EUROPEAN UNION

European Center for Theoretical Studies
in Nuclear Physics and Related Areas (ECT*)

Giant and soft modes of excitation in nuclear structure and astrophysics

24 October 2022 — 28 October 2022

A Microscopic Approach to the Study of Pygmy and Giant Resonances

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Extreme Light Infrastructure-Nuclear Physics

eli nuclear physics

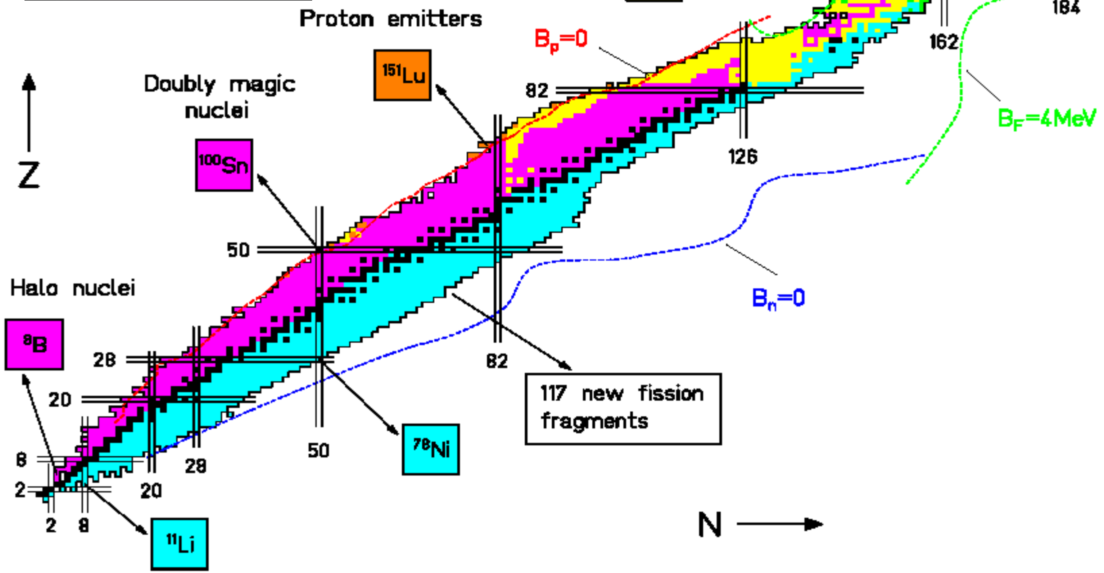
IFIN-HH

AGENDA

- Introduction
- The Theoretical Model
  - Phenomenological EDF approach of nuclear ground states
  - Three-phonon QPM + reaction theory
- Theoretical Results
  - Accessing the single-particle and of the pygmy dipole resonance
  - Multi-configuration mixing of pygmy dipole and pygmy quadrupole resonances
  - Branching ratios
  - Impact of quasicontinuum on low energy dipole strength
  - First theoretical evidence of PDR built on excited states
  - Pygmy resonanses and stellar nucleosynthesis
- Conclusions and Outlook

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

ρ ~ $10^8/cm^3$

life time

τ ~ 1 – 10 years

r – process - rapid neutron captures

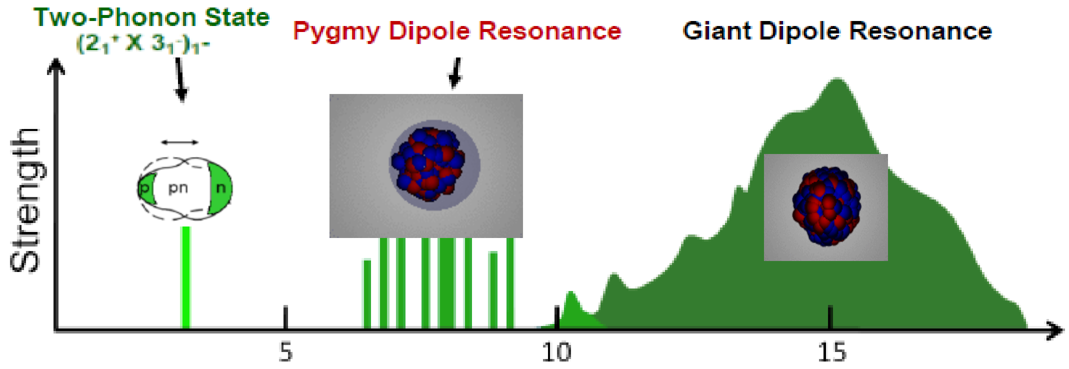
ρ ~ $10^{20}/cm^3$

Photons as Probes for Nuclear Structure

Electric Dipole Response

N. Tsoneva, H. Lenske, Physics of Atomic Nuclei, Vol. **79**, No. 6, pp. 885–903 (2016).
H. Lenske, N. Tsoneva, Eur. Phys. J. A (2019) 55: 238.

K. A. Tanaka,…,N.T. et al., Matter Radiat. Extremes **5, 024402 (2020).**



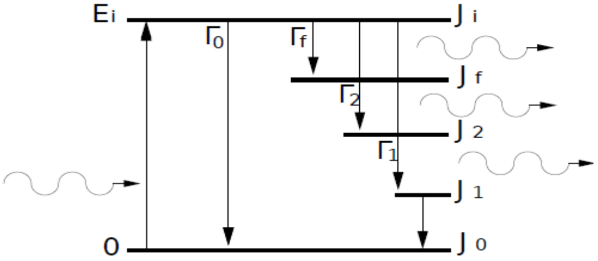
- **Two-Phonon 1^- Excitation: B(E1) ~ 10^{-3} W.u..**
- **Pygmy Dipole Resonance: B(E1) ~ 0.5 W.u.**
- **Giant Dipole Resonance : B(E1) ~ 5 - 12 W.u.**

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).

Nuclear Resonance Fluorescence (NRF)

VEGA γ-beam system at ELI-NP

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 pygmy dipole resonance (PDR) and giant dipole resonances (GDR) .



Density Functional Theory

N. Tsoneva, H. Lenske, Physics of Atomic Nuclei, Vol. **79**, No. 6, pp. 885–903 (2016).
H. Lenske, N. Tsoneva, Eur. Phys. J. A (2019) 55: 238.

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

A mapping of the complicated many-body problem to a simple one-body problem which preserves the local density ρ(r), the energy E(ρ) and quantities depending on ρ(r).

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

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

HF Mean-Field

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

Residual Interaction ⟹ **Nuclear Excitations**

The Model Hamiltonian

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; Physics of Atomic Nuclei, Vol. 79, No. 6, pp. 885–903 (2016);
H. Lenske, N. Tsoneva, Eur. Phys. J. A (2019) 55: 238.

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

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

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

Nuclear Ground State

Quasiparticle States

Phenomenological EDF approach based on a fully microscopic self-consistent Skyrme HFB theory.
In the QPM, the pairing part is simplified by using a constant matrix element.

Bogoljubov transformation to quasiparticles

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

Excited States

H_M^{ph} - separable multipole *p-h* interaction ;
H_{SM}^{ph} - separable spin-multipole *p-h* interaction ;
H_M^{pp} - separable multipole *p-p* interaction .

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:

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

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

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

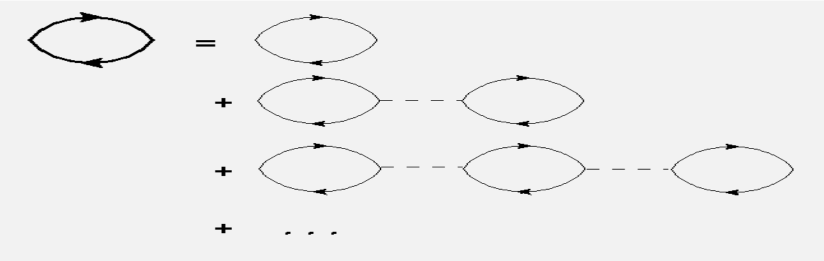
$$\left[Q_{\lambda\mu i}, Q^+_{\lambda'\mu' i'}\right] = \delta_{\lambda\lambda'}\delta_{\mu\mu'}\delta_{ii'} +$$

fermionic corrections

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

QRPA equations 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

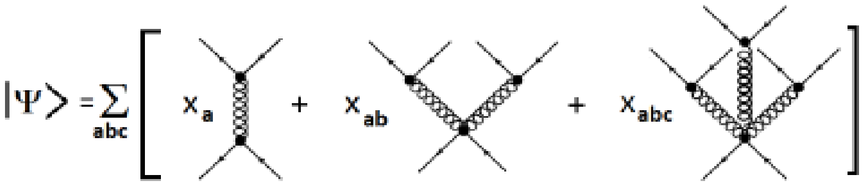
N. Tsoneva, H. Lenske, Physics of Atomic Nuclei, Vol. **79**, No. 6, pp. 885–903 (2016).

Multi-Configuration Multi-Quasiparticle Wave Function

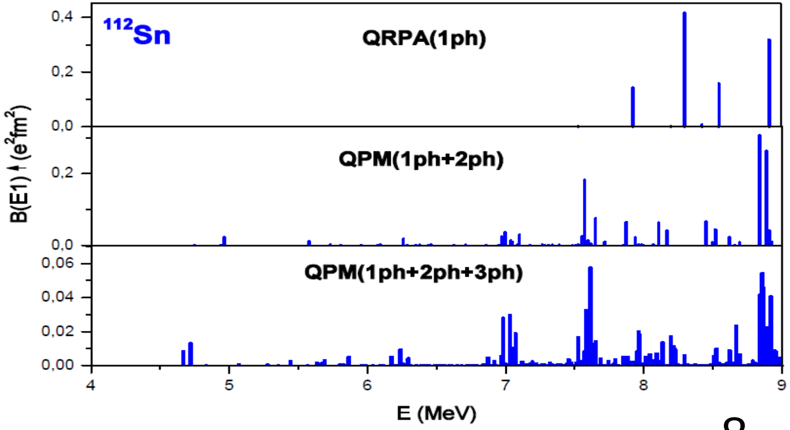
$$\Psi_\nu(JM) = \left\{ \sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_1 \mu_1 i_1} \otimes Q^+_{\lambda_2 \mu_2 i_2} \right]_{JM} \right. \quad (1)$$

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

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



- Basis of QRPA phonons
- „ph“ and „pp“- type configurations
- Pauli principle, orthogonality
- Core polarization effects
- Large multi-particle-multi-hole configuration space
- SPECTRAL FRAGMENTATION



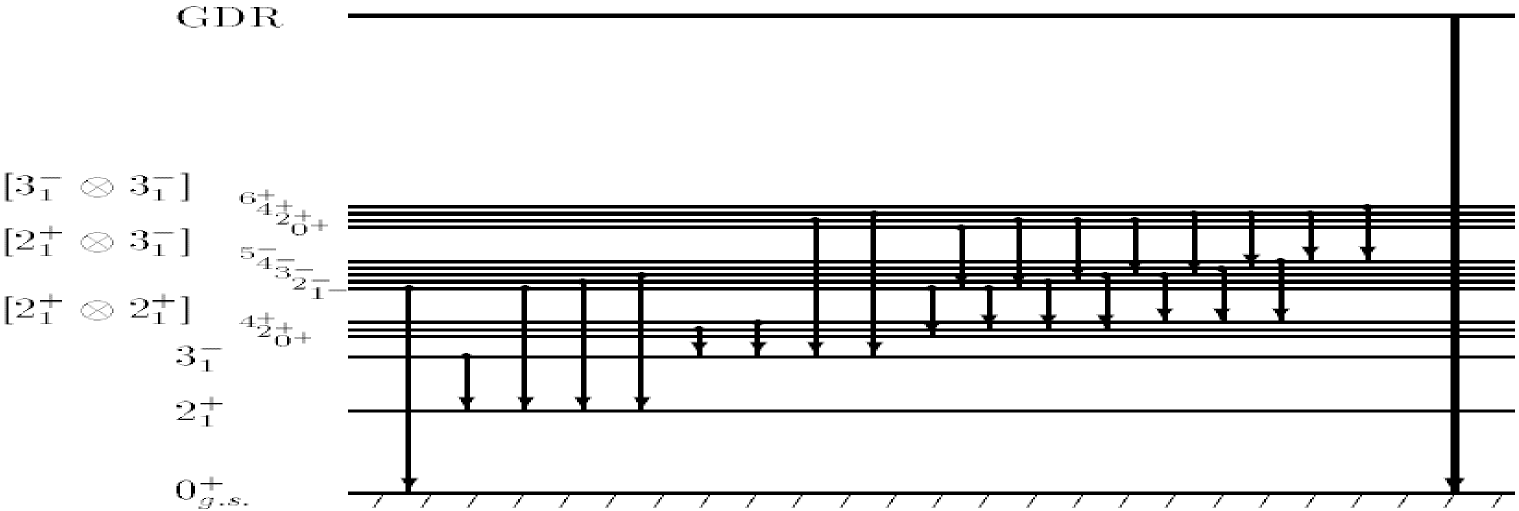
Nuclear Spectroscopy

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

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

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

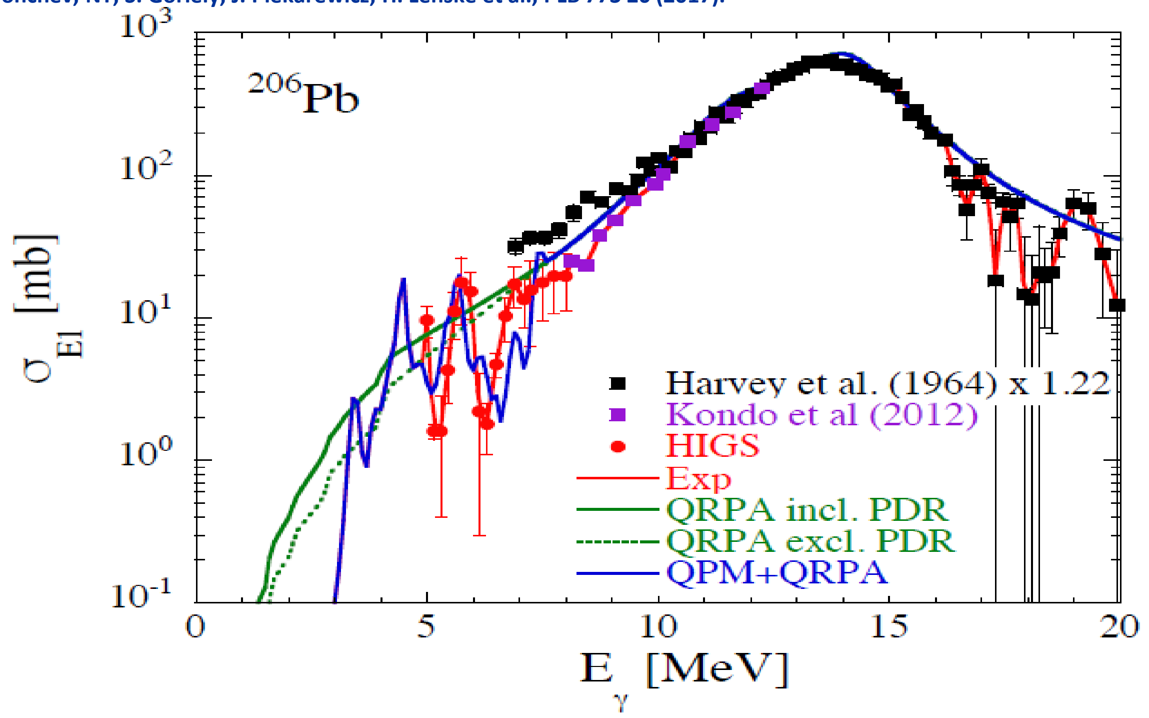
$B(X\lambda, J_i^{\pi_i} \longrightarrow J_f^{\pi_f}) \sim |M(X\lambda)|^2$ reduced transition probability



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

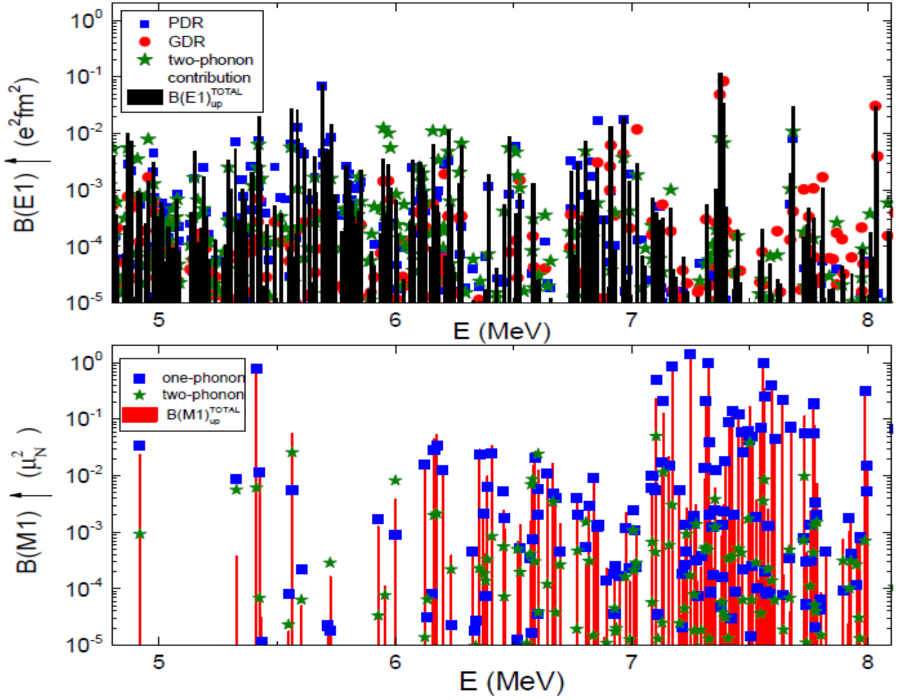
Electric Dipole Response of ^{206}Pb

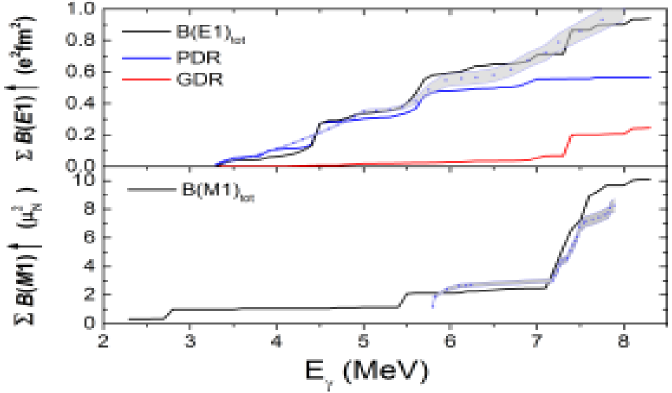
A. Tonchev, NT, S. Goriely, J. Piekarewicz, H. Lenske et al., PLB 773 20 (2017).

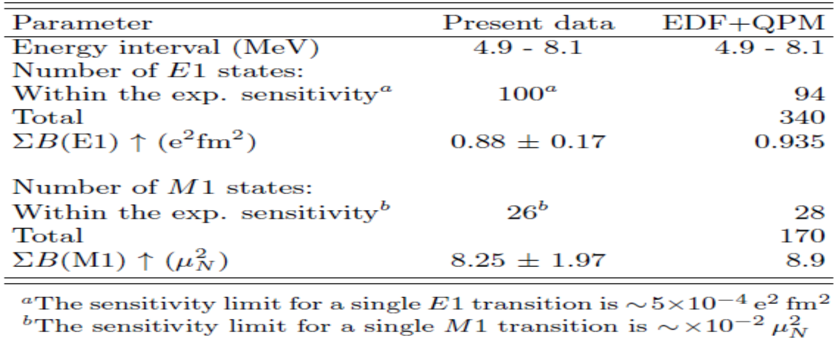


Separation of the PDR from the low-energy GDR in ^{206}Pb

A. Tonchev, N. Tsoneva, S. Goriely, J. Piekarewicz, H. Lenske et al., PLB 773 20 (2017).





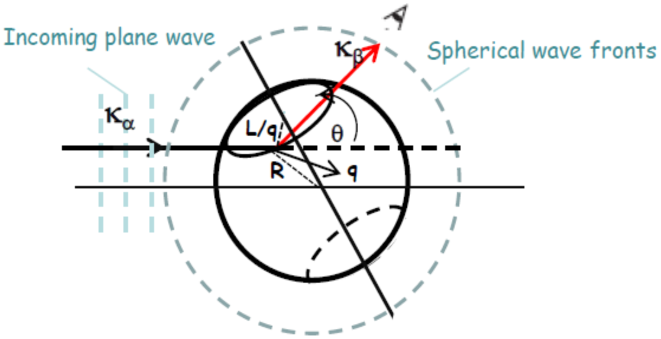


Parameter	Present data	EDF+QPM
Energy interval (MeV)	4.9 - 8.1	4.9 - 8.1
Number of $E1$ states:		
Within the exp. sensitivity[a]	100[a]	94
Total		340
$\Sigma B(E1)\uparrow$ (e^2fm^2)	0.88 ± 0.17	0.935
Number of $M1$ states:		
Within the exp. sensitivity[b]	26[b]	28
Total		170
$\Sigma B(M1)\uparrow$ (μ_N^2)	8.25 ± 1.97	8.9

[a] The sensitivity limit for a single $E1$ transition is $\sim 5\times10^{-4}$ e^2 fm^2
[b] The sensitivity limit for a single $M1$ transition is $\sim\times10^{-2}$ μ_N^2

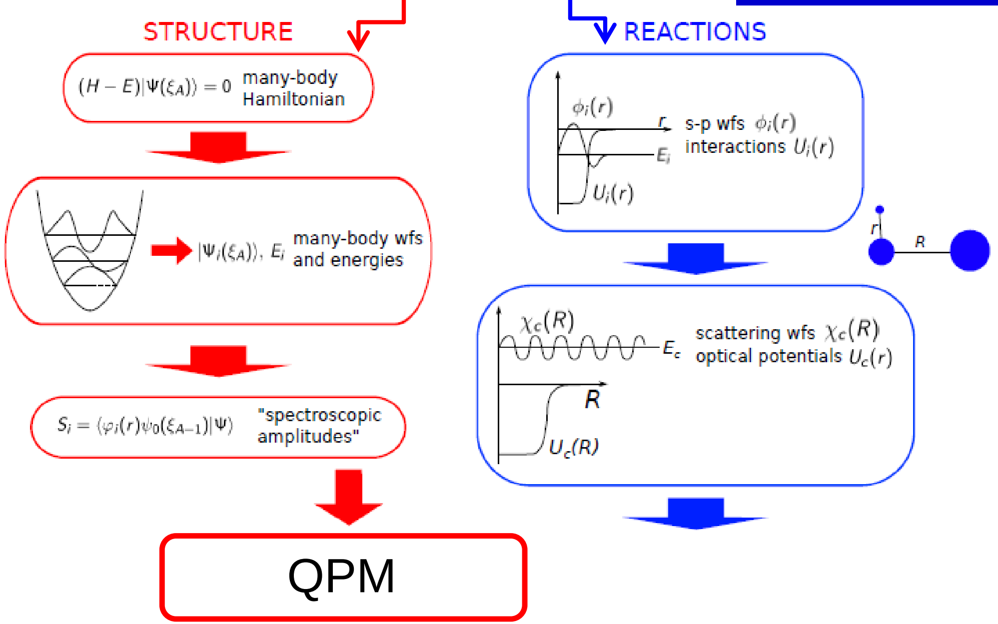
Probing the nuclear structure with transfer reactions

From the magnitude of the (d,p) cross section can be determined the strength of the single-particle state generated by the (d,p) reaction.



The single-particle orbit for the neutron provides only one component of the total wave function which includes as well excitations of the target nucleus plus neutron in other orbits

$$\frac{d\sigma^{exp}_{d,p}}{d\Omega} = S^2 \sigma^{(DWBA)}$$



STRUCTURE

$(H - E)|\Psi(\xi_A)\rangle = 0$ many-body Hamiltonian

$|\Psi_i(\xi_A)\rangle, E_i$ many-body wfs and energies

$S_i = \langle \varphi_i(r)\psi_0(\xi_{A-1})|\Psi\rangle$ "spectroscopic amplitudes"

QPM

REACTIONS

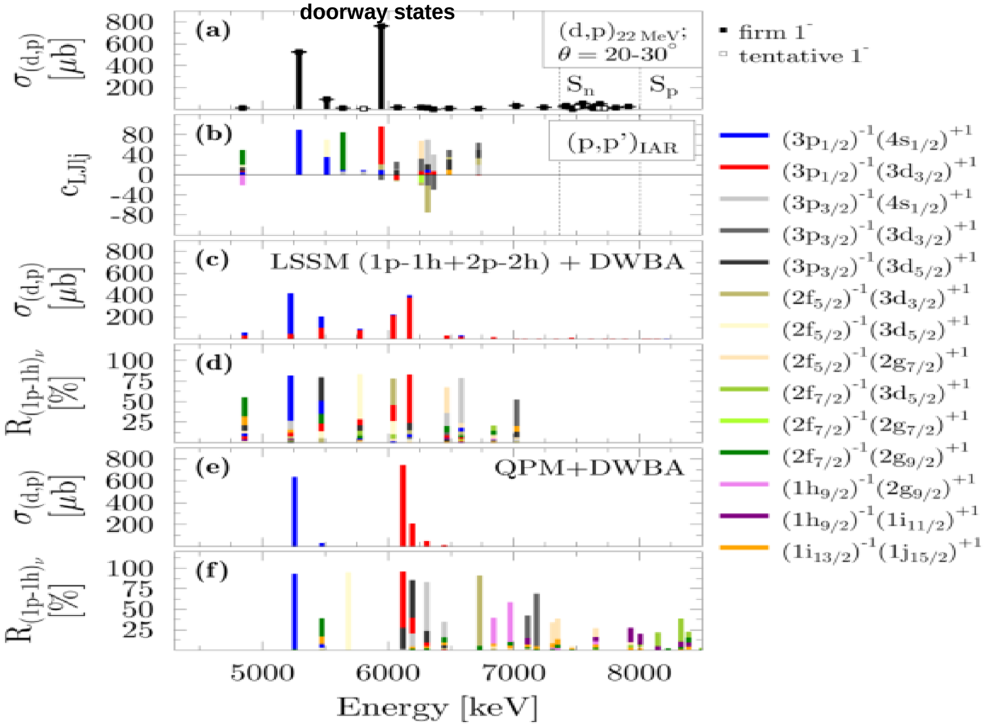
s-p wfs $\phi_i(r)$
interactions $U_i(r)$

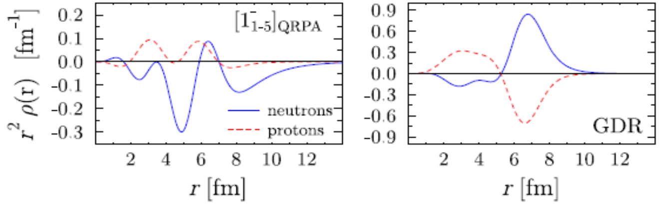
scattering wfs $\chi_c(R)$
optical potentials $U_c(r)$

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:

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

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

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

- Above S_n and up to S_p:

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

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

Accessing the Single-Particle Structure of the Pygmy Dipole Resonance

The microscopic structure of the low-energy electric dipole response of ^{120}Sn in a ^{119}Sn(d,pγ)^{120}Sn experiment

M. Weinert, M. Spieker, G. Potel, N. Tsoneva, M. Müscher, J. Wilhelmy and A. Zilges, 2021, PRL submitted.

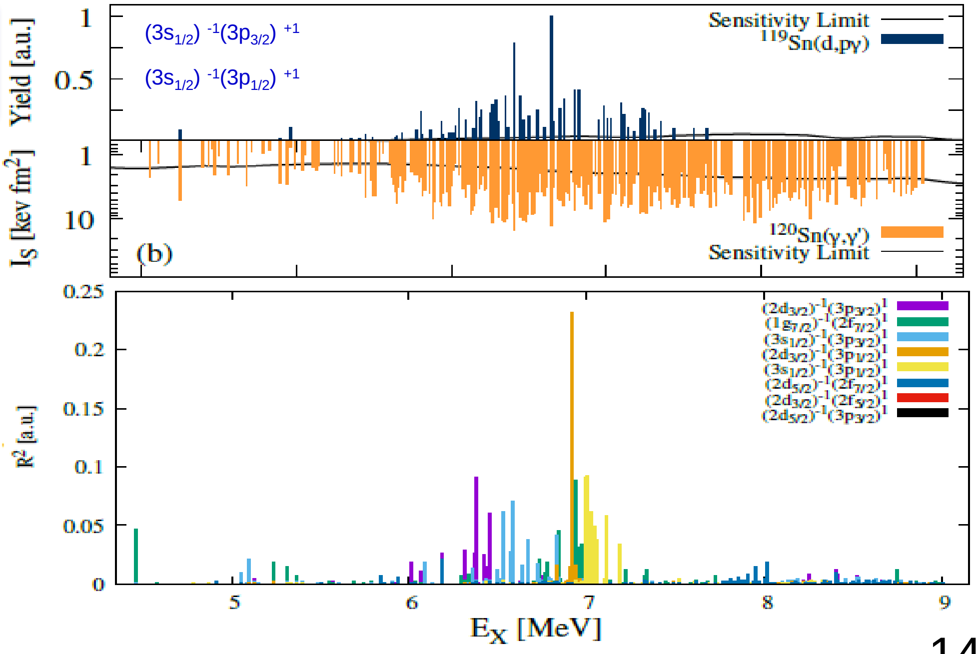
Novel EDF+QPM+reaction approach : Angular differential cross section populating a QPM 1^- state ν:

$$\frac{d\sigma_\nu}{d\Omega}(\theta) = \frac{\mu_i\mu_f}{(2\pi\hbar^2)^2}\frac{k_f}{k_i}\times$$

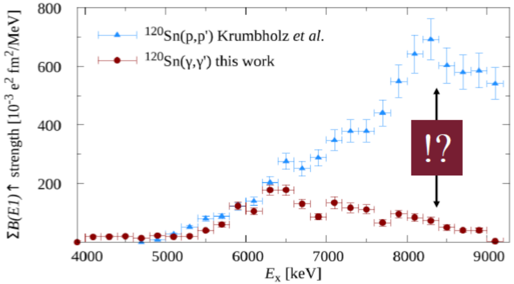
$$+ a_{3p_{3/2}} R_{3p_{3/2}}(\nu)\,\psi^{3\,p_{3/2}}_{\frac{1}{2}\,\frac{3}{2}}\,\mathcal{T}_{p_{3/2}}(\theta)\ \Big|^2$$

An indication of asymmetry between (n,γ) and (γ,n) and, thus, influence on the (n,γ)/(γ,n) equilibrium !

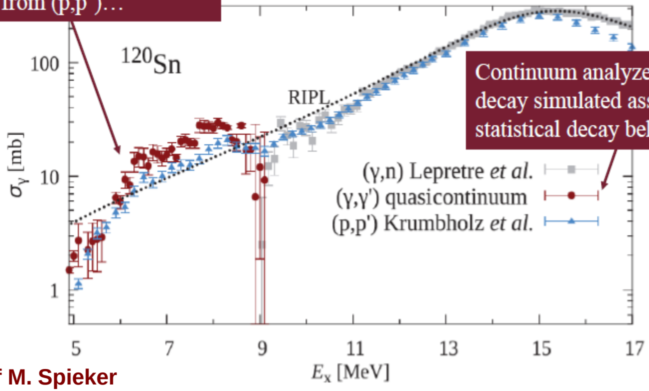
The experimental centroid energy including both $3p_{3/2}$ and $3p_{1/2}$, is E_{cm}^{exp}=6.49 MeV.
The QPM+Reaction approach predicts:
E_{cm}^{QPM} = 6.32 MeV.
Summed energy-integrated cross section
NRF data: $\sum I_s^{NRF}$ =337(21) keV , (d,pγ) yield >1%
$\sum I_S^{QPM}$ = 243 - 360 keV fm² for 1^- states with (d,pγ) yield >1% and >0.5%.



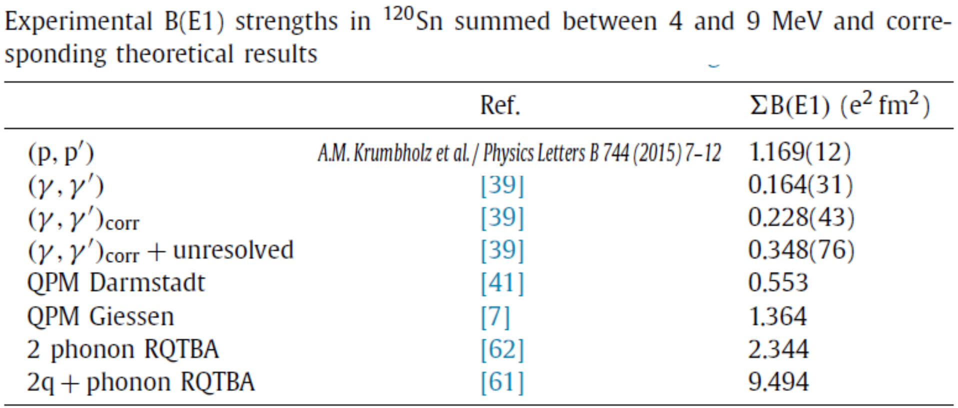
The Pygmy Dipole Strength : (γ,γ‘) vs. (p,p‘γ)



Now σ_γ from (γ,γ’) is larger than from (p,p’)…



Continuum analyzed and γ decay simulated assuming statistical decay behavior.



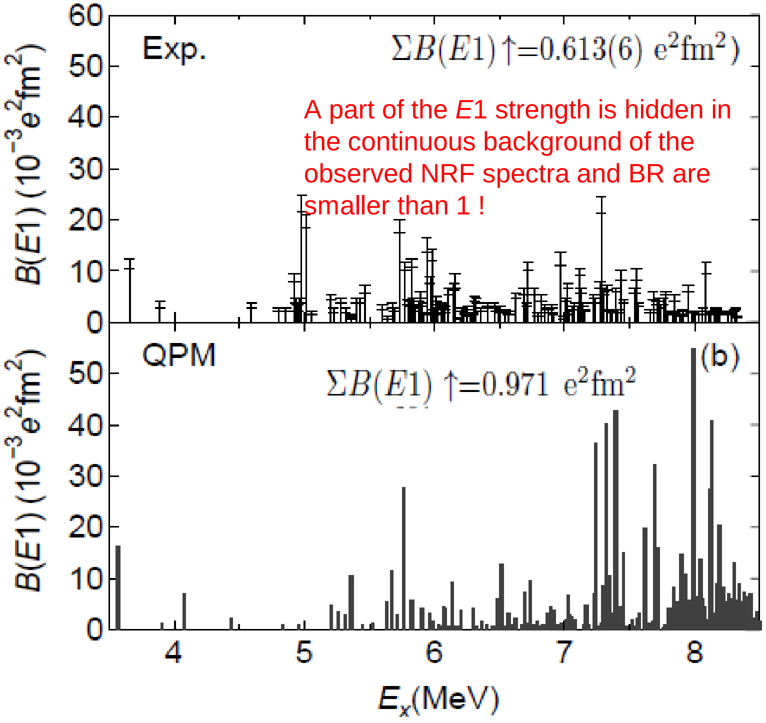
Experimental B(E1) strengths in ^{120}Sn summed between 4 and 9 MeV and corresponding theoretical results

	Ref.	ΣB(E1) (e^2 fm^2)
(p, p′)	A.M. Krumbholz et al. / Physics Letters B 744 (2015) 7–12	1.169(12)
(γ, γ')	[39]	0.164(31)
$(\gamma, \gamma')_{corr}$	[39]	0.228(43)
$(\gamma, \gamma')_{corr}$ + unresolved	[39]	0.348(76)
QPM Darmstadt	[41]	0.553
QPM Giessen	[7]	1.364
2 phonon RQTBA	[62]	2.344
2q + phonon RQTBA	[61]	9.494

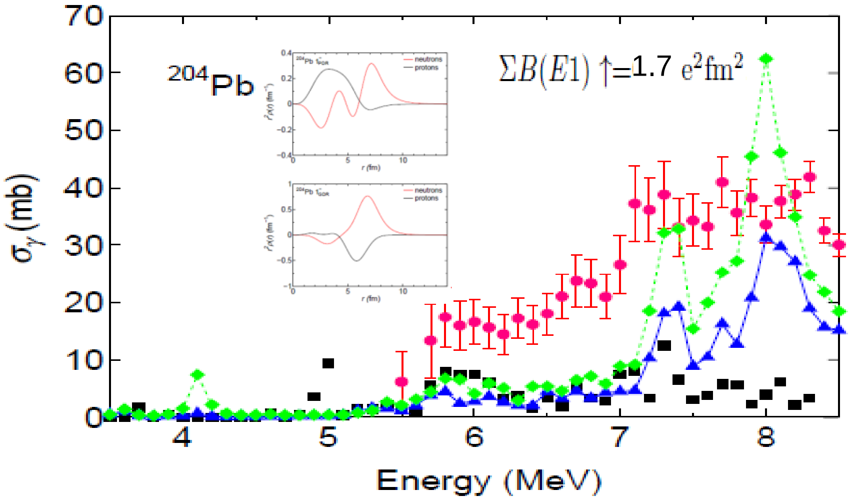
M. Müscher et al., PRC **102**, 014317 (2020)
(Cologne/Köln Group; A. Zilges)

Low-lying dipole strength distribution in ^{204}Pb

T. Shizuma,…,NT, PRC accepted



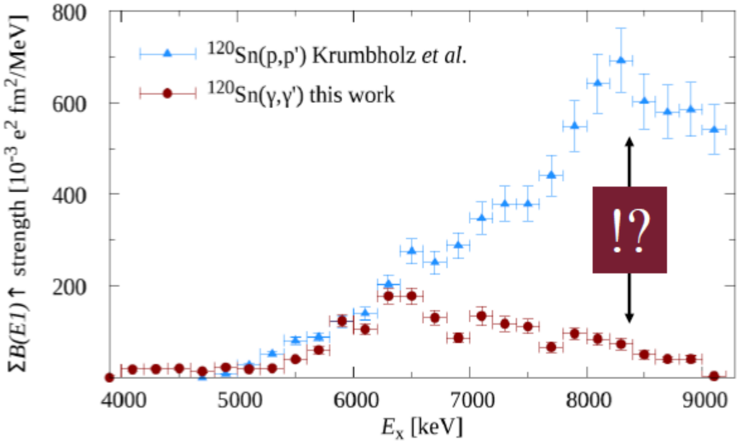
A part of the *E*1 strength is hidden in the continuous background of the observed NRF spectra and BR are smaller than 1 !

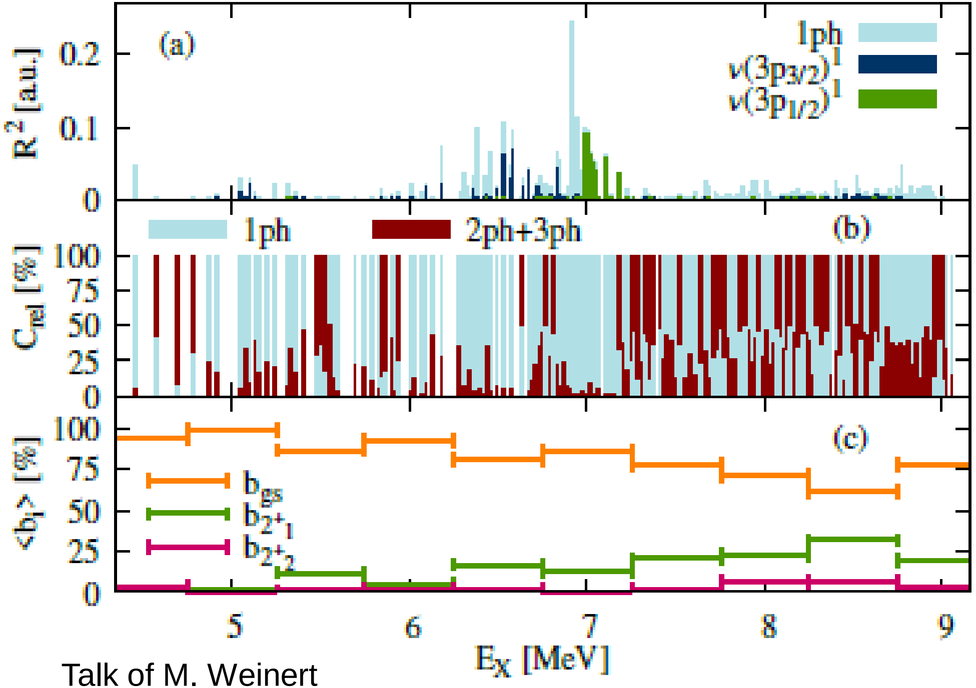


Experimental *γ*-ray absorption cross sections derived from resolved peaks (squares) and from the quasicontinuum analysis (red circles), averaged over energy bins of 100 keV. Also shown are cross sections predicted by EDF+threephonon QPM calculations confined in the NRF energy domain
(blue triangles) and extended EDF+two-phonon QPM (green diamonds) calculations, smeared by the Lorentzian width of 100 keV.

Pygmy Dipole Strength obtained from different probes: (γ,γ‘) vs. (p,p‘γ). Branching relationships indicate the effect of complex structures.

M. Weinert, M. Spieker, G. Potel, N. Tsoneva, M. Müscher, J. Wilhelmy and A. Zilges, 2021, PRL submitted.





Talk of M. Weinert

We claim that the discrepancies are caused by structural changes due to more complex configurations at higher energies, where due to these changes other γ-decay channels open up.

QPM spectral disrtibitions and cumulative B(E1) and B(E2) strengths related to PDR and PQR modes in ^{112,118,122}Sn

PQR theoretically predicted in 2011

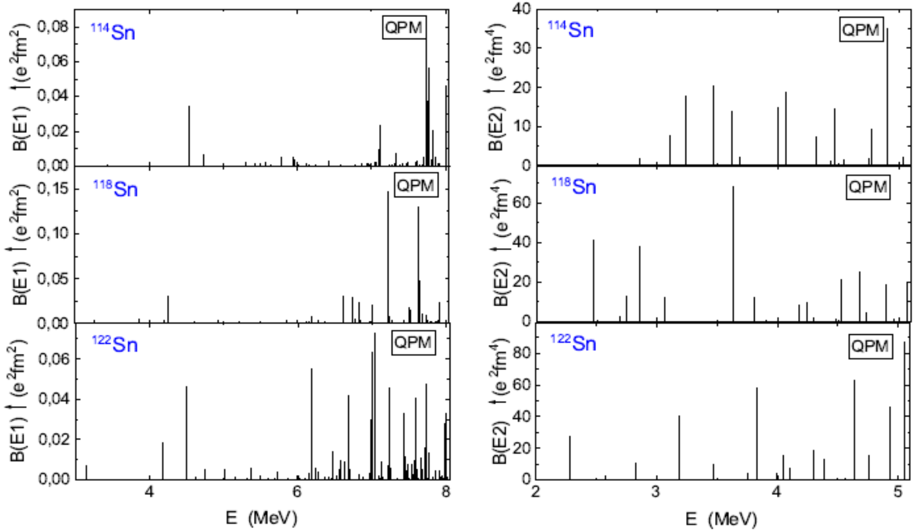
N. Tsoneva, H. Lenske, Phys. Lett. B695 174 (2011).

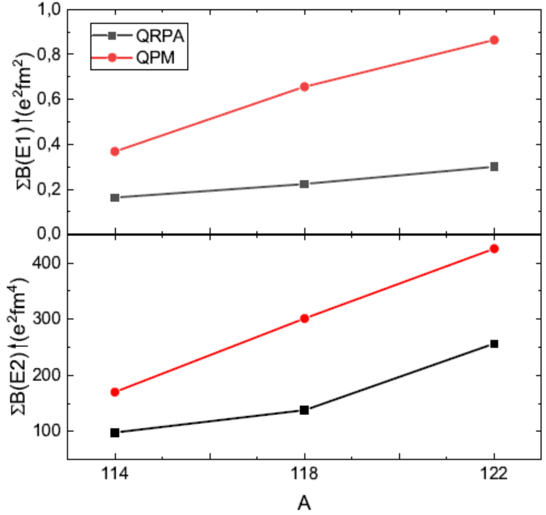
N>Z: PDR and PQR strengths increase with the neutron number

…experimentally confirmed in 2015/2016

^{124}Sn(^{17}O,^{17}O´γ) **L. Pellegri, A. Bracco, NT et al.,PRC 92, 014330 (2015).**

^{124}Sn(α,α‘γ) and ^{124}Sn (γ,γ‘) **M. Spieker, NT et al., Phys. Lett. B752, 102 (2016).**



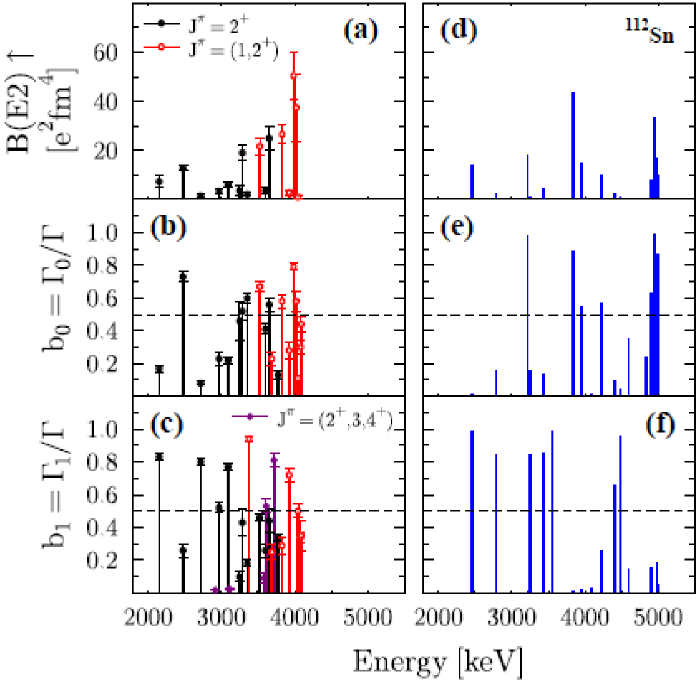


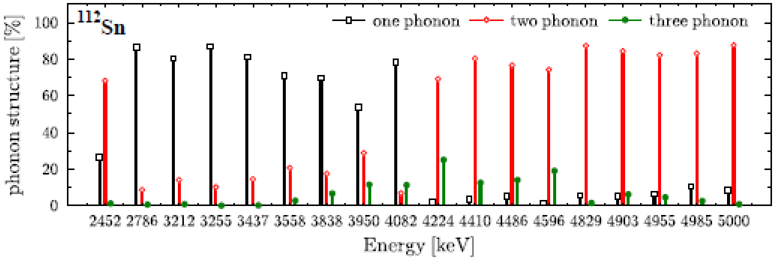
B(E2) strengths,b_0 and b_1 γ-decay branching ratios of PQR States from EDF+QPM calculations in comparison with (p,p‘γ) data in ^{112}Sn

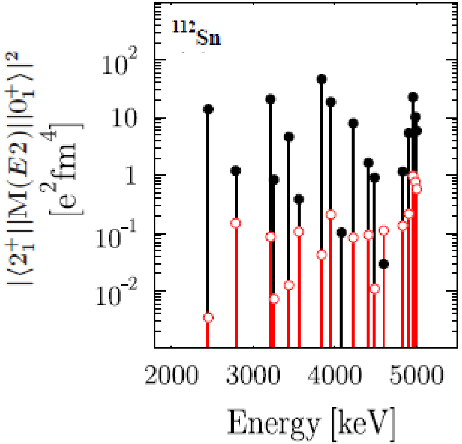
What is new?

- Many new states observed in ^{112}Sn and previously known confirmed.
- γ-decay behaviour studied.

- Branching ratios reveal the fine structure of the PQR states.
- Evidences for the existence of multi-phonon states.







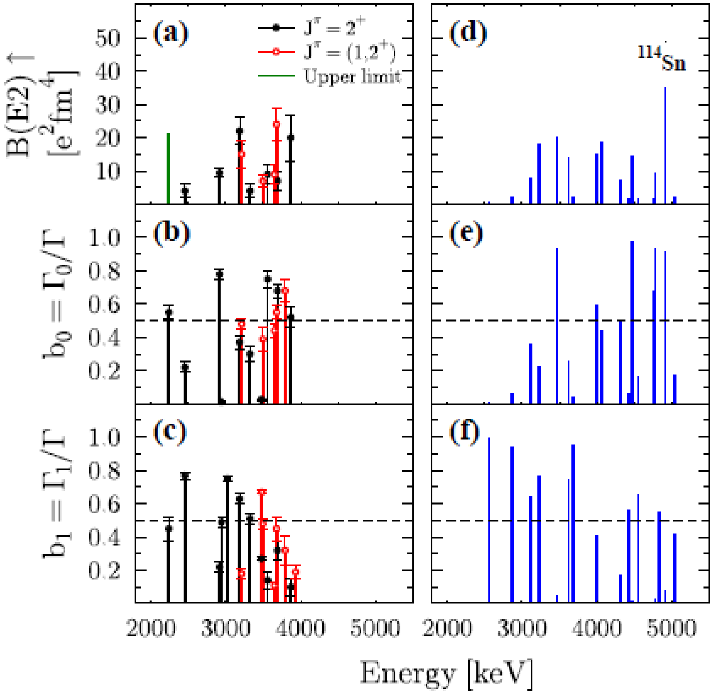
NT, M. Spieker, H. Lenske, and A. Zilges, NPA **990**, 183-198 (2019).

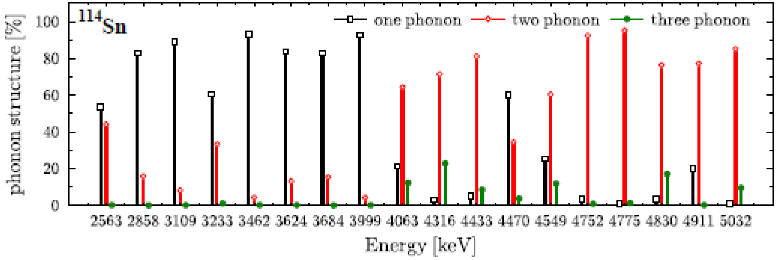
B(E2) strengths, b_0 and b_1 γ-decay branching ratios of PQR States from EDF+QPM calculations in comparison with (p,p'γ) data in ^{114}Sn

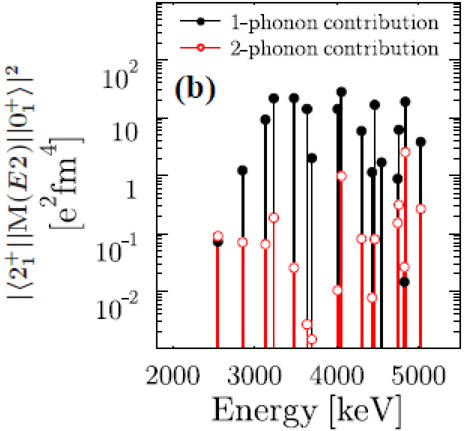
What is new?

- Lifetimes of 2^+ states determined in ^{114}Sn for the first time.
- γ-decay behaviour studied.

- Branching ratios reveal the fine structure of the PQR states.
- Evidences for the existence of multi-phonon states.



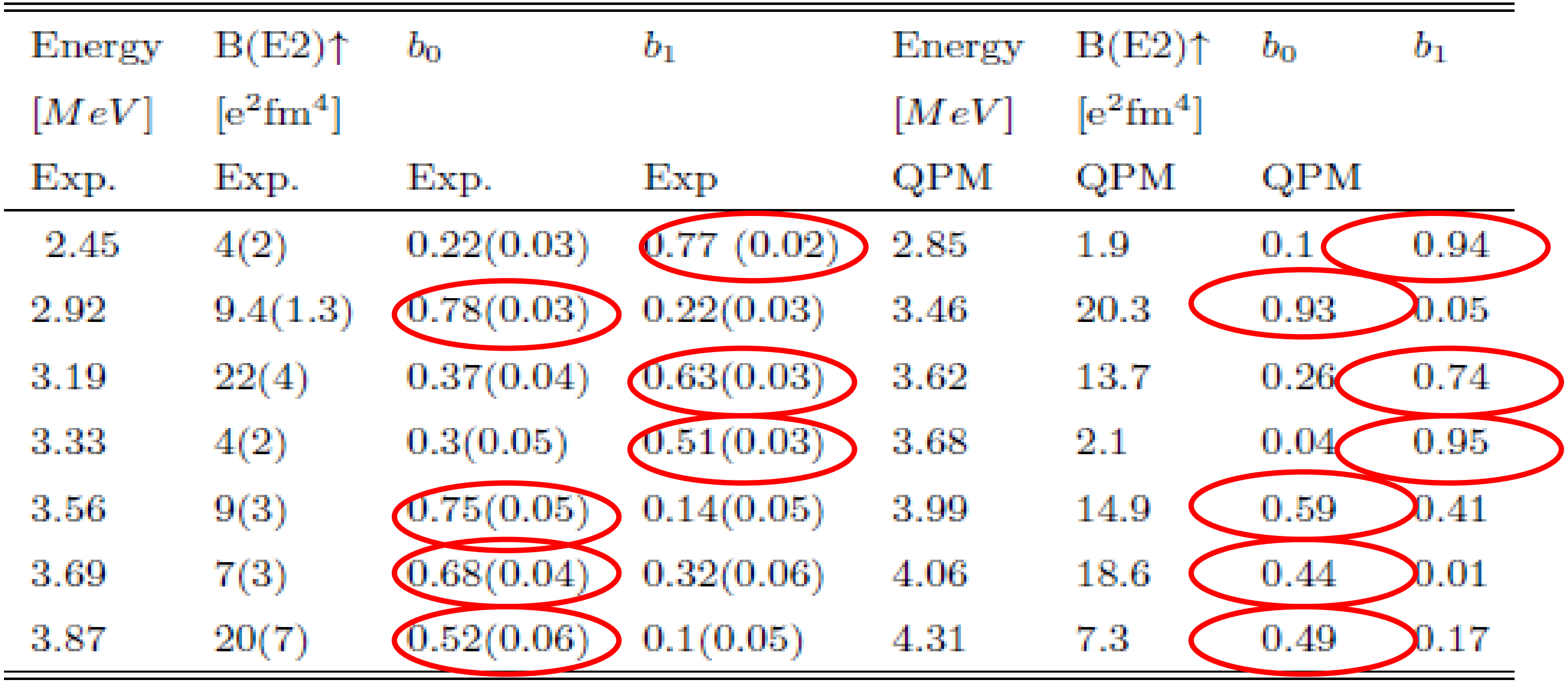




N. Tsoneva, M. Spieker, H. Lenske, and A. Zilges, NPA **990**, 183-198 (2019).

B(E2) strengths b_0 b_1 γ-decay branching ratios of PQR States from EDF+QPM calculations in comparison with (p,p‘γ) data in ^{114}Sn

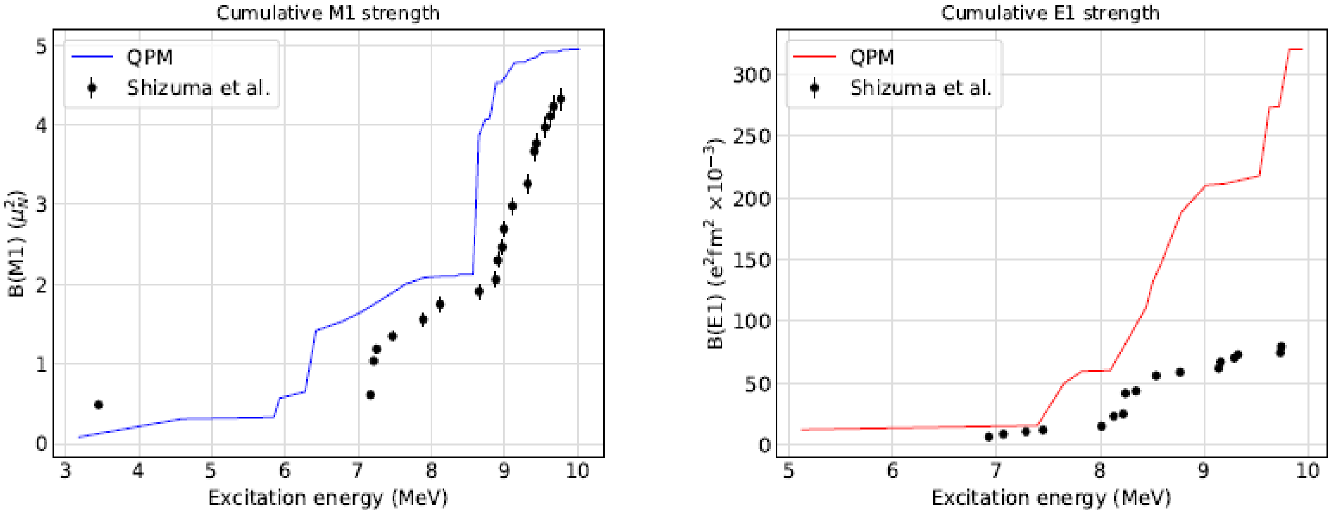
Commonly PQR states have large b_0 BR and prefer to decay directly to the ground state. However, due to the admixture of collective two-phonon configurations some PQR states might have larger b_1 BR instead.



Energy [MeV] Exp.	B(E2)↑ [e^{2}fm^4] Exp.	b_0 Exp.	b_1 Exp	Energy [MeV] QPM	B(E2)↑ [e^{2}fm^4] QPM	b_0 QPM	b_1
2.45	4(2)	0.22(0.03)	0.77 (0.02)	2.85	1.9	0.1	0.94
2.92	9.4(1.3)	0.78(0.03)	0.22(0.03)	3.46	20.3	0.93	0.05
3.19	22(4)	0.37(0.04)	0.63(0.03)	3.62	13.7	0.26	0.74
3.33	4(2)	0.3(0.05)	0.51(0.03)	3.68	2.1	0.04	0.95
3.56	9(3)	0.75(0.05)	0.14(0.05)	3.99	14.9	0.59	0.41
3.69	7(3)	0.68(0.04)	0.32(0.06)	4.06	18.6	0.44	0.01
3.87	20(7)	0.52(0.06)	0.1(0.05)	4.31	7.3	0.49	0.17

Dipole strength around and above the neutron threshold in ^{56}Fe

PANDORA COLLABORATION

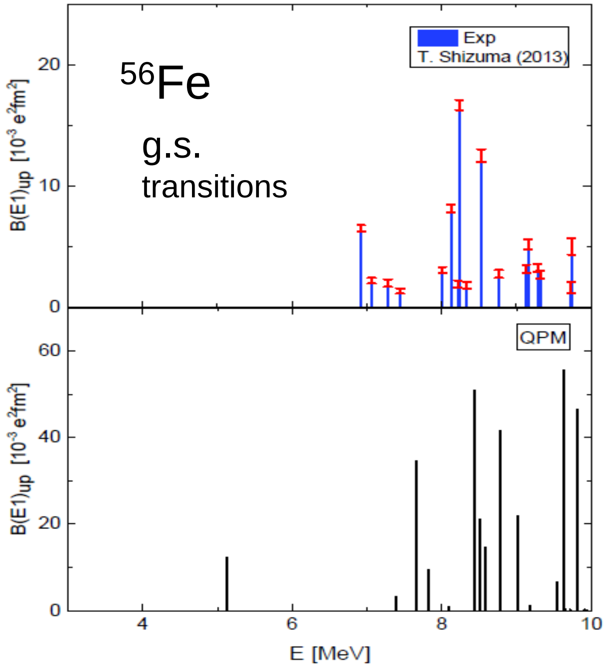


^{56}Fe is one of the most tightly bound naturally existing nuclei and the 6th most abundant nucleus in the solar system. It is the end product of the silicon burning phase that occurs in the collapse of a massive star. Thus, this nucleus plays a crucial role in the formation of heavier elements in the Universe in explosive stellar environments.

- Very similar to the experimental case of ^{120}Sn!
- γ-Decay channels that are inaccessible by NRF open up.

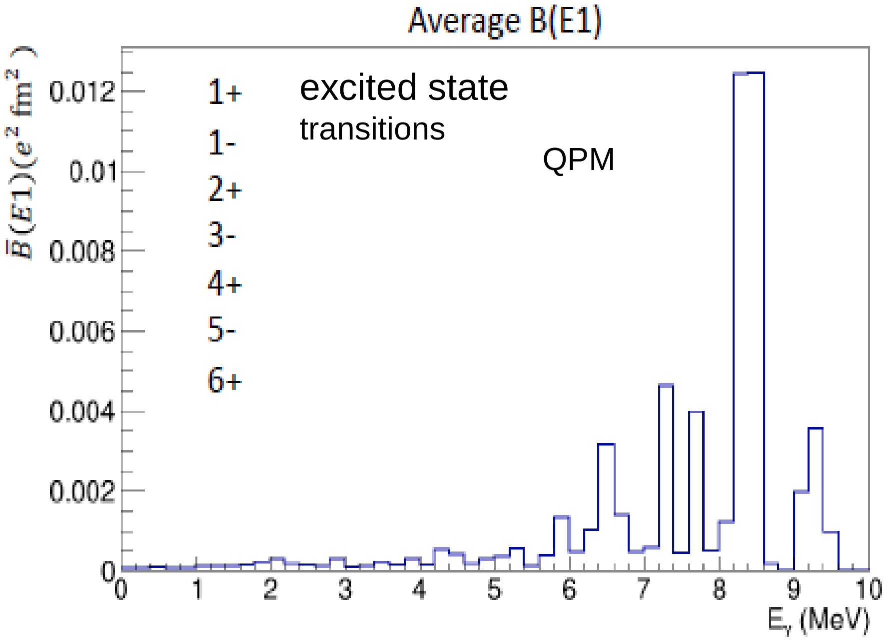
First theoretical observation of PDR built on excited states of ^{56}Fe

N.Tsoneva, A. Ramirez, A. Tonchev et al., in preparation



^{56}Fe

g.s. transitions



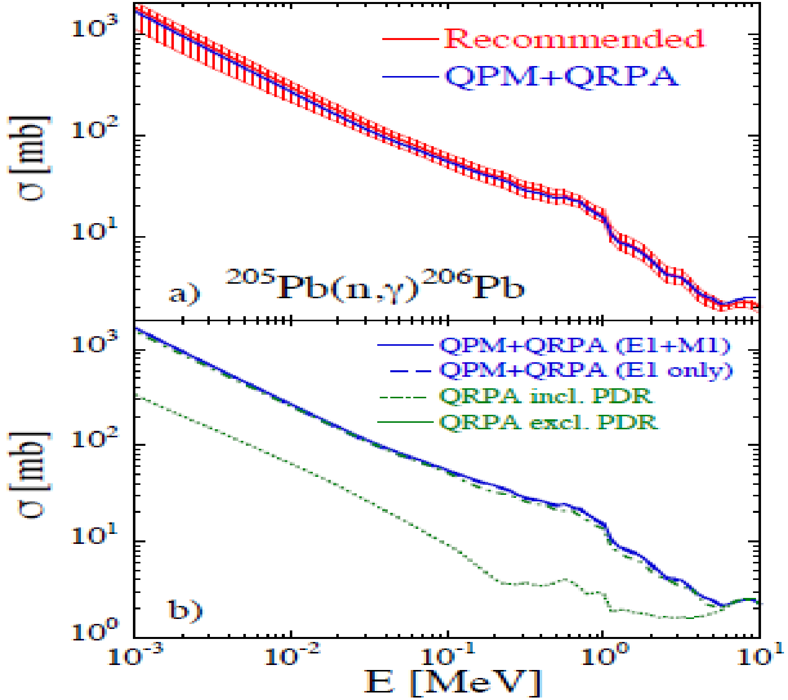
excited state transitions

QPM

Nuclear Pygmy Modes: Doorways to Nucleosynthesis

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).

A. Tonchev, N. Tsoneva, S. Goriely, J. Piekarewicz, H. Lenske et al., PLB 773 20 (2017).

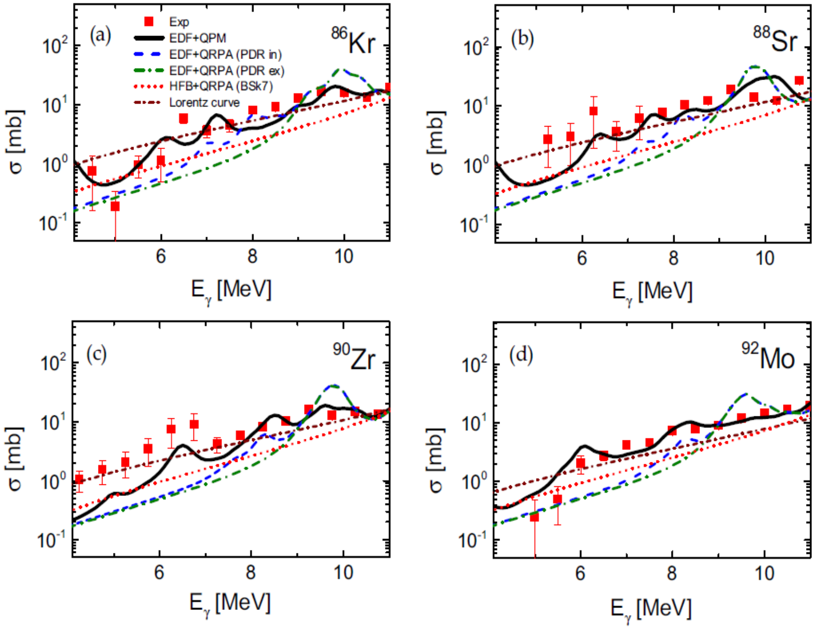


⇒The combined PDR plus core polarization contribution is crucial !

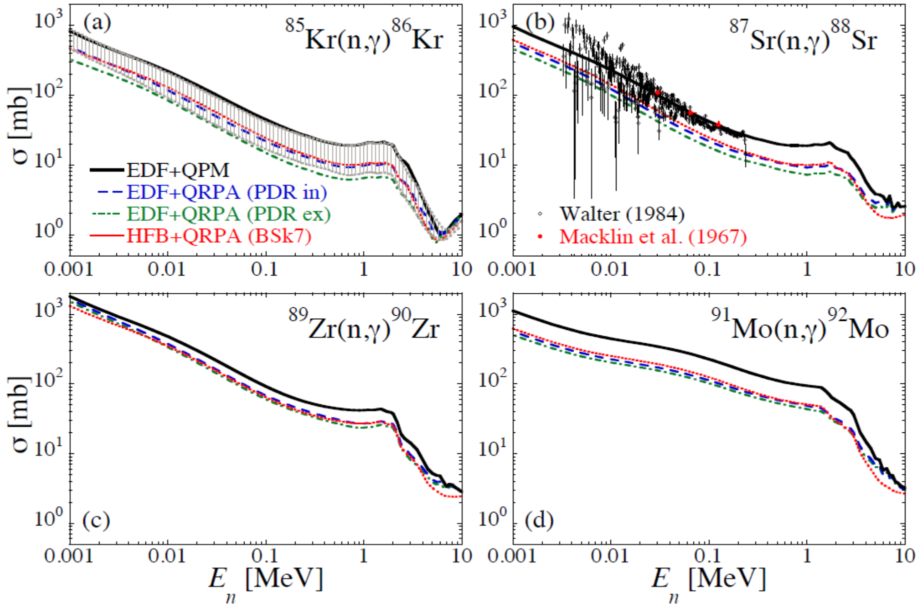
⇒M1 contribution small, less than 5%.

At stellar temperature of kT= 30 keV
MACS of 130(+25,-25) mb

QPM calculations of low-energy photoabsorption cross sections in N=50 isotones (Data: ELBE@Rossendorf)



Neutron Capture Cross Sections



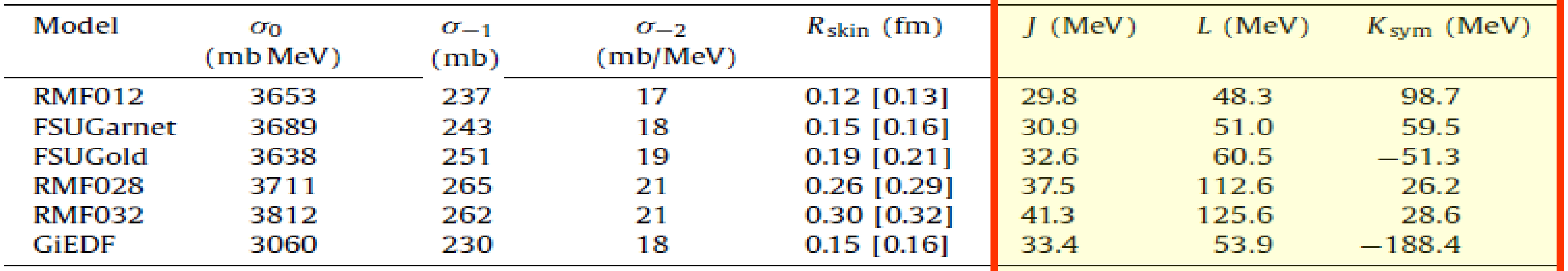
Moments of the Photoabsorption Cross Section

$$\sigma_{-n} = \int_0^\infty dE \frac{\sigma_\gamma(E)}{E^n} \quad \leftrightarrow \quad S_{-(n-1)} = \sum_c \frac{\left|M_{\gamma c}\right|^2}{E_c^{n-1}}$$

- **n = 0 : Energy Weighted Sum Rule (EWSR)**
- **n = 1 : Non-Energy Weighted Sum Rule (NEWSR) - total transition strength**
- **n = 2 : Polarizability sum rule**

A. Tonchev, N. Tsoneva, S. Goriely, J. Piekarewicz, H. Lenske et al., PLB 773 20 (2017).

Photoabsorption Cross Section Moments for ^{206}Pb (values for ^{208}Pb shown in [..]).



Model	σ_0 (mb MeV)	σ_{-1} (mb)	σ_{-2} (mb/MeV)	R_{skin} (fm)	J (MeV)	L (MeV)	K_{sym} (MeV)
RMF012	3653	237	17	0.12 [0.13]	29.8	48.3	98.7
FSUGarnet	3689	243	18	0.15 [0.16]	30.9	51.0	59.5
FSUGold	3638	251	19	0.19 [0.21]	32.6	60.5	−51.3
RMF028	3711	265	21	0.26 [0.29]	37.5	112.6	26.2
RMF032	3812	262	21	0.30 [0.32]	41.3	125.6	28.6
GiEDF	3060	230	18	0.15 [0.16]	33.4	53.9	−188.4

Symmetry Energy ↔ GDR Restoring Force:

$$S(\rho) \equiv \frac{1}{2}\left(\frac{\partial^2 \mathcal{E}(\rho,\delta)}{\partial \delta^2}\right)_{\delta=0} \approx \mathcal{E}(\rho,\delta=1) - \mathcal{E}(\rho,\delta=0).$$

$$S(\rho) = J + Lx + \frac{1}{2}K_{\rm sym}x^2 + \ldots \quad \text{with} \quad x \equiv \frac{\rho-\rho_0}{3\rho_0}.$$

PREX-2 R_{skin} (^{208}Pb) ~ twice larger than the obtained from (p,p‘) data; CREX Collaboration CREX R_{skin} (^{48}Ca) smaller than EDF predictictions!

CONCLUSIONS AND OUTLOOK

eli
nuclear physics

- **Predictions of new low-energy modes: PDR, PQR, PMR … ;**
- **Coarse and fine structure of pygmy resonances an ,pγ'), (α,α'γ) …. reaction rate studies, disturbed (n,γ)/(γ,n**
- **Predictions of branching rat multi-hole configuration mixing;**
- **The coupling of quasicontin considerably increase the total low-energy E1 strength**
- **First theoretical evidence of PDR built on excited states**
- **Correlations: PDR strength <-> skin thickness <-> polarizability <-> slope L <->…**
- **Strong impact of PDR on of s- and r- process nucleosynthesis rates.**

Thank you !

In a collaboration with
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