3 Workshop on Level Density and Gamma Strength

Low-energy Excitations and Giant Resonances in Skin Nuclei

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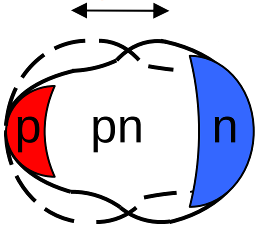
in a collaboration with H. Lenske

DIPOLE (ΔL=1) RESPONSE IN SKIN NUCLEI

ELECTRIC

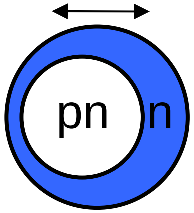
ISQODS



ΔT=0; ΔS=0

E*= 3-4 MeV
B(E1)=0.01 W.u.

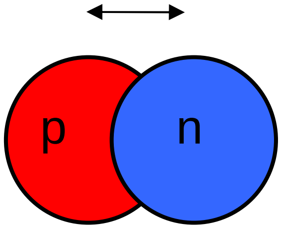
PDR



ΔT=0,1; Δ S=0

E*= 6-8 MeV
B(E1)= 0.2 W.u.

IVGDR



ΔT=1; Δ S=0

E*=16 MeV
B(E1)=10 W.u.

Exp. PDR

Stable nuclei: A. Zilges et al., PLB 542 (2002) 43.
Govaert et al., PRC 57 (1998) 2229.
N. Ryezayeva et al., PRL 89 (2002) 272502.

- **Mostly of electric character**

A. Tonchev et al., PRL 104, 072501 (2010);

- **Located below the particle emission threshold ;**
- **Up to 1% of EWSR**

Unstable nuclei:

A. Leistenschneider et al., PRL 86, (2001) 5442.
E. Tryggestad et al., PLB 541 (2002) 52.
P. Adrich et al., PRL 95 (2005) 132501.
O. Wieland et al., PRL 102, 092502 (2009)

- **Located closely above the particle emission threshold ;**
- **About 5-7% of EWSR**

The Quasiparticle-Phonon Model

V. G. Soloviev: *Theory of Complex Nuclei* **(Pergamon Press, Oxford,1976)**

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

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

Nuclear Ground State

Single-Particle States

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

Pairing and Quasiparticle States

BCS gap equation, solved separately for protons and neutrons

Residual Interaction

Separable Forces

$$V(r, r') = -\kappa_\lambda \upsilon_\lambda(r) \upsilon_\lambda(r')$$

$$V = -\frac{1}{2} \sum_{lm} \kappa_\lambda M^+_{\lambda\mu}(r) M_{\lambda\mu}$$

$$M_{\lambda\mu} = \sum_{j_1 j_2} \langle j_1 | \upsilon_\lambda Y_{lm}(\theta, \varphi) | j_2 \rangle a^+_{j_1} a_{j_2}$$

$$\kappa_\lambda = (\kappa^0_\lambda, \kappa^1_\lambda)$$

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

Phenomenological Density Functional Approach for Nuclear Ground States

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

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

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

$$\rho_q = \sum_k v_{kq}^2 \left|\varphi_{kq}(\vec{r})\right|^2 \qquad \text{number density}$$

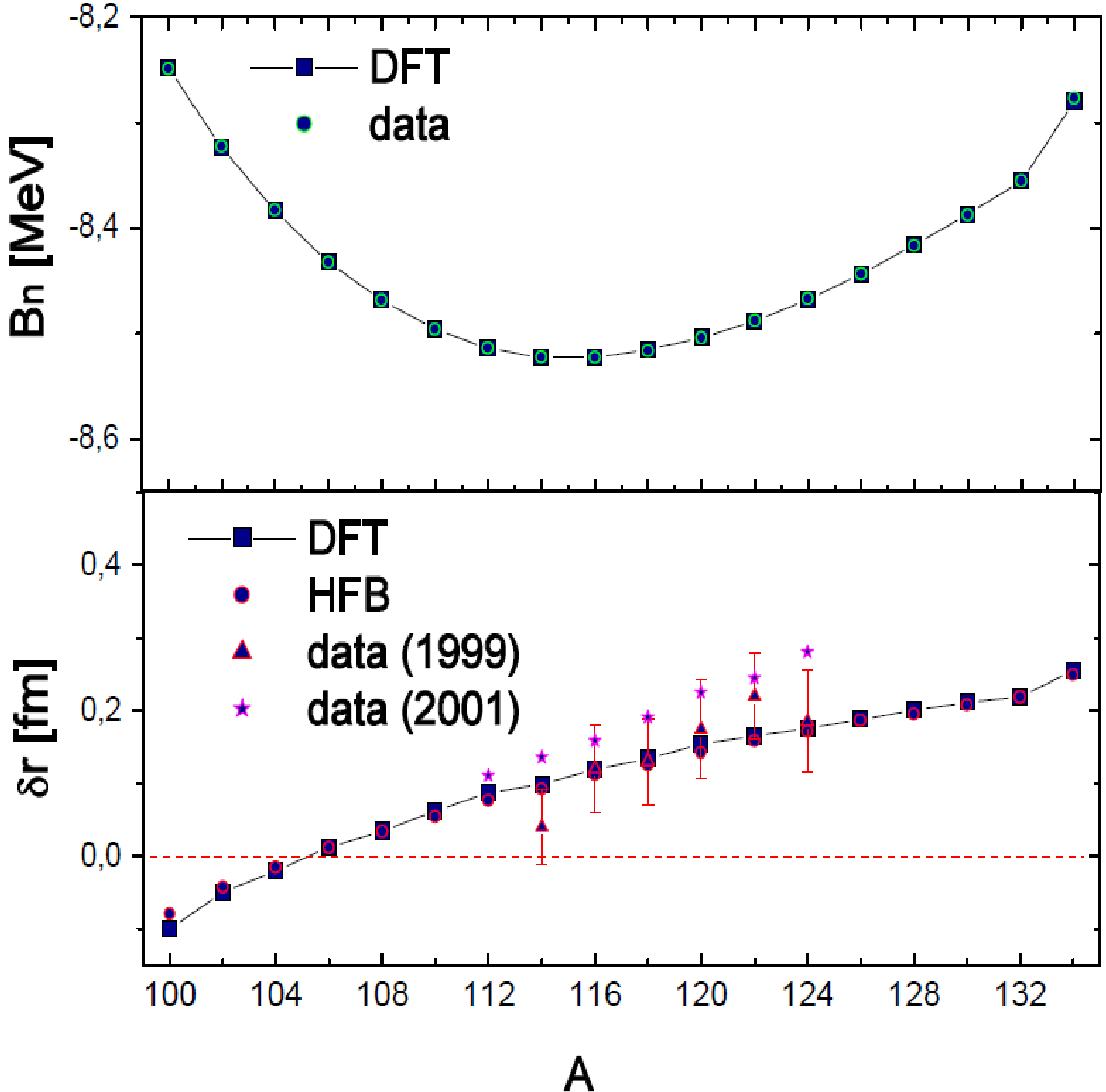
$$\tau_q = \sum_k v_{kq}^2 \left|\vec{\nabla}\varphi_{kq}(\vec{r})\right|^2 \qquad \text{kinetic density}$$

$$\kappa_q = \sum_k v_{kq} u_{kq} \left|\varphi_{kq}(\vec{r})\right|^2 \qquad \text{pairing density}$$

$$v_{kq}^2 = \frac{1}{2}\left(1 - \frac{e_q(k) - \lambda_q}{\sqrt{\left(e_q(k) - \lambda_q\right)^2 + \Delta_q(k)}} \right) \quad ; \quad v_{kq}^2 + u_{kq}^2 = 1$$

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

Binding energy and Skin Thickness

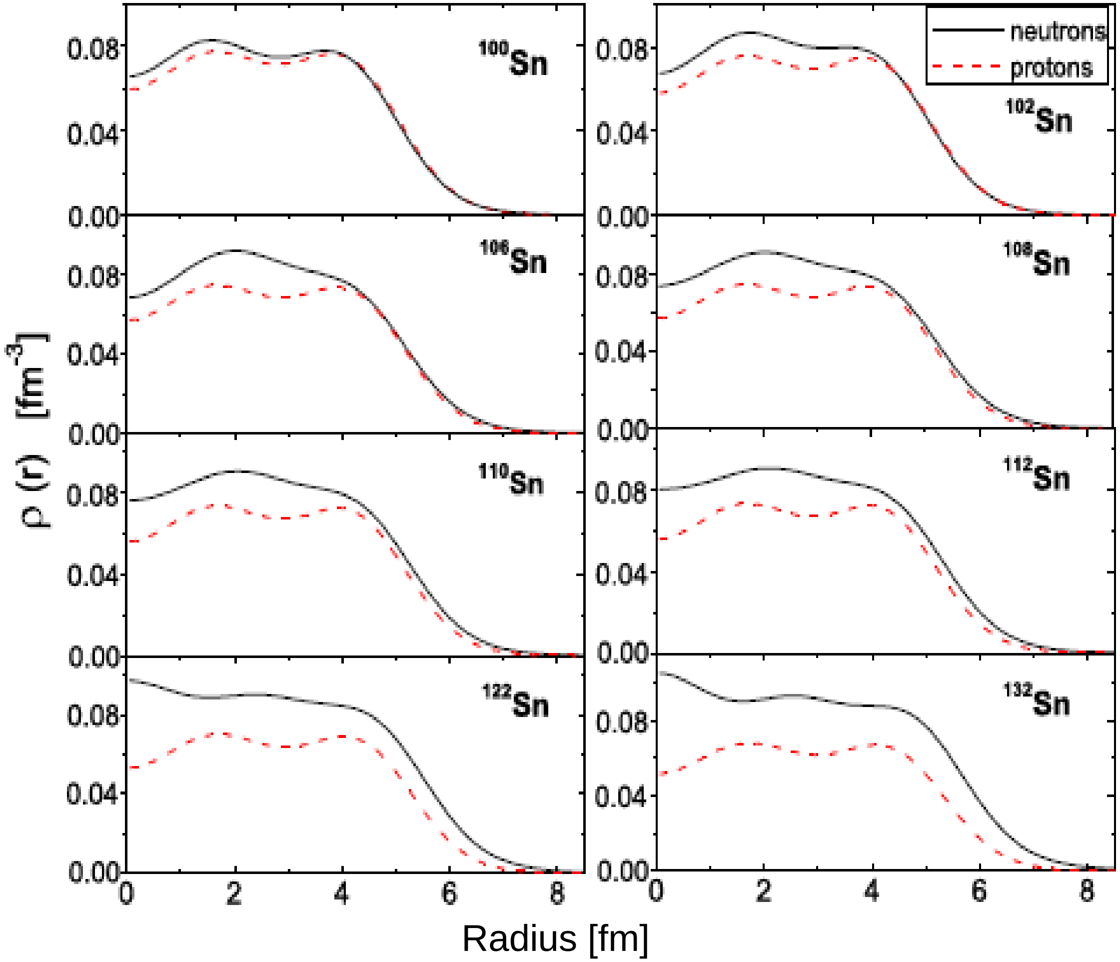


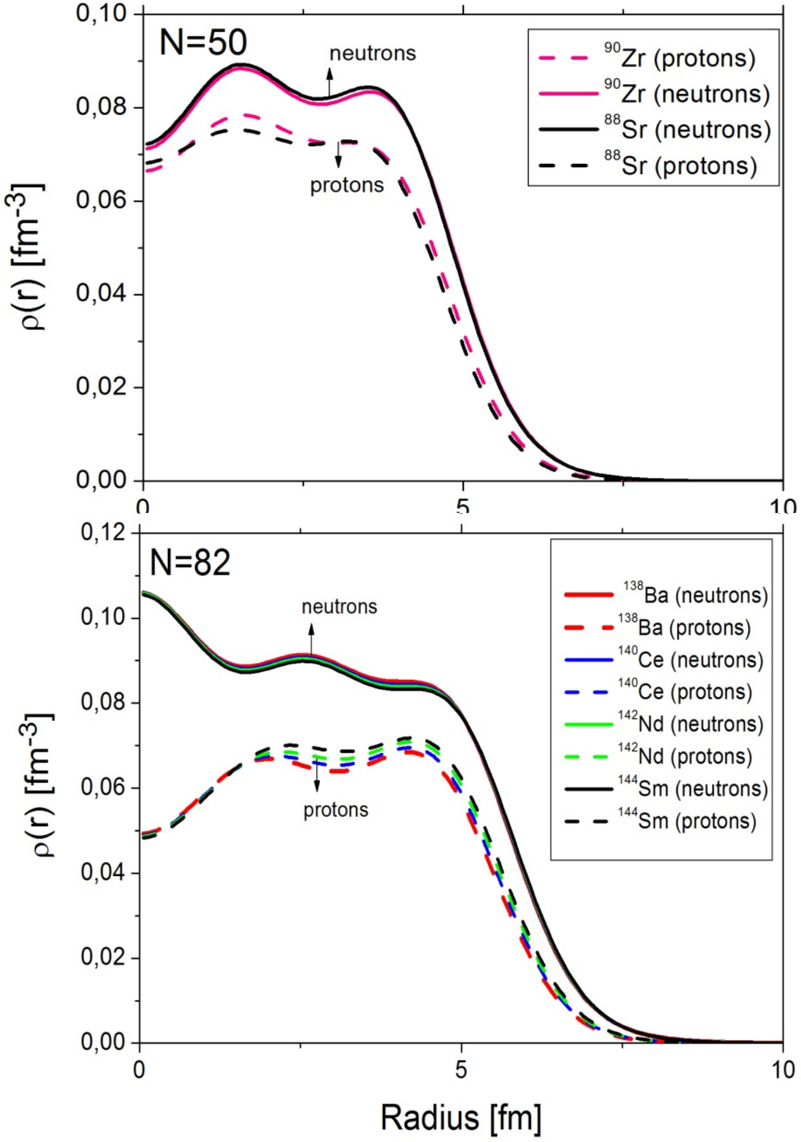
$$\delta r = \sqrt{< r^2 >_n} - \sqrt{< r^2 >_p}$$

N. Tsoneva, LDGS Oslo, 2011

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

$$\rho_q(r) = \frac{1}{4\pi r^2} \sum_{\alpha_q} v^2_{\alpha_q} (2j_{\alpha_q} + 1) R^2_{\alpha_q}(r)$$





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

The Excited States

V. G. Soloviev: Theory of Atomic Nuclei: *Quasiparticles and Phonons* (**Inst. Of Phys. Publ., Bristol, 1992)**

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

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

$$[Q_{\lambda\mu i}, Q^{+}_{\lambda'\mu' i'}] = \frac{\delta_{\lambda,\lambda'}\delta_{\mu,\mu'}\delta_{i,i'}}{2}\sum_{jj'}[\psi^{\lambda i}_{jj'}\psi^{\lambda i'}_{jj'} - \varphi^{\lambda i}_{jj'}\varphi^{\lambda i'}_{jj'}] - \sum_{\substack{jj'j_2\\ mm'm_2}}\boxed{\alpha^{+}_{jm}\alpha_{j'm'}}$$

$$\times\left\{\psi^{\lambda i}_{j'j_2}\psi^{\lambda' i'}_{jj_2}C^{\lambda\mu}_{j'm'j_2m_2}C^{\lambda'\mu'}_{jmj_2m_2} - (-)^{\lambda+\lambda'+\mu+\mu'}\varphi^{\lambda i}_{jj_2}\varphi^{\lambda' i'}_{j'j_2}C^{\lambda-\mu}_{jmj_2m_2}C^{\lambda'-\mu'}_{j'm'j_2m_2}\right\}$$

$$[H, Q^{+}_{\alpha}] = E_{\alpha}Q^{+}_{\alpha}$$

The Wave Function

For spherical nuclei the QPM Hamiltonian is diagonalized on an orthonormal set of wave functions with good total angular momentum JM.

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

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

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

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

BOSON FORBIDDEN TRANSITIONS

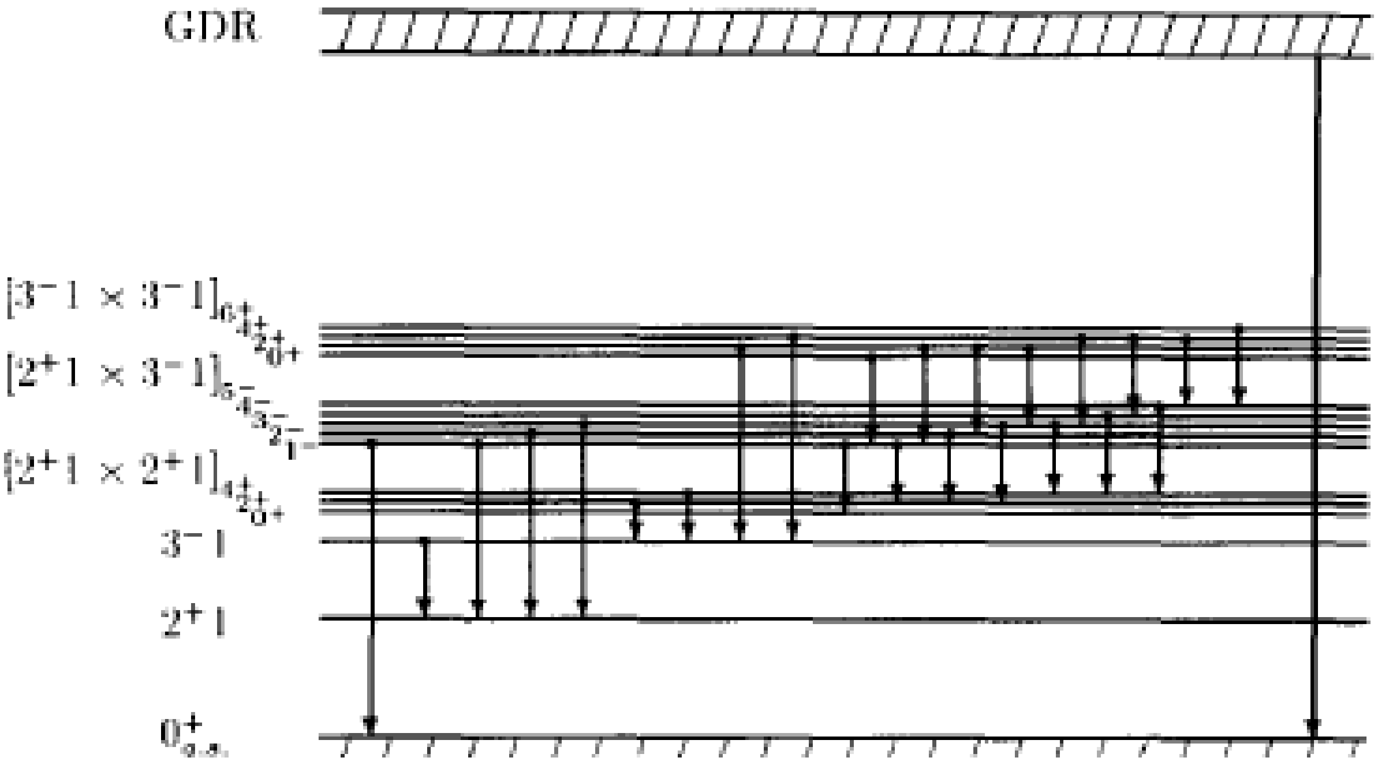
$$\left\langle Q_{\lambda_N i_N} \ldots Q_{\lambda_2 i_2} Q_{\lambda_1 i_1} \right\| M(E\lambda) \left\| Q^{+}_{\lambda i} Q^{+}_{\lambda_1 i_1} Q^{+}_{\lambda_2 i_2} \ldots Q^{+}_{\lambda_N i_N} \right\rangle \neq 0$$

QRPA

$$M(E(M)_{\lambda\mu}) = M^{Ph} + \boxed{M^{QPh}(E(M)_{\lambda\mu})}$$

$$\approx \left[\alpha^{+}_{j} \otimes \alpha^{+}_{j'}\right]$$

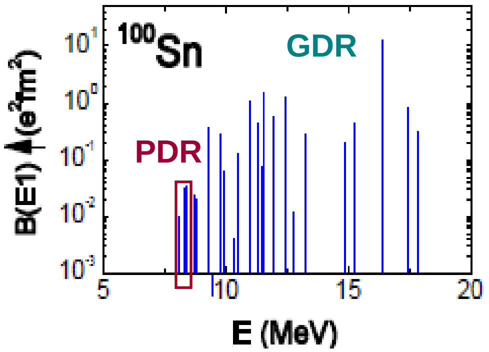
QPM

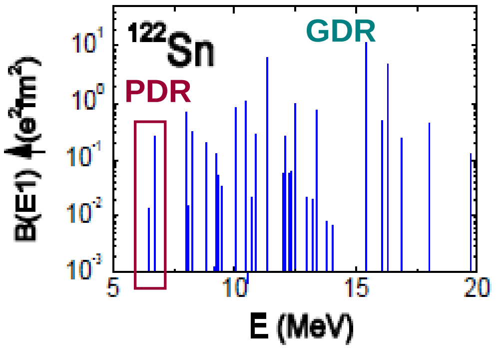


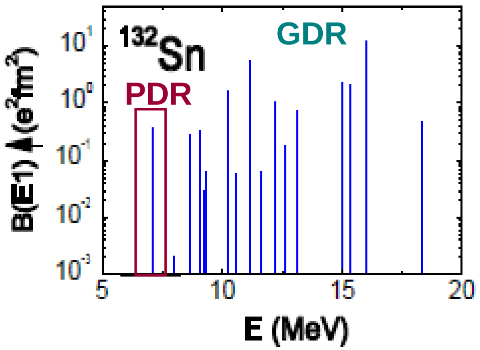
V. Ponomarev, Ch.Stoyanov, N. Tsoneva, M. Grinberg, Nucl. Phys. A 635 (1998) 470

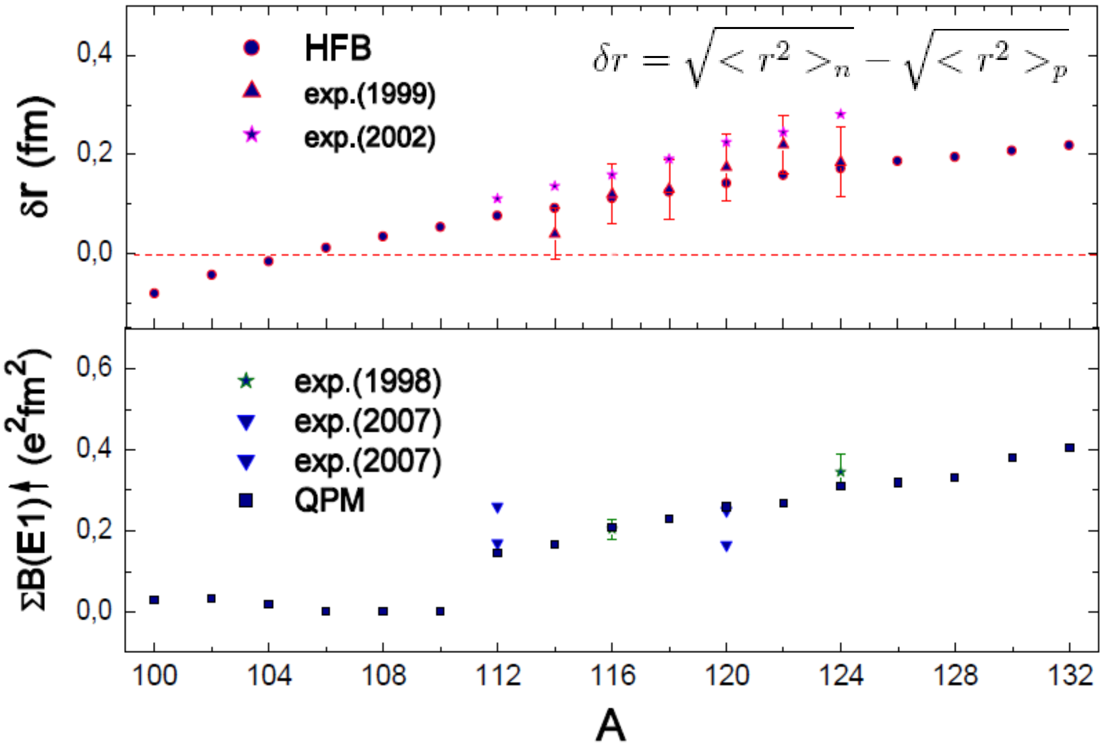
QRPA Calculations on the Dipole Response in Sn Isotopes

A connection between the total PDR strength and the neutron or proton skin









Neutron number increasing (Z=50)
Neutron skin increasing

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

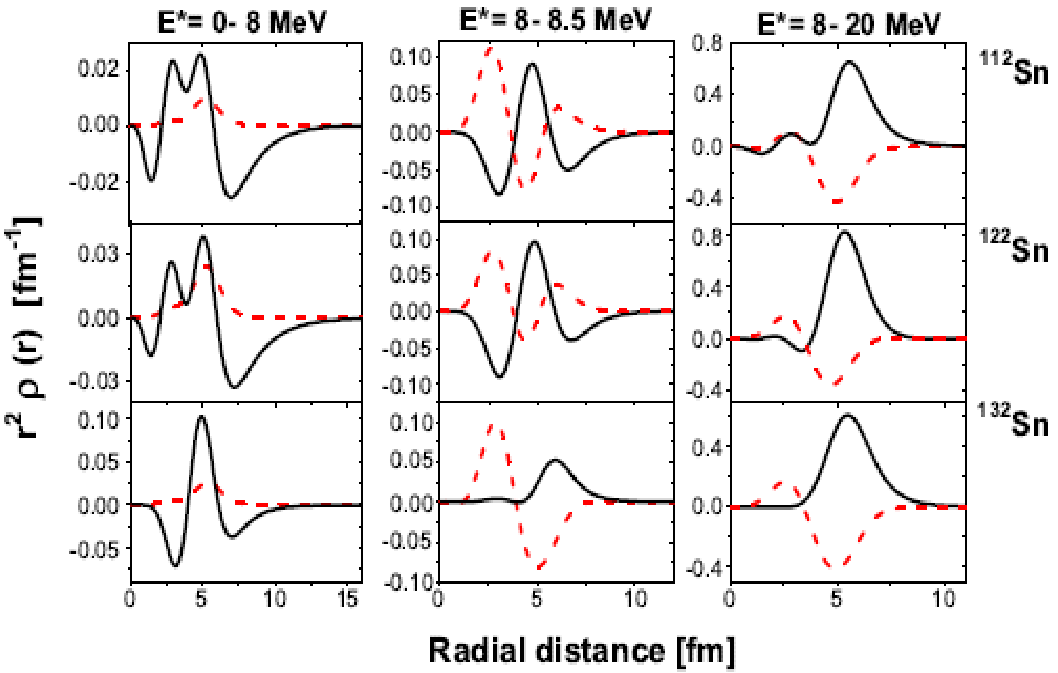
Proton number increasing (N=50,82)
Neutron skin decreasing

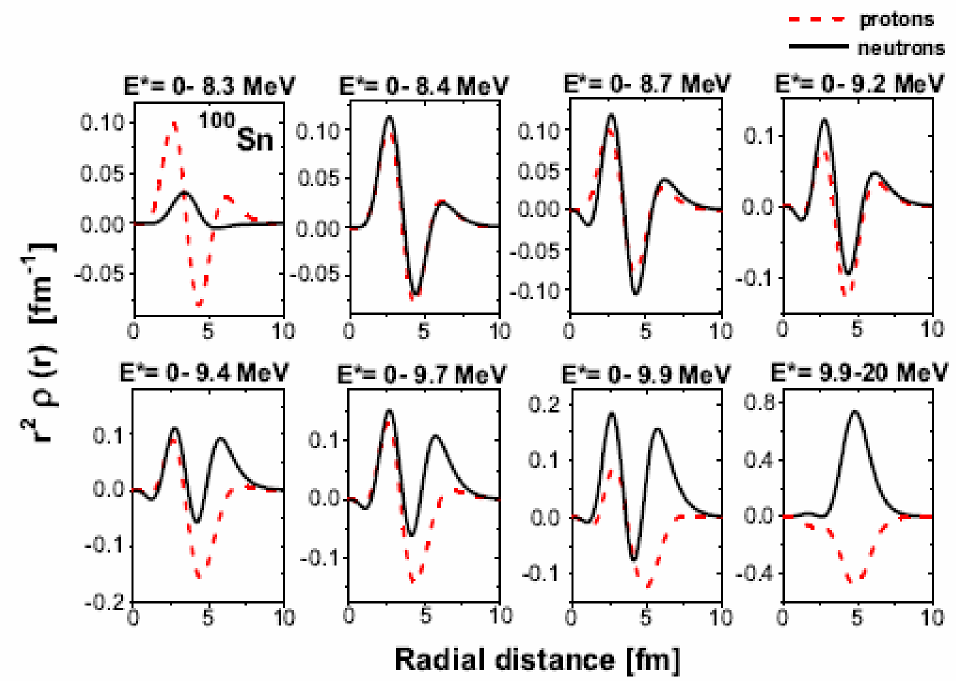
S. Volz et al., Nucl. Phys. A, 779 (2006) 1-20;
D. Savran et al.,PRL 100, (2008) 232501;
R. Schwengner et al, Phys. Rev. C 78 (2008) 064314.

Exp. in Sn-116 and Sn-124:
K. Govaert et al,
Phys. Rev. C 57 (1998) 2229.
Exp. in Sn-112,Sn-120:
B. Ozel et al,
Nucl. Phys. A 778 (2007) 385.

Dipole Transition Densities in Sn Isotopes

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





Skin Thickness and Electric Dipole Response

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

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

$$\Delta_3 r^2 = \sum_i \langle 0 | \tau_{3i} r_i^2 | 0 \rangle, \quad \tau_3 = \pm 1$$

Relation between the non-energy weighted dipole sum rule and the skin measure:

$$\Delta_3 r^2 = \frac{1}{4 q_0 q_1} \left(\sum_d B_d(E1) - q_0^2 \sum_d \left| M_d^{(0)} \right|^2 - q_1^2 \sum_d \left| M_d^{(1)} \right|^2 \right)$$

+ ground state pairing correlations

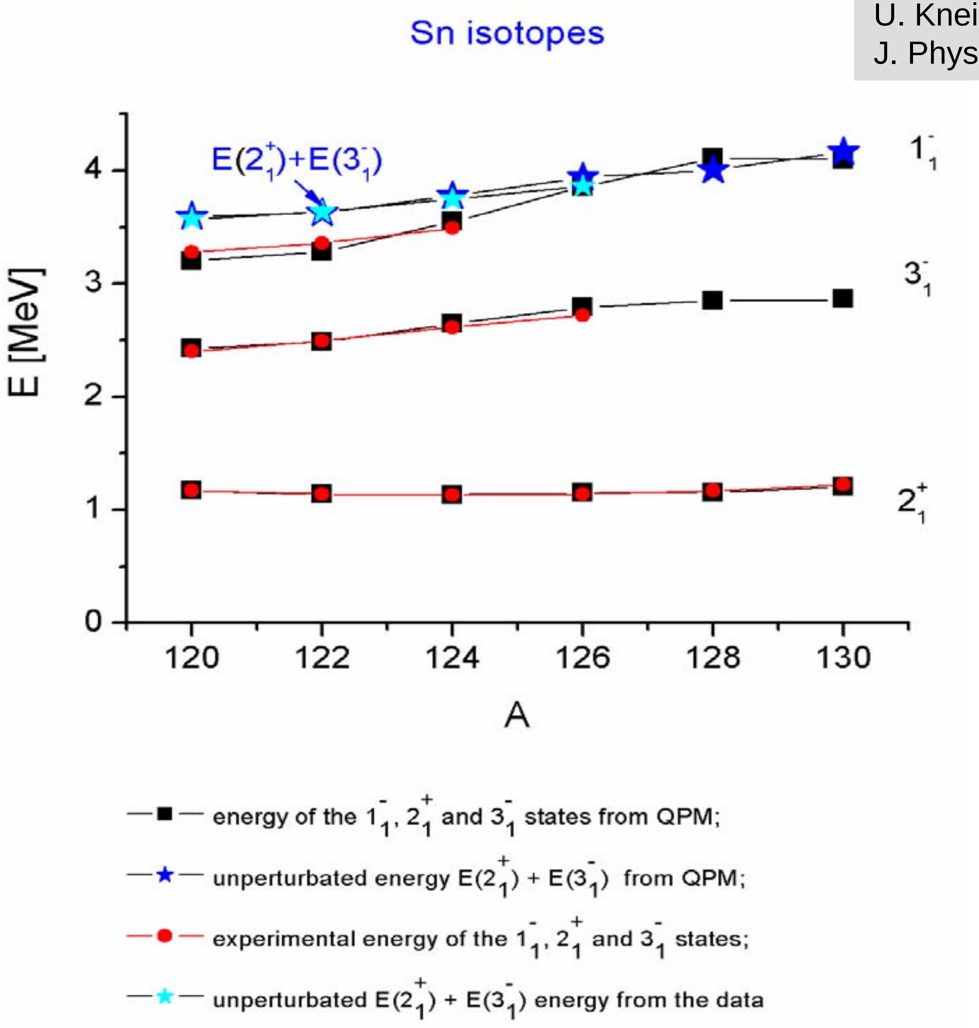
where $M_d^{(T)}$ and $B_d(E1)$ are the reduced isovector/isoscalar dipole transition moment and the dipole transition probability:

$$\vec{M}_d^{(T)} = \langle 0 \| (\tau_3)^T \vec{r} \| d \rangle; \quad B_d(E1) = \left| q_0 \vec{M}_d^{(0)} + q_1 \vec{M}_d^{(1)} \right|^2$$

$q_T = \frac{1}{2}(q_n + (-)^T q_p)$; isoscalar (T=0) and isovector (T=1) charges

Two-phonon 1^- states

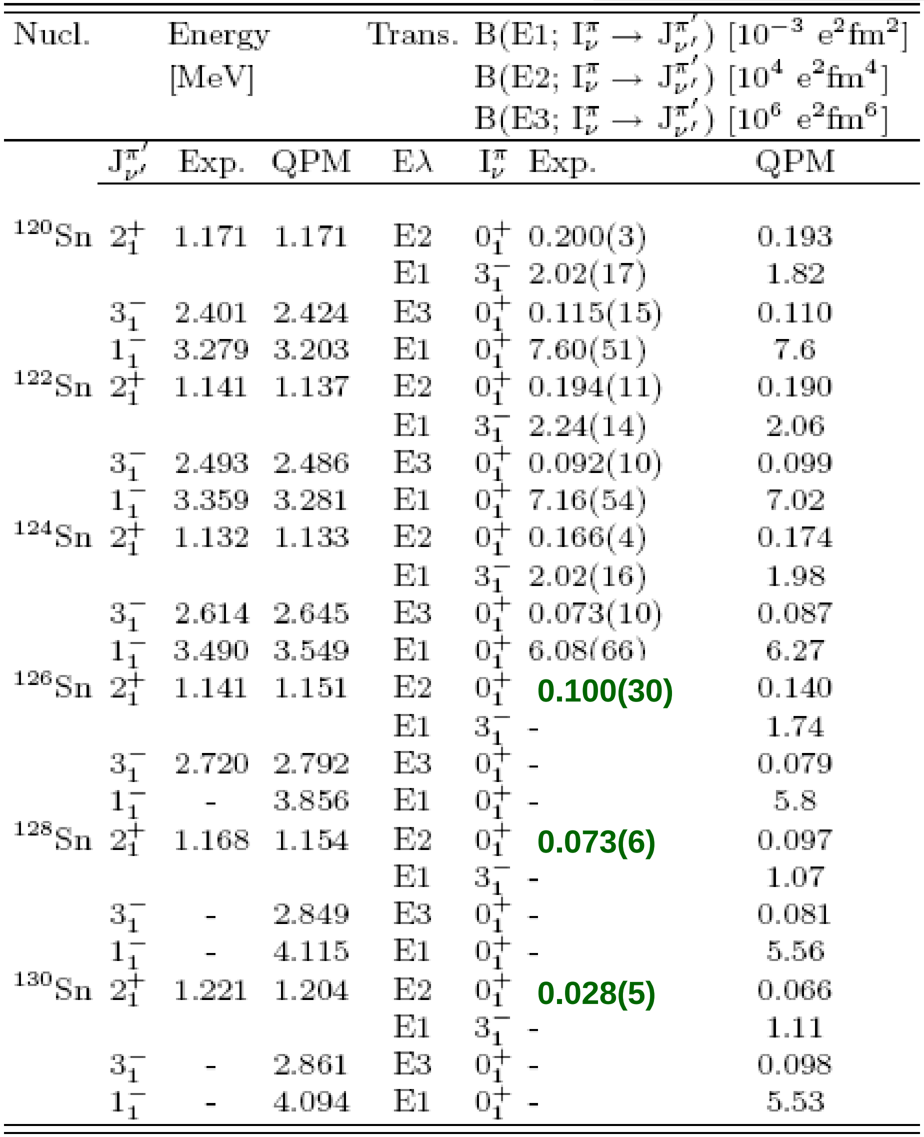
U. Kneissl, N. Pietralla, and A. Zilges,
J. Phys. G: Nucl. Part. Phys. **32,** R217 (2006)



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

Sn isotopes: QPM results for the energies and B(E1), B(E2) and B(E3) transition probabilities of the first 1$^-$, 2$^+$ and 3$^-$ states compared to experimental data.

N. Tsoneva, H. Lenske, Ch. Stoyanov, Phys. Lett. B 586 (2004) 213
D.C. Radford et al.,Nucl. Phys. A 746 (2004) 83c



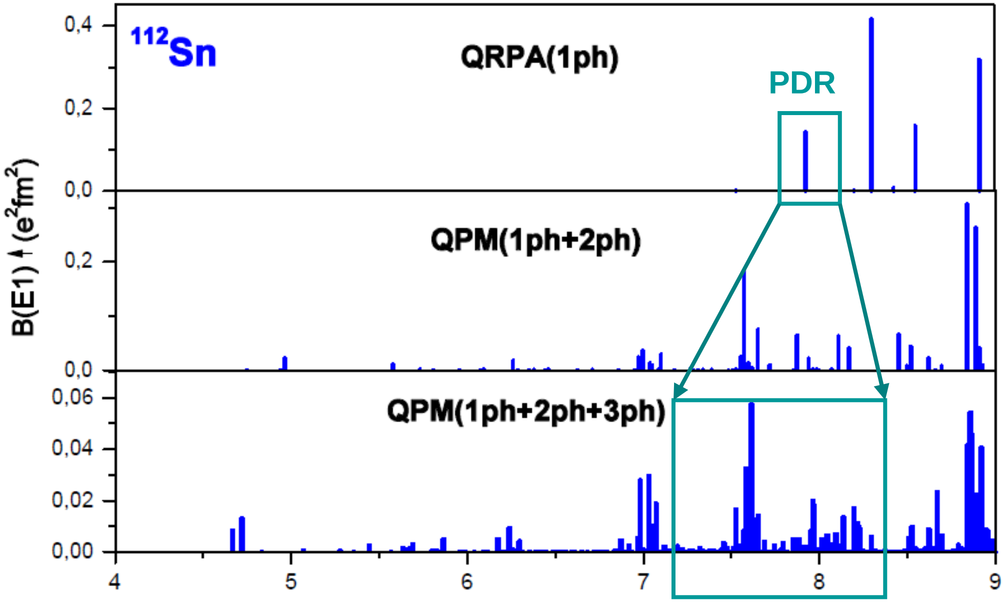
Nucl.		Energy [MeV]		Trans.	$B(E1; I^\pi_\nu \rightarrow J^{\pi'}_{\nu'})$ $[10^{-3}\ e^2fm^2]$ $B(E2; I^\pi_\nu \rightarrow J^{\pi'}_{\nu'})$ $[10^{4}\ e^2fm^4]$ $B(E3; I^\pi_\nu \rightarrow J^{\pi'}_{\nu'})$ $[10^{6}\ e^2fm^6]$		
	$J^{\pi'}_{\nu'}$	Exp.	QPM	Eλ	I^π_ν	Exp.	QPM
^{120}Sn	2^+_1	1.171	1.171	E2	0^+_1	0.200(3)	0.193
				E1	3^-_1	2.02(17)	1.82
	3^-_1	2.401	2.424	E3	0^+_1	0.115(15)	0.110
	1^-_1	3.279	3.203	E1	0^+_1	7.60(51)	7.6
^{122}Sn	2^+_1	1.141	1.137	E2	0^+_1	0.194(11)	0.190
				E1	3^-_1	2.24(14)	2.06
	3^-_1	2.493	2.486	E3	0^+_1	0.092(10)	0.099
	1^-_1	3.359	3.281	E1	0^+_1	7.16(54)	7.02
^{124}Sn	2^+_1	1.132	1.133	E2	0^+_1	0.166(4)	0.174
				E1	3^-_1	2.02(16)	1.98
	3^-_1	2.614	2.645	E3	0^+_1	0.073(10)	0.087
	1^-_1	3.490	3.549	E1	0^+_1	6.08(66)	6.27
^{126}Sn	2^+_1	1.141	1.151	E2	0^+_1	**0.100(30)**	0.140
				E1	3^-_1	-	1.74
	3^-_1	2.720	2.792	E3	0^+_1	-	0.079
	1^-_1	-	3.856	E1	0^+_1	-	5.8
^{128}Sn	2^+_1	1.168	1.154	E2	0^+_1	**0.073(6)**	0.097
				E1	3^-_1	-	1.07
	3^-_1	-	2.849	E3	0^+_1	-	0.081
	1^-_1	-	4.115	E1	0^+_1	-	5.56
^{130}Sn	2^+_1	1.221	1.204	E2	0^+_1	**0.028(5)**	0.066
				E1	3^-_1	-	1.11
	3^-_1	-	2.861	E3	0^+_1	-	0.098
	1^-_1	-	4.094	E1	0^+_1	-	5.53

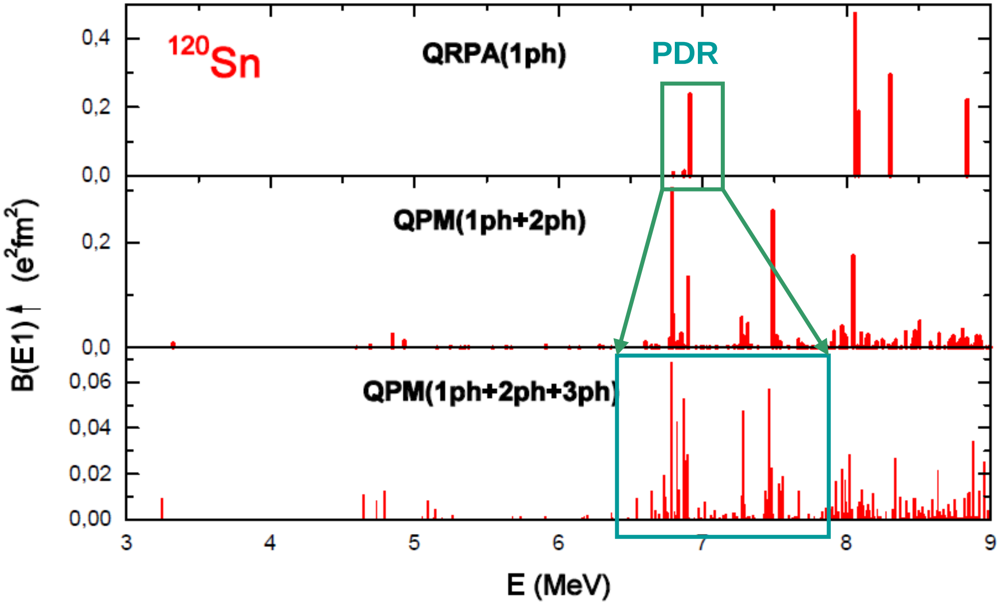
Multiphonon Calculations of E1 Transitions in ^{112,120}Sn

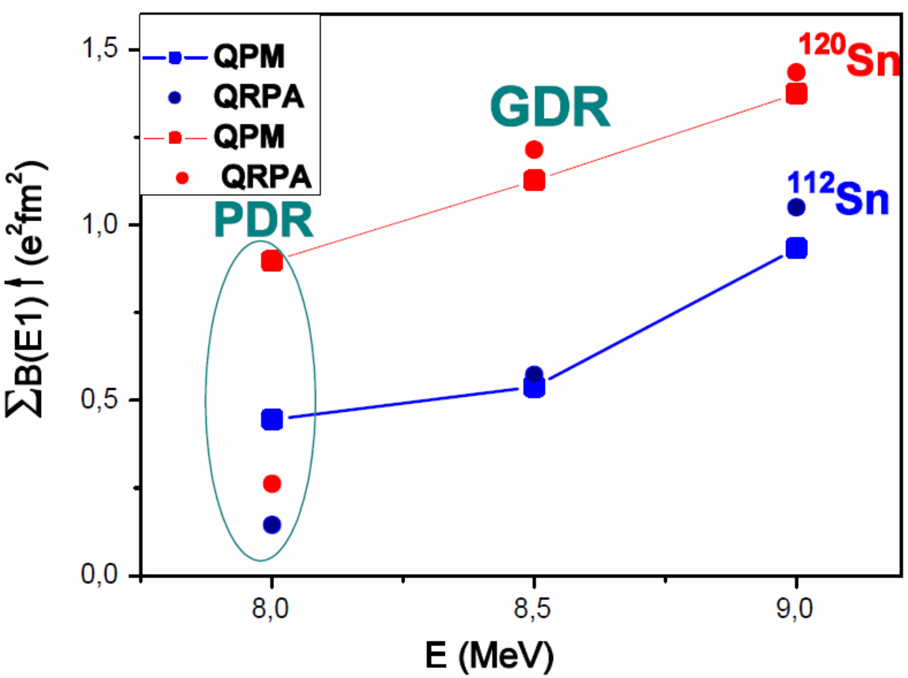
in preparation for PRC

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

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





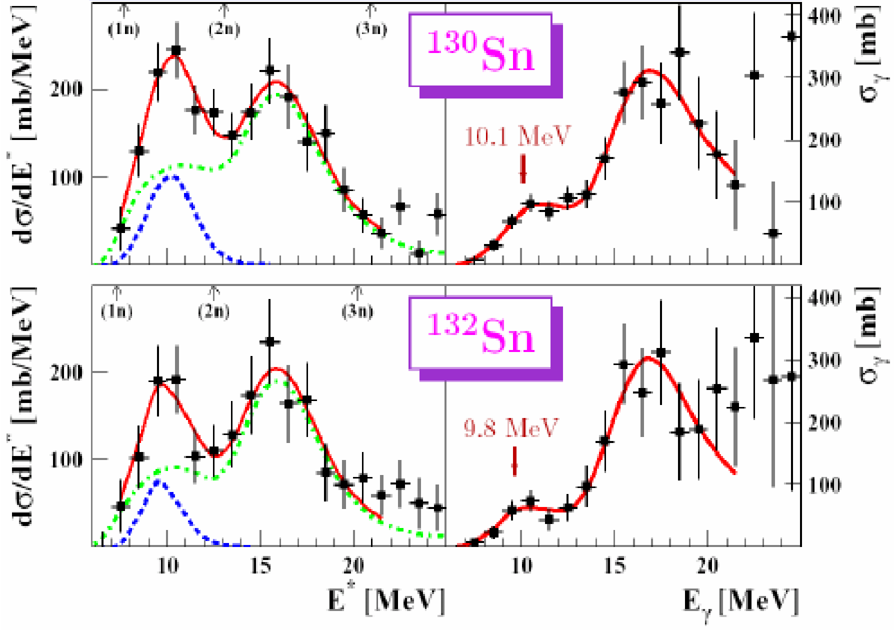


GDR (E*>8MeV)
PDR (1ph+2ph+3ph)

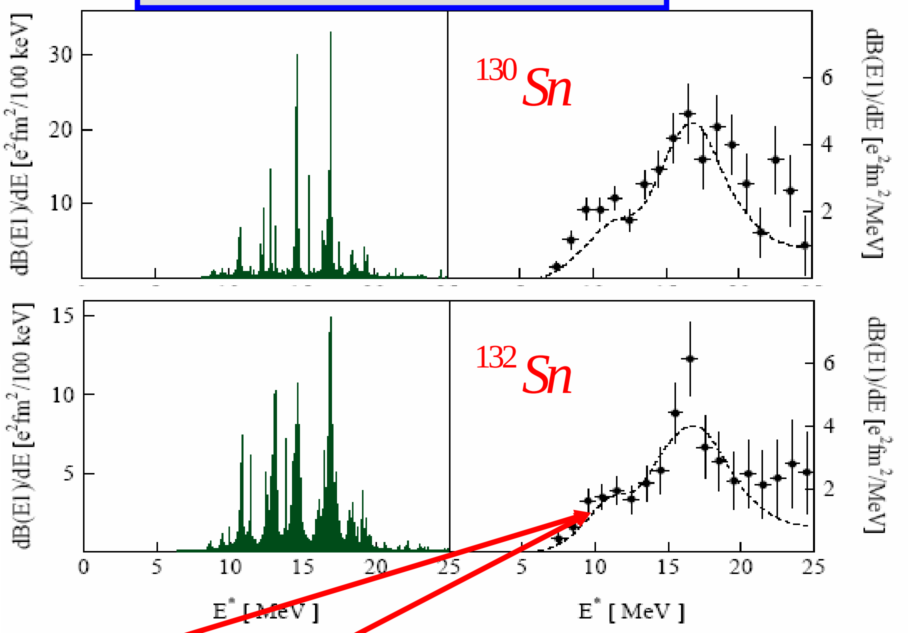
N. Tsoneva, LDGS Oslo, 2011

QPM calculations of excitation energies and integrated cross sections in ^{130,132}Sn in comparison with recent data / A. Klimkiewicz and the LAND-FRS collaboration, private communication/.*

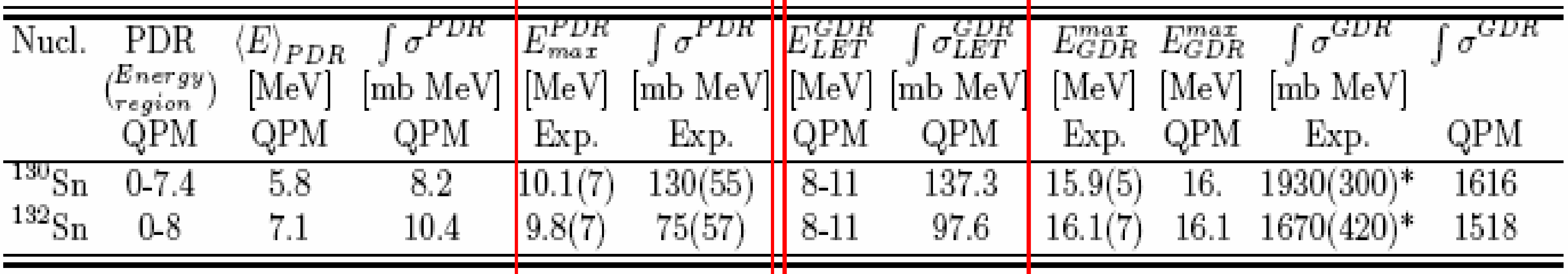
Exp. (P. Adrich et al., PRL 95 (2005) 132501)



QRPA and LAND-FRS data



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



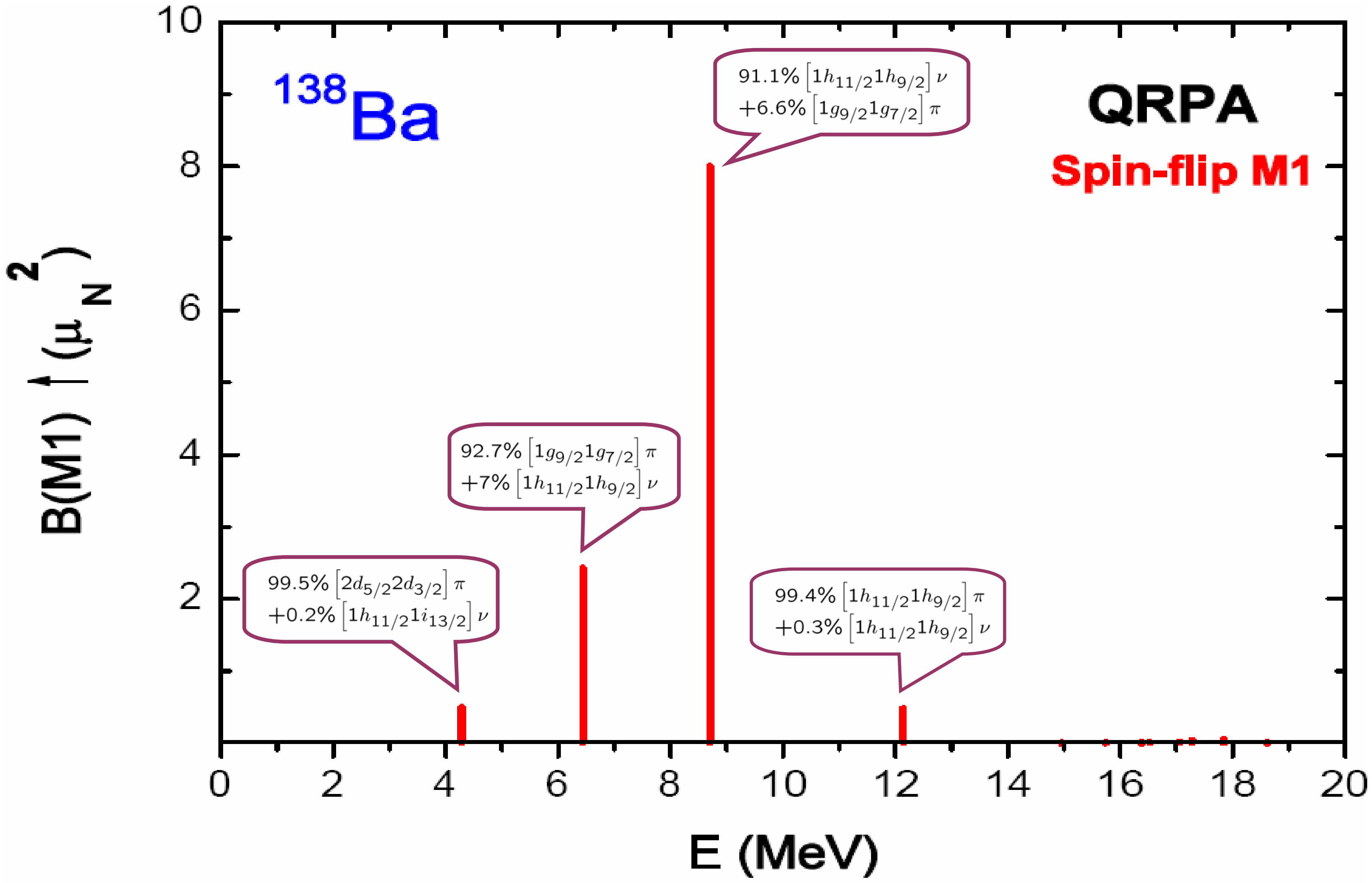
Nucl.	PDR (Energy region) QPM	$\langle E\rangle_{PDR}$ [MeV] QPM	$\int\sigma^{PDR}$ [mb MeV] QPM	E^{PDR}_{max} [MeV] Exp.	$\int\sigma^{PDR}$ [mb MeV] Exp.	E^{GDR}_{LET} [MeV] QPM	$\int\sigma^{GDR}_{LET}$ [mb MeV] QPM	E^{max}_{GDR} [MeV] Exp.	E^{max}_{GDR} [MeV] QPM	$\int\sigma^{GDR}$ [mb MeV] Exp.	$\int\sigma^{GDR}$ QPM
^{130}Sn	0-7.4	5.8	8.2	10.1(7)	130(55)	8-11	137.3	15.9(5)	16.	1930(300)*	1616
^{132}Sn	0-8	7.1	10.4	9.8(7)	75(57)	8-11	97.6	16.1(7)	16.1	1670(420)*	1518

*** The integration is taken up to 20 MeV.**

N. Tsoneva, IKP Seminar, 2011

Are There Other than E1 Dipole Excitations in the PDR Region ?

QRPA Calculations of 1^+ States in ^{138}Ba



91.1% $[1h_{11/2}1h_{9/2}]\,\nu$
+6.6% $[1g_{9/2}1g_{7/2}]\,\pi$

92.7% $[1g_{9/2}1g_{7/2}]\,\pi$
+7% $[1h_{11/2}1h_{9/2}]\,\nu$

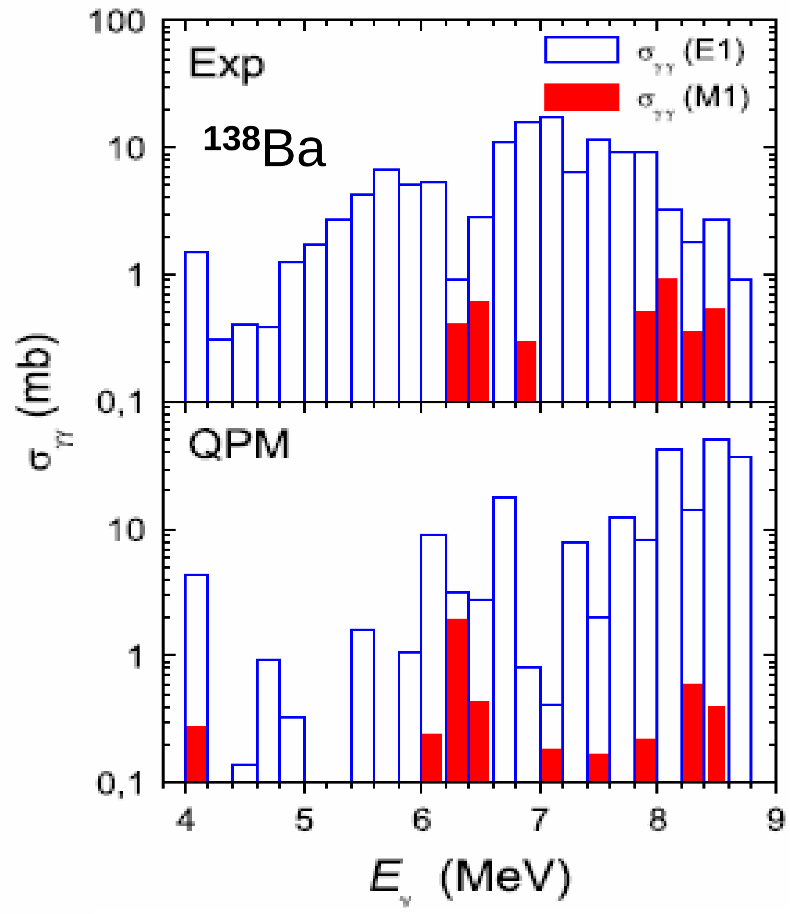
99.5% $[2d_{5/2}2d_{3/2}]\,\pi$
+0.2% $[1h_{11/2}1i_{13/2}]\,\nu$

99.4% $[1h_{11/2}1h_{9/2}]\,\pi$
+0.3% $[1h_{11/2}1h_{9/2}]\,\nu$

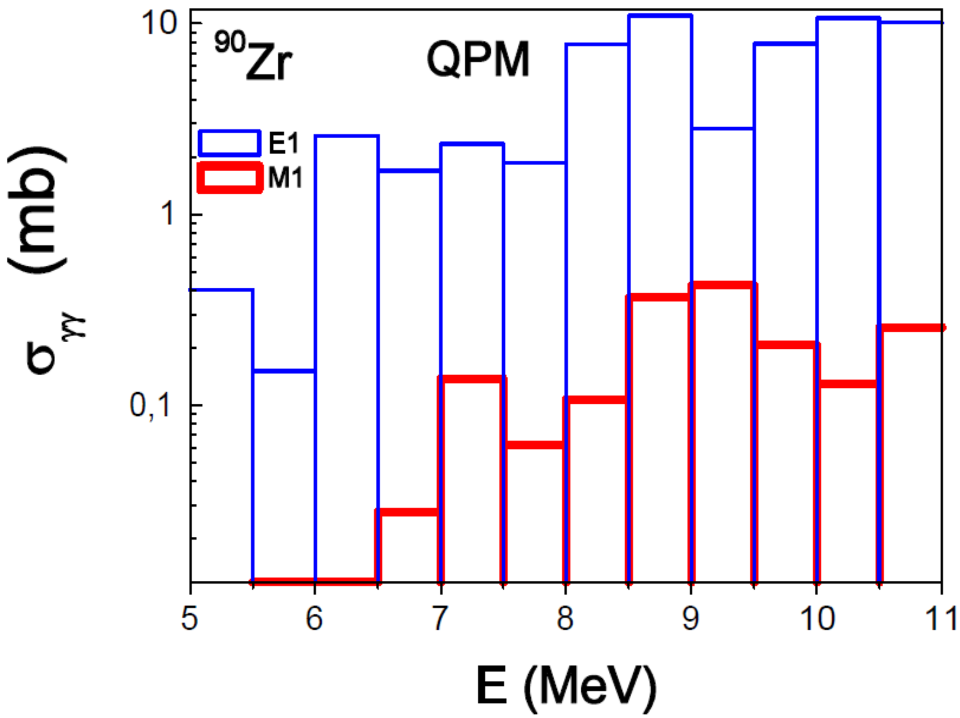
N. Tsoneva, LDGS Oslo, 2011

Parity Measurements with Polarized Photon Beams of Low-energy Dipole Excitations at HIGS, Duke, USA

Phys. Rev. Lett. 104, 072501 (2010)



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



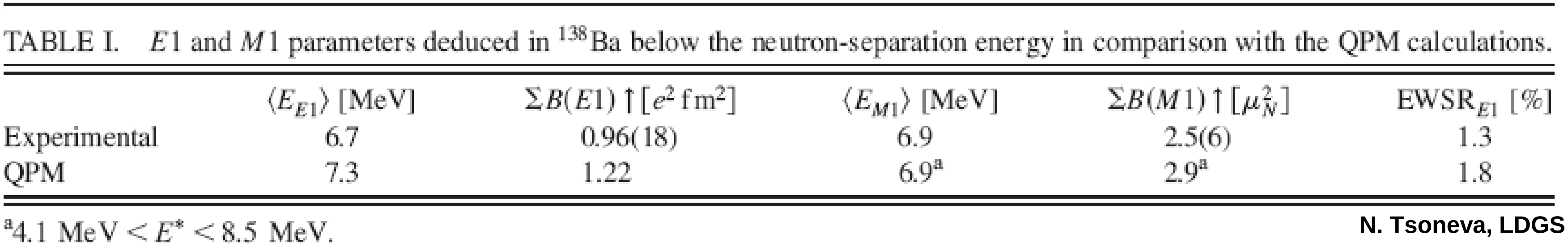


TABLE I. $E1$ and $M1$ parameters deduced in ^{138}Ba below the neutron-separation energy in comparison with the QPM calculations.

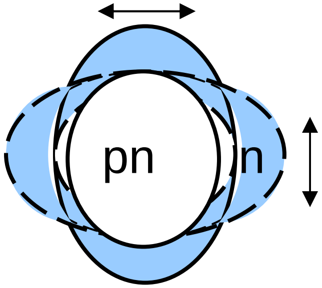
	$\langle E_{E1}\rangle$ [MeV]	$\Sigma B(E1)\uparrow[e^2\,\mathrm{fm}^2]$	$\langle E_{M1}\rangle$ [MeV]	$\Sigma B(M1)\uparrow[\mu_N^2]$	EWSR$_{E1}$ [%]
Experimental	6.7	0.96(18)	6.9	2.5(6)	1.3
QPM	7.3	1.22	6.9[a]	2.9[a]	1.8

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

N. Tsoneva, LDGS Oslo, 2011

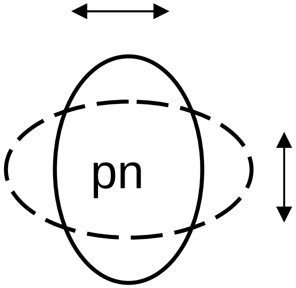
ELECTRIC QUADRUPOLE (ΔL=2) RESPONSE IN SKIN NUCLEI

PYGMY QUADRUPOLE RESONANCE



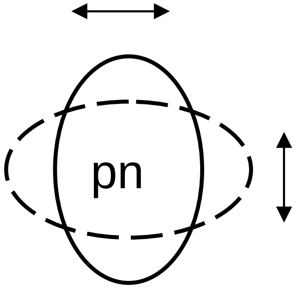
ΔT=0,1; ΔS=0

ISQS



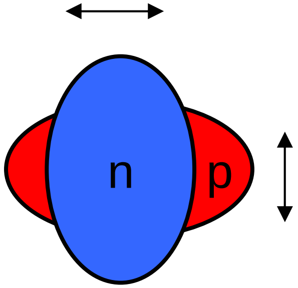
ΔT=0; ΔS=0

ISGQR



ΔT=0; ΔS=0

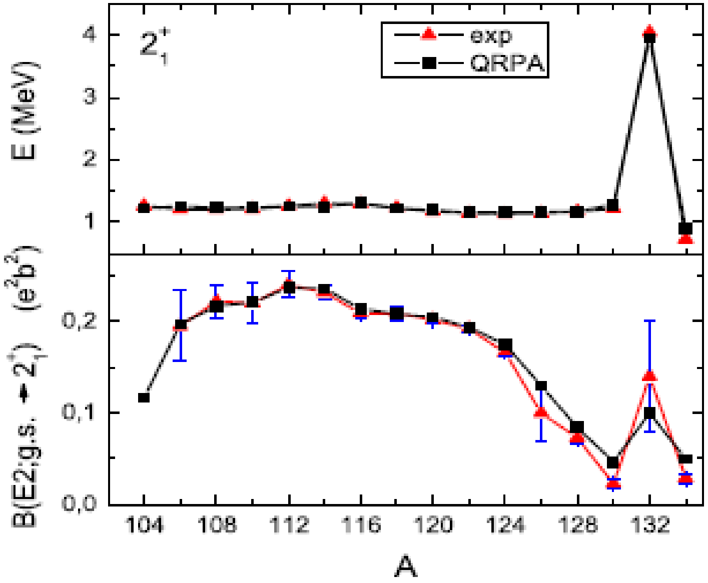
IVGQR



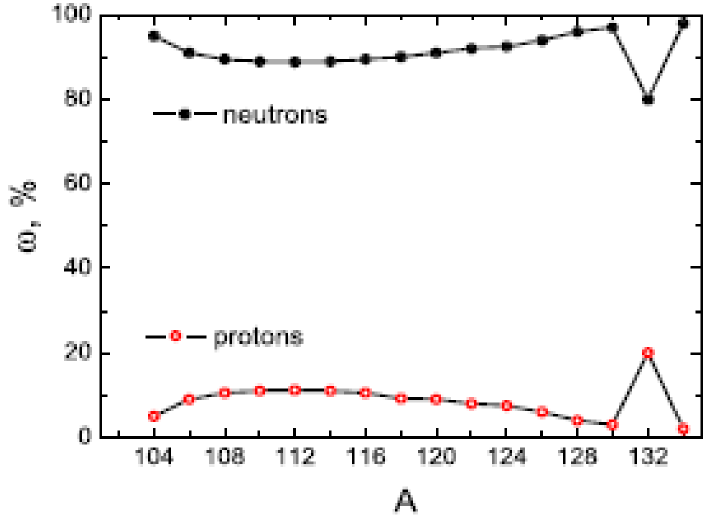
ΔT=1; ΔS=0

N. Tsoneva, LDGS Oslo, 2011

QRPA calculations of the first 2^+ states in Sn isotopes



$$\omega_{j_1 j_2}(\lambda i) = \left|\psi^{\lambda i}_{j_1 j_2}\right|^2 - \left|\varphi^{\lambda\mu i}_{j_1 j_2}\right|^2$$



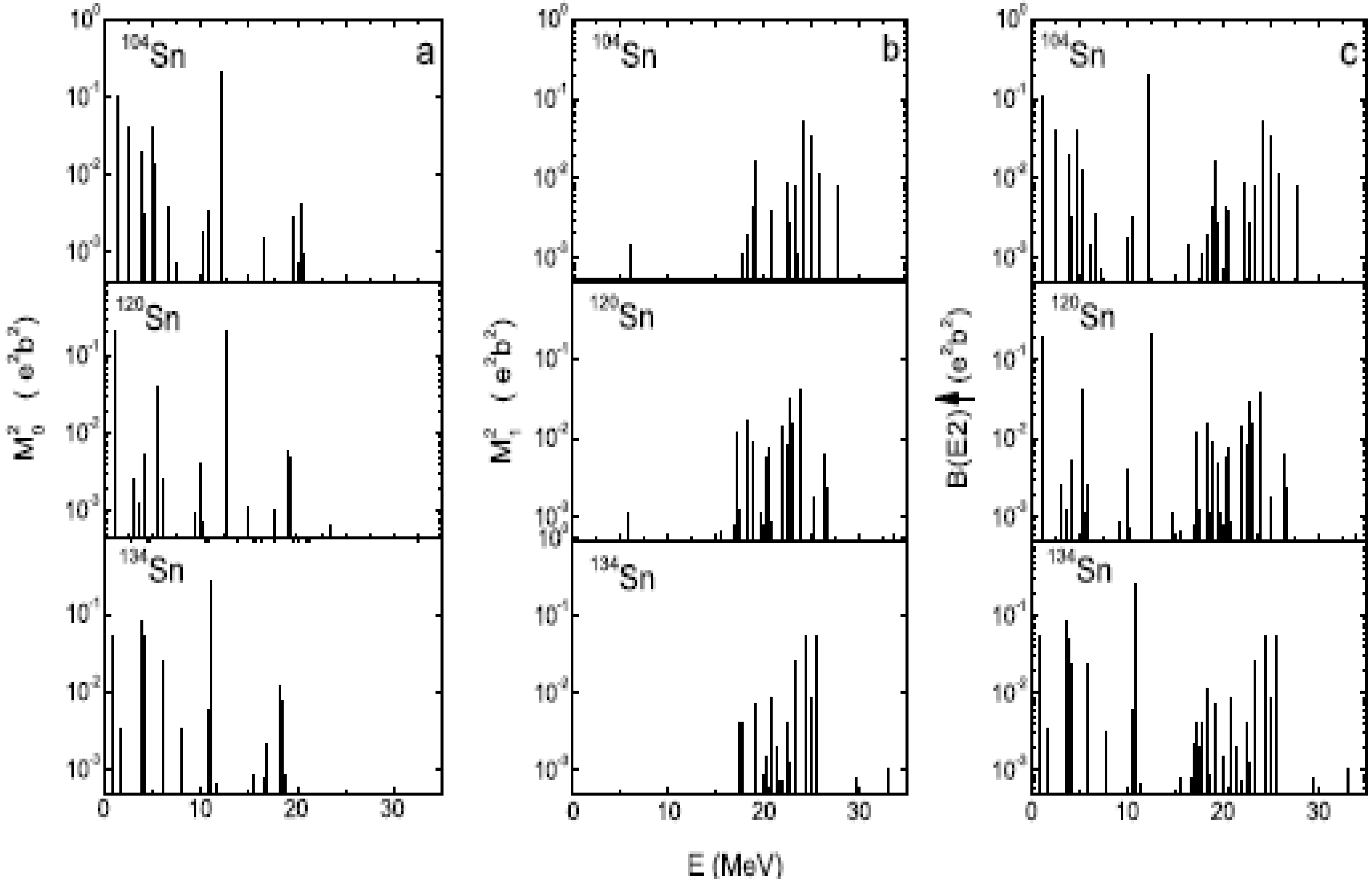
Nucleus	State	E (MeV)	$\omega_{j_1 j_2}$, %	$B(E2)\uparrow$ (e^2b^2)
		QRPA		QRPA
^{130}Sn	2^+_1	1.28	$64.1\%(1h_{11/2})^2_n + 1.3\%(1g_{9/2}2d_{5/2})_p$	0.047
^{132}Sn	2^+_1	3.98	$76\%(1h_{11/2}2f_{7/2})^2_n + 17\%(1g_{9/2}2d_{5/2})_p$	0.1
^{134}Sn	2^+_1	0.79	$86\%(2f_{7/2})^2_n + 0.9\%(1g_{9/2}2d_{5/2})_p$	0.05

N. Tsoneva, LDGS Oslo, 2011

QRPA CALCULATIONS OF ISOSCALAR AND ISOVECTOR QUADRUPOLE STATES IN SN ISOTOPES

N. Tsoneva and H. Lenske, Phys. Lett. B 695 (2011) 174–180

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



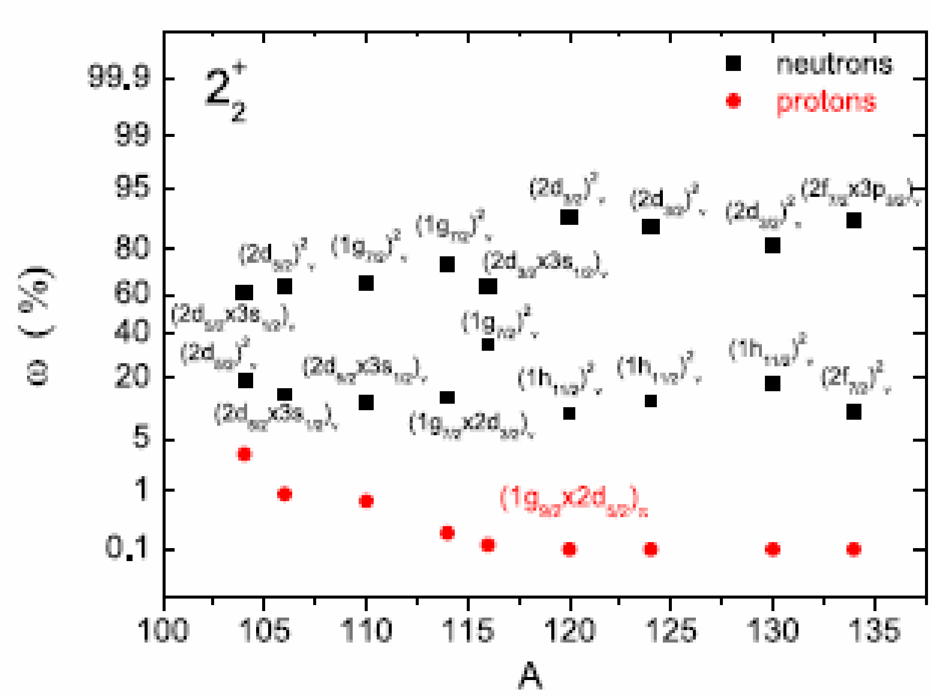
QRPA Calculations of Low-Energy 2^+ States Related to Skin Oscillations

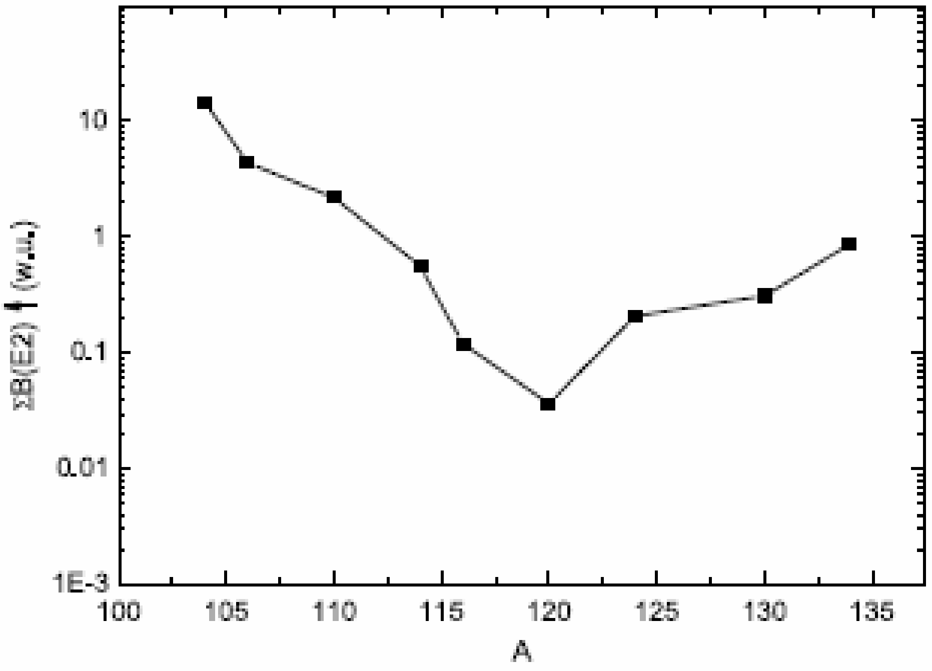
N. Tsoneva and H. Lenske, Phys. Lett. B 695 (2011) 174–180

NEW MODE different from the Scissors mode!

$B(M1) \approx 10^{-2}\mu_N^2$

B(E2) increases with the neutron number, $B(E2) \approx 1/|\epsilon_b|^2$

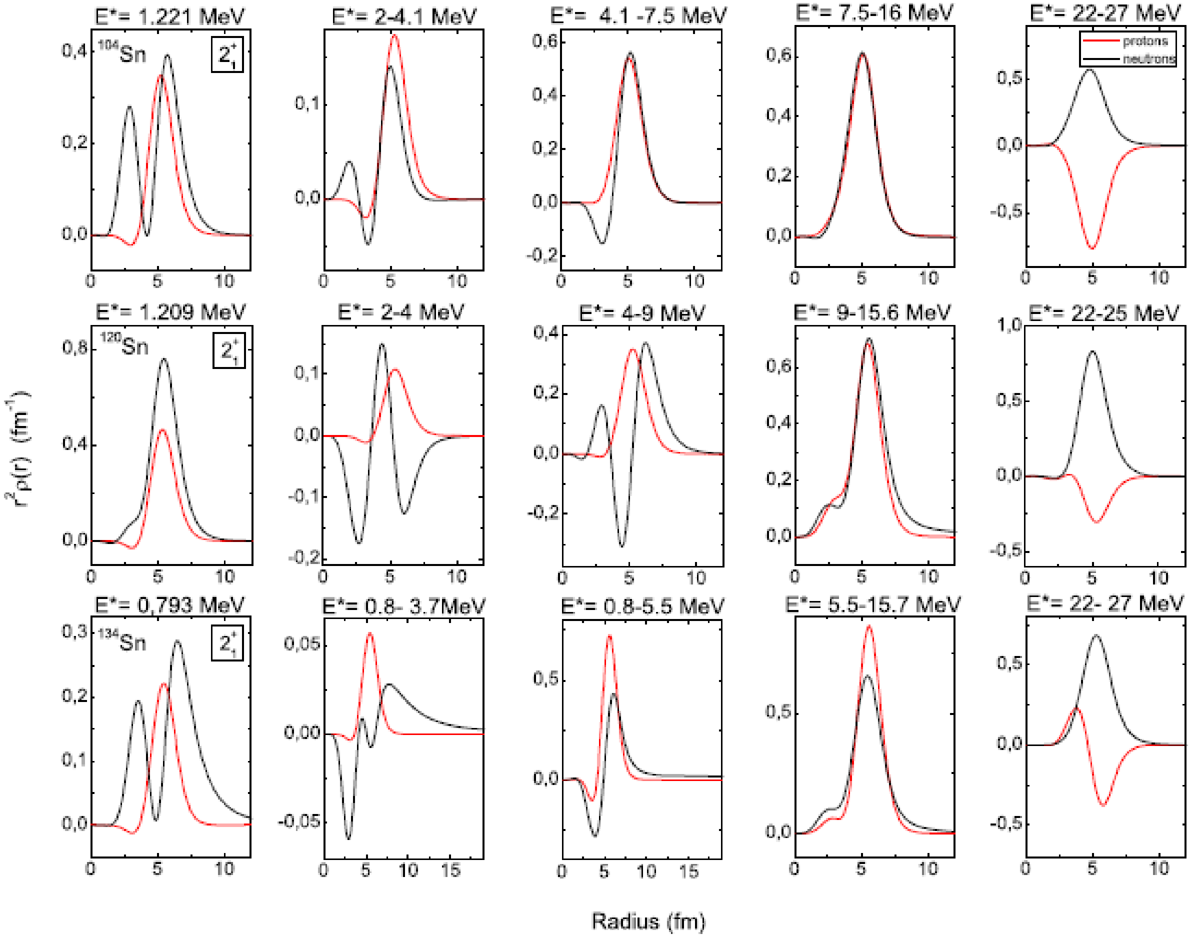




Quadrupole Transition Densities of Sn Isotopes

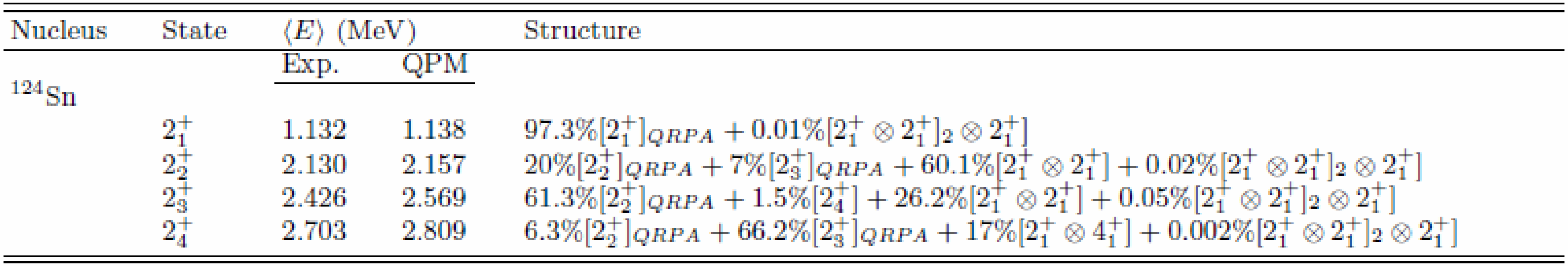
N. Tsoneva and H. Lenske, Phys. Lett. B 695 (2011) 174–180

A Possible Signature of a Pygmy Quadrupole Resonance

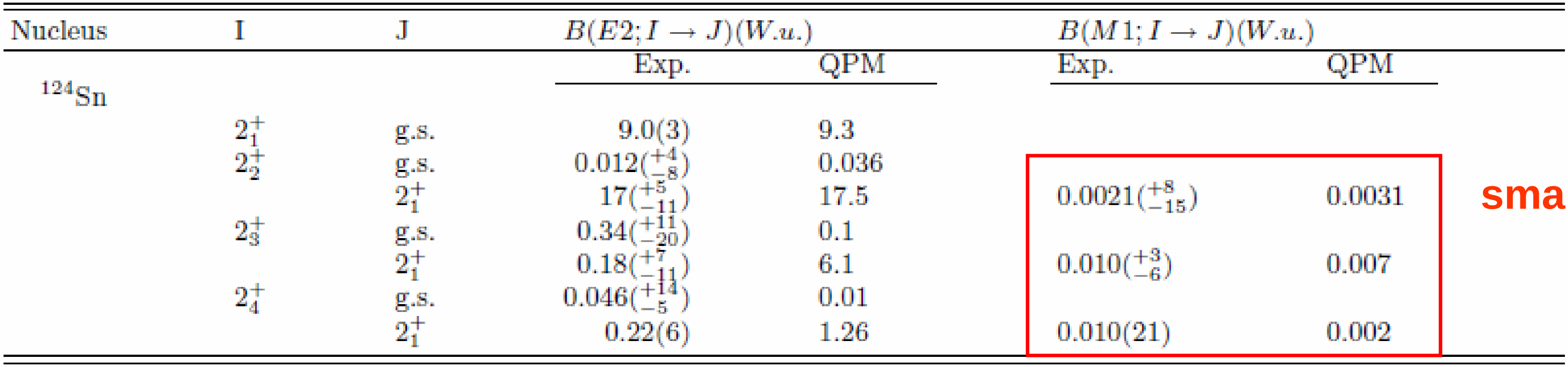


QPM Calculations of Low-Energy 2^+ States in ^{124}Sn

preliminary



Nucleus	State	$\langle E \rangle$ (MeV) Exp.	$\langle E \rangle$ (MeV) QPM	Structure
^{124}Sn				
	2_1^+	1.132	1.138	$97.3\%[2_1^+]_{QRPA} + 0.01\%[2_1^+ \otimes 2_1^+]_2 \otimes 2_1^+]$
	2_2^+	2.130	2.157	$20\%[2_2^+]_{QRPA} + 7\%[2_3^+]_{QRPA} + 60.1\%[2_1^+ \otimes 2_1^+] + 0.02\%[2_1^+ \otimes 2_1^+]_2 \otimes 2_1^+]$
	2_3^+	2.426	2.569	$61.3\%[2_2^+]_{QRPA} + 1.5\%[2_4^+] + 26.2\%[2_1^+ \otimes 2_1^+] + 0.05\%[2_1^+ \otimes 2_1^+]_2 \otimes 2_1^+]$
	2_4^+	2.703	2.809	$6.3\%[2_2^+]_{QRPA} + 66.2\%[2_3^+]_{QRPA} + 17\%[2_1^+ \otimes 4_1^+] + 0.002\%[2_1^+ \otimes 2_1^+]_2 \otimes 2_1^+]$



Nucleus	I	J	$B(E2; I \to J)(W.u.)$ Exp.	$B(E2; I \to J)(W.u.)$ QPM	$B(M1; I \to J)(W.u.)$ Exp.	$B(M1; I \to J)(W.u.)$ QPM
^{124}Sn						
	2_1^+	g.s.	9.0(3)	9.3		
	2_2^+	g.s.	$0.012(^{+4}_{-8})$	0.036		
		2_1^+	$17(^{+5}_{-11})$	17.5	$0.0021(^{+8}_{-15})$	0.0031
	2_3^+	g.s.	$0.34(^{+11}_{-20})$	0.1		
		2_1^+	$0.18(^{+7}_{-11})$	6.1	$0.010(^{+3}_{-6})$	0.007
	2_4^+	g.s.	$0.046(^{+14}_{-5})$	0.01		
		2_1^+	0.22(6)	1.26	0.010(21)	0.002

small B(M1)

N. Tsoneva, LDGS Oslo, 2011

Conclusions

- PDR is a common feature of skin nuclei. It is **independent of the type of nucleon excess**. The PDR strength is **correlated with the size of the neutron or proton skin**.

- Low-energy dipole strength in ^{138}Ba (N=82) and ^{90}Zr(N=50) **is related to E1 strength**. Even though, in order to determine the pure dipole strength associated with neutron skin phenomenon, the fine structure of the fragmentation pattern should be studied. Even small **the magnetic (M1) contribution should be identified and subtracted**.

- In $^{104-134}$Sn **a new quadrupole mode** confined mainly in the energy region 2-4 MeV is identified. It might be considered forming a **Pygmy Quadrupole Resonance**.

  The nature of the PQR excitations is determined as isoscalar or mixed symmetry for smaller N/Z ratios and **different from the known Scissors Mode**.

- The **correlation of the Pygmy Quadrupole Resonance transition strength with the neutron or proton skin** thickness manifests itself via a transition from a neutron PQR to a proton PQR in ^{104}Sn, the mass region where the neutron skin reverses into a proton skin. **Summed low-energy B(E2) strengths in Sn isotopes** could be related to **N/Z ratios**.