EUROPEAN UNION

Structural Instruments 2014-2020

Competitiveness Operational Programme (COP)

Extreme Light Infrastructure - Nuclear Physics (ELI-NP) – Phase II

Nuclear Photonics 2025

October 6 - 10, 2025 in Darmstadt, Germany

What can we learn from studying PDR and GDR with microscopic theory including phonon coupling

N. Tsoneva

eli nuclear physics

IFIN-HH

Content

Motivation

The Theoretical Model

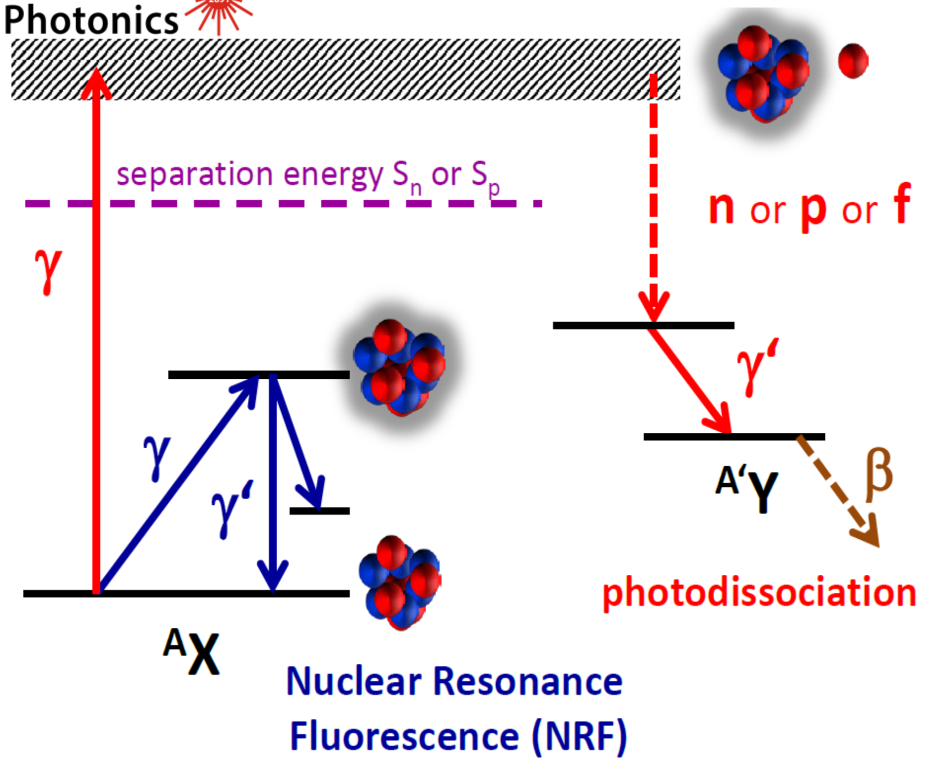
- Phenomenological EDF approach extened with three-phonon QPM theory.

Nuclear response on external EM and hadronic fields

- Two-phonon states, pygmy and giant resonances: Are the pygmy resonances related to the access of neutrons in nuclei?
- Spectroscopic properties of the PDR derived with different probes and techniques. Multi-configuration mixing and branching ratios. Fine structure of PDR.
- First study of the γ-strength functions in ^{112,114}Sn by using the Oslo method at ELI-NP&IFIN-HH. EQPM interpretation of the experimental data.
- γ-decay of GDR in ^{112}Sn.
- Testing the role of the quasicontinuum below the neutron threshold: (γ,γ’) vs. (p,p’).

Conclusions and Outlook

Nuclear Structure Studies with Photonuclear Reactions



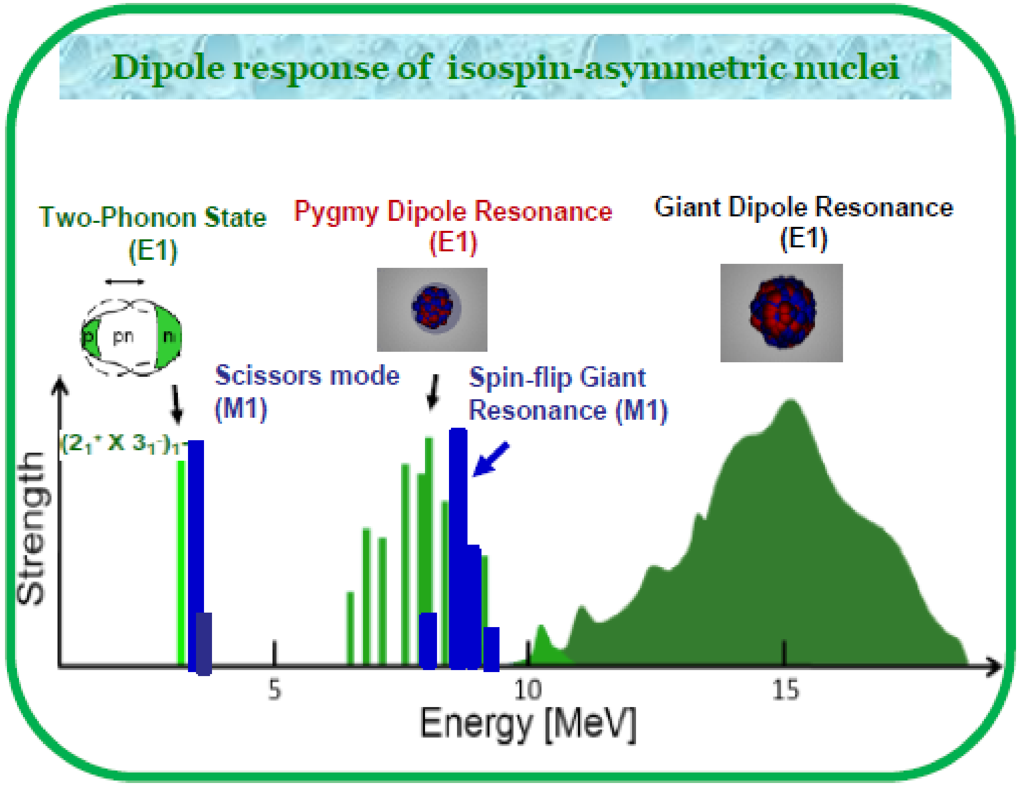
- Two-Phonon 1^- Excitation: B(E1) ~ 10^{-3} W.u.
- Pygmy Dipole Resonance: B(E1) ~ 0.5 W.u.
- Giant Dipole Resonance : B(E1) ~ 5 - 12 W.u.

GDR: M.N. Harakeh, A. van der Woude, Giant Resonances, Oxford University Press (2001).
PDR: D. Savran, T. Aumann, A. Zilges, PPNP 70, 210 (2013).
A. Bracco, F.C.L. Crespi, E.G. Lanza, EPJA 51, 99 (2015).
QOS: U. Kneissl, N. Pietralla, and A. Zilges, J. Phys. G32, R217 (2006).

Quasimonoenergetic, highly polarized γ beams at the High-Intensity γ -Ray Source (**HIγ S**) operated by the Triangle Universities Nuclear Laboratory (**TUNL**) in Durham, North Carolina, USA.

The γ-beam system at ELI-NP (under construction)

NRF experiments will play a special role at the ELI-NP facility involving detailed high-resolution studies of the dipole strength distribution in the region of the PDR and giant dipole resonances GDR.



Theory of nuclear ground and excited states: Model Hamiltonian

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The QPM Hamiltonian:

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

HFB

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

$$H = \sum_{\lambda\mu i} \omega_{\lambda i} Q^+_{\lambda\mu i} Q_{\lambda\mu i} + \frac{1}{2} \sum_{\lambda_1\lambda_2\lambda_3 i_1 i_2 i_3 \mu_1\mu_2\mu_3} C^{\lambda_3-\mu_3}_{\lambda_1\mu_1\lambda_2\mu_2} \times U^{\lambda_2 i_2}_{\lambda_1 i_1}(\lambda_3 i_3)[Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2} Q_{\lambda_3-\mu_3 i_3} + h.c.],$$

The QPM basis is built of phonons:

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

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

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

The phonons are not 'pure' bosons:

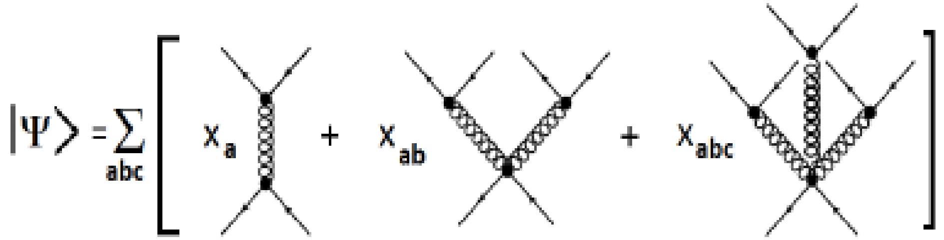
$$\left[Q_{\lambda\mu i}, Q^+_{\lambda'\mu' i'}\right] = \delta_{\lambda\lambda'}\delta_{\mu\mu'}\delta_{ii'} + \text{fermionic corrections} \sim \alpha^+_{j_1 m_1}\alpha_{j_2 m_2}$$

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

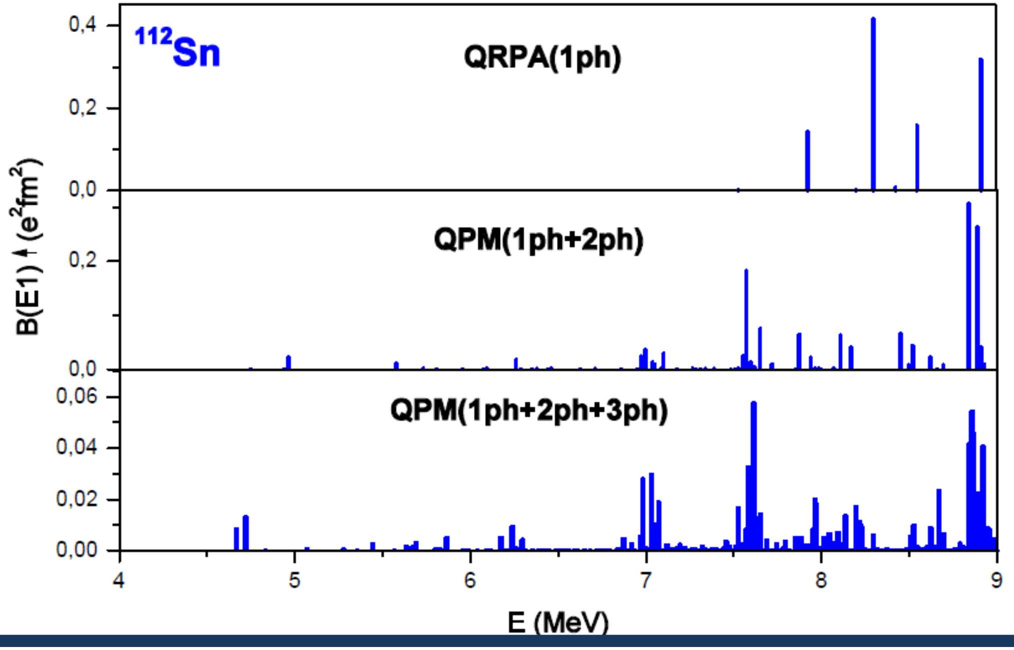
Multi-Configuration Multi-Quasiparticle Wave Function



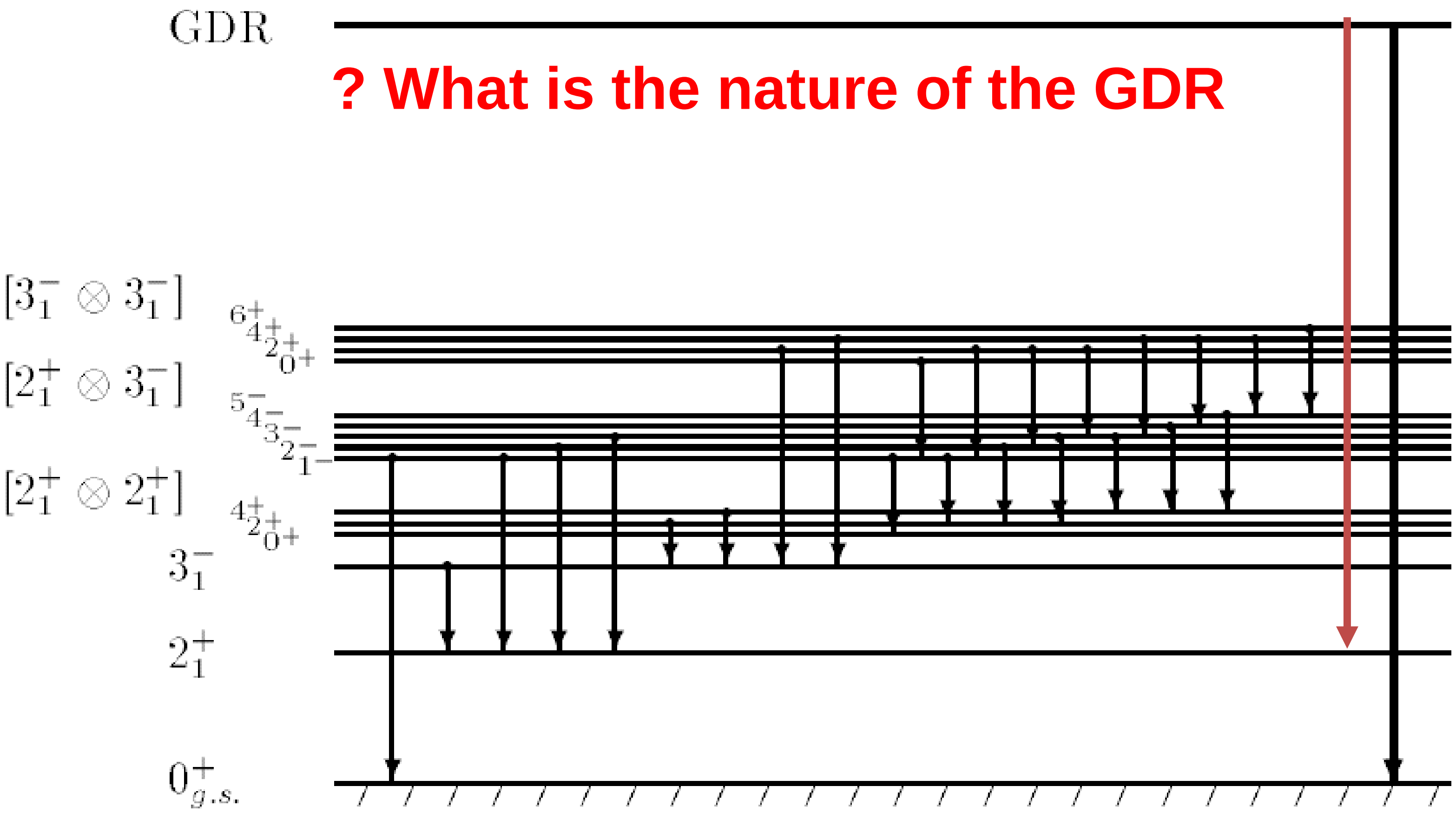
$$\Psi_\nu(JM) = \Bigg\{ \sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_1 \mu_1 i_1} \otimes Q^+_{\lambda_2 \mu_2 i_2} \right]_{JM} \quad (1)$$

$$+ \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2 \\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(J\nu) \left[\left[Q^+_{\lambda_1 \mu_1 i_1} \otimes Q^+_{\lambda_2 \mu_2 i_2} \right]_{IK} \otimes Q^+_{\lambda_3 \mu_3 i_3} \right]_{JM} \Bigg\} \Psi_0 \quad (2)$$

- 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**



Electromagnetic Transitions Beyond the Quasiboson Approximation



$$M(X\lambda) = \left\langle \Psi_f \left\| T(X\lambda) \right\| \Psi_i \right\rangle$$

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

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

J. Kleemann, N. Pietralla et al., PRL134 022503 (2025)
Gamma-decay of the IVGDR in ^{154}Sm

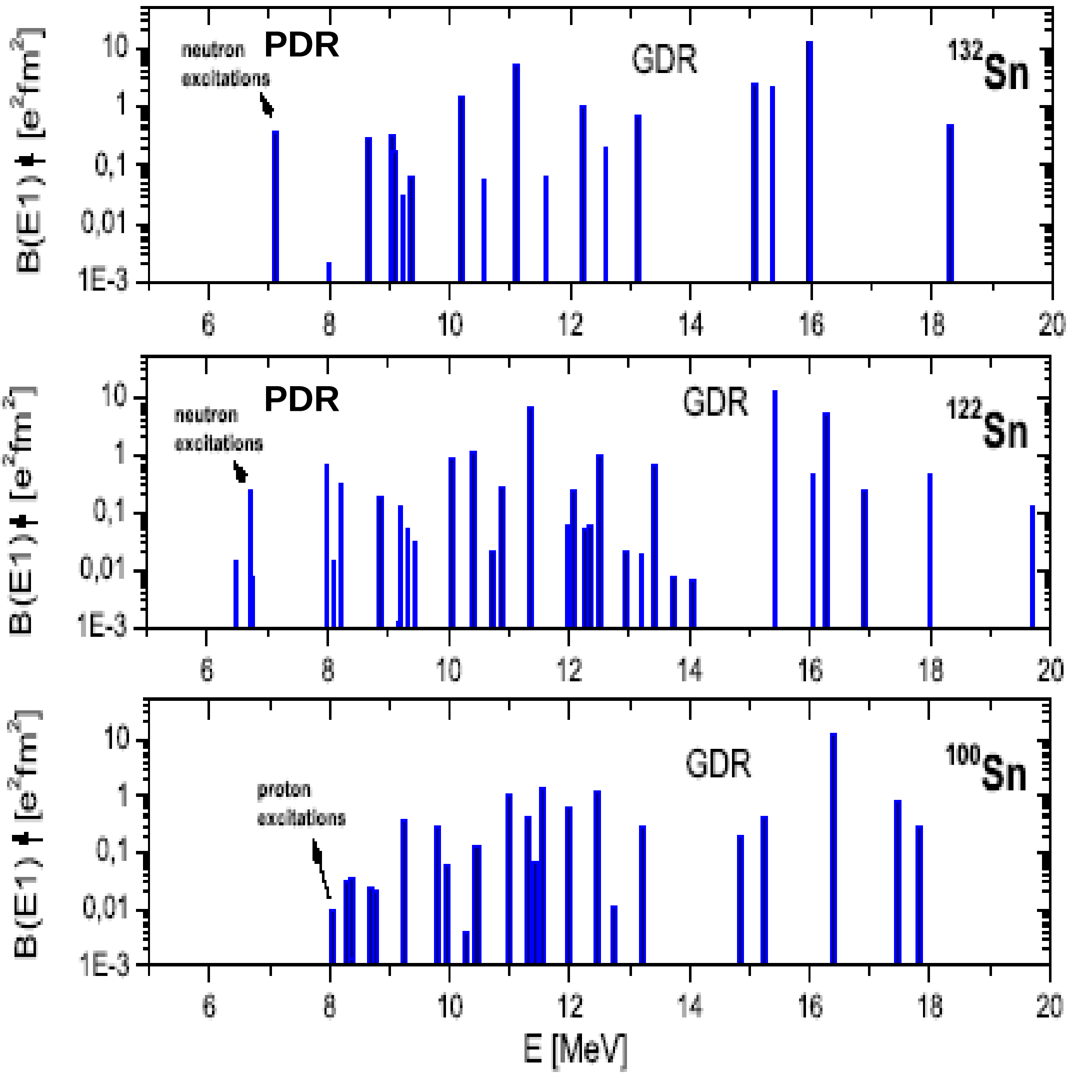
V. Ponomarev, Ch.Stoyanov, N. Tsoneva , M. Grinberg, Nucl. Phys. A 635, 470 (1998);
M. Grinberg, Ch. Stoyanov, N. Tsoneva, Phys. of Elem. Part. and At. Nucl., vol. 29 part. 6, 1456-1498 (1998).

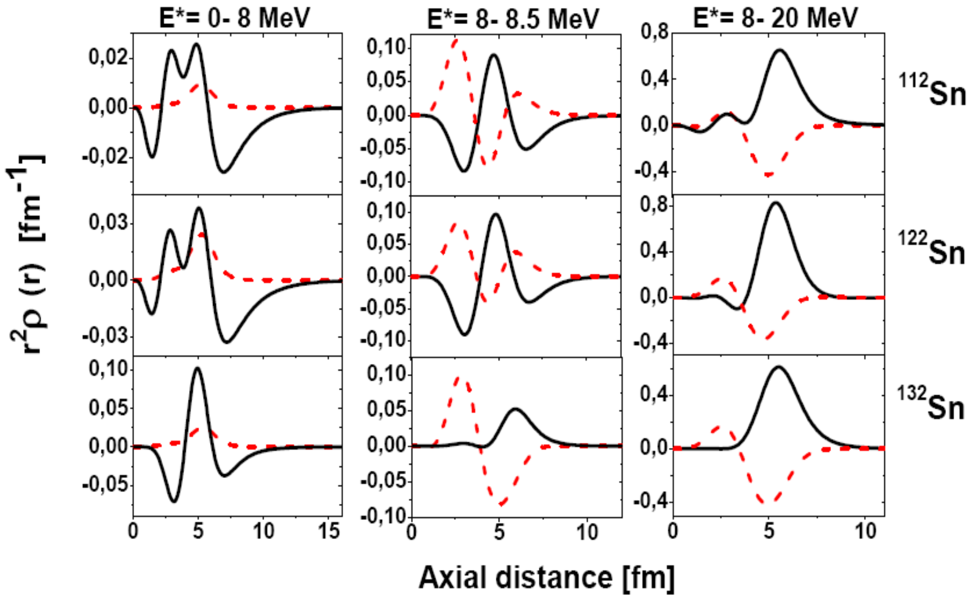
QRPA calculations on the dipole response in Sn Isotopes

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

H. Lenske, N.Tsoneva, Eur. Phys. J. A (2019) 55: 238 (2019)

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





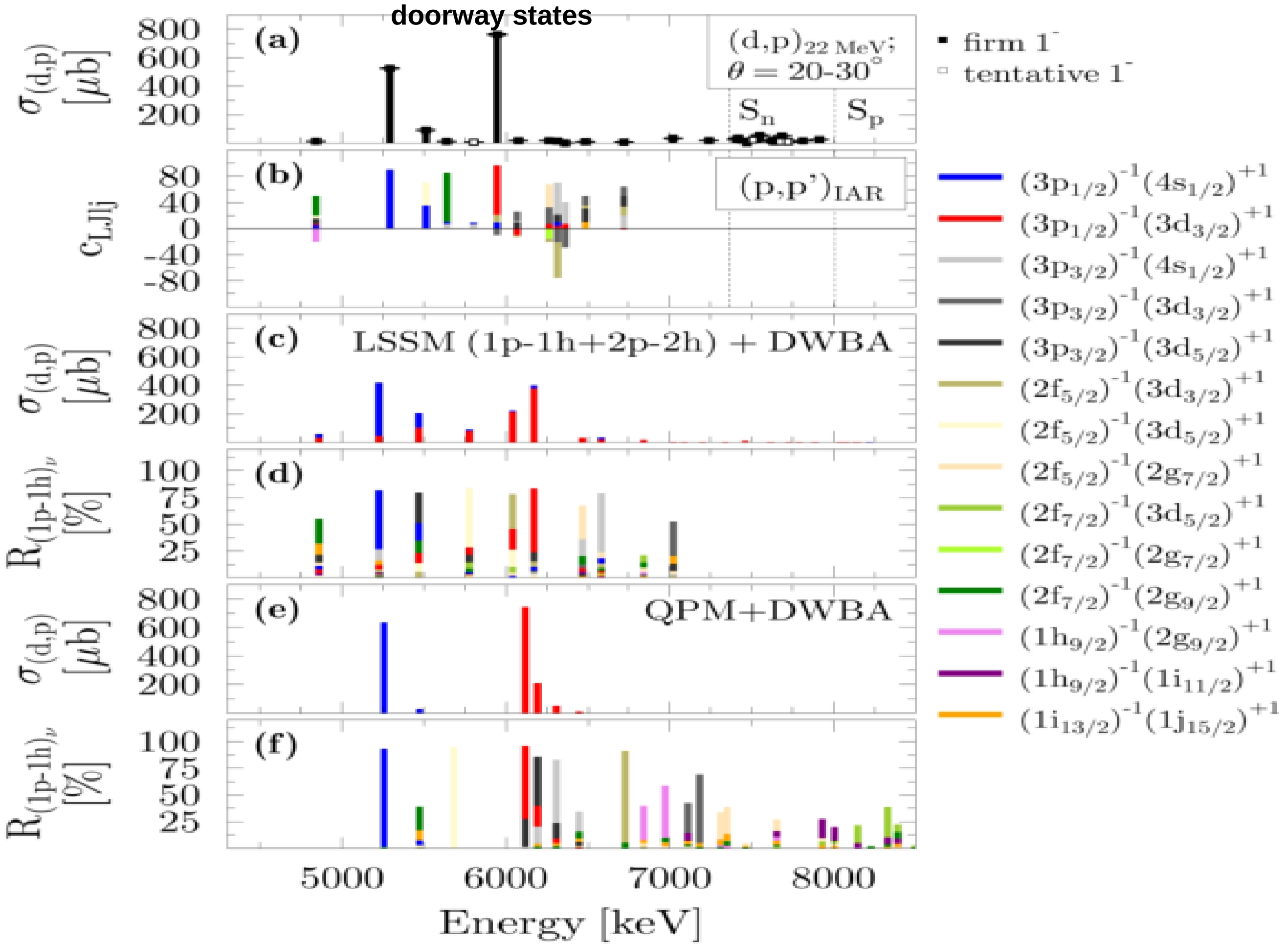
Relation between the non-energy weighted dipole sum rule and the skin measure

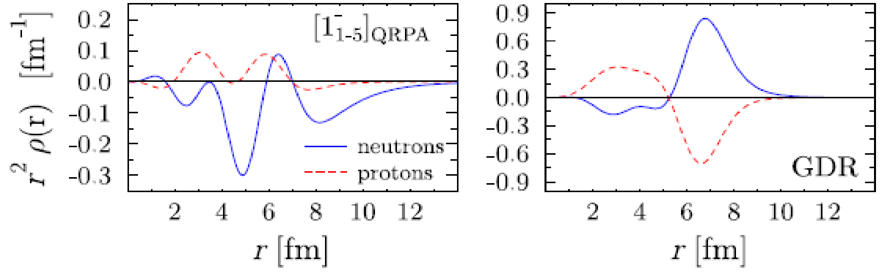
$$\Delta_3 r^2 = \frac{1}{4q_0 q_1}\left(\sum_d B_d(E1) - q_0^2 \sum_d \left|M_d^{(0)}\right|^2 - q_1^2 \sum_d \left|M_d^{(1)}\right|^2\right)$$

Accessing the Single-Particle Structure of the Pygmy Dipole Resonance in ^{208}Pb

M. Spieker, A. Heusler, B. A. Brown, T. Faestermann, R. Hertenberger, G. Potel, M. Scheck, N. Tsoneva, M. Weinert, H.-F. Wirth, and A. Zilges, **Phys. Rev. Lett. 125, 102503 (2020)**

Unprecedented access to the theoretical wave functions demonstrating the 1p-1h neutron origin of the PDR in ^{208}Pb





[B.A. Brown (LSSM) and N. Tsoneva (QPM)]

- Below S_n:

$$\sum \sigma_{(d,p);\mathrm{exp.}} = 1524(17)\ \mu b$$

$$\sum \sigma_{(d,p);\mathrm{LSSM}} = 1470\ \mu b$$

$$\sum \sigma_{(d,p);\mathrm{QPM}} = 1676\ \mu b$$

- Above S_n and up to S_p:

$$\sum \sigma_{(d,p);\mathrm{exp.}} = 254(9)\ \mu b$$

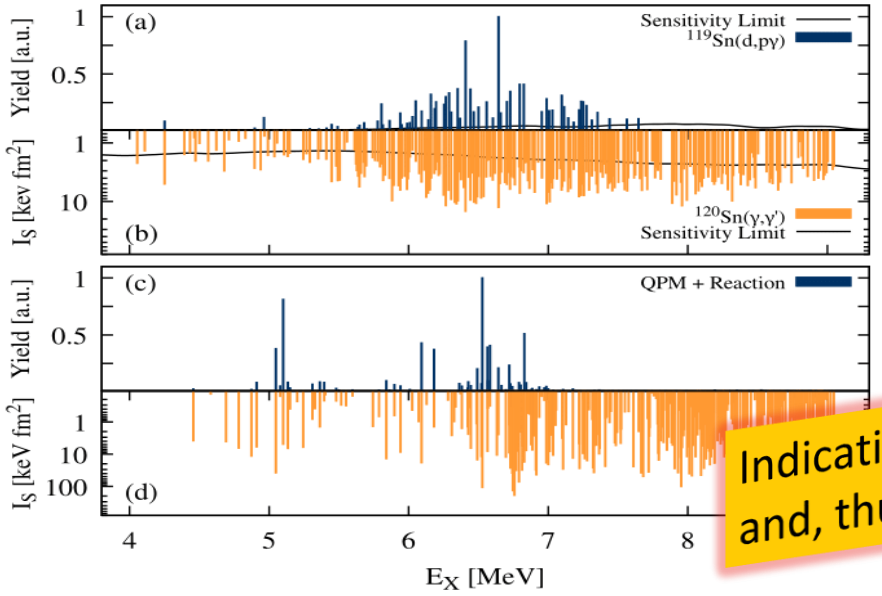
$$\sum \sigma_{(d,p);\mathrm{LSSM}} = 22\ \mu b$$

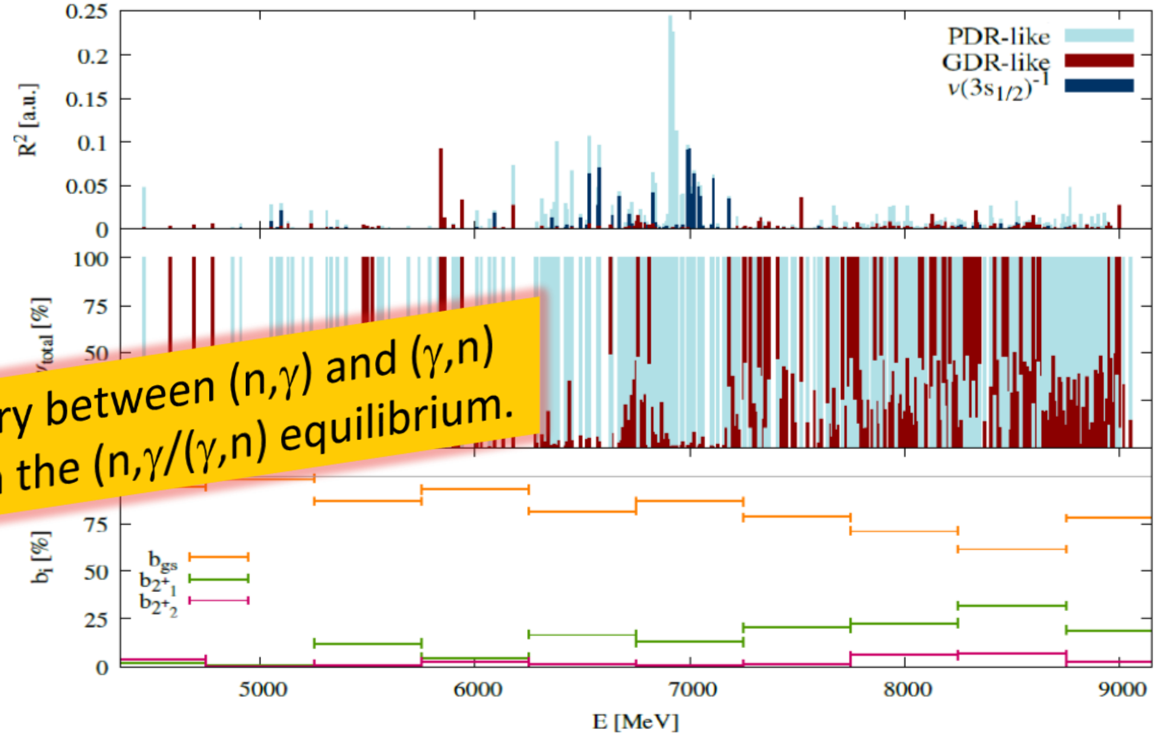
^{207}Pb(d,p)^{208}Pb @ Q3D at MLL (Garching, Germany)

Single-Particle Structure of the Pygmy Dipole Resonance in ^{120}Sn

M. Weinert, M. Spieker, G. Potel, N. Tsoneva, M. Müscher, J. Wilhelmy and A. Zilges, PRL 127, 242501 (2021)

EDF+QPM+reaction theory





Indication of asymmetry between (n,γ) and (γ,n) and, thus, influence on the (n,γ/(γ,n) equilibrium.

$$\frac{d\sigma_\nu}{d\Omega}(\theta) = \frac{\mu_i\mu_f}{(2\pi\hbar^2)^2}\frac{k_f}{k_i}\times \Bigg| u_{3p_{1/2}} R_{3p_{1/2}}(\nu)\, \psi^{3\,p_{1/2}}_{\frac{1}{2}\frac{1}{2}}\, \mathcal{T}_{p_{1/2}}(\theta) + u_{3p_{3/2}} R_{3p_{3/2}}(\nu)\, \psi^{3\,p_{3/2}}_{\frac{1}{2}\frac{3}{2}}\, \mathcal{T}_{p_{3/2}}(\theta) \Bigg|^2$$

E_{cm} for $3p_{3/2}$ and $3p_{1/2}$: E_{cm}^{exp}=6.49 MeV;
E_{cm}^{QPM} = 6.32 MeV.
Summed energy-integrated cross section:
NRF data: $\sum I_s^{NRF}$ =337(21) keV , (d,pγ) yield >1%
$\sum I_S^{QPM}$ = 243 - 360 keV fm^2 for 1^- states with (d,pγ) yield >1% and >0.5%.

Comprehensive study of the electric and magnetic dipole strength in semi-magic ^{50}Ti

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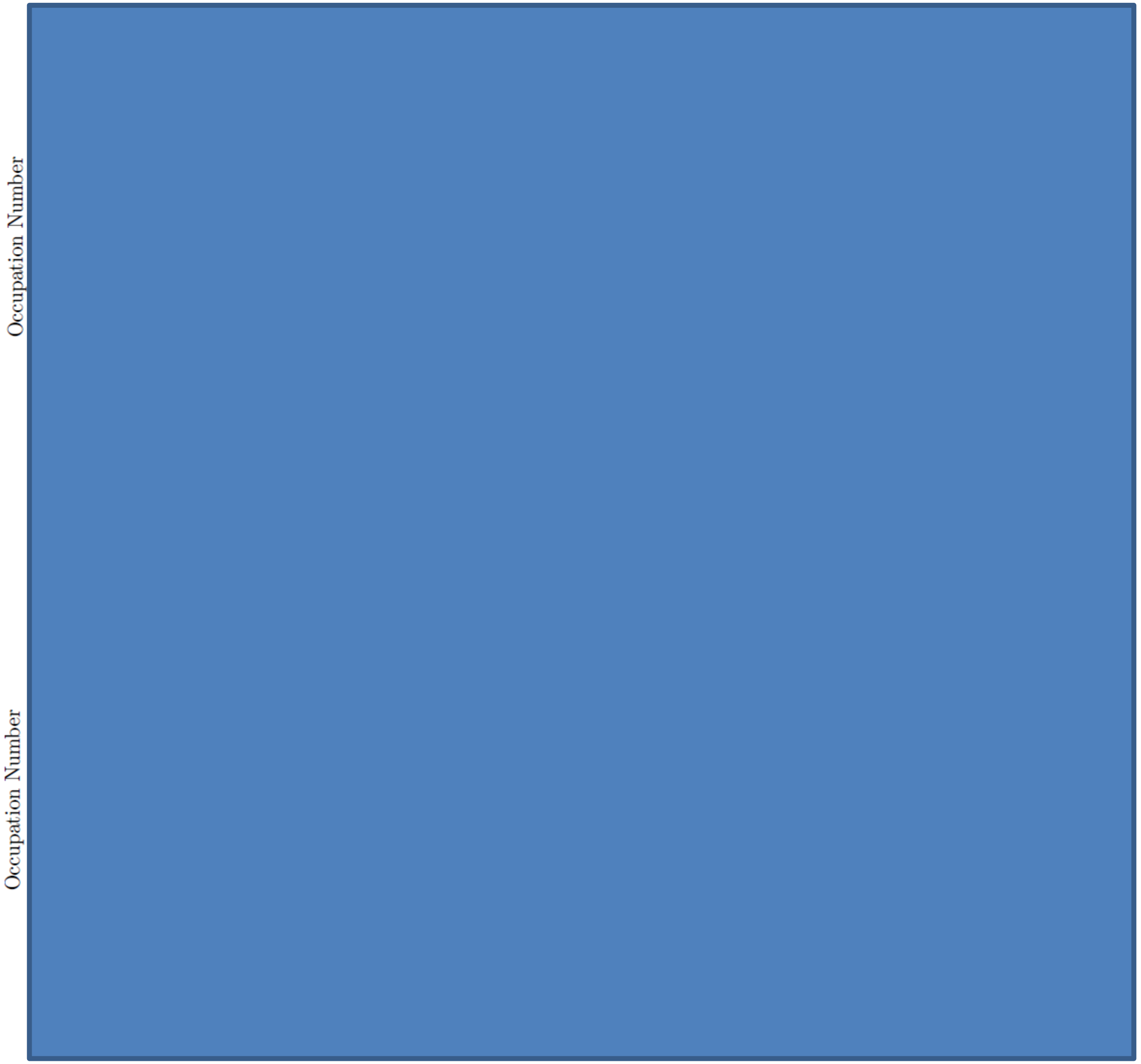

The study combines data from single-neutron transfer (d, p) obtained at the FSU John D. Fox Laboratory and real-photon scattering experiments from TU Darmstadt, and the HIGS facility of TUNL, which allowed us to map out the B(E1) and B(M1) strength fragmentation up to the neutron-separation energy, and to gain access to associated spectroscopic factors determined in (d,p). The experimental results are compared with three-phonon EQPM incl. configuration space with $J^{\pi}=1^{+,-}$-$6^{+,-}$

A detailed view at magnetic dipole strengths: The case of semi-magic ^{50}Ti
B. Kelly,U. Friman-Gayer, M. Spieker, L.T. Baby, A.L. Conley, J. Isaak,
E. Litvinova, H. Pai, N. Pietralla, N. Tsoneva, A. Volya, and V. Werner,
in preparation for submission.

Investigating the microscopic structure of the PDR near the N =50 region,
T. C. Khumalo, L. Pellegri, A. Spatafora, D. Carbone, M. Cavallaro, F. Cappuzzello,
N. Tsoneva, et al., in preparation.

^{97}Mo(p,d)^{96}Mo and ^{95}Mo(d,p)^{96}Mo transfer reactions were carried out using the MAGNEX magnetic spectrometer at INFN-LNS to test the PDR and its relationship to neutron skin oscillations. Extracted from measurements, model-dependent spectroscopic factors are compared with the three-phonon (EQPM) ones, in preparation for submission.

with the courtesy of B. Kelly and M. Spieker, FSU 2025

Study of the γ-strength function in ^{112,114}Sn at ELI-NP&IFIN-HH

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P-A Söderstöm, M. Markova, N. Tsoneva, et al., Phys. Rev. C (2025)

N. Tsoneva, Nucl. Phys. A 1060, 123114 (2025).

Total EDF+QPM dipole strength below the neutron separation threshold $\mathbf{S_n}$:

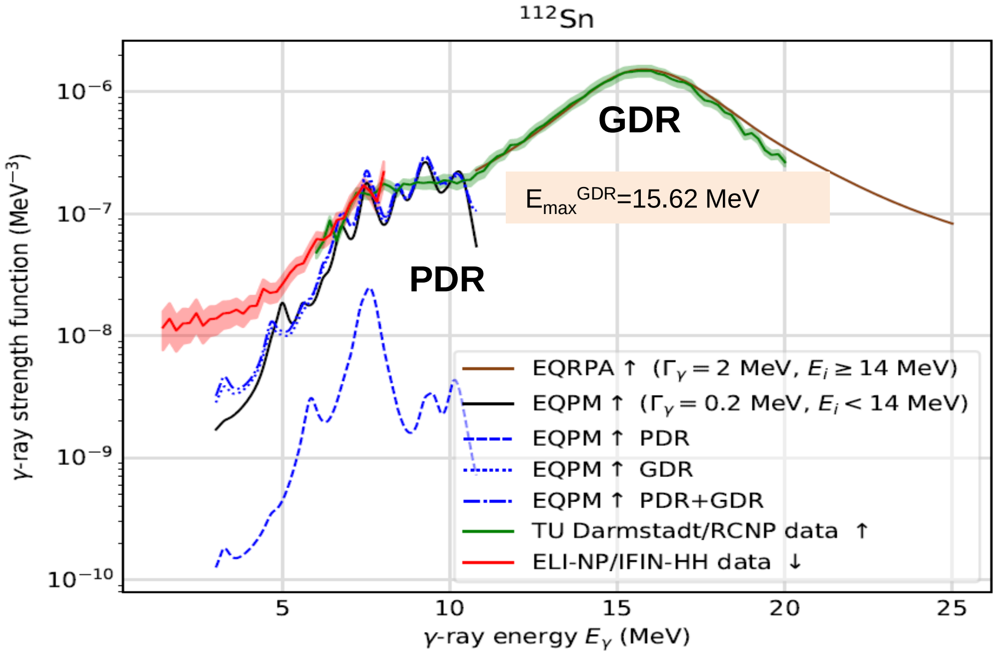
$\sigma_{EQPM}(E1)E_n$ = 127.3 mb·MeV in ^{112}Sn and $S_n\sigma_{EQPM}(E1)En$ = 107.3 mb·MeV in ^{114}Sn,

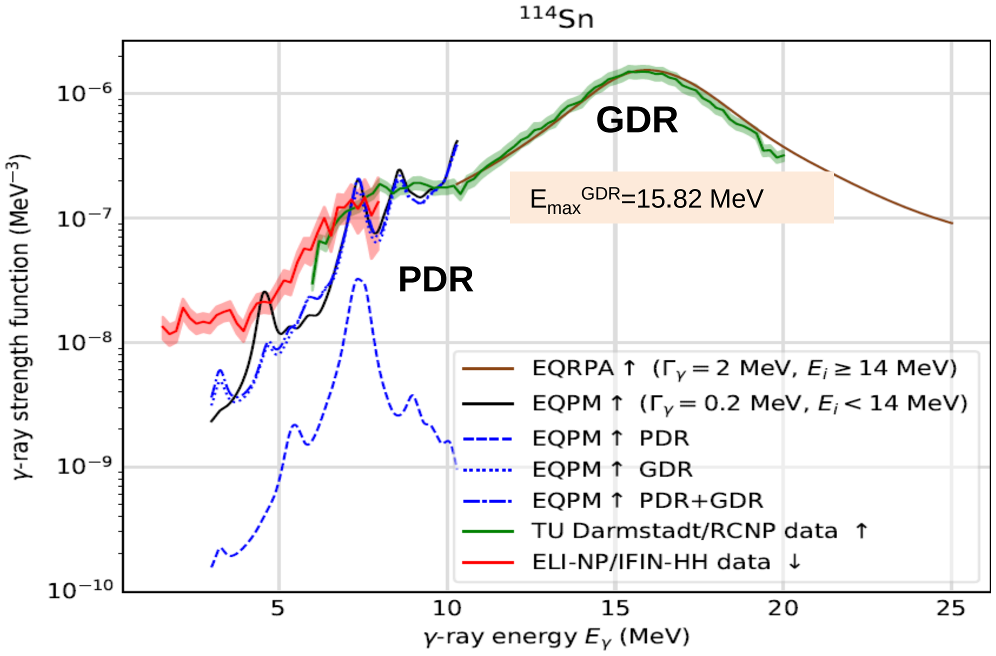
Experimental strength, below S_n :

$\sigma_{exp}(E1)E_n$ = 110(8) mb·MeV (^{112}Sn) and $\sigma_{exp}(E1)E_n$ = 91(8) mb·MeV in ^{112}Sn

From the calculation of the integrated pure PDR peak from the EQPM, we see that the total PDR strength increases with increasing neutron number, from 4.38 mb·MeV (^{112}Sn) (0.26% of the TRK EWSR) to 4.70 mb·MeV (^{114}Sn) (0.28% of the TRK EWSR), as expected, while the total lowßenergy dipole strength is decreasing due to the admixture of more complex configurations and the GDR.

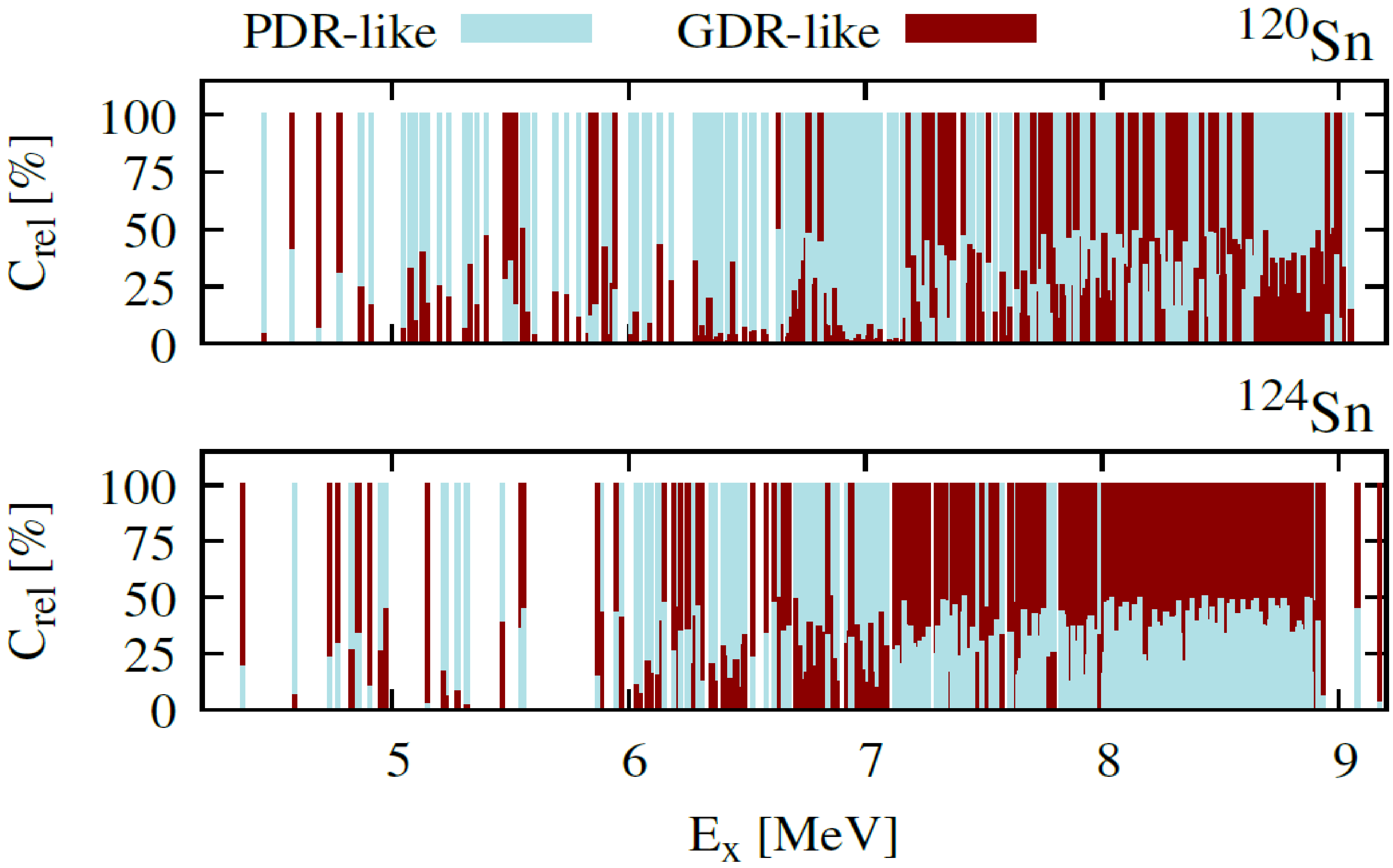
PDR strength increases with N number!





EQPM calculations of PDR and GDR counterparts to low-energy the 1- states in $^{120,124}Sn$

M. Weinert, M. Spieker, G. Potel, N. Tsoneva, M. Müscher, J. Wilhelmy and A. Zilges, PRL 127, 242501 (2021);



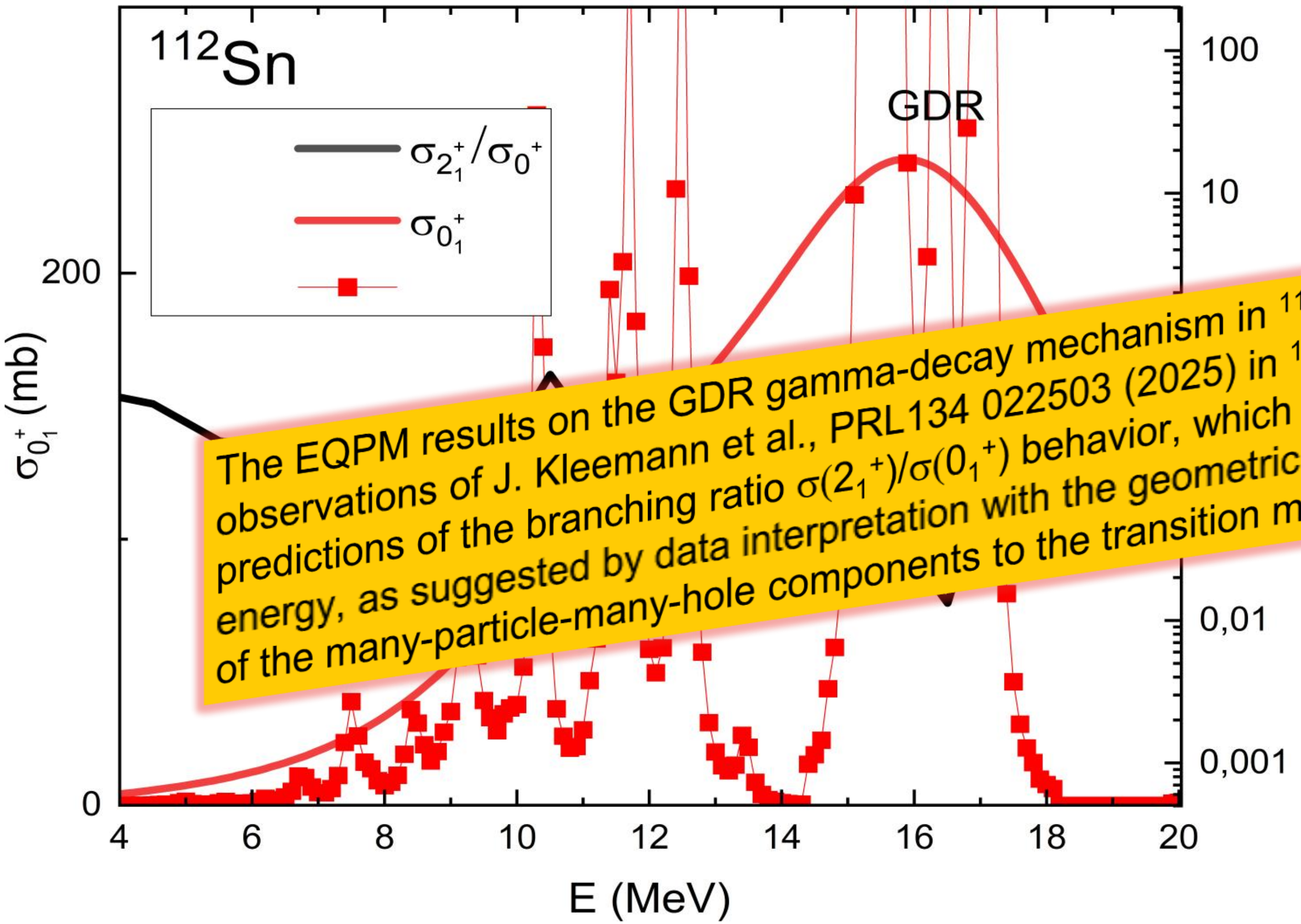
E^{GDR}_{max}= 15.40 MeV

E^{GDR}_{max}= 15.28 MeV

EQPM studies of the PDR and GDR decay properties

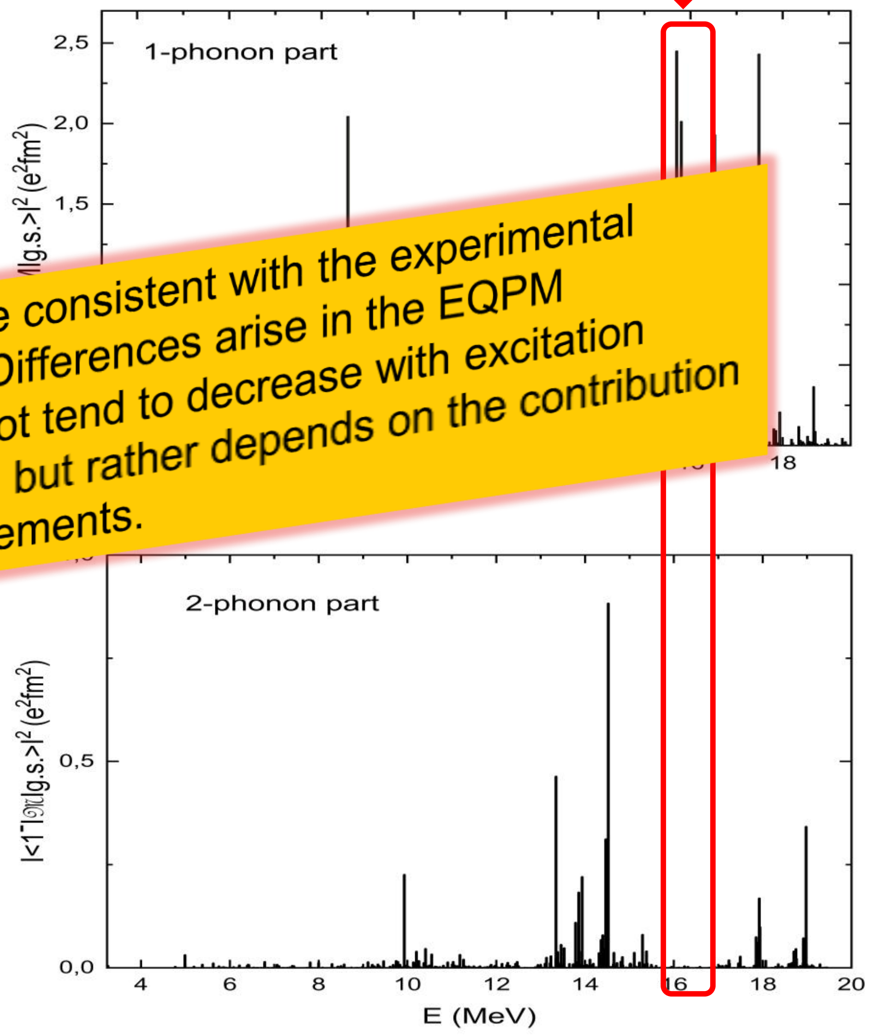
N. Tsoneva, in preparation

2-phonon EQPM calculations, model space of natural parity states with J=1-4



The EQPM results on the GDR gamma-decay mechanism in ^{112}Sn are consistent with the experimental observations of J. Kleemann et al., PRL134 022503 (2025) in ^{154}Sm. Differences arise in the EQPM predictions of the branching ratio $\sigma(2_1^+)/\sigma(0_1^+)$ behavior, which does not tend to decrease with excitation energy, as suggested by data interpretation with the geometric model, but rather depends on the contribution of the many-particle-many-hole components to the transition matrix elements.

γ-decay of the GDR through 1ph 1^- collective states



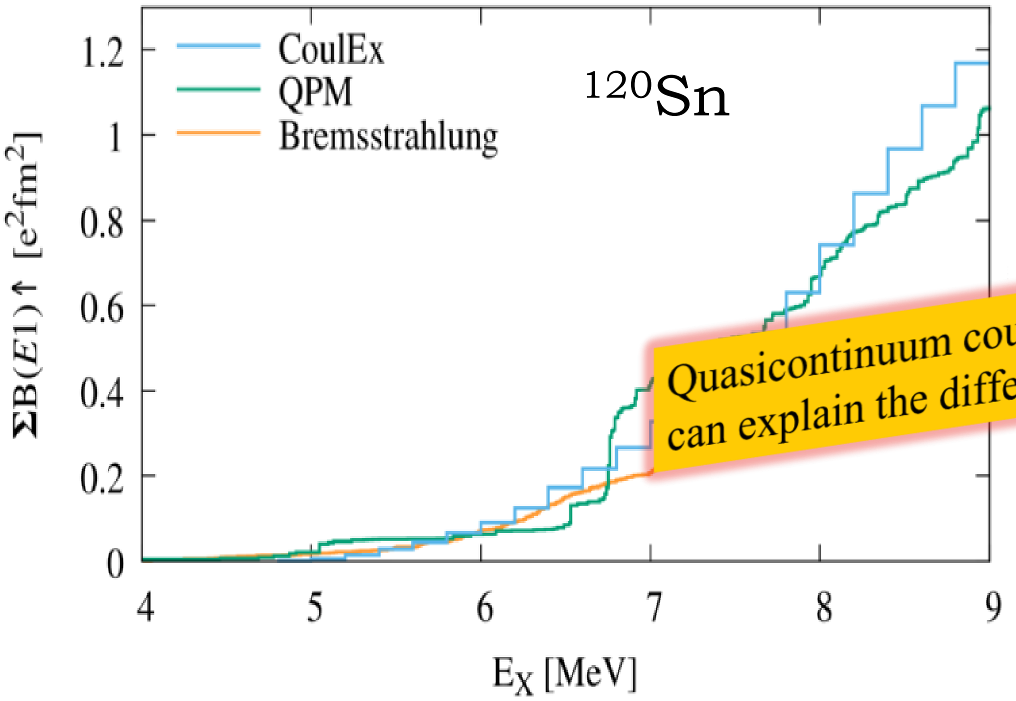
Electric dipole photoabsorption: (γ,γ´) vs. (p,p´)

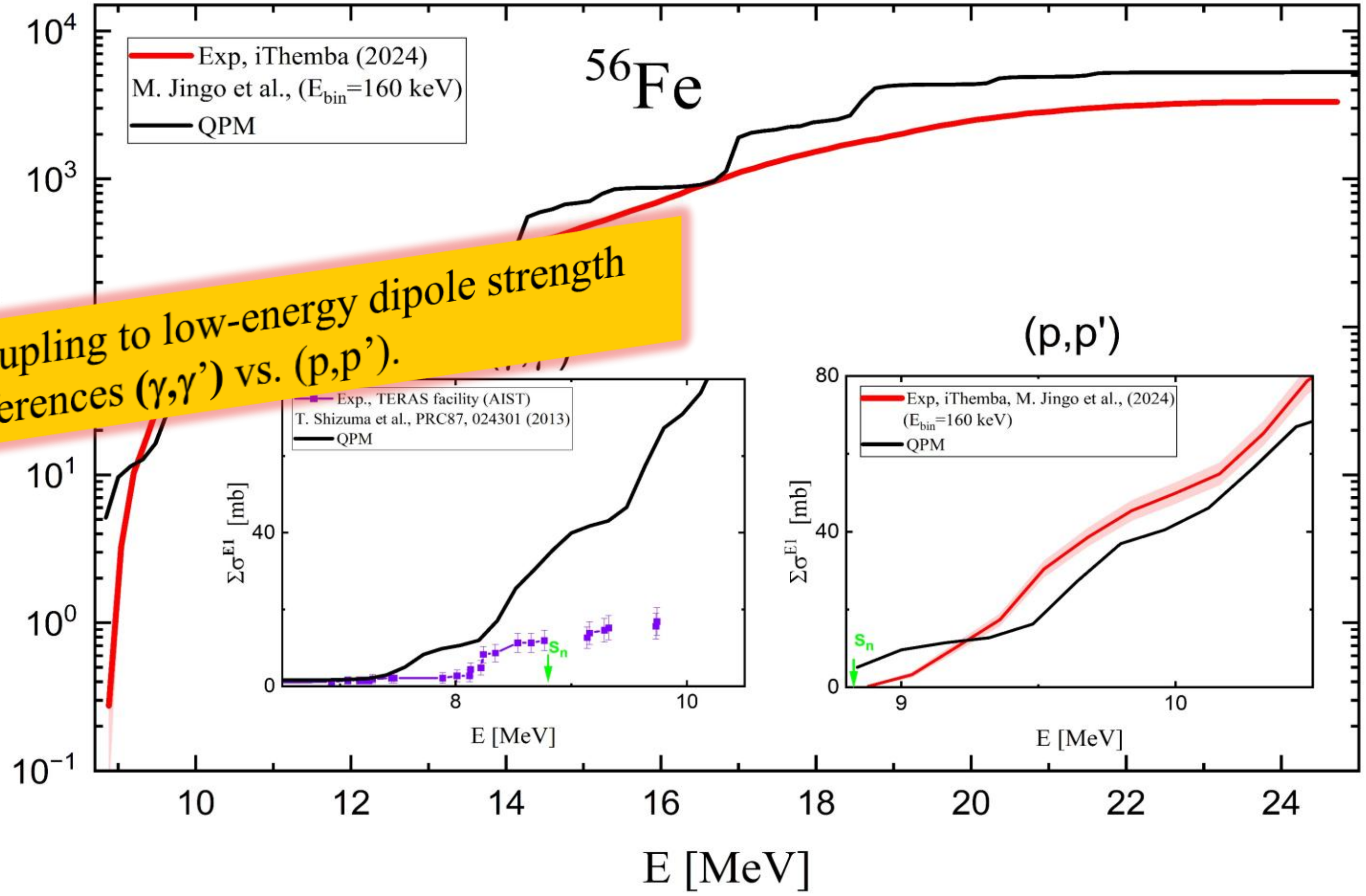
M. Müscher et al., PRC 102, 014317 (2020)

N. Tsoneva, A. Ramirez, A. Tonchev, J. Silano, R. Schwengner at al., in preparation

M. Weinert, M. Spieker, G. Potel, N. Tsoneva, M. Müscher, J. Wilhelmy and A. Zilges, PRL 127, 242501 (2021)

B(E1)↑ running sums from (γ,γ') and (p,p')-CoulEx



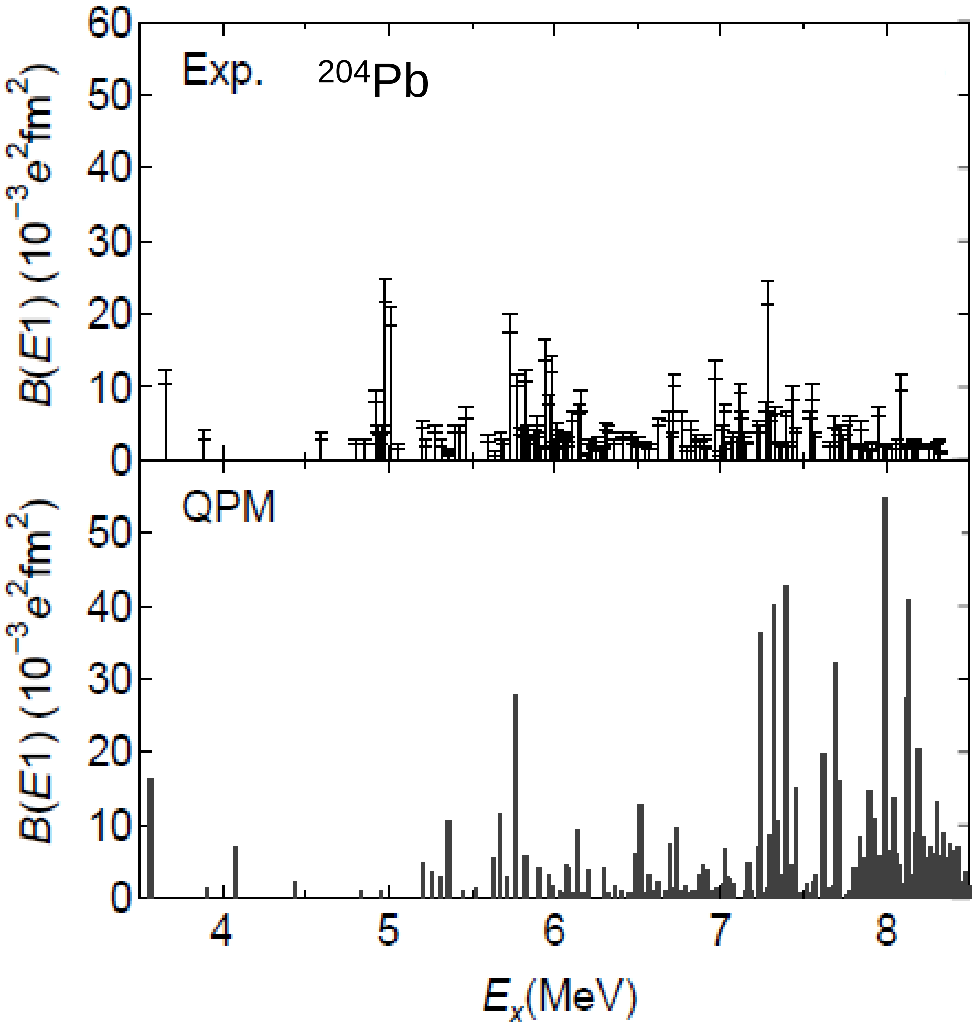


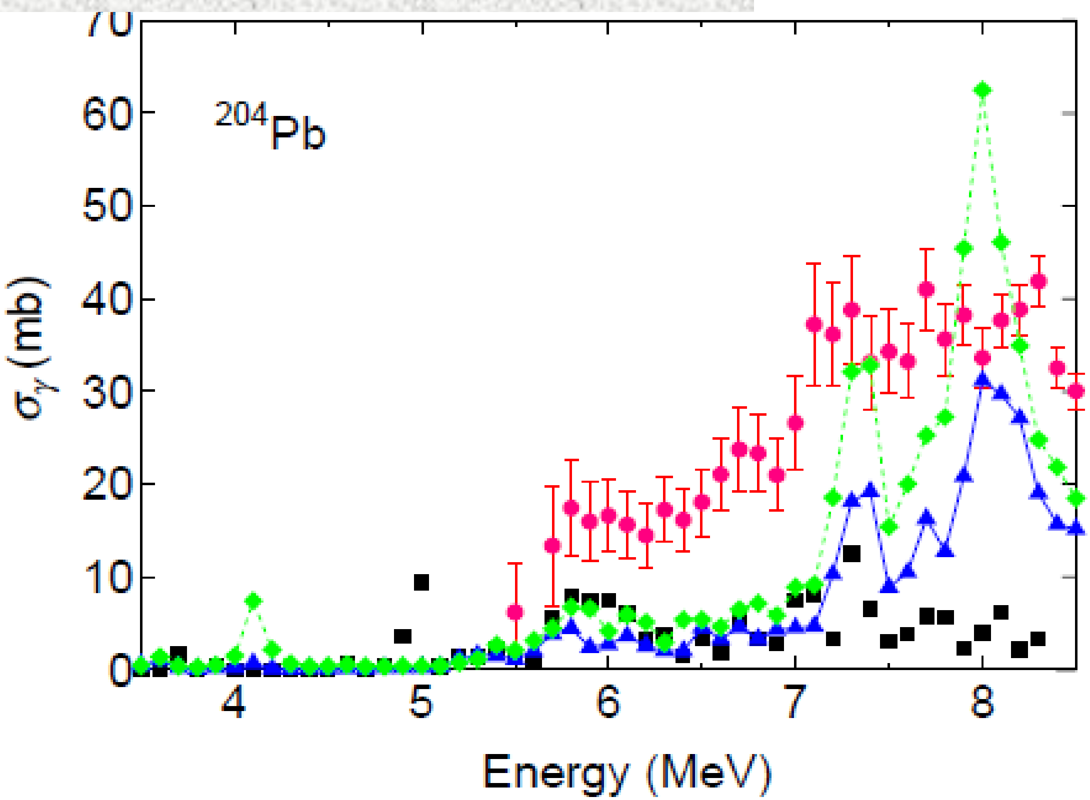
Quasicontinuum coupling to low-energy dipole strength can explain the differences (γ,γ') vs. (p,p').

QPM reproduces CoulEx data nicely!

Contribution of the quasicontinuum to the low-lying dipole strength in ^{204}Pb

T. Shizuma, S. Endo, A. Kimura, R. Massarczyk, R. Schwengner, R. Beyer, T. Hensel, H. Hoffmann, A. Junghans, K. Römer, S. Turkat, A. Wagner, and N. Tsoneva, Phys. Rev. C 106, 044326 (2022)





Exp.: γ-ray absorption cross sections derived from resolved peaks **(squares)** and from the quasicontinuum analysis **(red circles),** averaged over energy bins of 100 keV;
EDF+ 3-phonon QPM confined in the NRF energy domain (blue triangles) and extended EDF+2-phonon QPM (green diamonds) calculations, smeared by the Lorentzian width of 100 keV.

Conclusions & Outlook

A theoretical semi-microscopic approach based on EDF+QPM and nuclear reaction theory is applied in studies of nuclear structure properties and dynamics of nuclear excitations up to GDR energies:

-> enables a uniform description of multiphonon states, pygmy and giant resonances with the highest precision;

-> EQPM plus reaction theory studies of PDR - (γ,γ') vs. (d,p): 1p-1h coherently exci[illegible] neutron states, located in a confined energy region

-> Studies on PDR strength in ^{112}Sn and ^{114}Sn: total PD[illegible] ng[illegible] the [illegible]RK sum rule; the PDR strength increases wi[illegible] er, t[illegible] pole strength below the neutron threshold depends on the coupl[illegible]

Thank you !

-> The two-phonon EQPM predic[illegible] R g-decay in ^{112}Sn: through 1ph 1-collective states, with almost no contribution from 2ph compon[illegible]. The results do not support the concept of γ-decay of the isovector GDR through a compound nucleus.

-> Differences arise in the EQPM predictions and geometrical model interpretation of experimental data in ^{154}Sm of the branching ratio $\sigma(2_1^+)/\sigma(0_1^+)$, which does not tend to decrease with excitation energy, but rather depends on the contribution of the many-particle-many-hole components to the transition matrix elements.

-> Branching ratios to ground and excited <-> multi-particle-multi-hole configuration mixing;

-> Quasicontinuum coupling to low-energy dipole strength can explain the differences **(γ,γ')** vs. (p,p').