5th Workshop on Nuclear Level Density and Gamma Strength

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Nuclear microscopic strength functions in astrophysical applications

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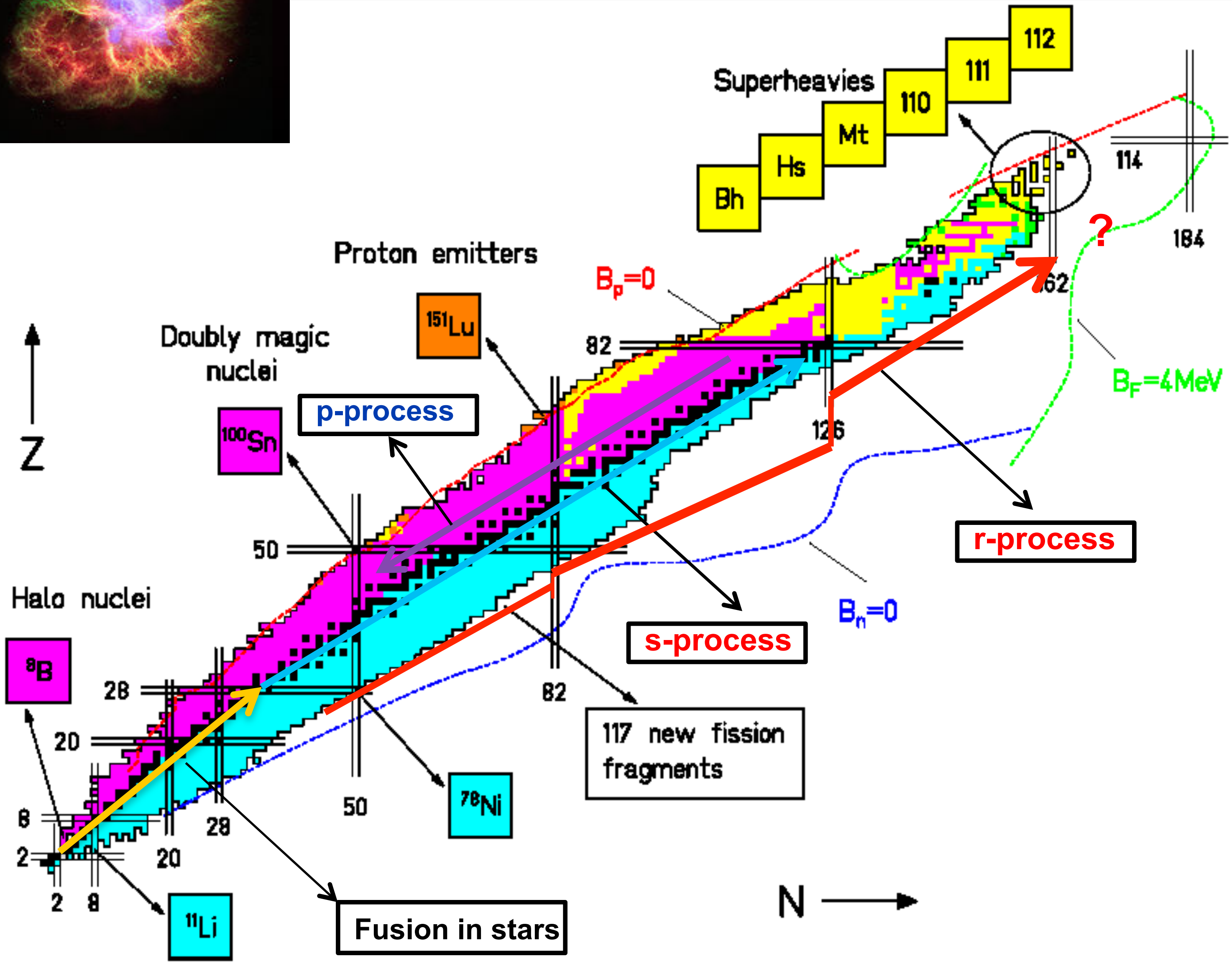
NUCLEOSYNTHESIS OF HEAVIER ELEMENTS

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

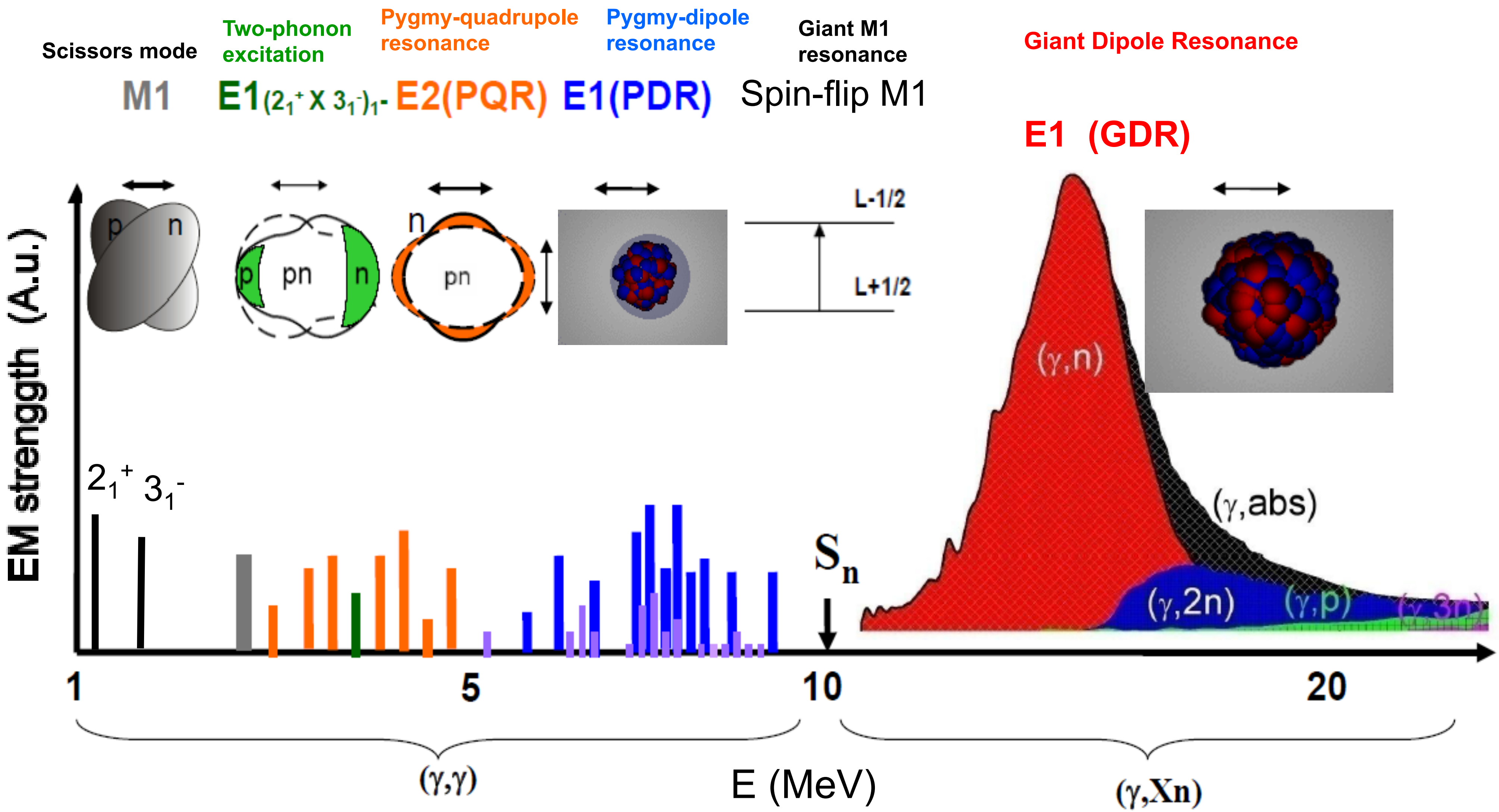
$\tau \sim 1 - 10$ years

r – process - rapid neutron captures

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

…other processes

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

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

$$H_{MF} = H_{sp} + H_{pair}$$

$$H_{res} = H_M^{ph} + H_{SM}^{ph} + H_M^{pp}$$

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

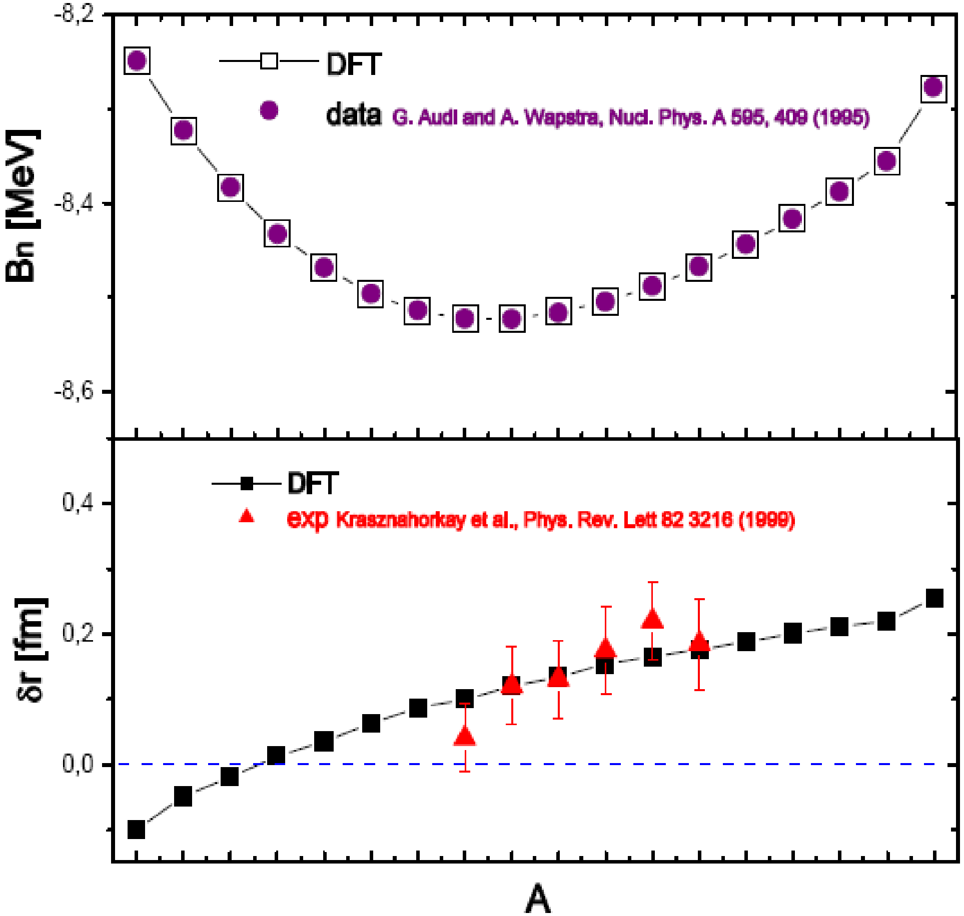
The total binding energy B(A) is expressed as an integral over an energy-density functional

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

effective potential

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

ρ_q, τ_q, k_q – number, kinetic and pairing density

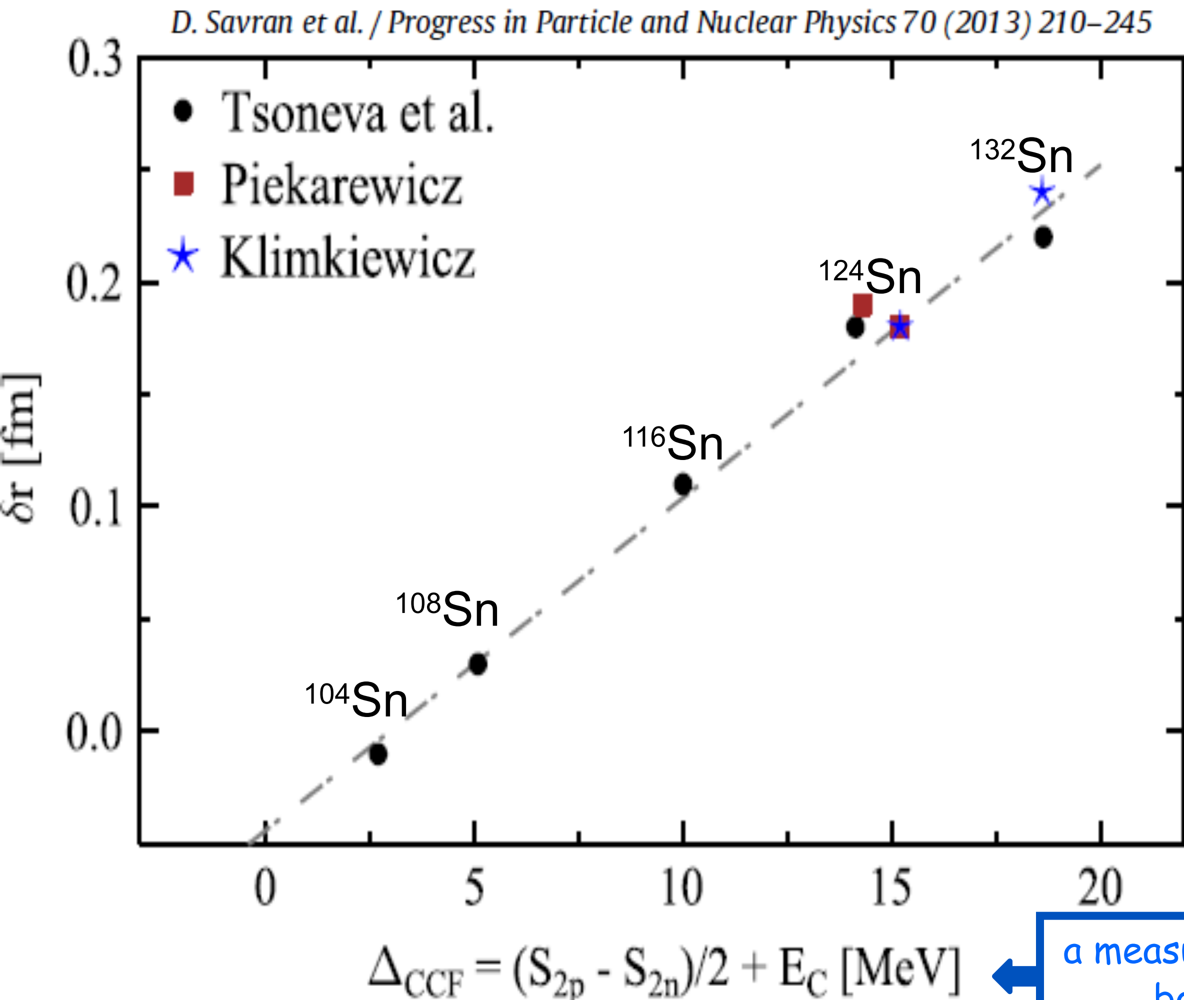


neutron skin thickness

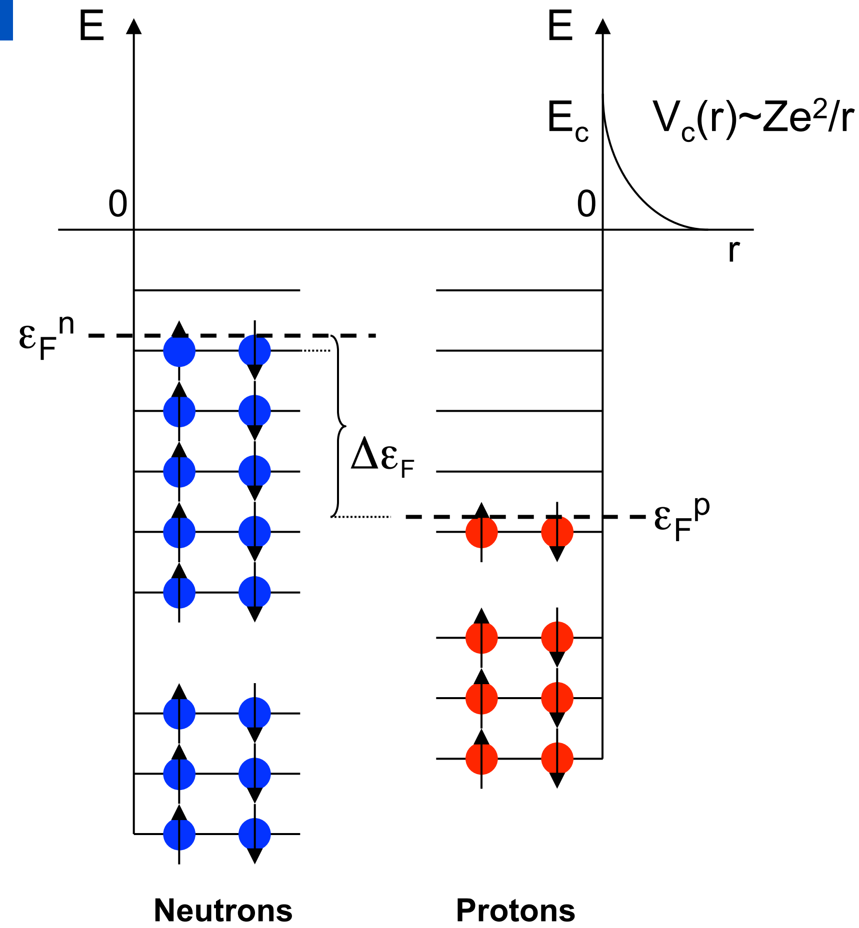
$$\delta r = \sqrt{<r^2>_n} - \sqrt{<r^2>_p}$$

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

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.



Even-Even Neutron-Rich Nucleus

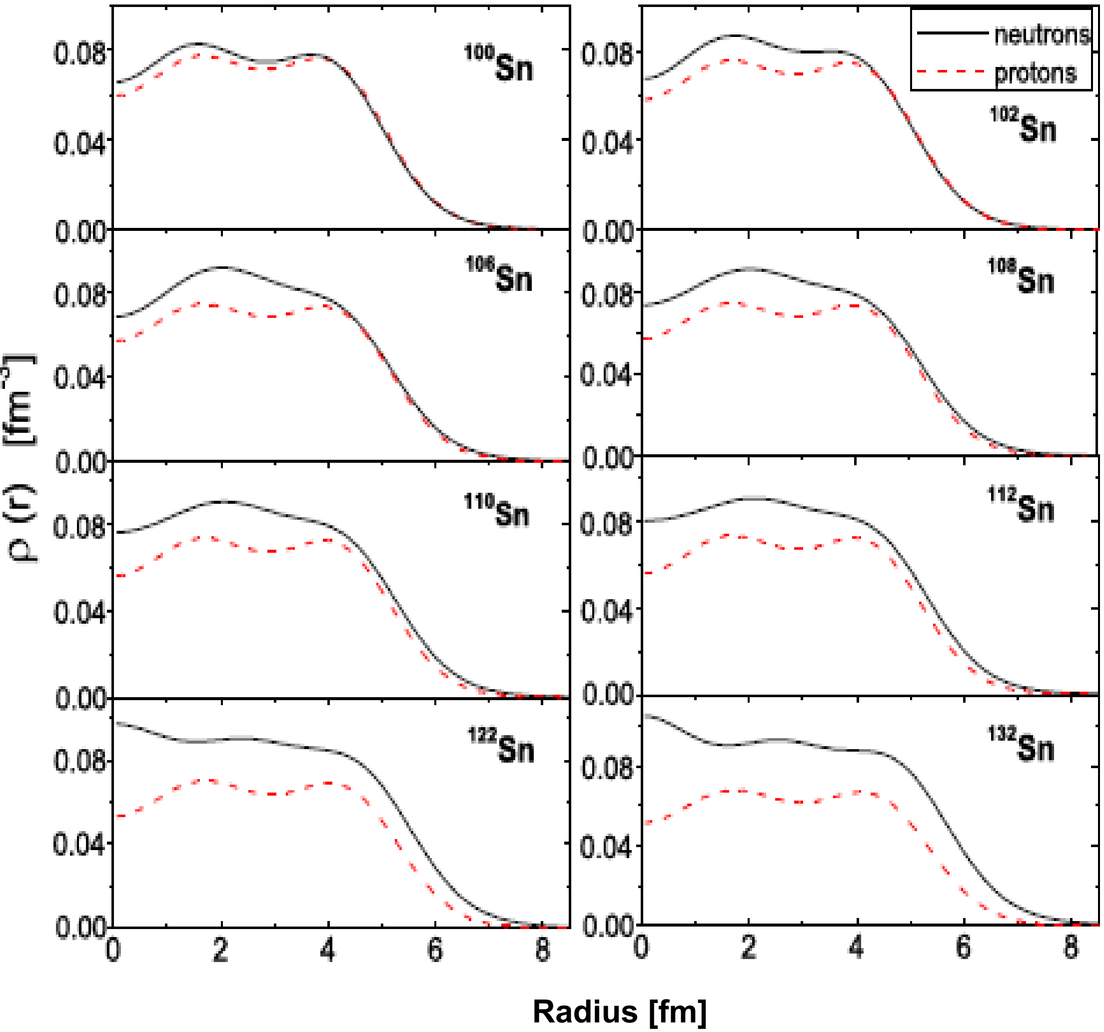


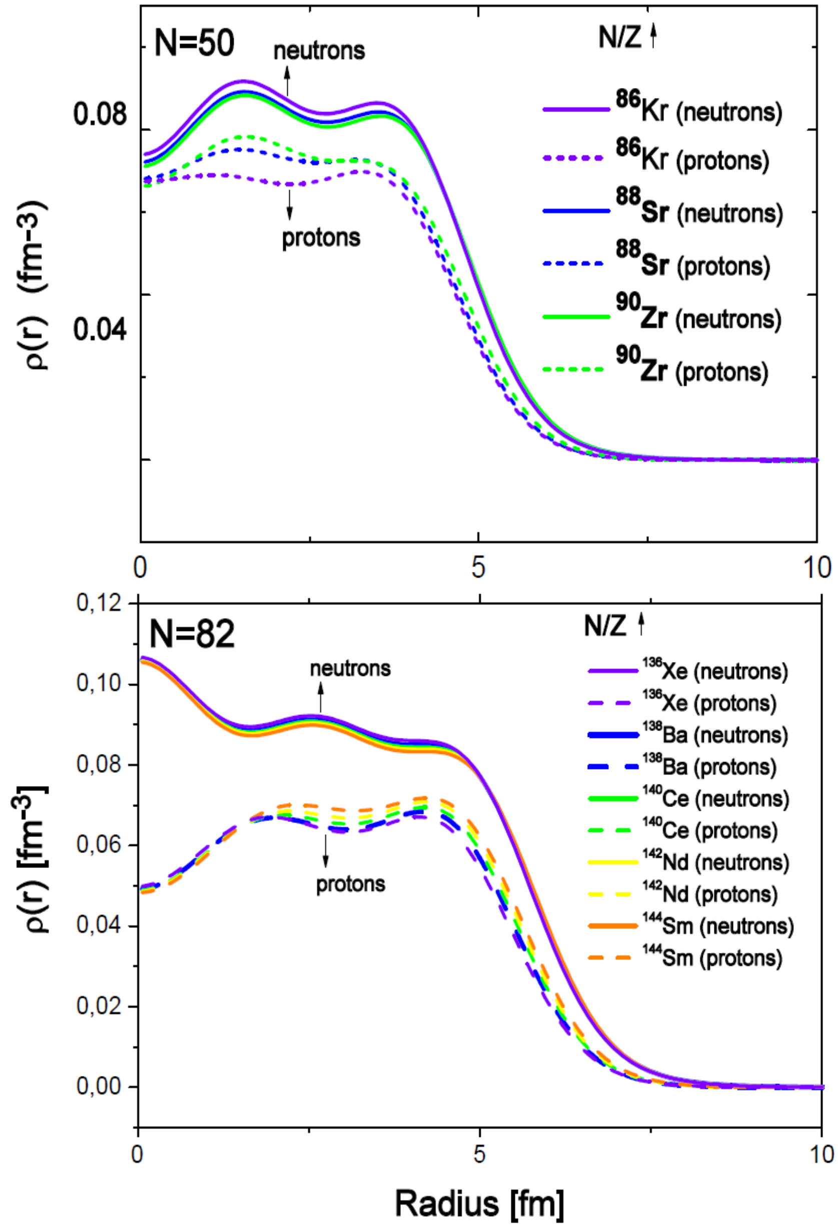
a measure of how loosely the neutrons are bound compared to the protons.

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)

Calculations of Ground State Densities in Z=50, N=50,82 Nuclei

$$\rho_q(r) = \frac{1}{4\pi r^2} \sum_{\alpha_q} v_{\alpha_q}^2 (2j_{\alpha_q} + 1) R_{\alpha_q}^2(r)$$





N. Tsoneva, H. Lenske, Phys. Rev. C 77 (2008) 024321
R. Schwengner et al., Phys. Rev. C 78 (2008) 064314

THEORY OF NUCLEAR EXCITATIONS

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

The QPM basis is built of phonons:

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

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

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

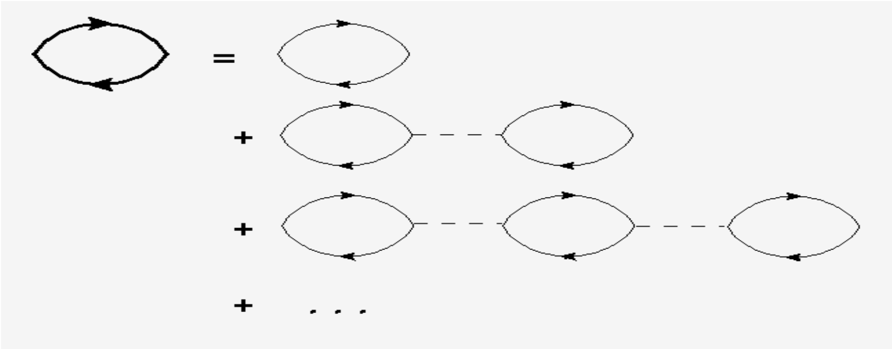
i — **labels the number of the QRPA state**

The phonons are not 'pure' bosons: Pauli principle

$$\left[Q_{\lambda\mu i}, Q^{+}_{\lambda'\mu' i'}\right] = \delta_{\lambda\lambda'}\delta_{\mu\mu'}\delta_{ii'} + \text{ fermionic corrections } \sim \alpha^{+}_{j_1 m_1}\alpha_{j_2 m_2}$$

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

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

one-phonon part

two-phonon part

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

three-phonon part

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

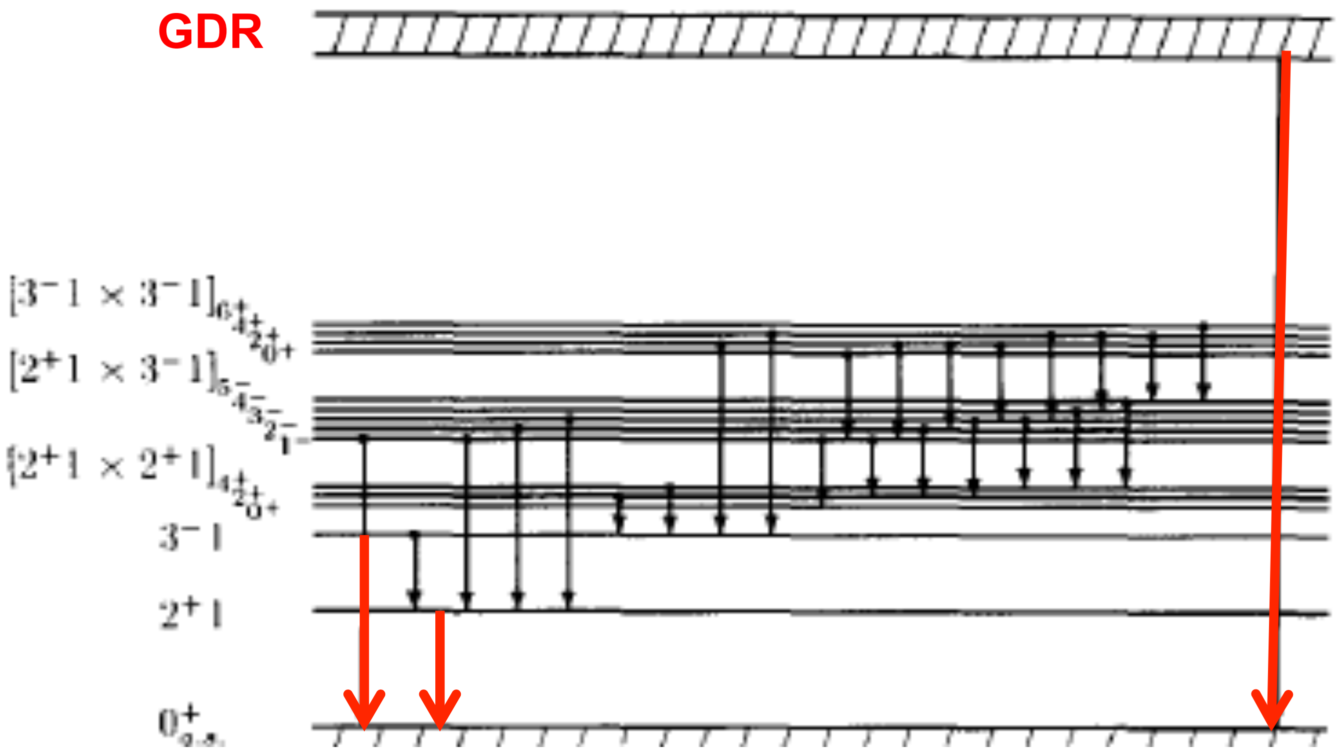
NUCLEAR SPECTROSCOPY

$$\mathbf{M}(E\lambda) = \left\langle \Psi_f \left\| T(E\lambda) \right\| \Psi_i \right\rangle$$

$$T(E\lambda) = T^{Ph}(E\lambda) + T^{QPh}(E\lambda)$$

QRPA $\sim Q^{+}_{\lambda\mu}$ **QPM** $\sim \alpha^{+}_{jm}\alpha_{j'm'}$

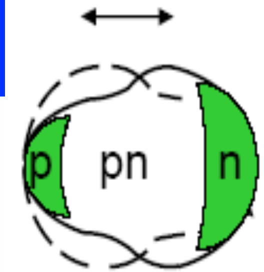
$B(E\lambda,\ J_i^{\pi_i} \longrightarrow J_f^{\pi_f}) \sim \left| M(E\lambda) \right|^2$ reduced electric transition probability



V. Ponomarev, Ch.Stoyanov, N. Tsoneva, M. Grinberg, Nucl. Phys. A 635 (1998) 470

N.Tsoneva, OSLO15

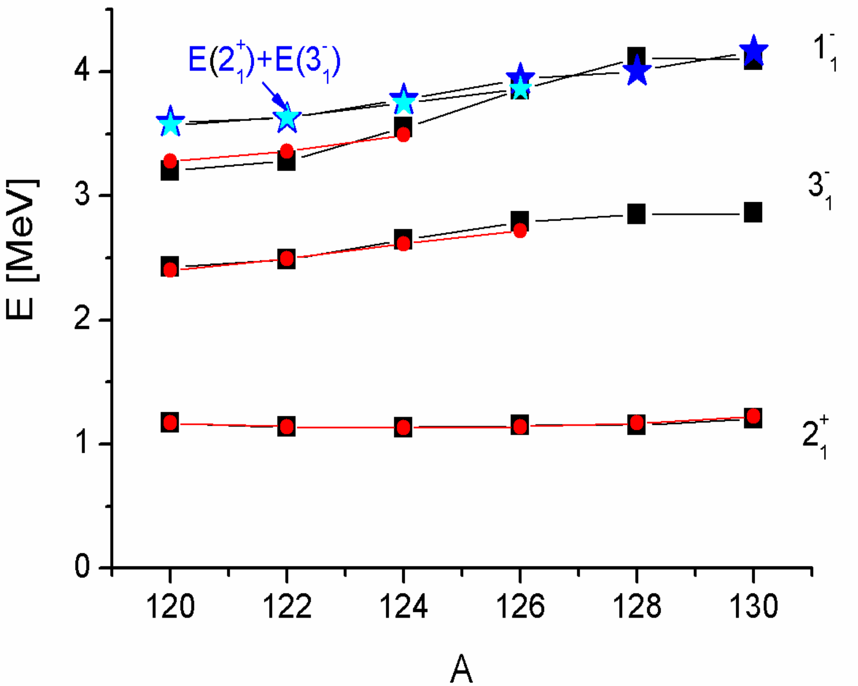
TWO-PHONON 1^- STATES



U. Kneissl, N. Pietralla, and A. Zilges, J. Phys. G: Nucl.Part.Phys. **32,** R217 (2006)

N. Tsoneva, H. Lenske, Ch. Stoyanov, Phys. Lett. B 586 (2004) 213

stable and unstable Sn nuclei



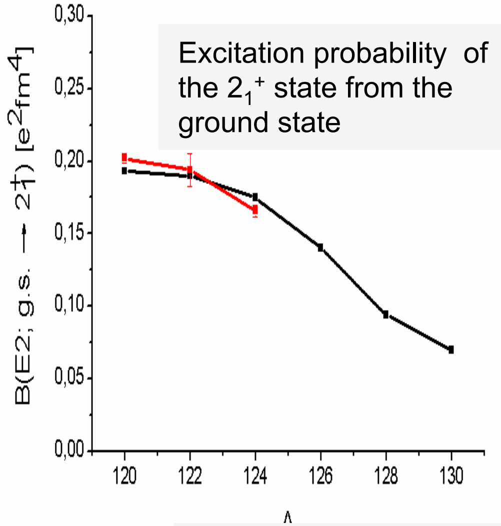
— ■ — energy of the 1^-_1, 2^+_1 and 3^-_1 states from QPM;

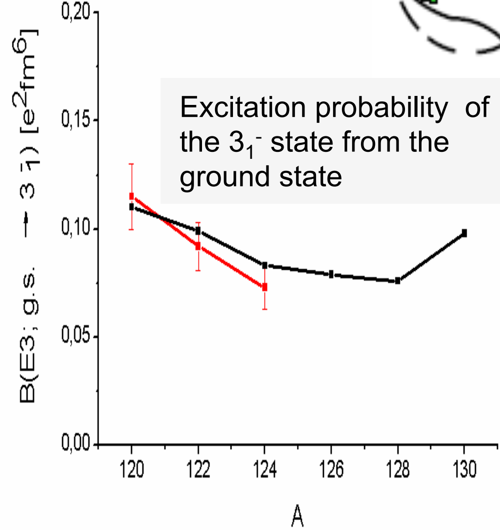
— ★ — unperturbated energy $E(2^+_1) + E(3^-_1)$ from QPM;

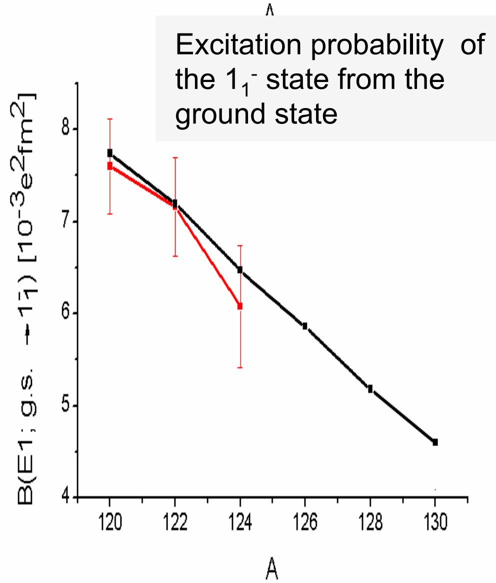
— ● — experimental energy of the 1^-_1, 2^+_1 and 3^-_1 states;

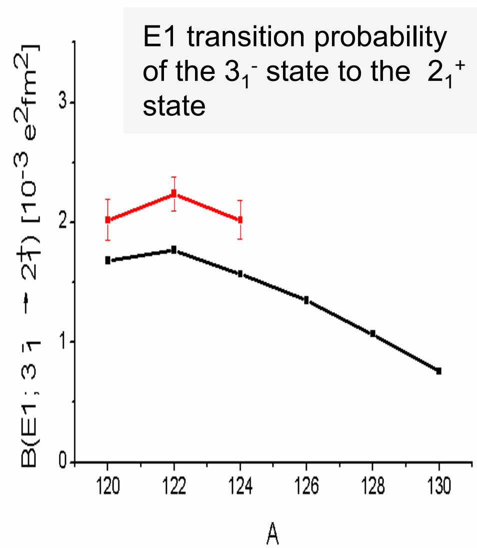
— ★ — unperturbated $E(2^+_1) + E(3^-_1)$ energy from the data

The data are taken from J. Bryssinck et al., Phys. Rev. C59(1999)1930

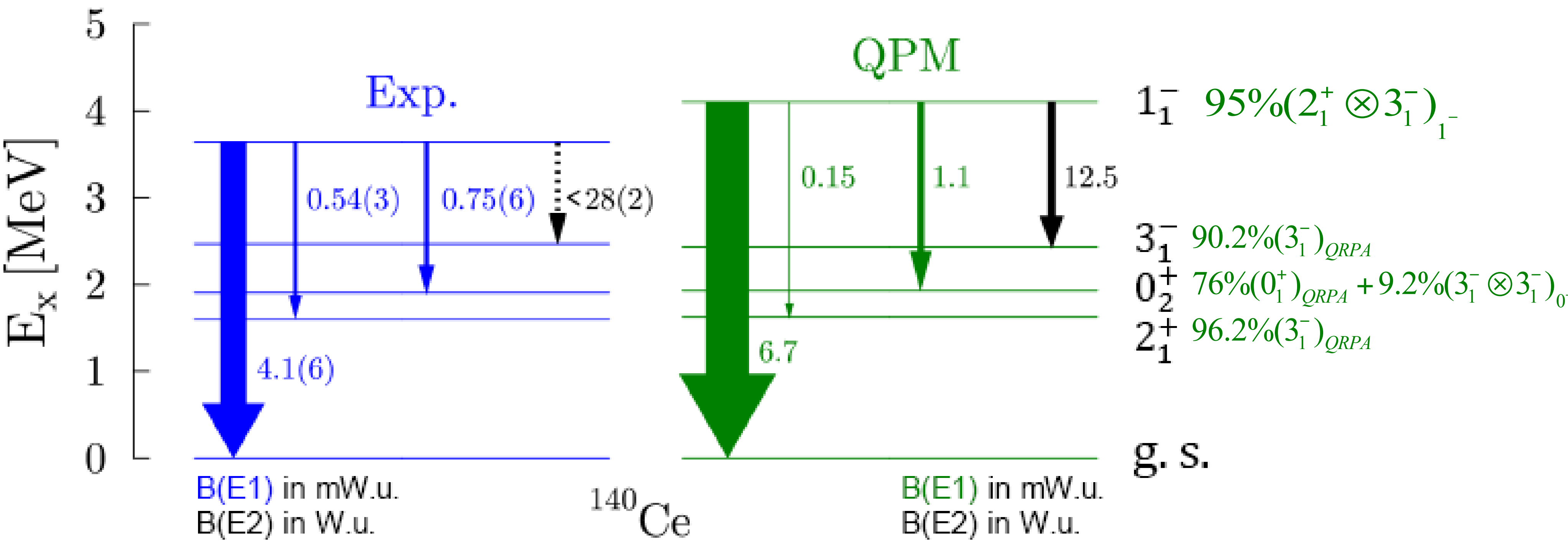








Systematic studies of two-phonon states in N=82 isotones

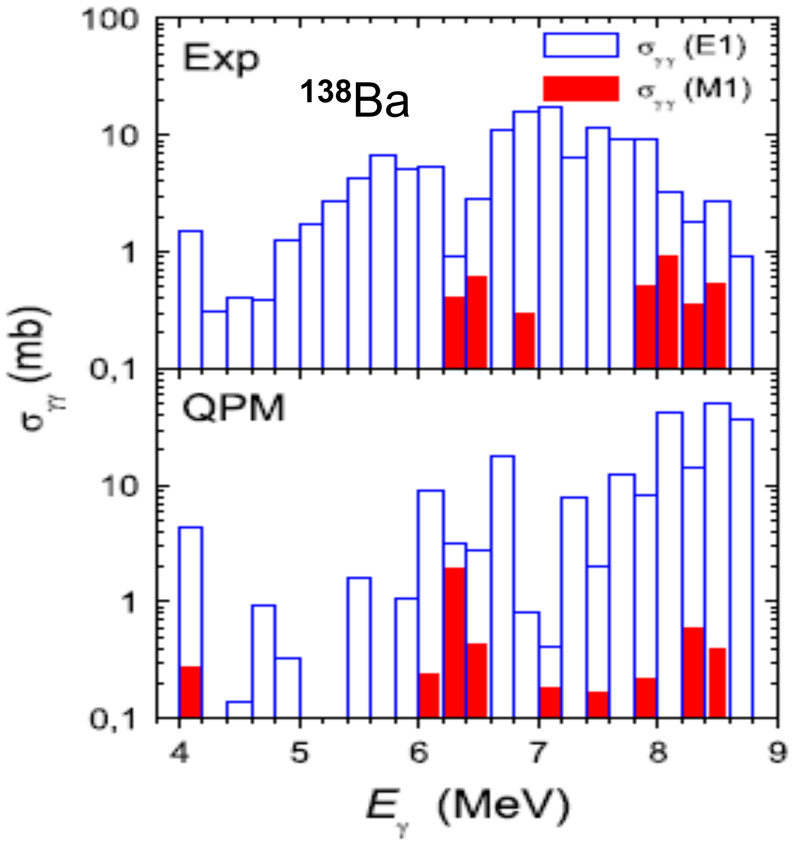


V. Derya, private communications

Parity Measurements with Polarized Photon Beams of Low-energy Dipole Excitations at HIγS, Duke University

A. Tonchev et al., Phys. Rev. Lett. 104, 072501 (2010)

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



First systematic spin and parity measurements in comparison with QPM calculations:

- [138]Ba verified for the first time that the pygmy dipole resonance is predominantly electric dipole in nature.
- The fine structure of the M1 spin-flip mode is explained.
- Separation of the PDR to isoscalar and isovector. Interplay between the GDR and the PDR at higher energies.

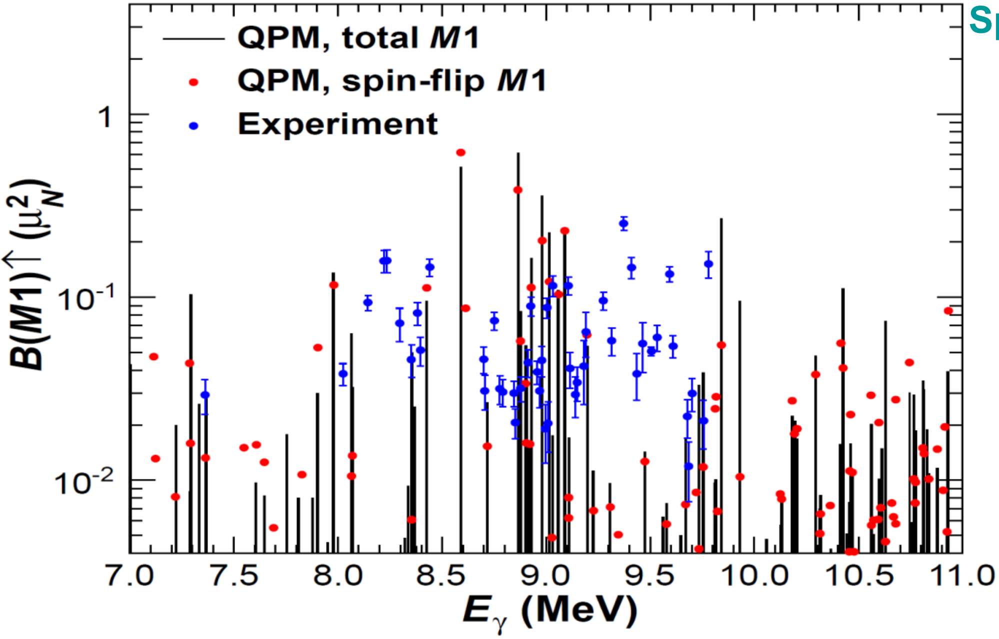
TABLE I. $E1$ and $M1$ parameters deduced in ^{138}Ba below the neutron-separation energy in comparison with the QPM calculations.

	$\langle E_{E1}\rangle$ [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 of the Giant M1 Resonance in ^{90}Zr

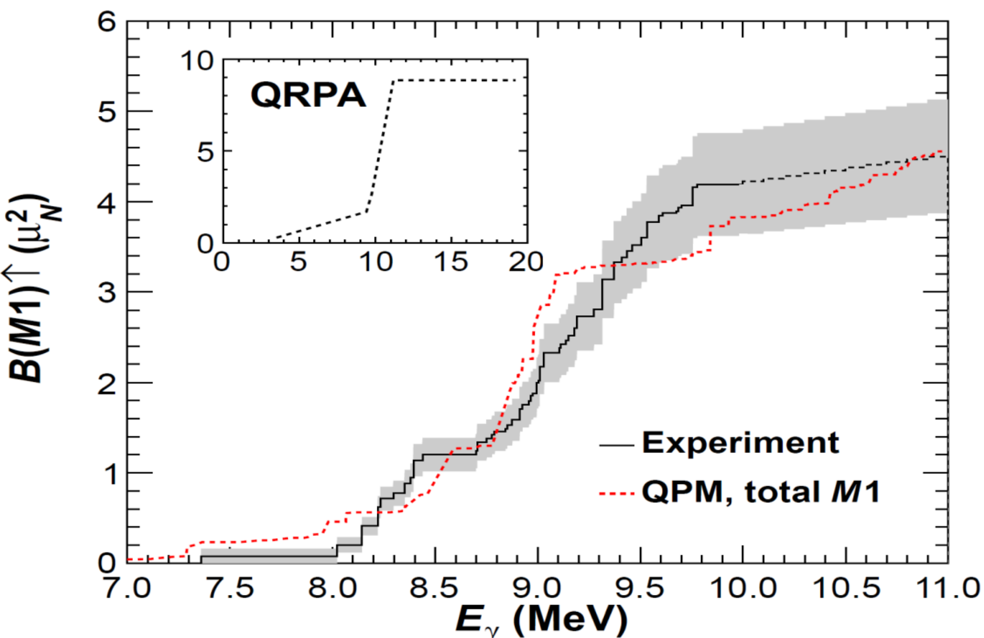
Precision data on M1 strength distributions are of fundamental importance



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.



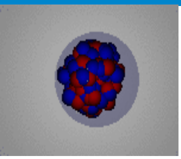
$\Sigma B(M1)_{Exp.}^{\uparrow} = 4.5\,(6)\ \mu_N^2$ $\Sigma B(M1)_{QPM.}^{\uparrow} = 4.6\ \mu_N^2$

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

Polarized photon scattering off ^{52}Cr:

Determining the parity of J=1 states.

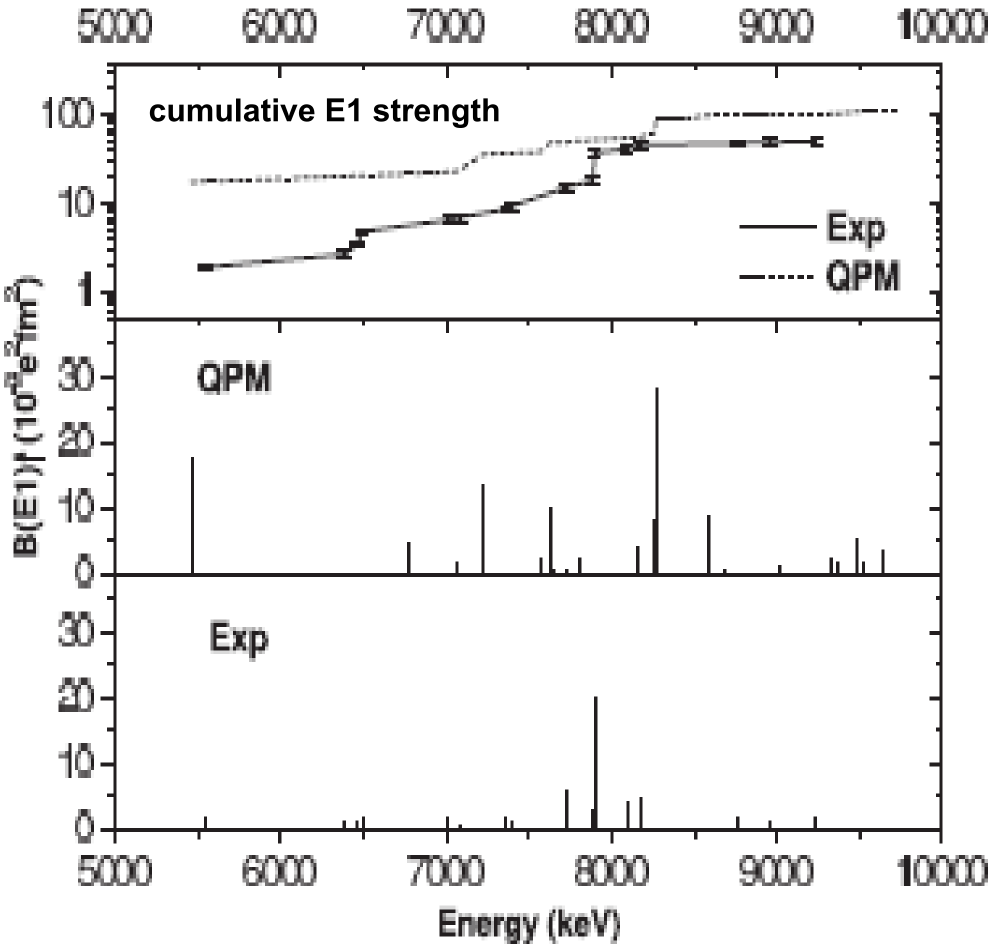
Krishichayan et al., PRC 91, 044328 (2015)

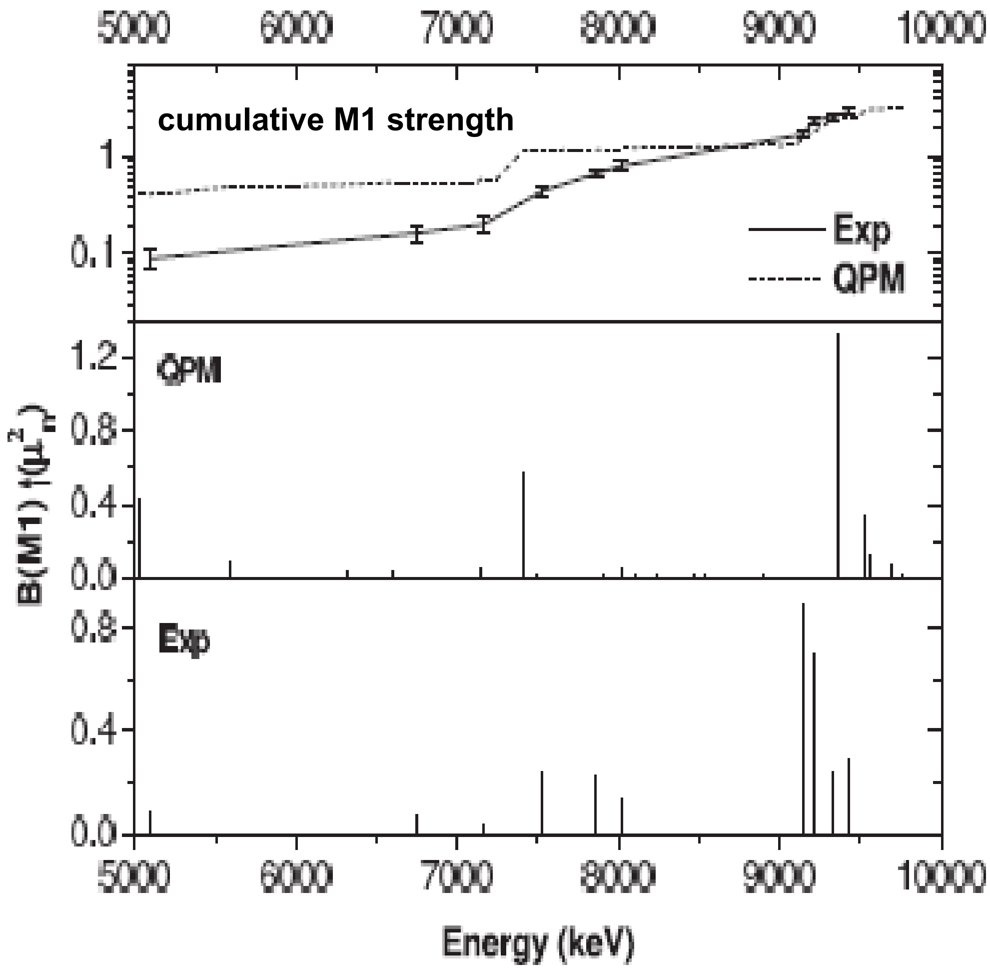


$$\Sigma_{0\,\mathrm{MeV}}^{9.5\,\mathrm{MeV}} B(E1; \mathrm{g.s.} \rightarrow 1^-_{\mathrm{PDR}})_{\mathrm{QRPA}} \uparrow = 13 \times 10^{-3}\, e^2\, \mathrm{fm}^2$$

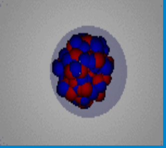
$$\delta r = \sqrt{< r^2 >_n} - \sqrt{< r^2 >_p} = 0.056 \text{ fm}$$

PDR: TRK sum rule ~ 0.1%





N.Tsoneva, OSLO15



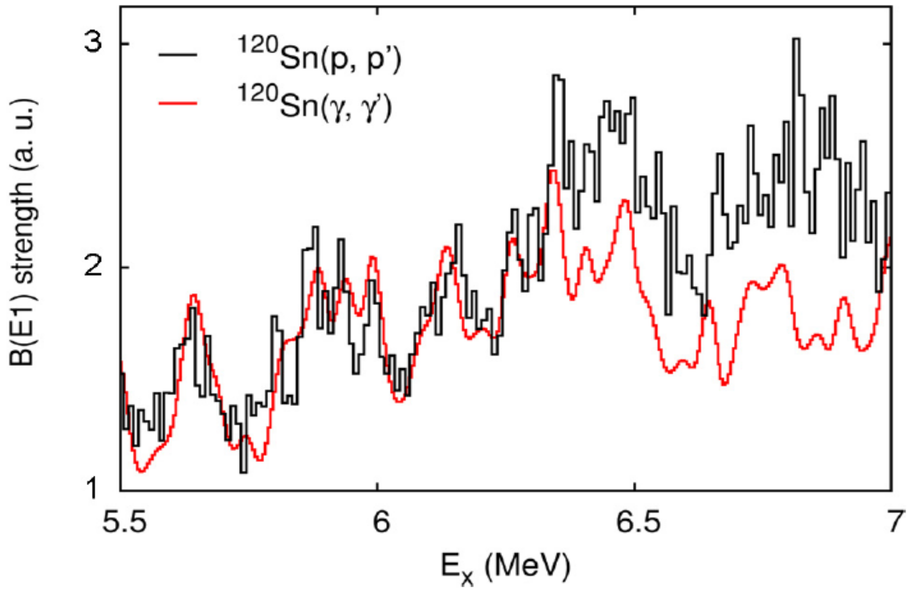
LOW-ENERGY ELECTRIC DIPOLE RESPONSE IN ^{120}Sn

extracted from proton inelastic scattering experiments

^{120}Sn(p,p'): A.M.Krumbholz, P.von Neumann-Cosel, T.Hashimoto, *et al.*,PLB 744, 7 **(2015).**

^{120}Sn(γ,γ'): B. Özel-Tashenov, et al., PRC 90, 024304 **(2014).**

TECHNISCHE UNIVERSITÄT DARMSTADT



Exp.&Theoretical predictions	Ref.		$\Sigma B(E1)$ (e^2 fm^2)
(p, p′)	present		1.169(12)
(γ,γ')	[39]		0.164(31)
$(\gamma,\gamma')_{corr}$	[39]	(2014)	0.228(43)
$(\gamma,\gamma')_{corr}$ + unresolved	[39]		0.348(76)
QPM Darmstadt	[41]	(2014)	0.553
QPM Giessen	[7]	(2008)	1.364
2 phonon RQTBA	[62]	(2013)	2.344
2q + phonon RQTBA	[61]	(2007)	9.494

A.M. Krumbholz et al. / Physics Letters B 744 (2015) 7–12

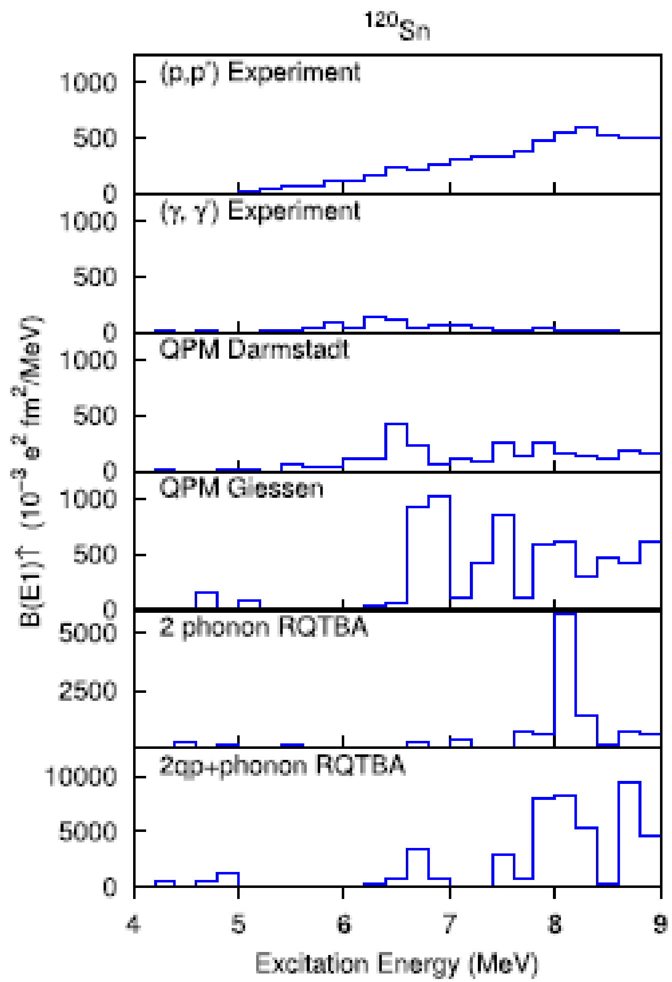
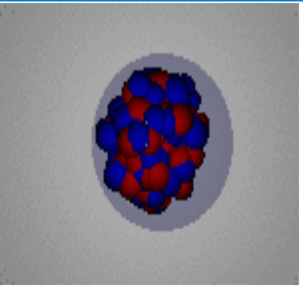


Fig. 6. B(E1) strength distribution for the (p, p′) and (γ, γ′) data and microscopic models in the energy range E_x = 4–9 MeV in 200 keV bins.

FIRST SYSTEMATIC STUDIES OF THE PDR IN N=50 ISOTONES



Proton number increasing, neutron skin decreasing

S. Volz et al., Nucl. Phys. A, 779 (2006) 1-20;
D. Savran et al.,PRL 100, (2008) 232501;
R. Schwengner et al, Phys. Rev. C 78 (2008) 064314;
R. Schwengner et al, Phys. Rev. C 87, 024306 (2013) .

N=50,82 isotones

Neutron number increasing, neutron skin increasing

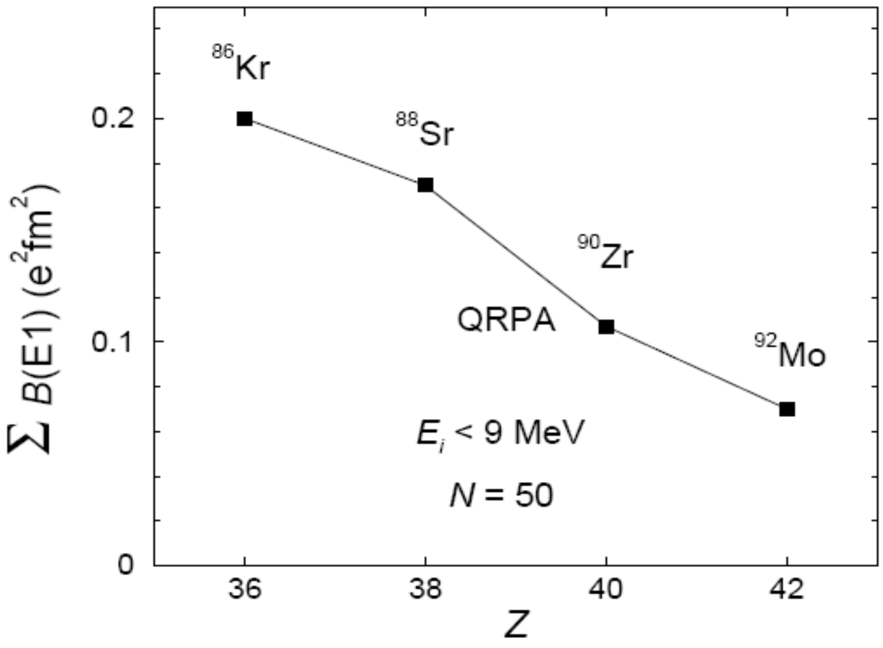
N. Tsoneva, H. Lenske, Ch. Stoyanov, Phys. Lett. B 586 (2004) 213
N. Tsoneva, H. Lenske, Phys. Rev. C 77 (2008) 024321;
A. Tonchev et al.. to be submitted.

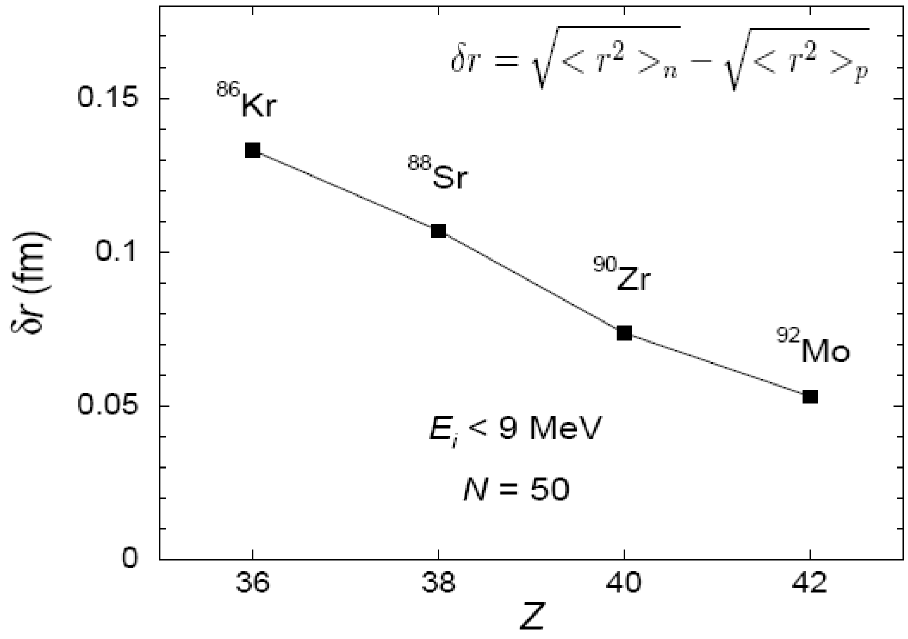
Z=50,82 chains

Theoretical prediction of Pygmy Quadrupole Resonance

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

Z=50 isotopes



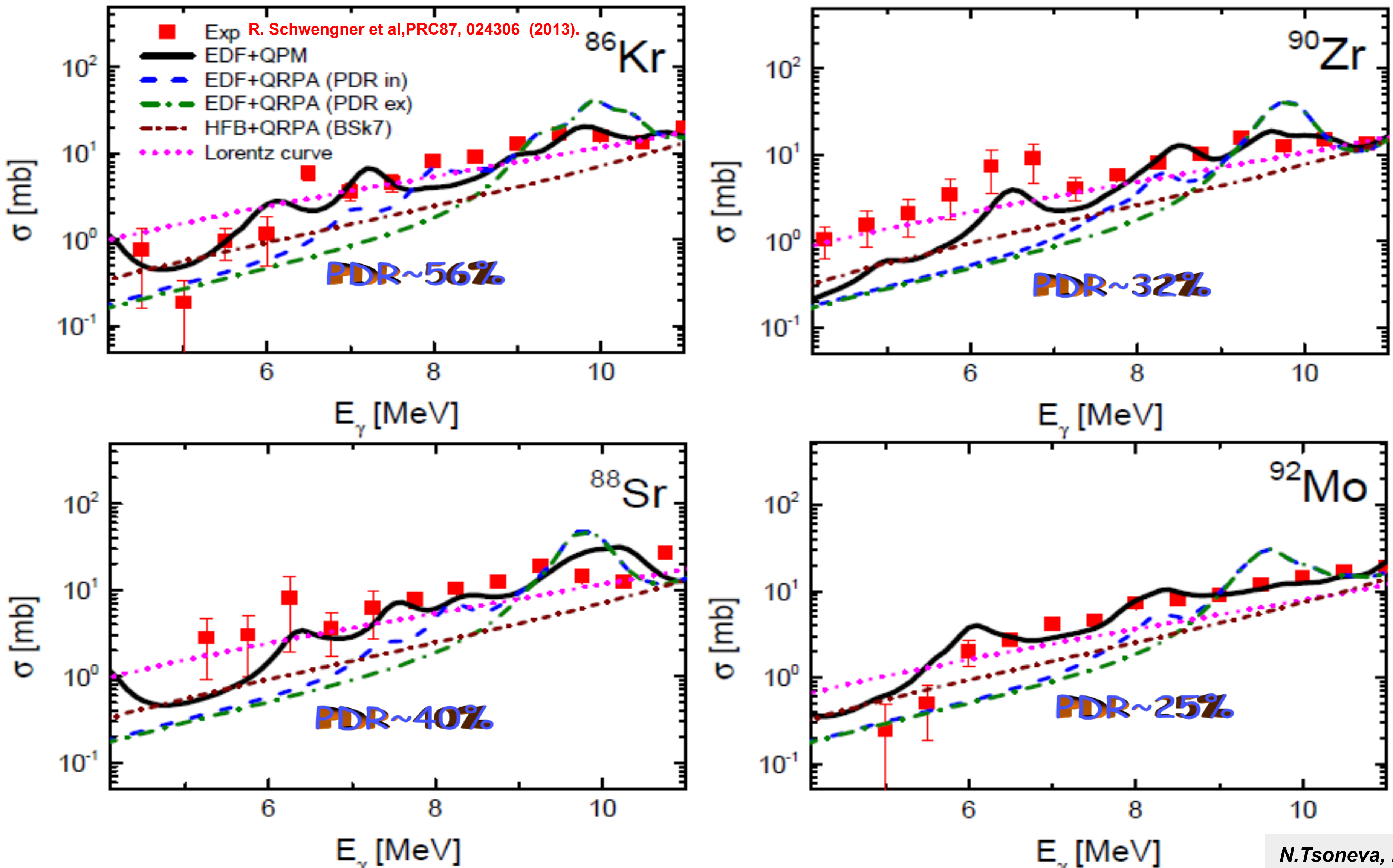


R. Schwengner et al., Phys. Rev. C 87, 024306 (2013)

DYNAMICS OF 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, PRC 91, 044318 (2015).

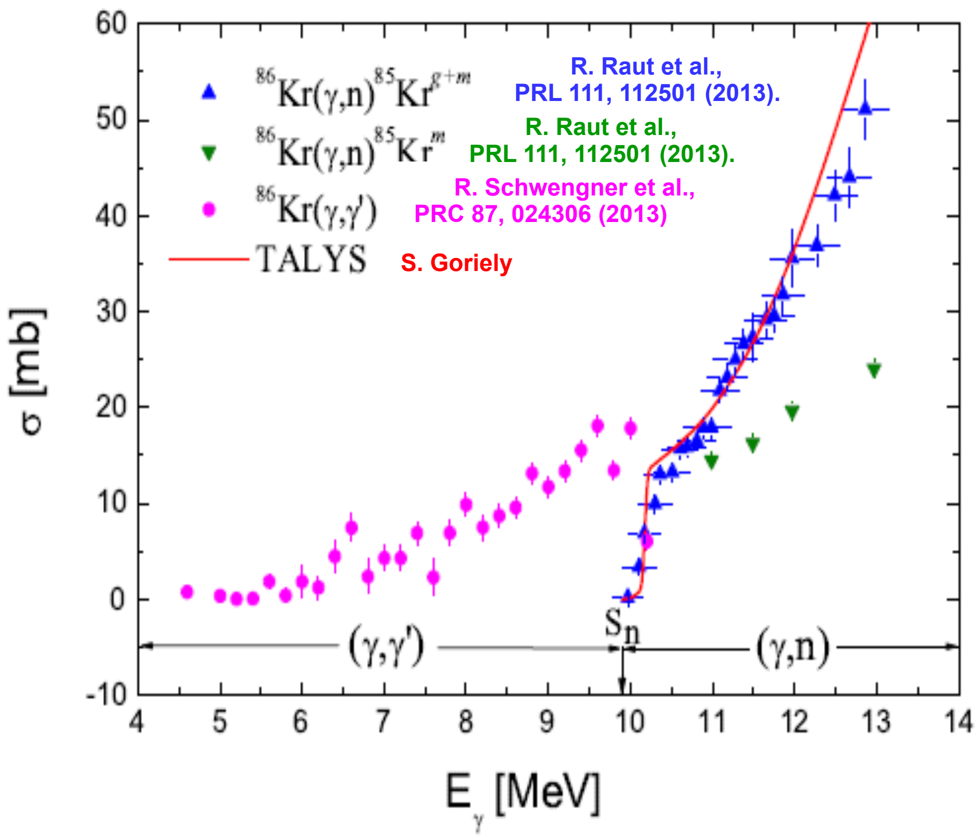


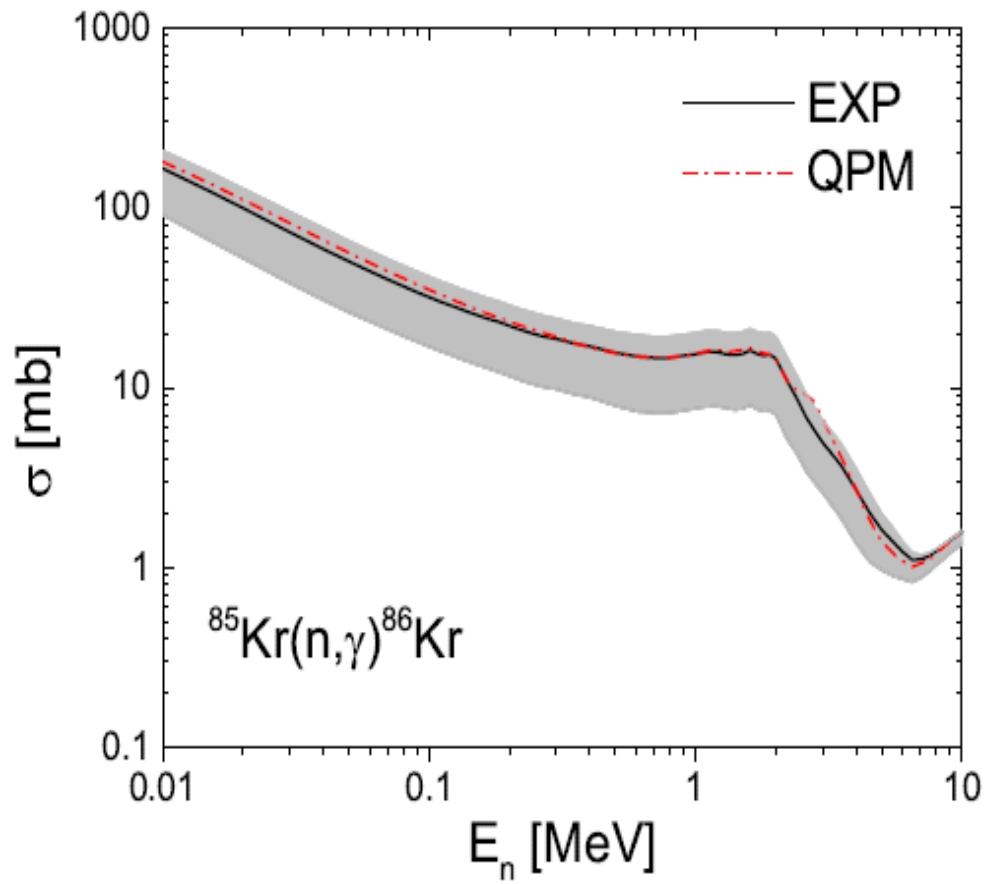
N.Tsoneva, DPG15

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

R. Raut 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.

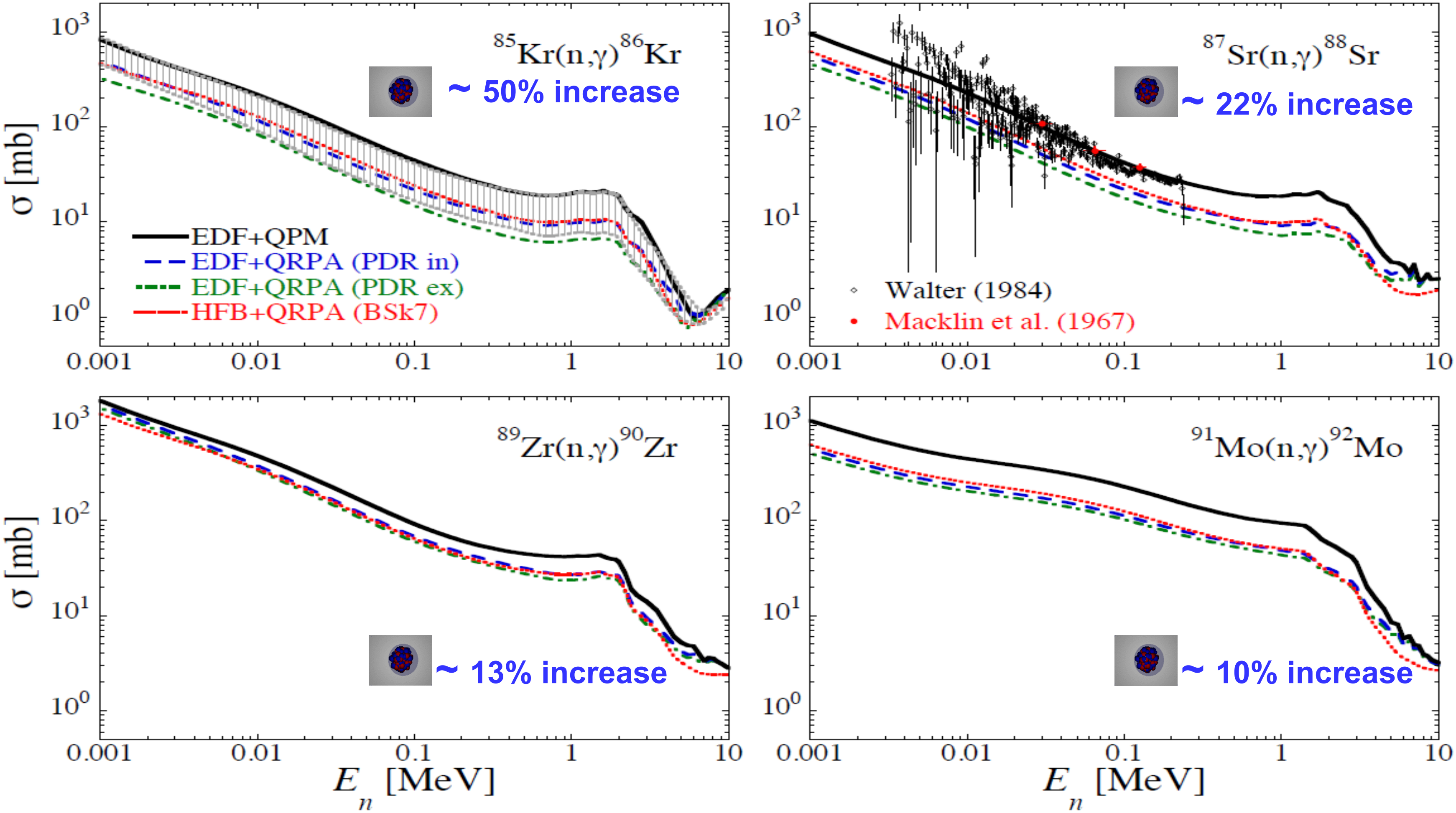




NEUTRON CAPTURE CROSS SECTIONS

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 three-phonon QPM strength functions.

N. Tsoneva, S. Goriely, H. Lenske, R.Schwengner, PRC 91, 044318 (2015).

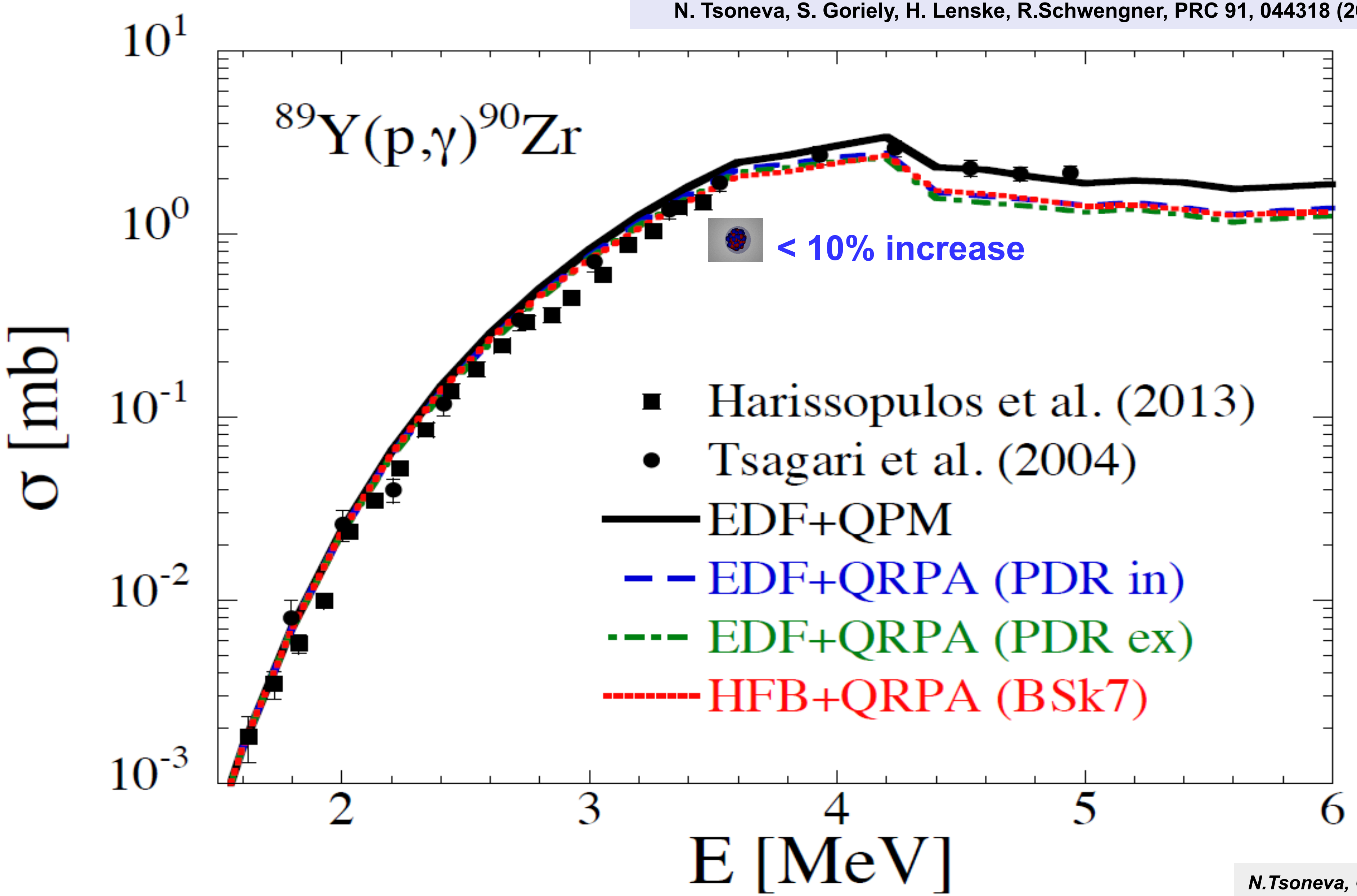


For ^{85}Kr(n,γ)^{86}Kr cross sections, the hashed area corresponds to the cross section determined with the experimental strength as derived in R. Raut et al., Phys. Rev. Lett. 111, 112501 (2013).

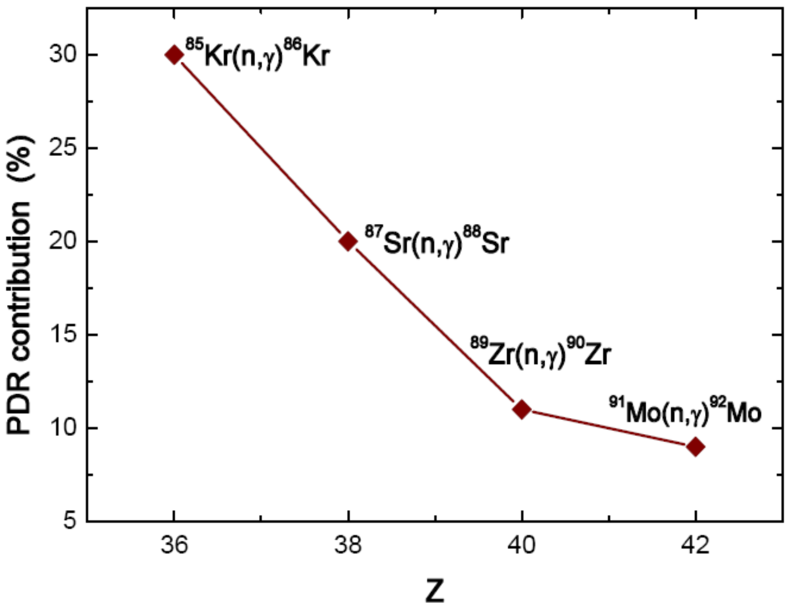
For ^{87}Sr(n,γ)^{88}Sr, TALYS cross sections are compared with experimental data G. Walter, Kernforschungszentrum Karlsruhe Reports No.3706 (1984); R.L. Macklin and J.H. Gibbons, Phys. Rev. 159, 1007 (1967).

Proton capture cross section of the $^{89}Y(p,\gamma)^{90}Zr$ calculated with TALYS using EDF +QRPA, HFB+QRPA and three-phonon QPM strength functions.

N. Tsoneva, S. Goriely, H. Lenske, R.Schwengner, PRC 91, 044318 (2015).



Maxwellian-averaged cross sections (in mb) at thermal energy of kT=30 KeV.

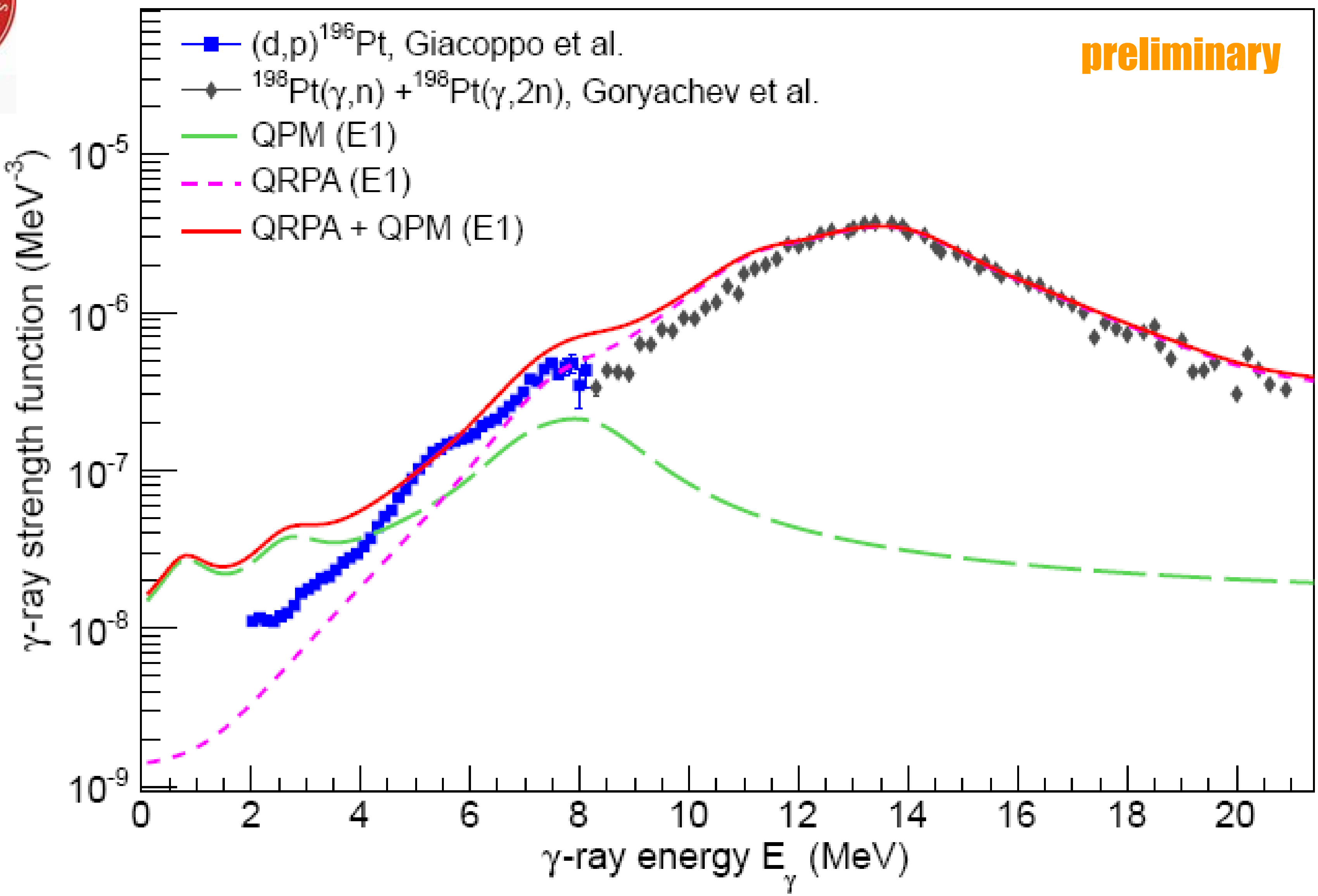


N. Tsoneva, S. Goriely, H. Lenske, R.Schwengner, PRC 91, 044318 (2015).

	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 *et al.*, PRL 111, 112501 (2013).**
[7] Z. Y. Bao *et al*., At. Data Nucl. Data Tables 76, 70 (2000).

OBSERVATION OF DOUBLE PYGMY RESONANCES IN ^{196}Pt



Conclusions

- **A new 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-e[illegible]gy single-particle, multiple-phonon states and the giant resonance[illegible] is [illegible]ble.

- **Different a[illegible]**

Thank you !

- systematic s[illegible]pole strengths reveal new mode of nuclear excitation - Py[illegible] 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.

- studies of low-energy 0^+ and multi-phonon states.

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

- nuclear structure input for astrophysics