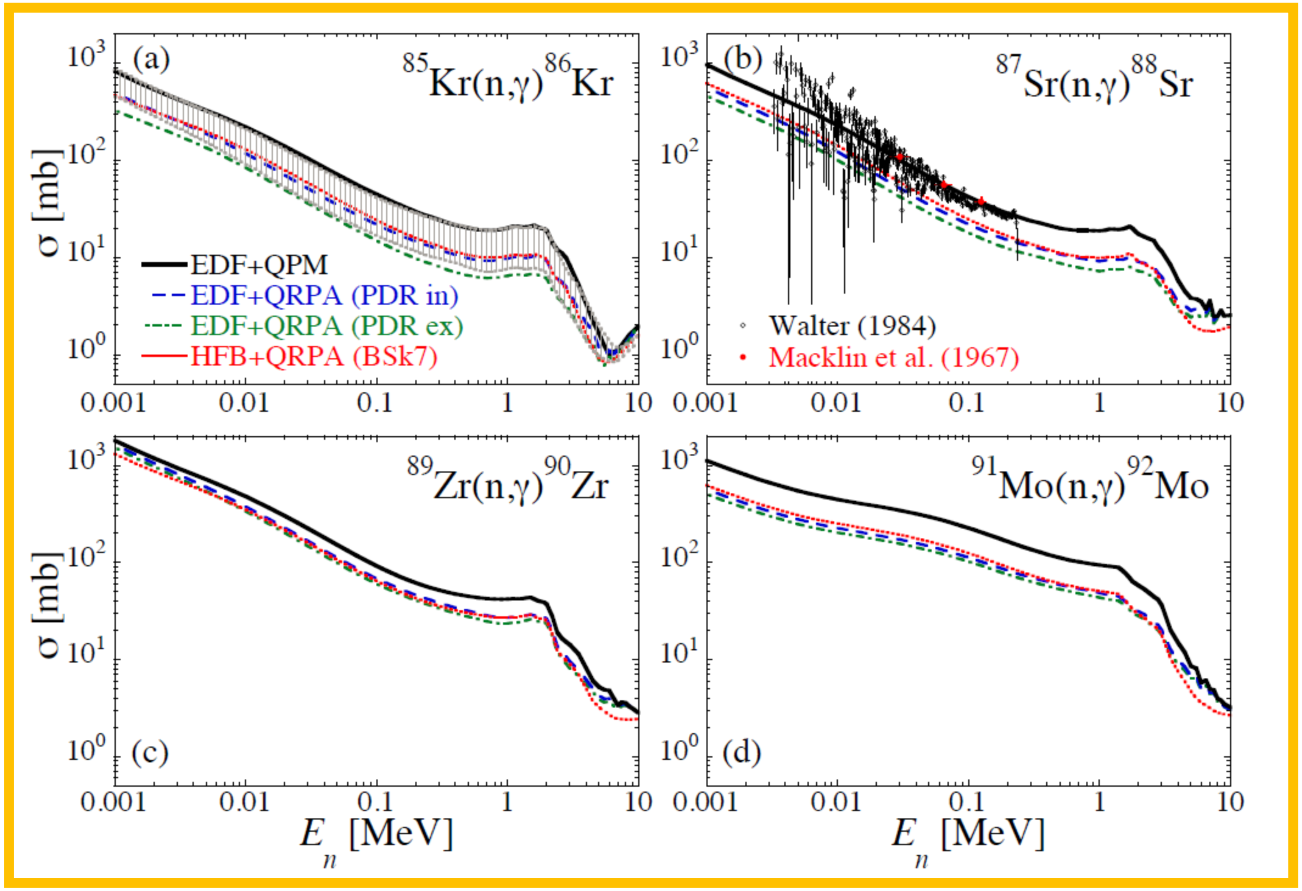
R. Schwengner,[1] R. Massarczyk,[1,2] G. Rusev,[3,4,*] N. Tsoneva,[5,6] D. Bemmerer,[1] R. Beyer,[1] R. Hannaske,[1,2] A. R. Junghans,[1] J. H. Kelley,[4,7] E. Kwan,[3,4,†] H. Lenske,[5] M. Marta,[1,‡] R. Raut,[3,4,§] K. D. Schilling,[1] A. Tonchev,[3,4,†] W. Tornow,[3,4] and A. Wagner[1]

Photo-Absorption Cross Sections
(Data: ELBE@Rossendorf and HIγS@Duke)



PhysRevC.91.044318 (2015)

Neutron Capture Cross Sections



PhysRevC.91.044318 (2015)

Note:

The (n,γ) reactions are NOT part of nucleo-synthesis reactions but the inverse (γ,n) reactions act to destroy the N=50 isotones

Maxwellian –Averaged Neutron Capture Cross Sections at kT= 30 keV
N=50 Nuclides

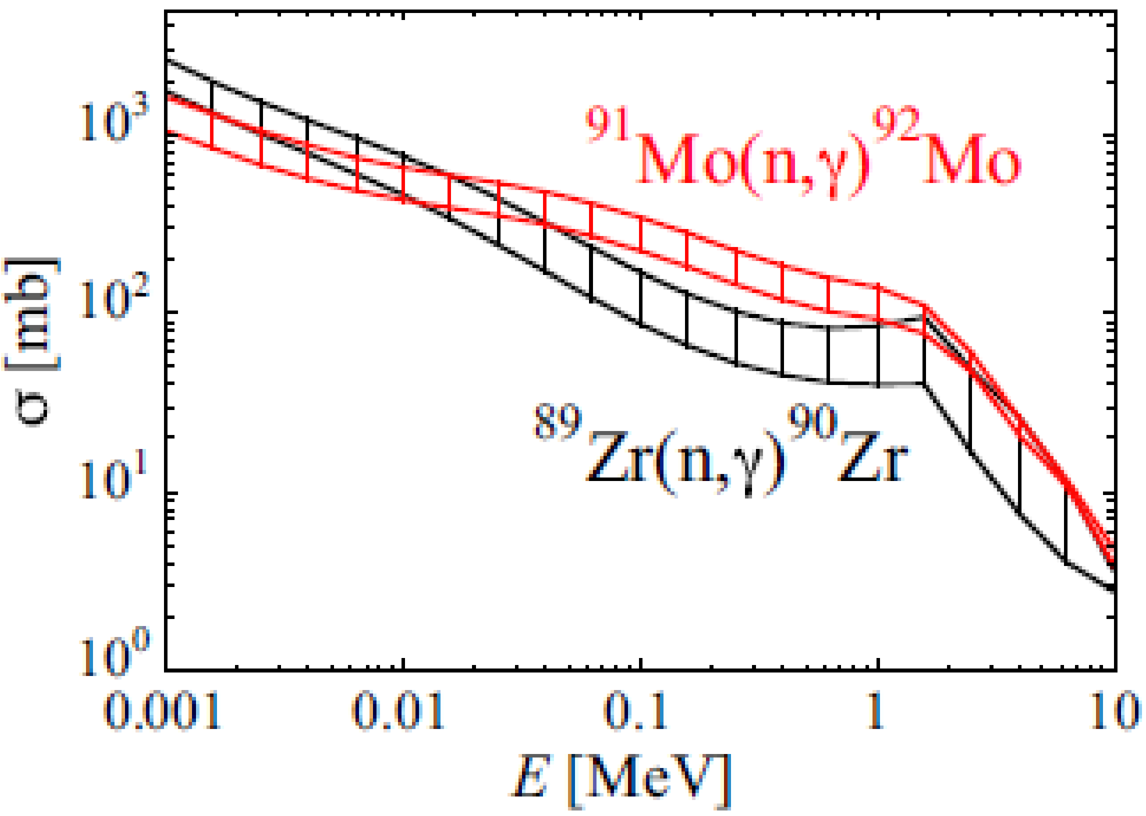
	Exp.	EDF + QPM	EDF + QRPA (PDR in)	EDF + QRPA (PDR ex)	HFB + QRPA (BSk7)
$^{85}Kr(n,\gamma)^{86}Kr$	83^{+23}_{-38} [5]	104.0	53.1	37.3	59.0
$^{87}Sr(n,\gamma)^{88}Sr$	92 ± 4 [7]	103.1	54.2	44.4	62.1
$^{89}Zr(n,\gamma)^{90}Zr$	–	224.3	170.4	152.1	159.8
$^{91}Mo(n,\gamma)^{92}Mo$	–	349.8	174.8	158.4	195.0

[5] R. Raut, A. P. Tonchev, G. Rusev, W. Tornow, C. Iliadis, M. Lugaro, J. Buntain, S. Goriely, J. H. Kelley, R. Schwengner, A. Banu, and N. Tsoneva, Phys. Rev. Lett. **111**, 112501 (2013).

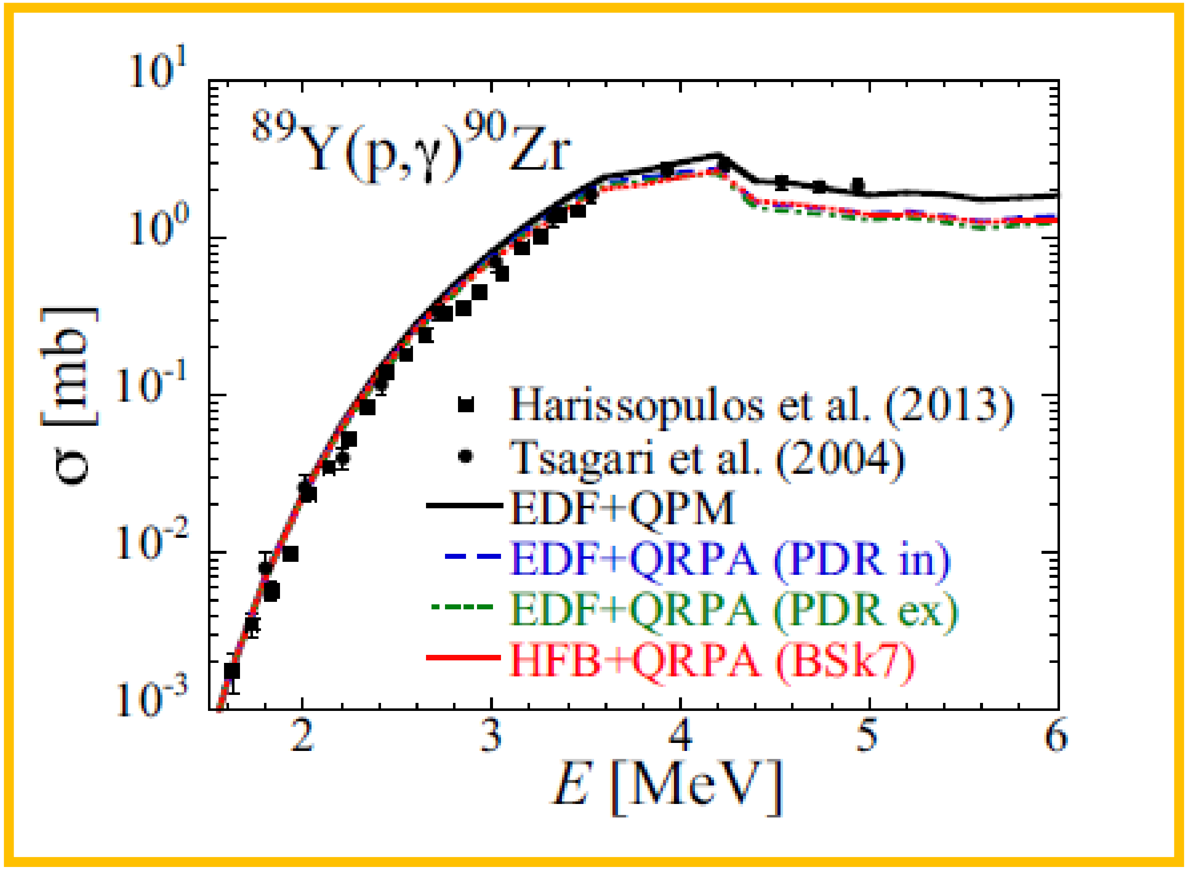
[7] Z. Y. Bao, H. Beer, F. Käppeler, F. Voss, K. Wisshak, and T. Rauscher, At. Data Nucl. Data Tables **76**, 70 (2000).

Theoretical Uncertainty in Neutron Capture Cross Sections

Dynamical 3-Phonon and Statistical NLD TALYS Results



Proton Capture Reactions



- **cross section sensitive to the *γ* -strength function only above the neutron emission threshold ($E_{thr} \approx 3.6$ MeV).**
- **Below that threshold, the cross section is dominated by the p+A optical potential.**

Cosmo-Chronometry: ^{206}Pb

Explosive r- and AGB s-process production:

$^{238}U(t_{1/2}=4.5\cdot 10^{+9} y) \rightarrow \ldots \rightarrow$ ^{206}Pb and ^{205}Pb + n $\rightarrow$ ^{206}Pb

- → **Geo-chemical r-process indicator**
- → **Tracer for the now extinct $^{205}Pb(t_{1/2}=1.73\cdot 10^{+7}$ y)**
- → **Solidification of the solar nebula**

$(\vec{\gamma},\gamma')$ experiment at the HI$\vec{\gamma}$S facility

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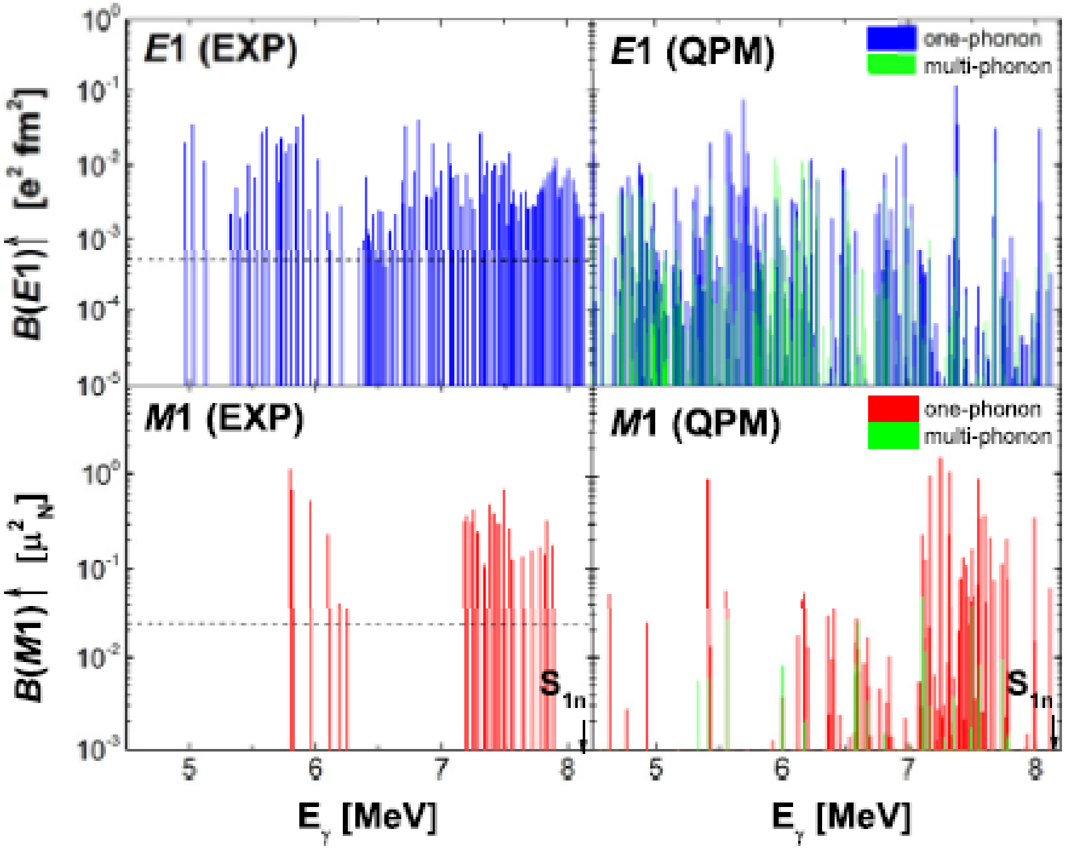
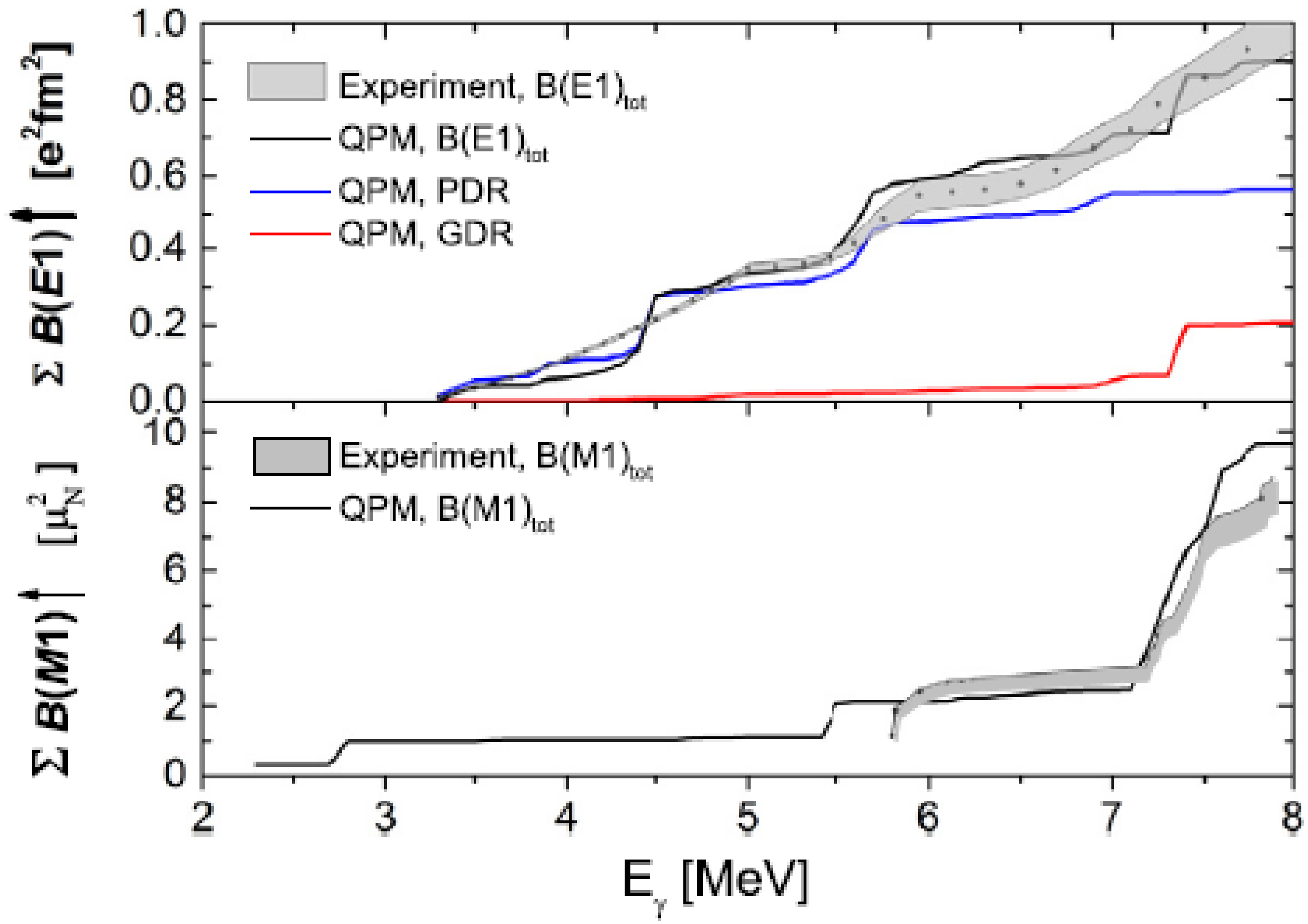
Pygmy and core polarization dipole modes in ^{206}Pb: Connecting nuclear structure to stellar nucleosynthesis

A.P. Tonchev[a,b,*], N. Tsoneva[c], C. Bhatia[d,b,e], C.W. Arnold[f,g], S. Goriely[h], S.L. Hammond[i,e], J.H. Kelley[i,e], E. Kwan[j], H. Lenske[c], J. Piekarewicz[k], R. Raut[l], G. Rusev[g], T. Shizuma[m], W. Tornow[b,e]

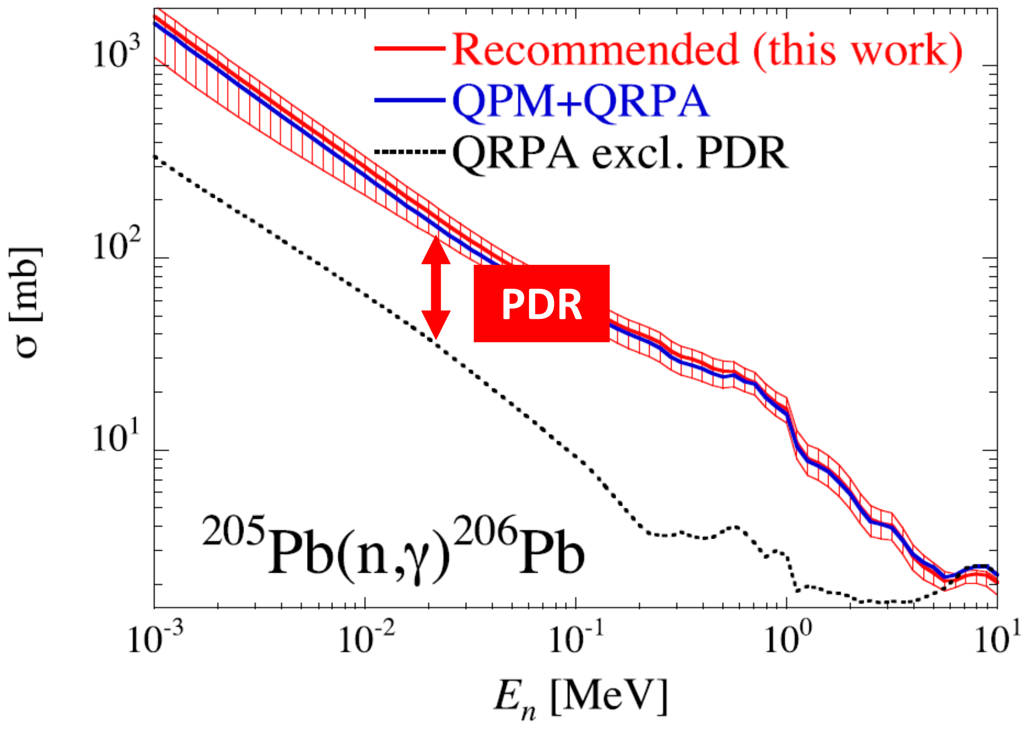
^{206}Pb Electric and Magnetic Dipole Reponse



Cumulative Electric and Magnetic Dipole Strength Functions



Neutron Capture Cross Section



Phys.Lett. B773 (2017) 20

Moments of the Photo-Absorption Cross Section

$$\sigma_{-n} = \int_0^\infty dE \, \frac{\sigma_\gamma(E)}{E^n} \quad \leftrightarrow \quad S_{-(n-1)} = \sum_c \frac{\left|M_{\gamma c}\right|^2}{E_c^{n-1}}$$

n = 0 : Energy Weighted Sum Rule (EWSR)
n = 1 : Non-Energy Weighted Sum Rule (NEWSR) - total transition strength
n = 2 : Polarizability sum rule

$$\alpha_D = \frac{1}{2\pi^2\alpha} \int_0^\infty \frac{\sigma_\gamma(E)}{E^2} dE = \frac{\sigma_{-2}}{2\pi^2\alpha} = 6.942\,\sigma_{-2}$$

Dipole Polarizability

Photo-Cross Section Moments for ^{206}Pb
Comparison of Covariant EDF and GiEDF Results

Phys.Lett. B773 (2017) 20

Model	σ_0 (mb MeV)	σ_{-1} (mb)	σ_{-2} (mb/MeV)	R_{skin} (fm)	J (MeV)	L (MeV)	K_{sym} (MeV)
RMF012	3653	237	17	0.12 [0.13]	29.8	48.3	98.7
FSUGarnet	3689	243	18	0.15 [0.16]	30.9	51.0	59.5
FSUGold	3638	251	19	0.19 [0.21]	32.6	60.5	−51.3
RMF028	3711	265	21	0.26 [0.29]	37.5	112.6	26.2
RMF032	3812	262	21	0.30 [0.32]	41.3	125.6	28.6
GiEDF	3060	230	18	0.15 [0.16]	33.4	53.9	−188.4

Symmetry Energy ↔ GDR Restoring Force:

$$S(\rho) \equiv \frac{1}{2}\left(\frac{\partial^2 \mathcal{E}(\rho,\delta)}{\partial \delta^2}\right)_{\delta=0} \approx \mathcal{E}(\rho,\delta=1) - \mathcal{E}(\rho,\delta=0).$$

$$S(\rho) = J + Lx + \frac{1}{2}K_{\text{sym}}x^2 + \ldots \quad \text{with} \quad x \equiv \frac{\rho-\rho_0}{3\rho_0}.$$

Summary and Outlook

- **EDF variational approach to nuclear ground and excited states**
- **Microscopic energy density functional**
- **Nuclear spectra by HFB, QRPA, and M*RPA multi-phonon theory**
- **Low-energy PDR modes and capture cross sections**
- **Pygmy modes as signatures for skin dynamics**
- ***Correspondong studies for the N=82 isotones***
- ***Low-energy quadrupole excitations: the PQR modes***
  (Phys.Lett. B695 (2011) 174)

…in collaboration with S. Goriely, J. Piekarewicz, A. Tonchev, R. Schwengner, M. Spieker, A. Zilges, A. Richter …

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