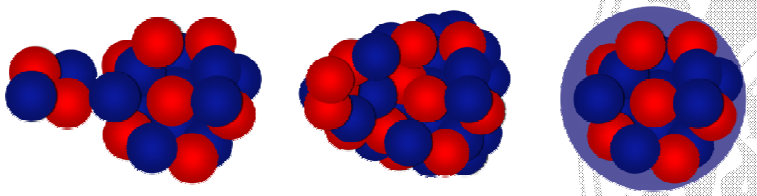
Origin of low-lying enhanced *E1* strength in rare-earth nuclei

Mark Spieker[1,*], Sorin Pascu[1,2], and Andreas Zilges[1]

[1]*Institute for Nuclear Physics, University of Cologne, Germany*
[2]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*



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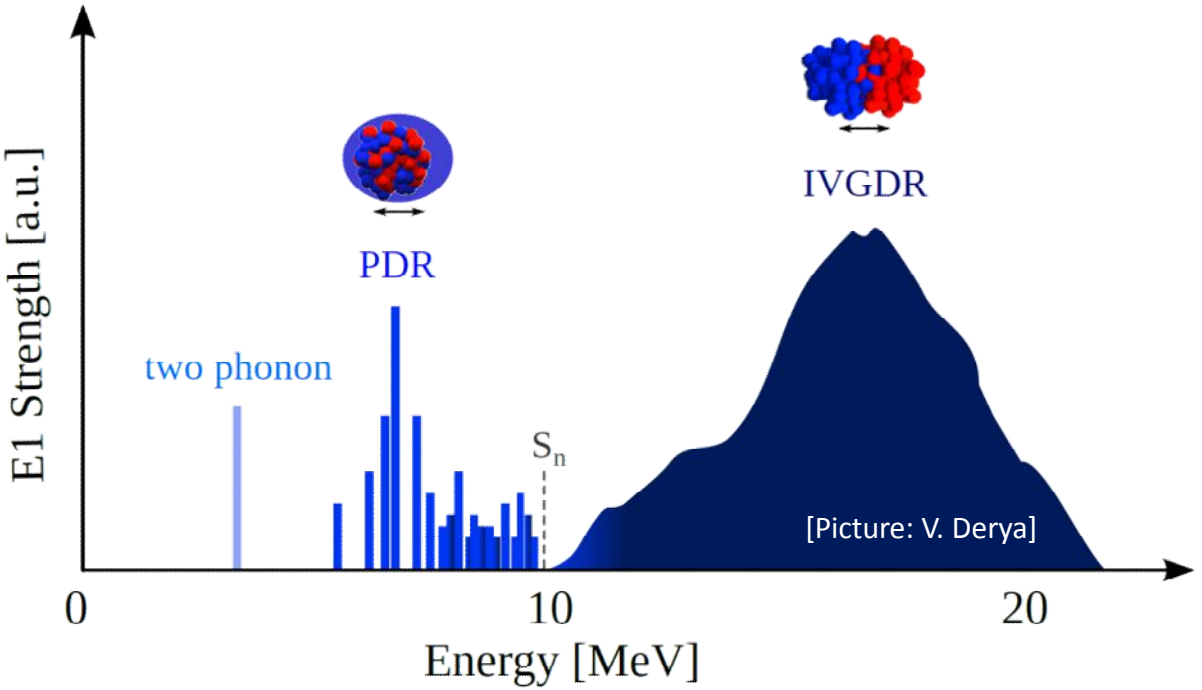
Special thanks to Francesco Iachello
*Supported by the Bonn-Cologne Graduate School of Physics and Astronomy

The nuclear *E1* response

E1 strength due to isospin-symmetry breaking



GDR: M.N. Harakeh, A. van der Woude, Giant Resonances, Oxford University Press (2001)
PDR: D. Savran, T. Aumann, and A. Zilges, PPNP **70**, 210 (2013)
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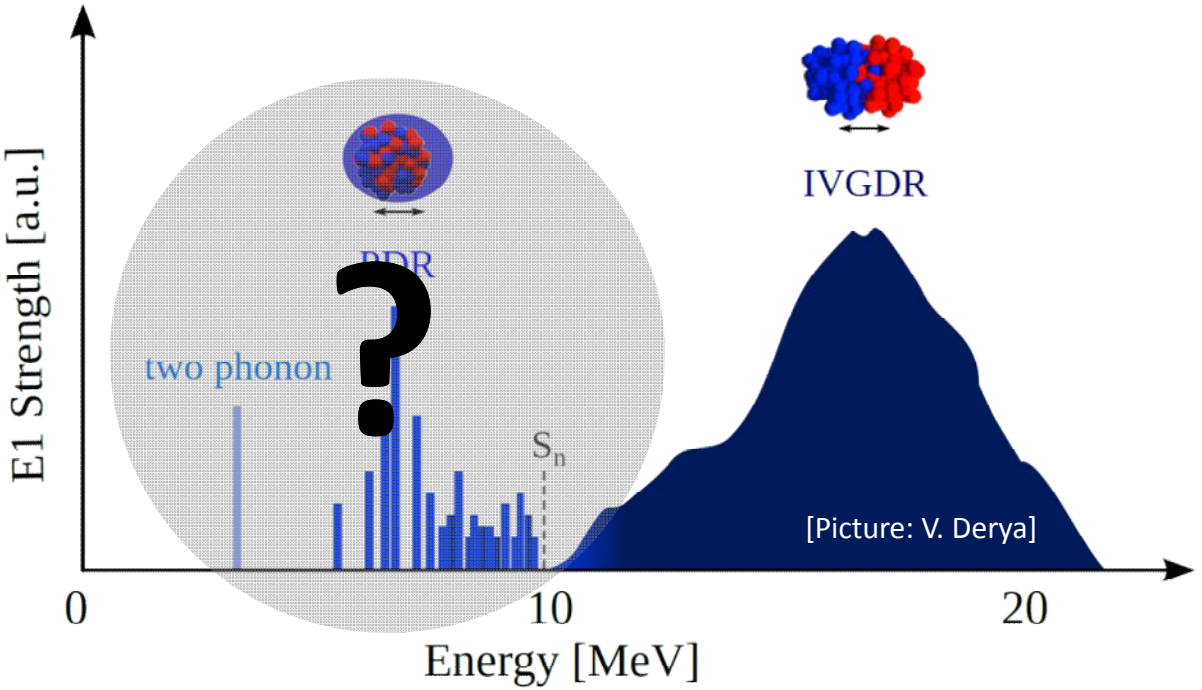

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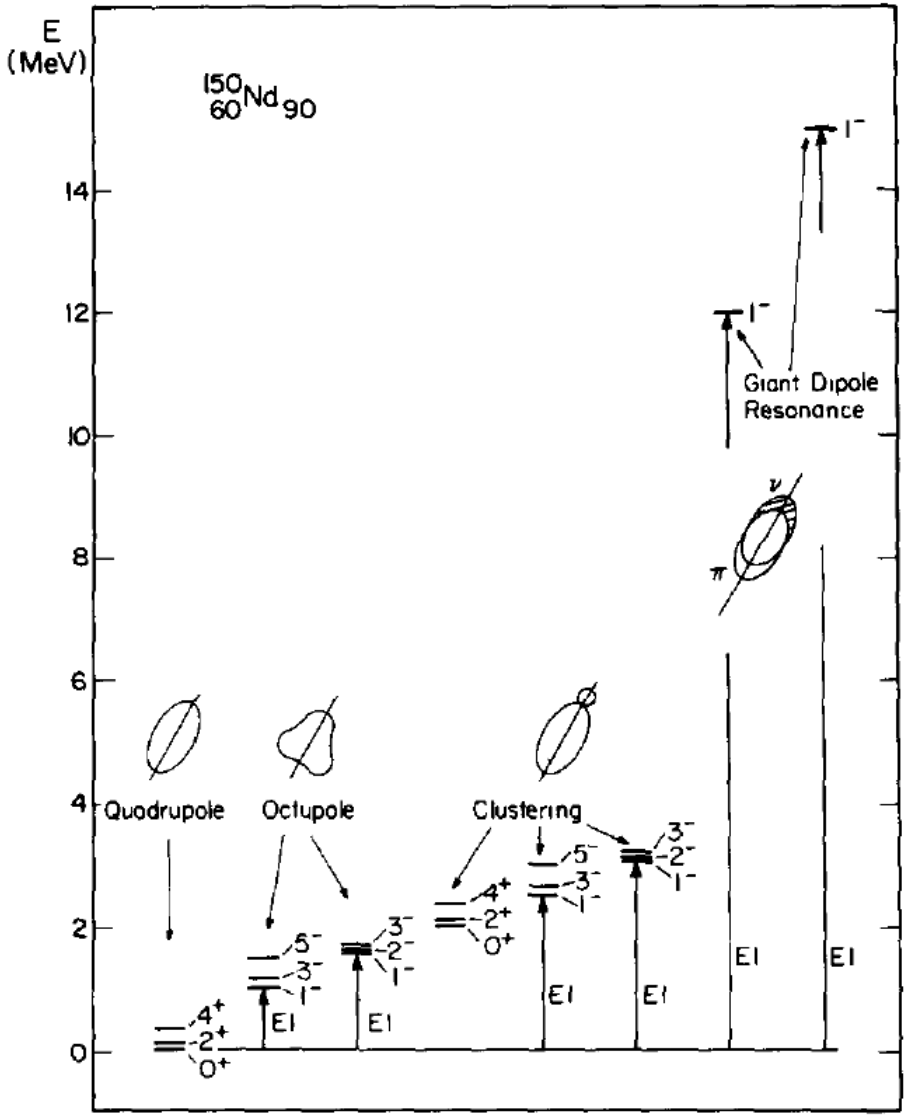
… are there more generating mechanisms?

Isospin-symmetry breaking in atomic nuclei



[F. Iachello, PLB **160**, 1 (1985)]

Low-lying *E1* strength due to isospin-symmetry breaking

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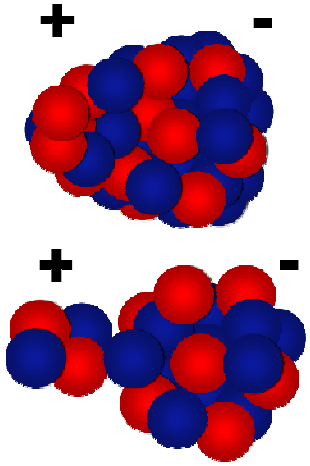
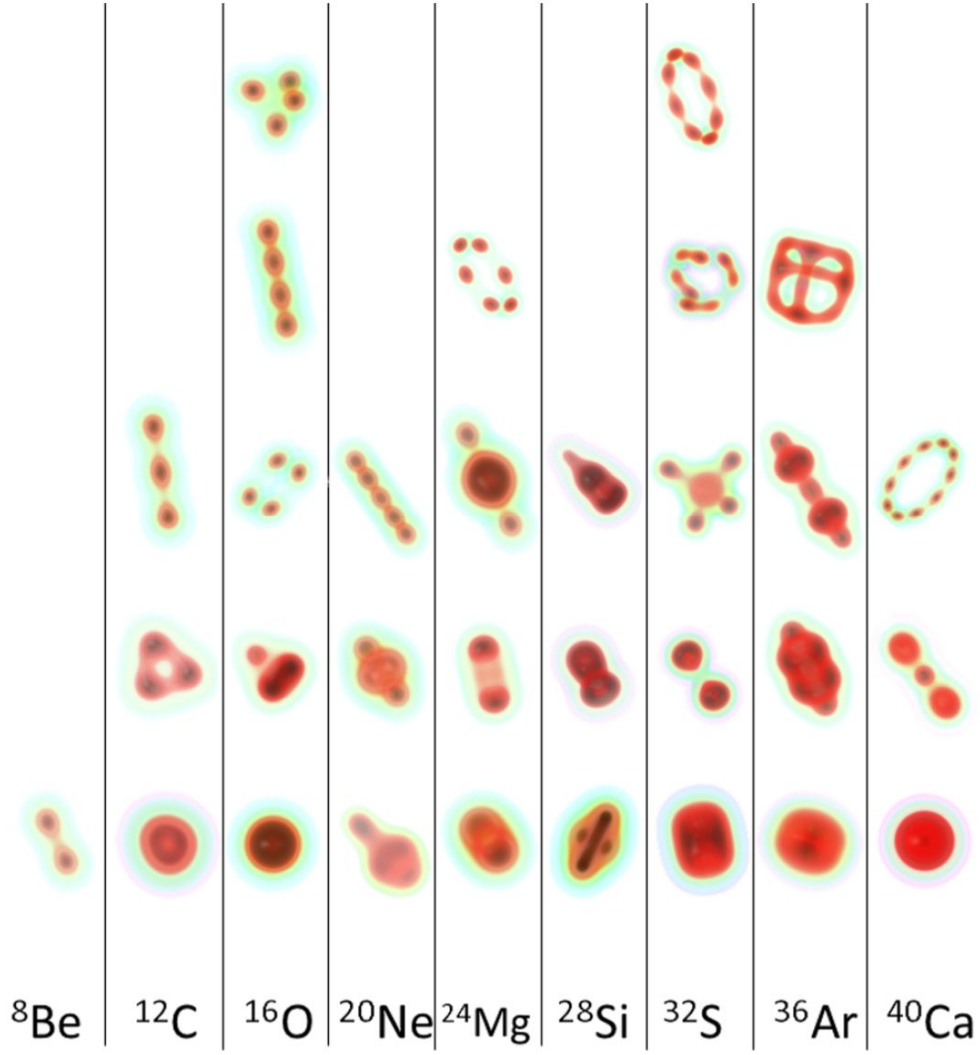
Two components:

- Quadrupole-octupole coupling (static/dynamic)
- α-clustering mode

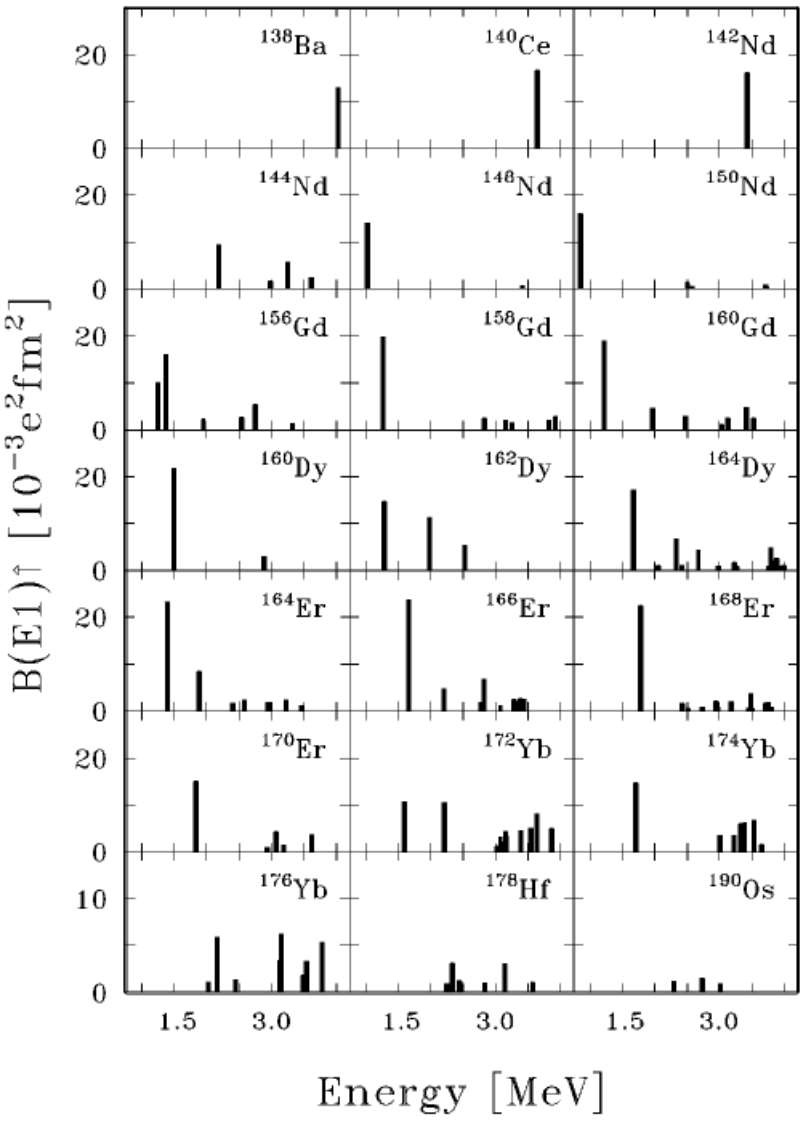


Is clustering a general phenomenon in nuclei?



[J.-P. Ebran *et al.*, PRC **90**, 054329 (2014)]

Low-lying *E1* strength in rare-earth nuclei



[C. Fransen *et al.*, PRC **57**, 129 (1998)]

E1 strength in rare-earth nuclei

(combined experimental efforts of Stuttgart, Giessen, Köln, and Darmstadt in '80s and '90s)

- **Nuclear resonance fluorescence** (NRF) using Stuttgart and Darmstadt setups
- Most selective probe to study dipole strength
- **Complete dipole strength** between 0.8 – 4.1 MeV
- **Parity measurements** using Compton polarimeters
  → Parity of strongly excited states accessible (*E1* or *M1* excitation?)
- **γ-decay branching** of strongly excited states
  → *K* quantum number assignment (ΔK=0 or ΔK=1 excitation?)

Large experimental data base!

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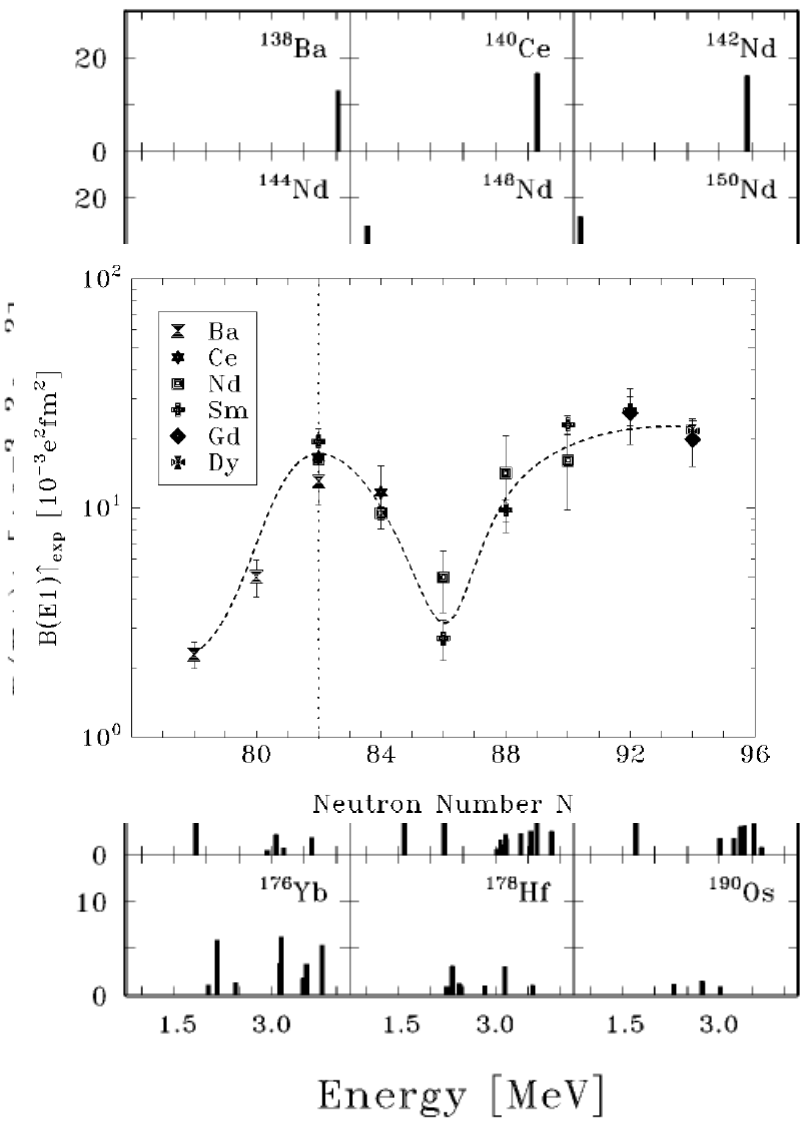

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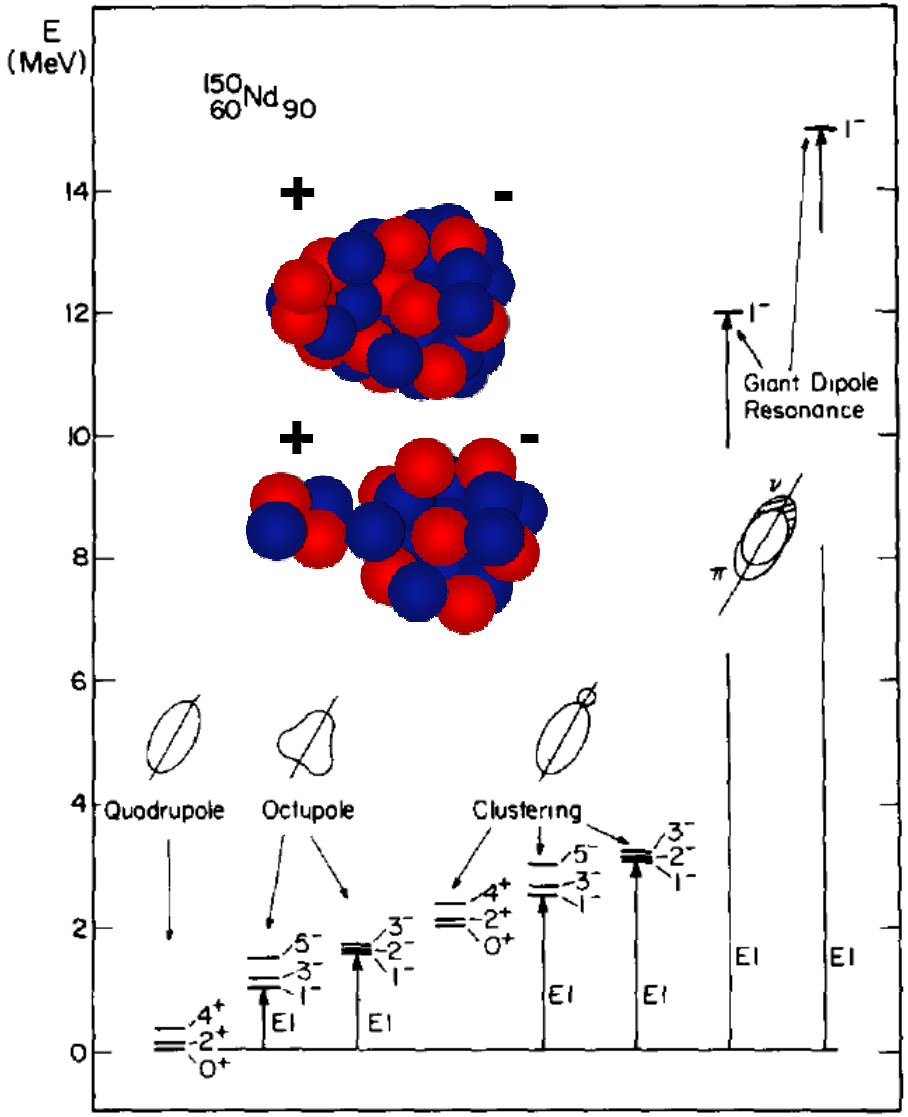

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Two components:

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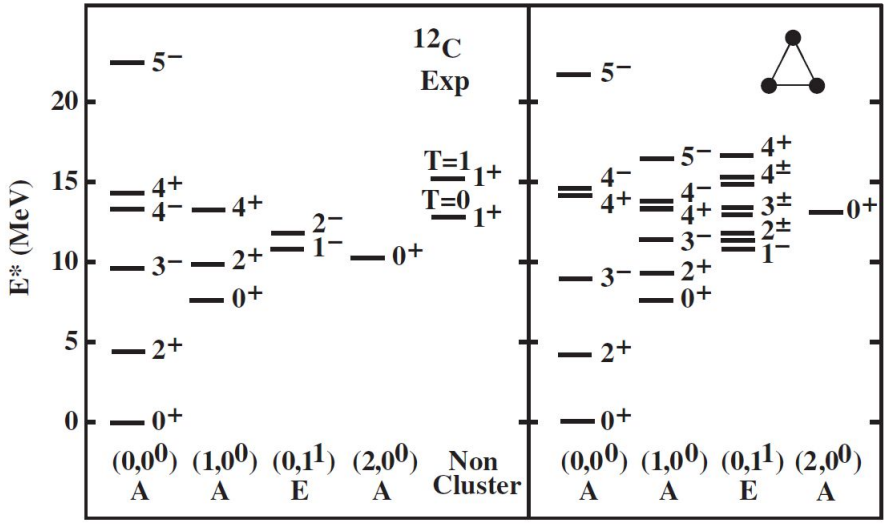
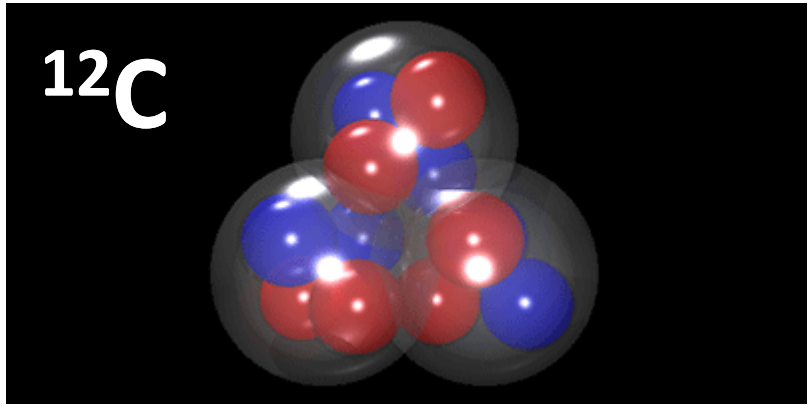
How to describe these two modes with one "simple" model?

Clustering in atomic nuclei – $U(\nu+1)$



[D. J. Marín-Lámbarri *et al.*, PRL **113**, 012502 (2014)]



[M. Freer/University of Birmingham]

Theoretical description of cluster configurations

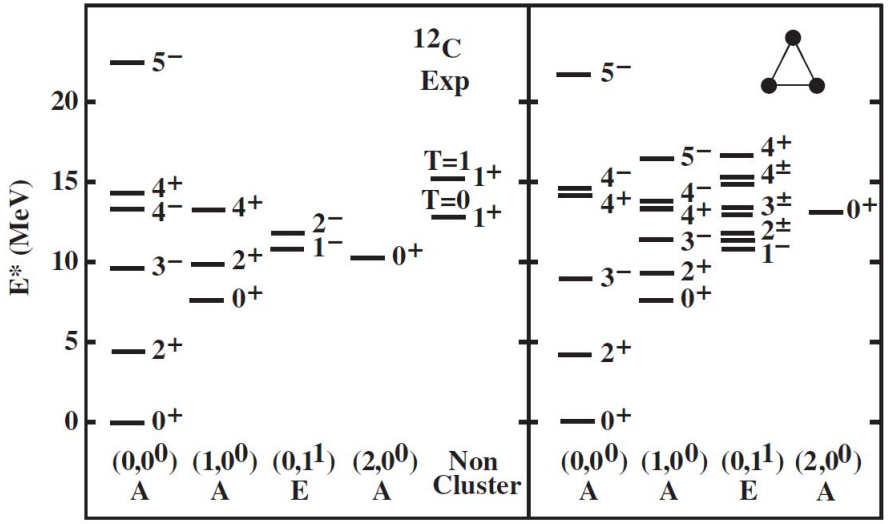
- Cluster states can be explained by the algebra of $U(\nu+1)$, *e.g.*, ^{12}C and ^{16}O!
- $\nu = 3n-3$, where n = #clusters

[R. Bijker, F. Iachello, PRC **61**, 067305 (2000)]

[R. Bijker, F. Iachello, PRL **112**, 152501 (2014)]

- U(4) for two-body clusters
- U(4) is the algebra of the *sp* interacting boson model

Clustering in atomic nuclei – $U(\nu+1)$



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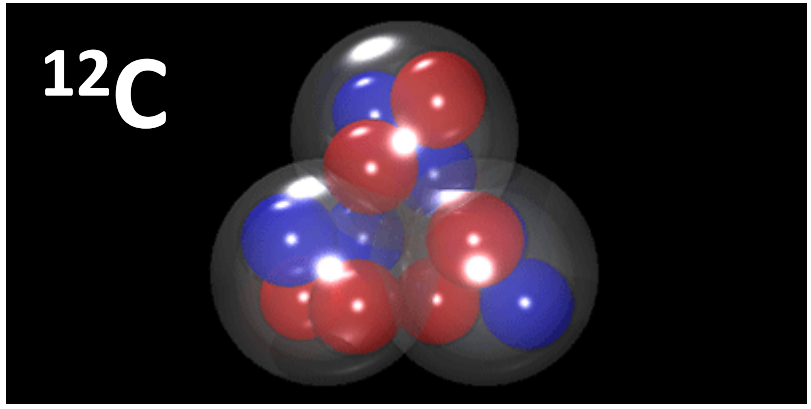

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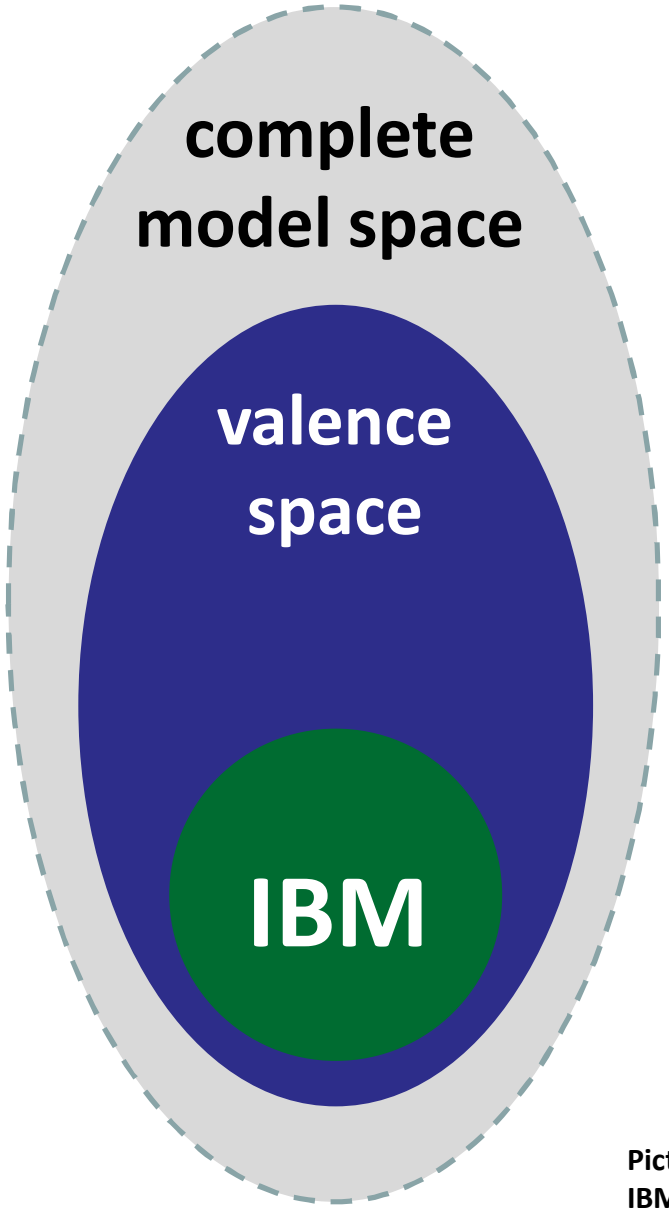
- U(4) for two-body clusters
- U(4) is the algebra of the *sp* interacting boson model

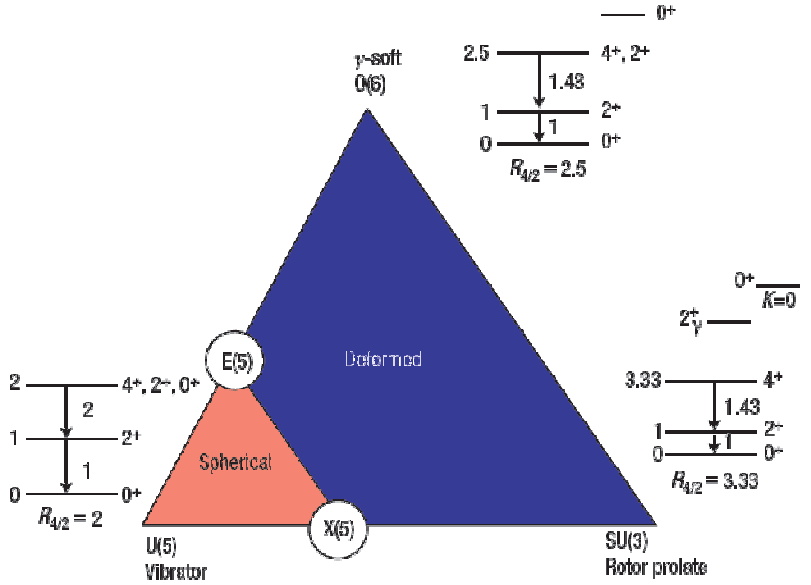
→ ***spdf*** **IBM to describe octupole mode and α-clustering mode!**

The interacting boson model (IBM)



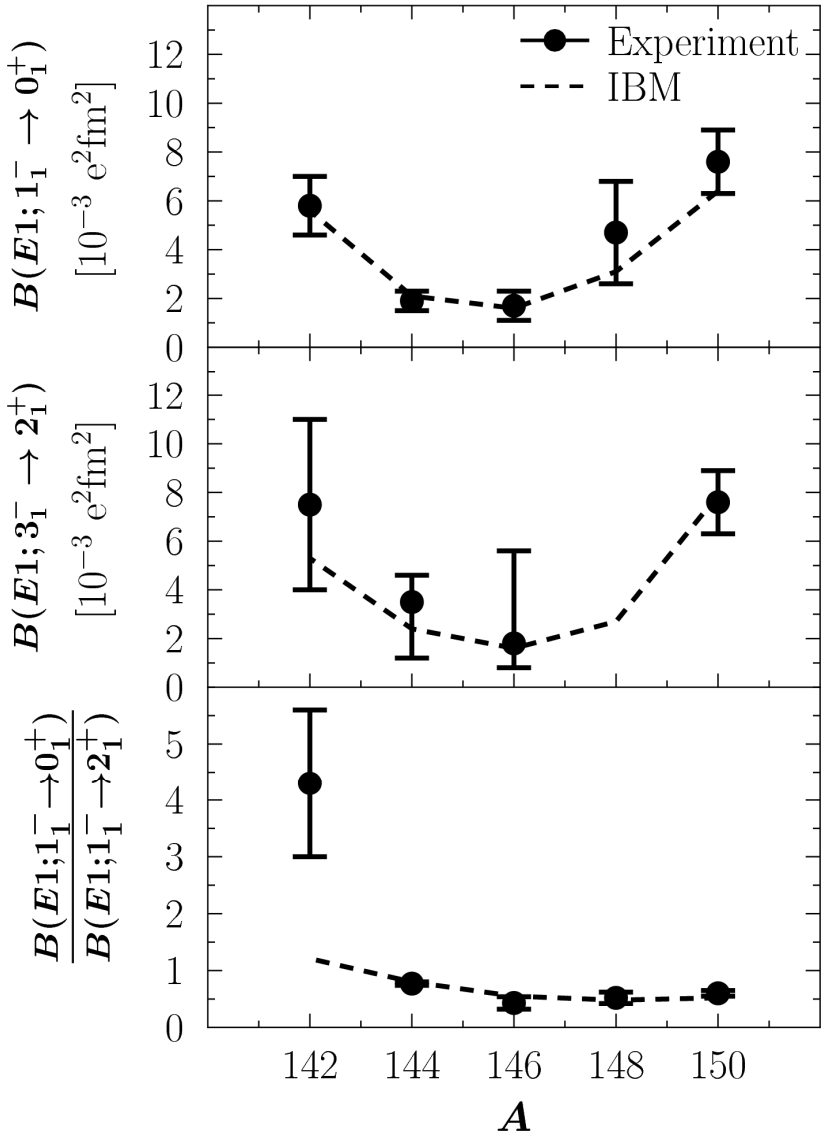
The interacting boson model

- Drastic truncation of the valence space in terms of bosons of different multipolarities, e.g., l = 0 - 3 (s, p, d, and f bosons)
- Description of collective nuclear properties in an algebraic approach

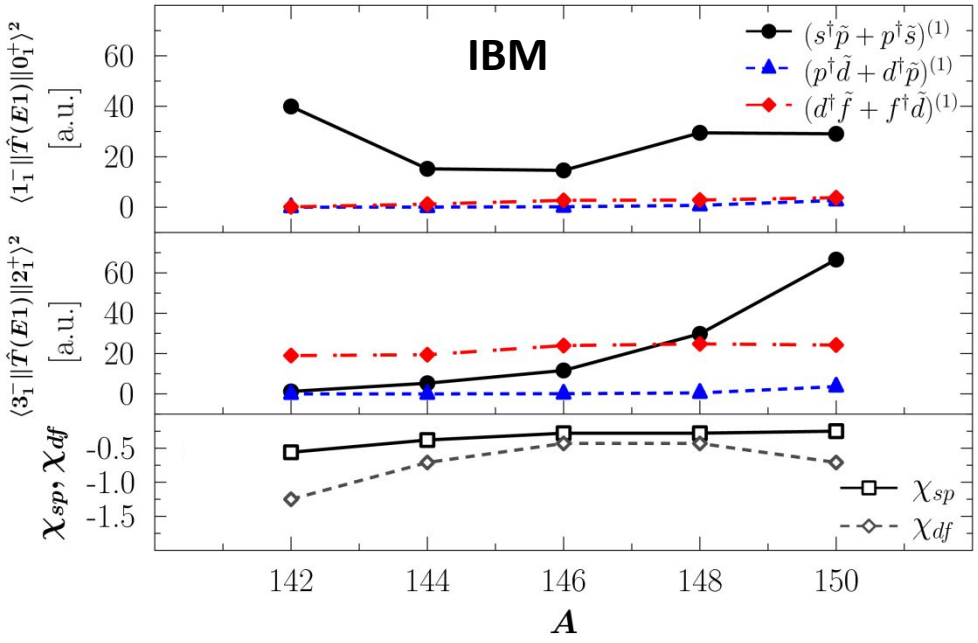


Picture: R.F. Casten, Nature Physics **2**, 811 (2006)
IBM: F. Iachello, A. Arima, The interacting boson model, Cambridge University Press (1987)

E1 strength in Nd isotopes



$$\hat{T}(E1) = e_1[\chi_{sp}(s^\dagger\tilde{p} + p^\dagger\tilde{s})^{(1)} + (p^\dagger\tilde{d} + d^\dagger\tilde{p})^{(1)} + \chi_{df}(d^\dagger\tilde{f} + f^\dagger\tilde{d})^{(1)}]$$

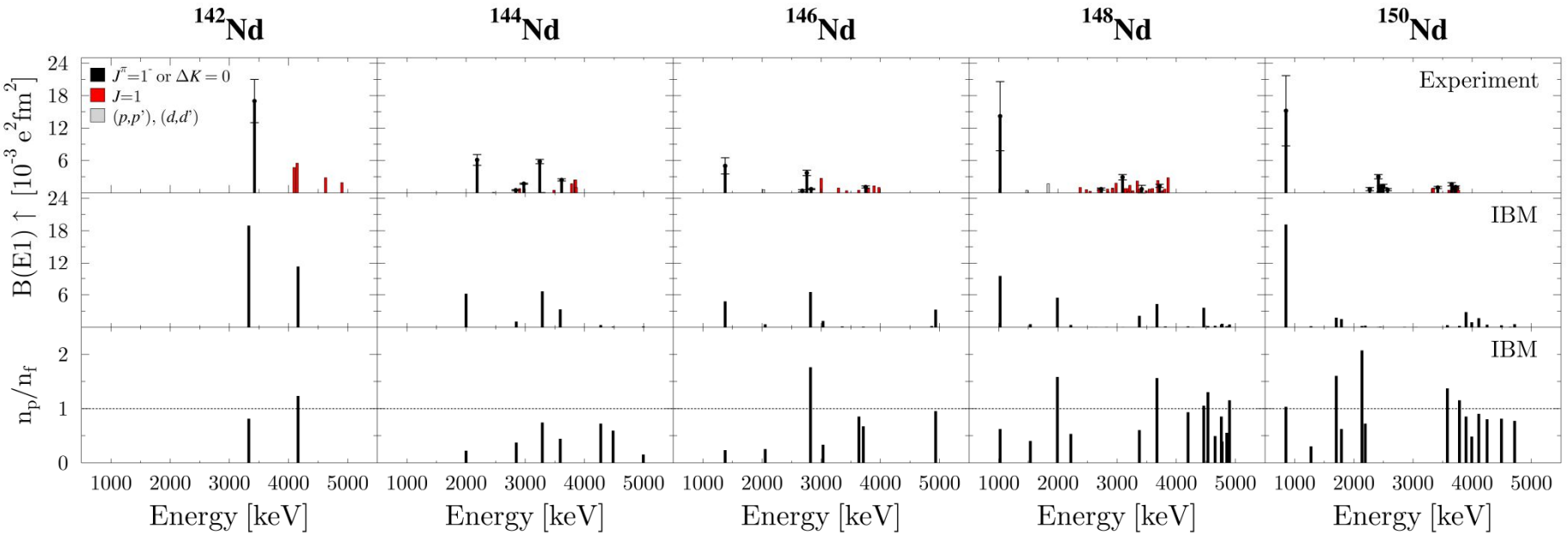


[MS, S. Pascu, A. Zilges, and F. Iachello, PRL **114**, 192504 (2015)]

First 1$^-$ state:

- *p*-boson is responsible for parabolic evolution of the *E1* strength!

E1 strength in Nd isotopes



Experimental data from: [H.H. Pitz *et al.*, NPA **509**, 587 (1990)]
[H. Friedrichs *et al.*, PRC **45**, 892(R) (1992)]
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[ENSDF, 2015]

IBM Results: [MS, S. Pascu, A. Zilges, and F. Iachello, PRL **114**, 192504 (2015)]

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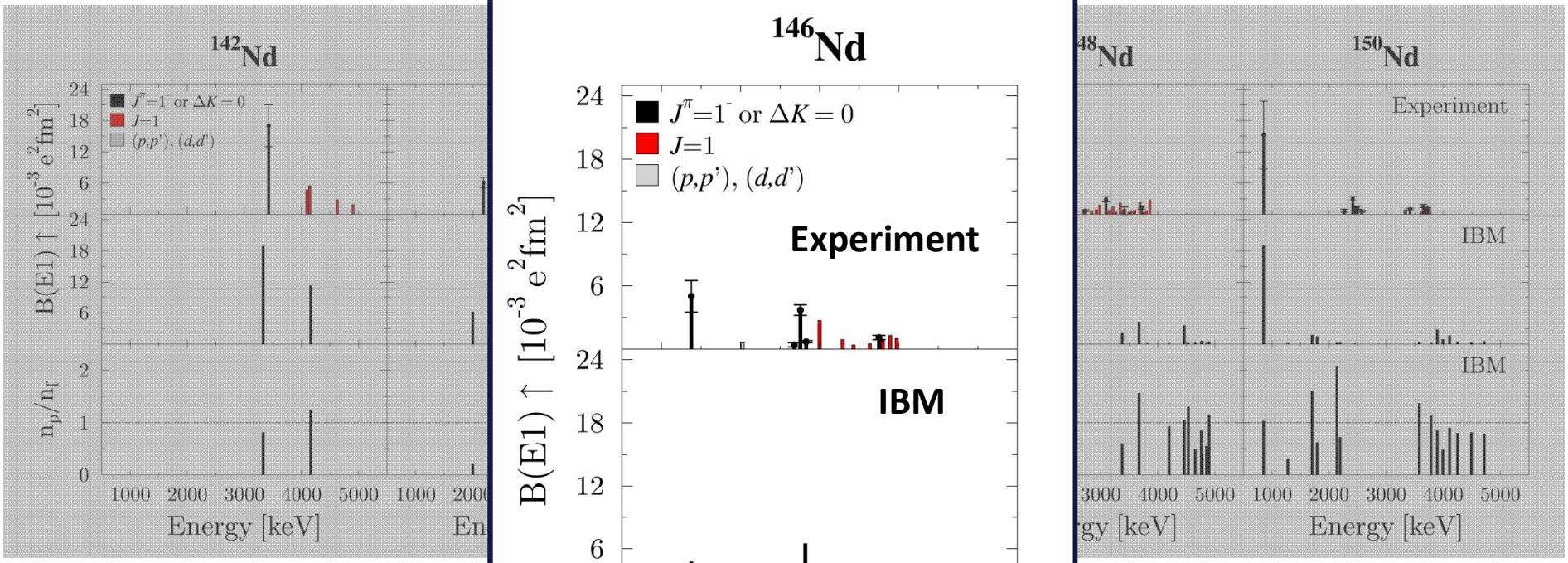

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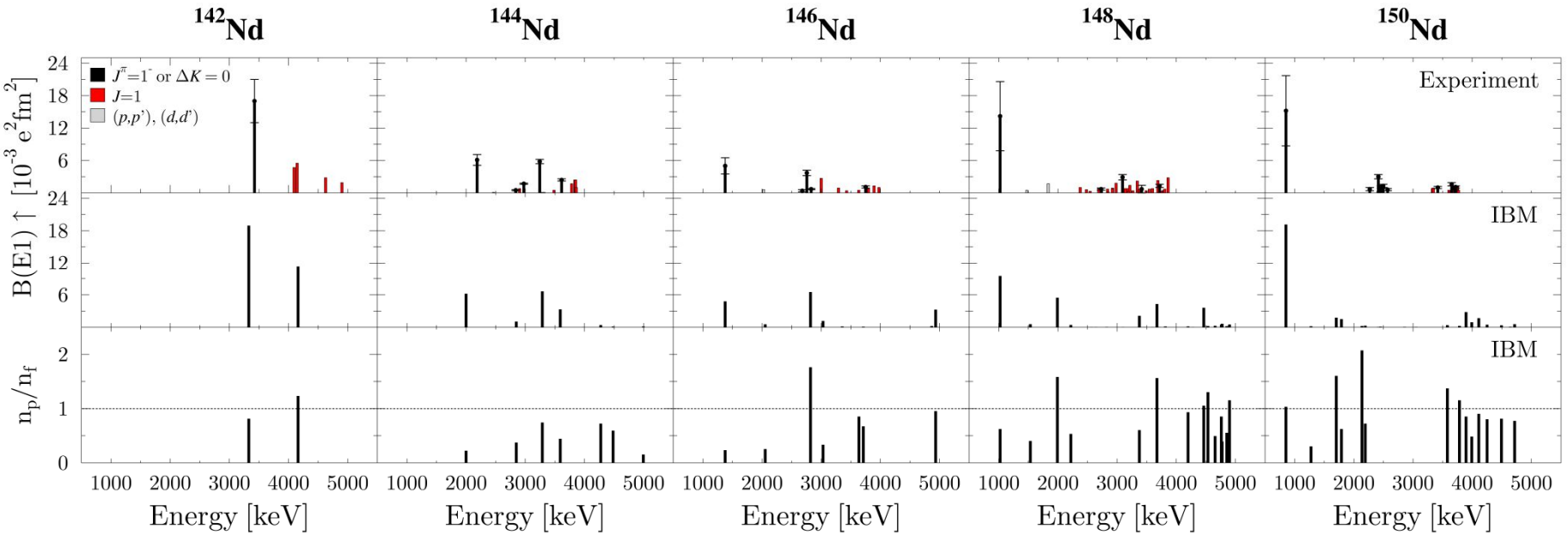

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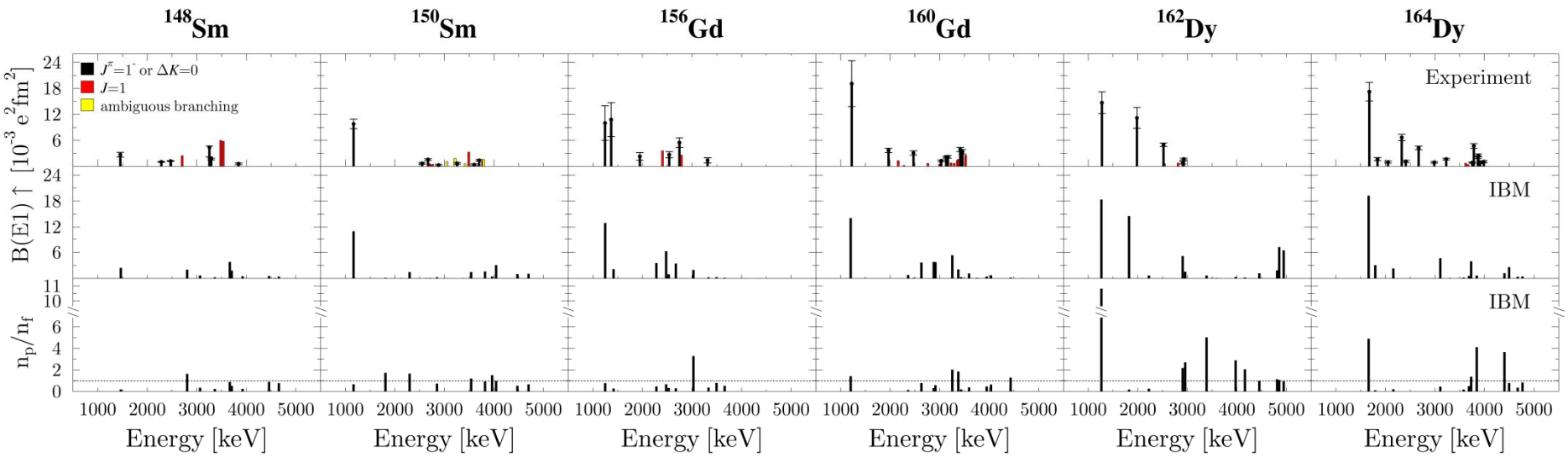
[ENSDF, 2015]

IBM Results: [MS, S. Pascu, A. Zilges, and F. Iachello, PRL **114**, 192504 (2015)]

Results:

- Good agreement with experimental data for almost all known low-lying 1^- states (strength and centroid energy)
- Strong *p*-boson states are observed ($n_p/n_f > 1$)

E1 strength in other rare-earth nuclei



Experimental data from: [W. Ziegler *et al.*, NPA **564**, 366 (1993)]
[H.H. Pitz *et al.*, NPA **492**, 411 (1989)]
[J. Margraf *et al.*, PRC **52**, 2429 (1995)]
[ENSDF, 2015]

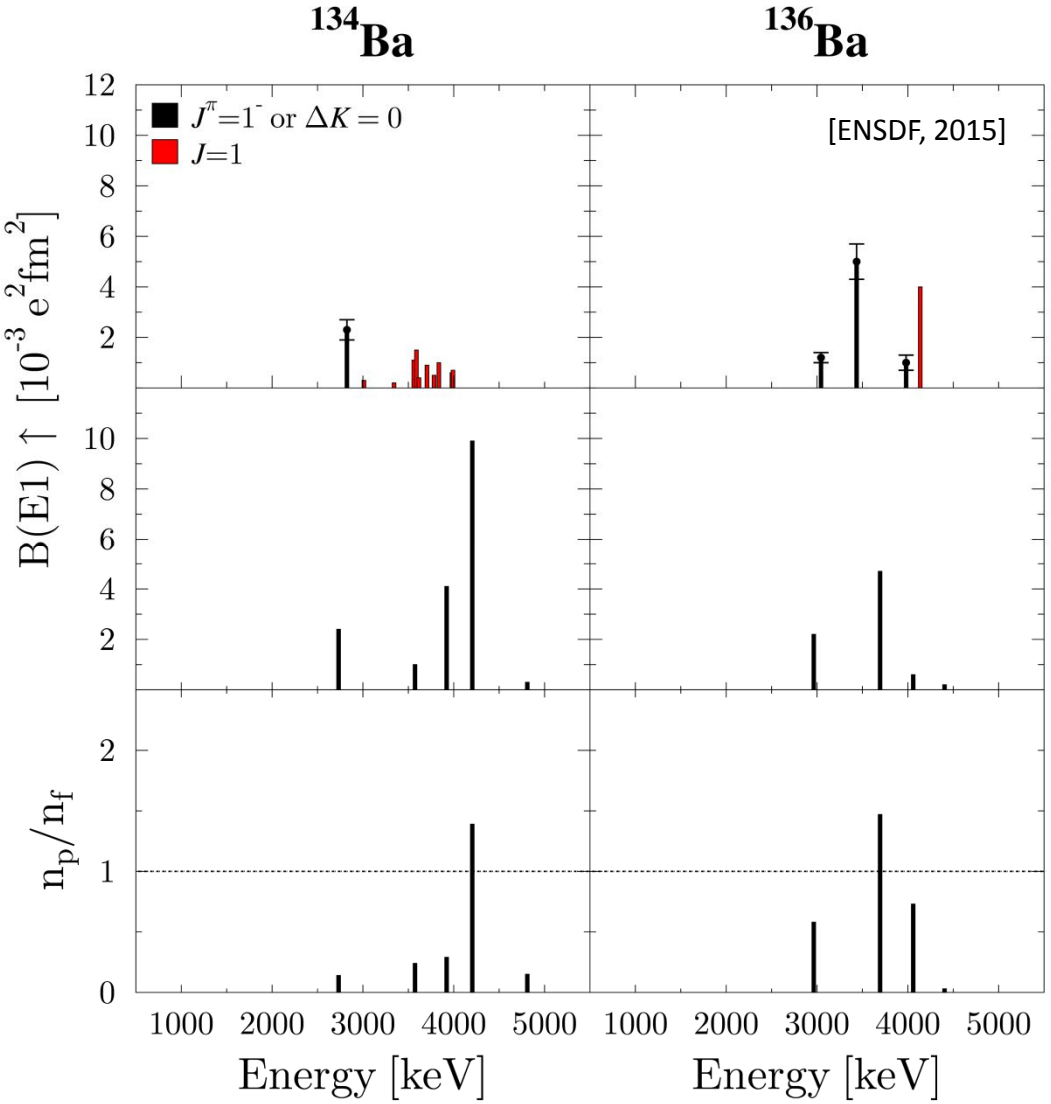
***sd*-IBM parameters for Dy:** [E.A. McCutchan *et al.*, PRC **69**, 064306 (2004)]
(Gd parameters similar)

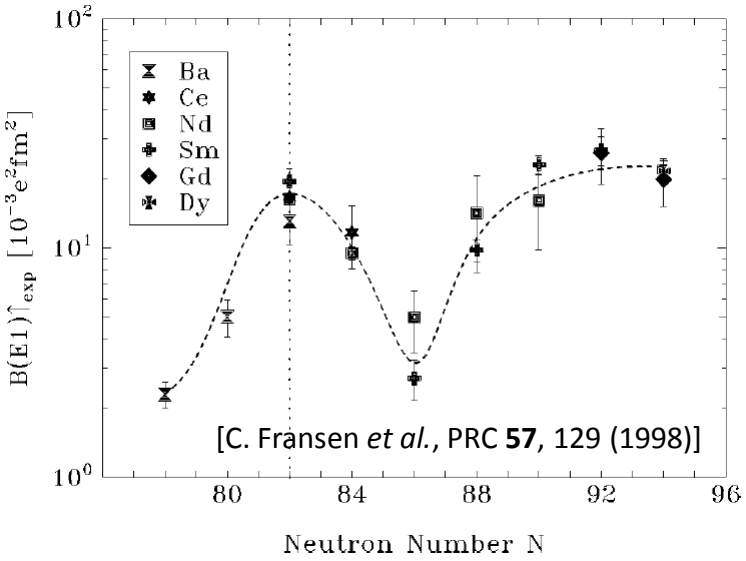
IBM Results: [MS, S. Pascu, A. Zilges, and F. Iachello, PRL **114**, 192504 (2015)]

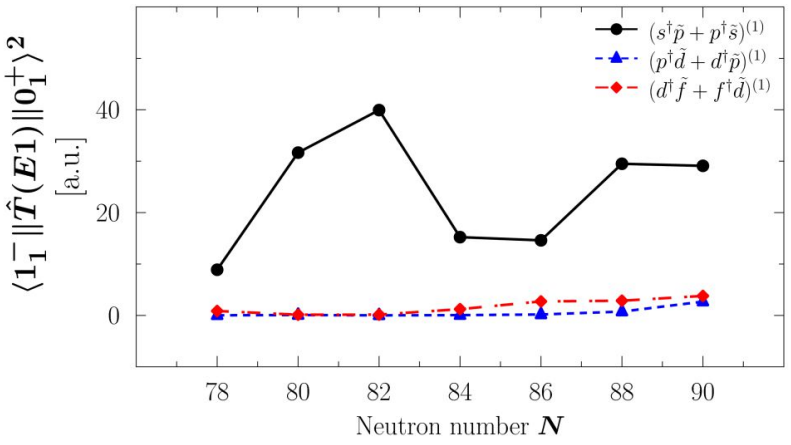
Results:

- *spdf*-IBM is able to describe the low-lying *E1* strength in rare-earth nuclei!
- *U*(4), *i.e.*, two-body cluster, plays a crucial role!

Neutron-deficient rare earths – Ba isotopes







***sd*-IBM parameters:** [S. Pascu *et al.*, PRC **81**, 054321 (2010)]

[M. Spieker et al., *to be published*]

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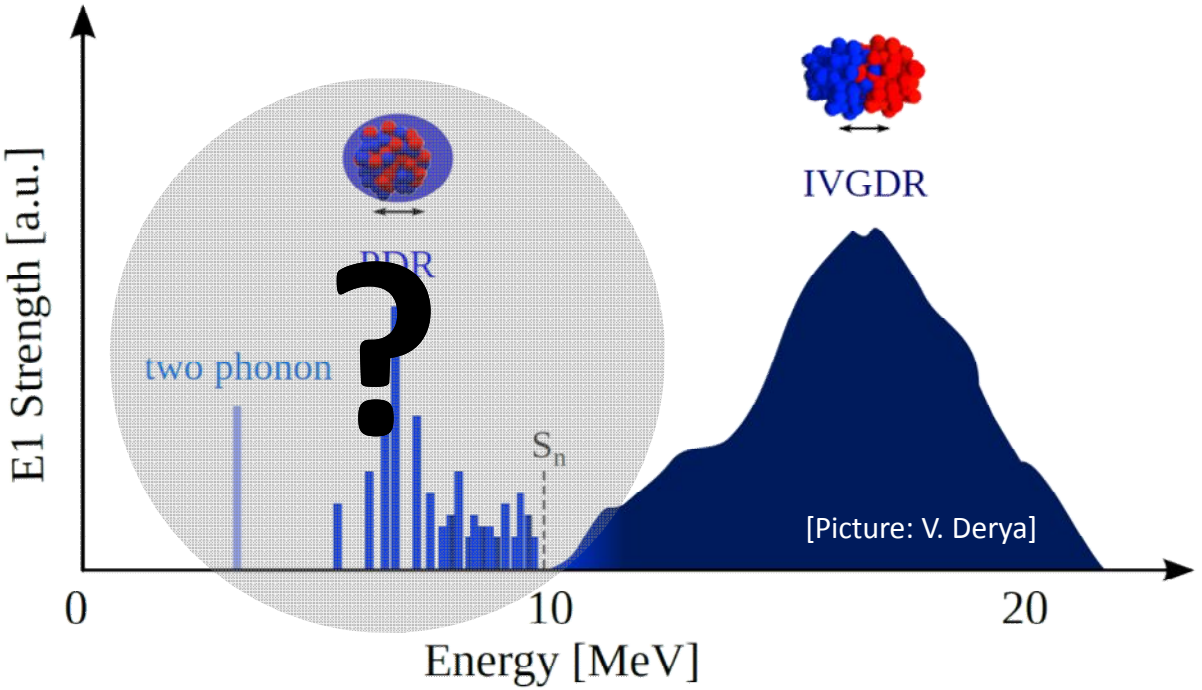

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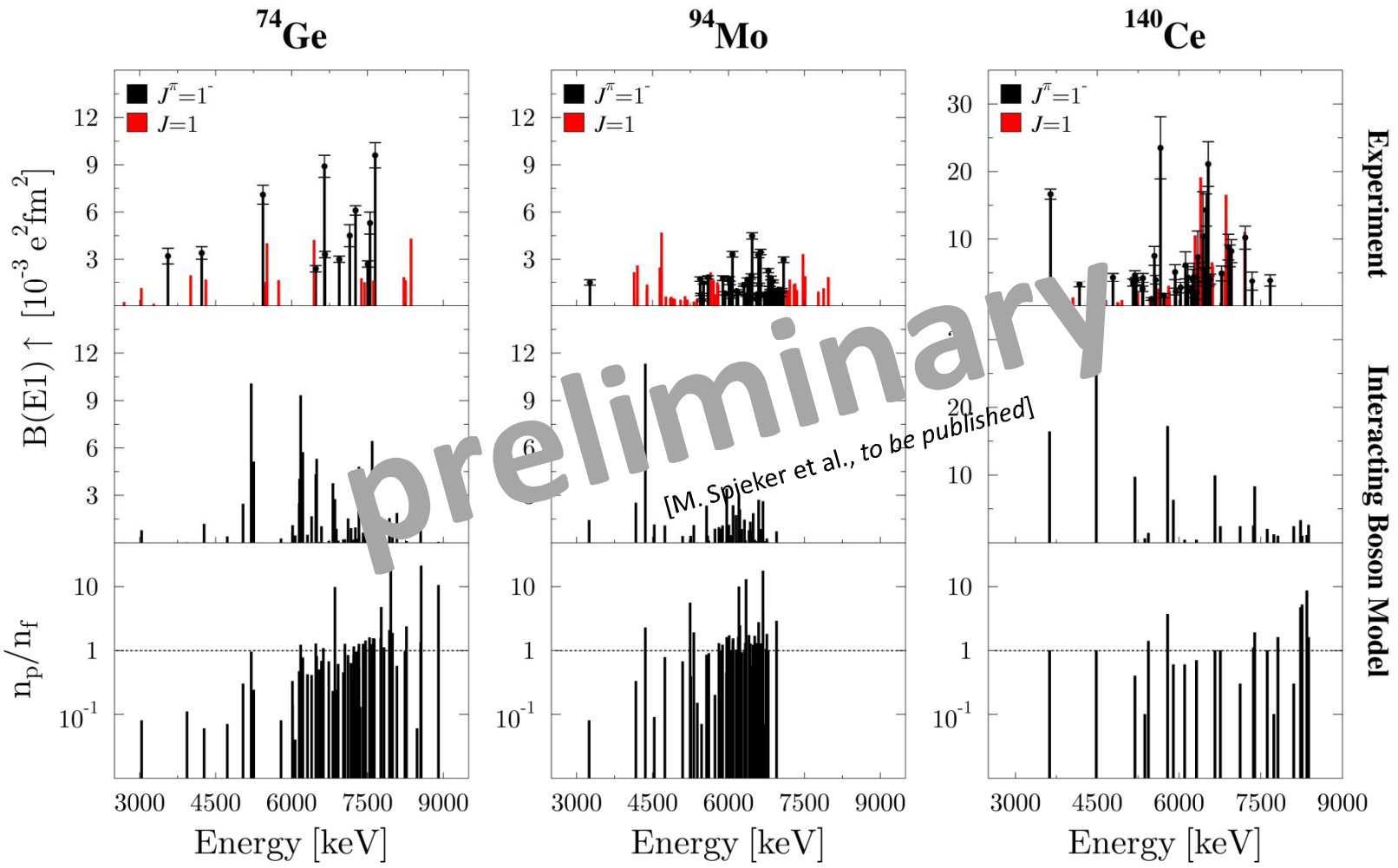
… are there more generating mechanisms?
… is there a cluster component in the PDR?

α clusters and the PDR?



Experimental Data:
[A. Jung et al., NPA **584**, 103 (1995)]
[C. Romig et al., PRC **88**, 044331 (2013)]
[S. Volz et al., NPA 779, 1 (2006)]

… is there a cluster component in the PDR?

[see also: S. Pascu et al., PRC **85**, 064315 (2012)]

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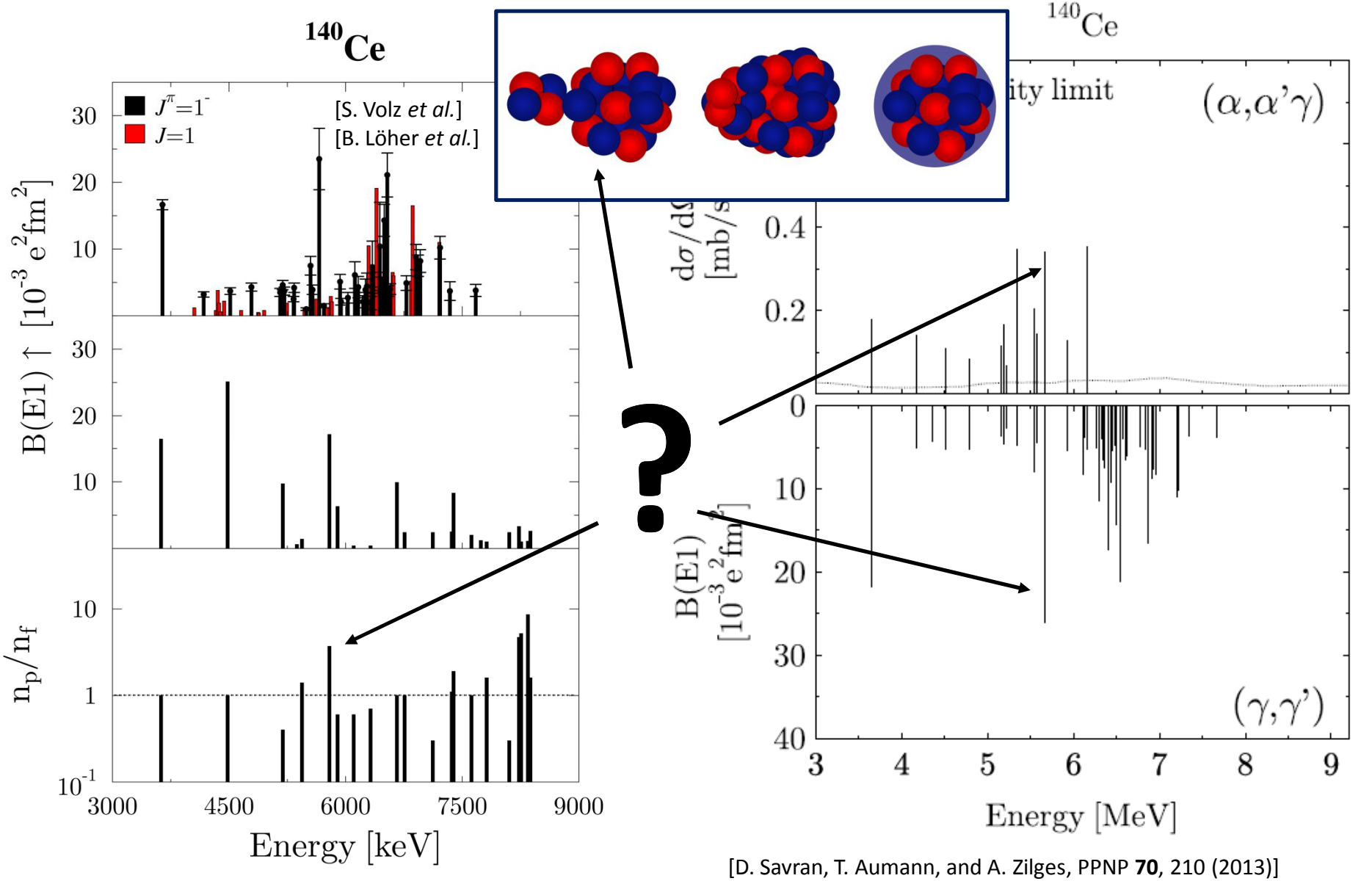
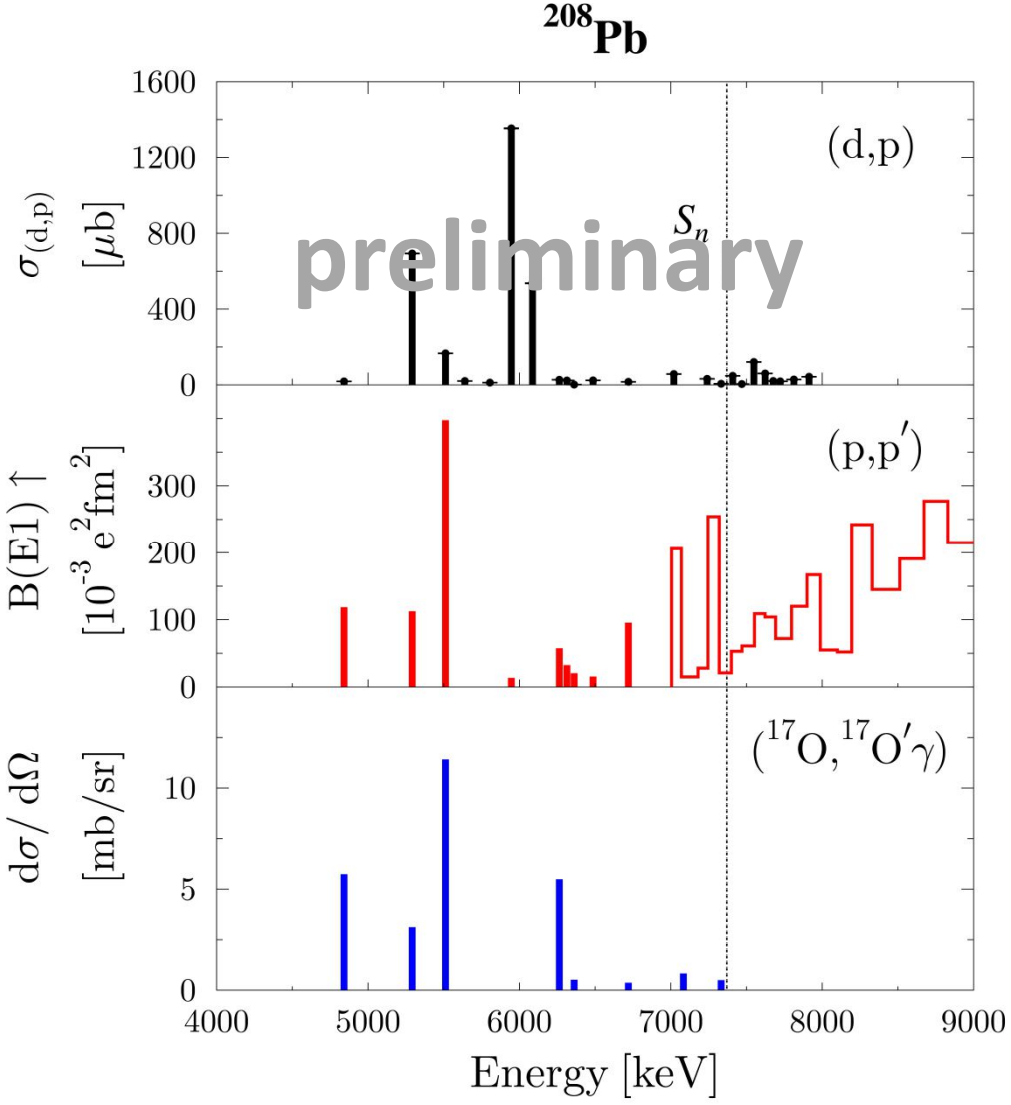
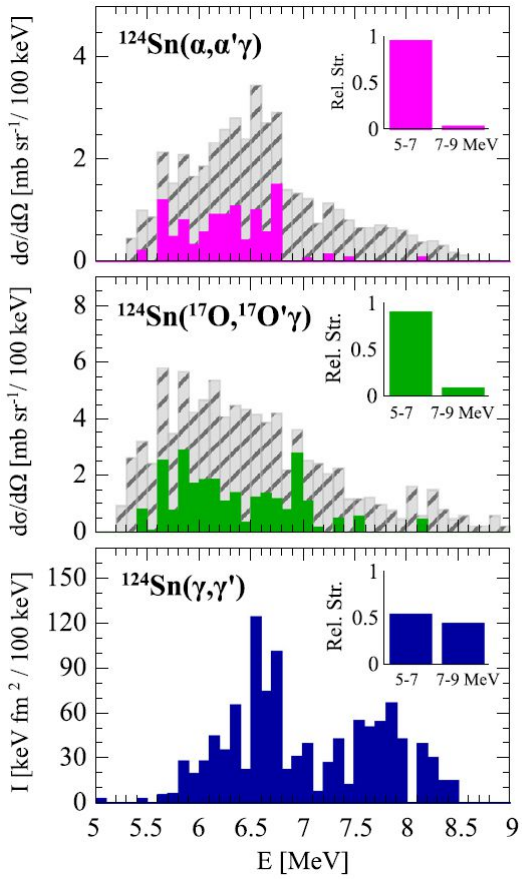


[D. Savran, T. Aumann, and A. Zilges, PPNP **70**, 210 (2013)]

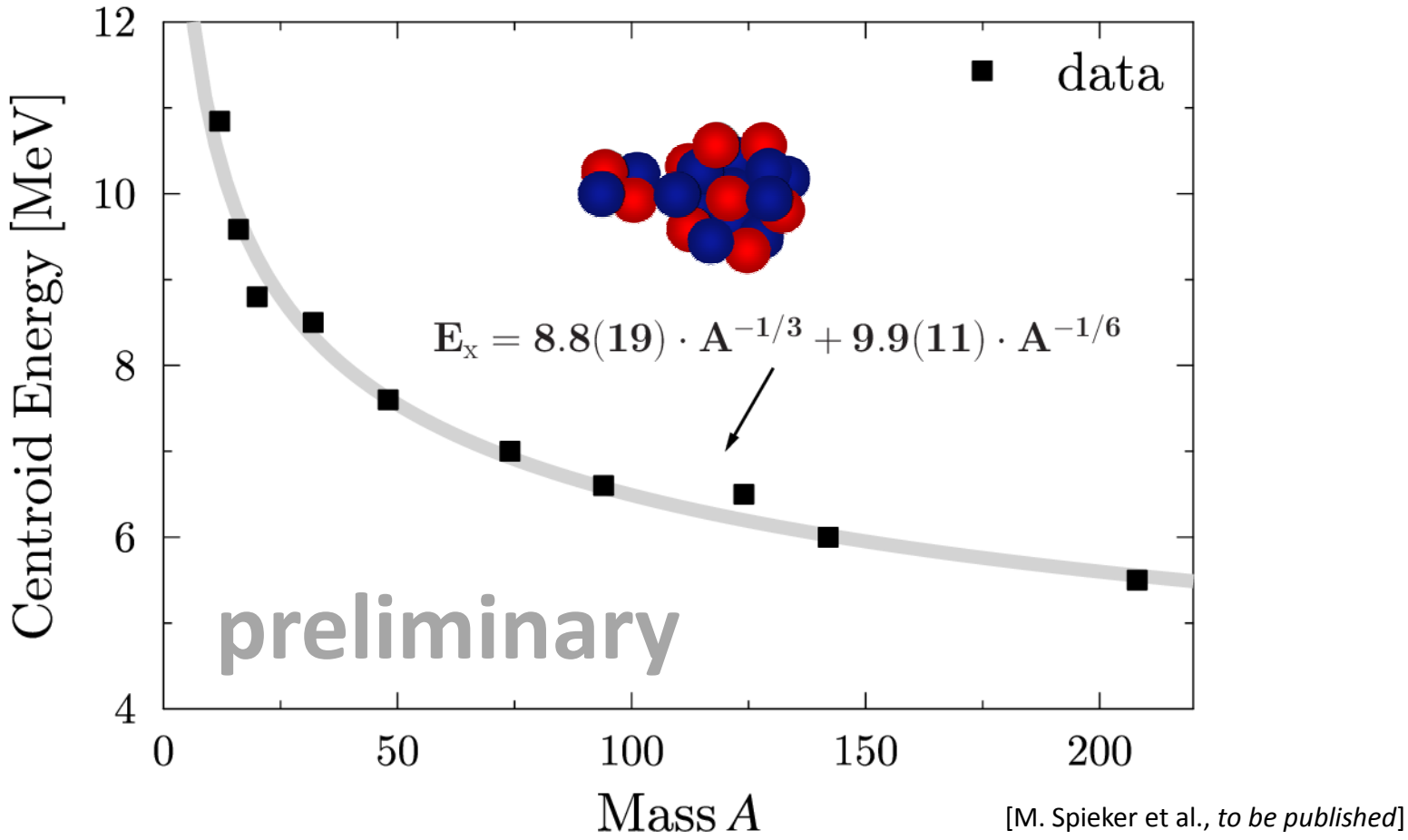
Experimental identification?





(d,p): M. Spieker et al., to be published
(p,p'): I. Poltoratska et al., PRC **85**, 041304(R) (2012)
(^{17}O,^{17}O'): F.C.L Crespi et al., PRL **113**, 012501 (2014)
L. Pellegri et al., PLB **738**, 519 (2014)
(α,α'): J. Endres et al., PRL **105**, 212503 (2010)

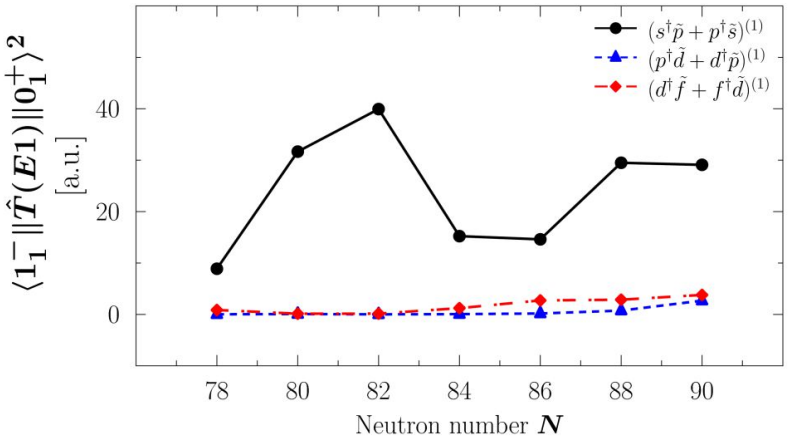
Dipole α vibrations – a universal collective mode?

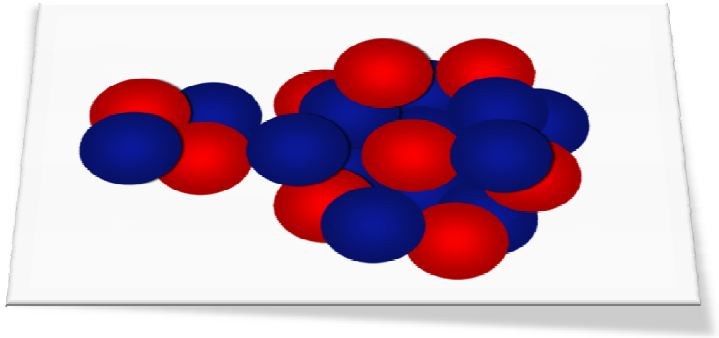


[M. Spieker et al., *to be published*]

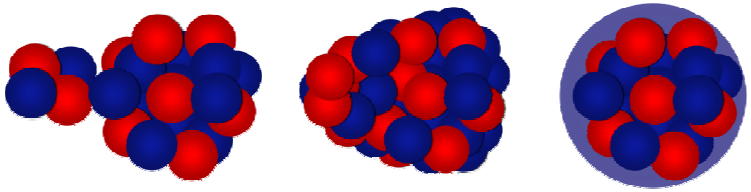
Centroid energy evolves smoothly as expected for a collective mode!

Summary & open questions





Connection of different modes?



- **Summary**
- **Possible signatures of an α-cluster**
  - *p*-boson describes in a natural way parabolic behavior of *E1* strength
  - Existence of cluster states in heavy nuclei possible!
  - Enhanced *E1* transitions might serve as an indicator

  [MS, S. Pascu, A. Zilges, and F. Iachello, PRL **114**, 192504 (2015)]

- **Some open questions**

Theory:

- Unambiguous correspondence of *sp*-IBM, *i.e.*, U(4) with cluster configurations?

  → Microscopic calculations including 4QP *a priori*, *i.e.*, α-particles needed!

Experiment:

- Further experimental observables?
- Parity of dipole states?
- Link between deformed and spherical nuclei/ connection with PDR?
- Is there a mass dependence?