Thank you very much, Angela, and all the best.

Experimental studies of the microscopic structure of the pygmy dipole resonance

Mark Spieker

Symposium on resonances and related topics, Bormio (Italy), 2025

FSU | FLORIDA STATE UNIVERSITY

Save the date!

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8th International Conference on Collective Motion in Nuclei under Extreme Conditions

The electric dipole response of atomic nuclei [Example of ^{208}Pb and isovector response]

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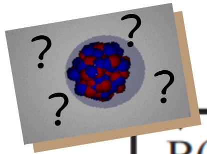
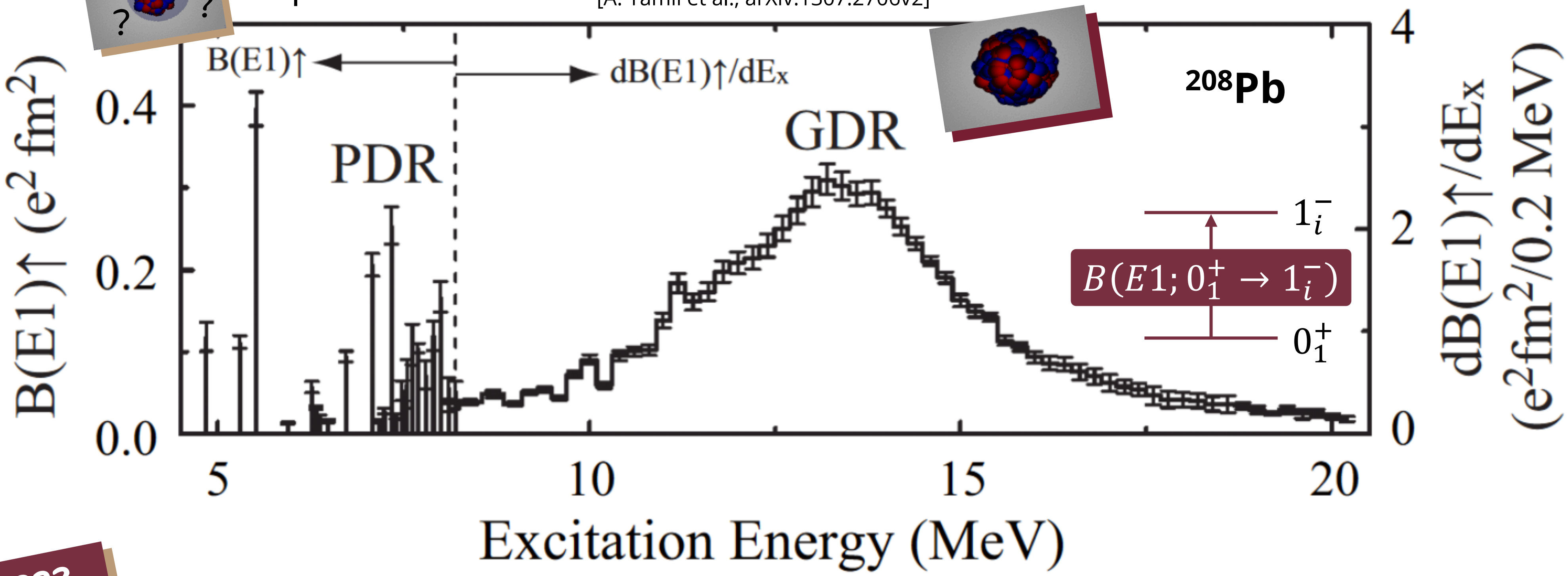


Experimental data! [A. Tamii et al., arXiv:1307.2706v2]



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Pygmy Dipole Resonance (PDR)	Isovector Giant Dipole Resonance (IVGDR)
The **valence** neutrons (light blue) oscillate against the N = Z core = **smaller** (pygmy) dynamic dipole moment	**All** protons (red) oscillate against **all** neutrons (blue) = **large** (giant) dynamic dipole moment

The electric dipole response of atomic nuclei [Example of ^{208}Pb and isovector response]

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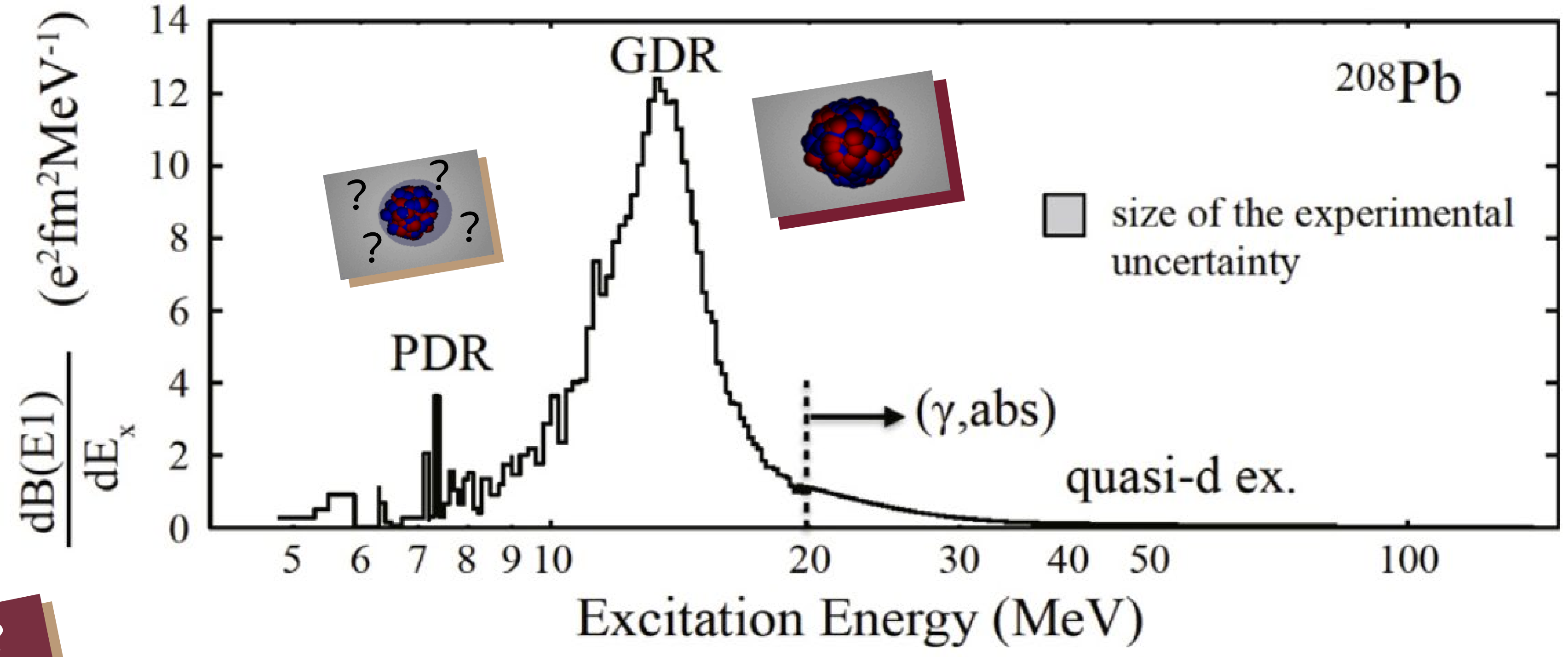
Experimental data! [Figure from A. Bracco, E.G. Lanza, A. Tamii, Prog. Part. Nucl. Phys. **106**, 360 (2019)]



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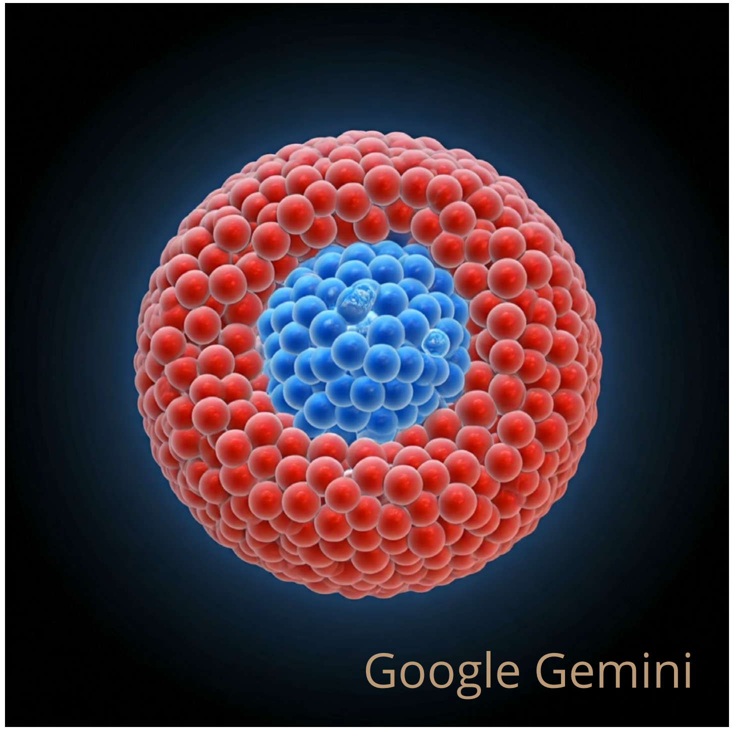
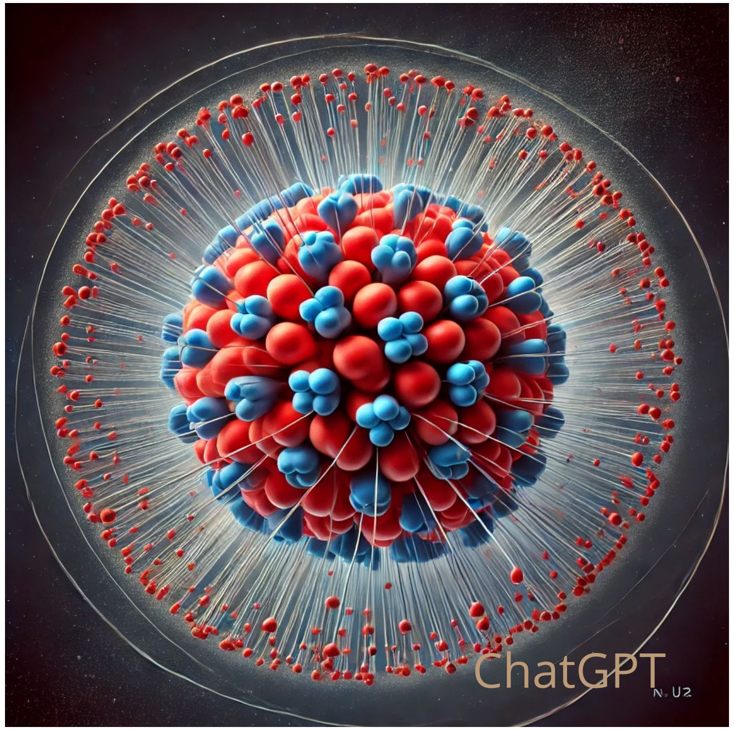
How AI pictures the PDR... [idea “stolen” from Andreas Zilges (University of Cologne)]

“A neutron skin of 24 neutrons oscillates against a core of 50 neutrons and 50 protons of an atomic nucleus. Protons are red and neutrons are blue. Do not add electron orbits.”





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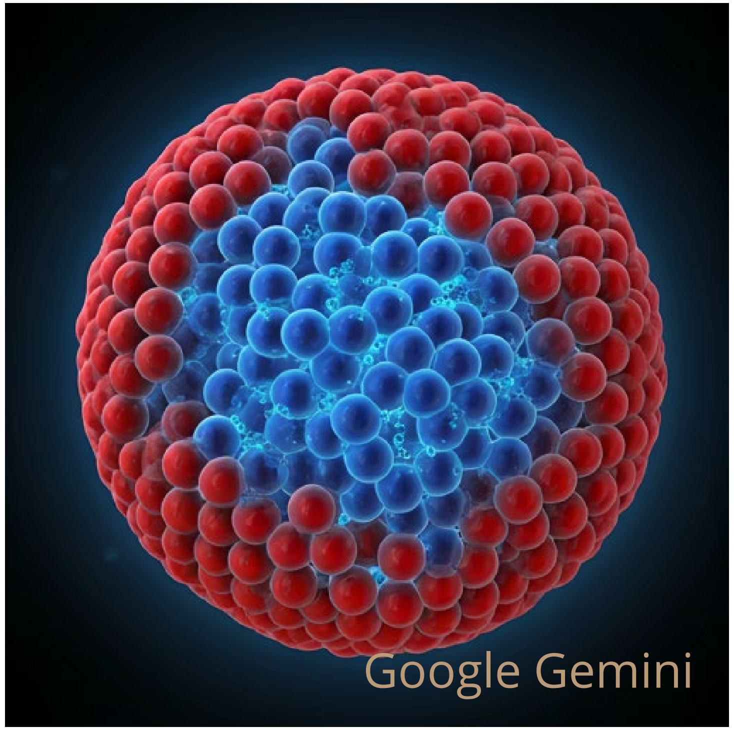

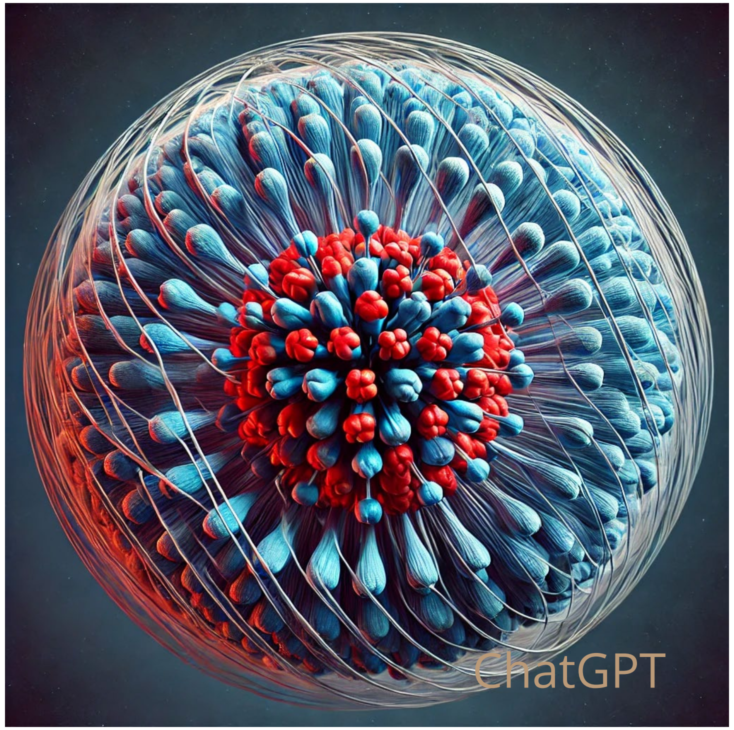

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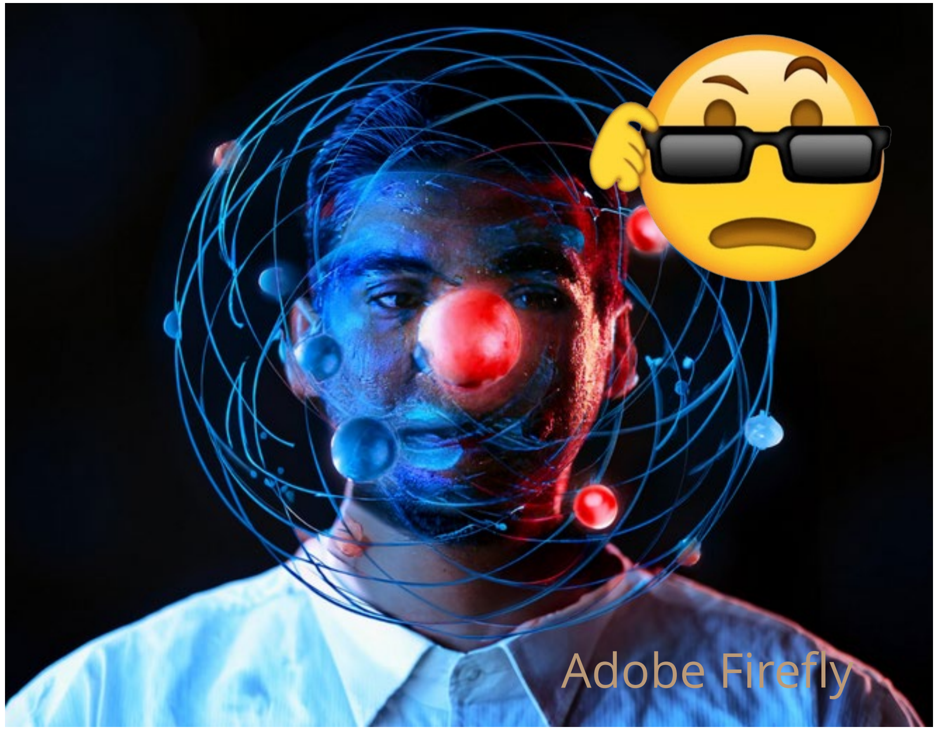

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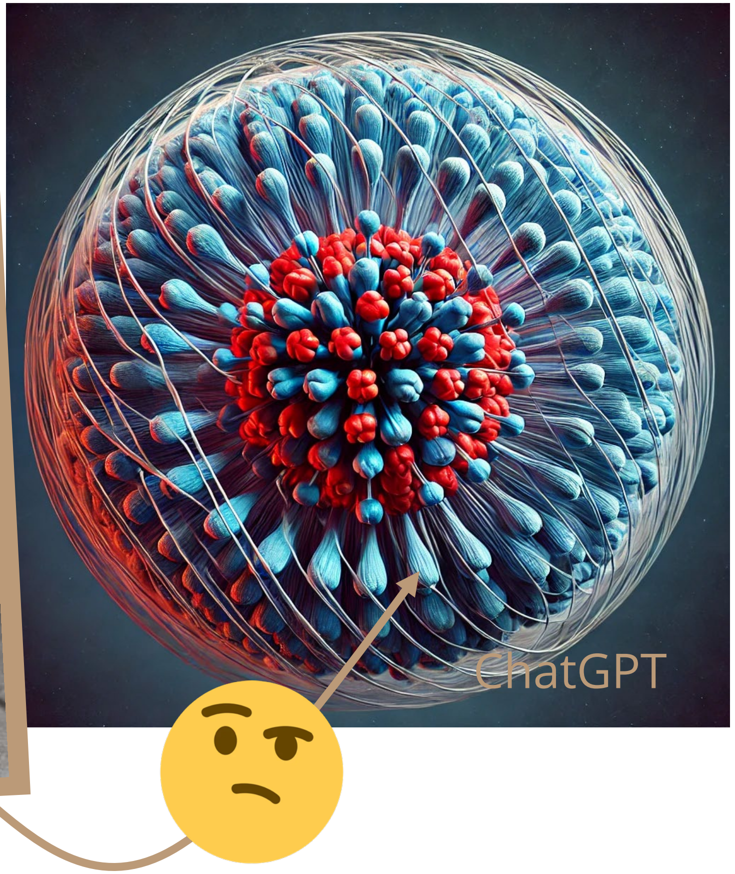
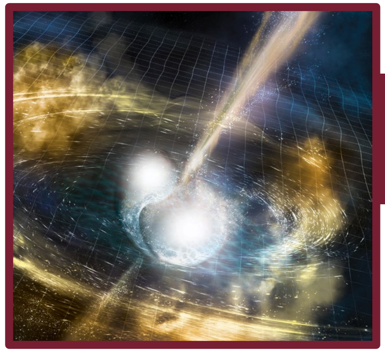


The r process and neutron capture (n,γ) rates

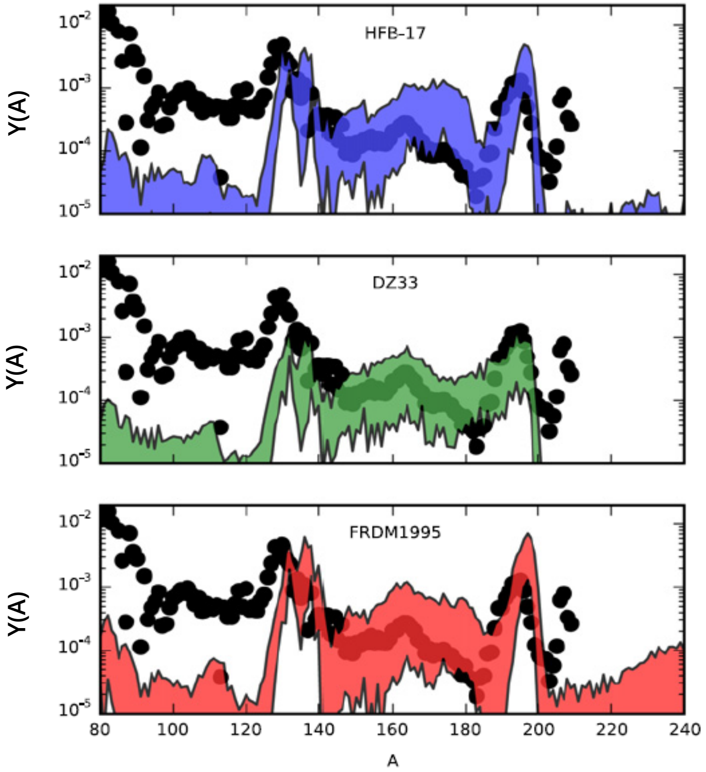


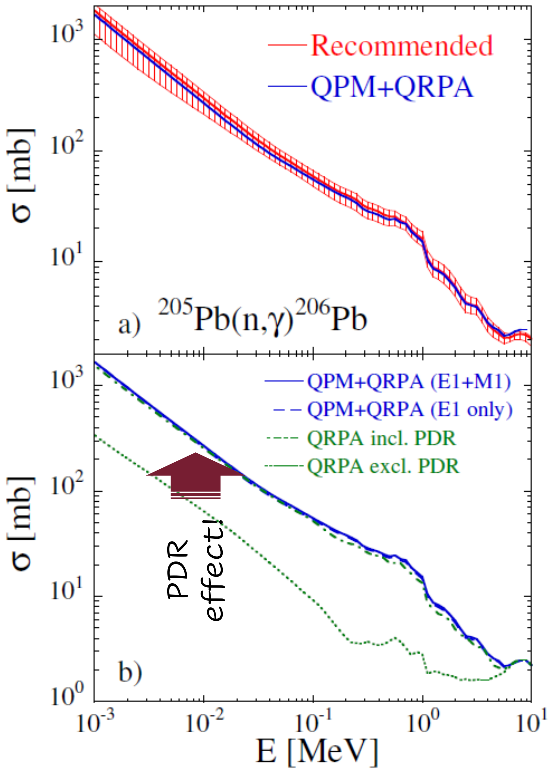
How and where are the elements heavier than iron synthesized?

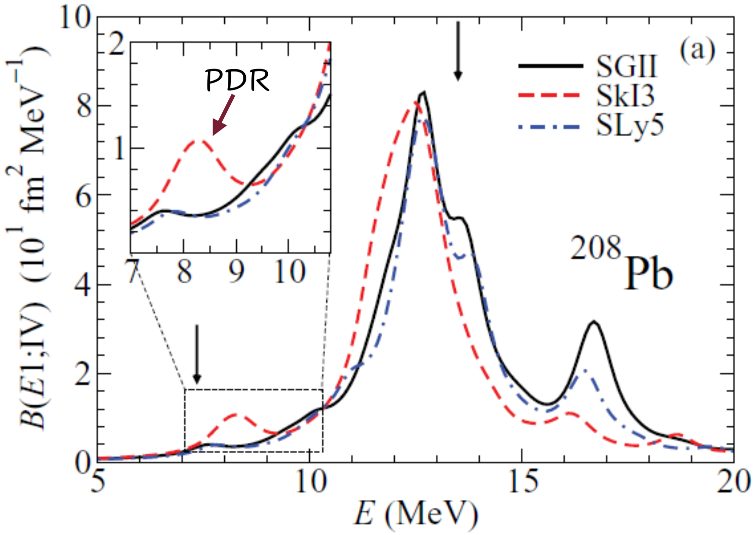
[A New Era of Discovery: The 2023 Long Range Plan for Nuclear Science; The NuPECC Long Range Plan 2024 for European Nuclear Physics]

[**Figure 1:** https://www.ligo.org/science/Publication-GW170817MMA/]
[**Figure 2**: M. Mumpower *et al.*, PPNP **86**, 86 (2016)]

[**Figure 3**: H. Lenske and N. Tsoneva, EPJA **55**, 238 (2019)]
[**Figure 4:** X. Roca-Maza *et al.*, PRC **85**, 024601 (2012)]



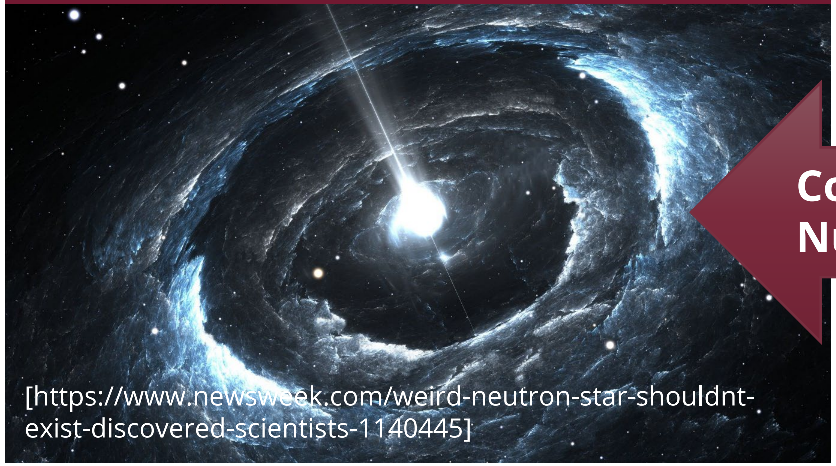




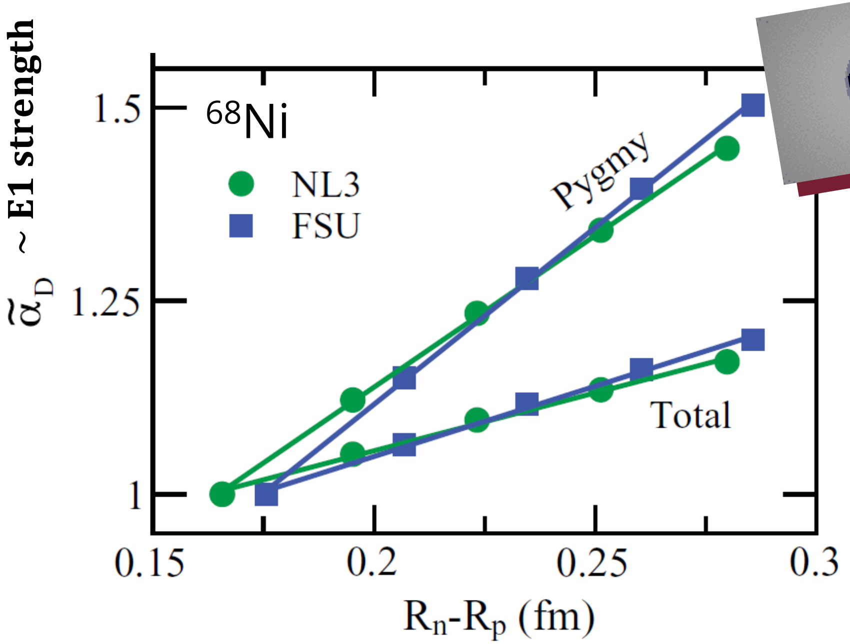
Appearance of PDR is strongly model-dependent!

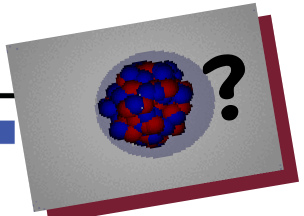
From the PDR to the neutron skin to neutron-star radii

How big is this thing?



Constraints from Nuclear Physics





$= \textbf{neutron} - \textbf{skin thickness}$

Measure the neutron skin (10^{-16} m) and constrain possible neutron-star radii (10^4 m)

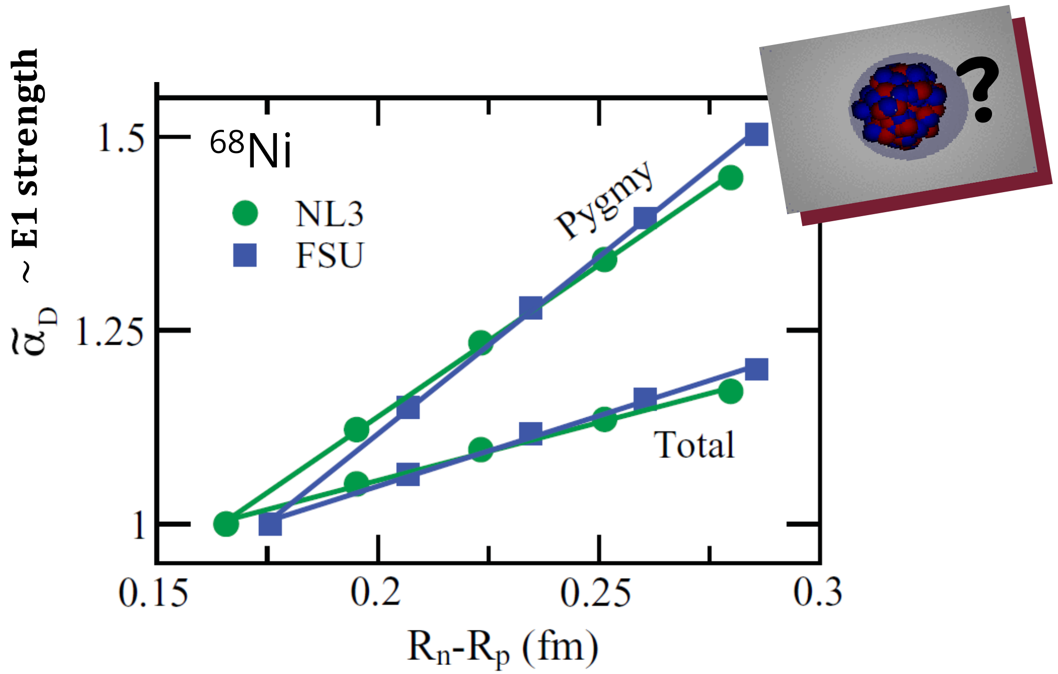
20 orders of magnitude difference!

The problem remains! Can we reliably predict the PDR or identify it experimentally?

[**Figure 2:** J. Piekarewicz, PRC **83**, 034319 (2011)]

From the PDR to the neutron skin to neutron-star radii

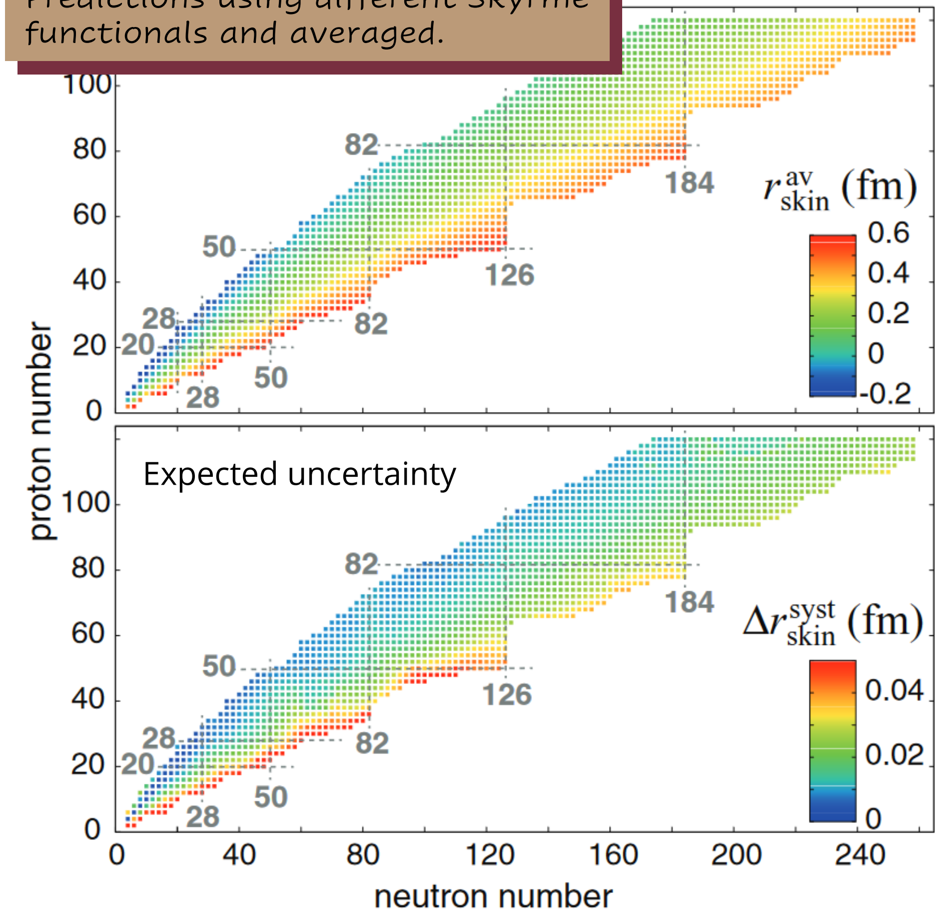
What can we expect at rare isotope beam facilities?



$= \textbf{neutron} - \textbf{skin thickness}$

[**Figure 1:** J. Piekarewicz, PRC **83**, 034319 (2011)]

Predictions using different Skyrme functionals and averaged.

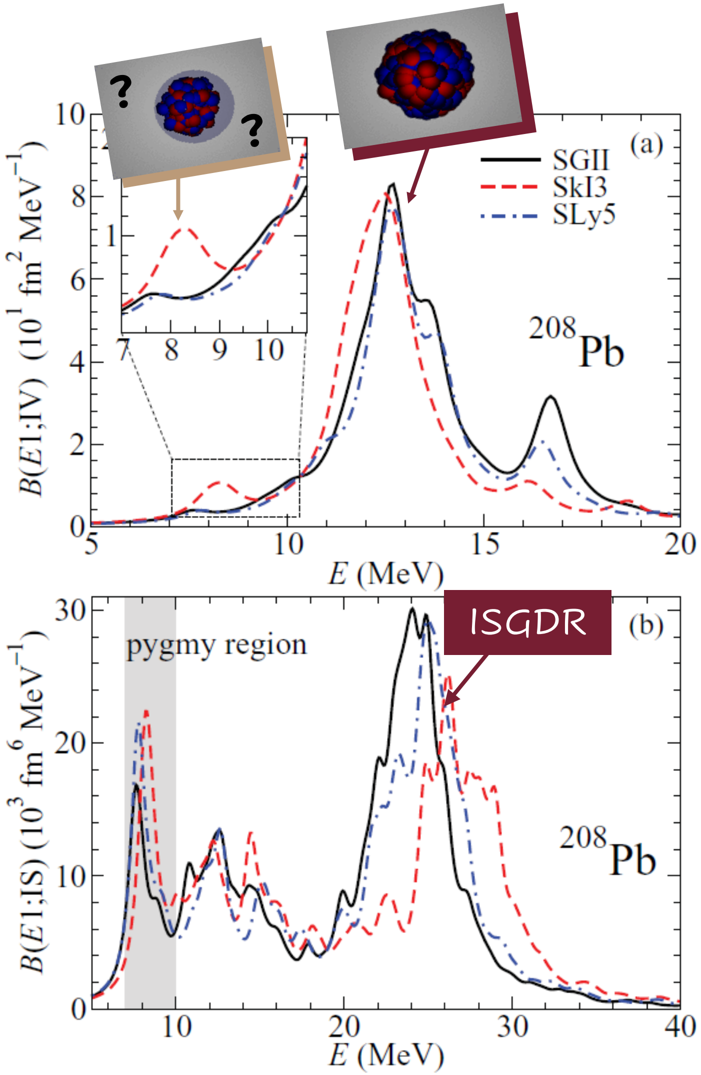


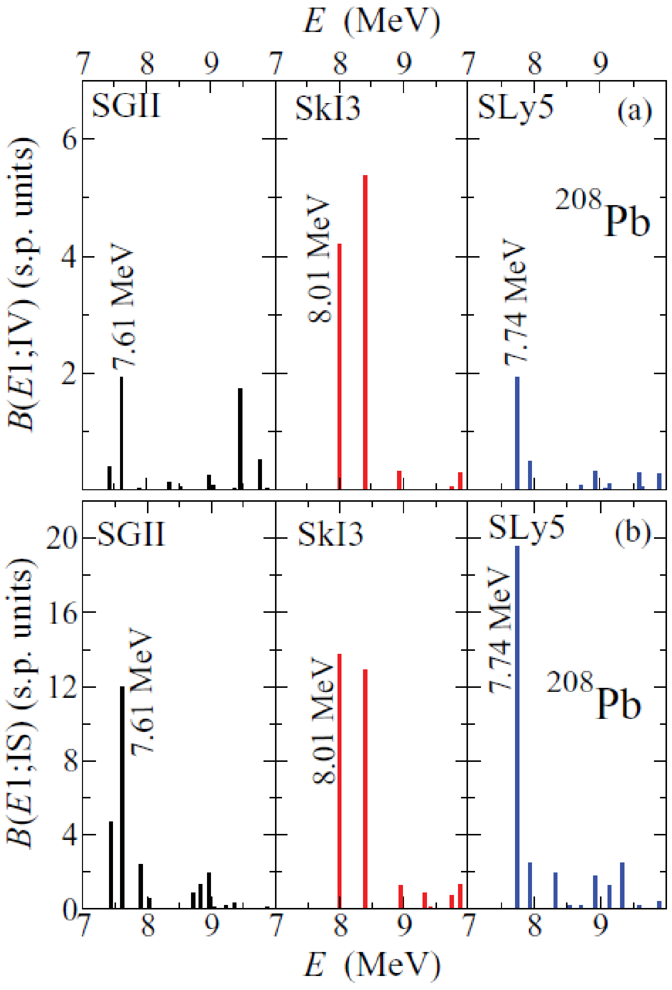
[**Figure 2:** M. Kortelainen *et al.*, PRC **88**, 031305(R) (2013)]

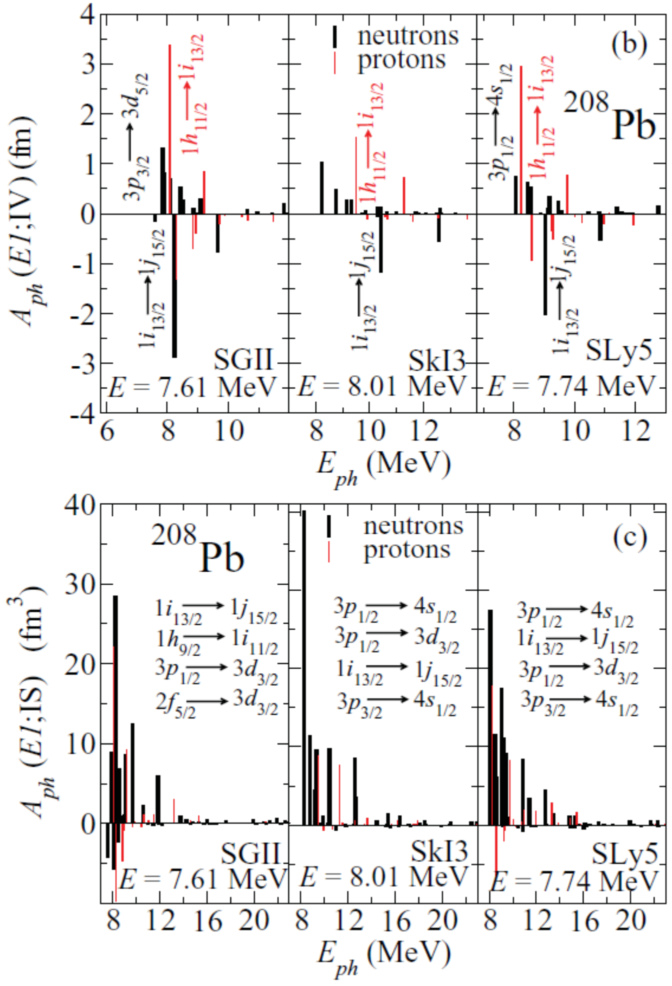
Massive neutron skins expected in neutron-rich isotopes (~ 0.4 – 0.6 fm). Reminder PREX result indicates ~ 0.28 fm for ^{208}Pb.

What causes the low-energy E1 bump that also influences (n,γ) rates?

(What is the single-particle structure of the PDR?)







[X. Roca-Maza et al., PRC **85**, 024601 (2012); see also A. Bracco et al., PPNP **106**, 360 (2019)]

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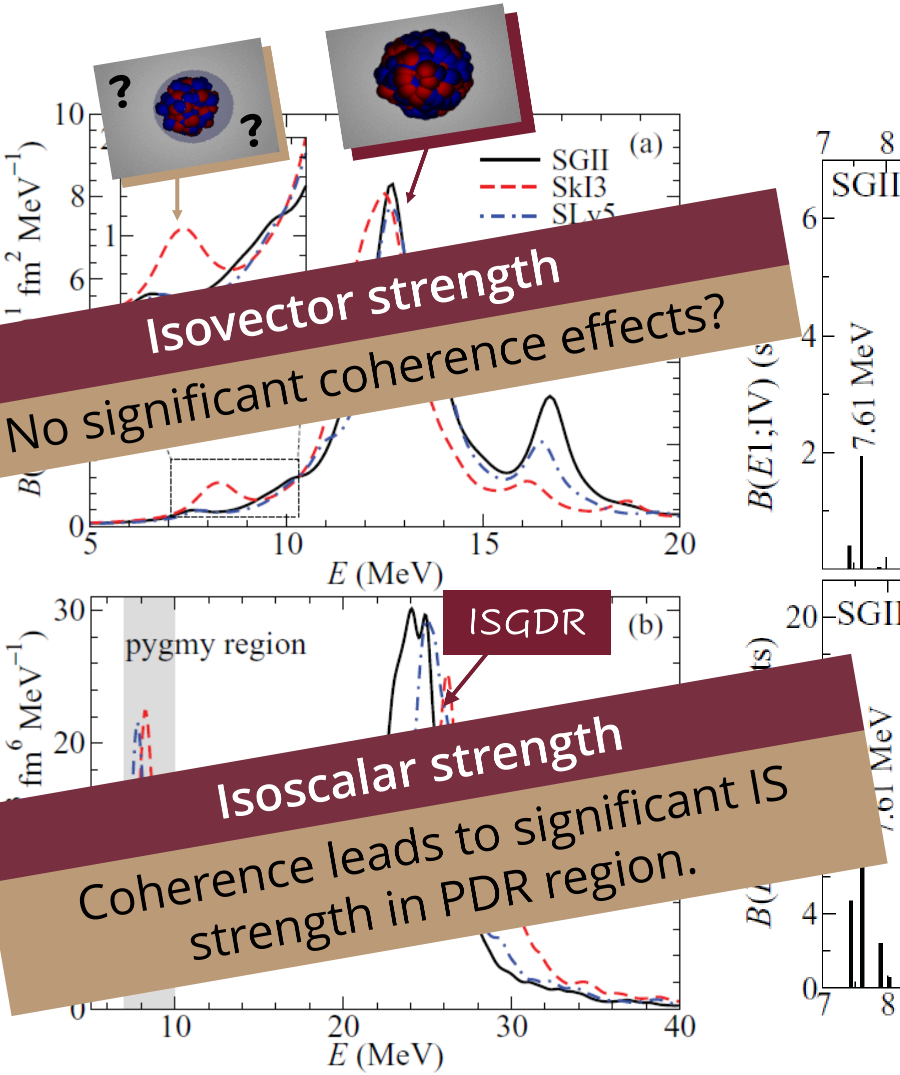
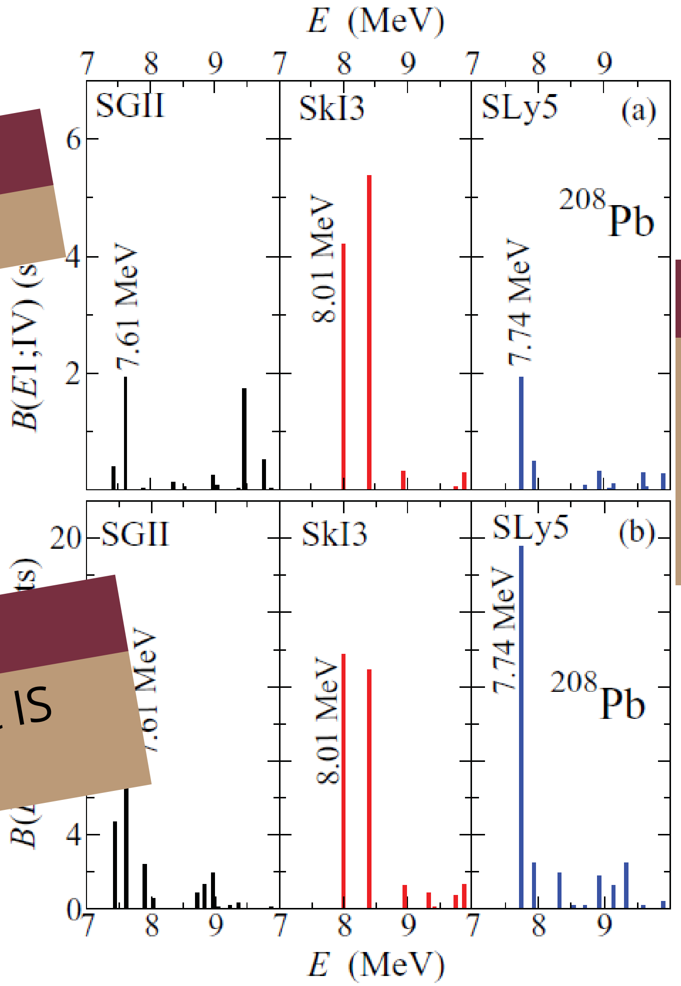


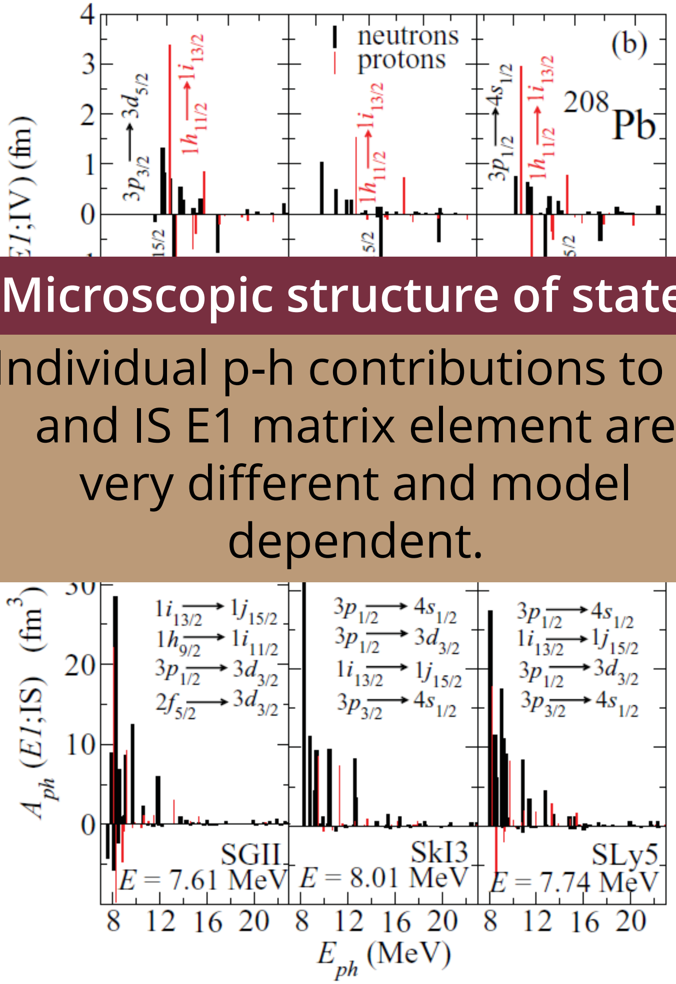
Isovector strength

No significant coherence effects?

Isoscalar strength

Coherence leads to significant IS strength in PDR region.





Microscopic structure of states

Individual p-h contributions to IV and IS E1 matrix element are very different and model dependent.

[X. Roca-Maza et al., PRC **85**, 024601 (2012); see also A. Bracco et al., PPNP **106**, 360 (2019)]

Are the PDR strength and neutron-skin thickness correlated?

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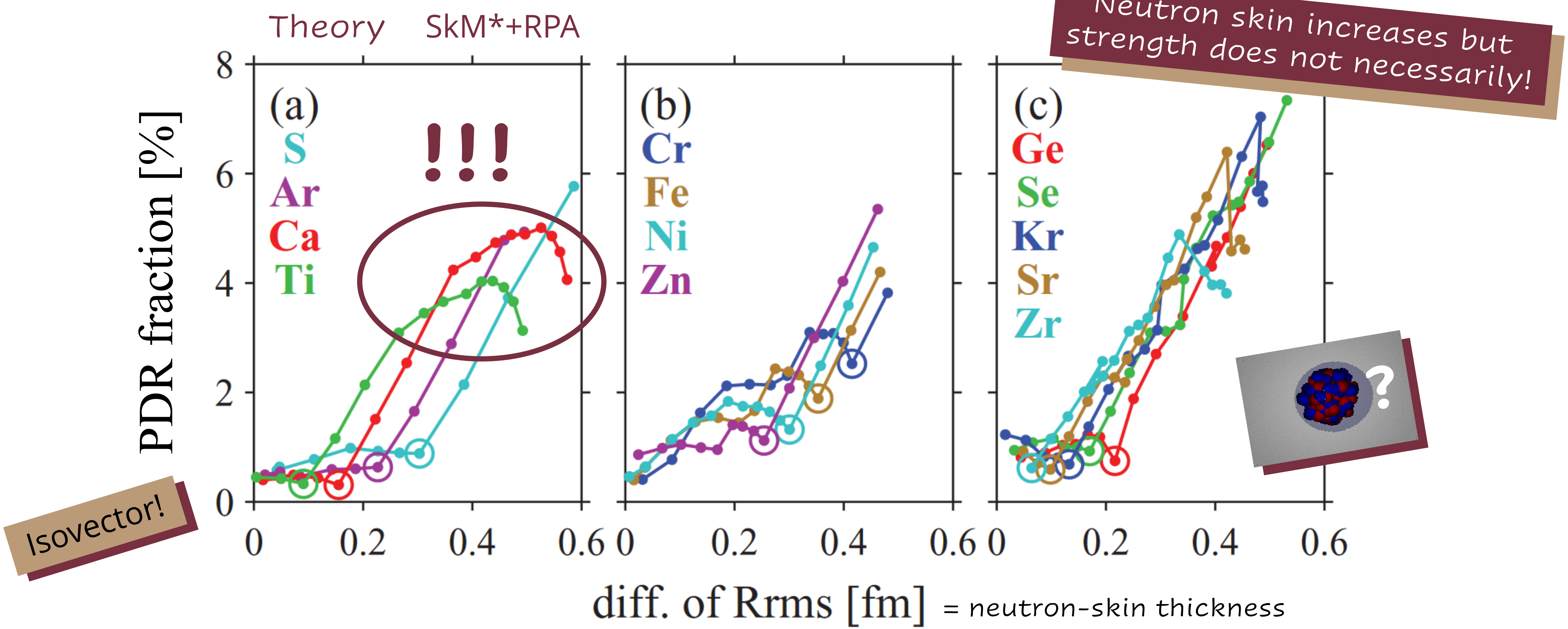
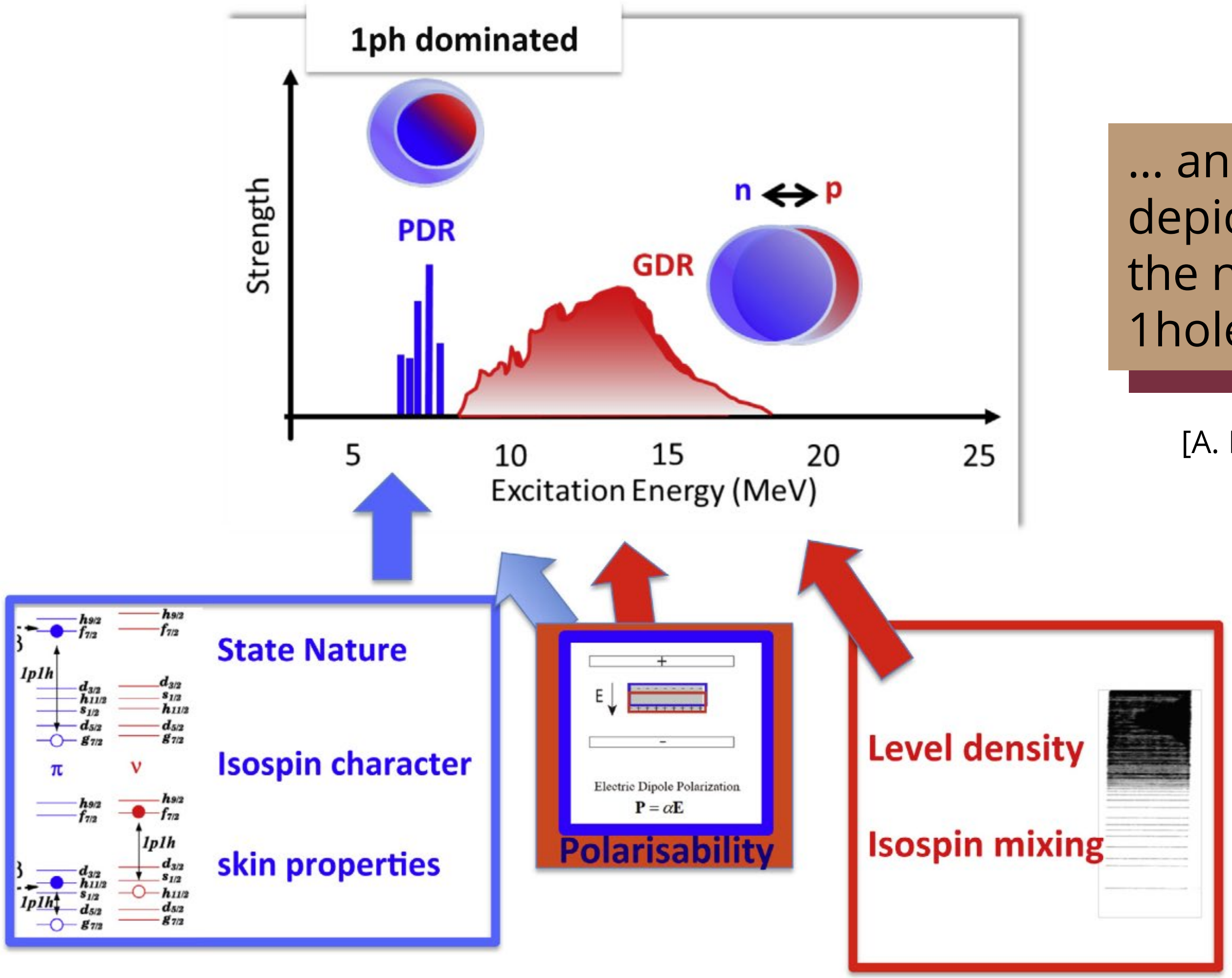
Single-particle structure influences strengths significantly!

→ Only occupation of low-L orbitals leads to significantly more IV strengths?



[T. Inakura et al., PRC **84**, 021302(R) (2011)]

…, so, let us probe that neutron 1p-1h nature of the PDR.

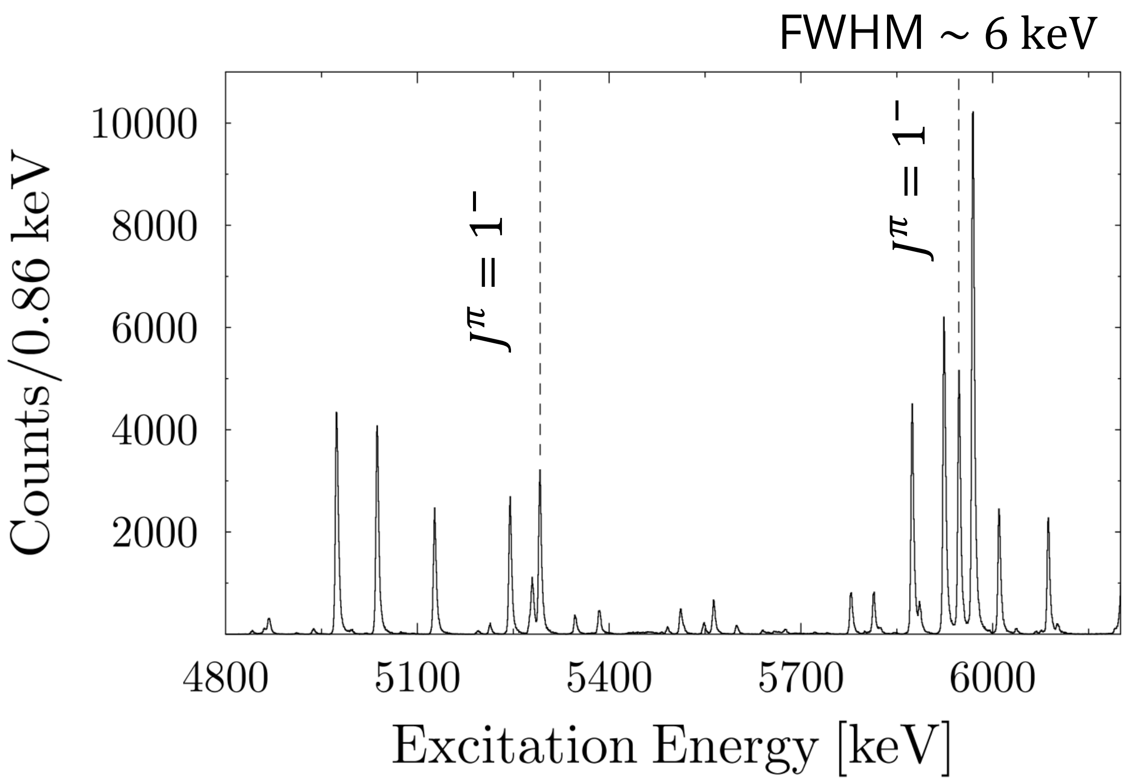


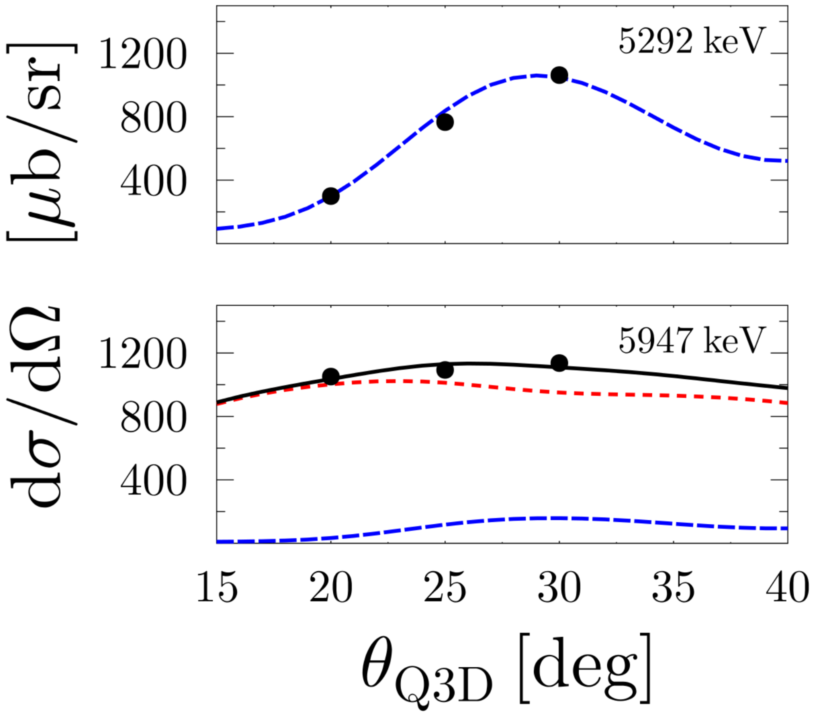
… and the Pygmy Dipole Resonance (PDR) is depicted in neutron-rich nuclei as a property of the neutron skin (neutron states of 1particle–1hole nature).

[A. Bracco, E.G. Lanza, A. Tamii, Prog. Part. Nucl. Phys. **106**, 360 (2019)]

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

[M. Spieker et al., PRL **125**, 102503 (2020)]





- E_d = 22 MeV
- ^{207}Pb target (0.11 mg/cm^2; 99% enrichment) on thin Carbon backing.

Lines DWBA calculations for:

Blue: $(3p_{1/2})^{-1}(4s_{1/2})^{+1}$ $(l = 0)$

Red: $(3p_{1/2})^{-1}(3d_{3/2})^{+1}$ $(l = 2)$

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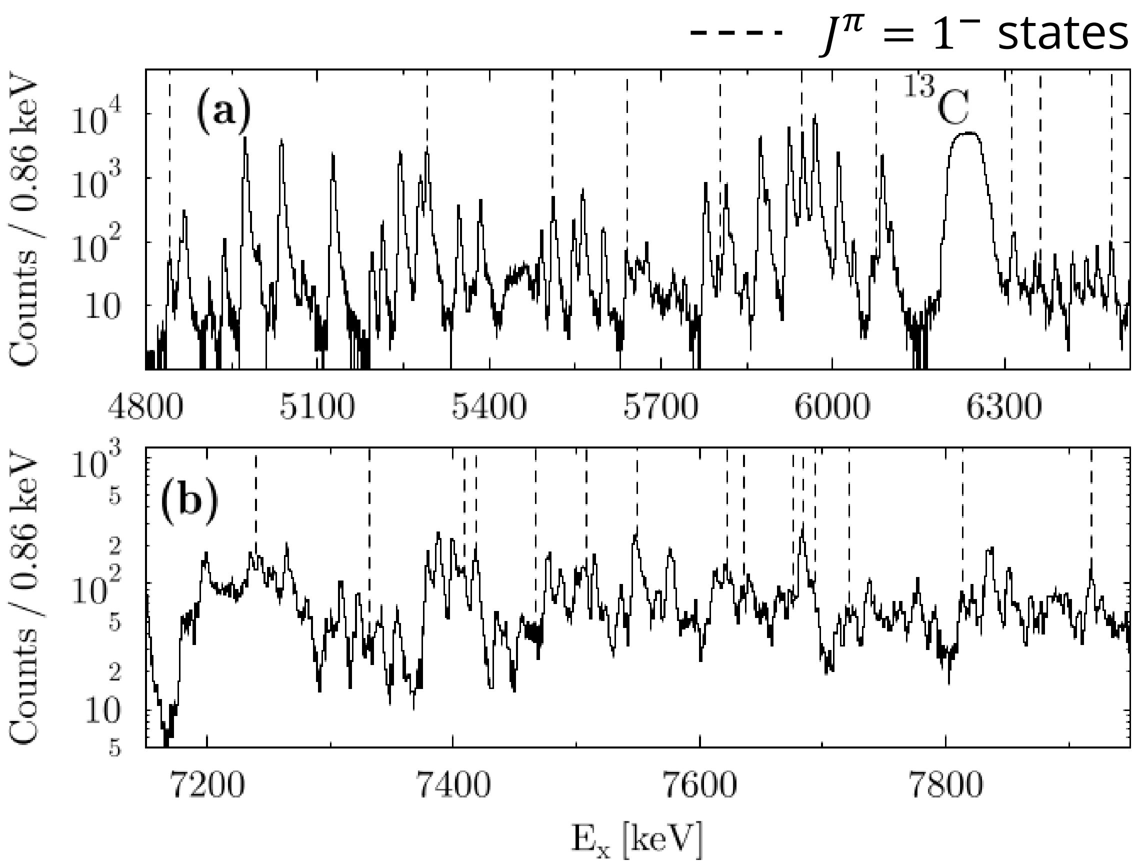
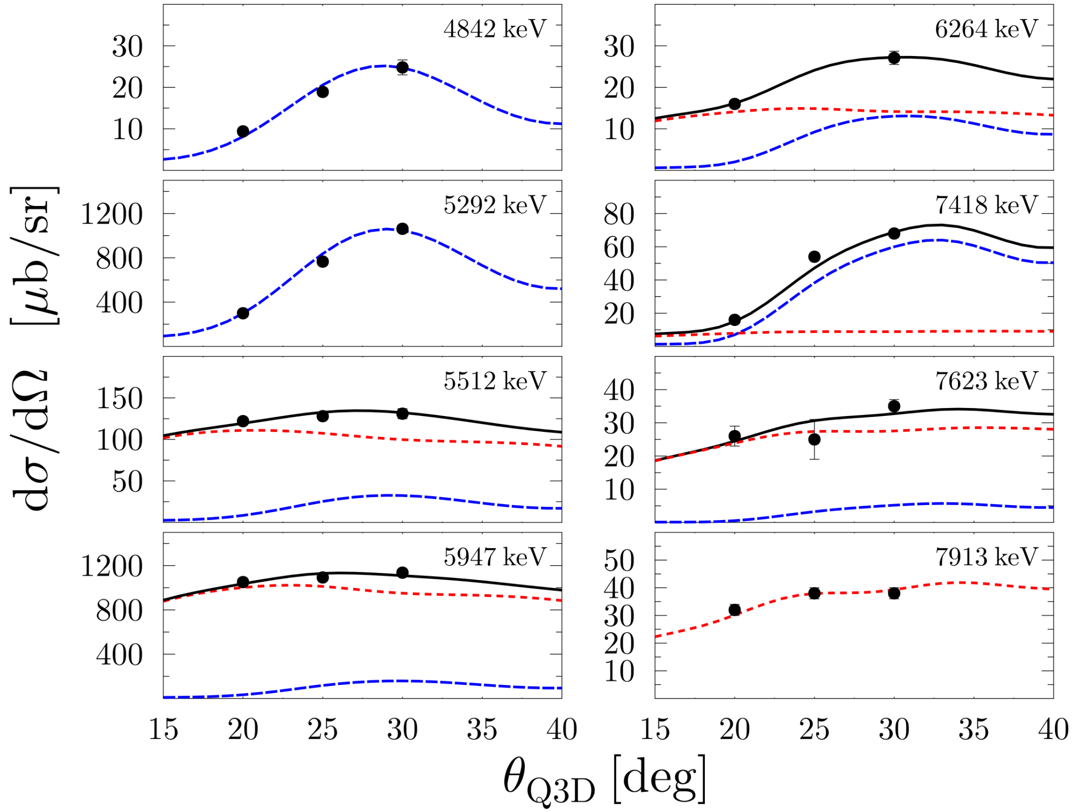
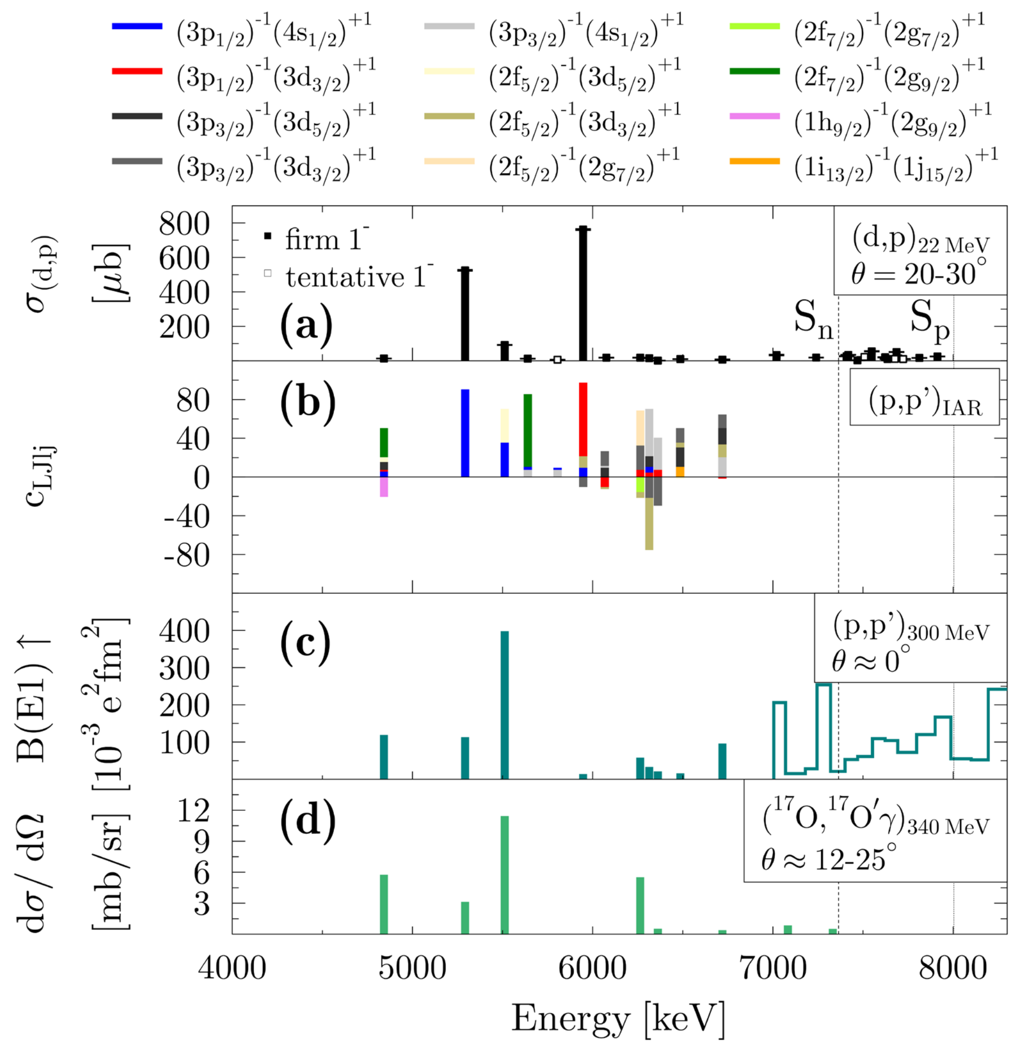




Excitation energies of 1$^-$ states were known from previous experiments.
Calculated angular distributions are in **excellent agreement with data**.

(d,p) and $(p,p')_{IAR}$ data compared to other probes (Experiment)

[M. Spieker et al., PRL **125**, 102503 (2020)]



Main observations:

Two strong states. Remaining strength fragmented up to S_p.

Dominant fragments for some p-h excitations at “low” E_x. In general, strength is fragmented among several states.

One dominating state but significant IV strength below S_n. (PDR < 8.3 MeV?)

IS strength below S_n carried by four states.

[$(p,p')_{300\ MeV}$: I. Poltoratska et al., PRC **85**, 041304(R) (2012)]
[$(^{17}O,^{17}O'\gamma)$: F.C.L. Crespi, A. Bracco, et al., PRL **113**, 012501 (2014)]
[$(p,p')_{IAR}$ analysis: A. Heusler]

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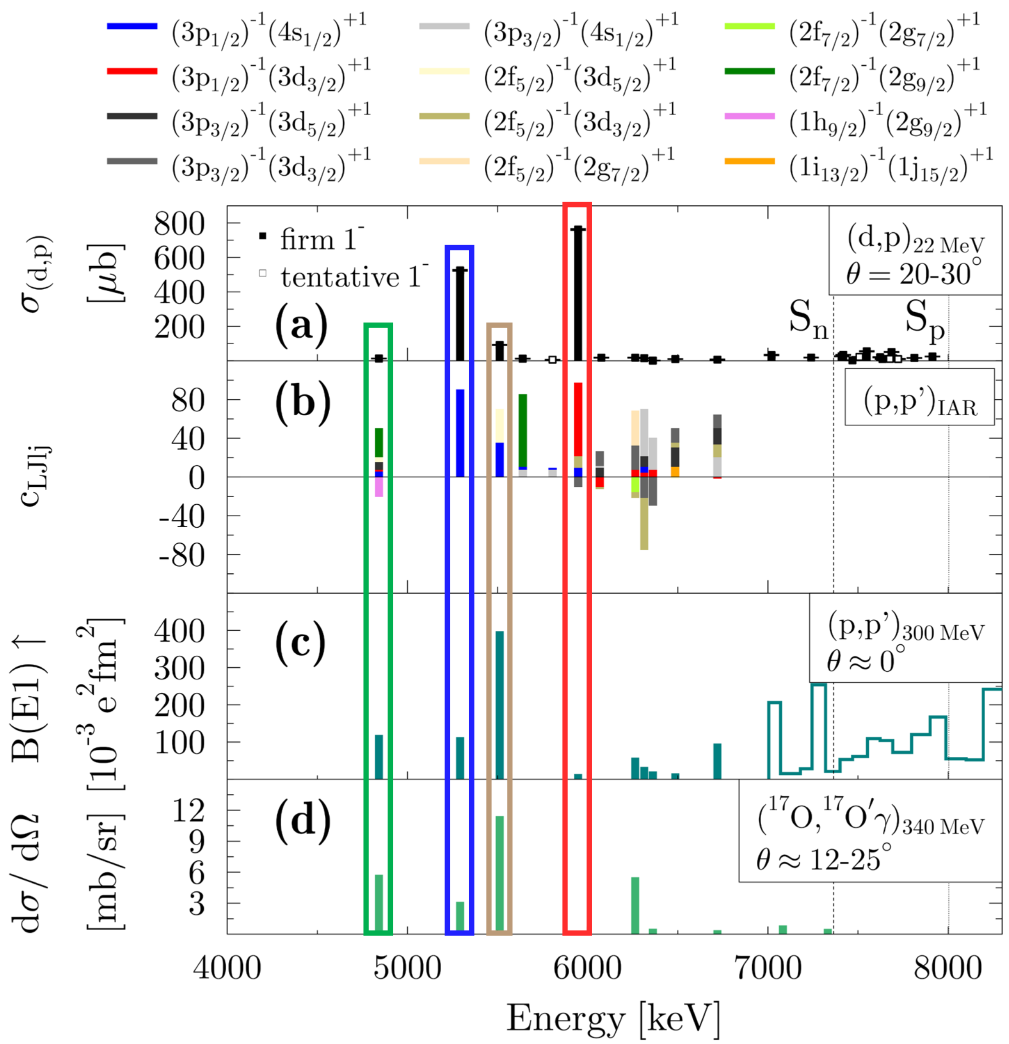
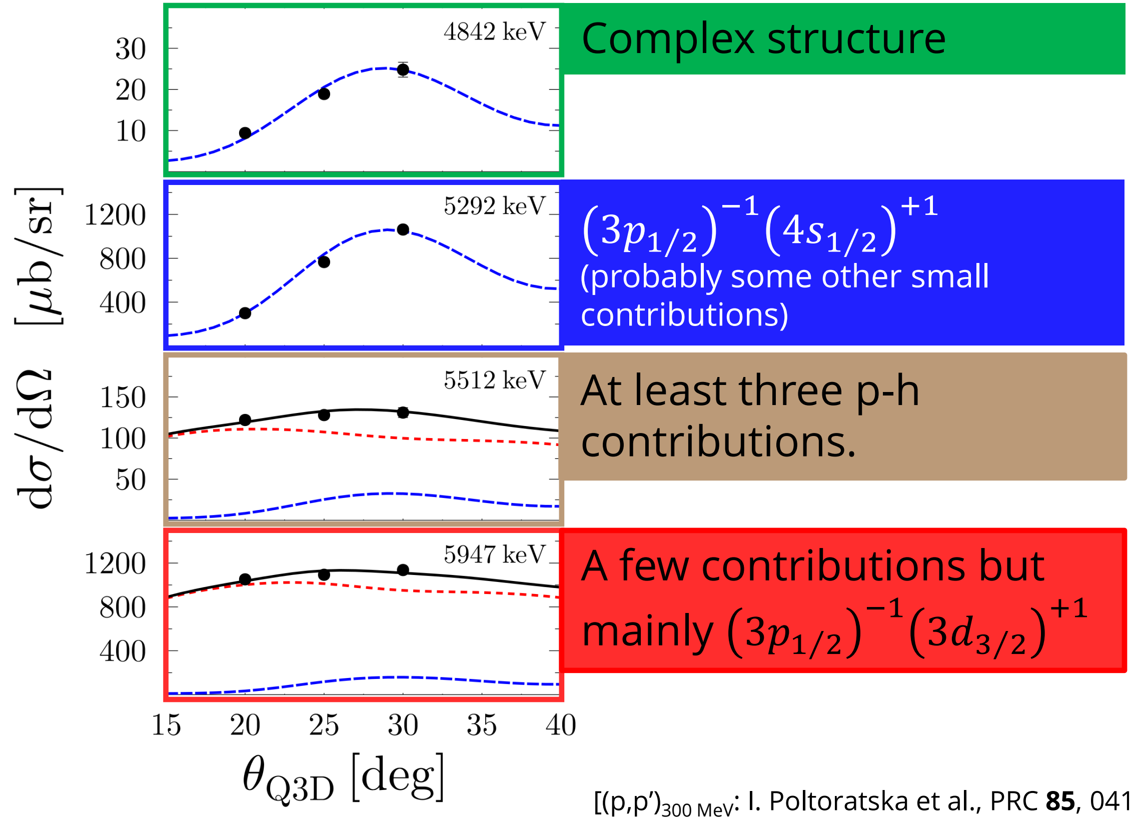


Detailed spectroscopy can provide access to some of the p-h E1 matrix elements.

(d,p) angular distributions



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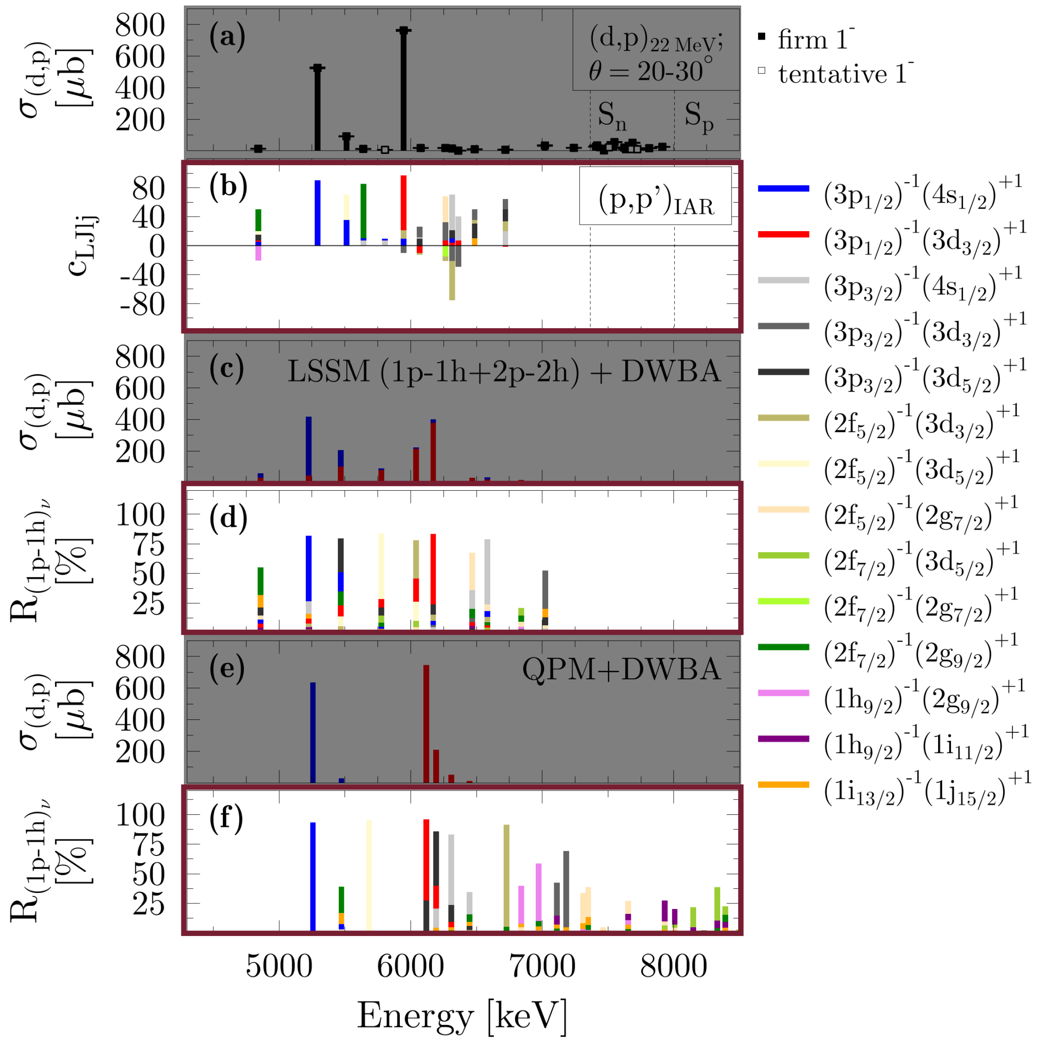
Experimental observables compared to LSSM and QPM calculations

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



Microscopic structure of 1^- states

Some states seem to be rather pure 1p-1h excitations (one configuration clearly dominates), others have many 1p-1h excitations contributing to their state vector. Structures become more complex at higher E_x.

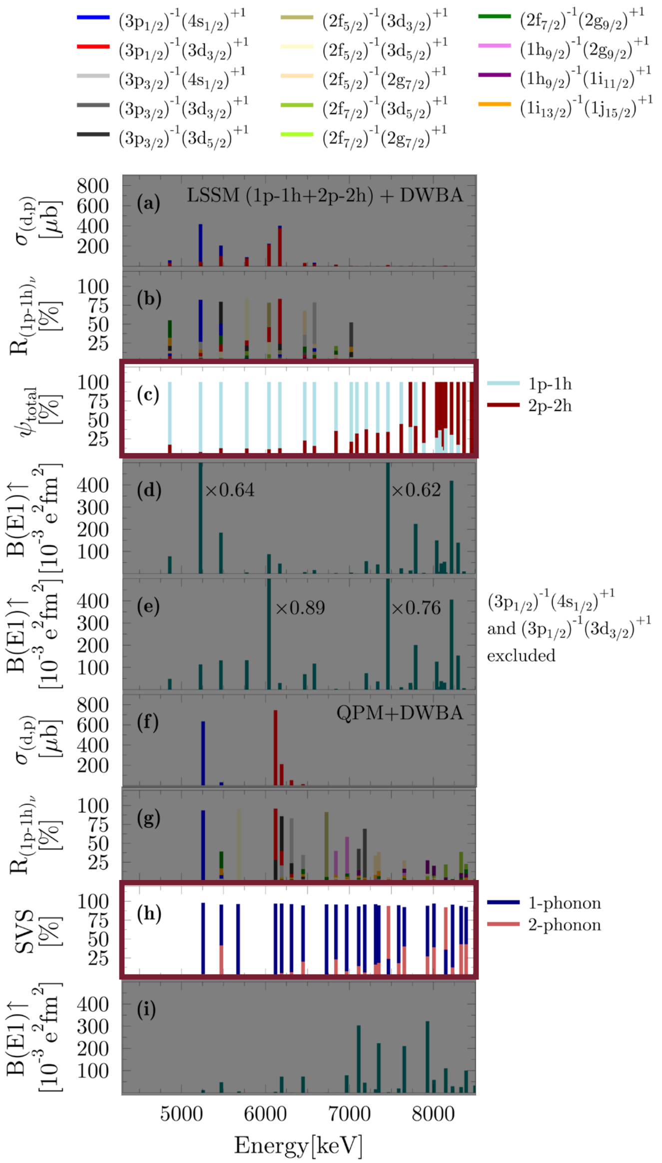
LSSM wave functions more complex than QPM.

Is there a clear transition from more 1p-1h dominated wavefunctions to wavefunctions with more complex contributions? Will that tell us anything about the microscopic structure of the PDR?

[M. Spieker et al., PRL **125**, 102503 (2020)]

Comparison LSSM and QPM

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

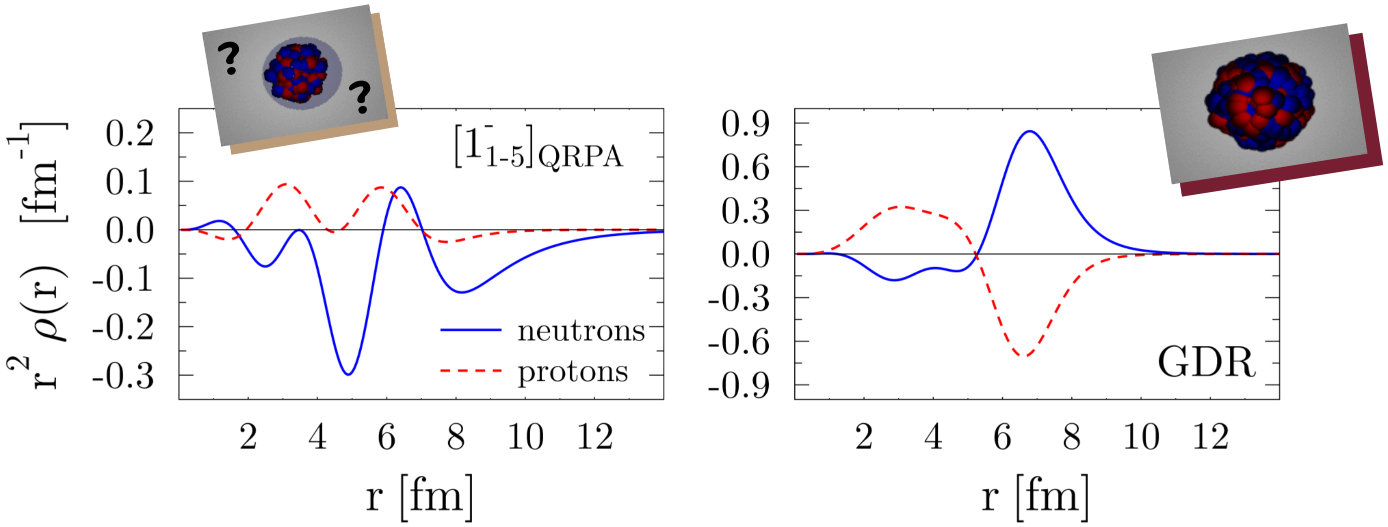


2p-2h (or 2-phonon) excitations are not negligible and start contributing significantly to the states' structure above 7 MeV.

[3-phonon contributions start contributing above 9 MeV]

However, the low-lying states are dominated by 1p-1h (1-phonon) excitations!

→ Are these the "real" PDR states in ^{208}Pb?



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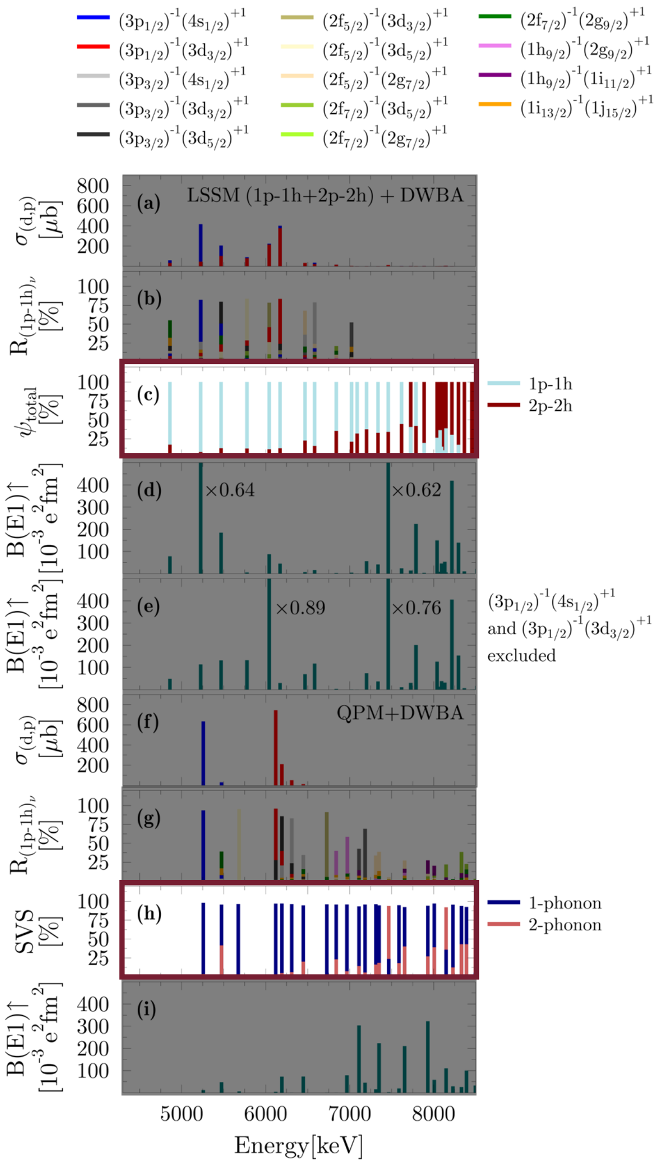

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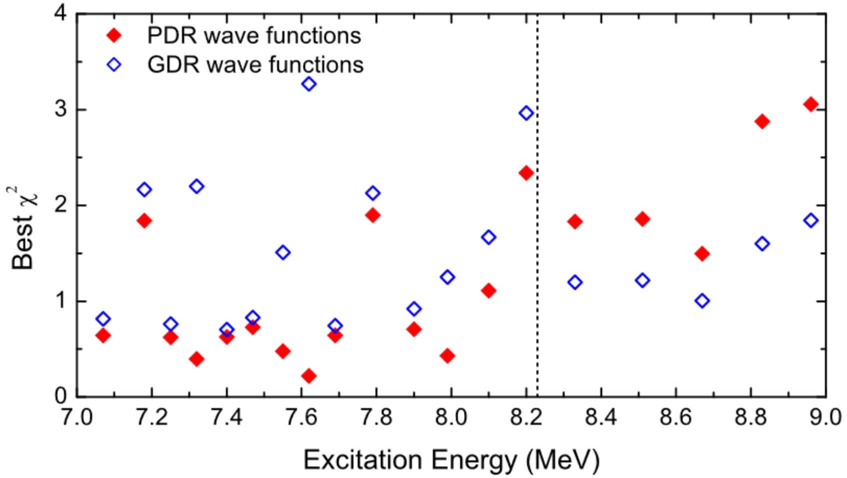
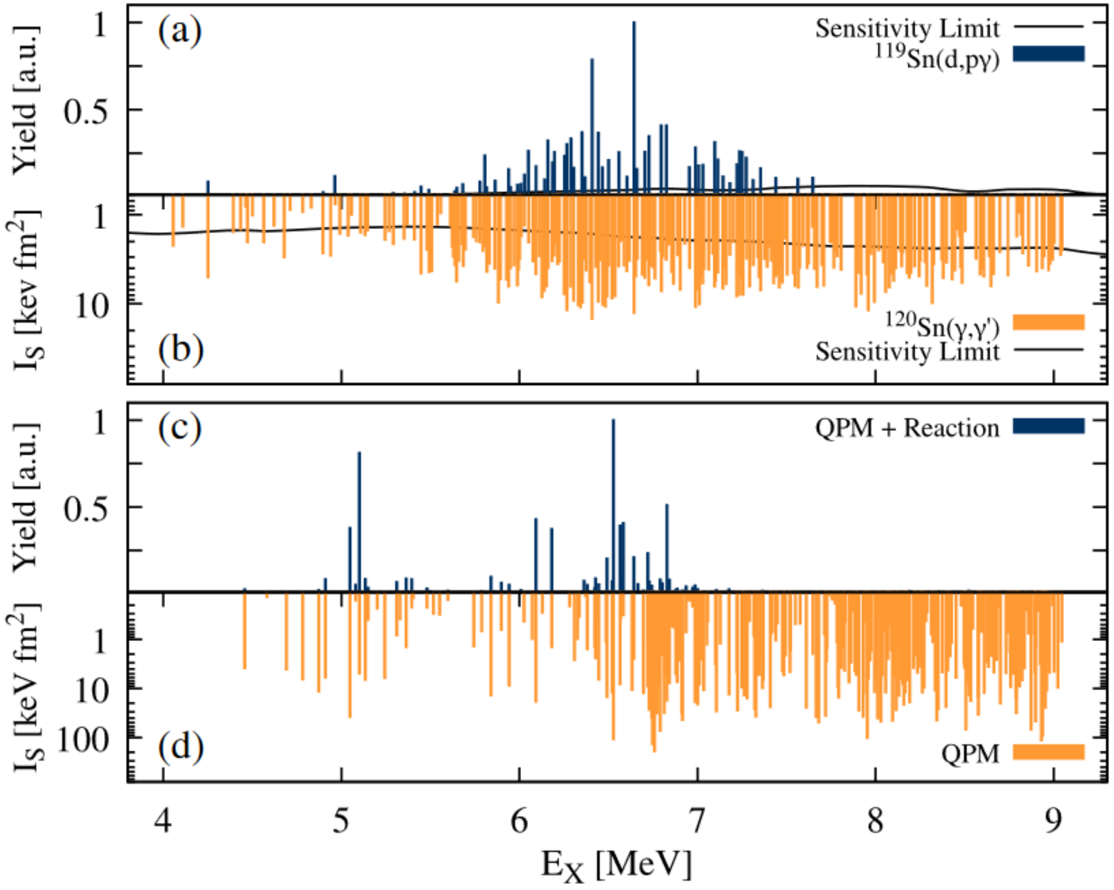


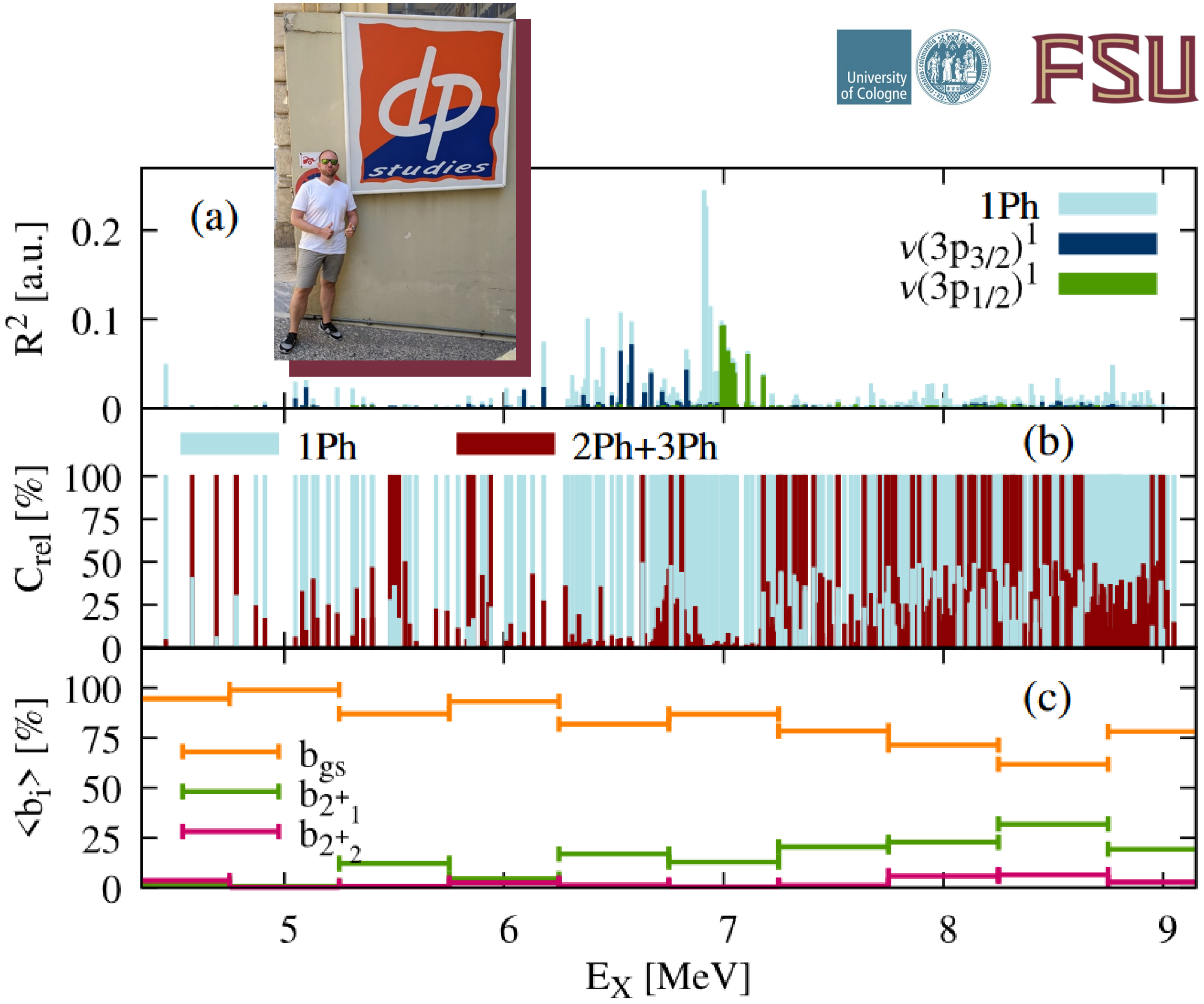
In general, findings agree with conclusions presented by Poltoratska et al.

[M. Spieker et al., PRL **125**, 102503 (2020)]

Story in ^{120}Sn is analogous

[M. Weinert et al., PRL **127**, 242501 (2021)]





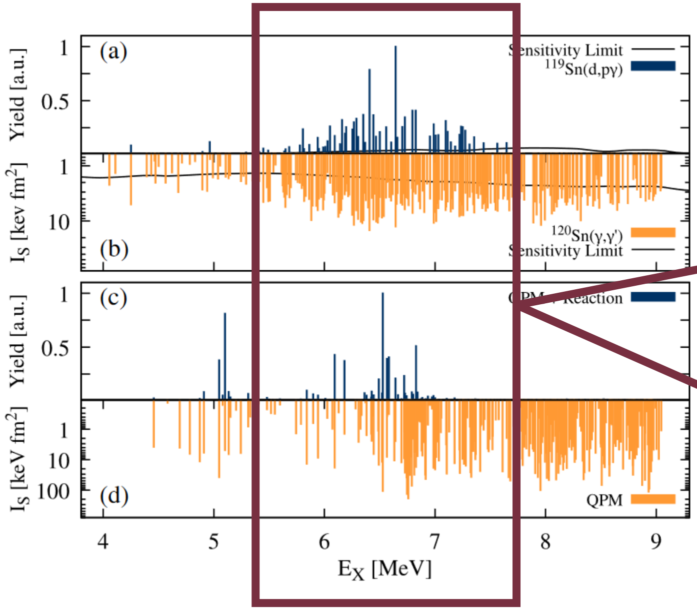
Obvious question when seeing this clear separation between 1p-1h dominated states and states with contributions from more complex configurations: **Is the isospin splitting connected to this?**

Story in ^{120}Sn is analogous

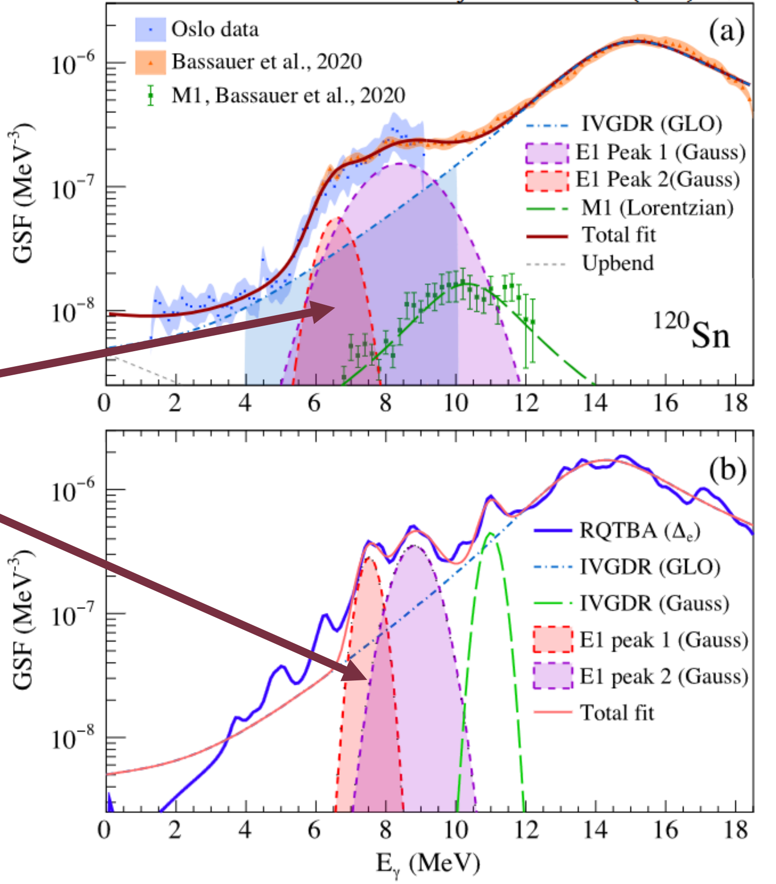
[M. Weinert et al., PRL **127**, 242501 (2021)]

PDR IV strength is small!

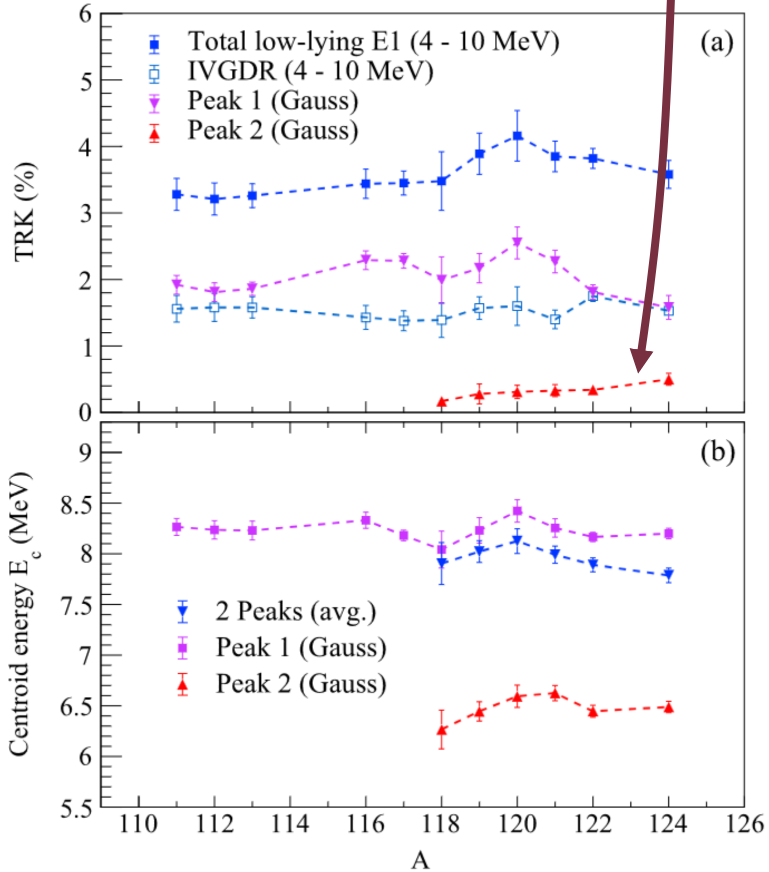
Conclusions supported by recent Oslo-type study of isovector E1 strength in Sn isotopes.



Physics Letters B 860 (2025) 139216

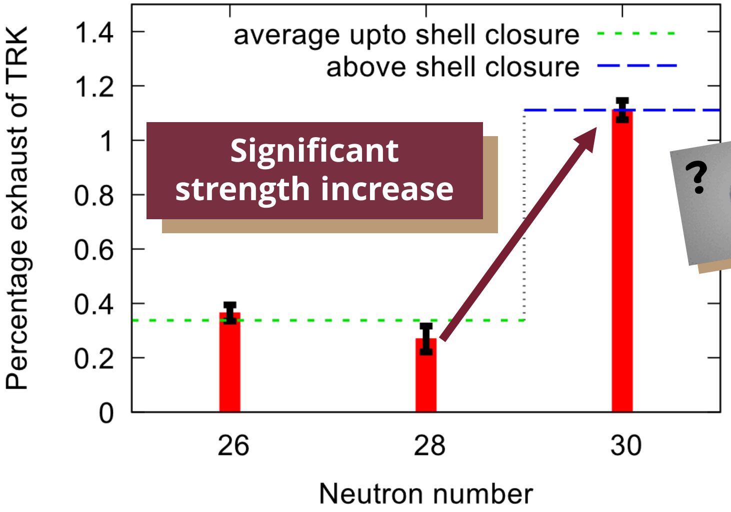


M. Markova, P. von Neumann-Cosel and E. Litvinova

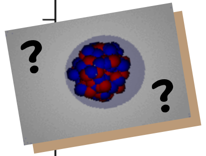


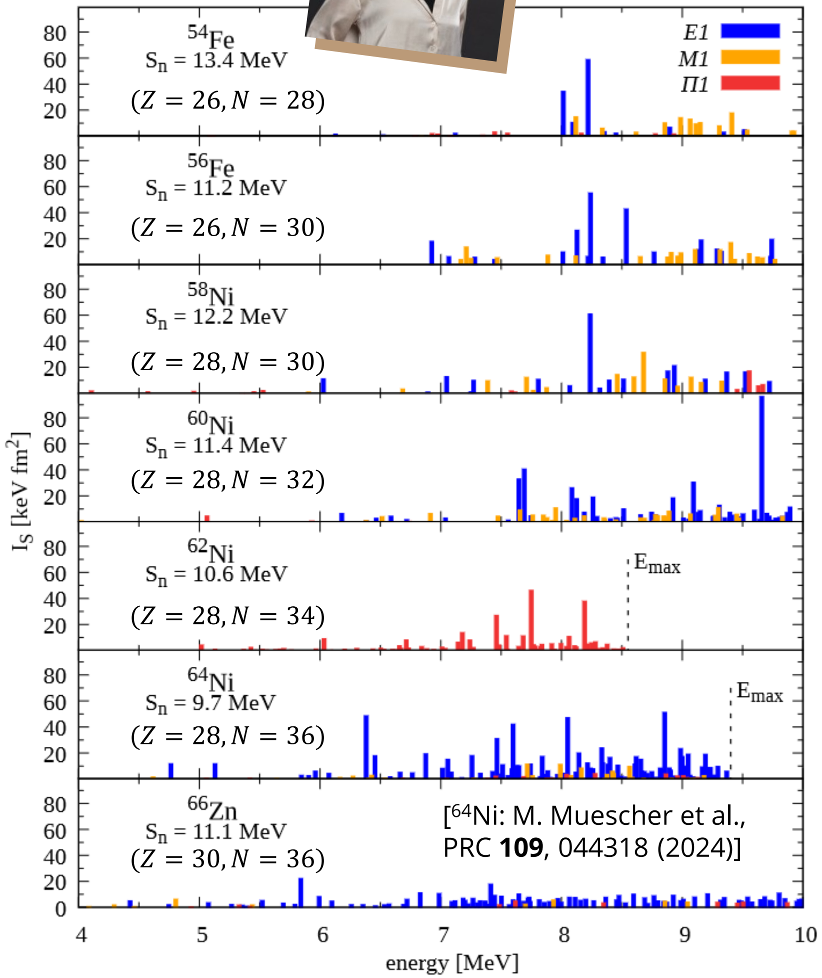
B(E1) strength increase beyond N=28 – Onset of the PDR?

[P. Ries et al., PRC **100**, 021301(R) (2019)]



Significant strength increase





- Ries et al. observed significant strength increase in ^{54}Cr.

→ In line with experimental data for other nuclei around N=28.

- E1 strength shifts down significantly with increasing neutron number.
- Strength appears significantly more fragmented for “doubly” open-shell nuclei, i.e., ^{66}Zn.

[Figure 2: Miriam Müscher, “*The low-lying dipole response of medium-mass nuclei - Study of ^{64}Ni using complementary real-photon scattering experiments*”, PhD thesis, Universität zu Köln (2024)]

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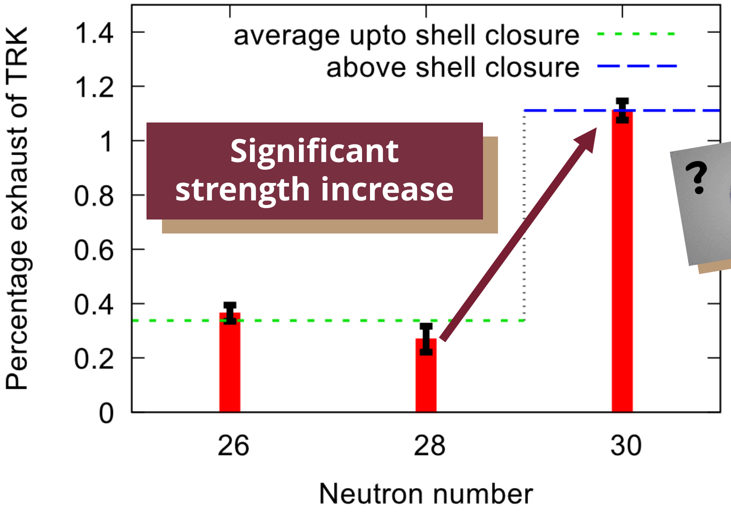

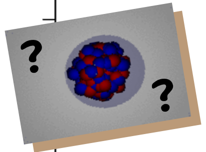

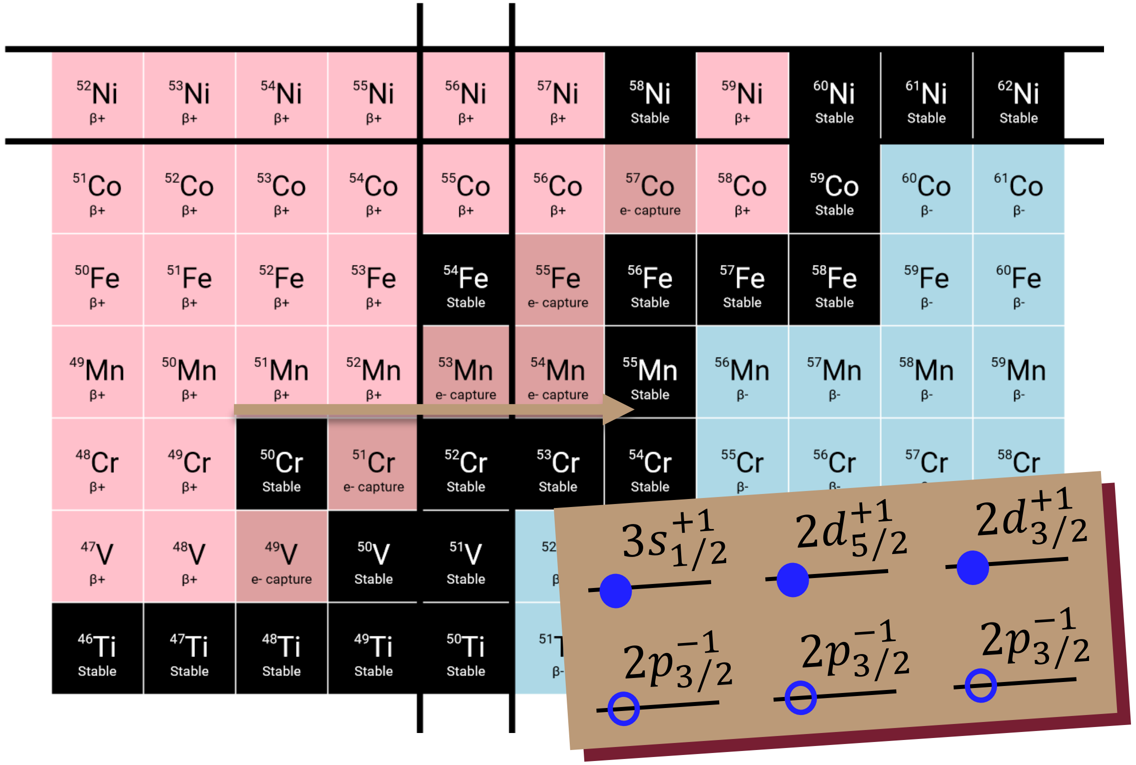

Possible cause: Change of single-particle structure

^{49}**Cr:** $J^{\pi}_{gs} = {}^{5}/_{2}{}^{-} \rightarrow (1f_{7/2})^{-1}(2d_{5/2})^{+1}, (1f_{7/2})^{-1}(1g_{9/2})^{+1}$ (deformed)

^{51}**Cr:** $J^{\pi}_{gs} = {}^{7}/_{2}{}^{-} \rightarrow (1f_{7/2})^{-1}(2d_{5/2})^{+1}, (1f_{7/2})^{-1}(1g_{9/2})^{+1}$

^{53}**Cr:** $J^{\pi}_{gs} = {}^{3}/_{2}{}^{-} \rightarrow (2p_{3/2})^{-1}(2d_{5/2})^{+1}, (2p_{3/2})^{-1}(2d_{3/2})^{+1}, (2p_{3/2})^{-1}(3s_{1/2})^{+1}$

All these neutron one-particle one-hole (1p-1h) configurations can contribute to $J^{\pi}=1^{-}$ states' (PDR) wavefunctions

Inakura et al. indeed predict that occupation of low-L orbitals near Fermi surface causes strength increase!

[T. Inakura et al., PRC **84**, 021302(R) (2011)]

[https://people.physics.anu.edu.au/~ecs103/chart/]

B(E1) strength increase beyond N=28 – Onset of the PDR?

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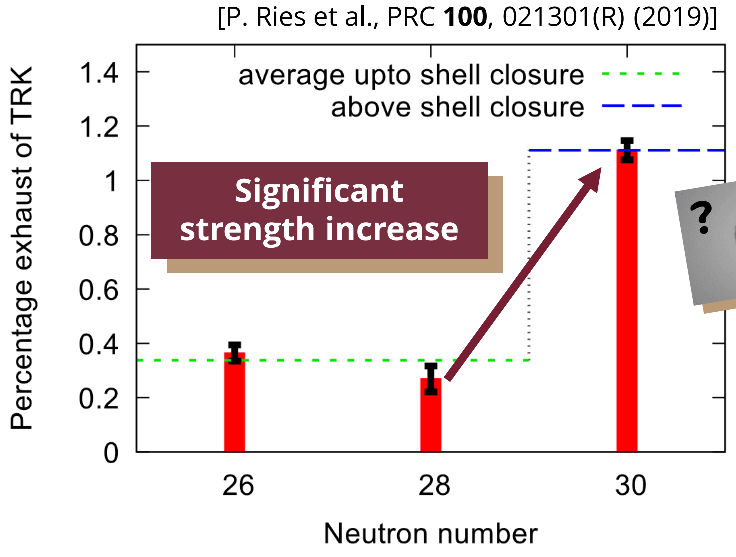
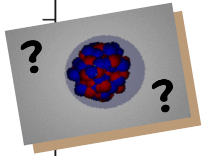
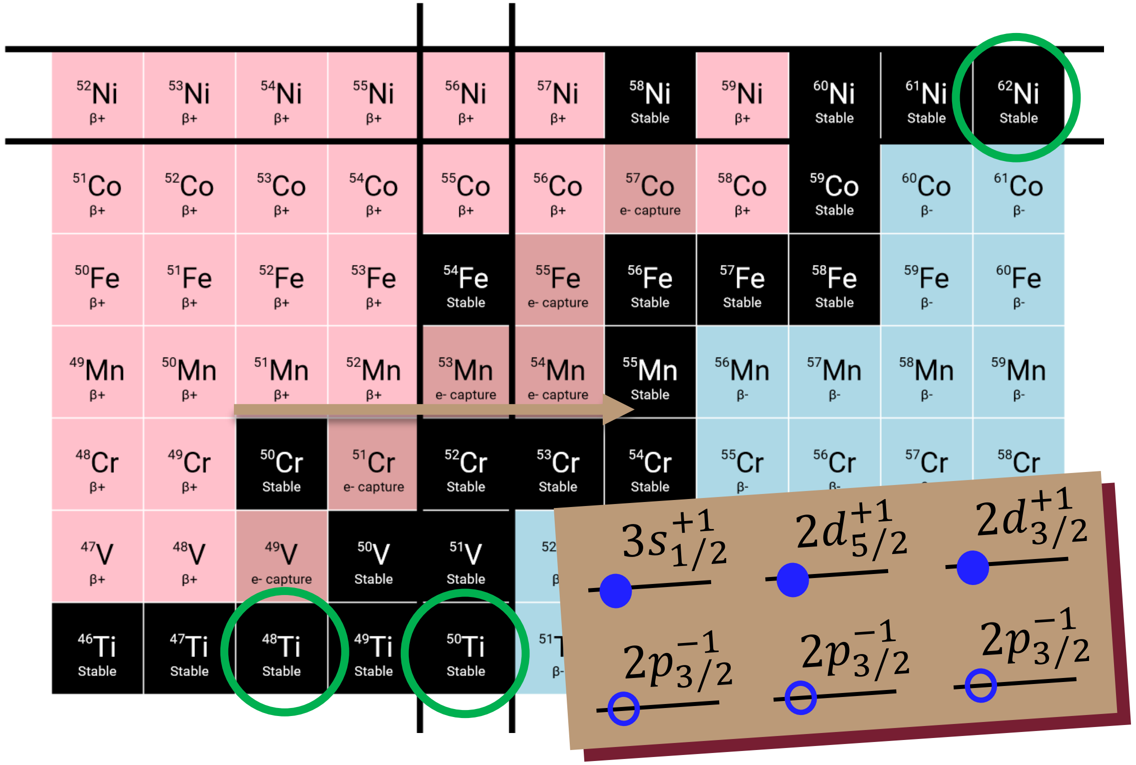
[P. Ries et al., PRC **100**, 021301(R) (2019)]







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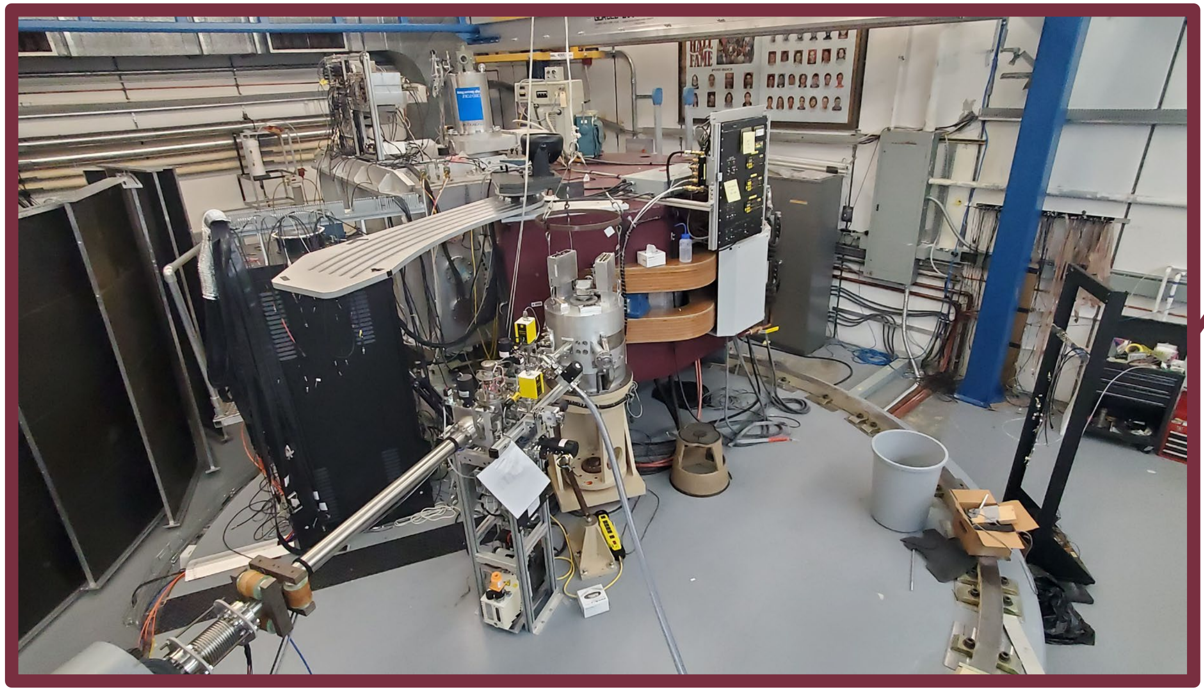
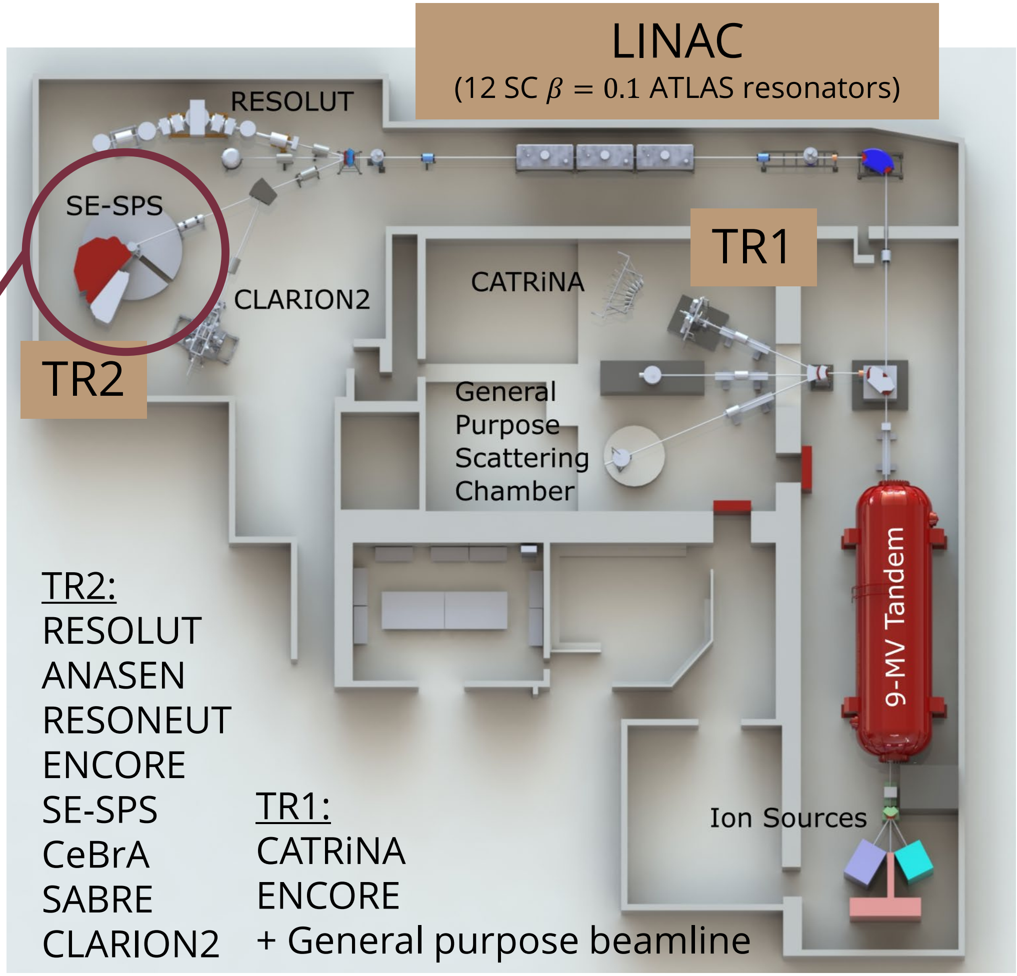
The John D. Fox Superconducting Linear Accelerator Laboratory

FSU

The Super-Enge Split-Pole Spectrograph at FSU



https://doi.org/10.3389/fphy.2024.1511394

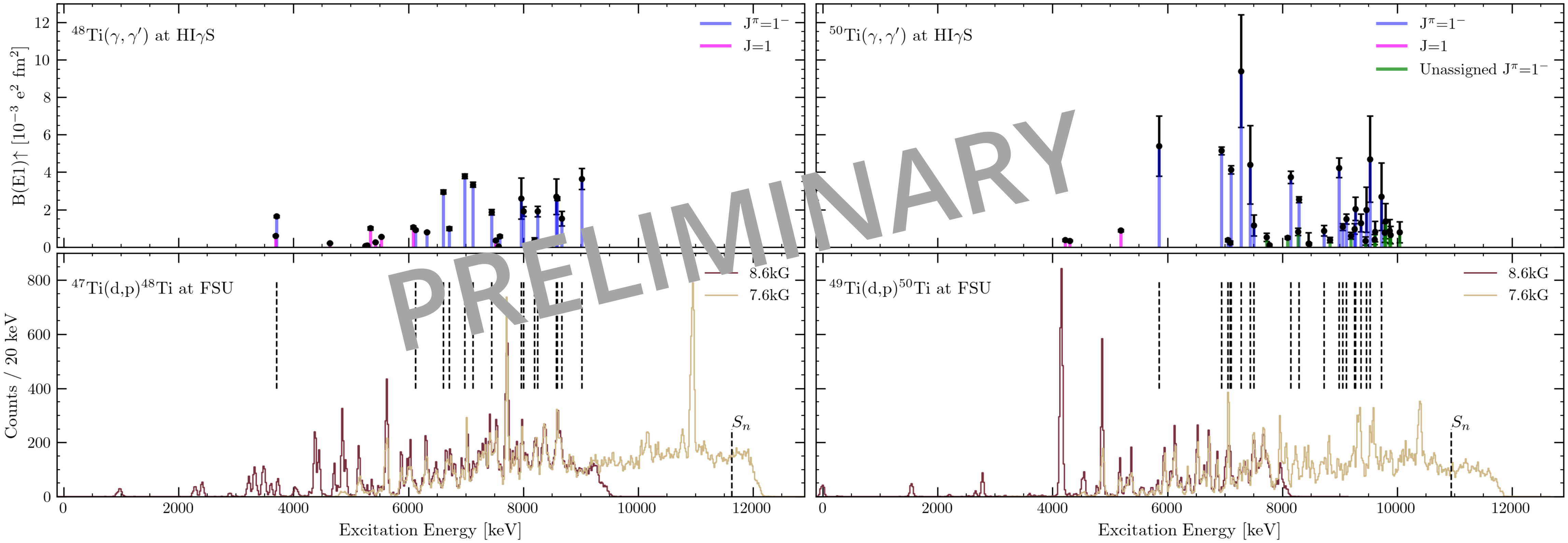


Visit us at https://fsunuc.physics.fsu.edu

^{47,49}Ti(d,p) at the FSU SE-SPS

Part of PhD thesis project of B. Kelly (ongoing analysis)

FSU

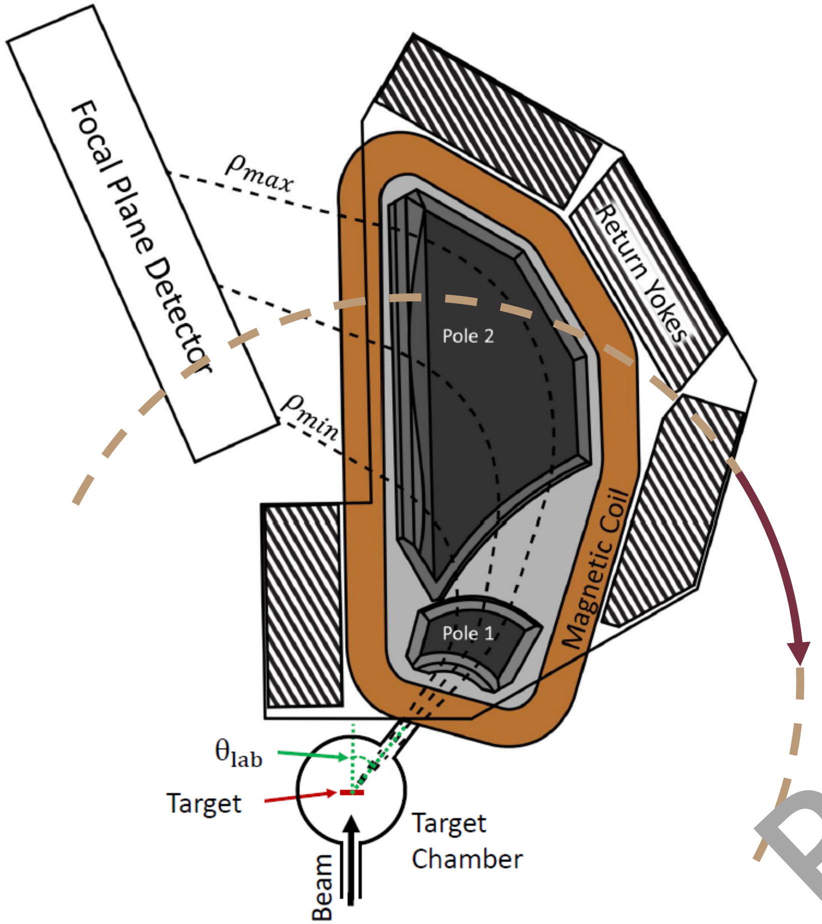


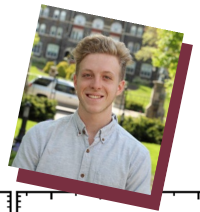
We can easily study the excitation spectrum up to and beyond S_n at the SE-SPS (if Q value permits!).
Energy resolution (FWHM) for ~400-500 μg/cm^2 targets is typically 40-70 keV.

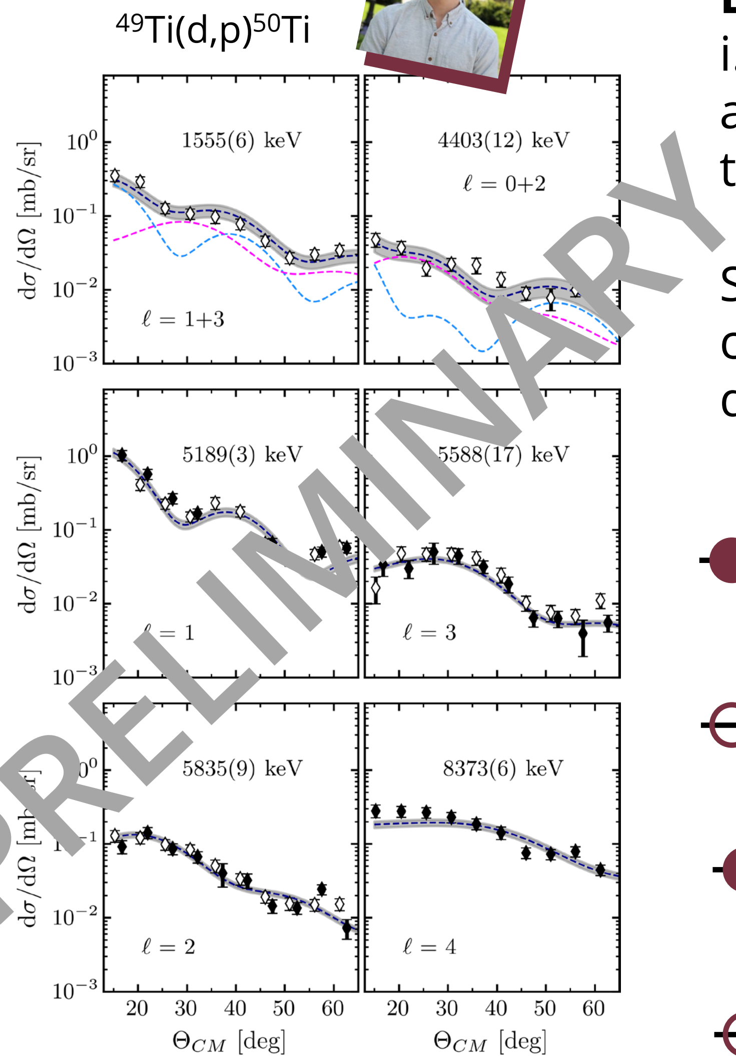
[(γ, γ ‘) **data:** U. Gayer, Master’s thesis, TU Darmstadt (Germany)]

^{47,49}Ti(d,p) at the FSU SE-SPS

Part of PhD thesis project of B. Kelly (ongoing analysis)

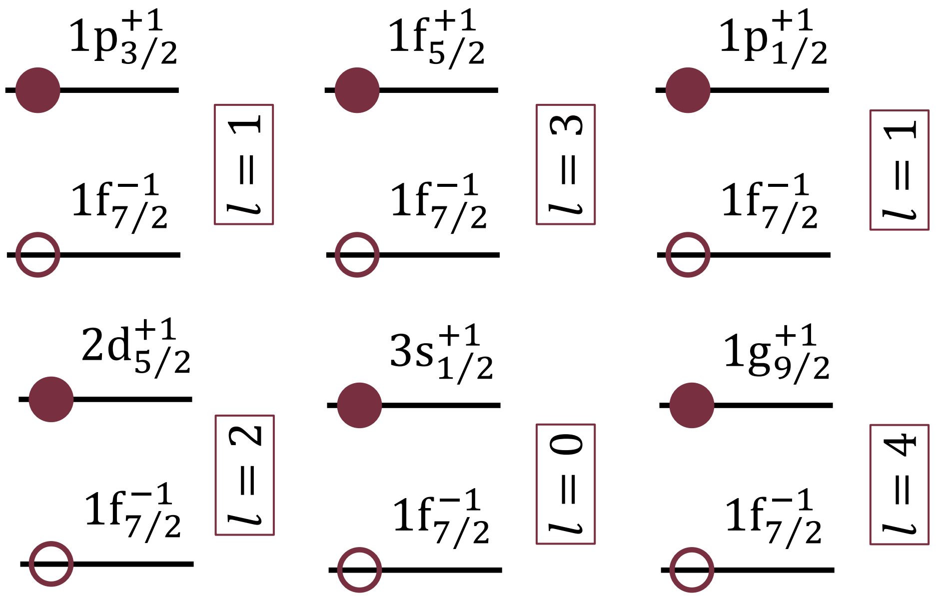






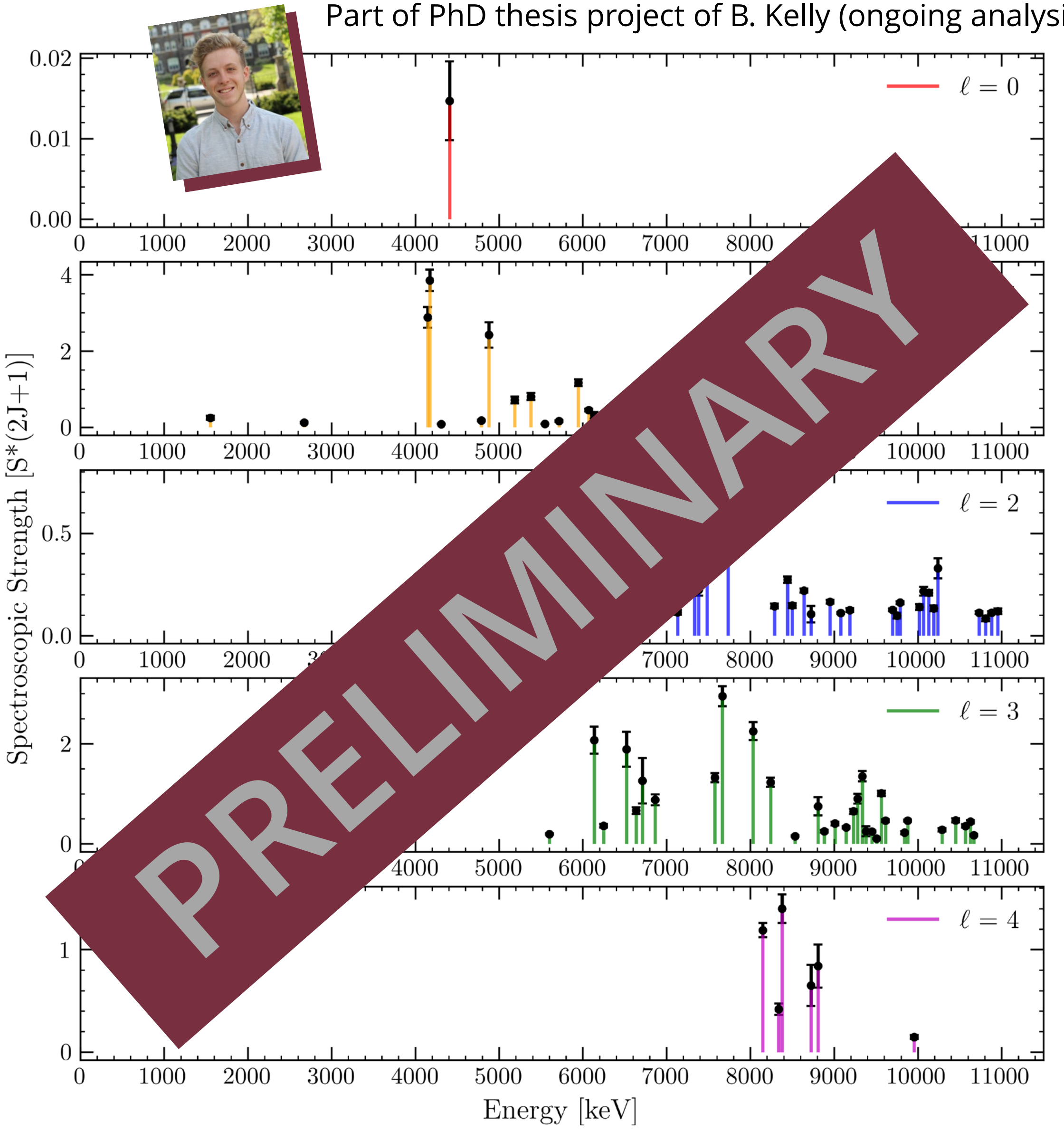
Basic idea: Measure angular distributions, i.e., particle yields at different scattering angles, to determine angular momentum transfer.

SE-SPS on rails and sliding seal scattering chamber to facilitate measurements at different scattering angles.



Single-particle strength in ^{50}Ti

Part of PhD thesis project of B. Kelly (ongoing analysis)



Strength distribution for different angular-momentum, l, transfers.

Single-particle strength in ^{50}Ti

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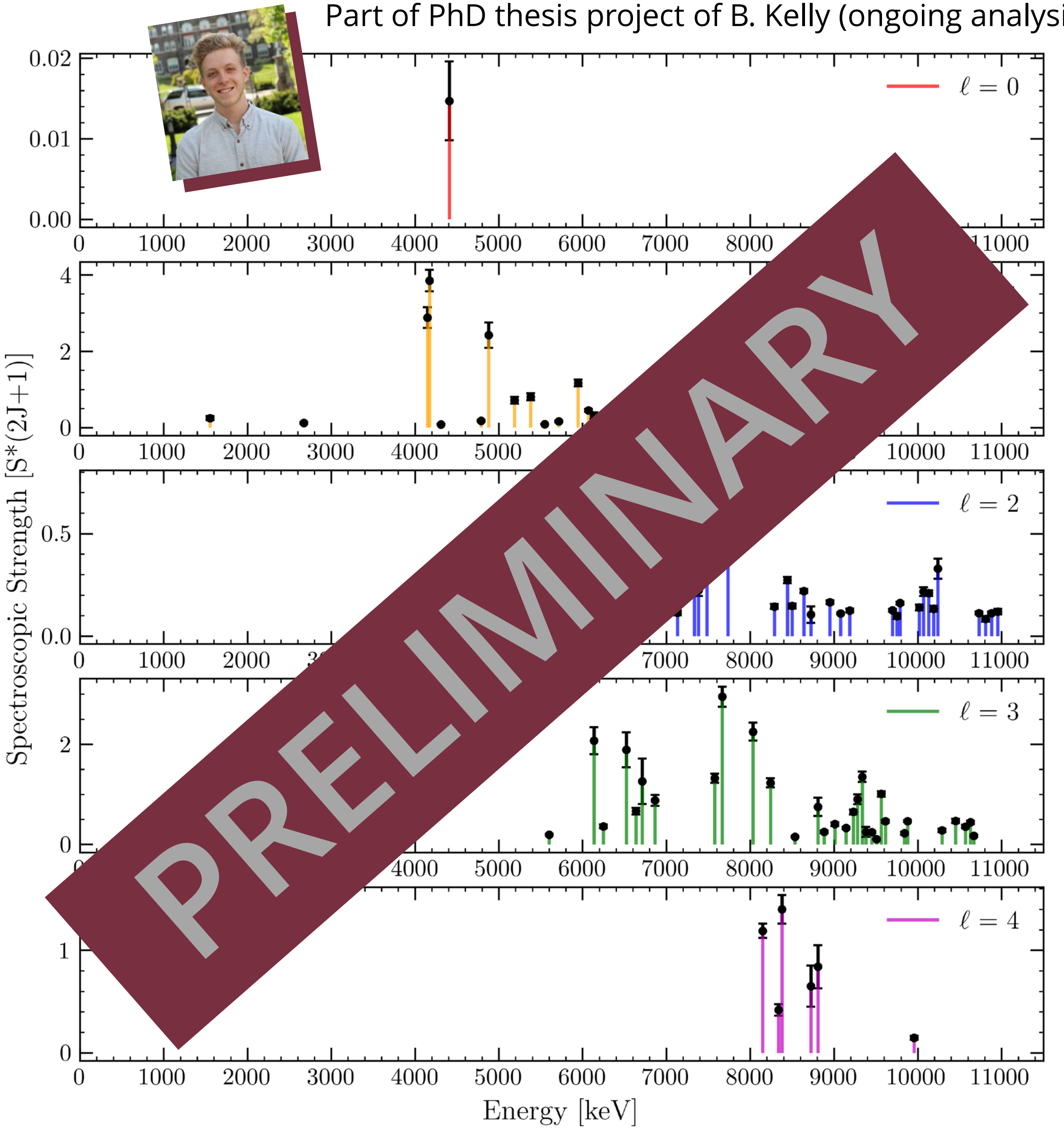
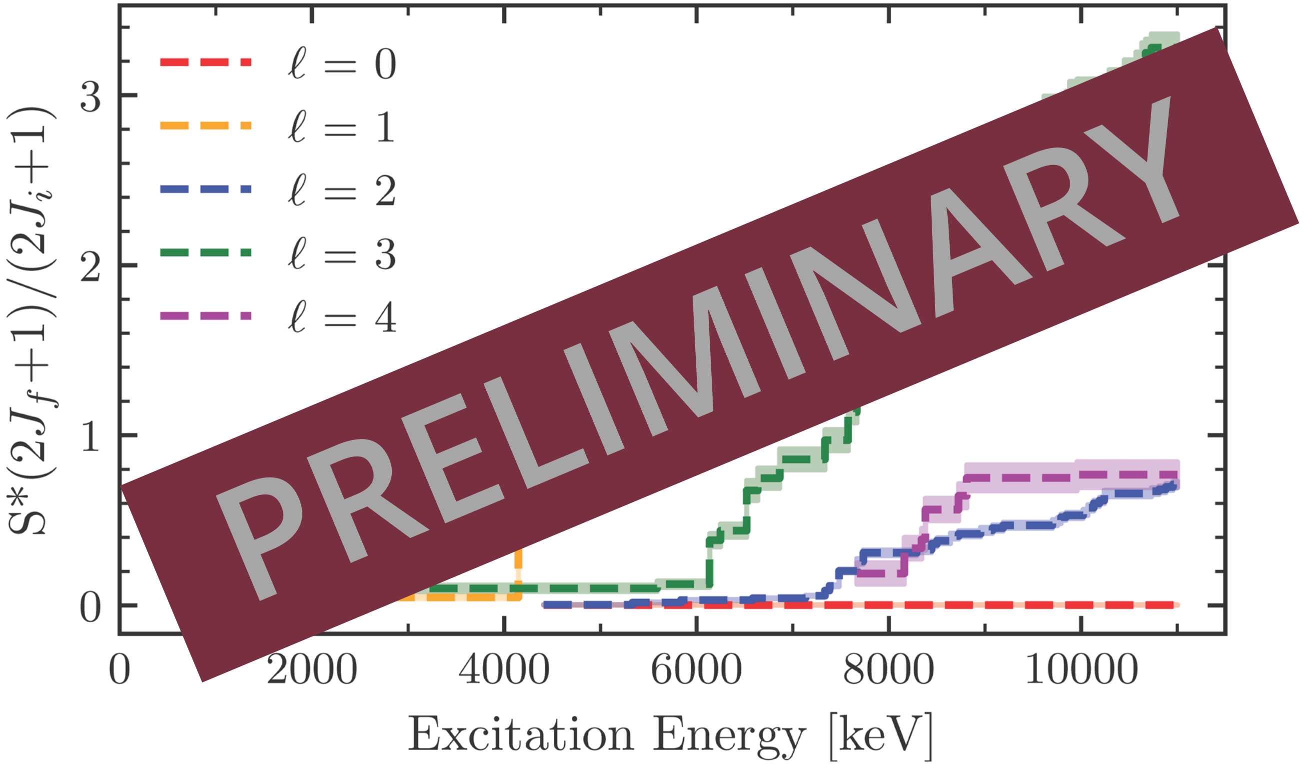
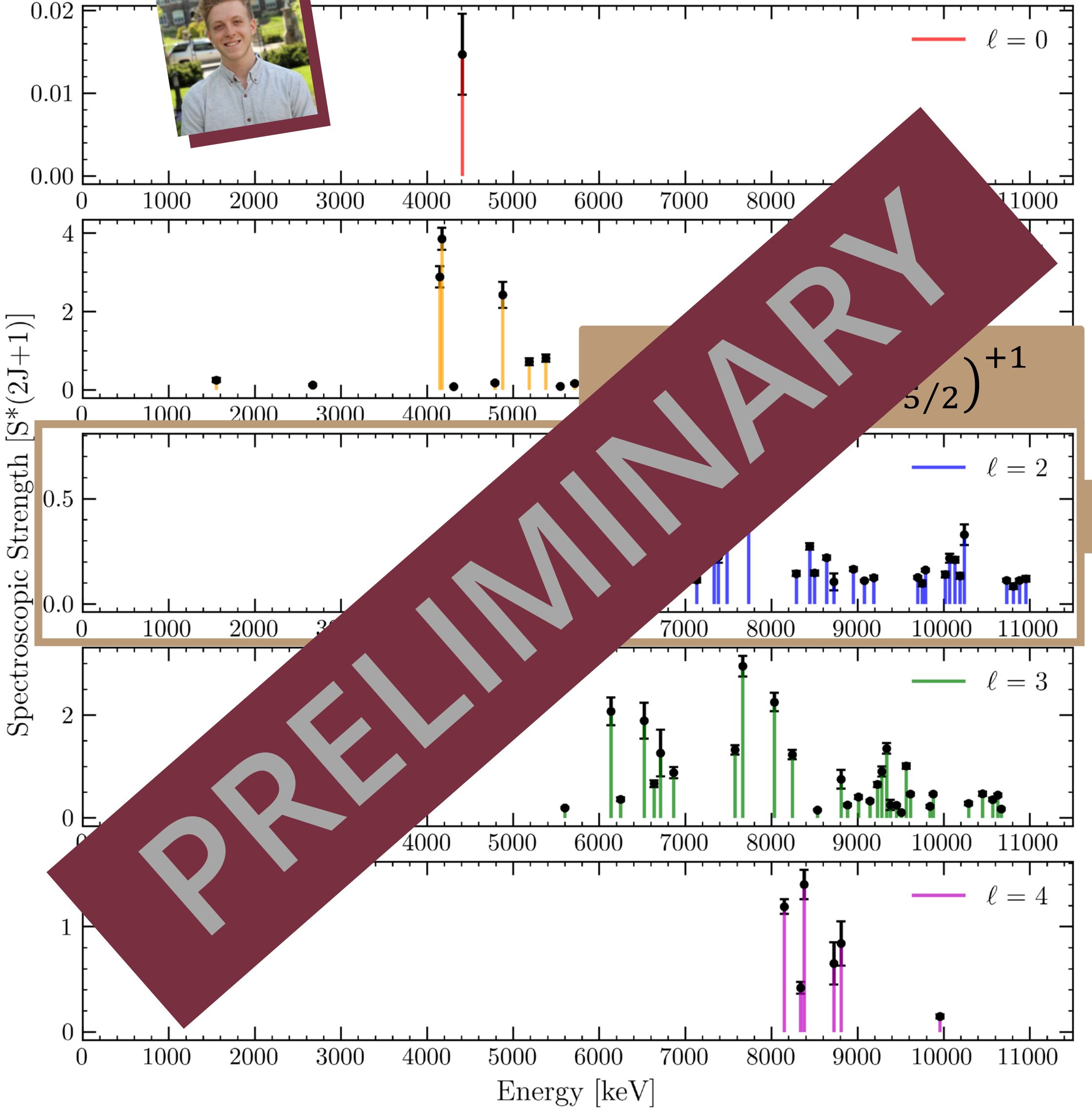


Summing the spectroscopic strengths gives us in first order the occupancy of the respective orbitals.



Single-particle character of the Pygmy Dipole Resonance in ^{50}Ti

Part of PhD thesis project of B. Kelly (ongoing analysis)

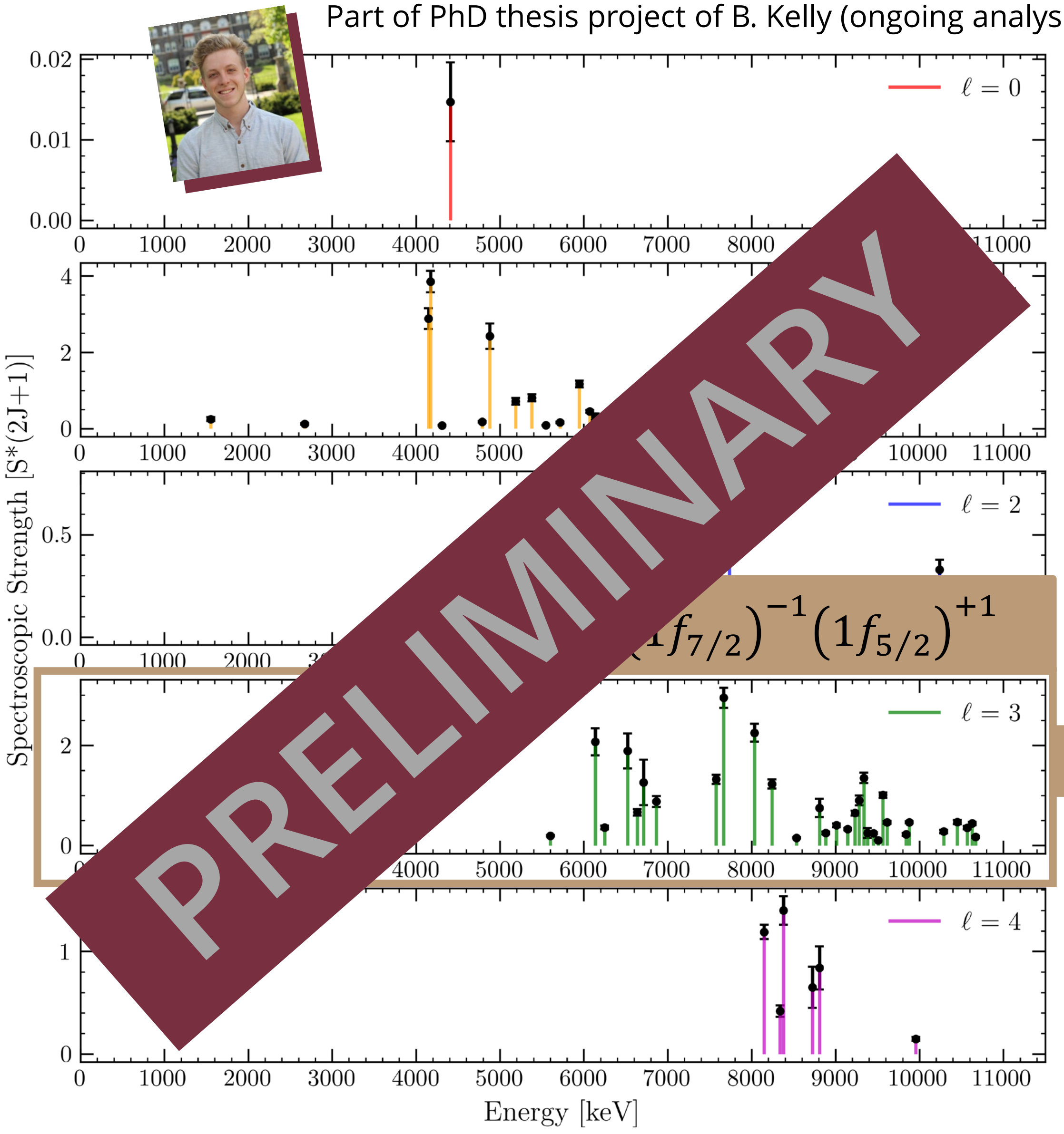


[**(γ, γ ') data:** U. Gayer, Master's thesis, TU Darmstadt (Germany)]

PRELIMINARY

Spin-flip excitations in ^{50}Ti

Part of PhD thesis project of B. Kelly (ongoing analysis)

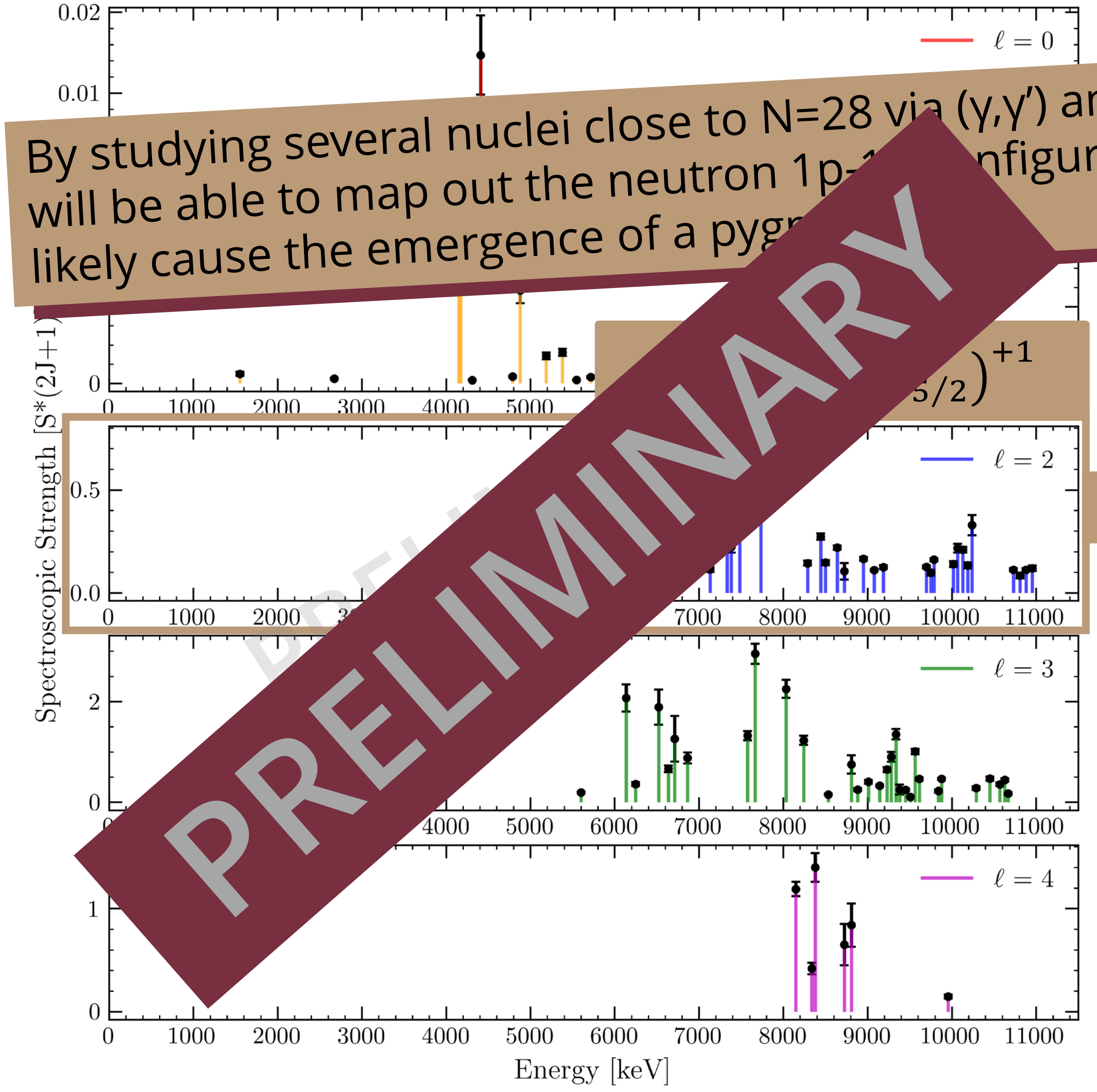


[(γ, γ ') data: U. Gayer, Master's thesis, TU Darmstadt (Germany)]

PRELIMINARY

Single-particle character of the Pygmy Dipole Resonance in ^{50}Ti

Part of PhD thesis project of B. Kelly (ongoing analysis)



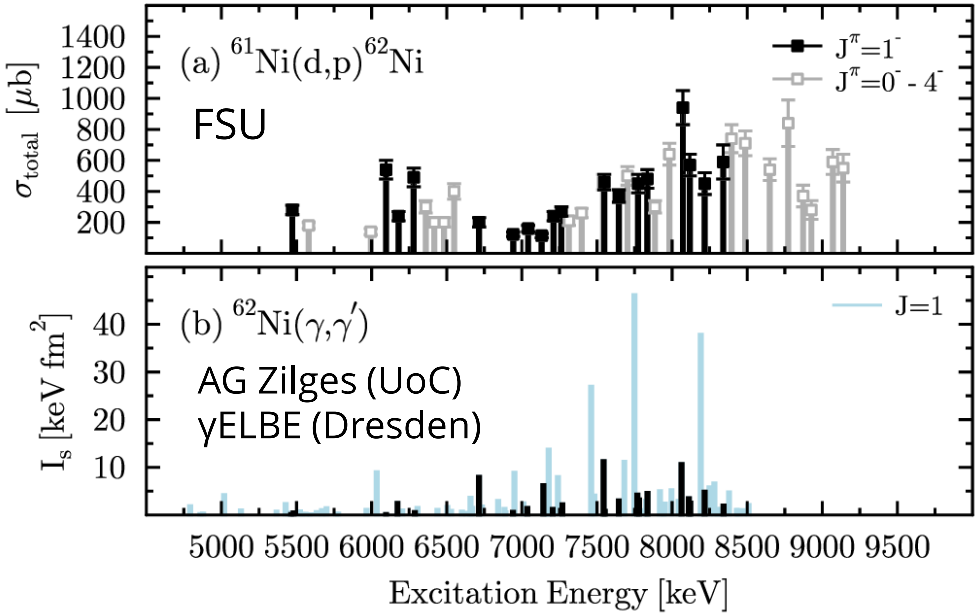
By studying several nuclei close to N=28 via (γ,γ') and (d,p), we will be able to map out the neutron 1p-1h configurations that likely cause the emergence of a pygmy

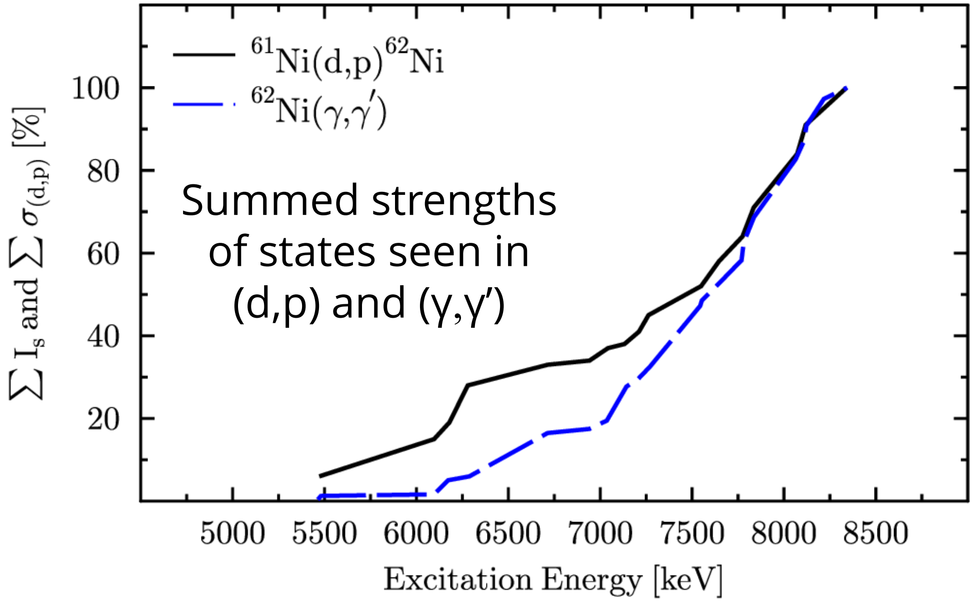
[(γ, γ ') data: U. Gayer, Master's thesis, TU Darmstadt (Germany)]

PRELIMINARY

Single-particle character of the Pygmy Dipole Resonance

Theoretical prediction: $(2p_{3/2})^{-1}(2d_{5/2})^{+1}$, $(2p_{3/2})^{-1}(2d_{3/2})^{+1}$, and $(2p_{3/2})^{-1}(3s_{1/2})^{+1}$ neutron one-particle-one-hole contributions cause observed strength increase beyond N=28. [T. Inakura et al., PRC **84**, 021302(R) (2011)]





Observations:

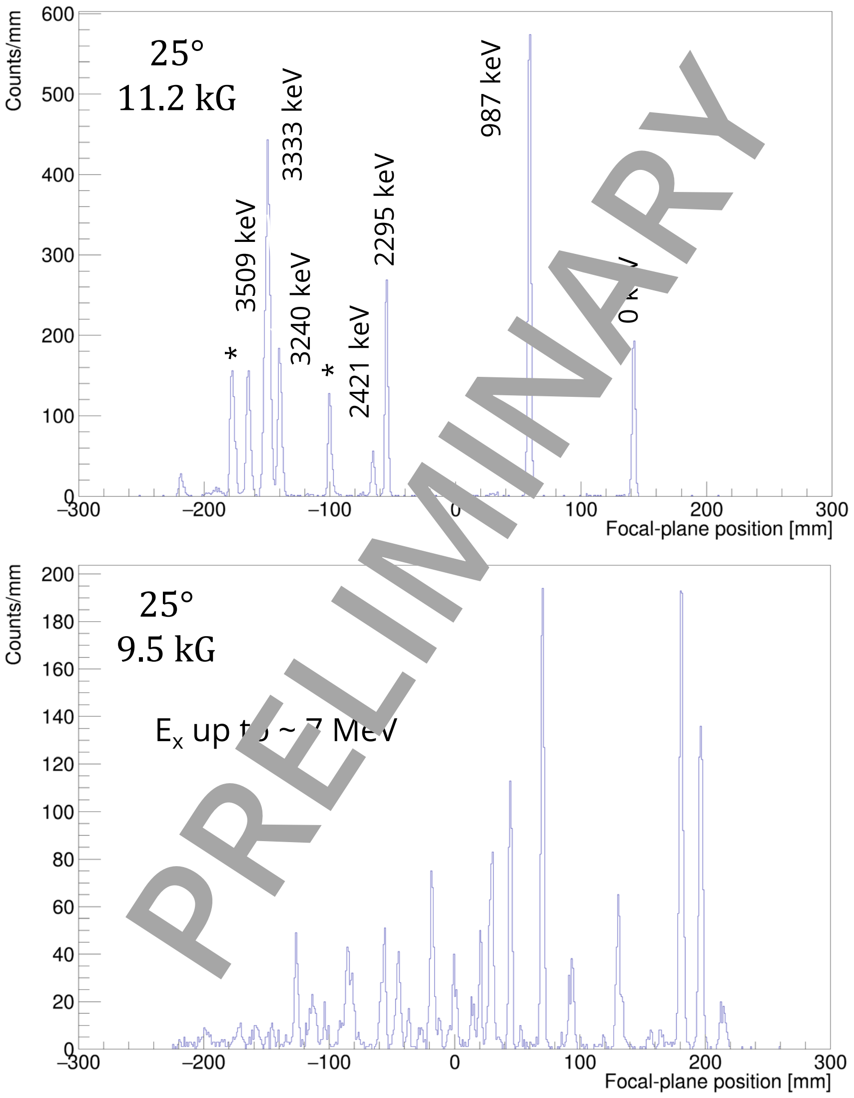
- Most strongly populated states in (γ,γ') not populated in (d,p).
- Only L=2 angular momentum transfers populated 1^- states below S_n in (d,p).
- Relative strength evolution does not follow the same trend in 5.5-7.5 MeV energy window.

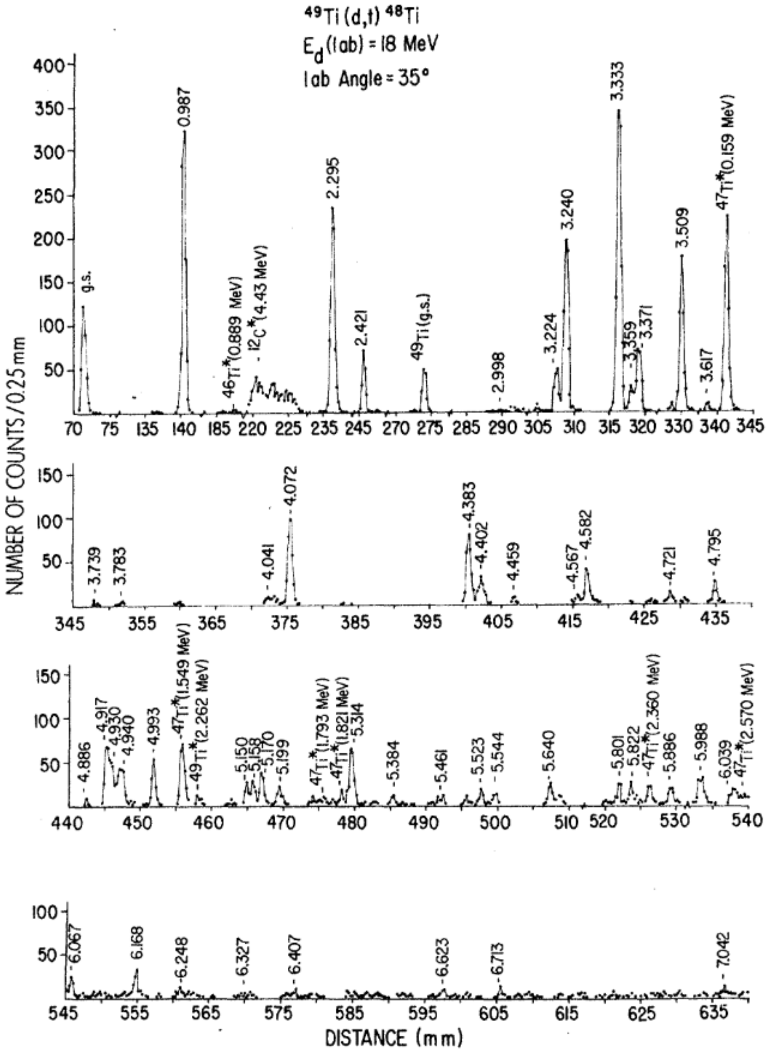
→ **Systematic studies needed to test details of Inakura's theoretical predictions and other models!**

[MS et al., Phys. Rev. C **108**, 014311 (2023)]

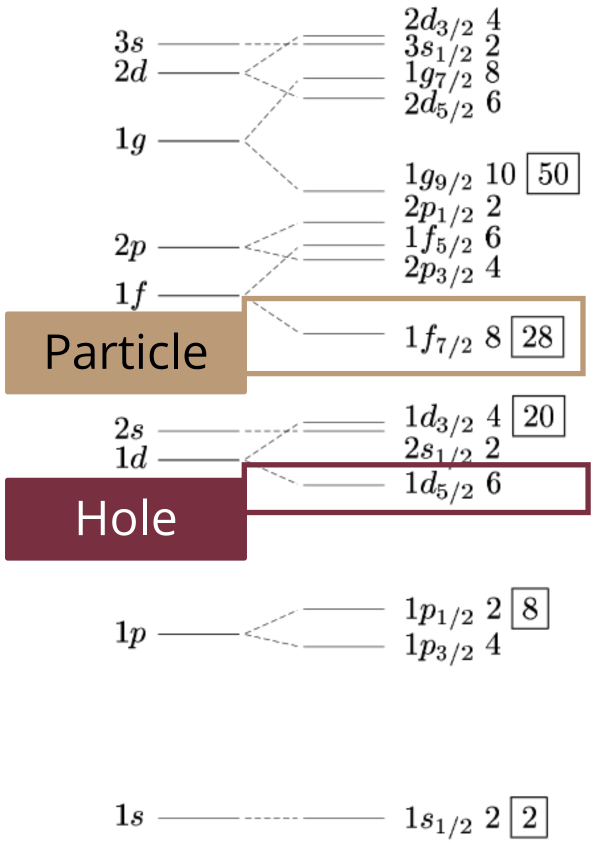
Outlook – other transfer reactions

^{49}Ti(d,t)^{48}Ti+friends at FSU SE-SPS (March 2024)





[A. Jamshidi and W. P. Alford, Phys. Rev. C **8**, 1796 (1973)]



Will study contributions from below the Fermi surface up to E_x~8.5 MeV.

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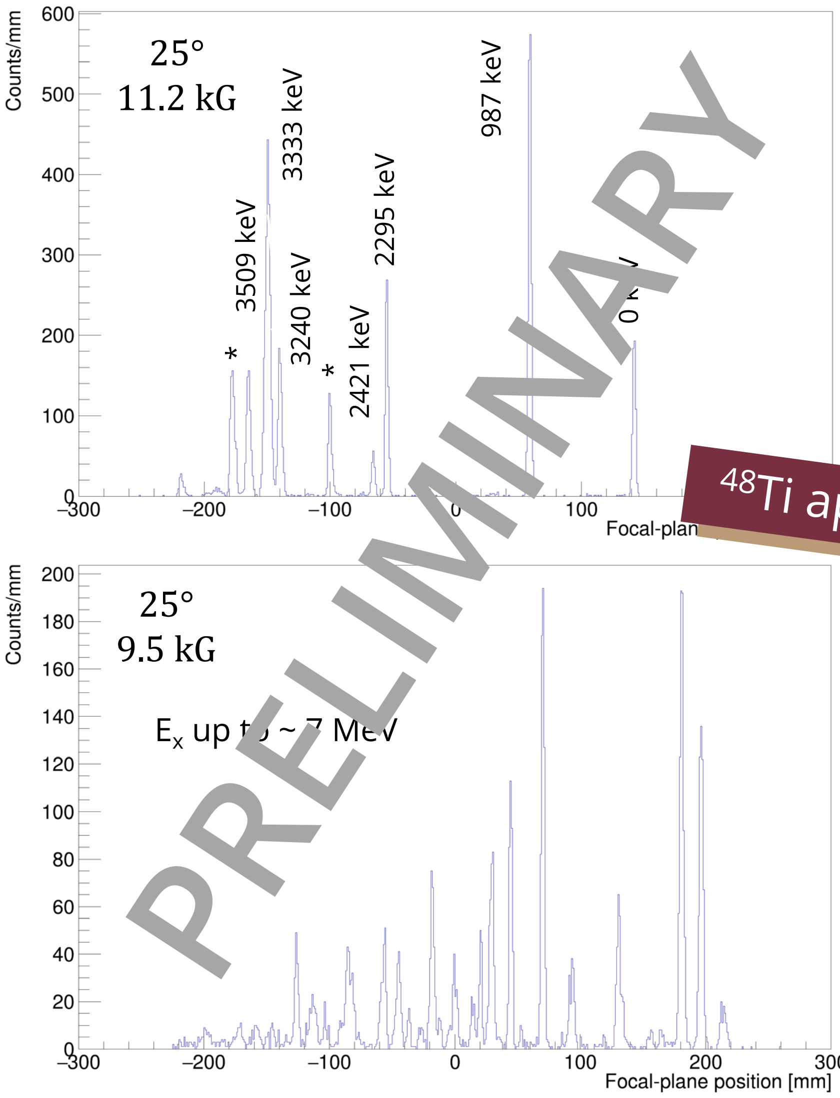
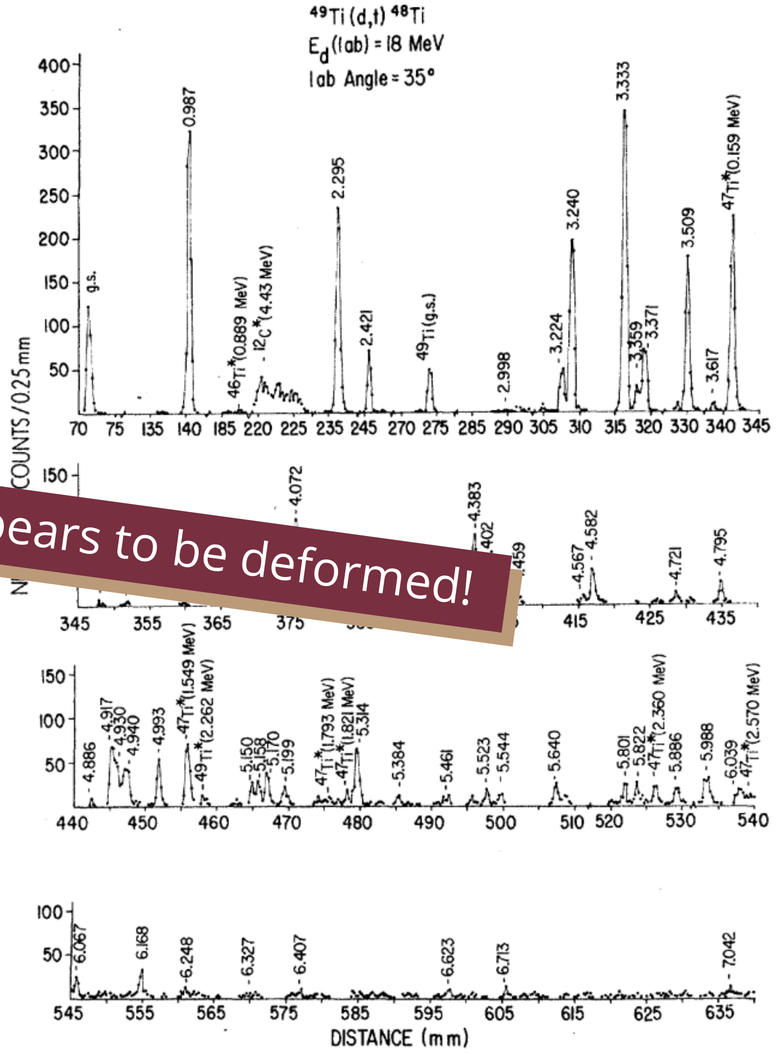


^{48}Ti appears to be deformed!



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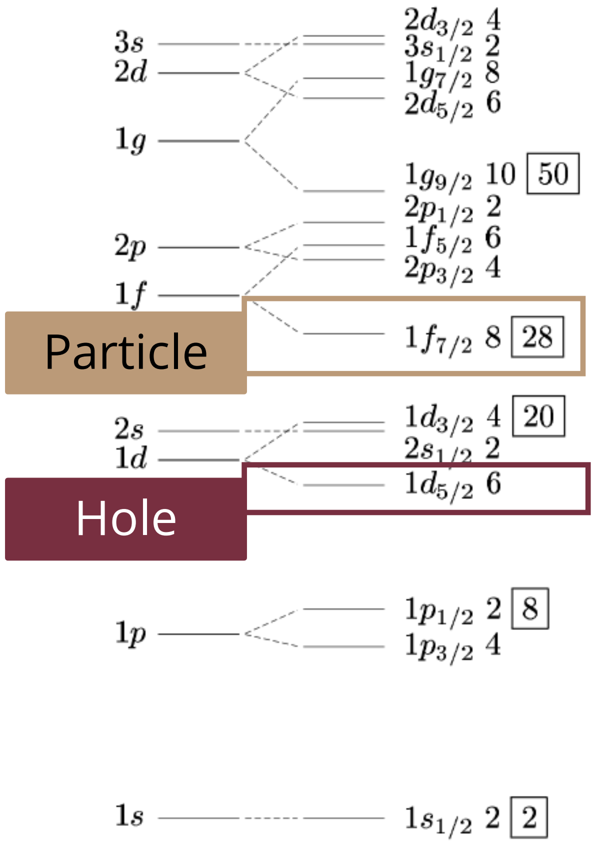

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A pygmy quadrupole resonance?

Yes: N. Tsoneva and H. Lenske, PLB **695**, 174 (2011)
No: E. Yüksel, G. Colo, et al., PRC **97**, 064308 (2018)

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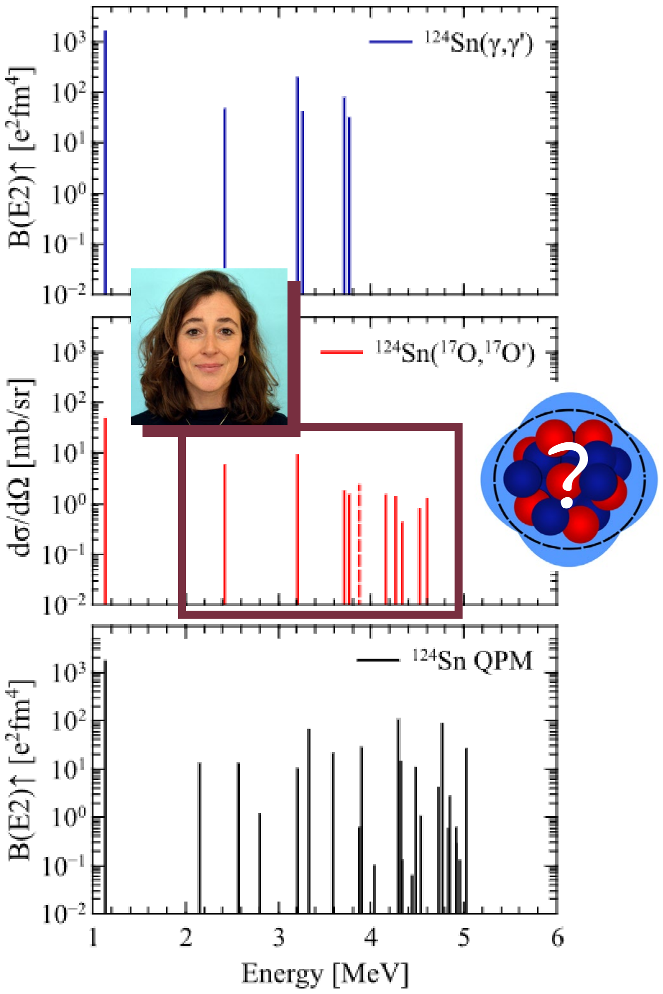
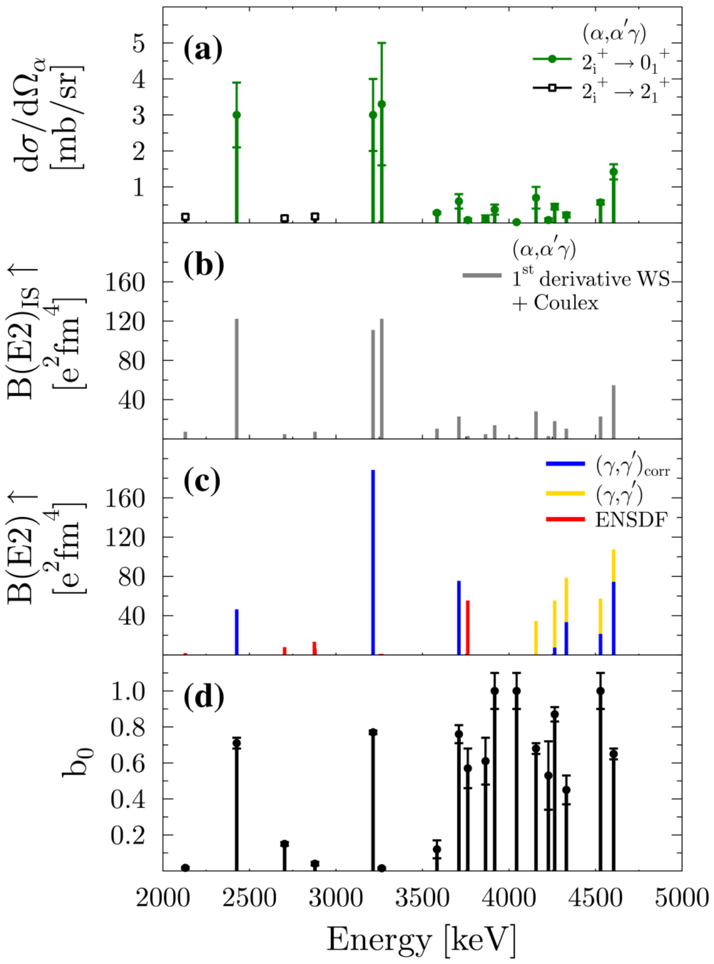
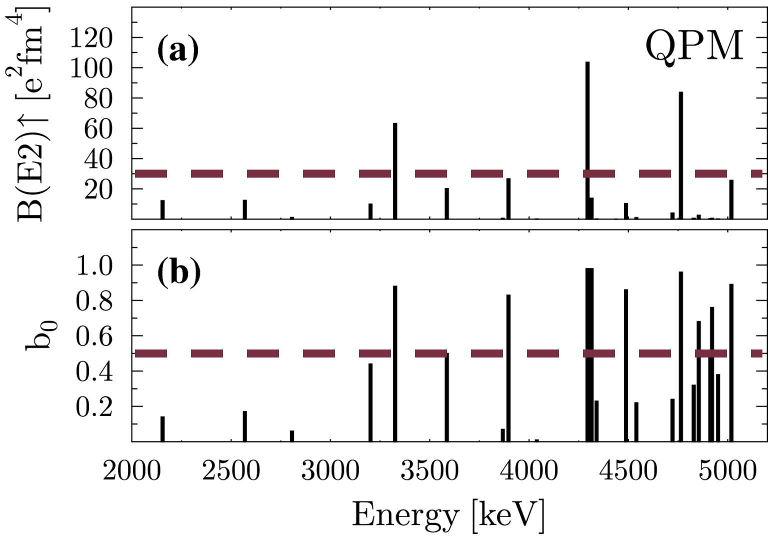
Hint at existence?



L. Pellegri, A. Bracco, N. Tsoneva, *et al.*, PRC **92**, 014330 (2015)



MS, N. Tsoneva, *et al.*, PLB **752**, 102 (2016)



Is “favored” g.s. decay the critical observable?

MS, N. Tsoneva, *et al.*, PLB **752**, 102 (2016)

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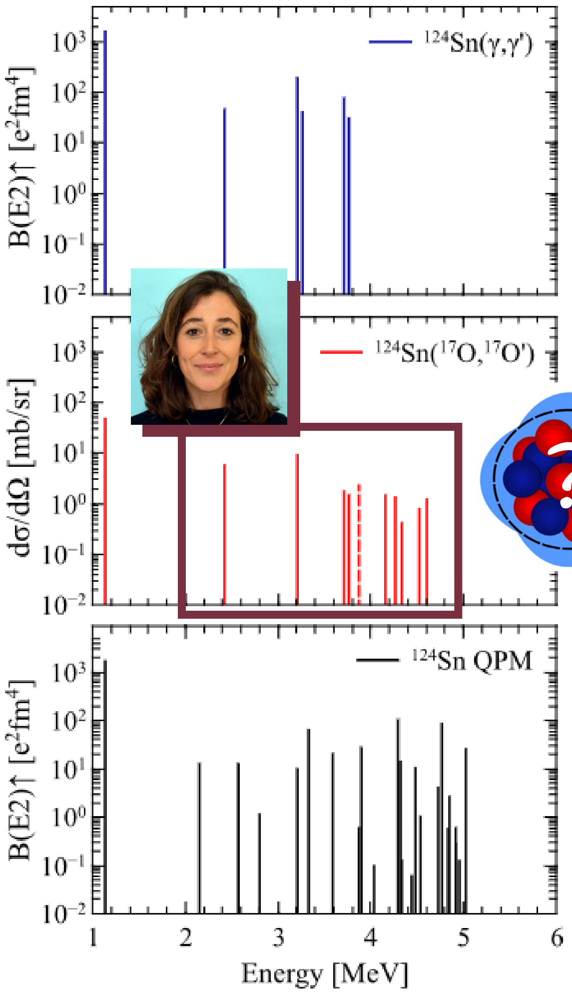

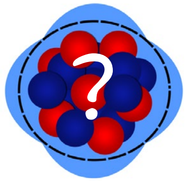

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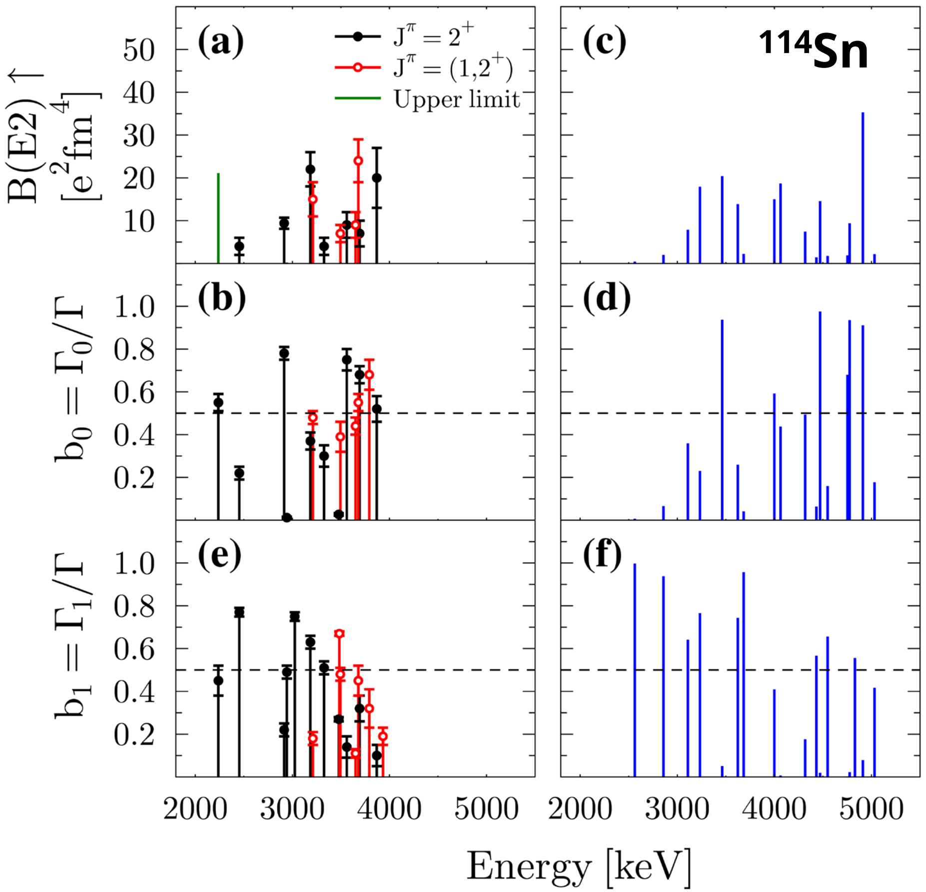

[^{112,114}Sn: N. Tsoneva, MS, H. Lenske, A. Zilges, NPA **990**, 183 (2019)]

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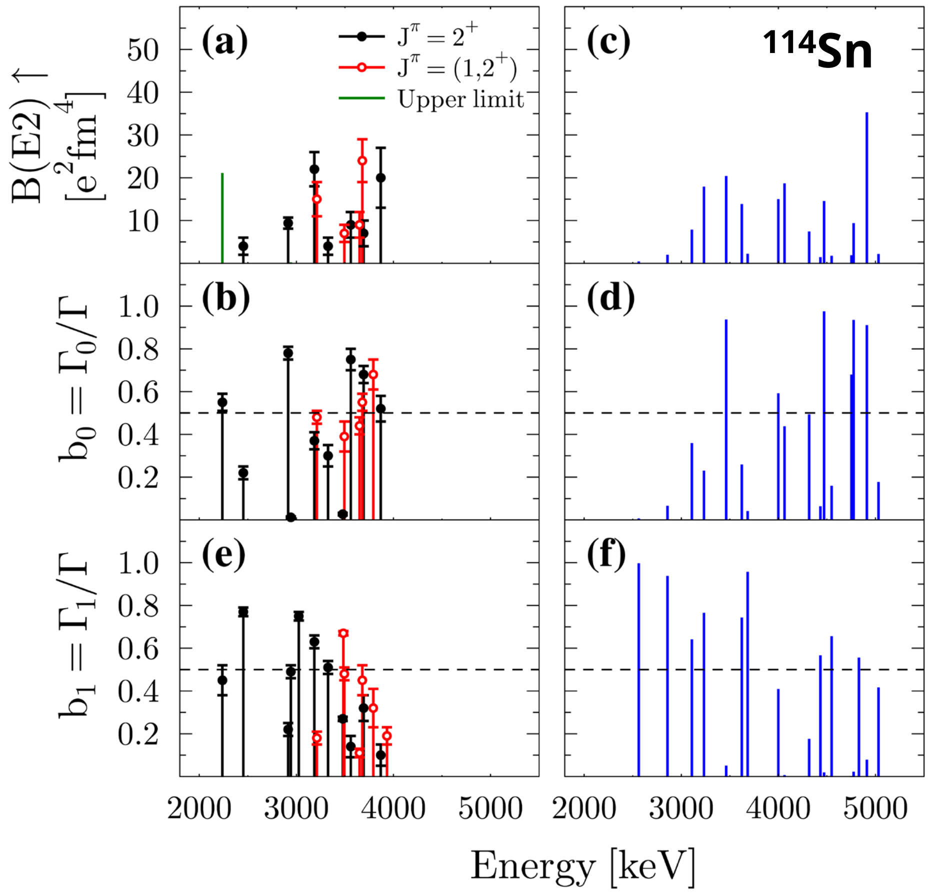
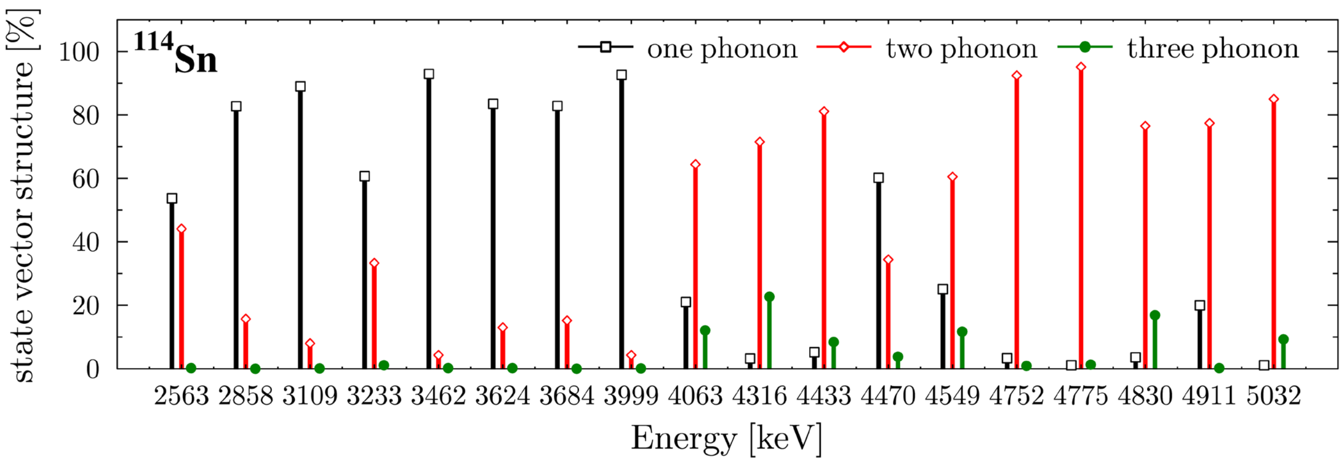
Is “favored” g.s. decay the critical observable?

→ **Not as straightforward as initially thought!**

MS, N. Tsoneva, *et al.*, PLB **752**, 102 (2016)



[112,114Sn: N. Tsoneva, MS, H. Lenske, A. Zilges, NPA **990**, 183 (2019)]



Possible PQR states at higher energies are dominantly two-phonon states in ^{114}Sn. Very different from PDR! Thus, situation appears to be way more complex!

I would say we do not have a clear understanding of what is going on here and cannot claim that a PQR exists (or does not exist).

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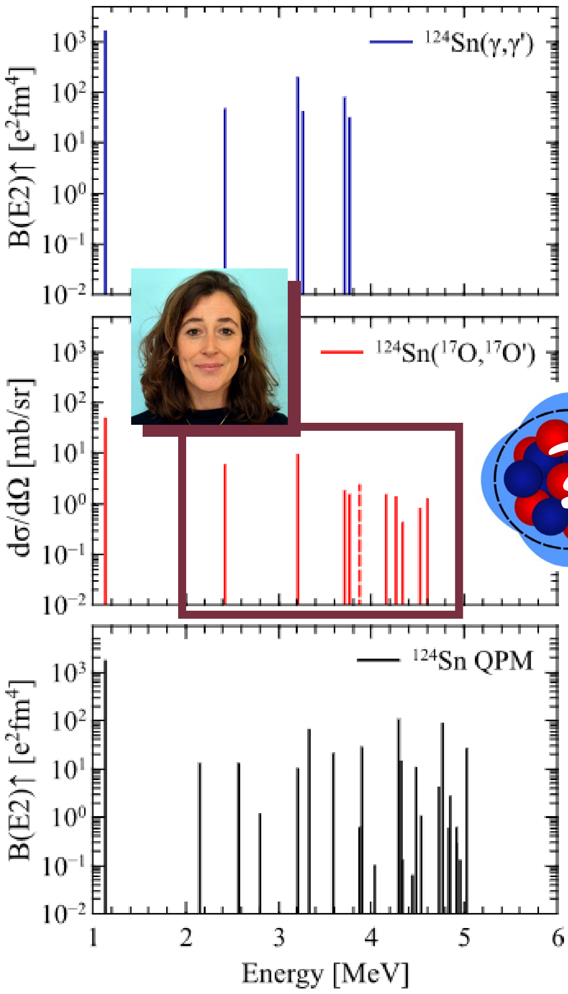
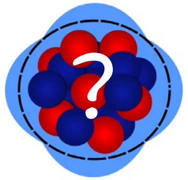




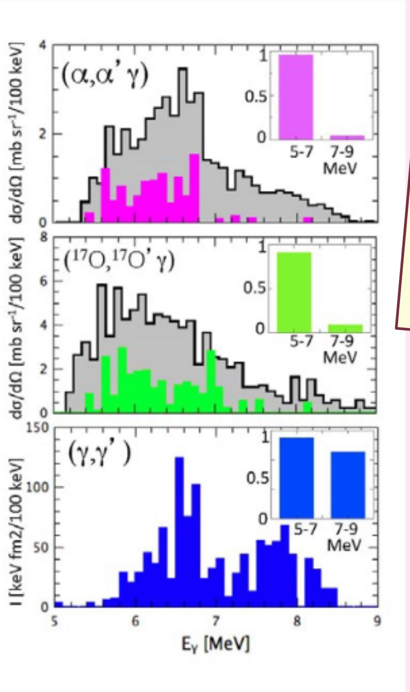
L. Pellegri, A. Bracco, N. Tsoneva, *et al.*, PRC **92**, 014330 (2015)

NuPECC Long Range Plan 2017 – Perspectives in Nuclear Physics

Box 4. Pygmy Resonances

In neutron-rich systems, the neutron excess is expected to form a skin, often assumed to oscillate outside the proton-neutron core: this results in a concentration of E1 strength in the region around the particle binding energy (< 10 MeV) - the Pygmy Dipole Resonance. Experiments are ongoing for few exotic nuclei above separation-energy threshold, using advanced and complex setups at fragmentation facilities, while stable systems, below threshold, have been largely investigated by different probes – from photons, high energy protons and alphas and heavy ions at intermediate energies. A quite complex nature of pygmy states has been evidenced, as in the case of ^{124}Sn where isoscalar and isovector states seem to co-exist in the same energy region, and the character of these excitations appears to be hybrid, with mixture of compressional or non-collective character.

New experiments are envisaged to better clarify the features of the low-lying dipole strength with neutron excess and the existence of pygmy states of other multipolarities, E2 in particular. At ISOL facilities, inelastic scattering at 10-15 MeV/nucleon in inverse kinematics will shed light on the nature of the pygmy resonance below particle threshold, while exclusive measurements based on the detection of high resolution γ rays and particle decay at intense gamma-beam facilities, such as ELI-NP, will pin down the fine structure of the entire resonance response in stable systems, shedding light on damping mechanisms.



γ-decay spectra from the pygmy resonance in ^{124}Sn, as measured with α scattering at 34 MeV/A (top, KVI data), heavy ion at 20 MeV/nucleon (middle, AGATA at LNL) and γ scattering (bottom, Darmstadt data). Coloured histograms give the strength resolved in individual transitions, with energy-integrated relative intensities (insets).

Acknowledgments

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FSU – Sergio Almaraz-Calderon, Lagy T. Baby, Paul D. Cottle, Kevin Fossez, Kirby W. Kemper, Jorge Piekarewicz, Samuel Tabor, Tsz Leung (Ryan) Tang, Vandana Tripathi, Alexander Volya, Ingo Wiedenhoever, graduate & undergraduate students, postdoctoral researchers

LSU – J. Blackmon, C. Deibel, postdoctoral researchers, graduate students
Oak Ridge National Laboratory – A.M. Allmond and T.J. Gray
Ursinus College – L.A. Riley and undergraduate students
Davidson College – A.N. Kuchera and undergraduate students
Argonne National Laboratory – C.R. Hoffman, C. Müller-Gatermann
Lawrence Livermore National Laboratory – G. Potel-Aguilar, R. Hughes
Ohio University – A. Richard
FRIB/MSU – B.A. Brown
University of Cologne – A. Zilges and his research group
ELI-NP – N. Tsoneva
Mississippi State University – B. Crider

The FSU group acknowledges support by the U.S. National Science Foundation (NSF) under Grant Nos. PHY-2012522 [WoU-MMA: Studies of Nuclear Structure and Nuclear Astrophysics] and PHY-2412808 [Studies of Nuclear Structure and Nuclear Astrophysics], and by the U.S. Department of Energy, National Nuclear Security Administration (NNSA) under Grant No. DE-NA0004150 [Center for Excellence in Nuclear Training And University-based Research (CENTAUR)] as part of the Stewardship Science Academic Alliances Centers of Excellence Program. Support by Florida State University is also gratefully acknowledged.