Nuclear Structure 2016
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Energy-density functional plus multi-phonon theory as a powerful tool for nuclear structure and astrophysics

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The Theoretical Model

N. Tsoneva, H. Lenske, Ch. Stoyanov, Phys. Lett. B586, 213 (2004).
N. Tsoneva, H. Lenske, Phys. Rev. C 77 (2008) 024321.

The Nuclear Energy-Density Functional: a Functional of Neutron and Proton Densities

P. Hohenberg and W. Kohn, Phys. Rev.136, B864 (1964).
W. Kohn and L. J. Sham, Phys. Rev.140, A1133 (1965).

$$\mathcal{E}(\rho_n,\rho_p)=\sum_q \tau_q(\rho_q)+\mathcal{E}_{\rm int}(\rho_n,\rho_p)$$

τ_q, ρ_q - kinetic and number densities; q denotes neutrons or protons

$$\mathcal{E}_{\rm int}(\rho_n,\rho_p)=\mathcal{E}_{\rm int}(\rho_n^{(0)},\rho_p^{(0)})+\sum_q U_q\delta\rho_q+\frac{1}{2}\sum_{q_1,q_2} f_{q_1,q_2}\delta\rho_{q_1}\delta\rho_{q_2}$$

$$U_q=\frac{\delta\mathcal{E}_{\rm int}}{\delta\rho_q}\Bigg\}$$

MF interaction →

Phenomenological EDF approach based on a fully microscopic self-consistent Skyrme HFB theory
F. Hofmann and H. Lenske, Phys. Rev. C57, 2281 (1998).

$$f_{q_1,q_2}=\frac{\delta^2\mathcal{E}_{\rm int}}{\delta\rho_{q_1}\delta\rho_{q_2}}\Bigg\}$$

residual interaction & nuclear excitations →

Quasiparticle-Phonon Model
/V. G. Soloviev: *Theory of Atomic Nuclei: Quasiparticles and Phonons* (Bristol, 1992)./
- Multipole- and spin- multipole interactions in p-h and p-p channels;
- Model basis built of phonons solved by QRPA equations.
- Wave functions of the excited states built of up to three-phonon configurations.

Theory of Nuclear Excitations

QPM phonons: commute as fermions and thus obey the Pauli principle.
Structure properties: obtained by solving of QRPA equations.

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

i — labels the number of the QRPA state

QPM wave functions are a mixture of one-, two- and three-phonon components: anharmonicities included.

$$\Psi_{\nu}(JM) = \left\{\sum_{i}\underbrace{R_i(J\nu)Q^{+}_{JMi}}_{\text{one-phonon part}} + \sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}}\underbrace{P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)\left[Q^{+}_{\lambda_1\mu_1 i_1}\otimes Q^{+}_{\lambda_2\mu_2 i_2}\right]_{JM}}_{\text{two-phonon part}}\right.$$

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

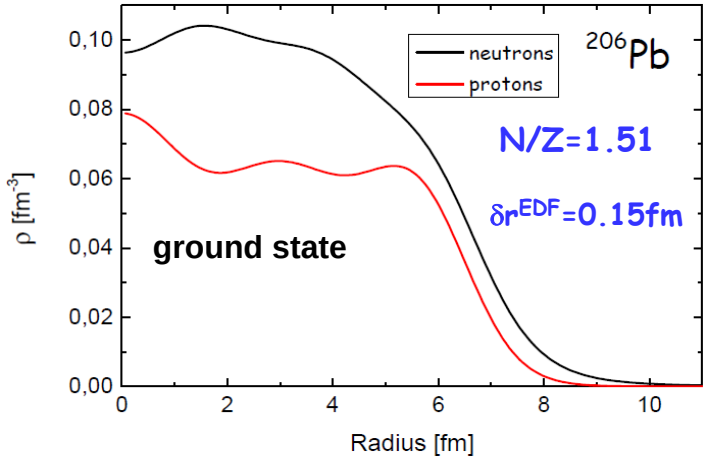
ν — labels the number of the QPM excited state

M. Grinberg, Ch. Stoyanov, Nucl. Phys. A. 573 231 (1994).
V. Yu. Ponomarev, Ch. Stoyanov, N. Tsoneva, M. Grinberg, Nucl. Phys. A635, 470 (1998).

Exploratory investigations of new modes of nuclear excitations in stable and exotic nuclei within the EDF+QPM approach

neutron skin

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



transition densities

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

dipole polarizability $\alpha_D = \frac{\sigma_{-2}}{2\pi^2\alpha},$

$$\sigma_{-2} = \int \frac{\sigma(E)}{E^2} d(E)$$

and α is the fine structure constant

N. Tsoneva, H. Lenske, Phys. Rev. C 77 (2008) 024321.

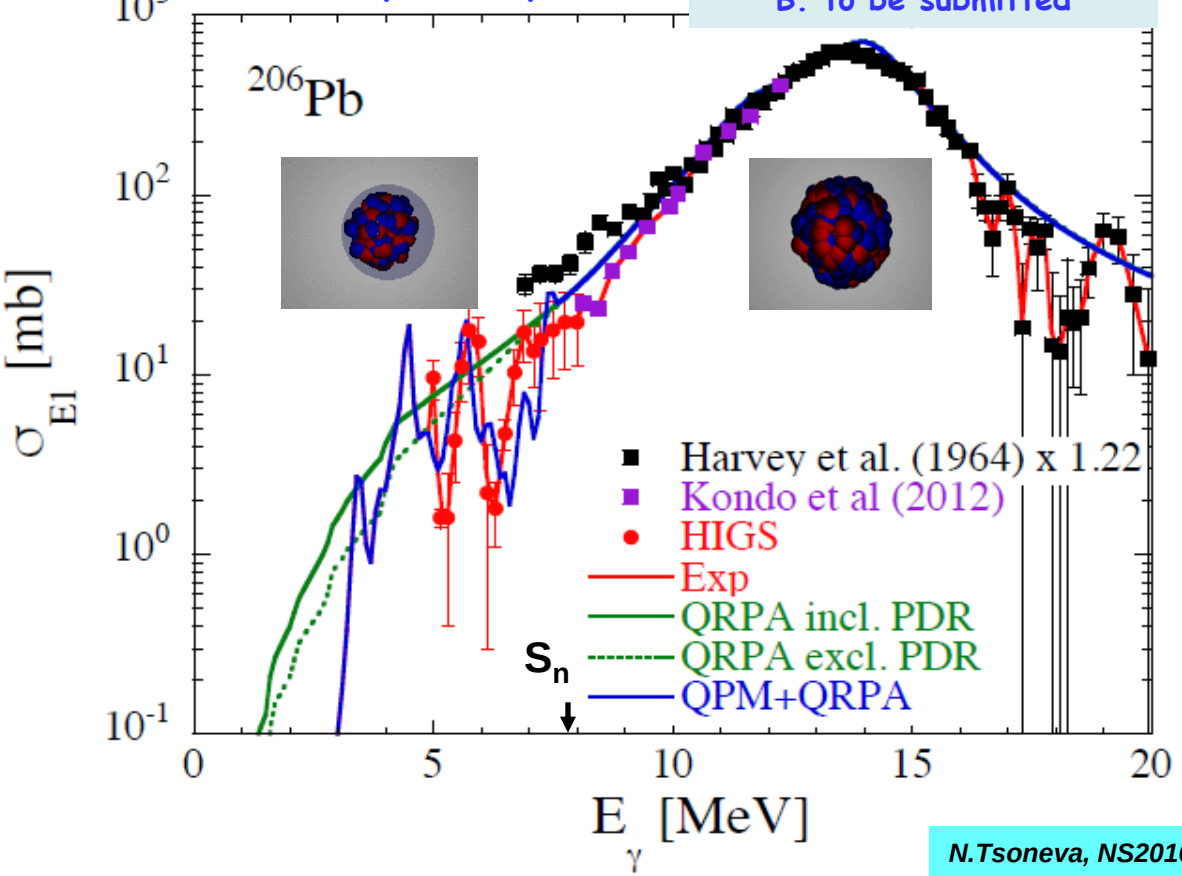
PDR is independent of the type of nucleon excess (neutron or proton) and closely connected with the thickness of the nuclear skin.

PDR ≤ 1% of the TRK sum rule (S_{TRK} ~ NZ/A)

=> Generic mode of excitation

electric dipole response

A. Tonchev et al., B. to be submitted



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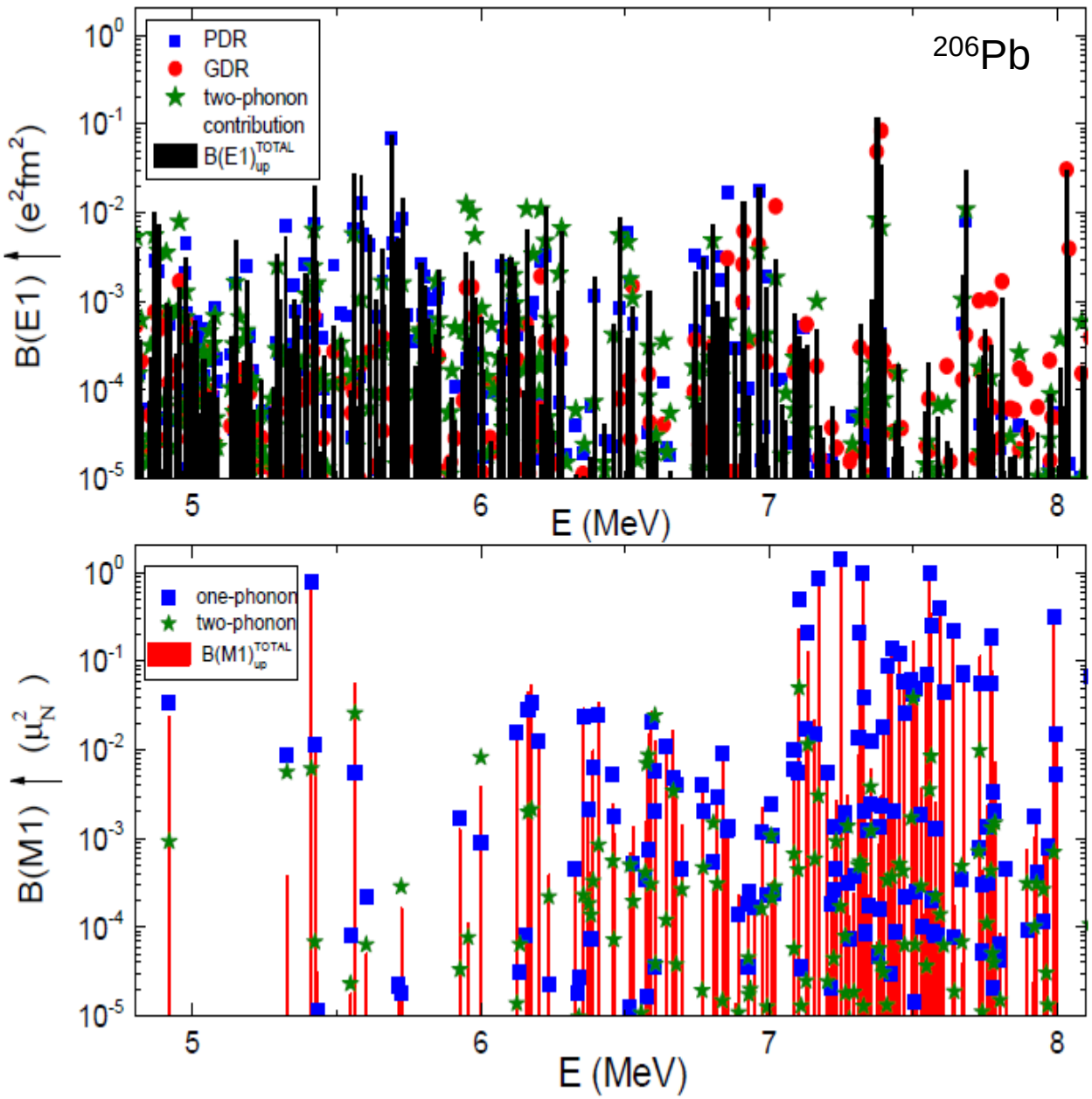
EDF+QPM calculations of the fine structure of low-energy E1 and M1 excitations in ^{206}Pb



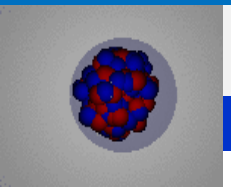
Presently, this is the only existing method allowing for self consistent determination of nuclear ground state and unified description of low-energy single-particle, multi-phonon states and giant resonances in a large multi-particle-multi-hole configuration space.

Spectral structure of the pygmy dipole resonance
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).

Fine structure of the giant M1 resonance in ^{90}Zr
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).**

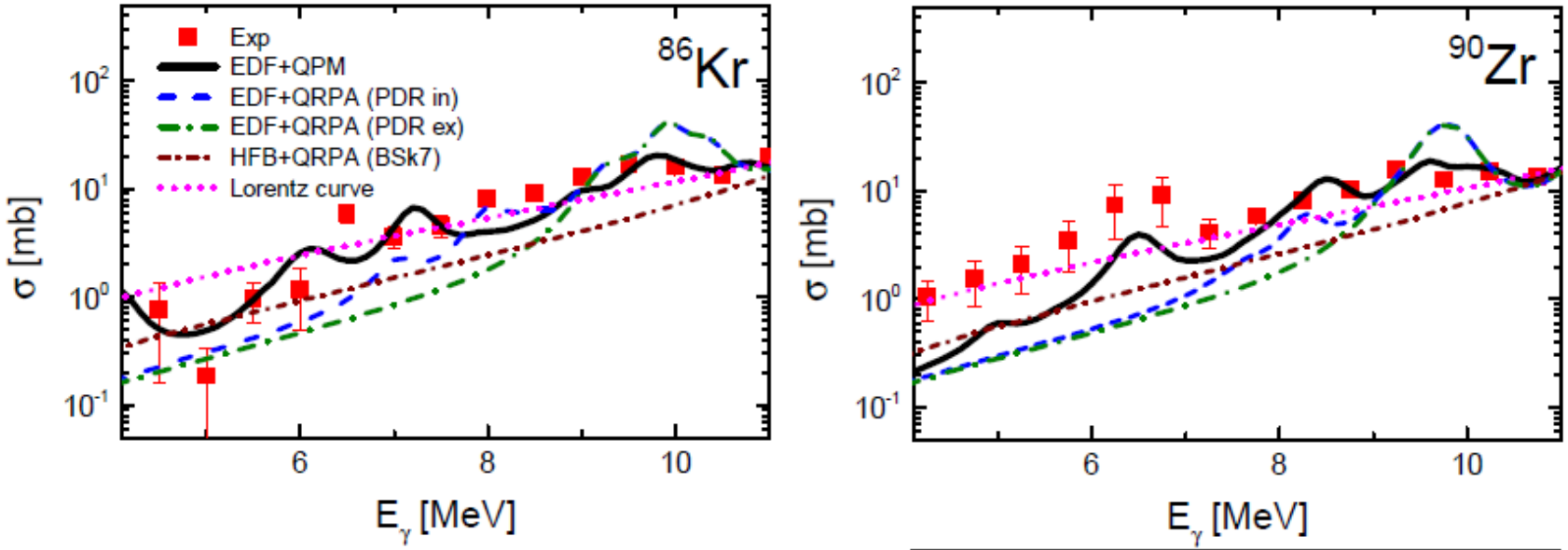
Polarized photon scattering off ^{52}Cr: Determining the parity of J=1 states
Krishichayan, Megha Bhike, W. Tornow, G. Rusev, A. P. Tonchev, N. Tsoneva, and H. Lenske,
Phys. Rev. C 91, 044328 (2015).

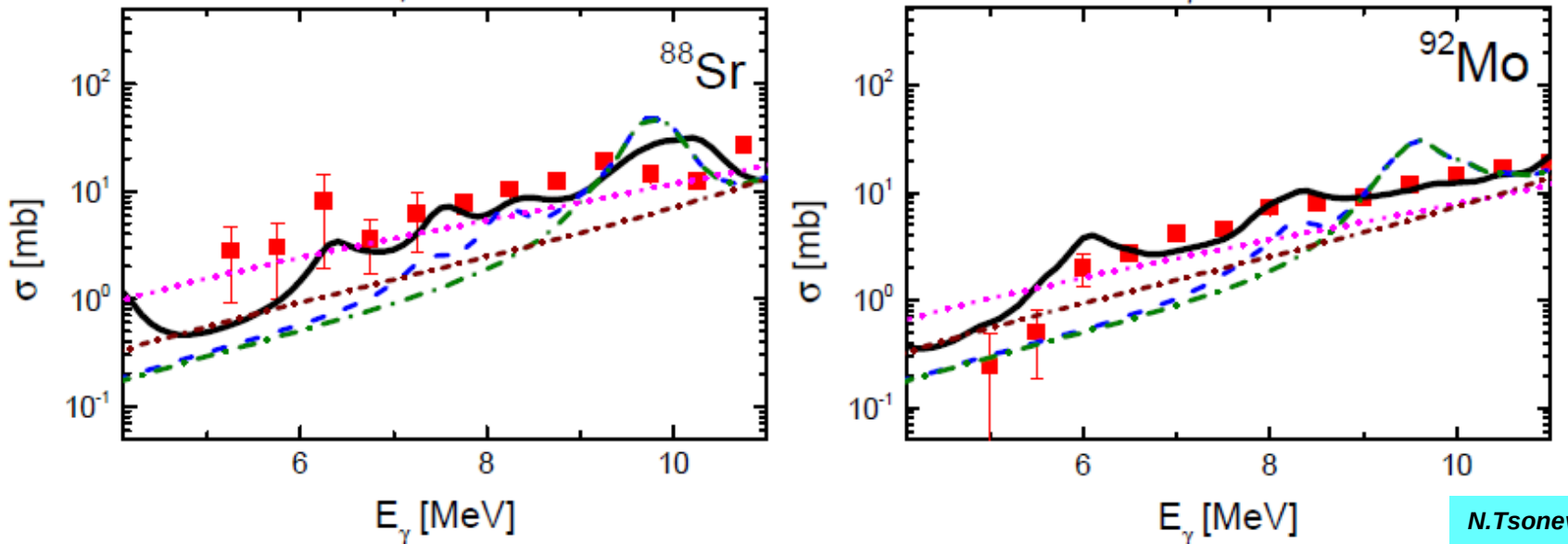
DYNAMICS OF LOW_ENERGY NUCLEAR EXCITATIONS IN N=50 ISOTONES



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).





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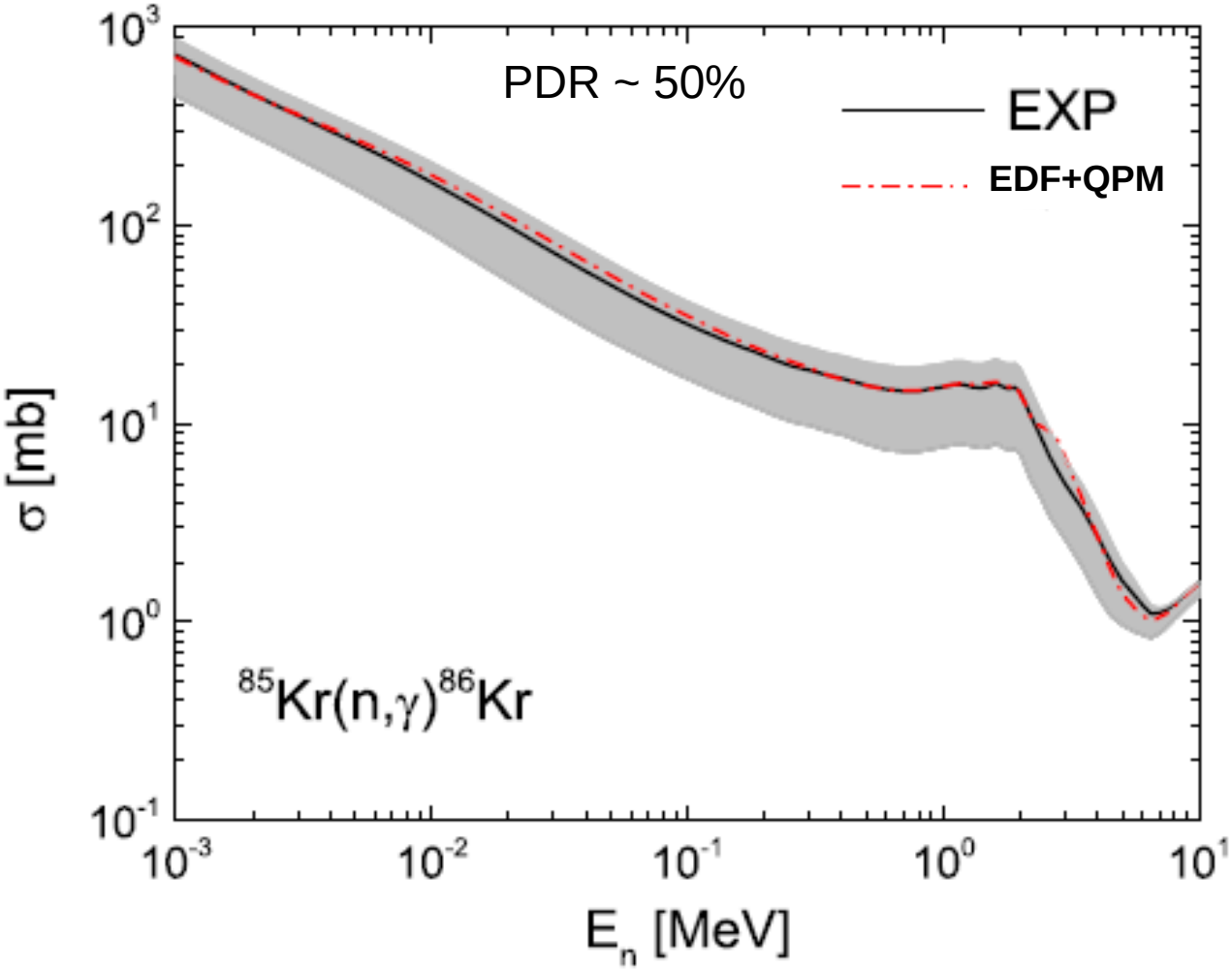
Total cross section of $^{85}Kr^{g}(n,\gamma)^{86}Kr$ reaction

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).

N. Tsoneva, S. Goriely, H. Lenske, R. Schwengner, Phys. Rev. C 91, 044318 (2015).

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.

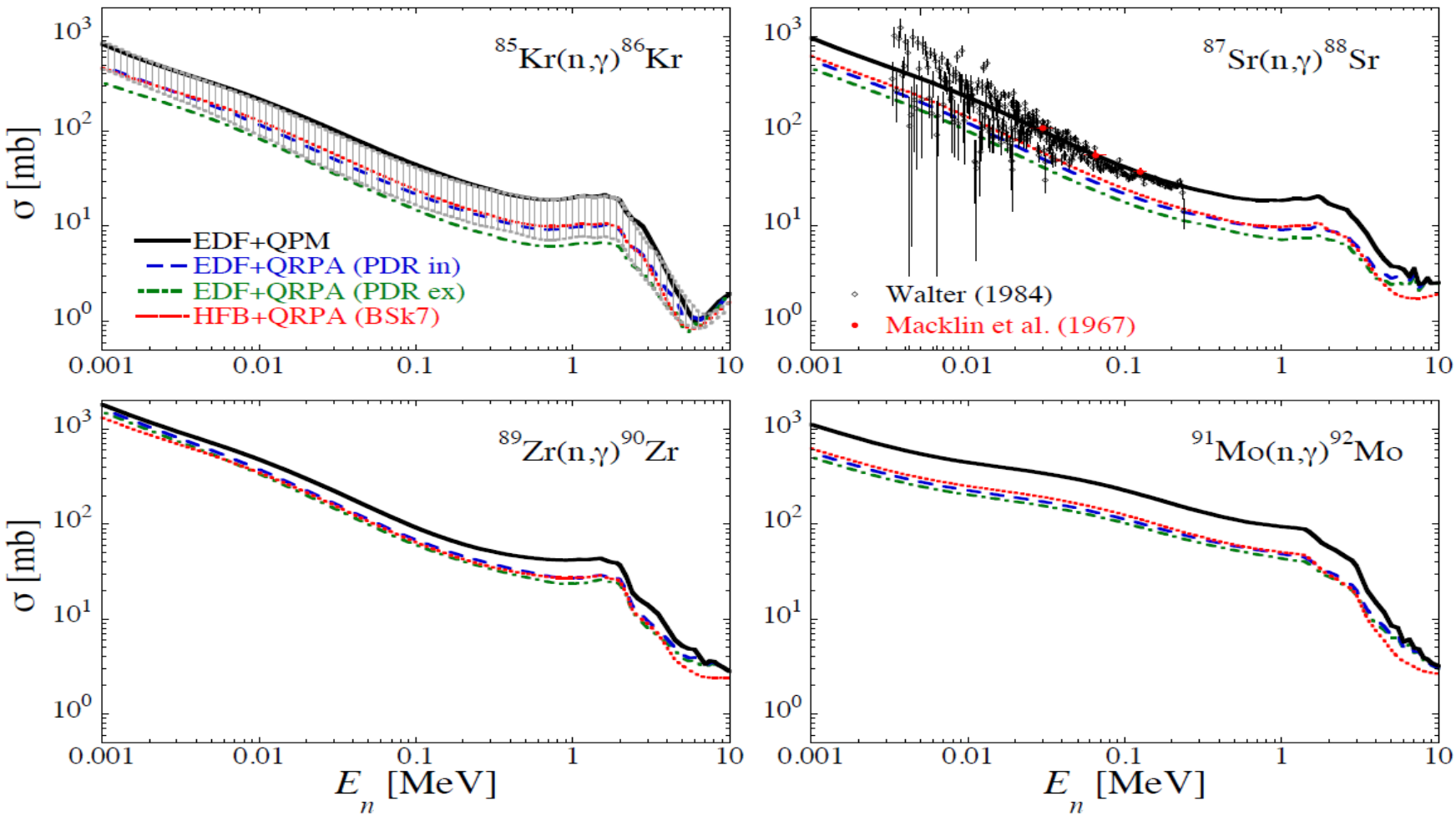


- At stellar temperature of kT= 30 keV we obtain MACS of 83(+23,-38) mb which is about 50% higher than the value of Z.Y. Bao *et al.*, At. Data Nucl. Data Tables 76, 70 (2000).
- The new MACS value explains the higher 86Kr:82Kr ratios measured in large star dust SiC grains.
- The experimental uncertainty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

NEUTRON CAPTURE CROSS SECTIONS

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

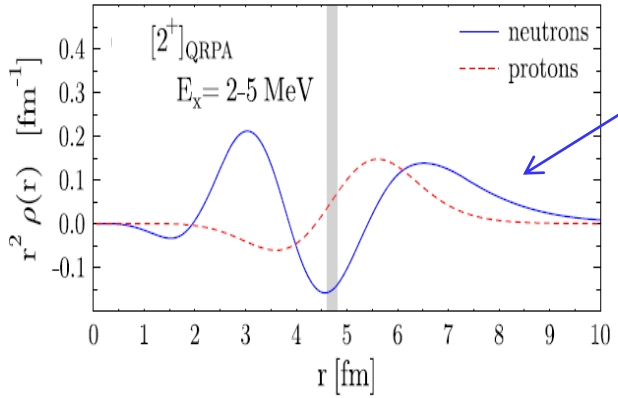
N. Tsoneva, S. Goriely, H. Lenske, R. Schwengner, Phys. Rev. C91, 044318 (2015).



$^{85}Kr(n,\gamma)^{86}Kr$ 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).

$^{87}Sr(n,\gamma)^{88}Sr$, 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).

Theoretical prediction of Pygmy Quadrupole Resonance

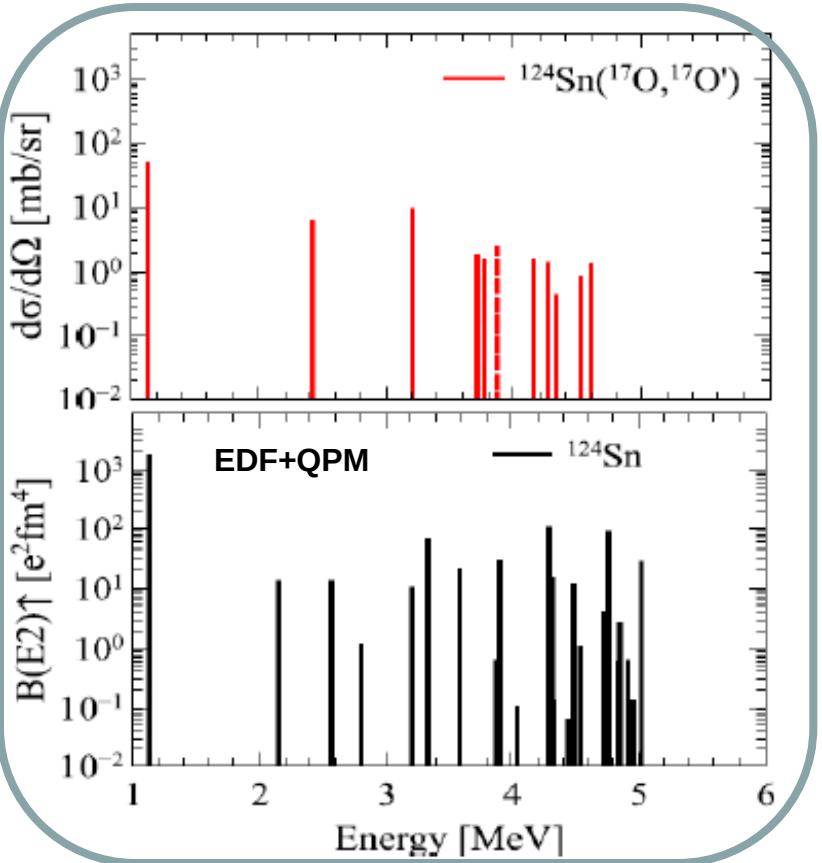


quadrupole neutron skin oscillations in ^{124}Sn

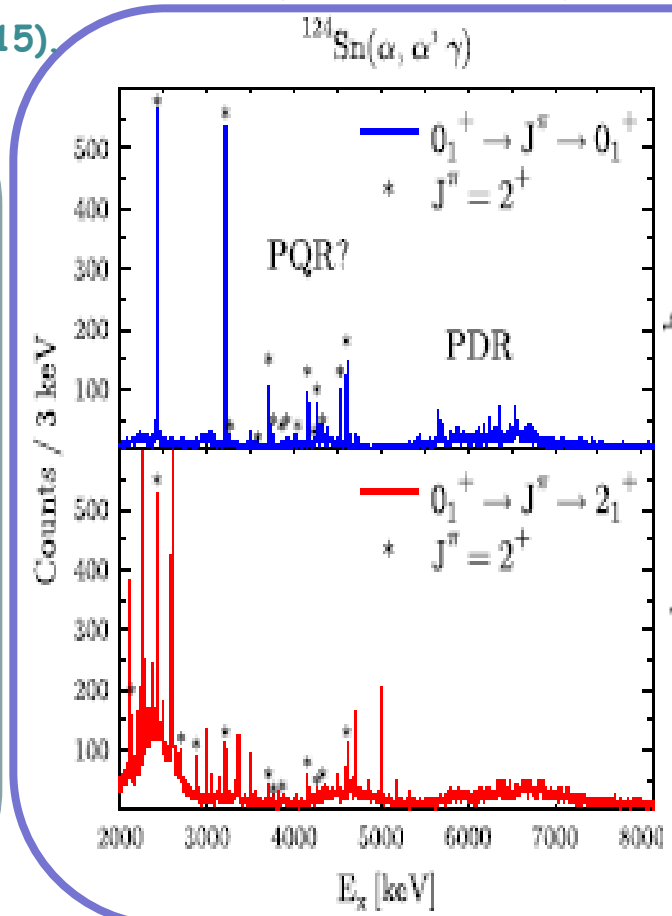
N. Tsoneva, H. Lenske, Phys. Lett. B695 174 (2011).

The pygmy quadrupole resonance and neutron skin modes: First experimental evidences of the existence PQR in ^{124}Sn

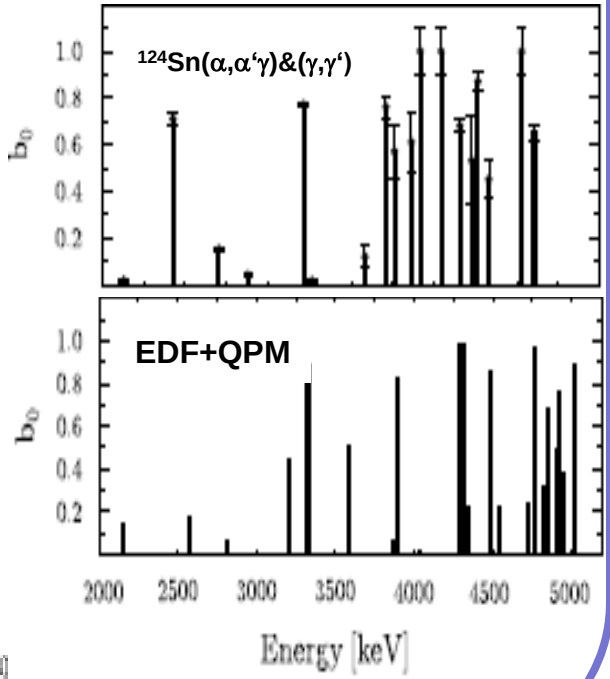
L. Pellegri et al.,Phys. Rev. C92, 014330 (2015).



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



γ-decay branching ratios



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W. Tornow, A.P. Tonchev, G. Rusev, C. Illiadis, Krishichayan et al.

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Thank you!

Universität zu Köln

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(**AGATA** collaboration)