Multiparticle resonances in hadrons, nuclei, and ultracold gases
International Workshop XLVI on Gross Properties of Nuclei and Nuclear Excitations
Hirschegg, Kleinwalsertal, Austria, January 14 - 20, 2018

Microscopic description of pygmy and giant resonances within EDF plus QPM approach

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Extreme Light Infrastructure - Nuclear Physics (ELI-NP)

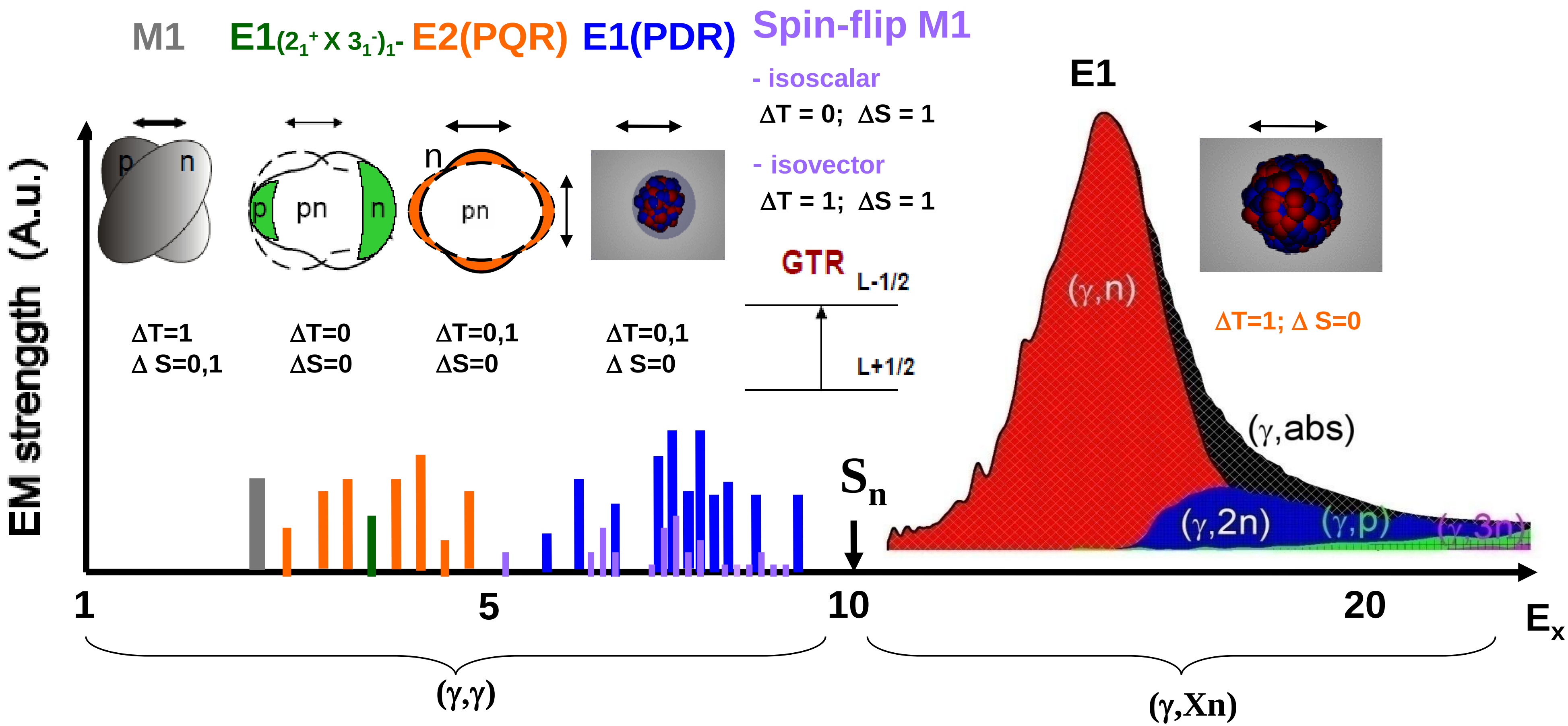
Agenda

- Pygmy modes: new low-energy modes of excitation in stable and exotic nuclei
- Microscopic theory of nuclear excitations
- Dipole and Quadrupole pygmy modes
- Pygmy modes, Dipole polarizability, Giant resonances,
- (n,γ), (p,γ) cross sections and nuclear reaction rates of stellar nucleosynthesis.

Our Goals

- Microscopic approach to infinite matter and finite nuclei
- Ground states and nuclear excitations
- Astrophysical investigations

The Richness of Nuclear Spectra…



Moderate and Heavy nuclei :

Theoretical prediction:
N. Tsoneva, H. Lenske,
Phys. Lett. B 695 (2011) 174.

- Orbital "Scissors" mode: E_x ~ 3 MeV, B(M1) ~ 3 μ_N^2
- Two Phonon Excitation: E_x ~ 4 MeV, B(E1) ~ 10^{-3} W.u.
- Pygmy Quadrupole Resonance: Ex ~ 2 - 5 MeV, B(E2) ~ 0.5 W.u.
- Pygmy Dipole Resonance: E_x ~ 6 - 9 MeV, B(E1) ~ 0.5 W.u.
- Spin-flip M1 excitations: E_x~ 4 - 12 MeV, B(E2) ~ 6 μ_N^2
- Giant Dipole Resonance: E_x ~ 10 - 20 MeV, B(E1) ~ 5 - 12 W.u.

Microscopic theory of nuclear excitations

The Model Hamiltonian

Quasiparticle-Phonon Model: V. G. Soloviev: Theory of Atomic Nuclei: Quasiparticles and Phonons (Bristol, 1992)

N. Tsoneva, H. Lenske, Ch. Stoyanov, Phys. Lett. B 586 (2004) 213
N. Tsoneva, H. Lenske, Phys. Rev. C 77 (2008) 024321

$$H = H_{MF} + H_{res}$$

$$H_{MF} = H_{sp} + H_{pair} \qquad H_{res} = H_M^{ph} + H_{SM}^{ph} + H_M^{pp}$$

Nuclear Ground State

Single-Particle States

Phenomenological density functional approach based on a fully microscopic self-consistent Skyrme Hartree-Fock-Bogoljubov (HFB) theory

Pairing and Quasiparticle States

$$a_{jm} = u_j \alpha_{jm} + (-)^{j-m} v_j \alpha^+_{j-m}$$

Excited states

H_M^{ph} - multipole interaction in the particle-hole channel;
H_{SM}^{ph} - spin-multipole interaction in the particle-hole channel;
H_M^{pp} - multipole interaction in the particle-particle channel

$$V(|\vec{r} - \vec{r}\,'|) \approx \sum_{\lambda\mu\tau} (-)^{\mu} R_\tau^\lambda(r, r') Y_{\lambda\mu}(\theta, \varphi) Y_{\lambda-\mu}(\theta', \varphi')$$

$$R_\tau^\lambda(r, r') = \kappa_\tau^\lambda R_\lambda(r) R_\lambda(r')$$

$\tau = 0$ isoscalar interaction

$\tau = 1$ isovector interaction

Theory of Nuclear Excitations

The QPM basis is built of phonons:

$$Q^{+}_{\lambda\mu i} = \frac{1}{2}\sum_{\tau}^{n,p}\sum_{jj'}\left\{\psi^{\lambda i}_{jj'}[\alpha^{+}_{j}\alpha^{+}_{j'}]_{\lambda\mu} - (-1)^{\lambda-\mu}\varphi^{\lambda i}_{jj'}[\alpha_{j'}\alpha_{j}]_{\lambda-\mu}\right\}$$

i — **labels the number of the QRPA state.**

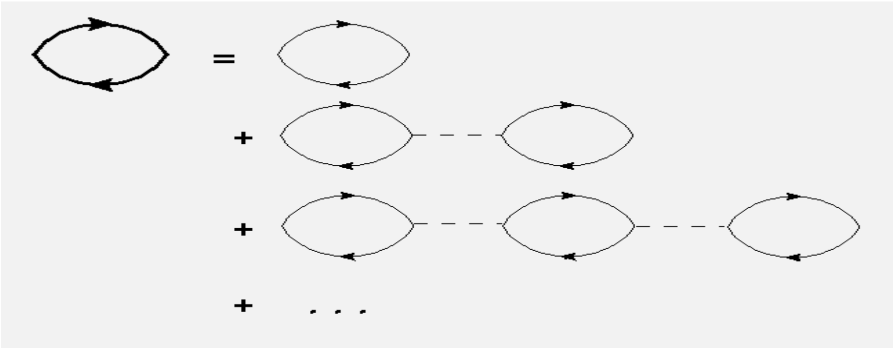
The phonons are not 'pure' bosons:

$$\left[Q_{\lambda\mu i}, Q^{+}_{\lambda'\mu' i'}\right] = \delta_{\lambda\lambda'}\delta_{\mu\mu'}\delta_{ii'} + \text{ fermionic corrections}$$

$$\sim \alpha^{+}_{j_1 m_1}\alpha_{j_2 m_2}$$

QRPA equations are solved:

$$\left[H, Q^{+}_{\lambda\mu i}\right] = E_{\lambda\mu i} Q^{+}_{\lambda\mu i}$$



Beyond QRPA: Including Anharmonicities. Expansions up to 6-QP Components

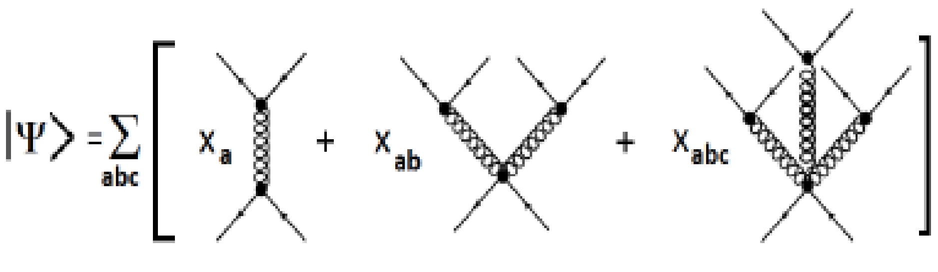
Multi-Configuration Multi-Quasiparticle Wave Function

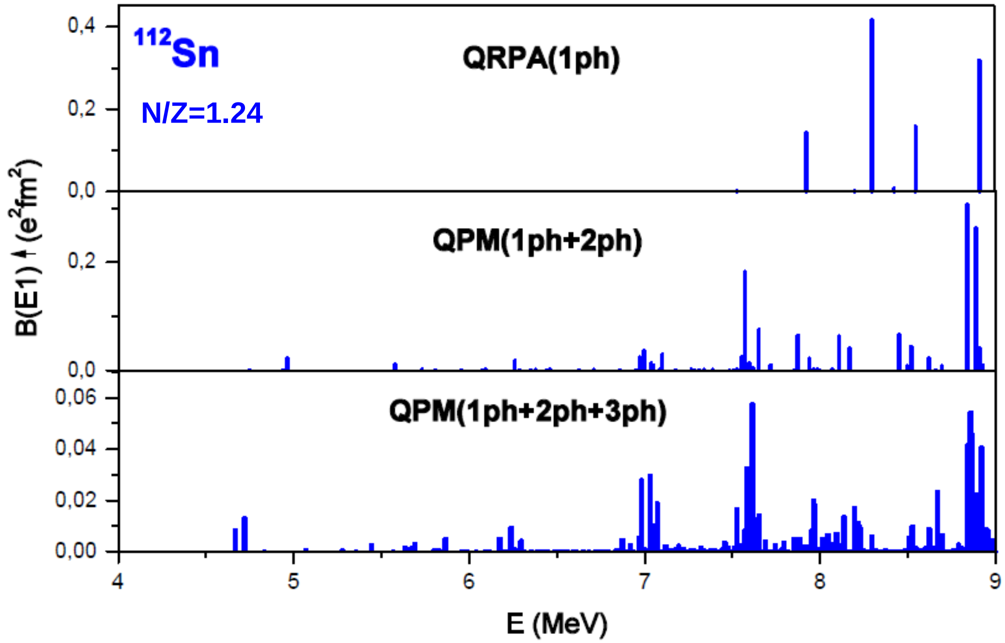
$$\Psi_\nu(JM) = \Bigg\{ \sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_1 \mu_1 i_1} \otimes Q^+_{\lambda_2 \mu_2 i_2} \right]_{JM}$$

$$+ \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2 \\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(J\nu) \left[\left[Q^+_{\lambda_1 \mu_1 i_1} \otimes Q^+_{\lambda_2 \mu_2 i_2} \right]_{IK} \otimes Q^+_{\lambda_3 \mu_3 i_3} \right]_{JM} \Bigg\} \Psi_0$$

- Basis of QRPA phonons
- „ph“ and „pp“- type configurations
- Pauli principle, orthogonality
- Core polarization effects
- Large multi-particle-multi-hole configuration space
- SPECTRAL FRAGMENTATION
- SPECTRAL SHIFTS

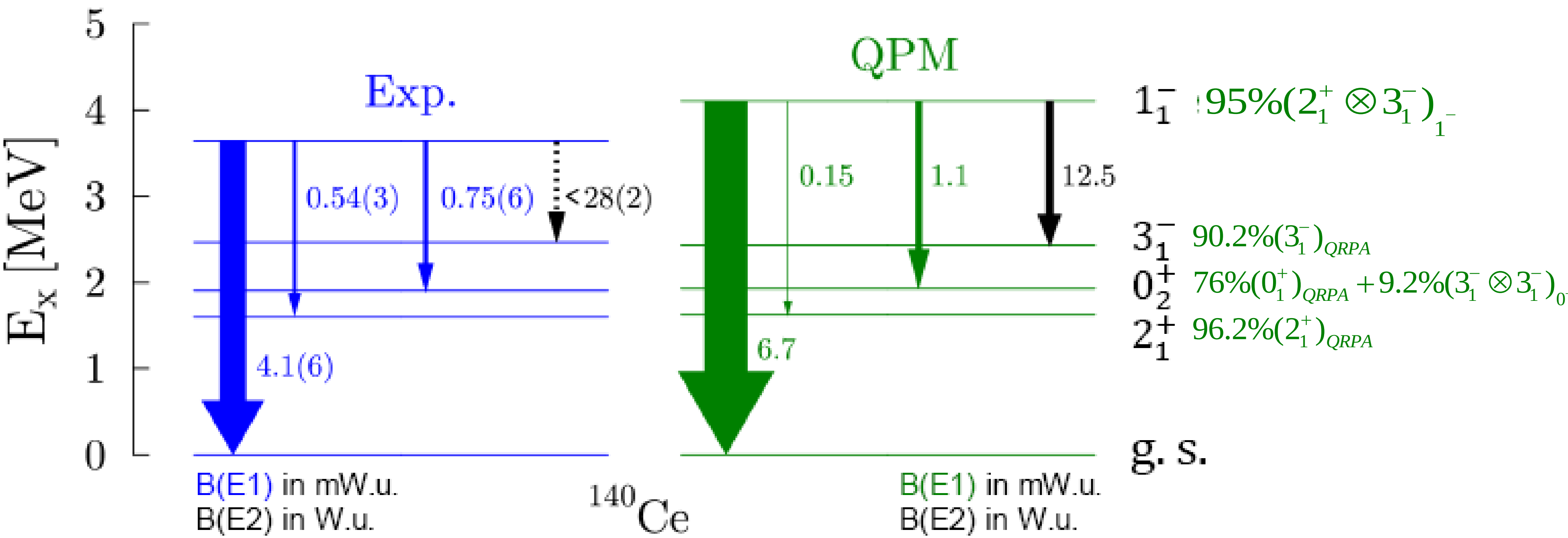
M. Grinberg, Ch. Stoyanov, Nucl. Phys. A. 573 (1994) 231





Multi-phonon nuclear excitations

Two-phonon states



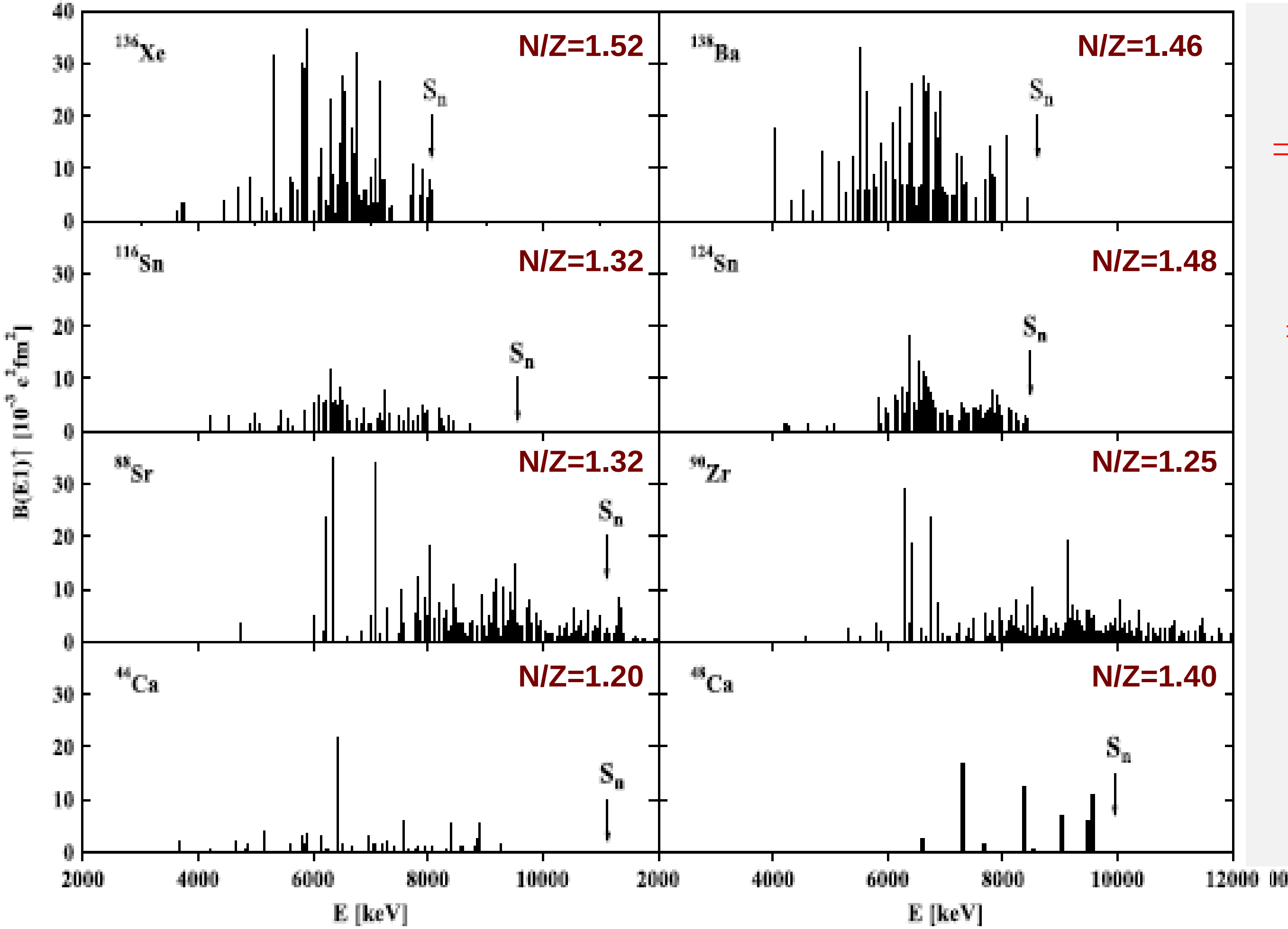
V. Derya, N.Tsoneva, et al., Phys. Rev. C 93, 034311 (2016).

The Pygmy Dipole Resonance

Observation of Pygmy Dipole Resnance in stable nuclei with moderate neutron excess (N > Z)

Neutron PDR strength increases with the N/Z ratio !

D. Savran et al. / Progress in Particle and Nuclear Physics 70 (2013) 210–245



PDR

⇒ Generic mode of excitation;

⇒ Below particle threshold;

⇒ Independent of the type of nucleon excess

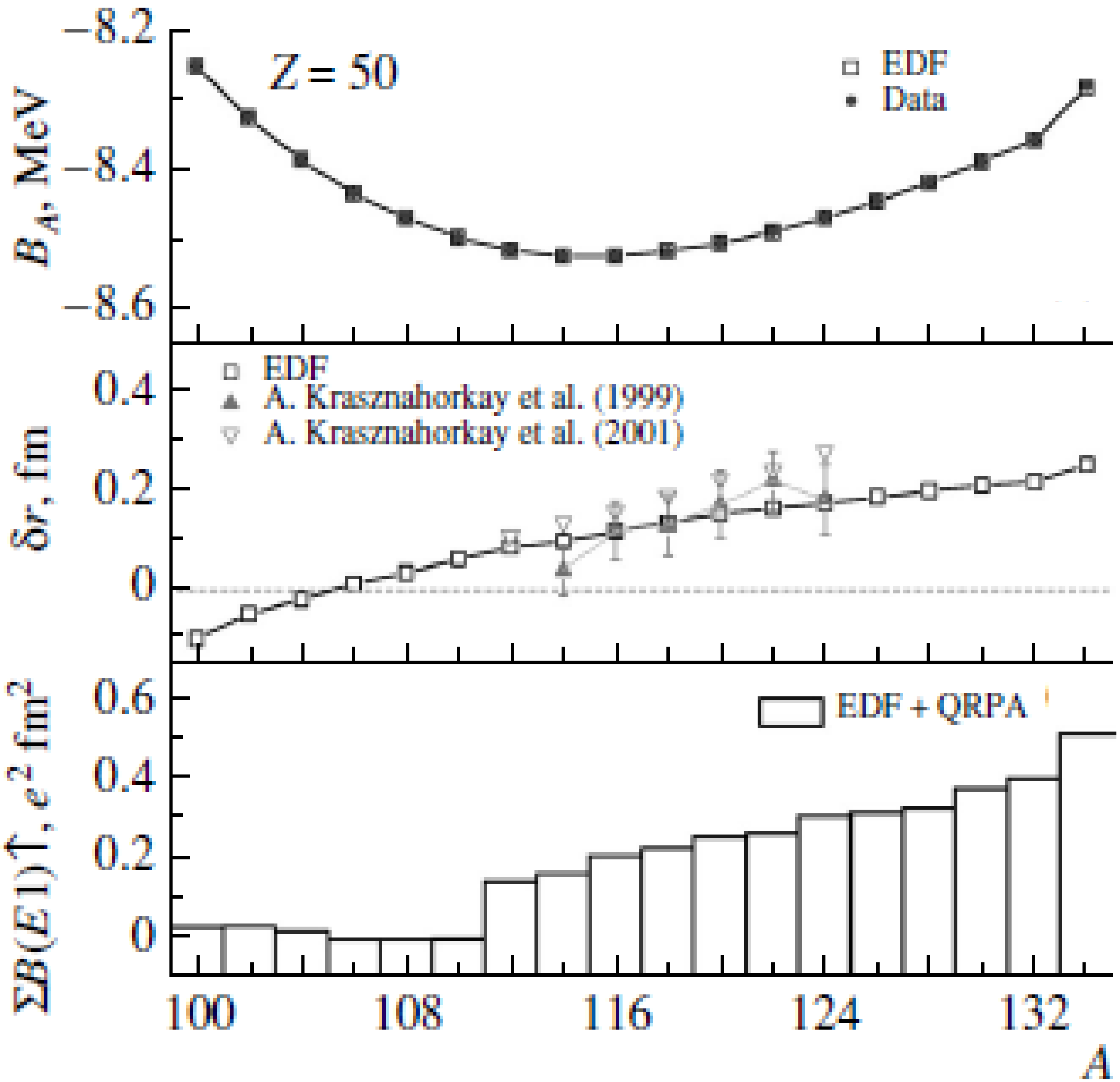
⇒ Depending on the size of N/Z;

⇒ ~ 1% of the Thomas-Reiche-Kuhn sum rule (S_{TRK} ~ NZ/A)

Binding Energy, Skin Thickness and PDR

N. Tsoneva, H. Lenske, *Physics of Atomic Nuclei, 2016, Vol. 76, pp. 885-903.*

N. Tsoneva, H. Lenske, PRC 77 (2008) 024321



Binding Energy

$$B_A(N,Z) = \int d^3r E(\rho_0(\mathbf{r}), \rho_1(\mathbf{r}))$$

$$= \int d^3r \left(E_{\rm kin}(\mathbf{r}) + E_{\rm int}(\mathbf{r})\right).$$

Skin thickness

$$\delta r = \sqrt{< r^2 >_n} - \sqrt{< r^2 >_p}$$

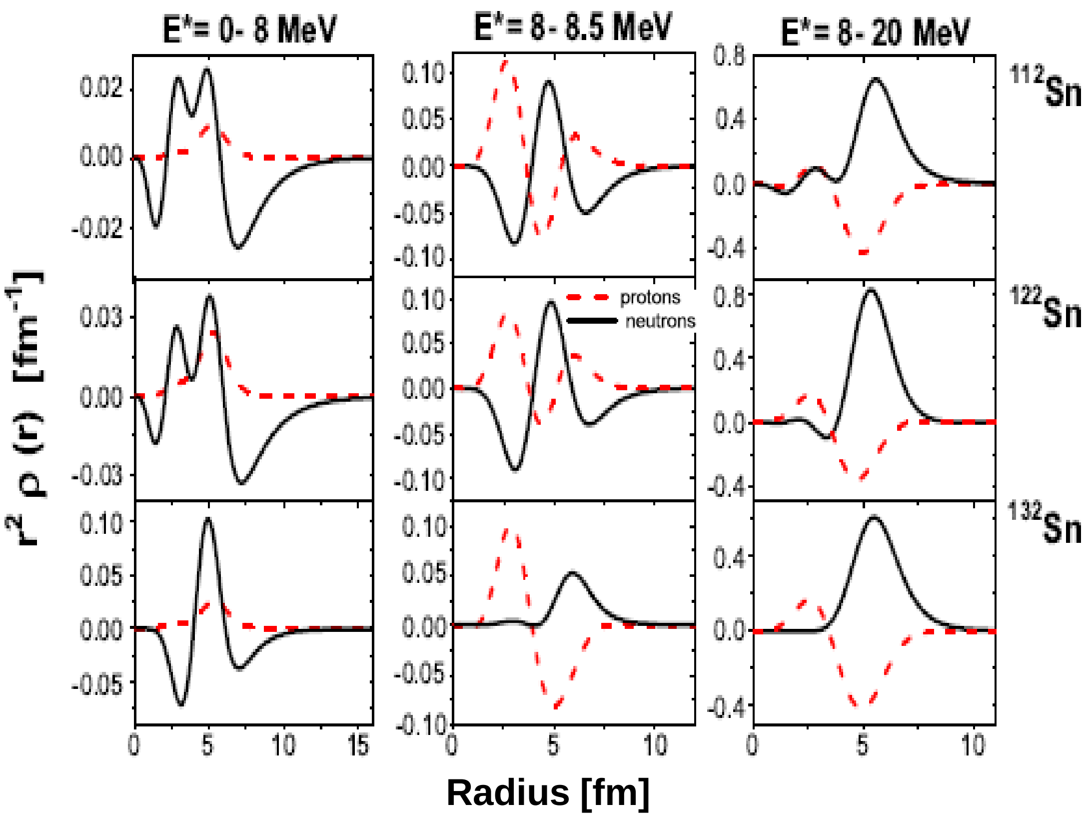
PDR Strength

$$B(E\lambda) \approx \left[\sum_{T=1}^{1} e_T^\lambda \int_0^\infty r^\lambda \rho_{\lambda i}^T(r) r^2 dr\right]^2$$

Identifying the Skin Mode: Dipole Transition Densities in Sn Isotopes

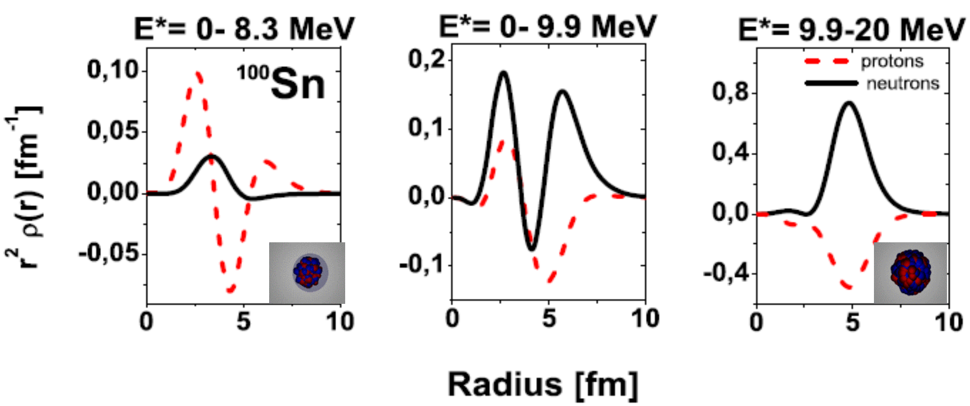
N. Tsoneva, H. Lenske, Ch. Stoyanov, Phys. Lett. B 586 (2004) 213
N. Tsoneva, H. Lenske, Phys. Rev. C 77 (2008) 024321

Neutron PDR **N>Z**

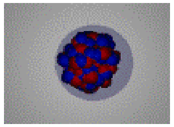


$$\delta\rho^{T}(\vec{r}) = \sum_{j_1 j_2;\lambda\mu} [i^{\lambda} Y_{\lambda\mu}(\hat{r})]^{\dagger} \rho^{\lambda T}_{j_1 j_2}(r) [a^{+}_{j_1} a_{j_2}]_{\lambda\mu}.$$

Proton PDR **N=Z**

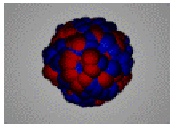


PDR **GDR**



Mixed

Transient



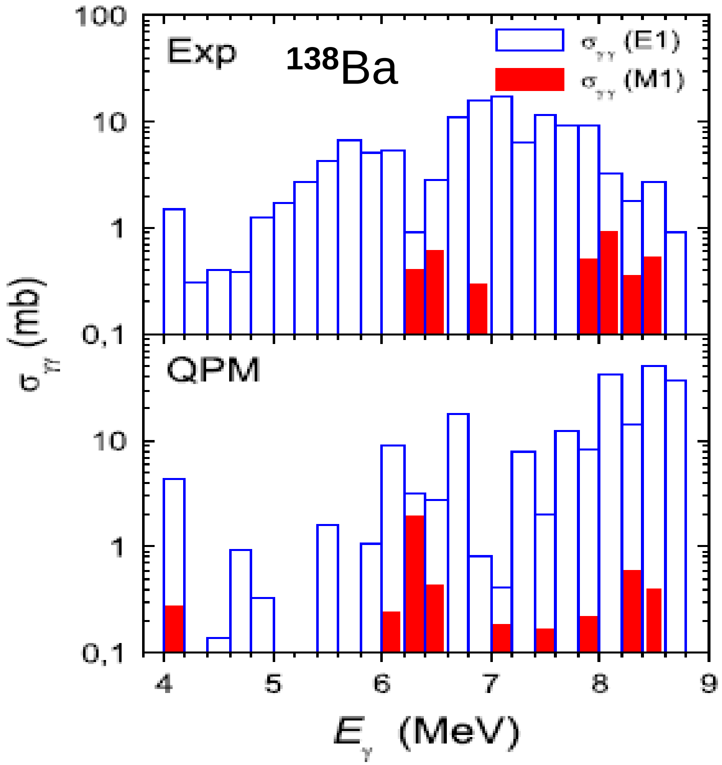
Parity assignment of the PDR

Parity Measurements of Low-Energy Dipole Excitations in ^{138}Ba

First experiment on parity assignment of PDR in ^{138}Ba at HIγS: E_γ=4-8.5 MeV

A. P. Tonchev, S. L. Hammond, J. H. Kelley, E. Kwan, H. Lenske, G. Rusev, W. Tornow, and N. Tsoneva, Phys. Rev. Lett. 104, 072501 (2010).

$\sigma_{\gamma\gamma}(M1)/\sigma_{\gamma\gamma}(E1)$ **~ 3%**



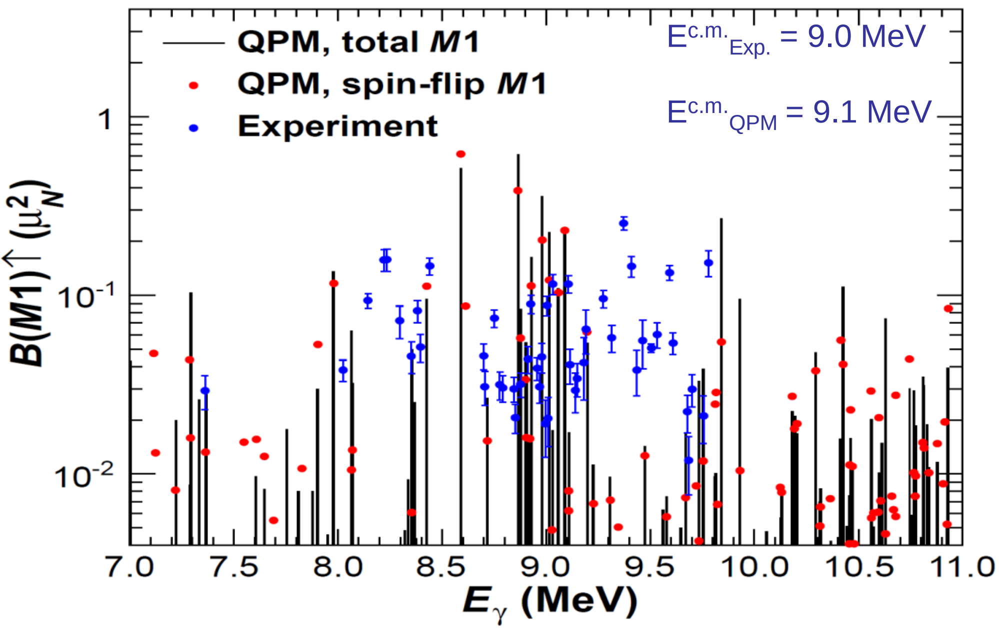
- **verified for the first time that the PDR is predominantly E1 in nature.**
- **The fine structure of the M1 spin-flip mode is explained.**
- **Low-energy E1 strength fragmentation: Interplay between PDR, multi-phonon excitations and core polarization related to the GDR**

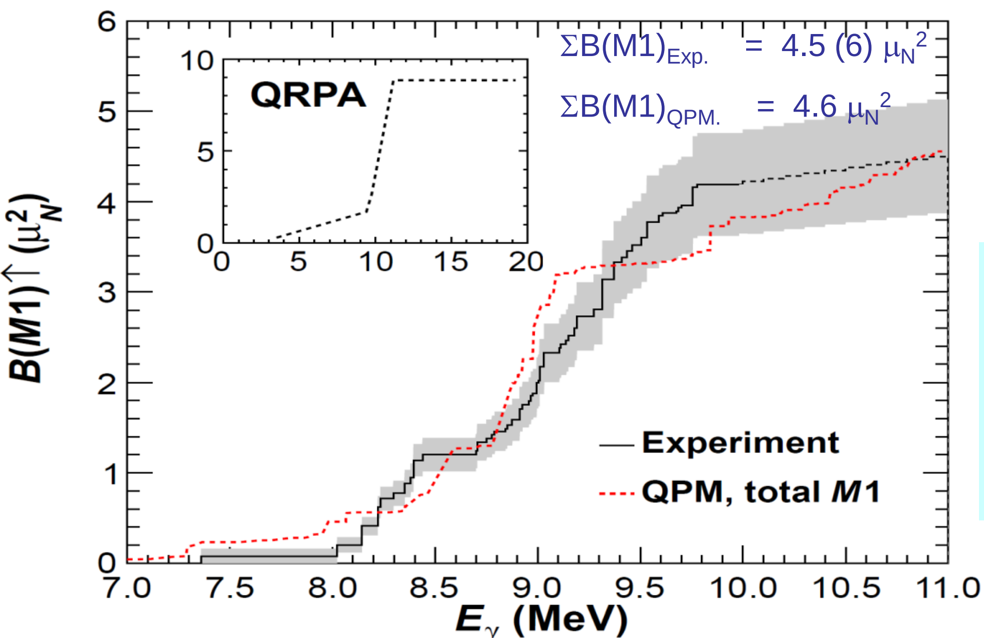
TABLE I. $E1$ and $M1$ parameters deduced in ^{138}Ba below the neutron-separation energy in comparison with the QPM calculations.

	$\langle E_{E1}\rangle$ [MeV]	$\Sigma B(E1)\uparrow [e^2\,\mathrm{fm}^2]$	$\langle E_{M1}\rangle$ [MeV]	$\Sigma B(M1)\uparrow [\mu_N^2]$	EWSR$_{E1}$ [%]
Experimental	6.7	0.96(18)	6.9	2.5(6)	1.3
QPM	7.3	1.22	6.9[a]	2.9[a]	1.8

[a]4.1 MeV $< E^* <$ 8.5 MeV.

Fine Structure Measurements of the Giant M1 Resonance in ^{90}Zr at HIγS





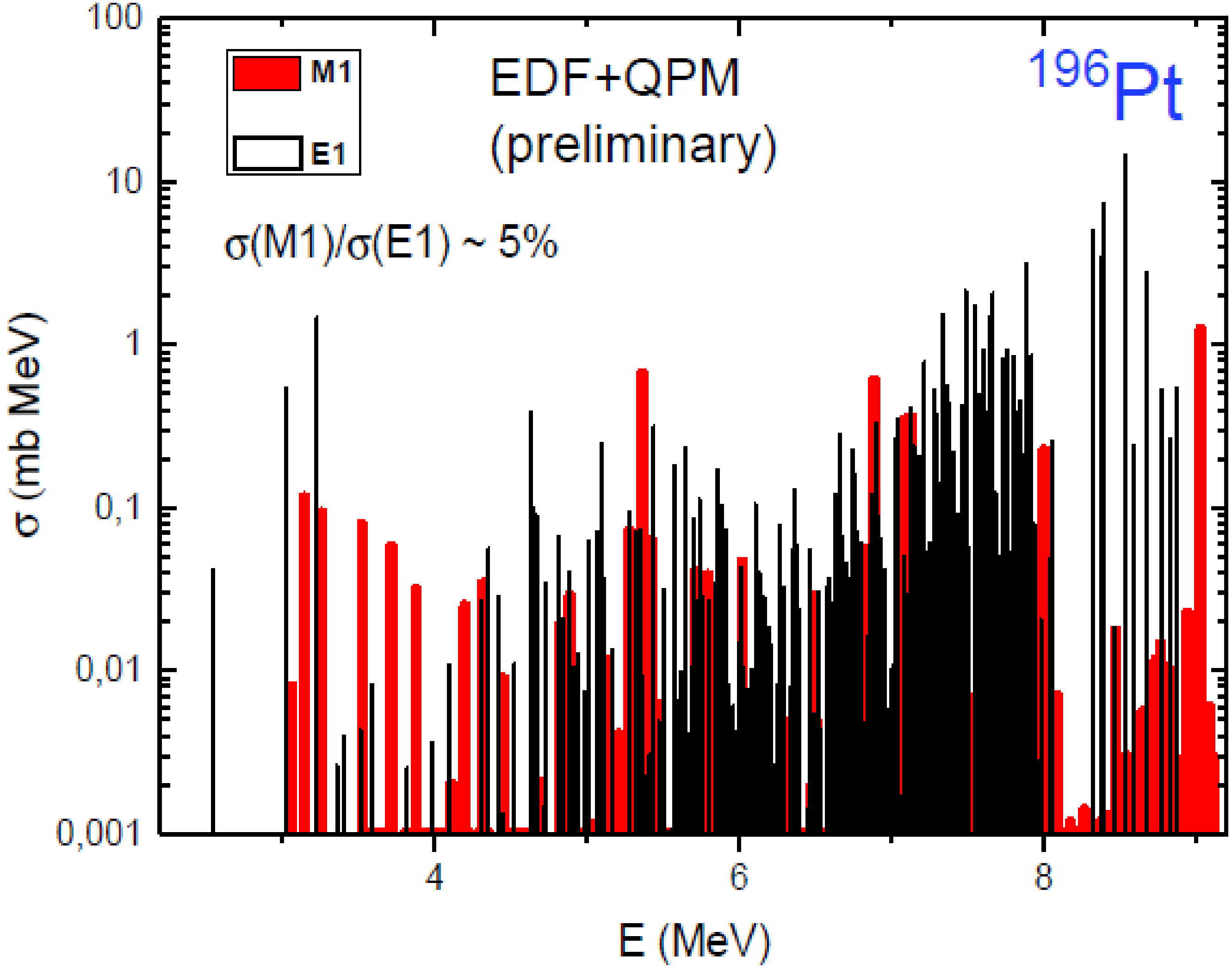
G. Rusev, N. Tsoneva, F. Dönau, S. Frauendorf, R. Schwengner, A. P. Tonchev, A. S. Adekola, S. L. Hammond, J. H. Kelley, E. Kwan, H. Lenske, W. Tornow, and A. Wagner, **Phys. Rev. Lett. 110, 022503 (2013).**

- Explaining the fragmentation pattern and the dynamics of the 'quenching'.
- Multi-particle multi-hole effects increase strongly the orbital part of the magnetic moment.
- QPM prediction of M1 strength at and above the neutron threshold.

Polarized photon scattering off ^{52}Cr: Determining the parity of J=1 states.

Krishichayan, M. Bhike, W. Tornow, G. Rusev, A. P. Tonchev, N. Tsoneva, and H. Lenske, *PRC 91*, 044328 (2015).

Fine structure of the low-energy dipole strength in the γ-soft ^{196}Pt

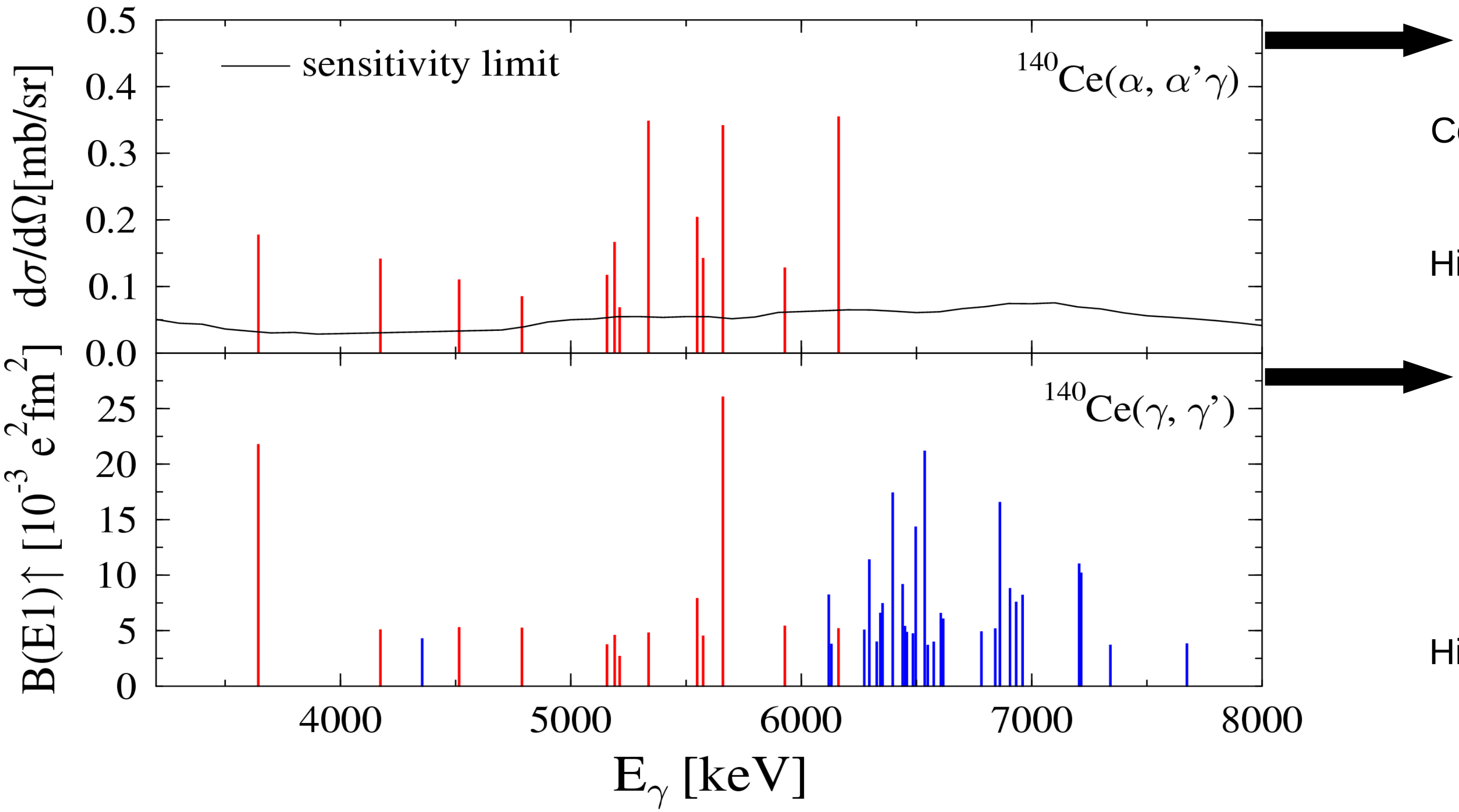


Research Proposal: approved

Physical Sciences Research Program 2018, SSC Facility iThemba Laboratory for Accelerator Based Sciences, Republic of South Africa

Distinguishment of the Pygmy Dipole Resonance from Other Modes

Complementary (α, α'γ) and (γ, γ') experiments : PDR splits to two parts with different structure



KVI

Coincident experiment

E_α = 130 MeV

High energy resolution

TUD

NRF experiment

Real photons

E_γ = 4 - 8 MeV

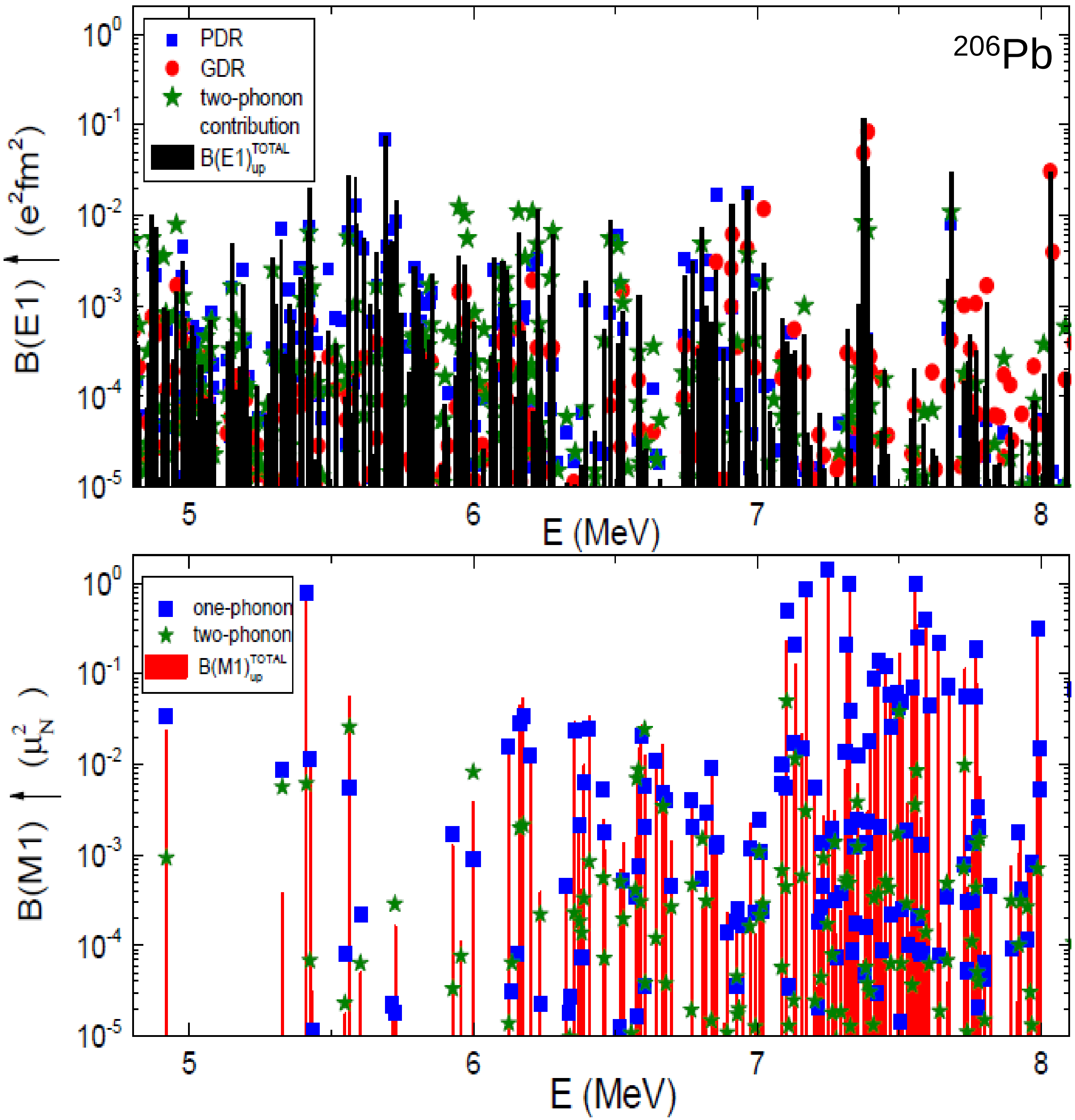
High energy resolution

D. Savran et al. PRL, **97** 172505 (2006)

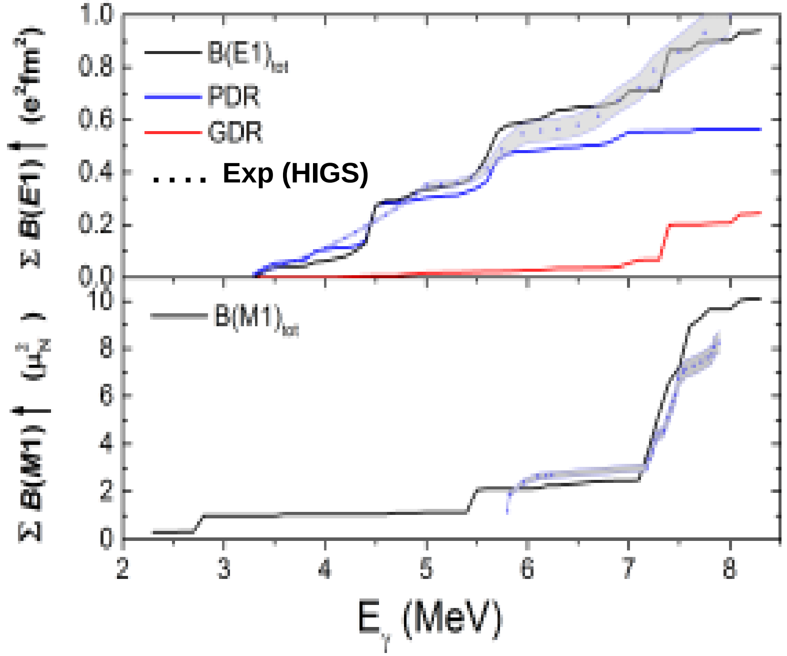
D. Savran et al. NIMA **564** 267 (2006)

J. Endres et al. PRL **105**, 212503 (2010)

GiEDF+QPM: Separation of the PDR from the low-energy GDR in ^{206}Pb

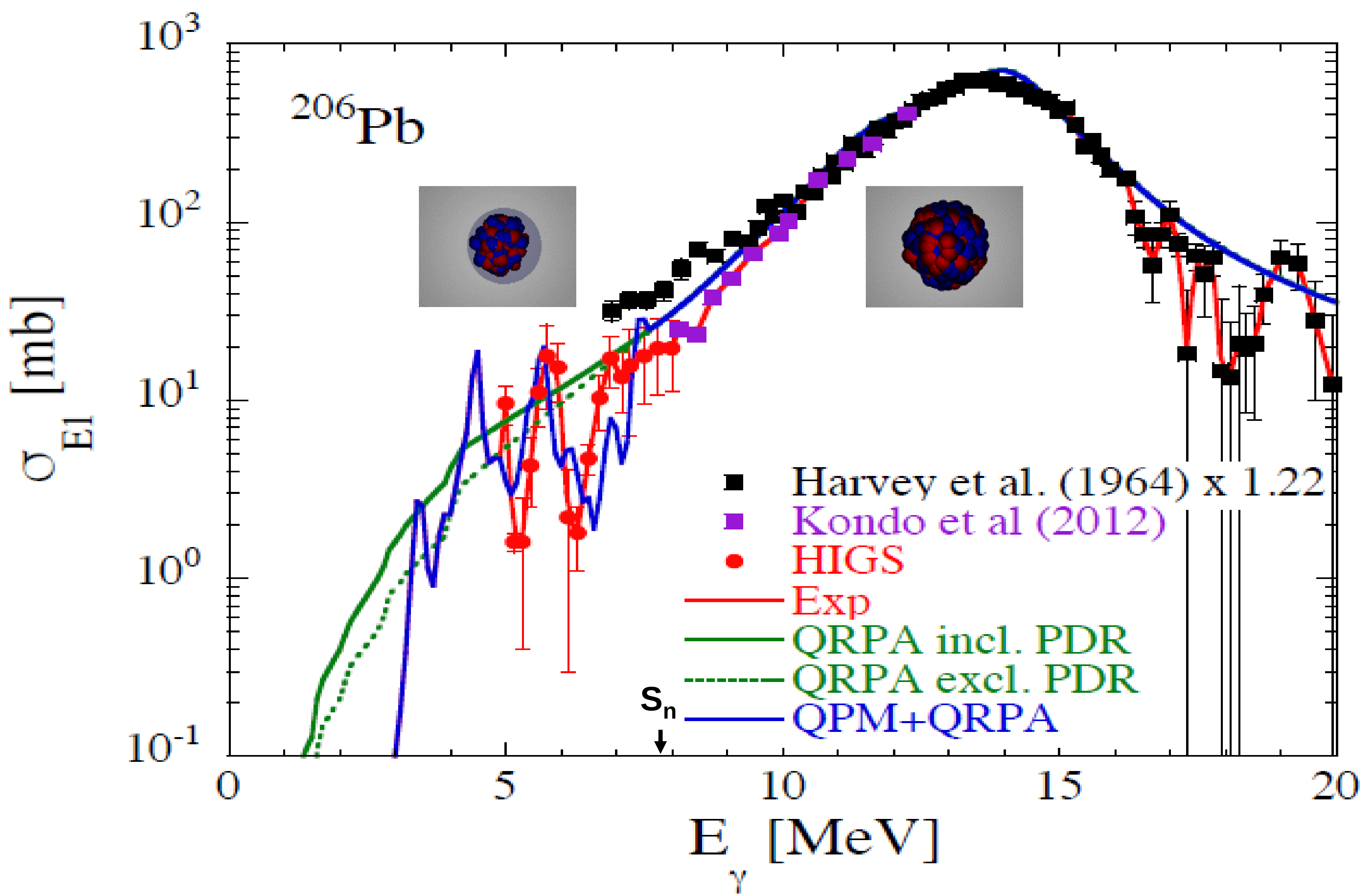


A.P.Tonchev,N.Tsoneva,C.Bhatia,C.W.Arnold,S.Goriely, S.L.Hammond,J.H.Kelley,E.Kwan,H.Lenske,J.Piekarewicz, R.Raut,G.Rusev,T.Shizuma,W.Tornow,
Phys. Lett. B, 773, p. 20-25, 10 October 2017;



Electric Dipole Response in ^{206}Pb

A. Tonchev, N.Tsoneva, S. Goriely, J. Piekarewicz, H. Lenske et al., PRL submitted.



New evidences on the existence of pygmy quadrupole resonance

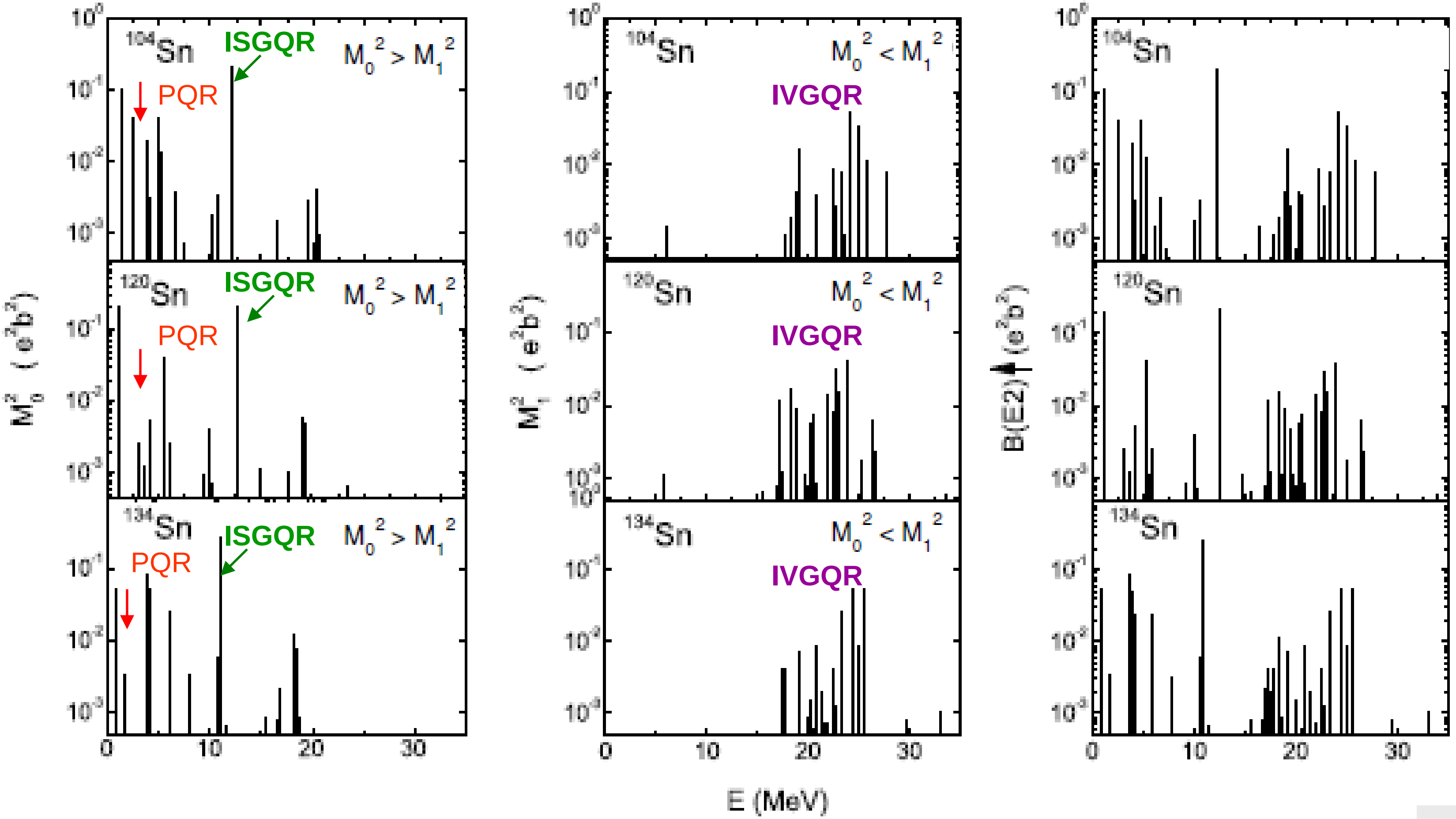
Theoretical Prediction of Pygmy Quadrupole Resonance

N. Tsoneva, H. Lenske, Phys. Lett. B 695 (2011) 174

QRPA Isoscalar and Isovector Quadrupole States up to 35 MeV in Sn Isotopes

$$M_I(2^+) \approx \langle 2^+ \| \sum_k^A r_k^2 Y_{2\mu}(\Omega_k)(\tau_3)^I \| g.s. \rangle$$

PQR – pygmy quadripole resonance
ISGQR – isoscalar giant quadrupole resonance
IVGQR – isovector giant quadrupole resonance



N.Tsoneva, Hirschegg18

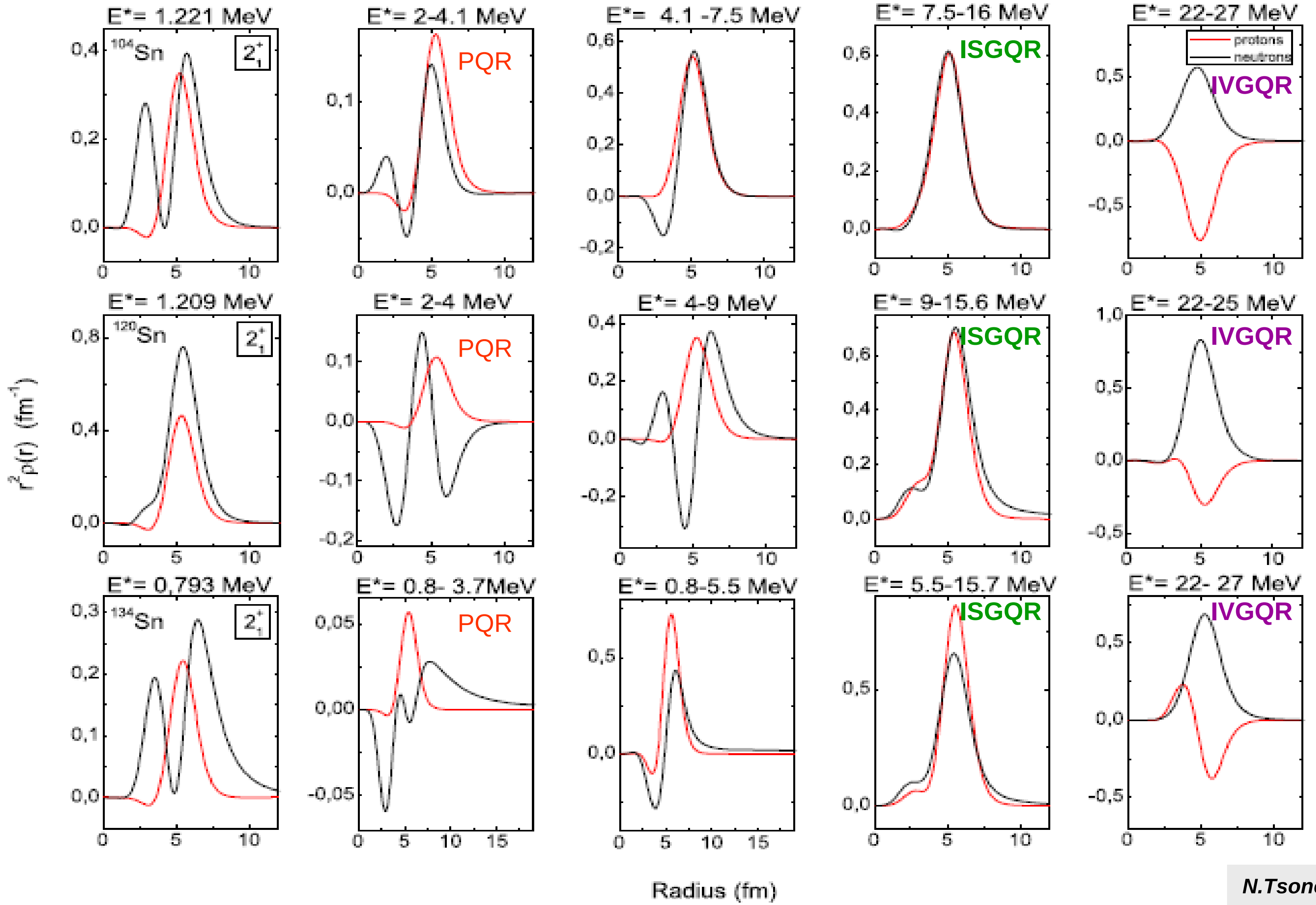
Quadrupole Transition Densities in Sn Isotopes

A Signature of Pygmy Quadrupole Resonance

PQR – pygmy quadripole resonance

ISGQR – isoscalar giant quadrupole resonance

IVGQR – isovector giant quadrupole resonance



N.Tsoneva, Hirschegg18

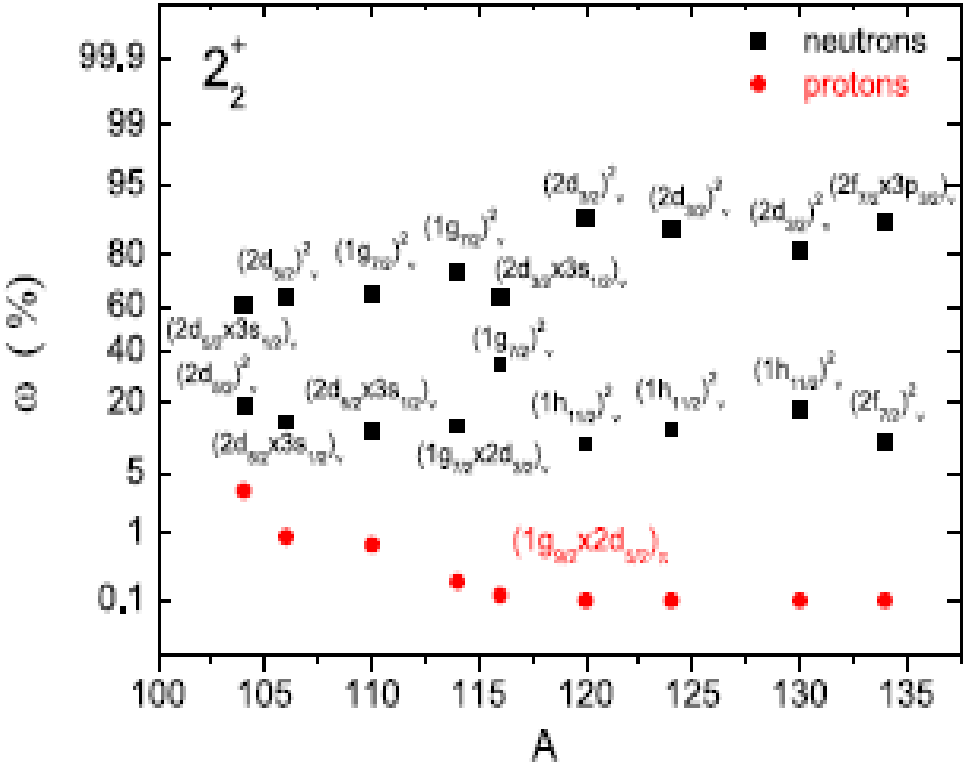
QRPA Calculations of Low-Energy 2^+ States Related to PQR

N. Tsoneva and H. Lenske, Phys. Lett. B 695, 174 (2011)

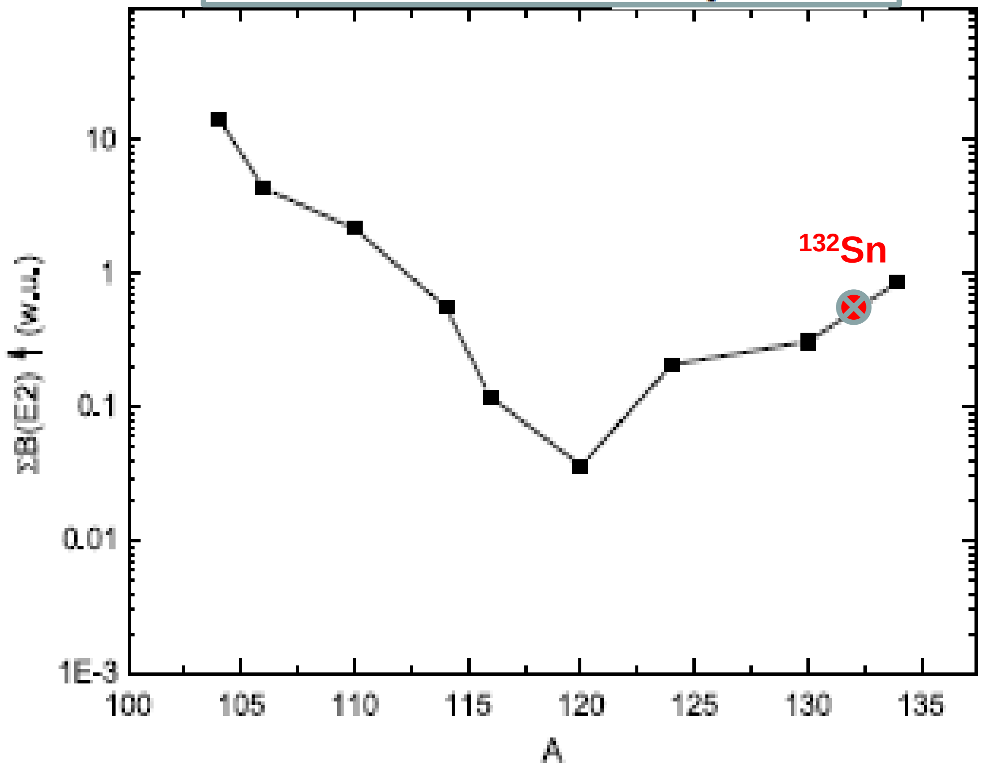
Pygmy quadrupole resonance is a genuine mode!

B(M1) to the first symmetric $2_1^+ \sim 10^{-2}\mu_N^2$ and $B(E2) \sim 1/\varepsilon_b^{\,2}$

B(E2) increases with the neutron number

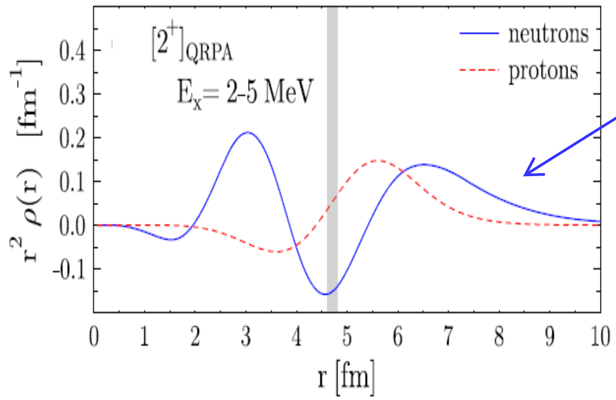


QRPA results for $B(E2)\uparrow$ transition probabilities summed over the $[2_2^+]_{QRPA}$ and $[2_3^+]_{QRPA}$ states



A change in the E_b of the $g_{9/2}$ which is the proton Fermi level in Sn isotopes when approaching the N=Z limit.
E_b= -12.88 MeV in ^{134}Sn ; E_b=-7.20 MeV in ^{104}Sn

The PQR mode-Quadrupole Oscillations of the Neutron Skin



quadrupole neutron skin oscillations in ^{124}Sn

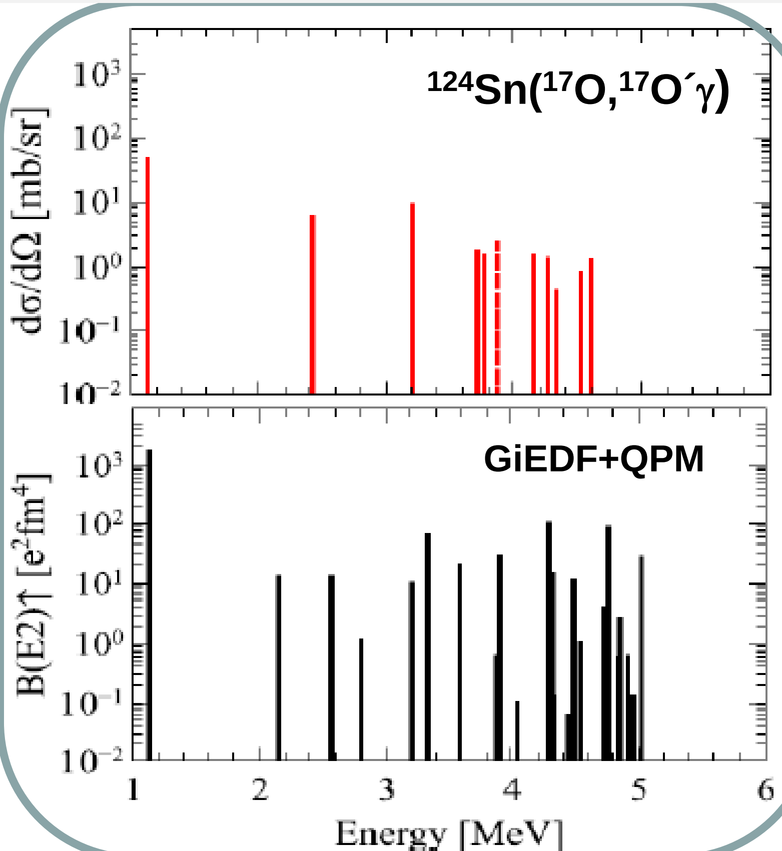
PQR …theoretically predicted in 2011

N. Tsoneva, H. Lenske, Phys. Lett. B695 174 (2011).

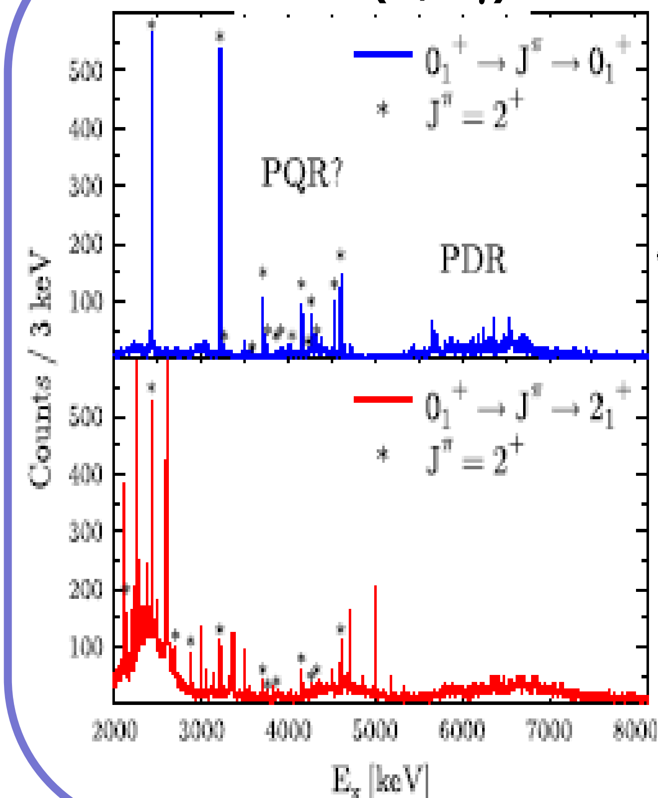
…experimentally confirmed in 2015/2016

M. Spieker, NT et al., Phys. Lett. B752, 102 (2016).

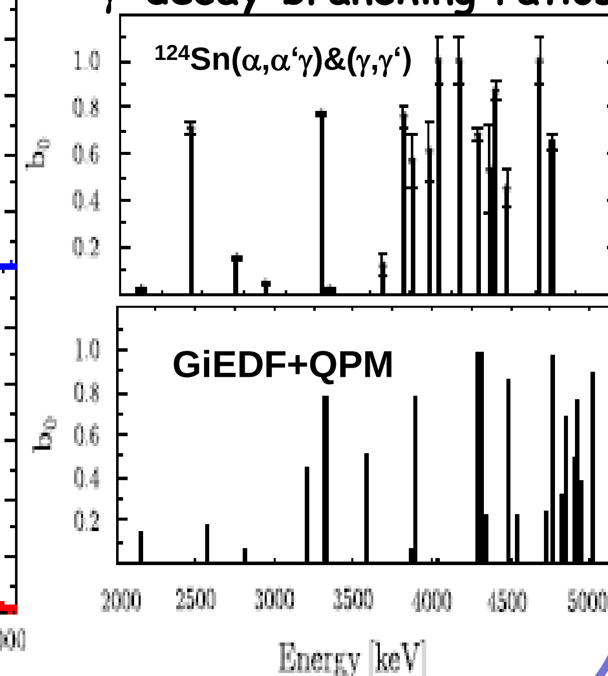
L. Pellegri, A. Bracco, NT et al.,PRC 92, 014330 (2015).



^{124}Sn(α,α'γ)



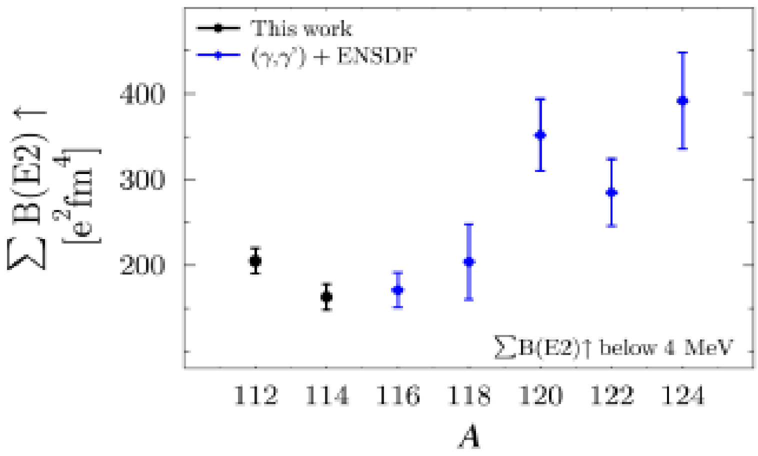
γ-decay branching ratios

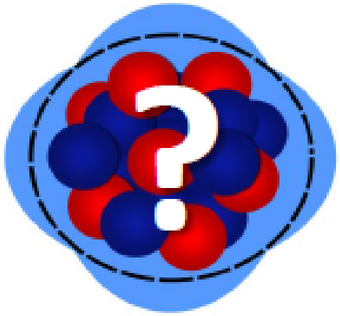


First Systematic Data on PQR in Tin Isotopes

Cologne (p,p'γ) DSA data

DPG spring meeting, 2017





From the γ-decay behavior

- Large b_0 values are observed in all stable even-even Sn isotopes
- At least two different modes are present!

Both observations are consistent with earlier QPM predictions for the PQR!

From the summed E2 strength

- Strength increases with increasing neutron number
- ... strength seems to be increasing when passing ^{114}Sn
- Is ^{120}Sn a special nucleus?

... shell-structure changes?

M. Spieker – The origin of low-lying collective *E1* and *E2* strength in atomic nuclei

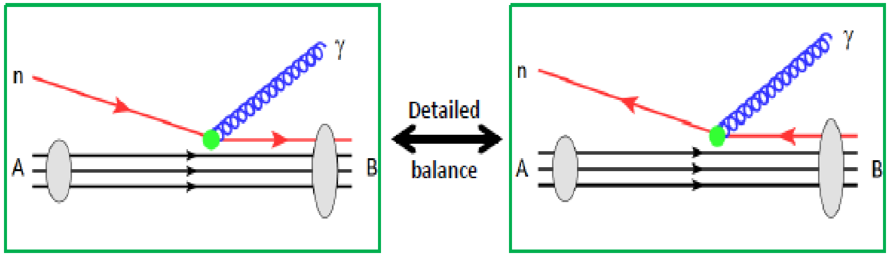
NUCLEON CAPTURE CROSS SECTIONS

Nuclear Structure and Astrophysical (n,γ) Capture Cross Sections

- Compound Nucleus Capture: Hauser-Feshbach Theory → Statistical Approach at High level densities

- Direct Capture: Population of Identifiable Nuclear States → Microscopic Reaction Theory

- Investigations by Detailed Balance: (n,γ) ↔ (γ,n)



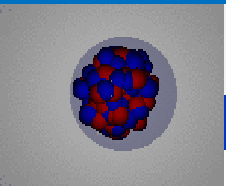
Total Capture Cross Section: Incoherent Superposition of Electric (E) and Magnetic (M) Multipoles

$$\sigma(E_{c.m.}) = \sum_{LSJ_iJ_f\ell} \frac{8\pi}{2J_f+1}\frac{\alpha}{v_{rel}}\frac{q}{1+q/m_f}\left[\left|E_\ell^{LSJ_iJ_f}(q)\right|^2 + \left|M_\ell^{LSJ_iJ_f}(q)\right|^2\right]$$

$$E_\ell^{LSJ_iJ_f}(q) \underset{q\to 0}{\to} \frac{q^L}{(2L+1)!!}\sqrt{B_{J_iJ_f}(EL)}\ \delta_{S0} \quad \text{etc.}$$

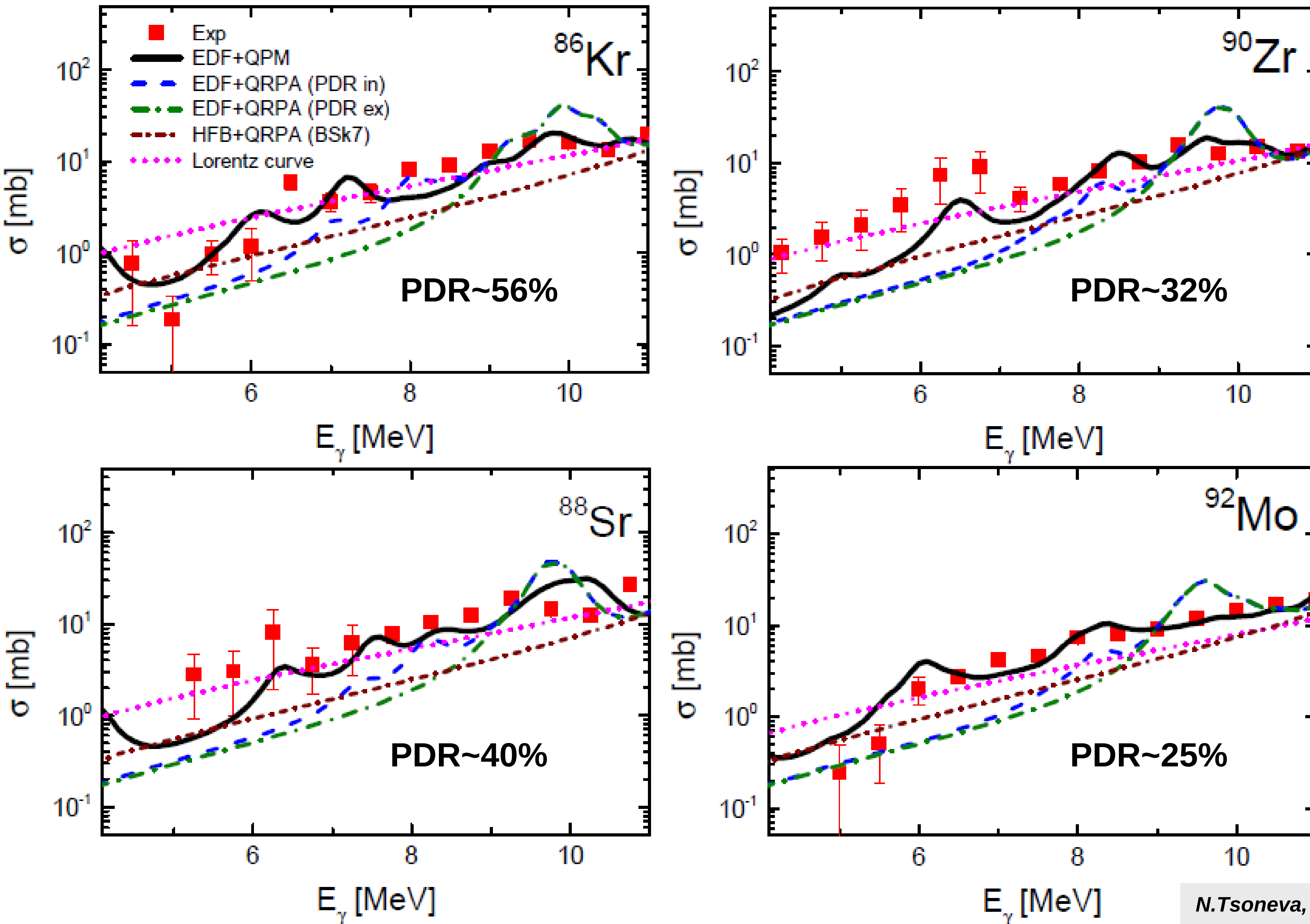
N.Tsoneva, Hirschegg18

DYNAMICS OF LOW ENERGY NUCLEAR EXCITATIONS IN N=50 ISOTONES



Exp: R. Schwengner et al., First systematic photon-scattering experiments in **N=50 nuclei**: using bremsstrahlung produced with electron beams at the linear accelerator ELBE, Rossendorf and quasi-monoenergetic γ – rays at HIγS facility, Duke university.

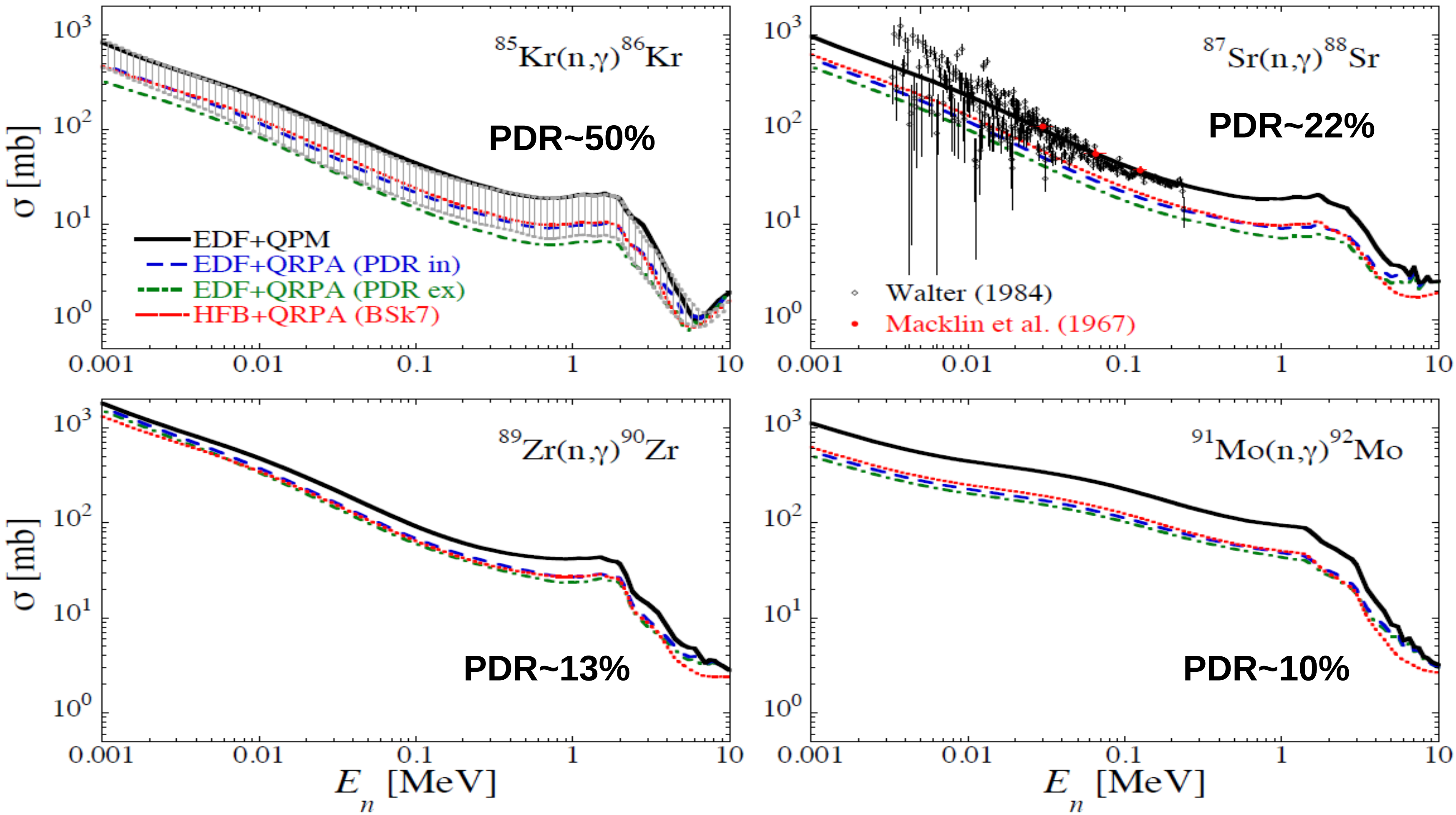
N. Tsoneva, S. Goriely, H. Lenske, R. Schwengner, Phys. Rev. C91, 044318 (2015).



NEUTRON CAPTURE CROSS SECTIONS

of the ^{85}Kr(n,γ)^{86}Kr, ^{87}Sr(n,γ)^{88}Sr, ^{89}Zr(n,γ)^{90}Zr and ^{91}Mo(n,γ)^{92}Mo reactions calculated with TALYS using EDF+QRPA, HFB+QRPA and EDF+three-phonon QPM

N. Tsoneva, S. Goriely, H. Lenske, R. Schwengner, Phys. Rev. C91, 044318 (2015).



^{85}Kr(n,γ)^{86}Kr cross sections, the hashed area corresponds to the cross section determined with the experimental strength as derived in R. Raut et al., Phys. Rev. Lett. 111, 112501 (2013).

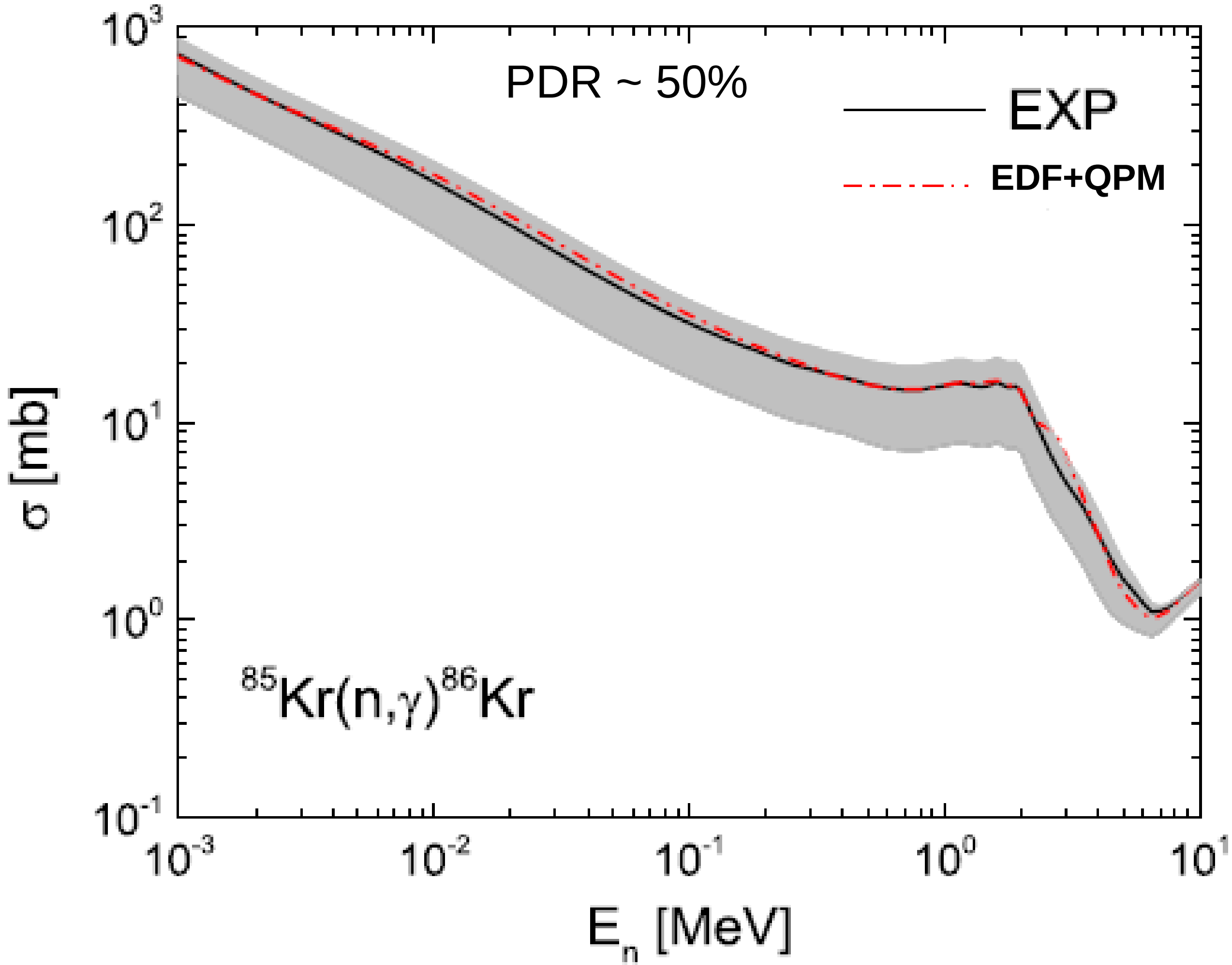
^{87}Sr(n,γ)^{88}Sr, TALYS cross sections are compared with experimental data G. Walter, Kernforschungszentrum Karlsruhe Reports No.3706 (1984); R.L. Macklin and J.H. Gibbons, Phys. Rev. 159, 1007 (1967).

Total cross section of $^{85}Kr(n,\gamma)^{86}Kr$ reaction

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).

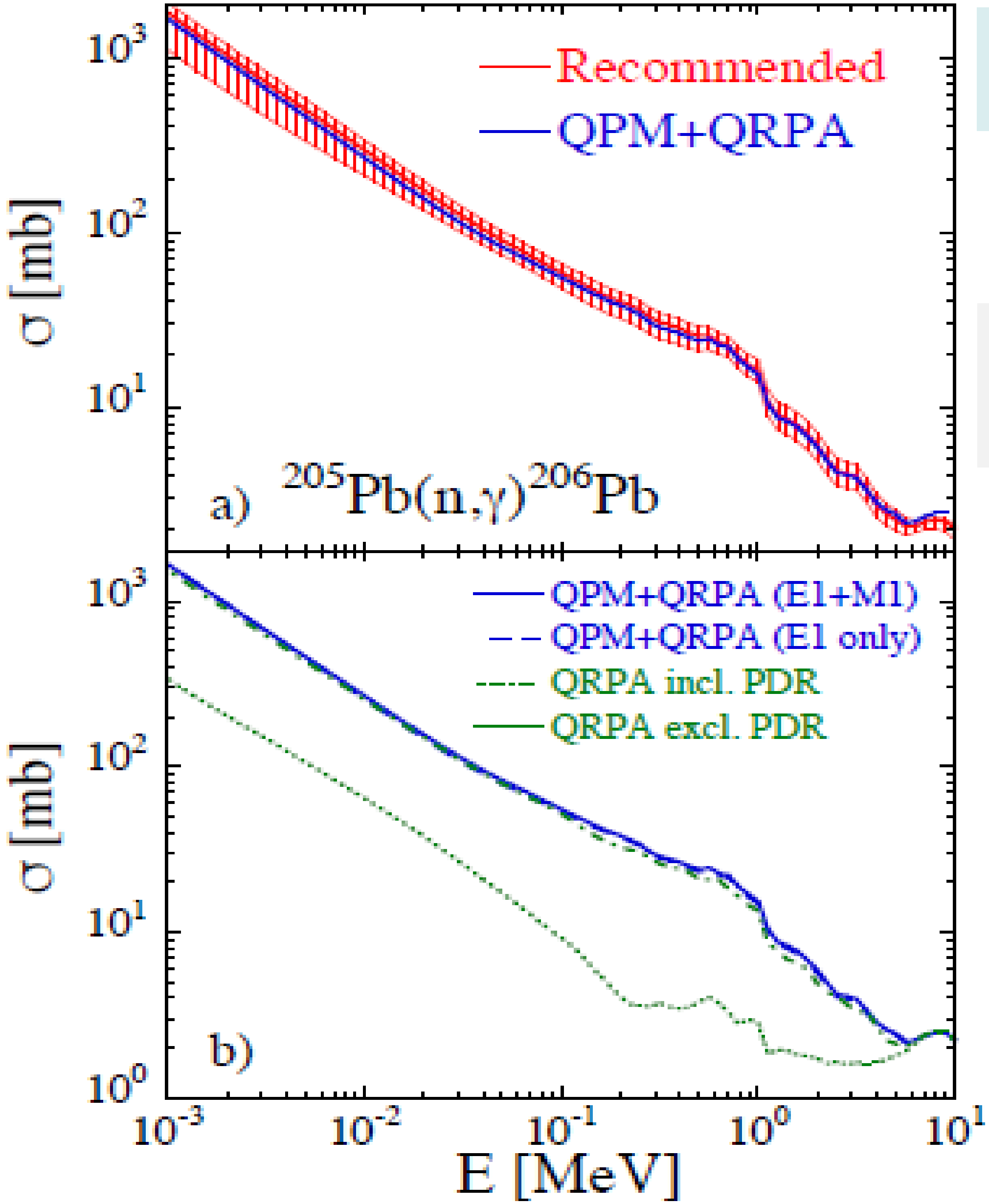
A way to investigate ^{85}Kr branching point and the s-process:

^{85}Kr (t ~ 10.57 Y) ground state is a branching point and thus a bridge for the production of ^{86}Kr at low neutron densities.



- At stellar temperature of kT= 30 keV we obtain MACS of 83(+23,-38) mb which is about 50% higher than the value of Z.Y. Bao *et al.*, At. Data Nucl. Data Tables 76, 70 (2000).
- The new MACS value explains the higher 86Kr:82Kr ratios measured in large star dust SiC grains.
- The experimental uncertainty is improved by a factor of ~3 to 50%.

Nuclear Pygmy Modes as Doorways to Nucleosynthesis:
Destruction of the s-process ^{205}Pb nuclide by n-capture via the PDR ?



A.P.Tonchev,N.Tsoneva,C.Bhatia,C.W.Arnold,S.Goriely,S.L.Hammond, J.H.Kelley,E.Kwan,H.Lenske,J.Piekarewicz,R.Raut,G.Rusev,T.Shizuma and W.Tornow, **Phys. Lett. B, 773, p. 20-25, 10 October 2017.**

- At stellar temperature of kT= 30 keV
  MACS of 130(+25,-25) mb

⇒The combined PDR plus core polarization contribution is crucial !

⇒M1 contribution small, less than 5%.

Collection of Observables Probing the n-p Matter

Neutron skin thickness

$$\delta r = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

Symmetry Energy

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

Density Dependence of the Symmetry Energy

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

Nuclear Dipole Polarizability and Photoabsorption

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

Summary of a few moments of the photoabsorption cross section of ^{206}Pb and ^{208}Pb

Nucleus	E_{max} (MeV)	60NZ/A (mb MeV)	σ_0 (mb MeV)	σ_{-1} (mb)	σ_{-2} (mb/MeV)	Ref.
^{206}Pb	26	2962	3544±294	241±17	18±1	Present+[46,49]
			3437	240	18	[ENDF]
^{208}Pb	25	2980	3981±331	287±18	20±1	[50]
			3404	239	18	[ENDF]

Photoabsorption cross sections & moments and Nuclear Matter

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

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E.Kwan,H.Lenske,J.Piekarewicz,R.Raut,G.Rusev,T.Shizuma,W.Tornow,
Phys. Lett. B, 773, p. 20-25, 10 October 2017

Summary and Outlook

- New low-energy modes: PDR, PQR …
- GiEDF+QPM:an extended DFT plus multi-phonon approach to nuclear spectra and astrophysics
- Subthreshold pygmy modes, multi-phonon excitations, GDR and capture cross sections
- Correlations: PDR ⟷ skin thickness ⟷ polarizability ⟷slope L⟷…?
- Predicions of s- and r-process nucleosynthesis rates

Thank you !

In collaboration with:

H. Lenske, V. Derya, S. Goriely, J. Piekarewicz,
R. Schwengner, M. Spieker, A. Tonchev, W. Tornow …