EGAN 2014 Workshop
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Nuclear Dynamics at the Particle Threshold

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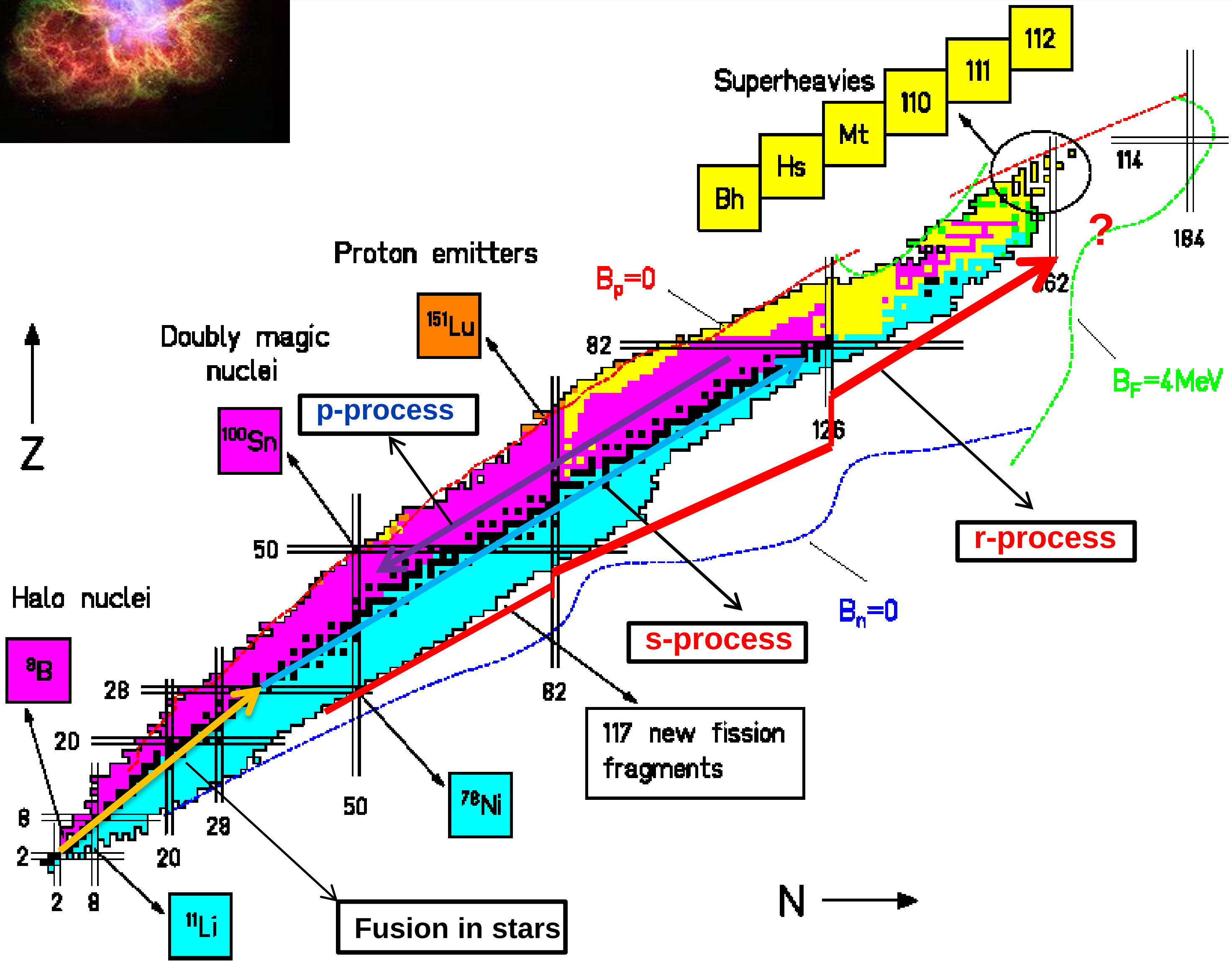
Nucleosynthesis of Heavier Elements

Heavier elements (Z> 26-28) can be assembled within stars by neutron capture processes.



Two main neutron capture processes

s- process – slow neutron capture, low neutron densities

$\rho \sim 10^8/cm^3$

life time

$\tau \sim 1 - 10$ years

r – process - rapid neutron captures

$\rho \sim 10^{20}/cm^3$

...other processes

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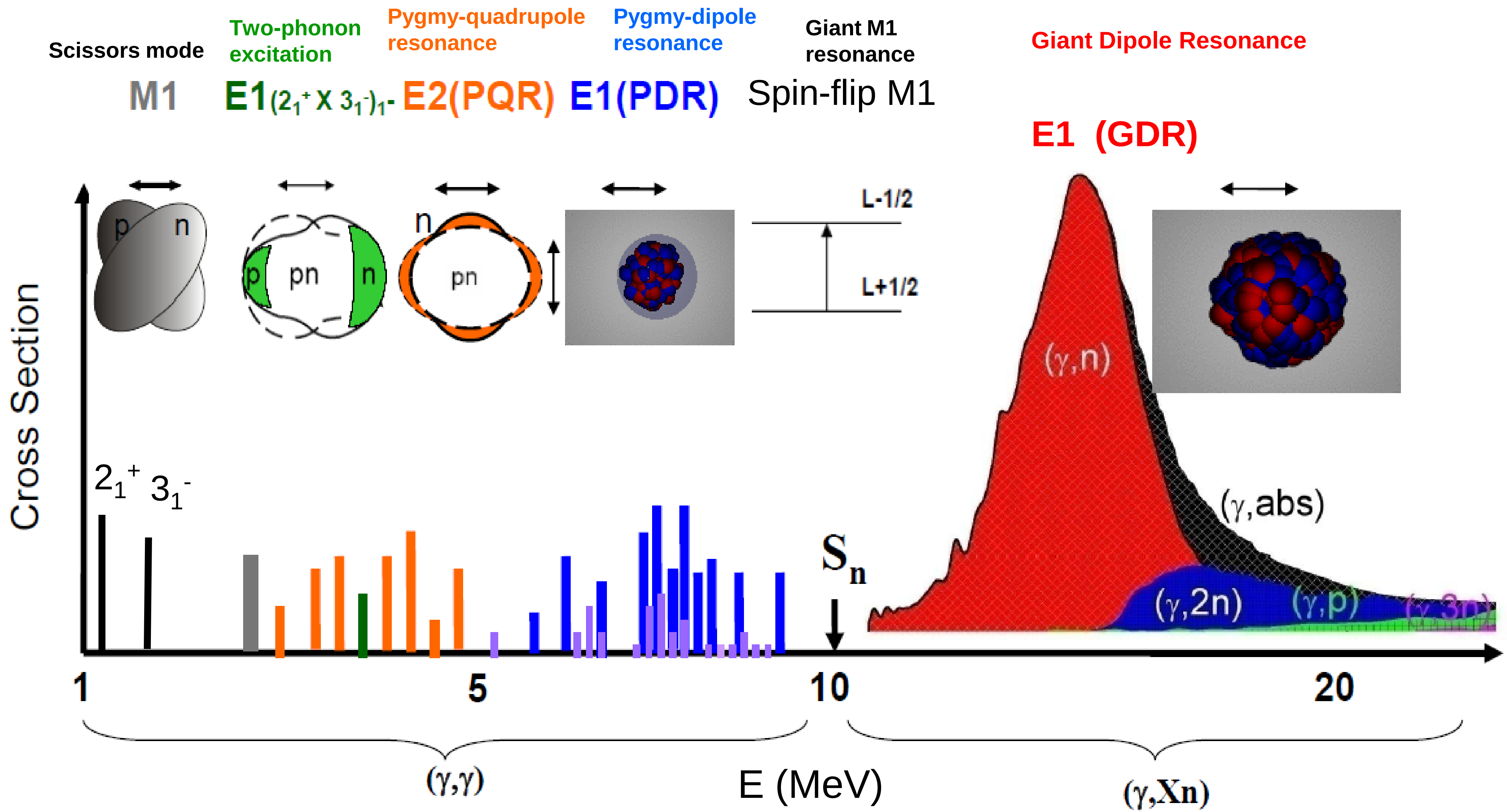
Characteristic Response of an Atomic Nucleus to EM Radiation



Moderate and Heavy nuclei

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

The Theoretical Model

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

Excited states

deformations, vibrations, rotations

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

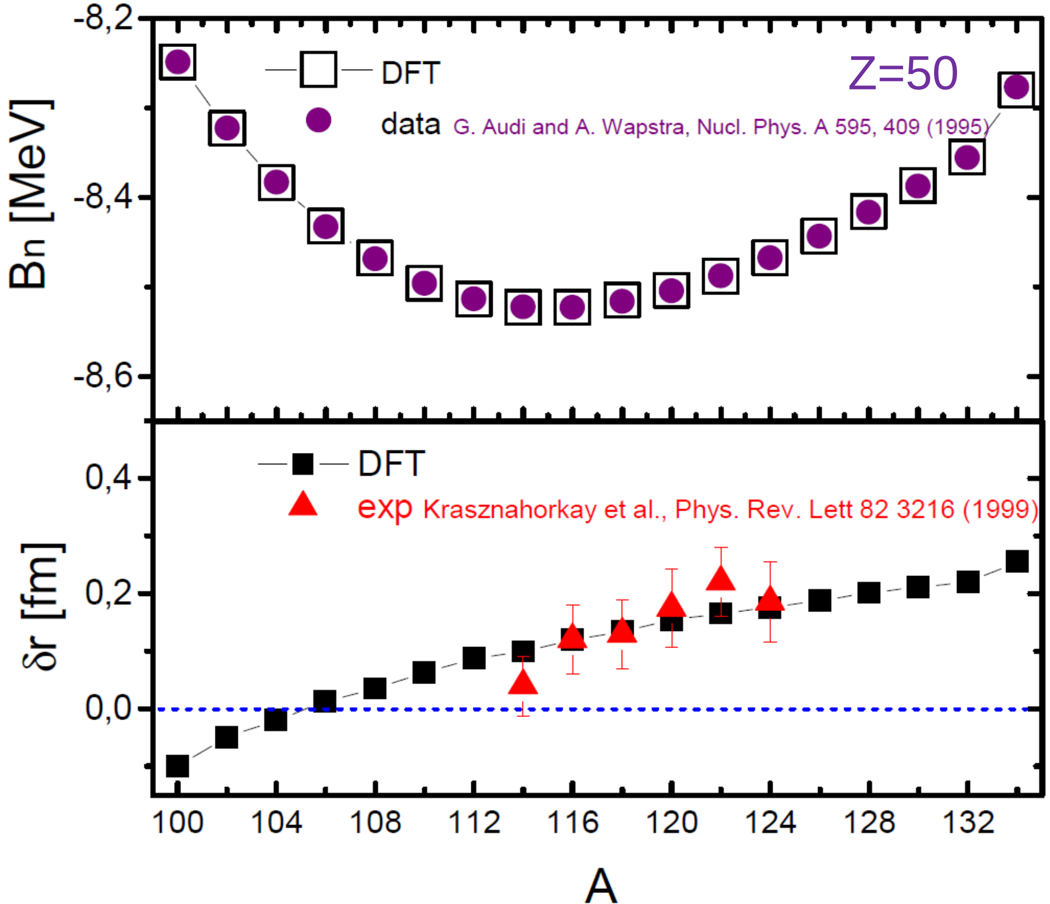
Phenomenological Density Functional Approach for Nuclear Ground States

P. Hohenberg, W. Kohn, Phys. Rev. 136 (1964) B864; W. Kohn, L. J. Sham, Phys. Rev. 140 (1965) A 1133.

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

The total binding energy $B(A)$ is expressed as an integral over an energy-density functional

$$B(A) = \sum_{q=p,n} \int d^3r \left(\tau_q(\rho) + \frac{1}{2}\rho_q U_q(\rho) \right) + E_q^{pair}(k,\rho)$$



effective potential

$$B(A)/\delta\rho_q \Rightarrow \Sigma_q(\rho) = U_q(\rho) + U_q^{(r)}(\rho)$$

$_q$, τ_q, k_q – number, kinetic and pairing density

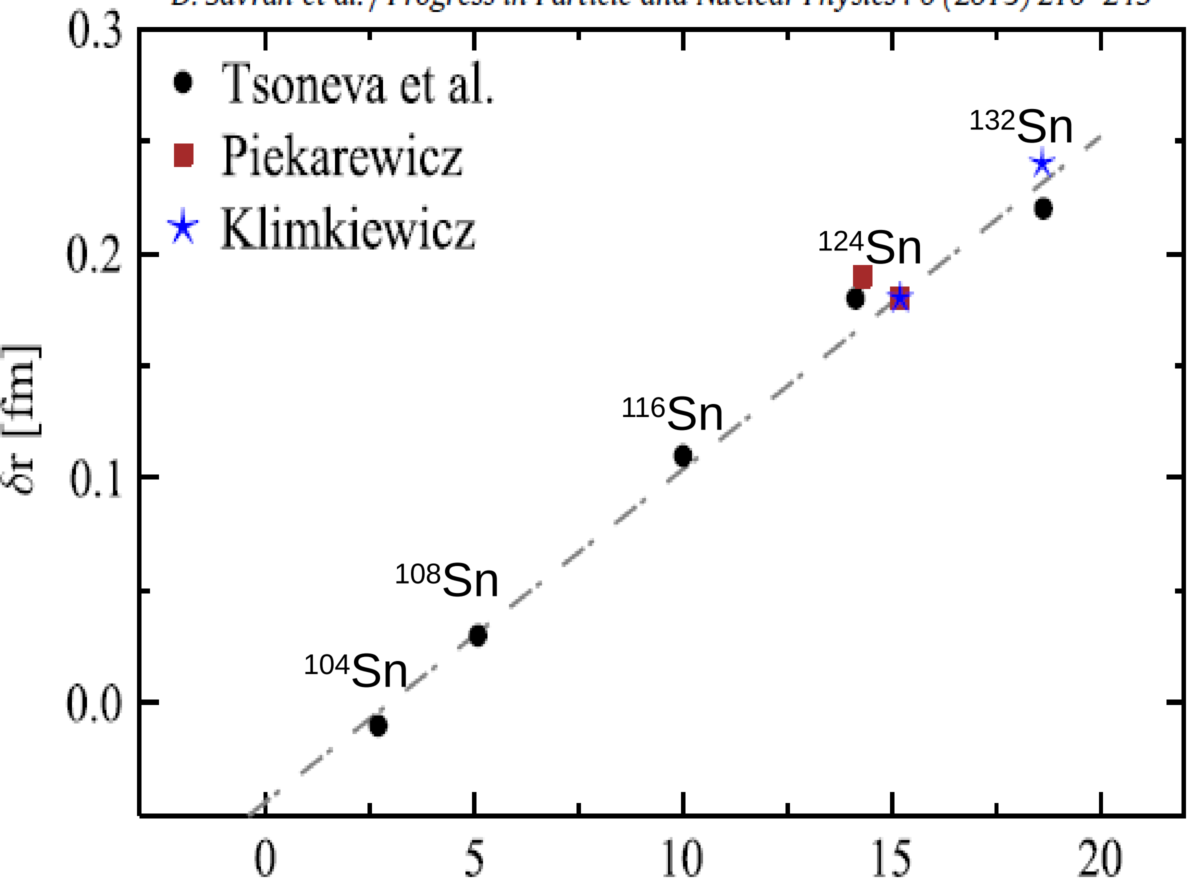
neutron skin thickness

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

$$\langle r_q^2 \rangle = \frac{1}{A_q} \int d^3r r^2 \rho_q(\vec{r})$$

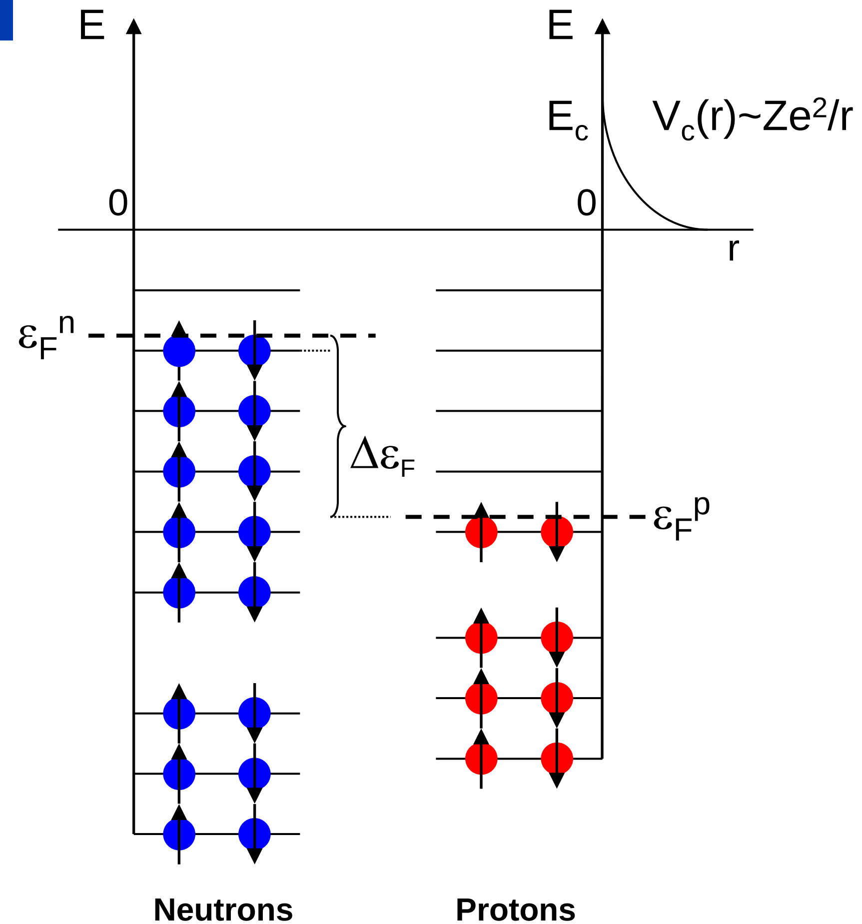
The thickness of the neutron skin scaled with the difference of the Fermi levels of the protons and neutrons $\Delta\varepsilon_F$ corrected for the Coulomb barrier.

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



$\Delta_{CCF} = (S_{2p} - S_{2n})/2 + E_C$ [MeV]

Even-Even Neutron-Rich Nucleus



a measure of how loosely the neutrons are bound compared to the protons.

S_{2p}, S_{2n} – two proton (neutron) separation energies,
E_C – the height of the Coulomb barrier at the nuclear radius
(CCF=Coulomb Corrected Fermi energy)

Theory of Nuclear Excitations

The QPM basis is built of phonons:

$$Q^{+}_{\lambda\mu i} = \frac{1}{2}\sum_{j_1 j_2}\left[\psi^{\lambda i}_{j_1 j_2} A^{+}_{\lambda\mu}(j_1, j_2) - (-1)^{\lambda-\mu}\varphi^{\lambda i}_{j_1 j_2} A_{\lambda-\mu}(j_1, j_2)\right]$$

$$A^{+}_{\lambda\mu}(j_1, j_2) = \sum_{m_1 m_2}\langle j_1 m_1 j_2 m_2 | \lambda\mu\rangle \, \alpha^{+}_{j_1 m_1}\alpha^{+}_{j_2 m_2}$$

$$A_{\lambda-\mu}(j_1, j_2) = \sum_{m_1 m_2}\langle j_1 m_1 j_2 m_2 | \lambda-\mu\rangle \, \alpha_{j_2 m_2}\alpha_{j_1 m_1}$$

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

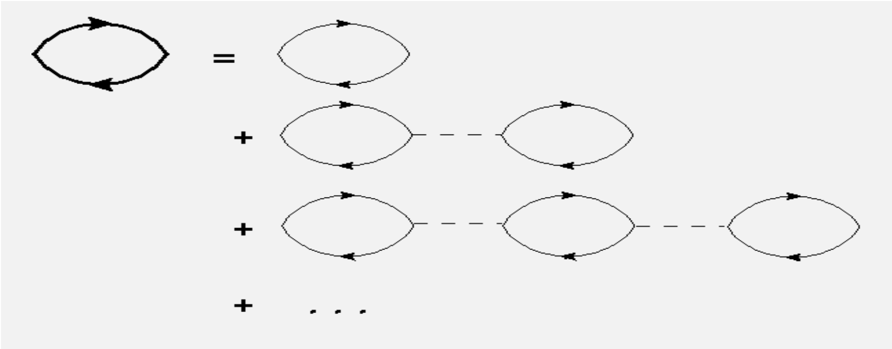
The phonons are not 'pure' bosons:

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

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

QRPA equations are solved:

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



Anharmonicities in Nuclear Wave Function

For even-even nucleus the QPM wave functions are a mixture of one-, two- and three-phonon components

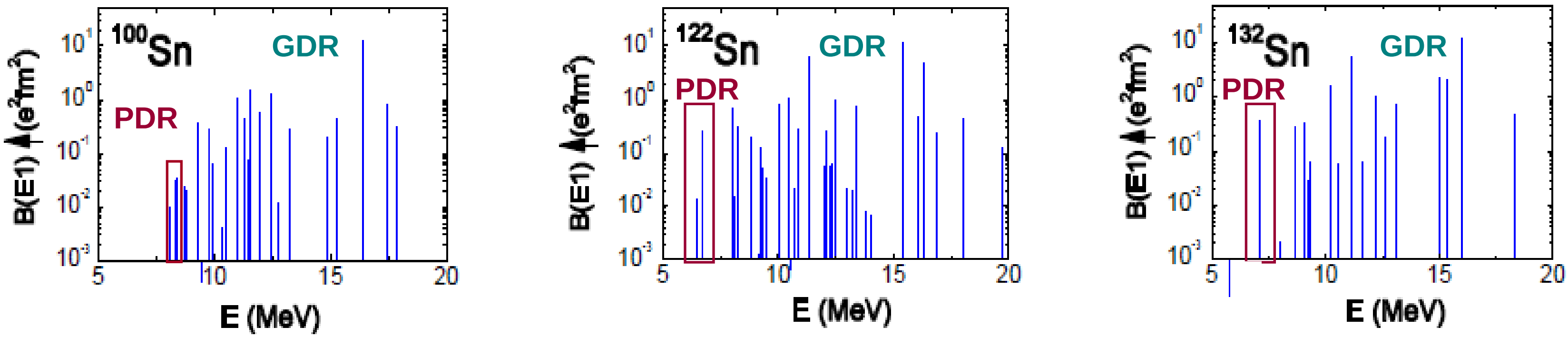
$$\Psi_\nu(JM) = \Big\{ \sum_i \underbrace{R_i(J\nu) Q^+_{JMi}}_{\text{one-phonon part}} + \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} \underbrace{P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_1 \mu_1 i_1} \otimes Q^+_{\lambda_2 \mu_2 i_2} \right]_{JM}}_{\text{two-phonon part}}$$

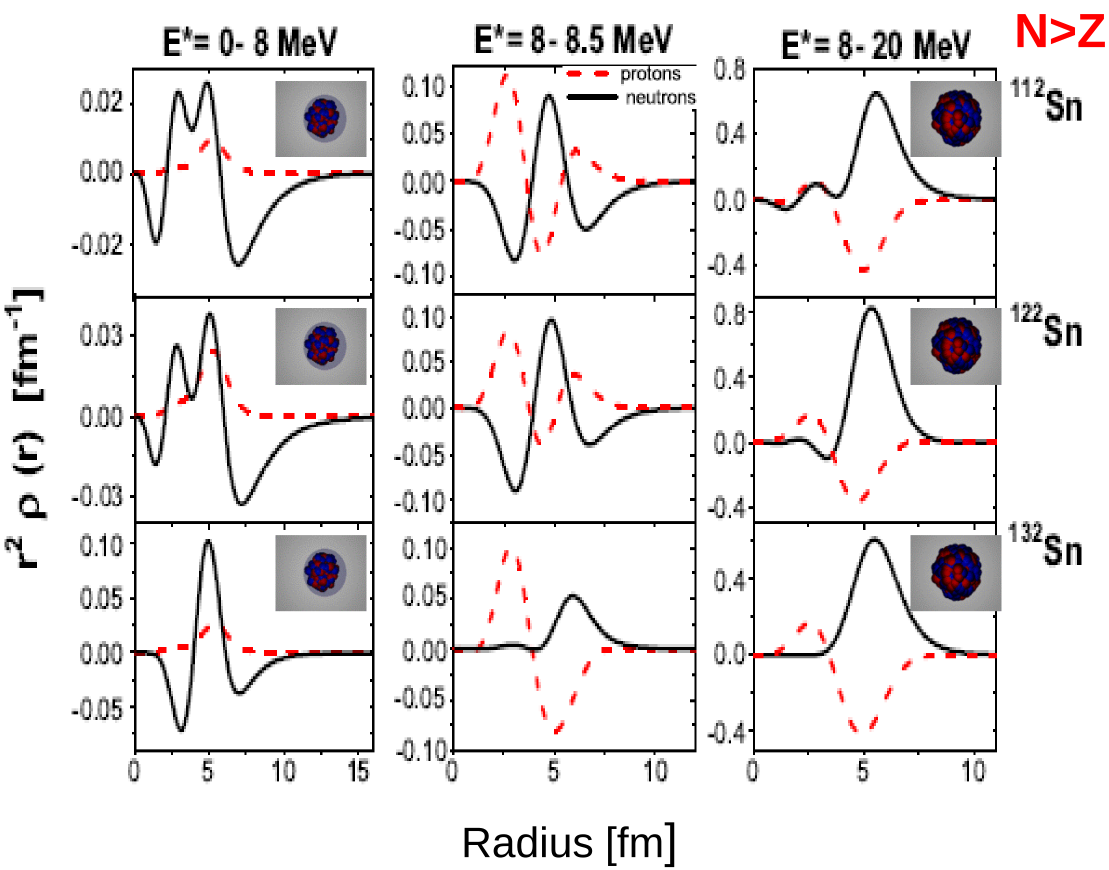
$$+ \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2 \\ \lambda_3 i_3 I}} \underbrace{T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(J\nu) \left[\left[Q^+_{\lambda_1 \mu_1 i_1} \otimes Q^+_{\lambda_2 \mu_2 i_2} \right]_{IK} \otimes Q^+_{\lambda_3 \mu_3 i_3} \right]_{JM}}_{\text{three-phonon part}} \Big\}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

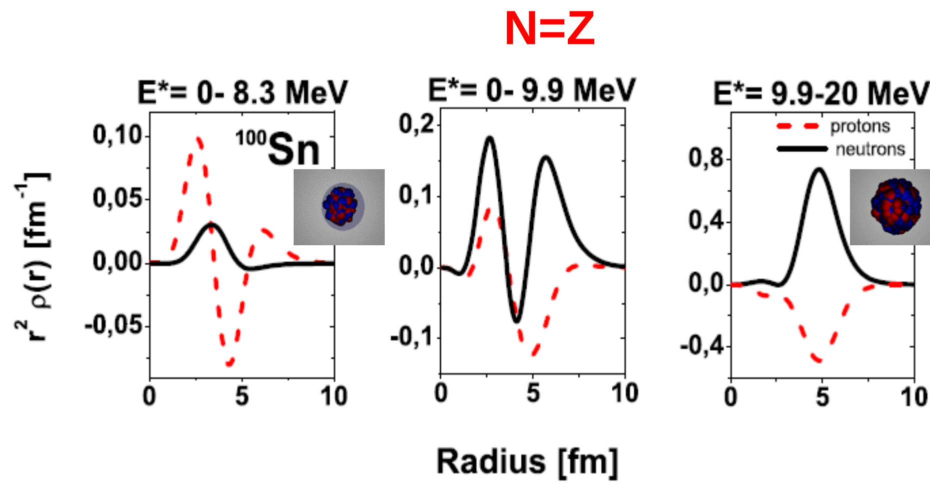
M. Grinberg, Ch. Stoyanov, Nucl. Phys. A. 573 (1994) 231

Pygmy Dipole Resonance in Sn Isotopes

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



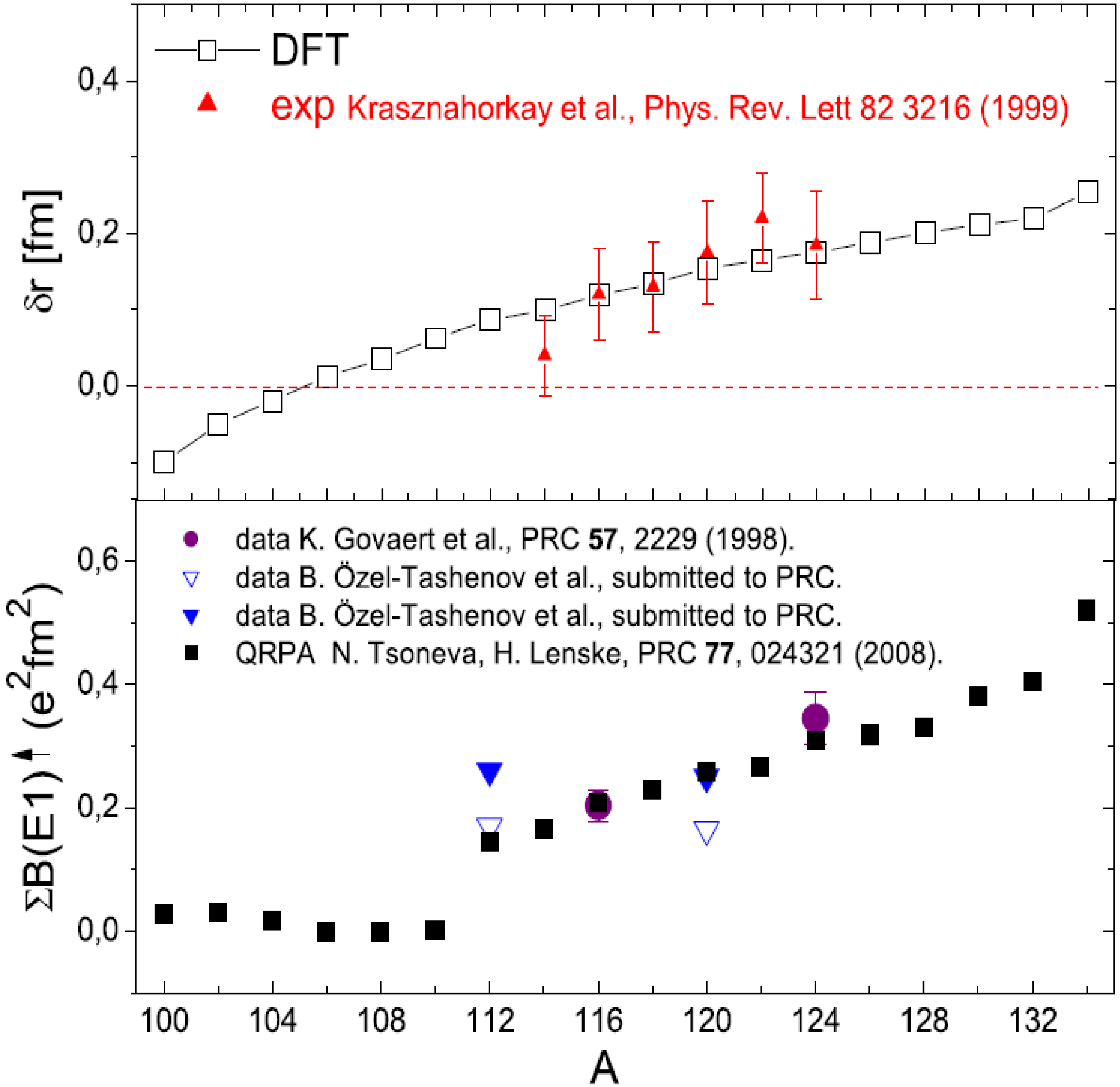




Transition densities are related to nuclear transition strengths

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

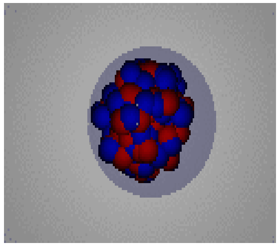
Pygmy Dipole Resonance and the Dynamics of Nuclear Skin



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

Neutron number increasing

Neutron skin increasing

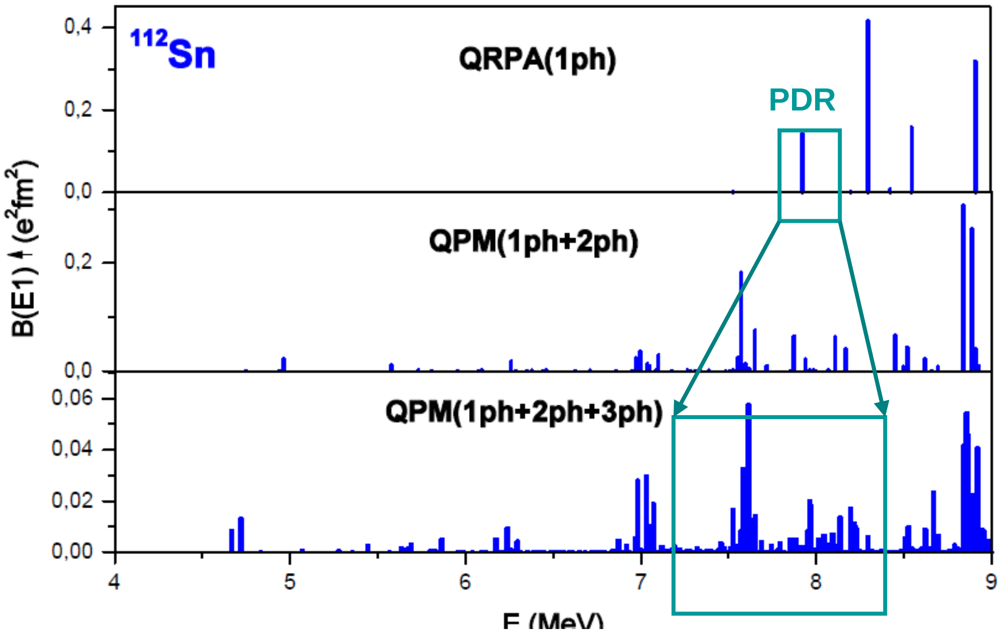


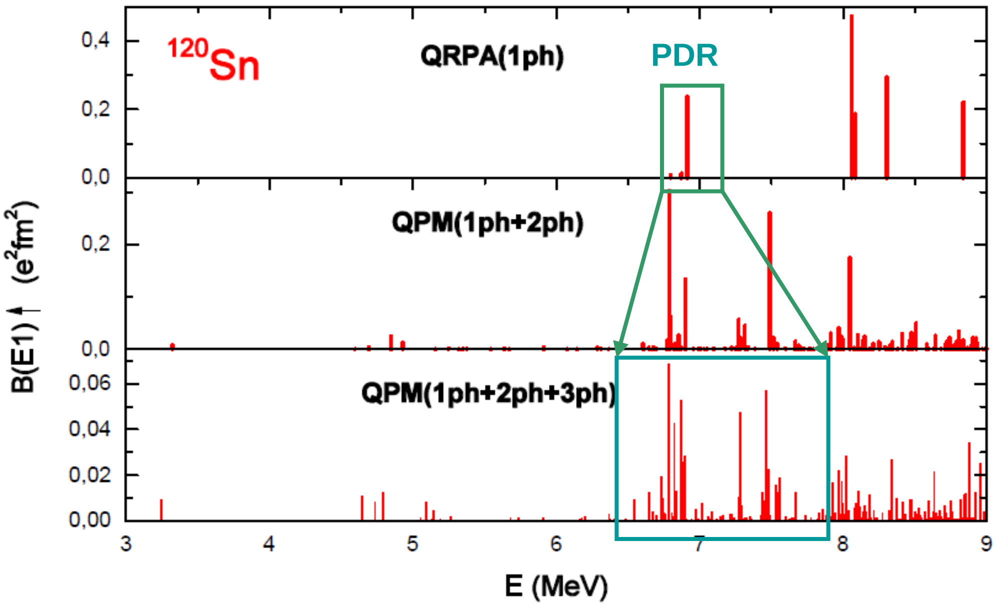
A connection between PDR strengths and neutron skins

Similar observations found also in N=50, 82 isotones !

Multiphonon Calculations of E1 Transitions in $^{112,120}Sn$

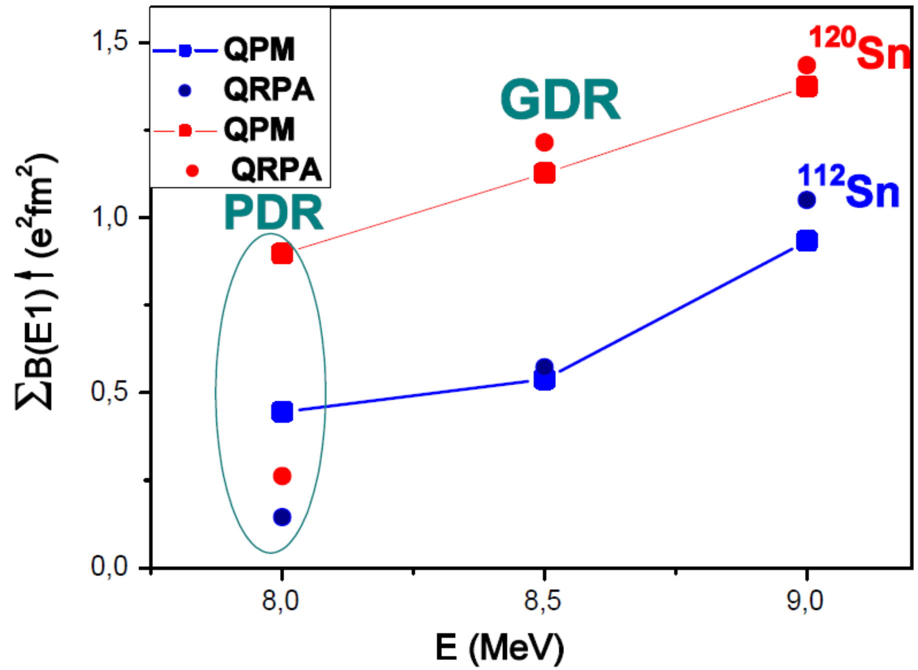
submitted to PRC





N/Z(^{112}Sn)= 1.24

N/Z(^{120}Sn)= 1.4



GDR (E*>8MeV) (1ph)

PDR (1ph+2ph+3ph)

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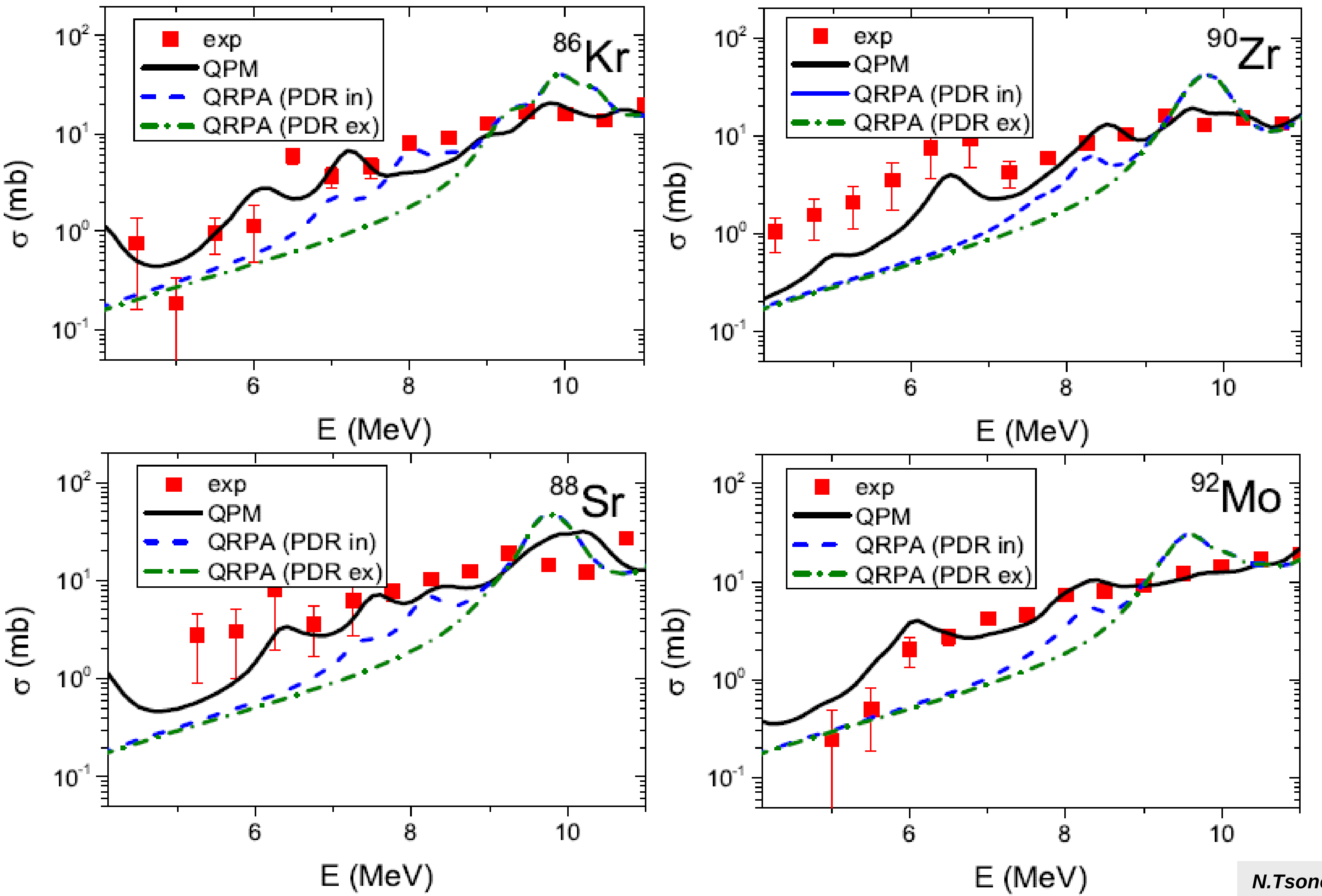
Dynamics of Neutron Skin Oscillations in N=50 Isotones

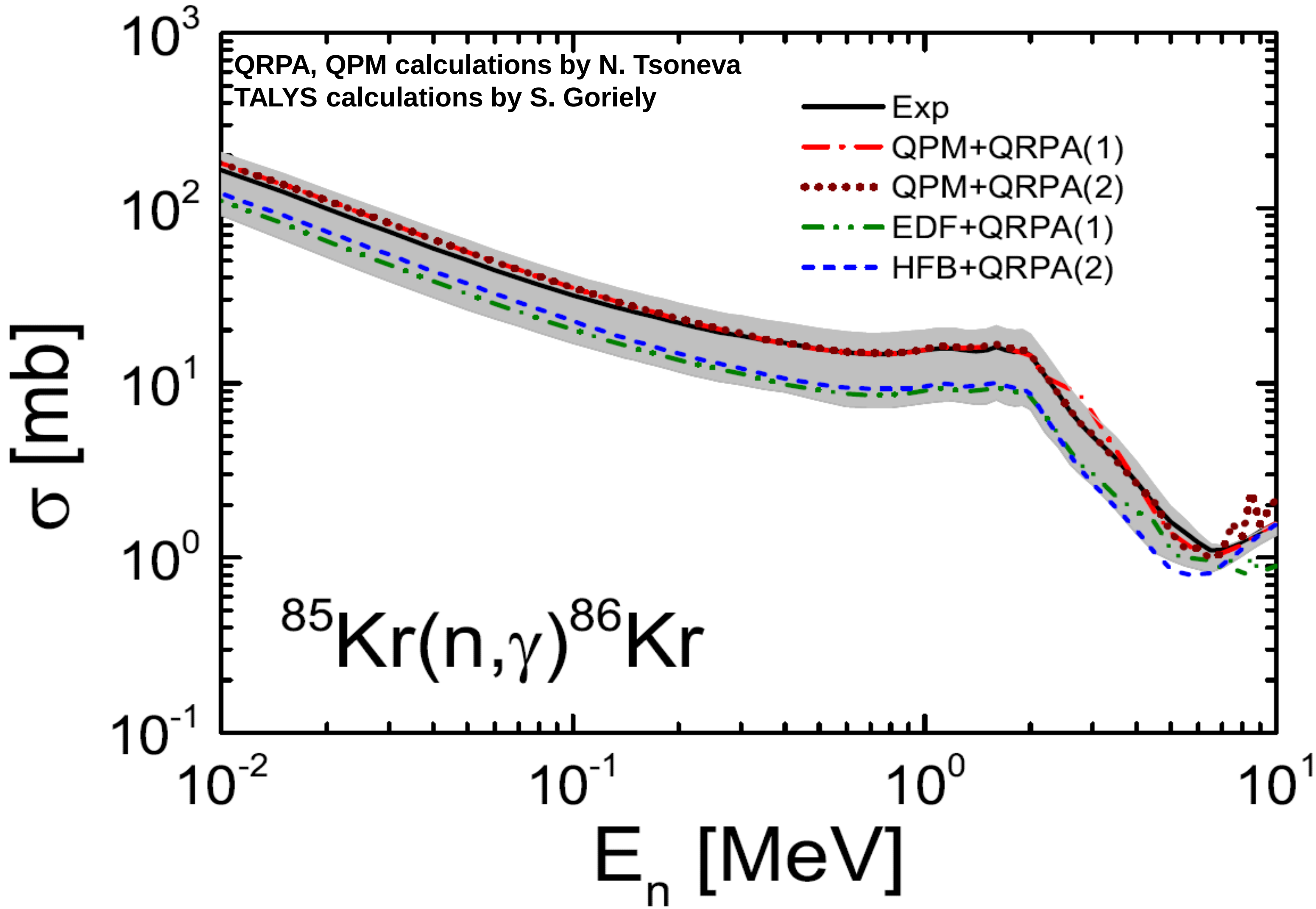
exp: R. Schwengner et al., First systematic photon-scattering experiments in N=50 nuclei: using bremsstrahlung produced with electron beams at the linear accelerator ELBE, Rossendorf and quasi-monoenergetic γ – rays at HIγS facility, Duke university.



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

R. Raut,…,N.Tsoneva et al., Phys. Rev. Lett. 111, 112501 (2013).

A way to investigate ^{85}Kr branching point and the s-process: ^{85}Kr (τ ~ 10.57 Y) ground state is a branching point and thus a bridge for the production of ^{86}Kr at low neutron densities.



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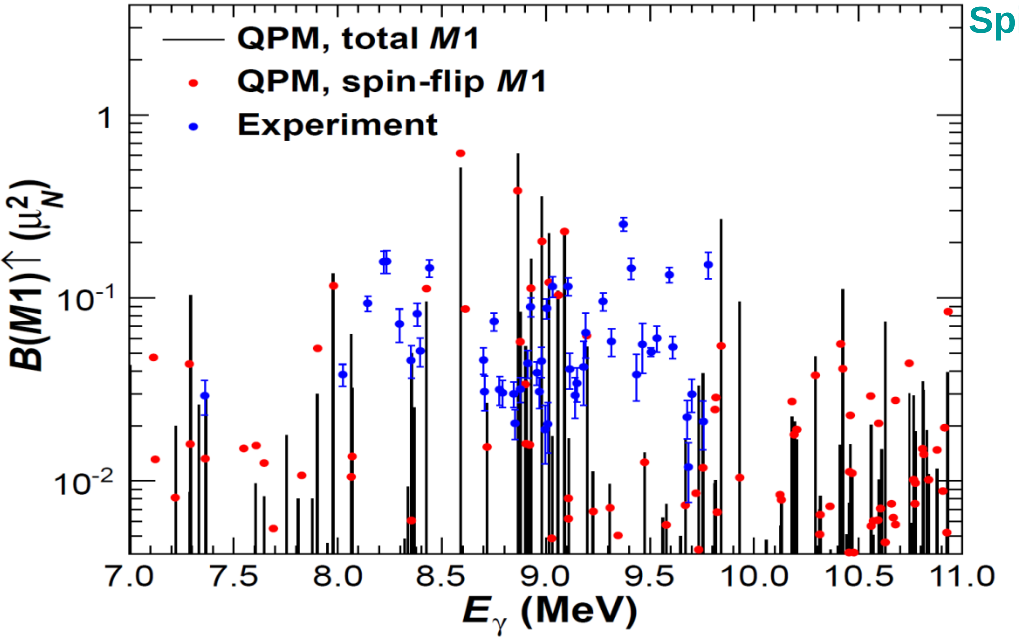
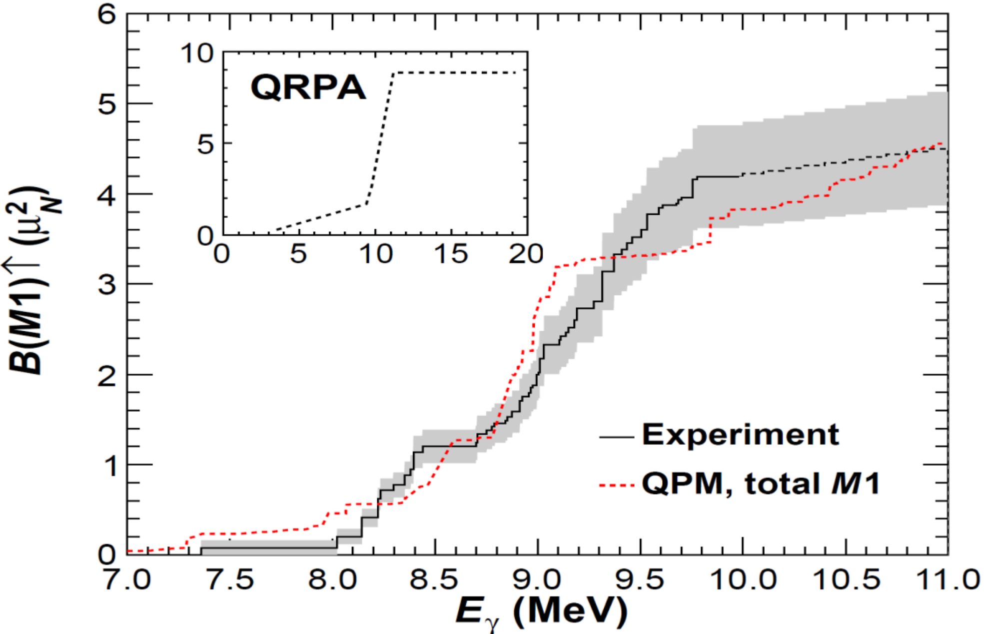
Fine Structure of the Giant M1 Resonance in ^{90}Zr

Precision data on M1 strength distributions are of fundamental importance





Spin and Parity Determination at HIγS, Duke University, USA

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.
- Prediction of M1 strength at and above the neutron threshold.

$\Sigma B(M1)_{Exp.}\uparrow = 4.5(6)\ \mu_N^2$ $\Sigma B(M1)_{QPM.}\uparrow = 4.6\ \mu_N^2$

$E^{c.m.}_{Exp.} = 9.0$ MeV $E^{c.m.}_{QPM} = 9.1$ MeV

Conclusions

- A theoretical method based on Density Functional Theory and Quasiparticle-Phonon Model is developed.

  Presently, this is the only existing method allowing for sufficiently large configuration space such that a unified description of low-energy single-particle, multiple-phonon states and the giant resonances is feasible.

- Different [illegible] presented:

Thank you !

- systematic [illegible] low energy dipole strengths reveal new mode of nuclear excitation - Pygmy Dipole Resonance as a unique mode of excitation correlated with the size of the neutron skin.

- theoretical prediction of a higher order multipole pygmy resonance – Pygmy Quadrupole Resonance.

- description of the fragmentation pattern of E1, E2 and M1 strengths

- nuclear structure input for astrophysics