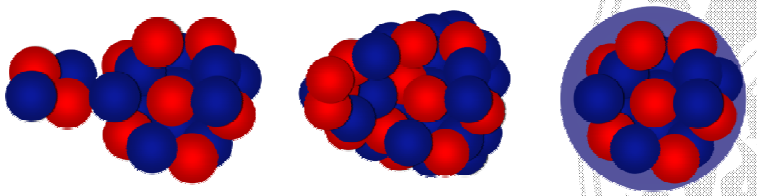
Origin of low-lying enhanced *E1* strength in rare-earth nuclei

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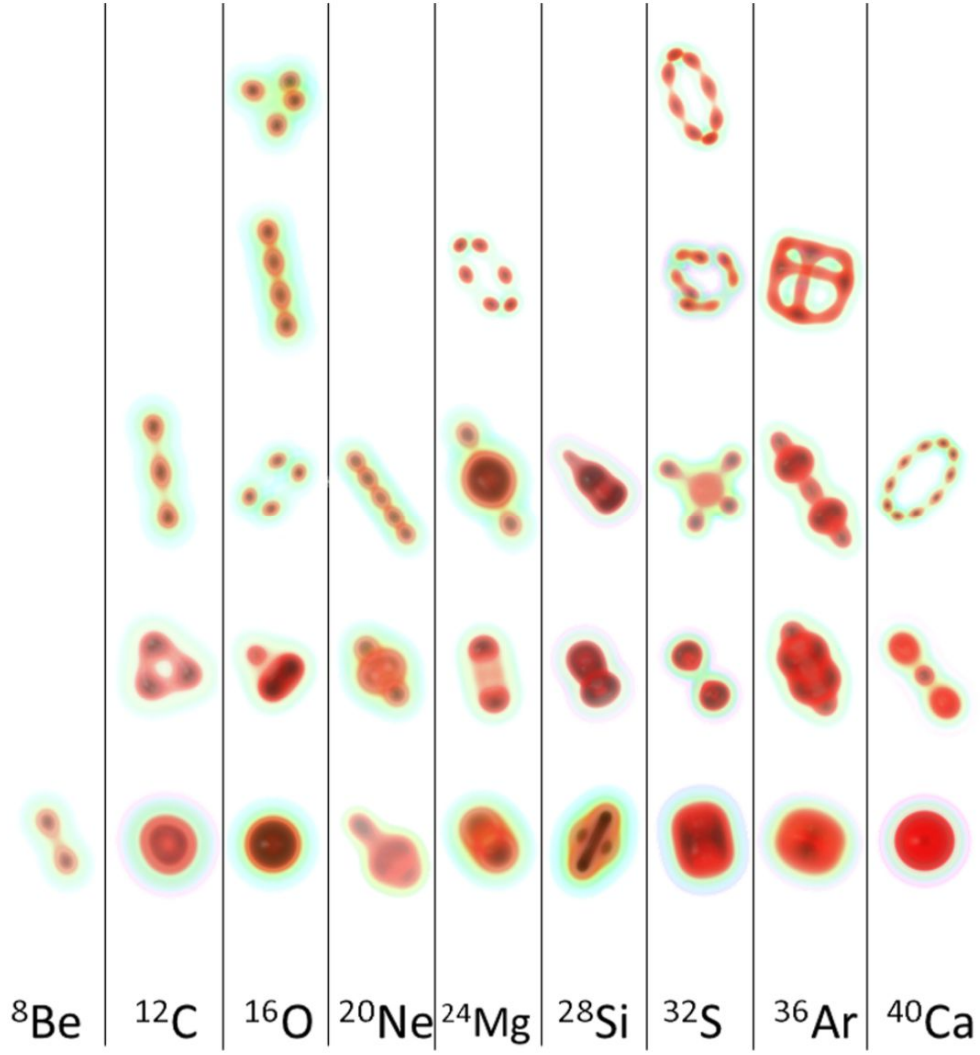
Special thanks to Francesco Iachello
*Supported by the Bonn-Cologne Graduate School of Physics and Astronomy

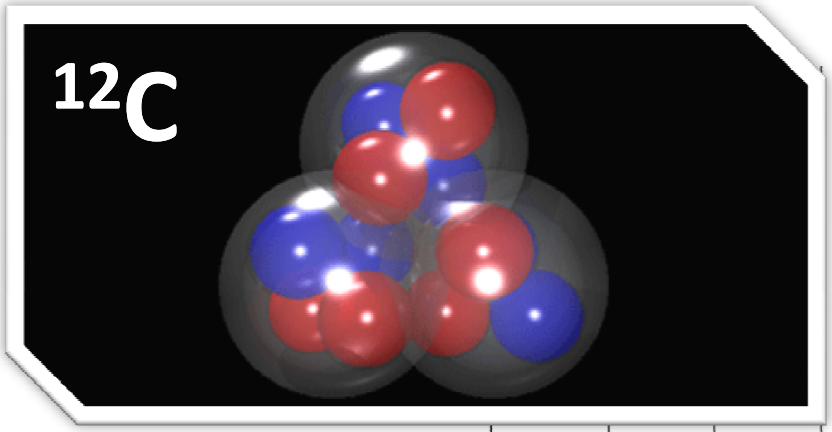
Is clustering a general phenomenon in nuclei?

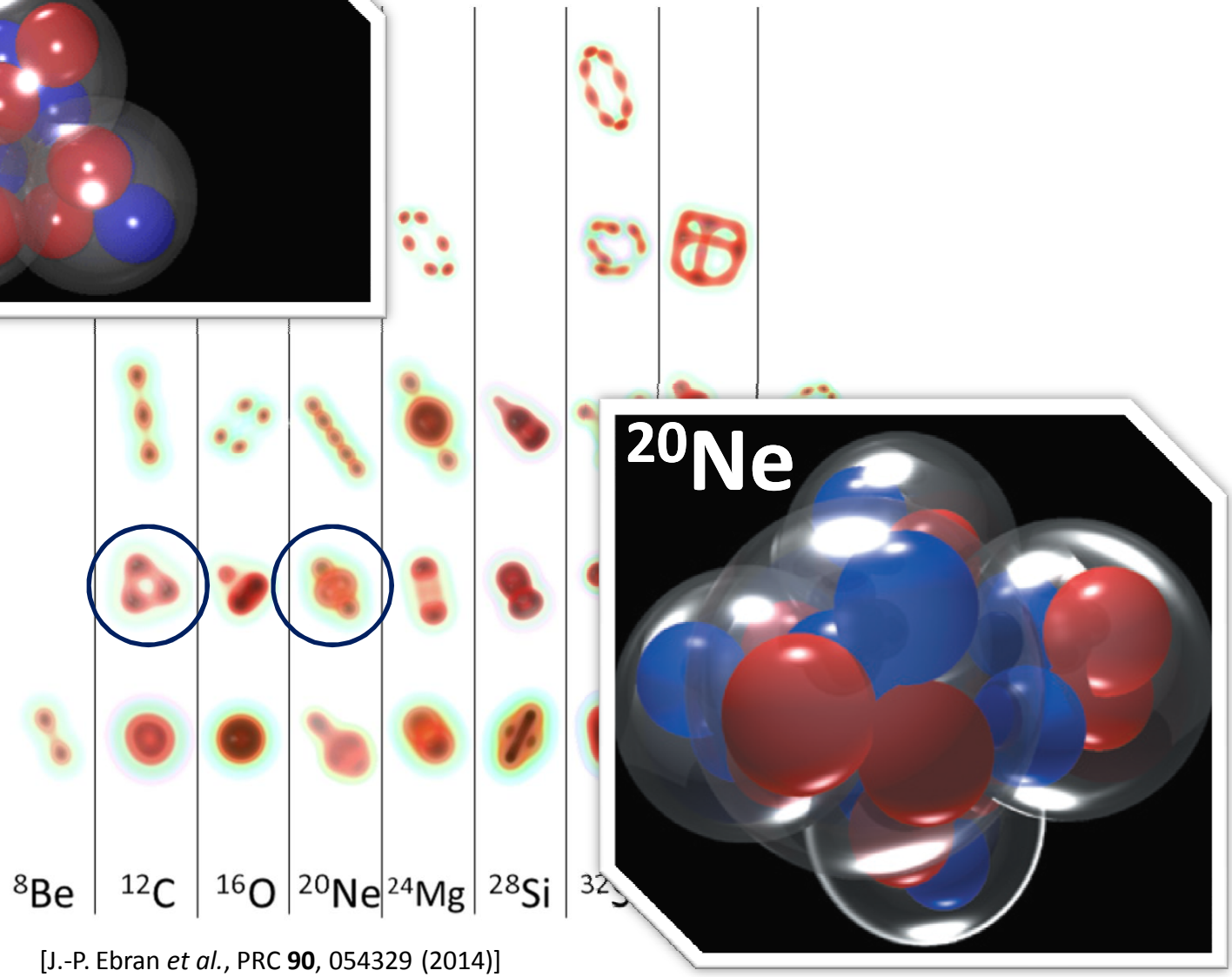


[J.-P. Ebran *et al.*, PRC **90**, 054329 (2014)]

Is clustering a general phenomenon in nuclei?

[Pictures: M. Freer/University of Birmingham]





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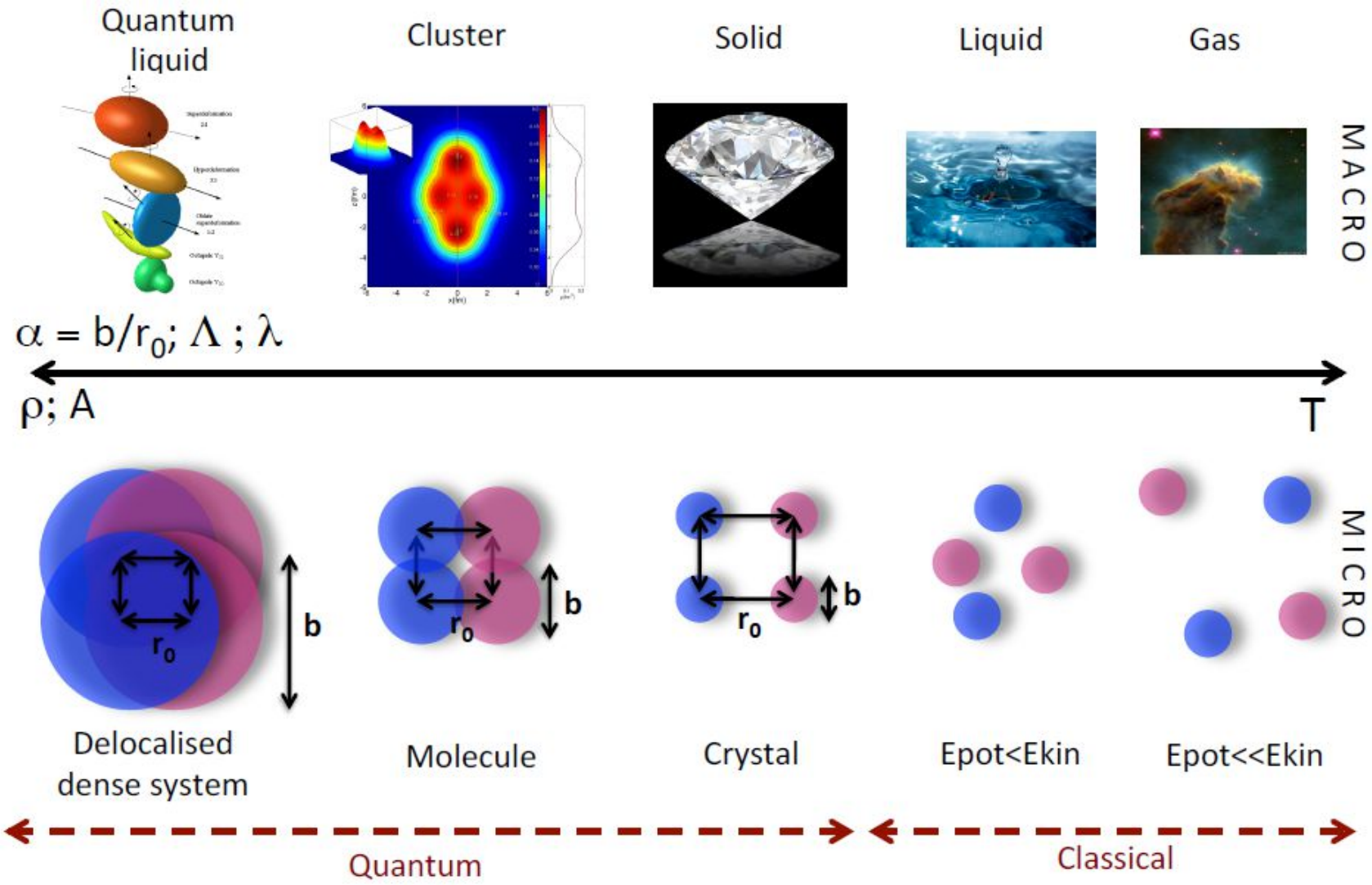
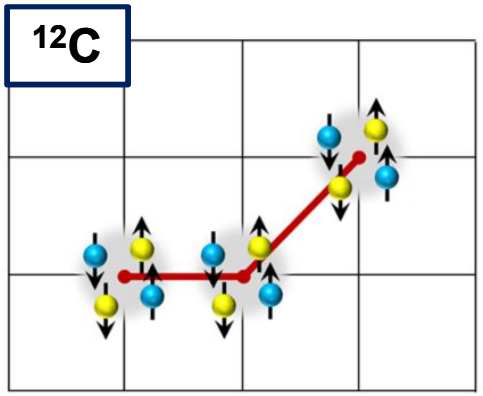
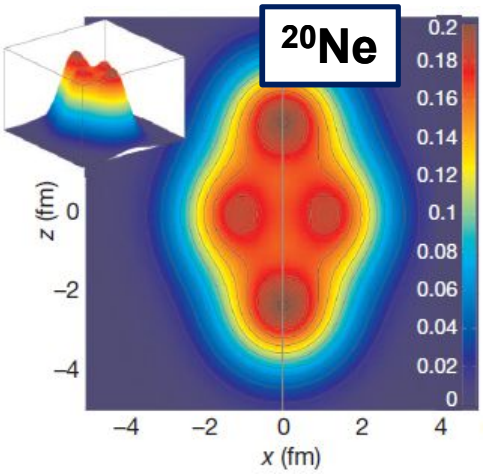
Clustering – a general state of nuclear matter?

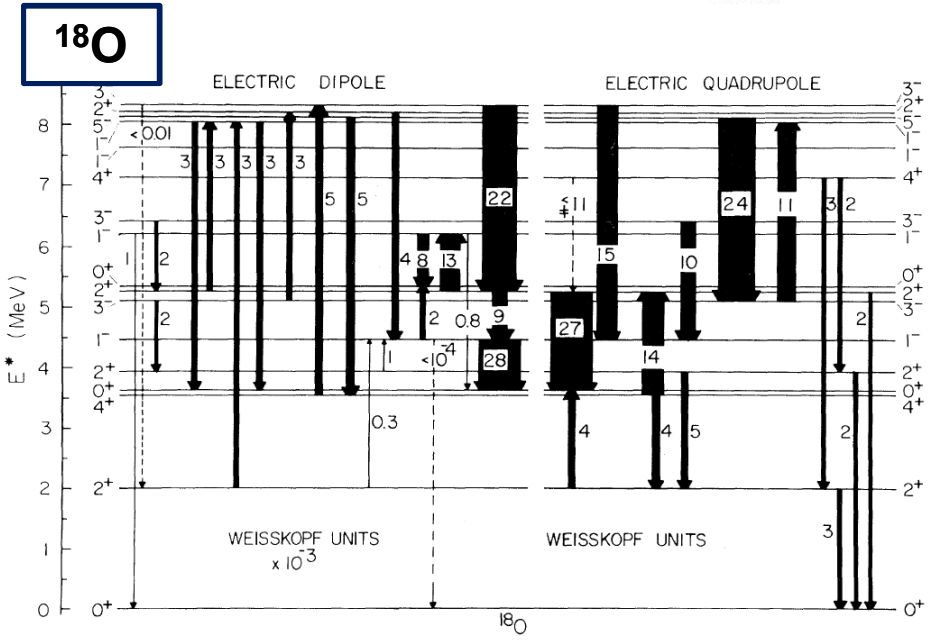


[Picture from: E. Khan *et al.*, J. Phys. Conf. Ser. **569**, 012006 (2014)]

Clustering in light nuclei







Clustering established in light nuclei

- Structure of **Hoyle state** in ^{12}C in *ab initio* lattice calculation

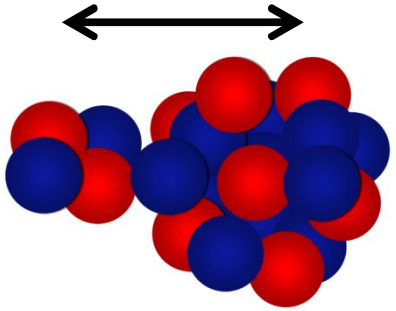
  [E. Epelbaum *et al.*, PRL **109**, 252501 (2012)]

- Clustering as a window into the **nature of the strong force** (EDF calculations)

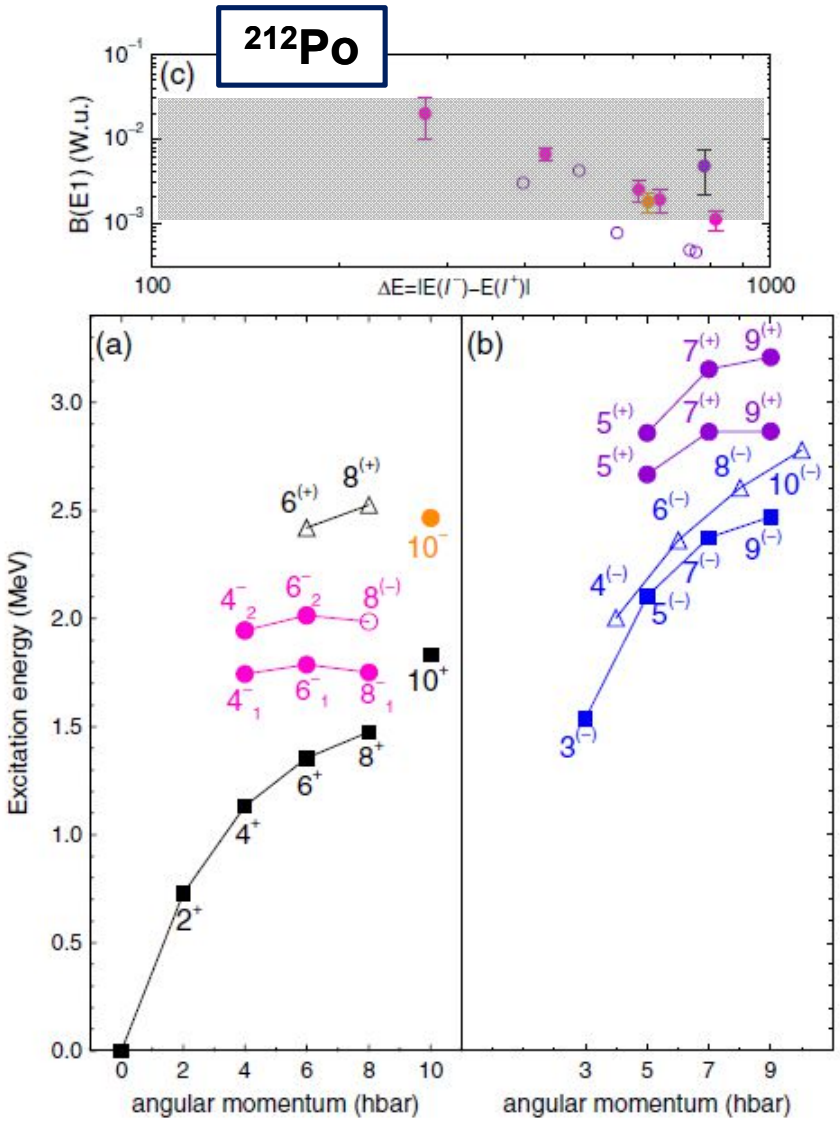
  [J.-P. Ebran *et al.*, Nature **487**, 341 (2012)]

- **Enhanced dipole strength** due to α+^{14}C system in ^{18}O experimentally observed

  [M. Gai *et al.*, PRL **50**, 239 (1983)]



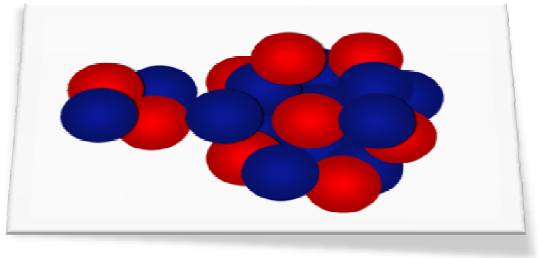
Clustering in heavy nuclei?



The case of ^{212}Po

- Strong indications of **α+^{208}Pb in ^{212}Po** by means of enhanced *E1* transitions

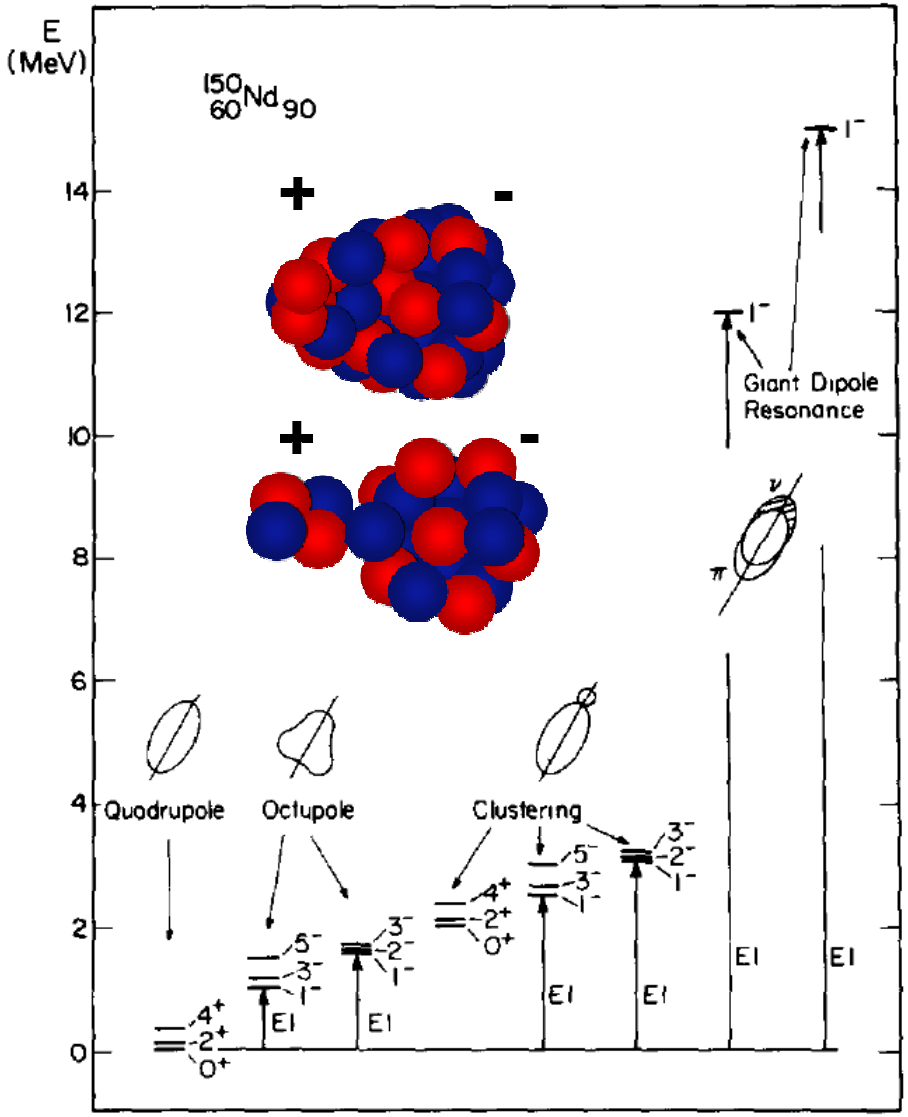
[A. Astier *et al.*, PRL **104**, 042701 (2010)]



- Possible existence of α+^{208}Pb at surface recently shown in **shell-model approach with four-particle correlations**

[G. Röpke *et al.*, PRC **90**, 034304 (2014)]

Isospin-symmetry breaking in atomic nuclei



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

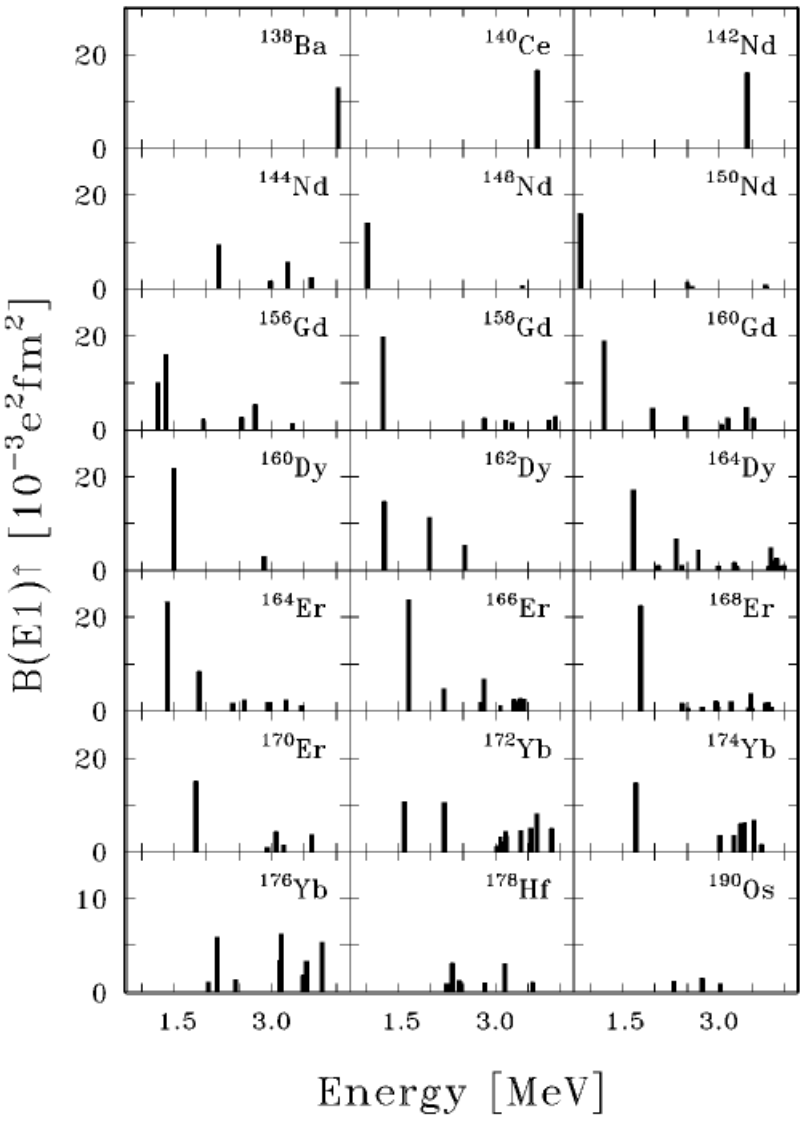
Low-lying *E1* strength due to isospin-symmetry breaking

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

Two components:

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

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



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

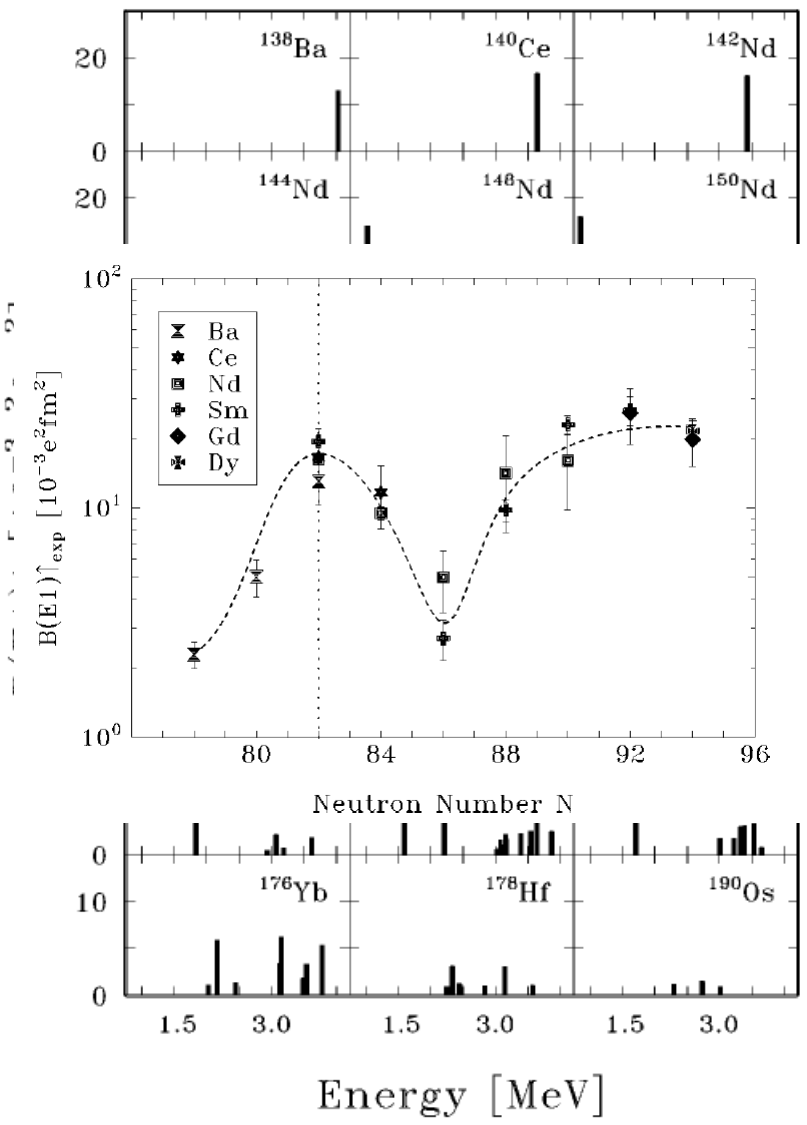
E1 strength in rare-earth nuclei

(combined experimental efforts of Stuttgart, 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!

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



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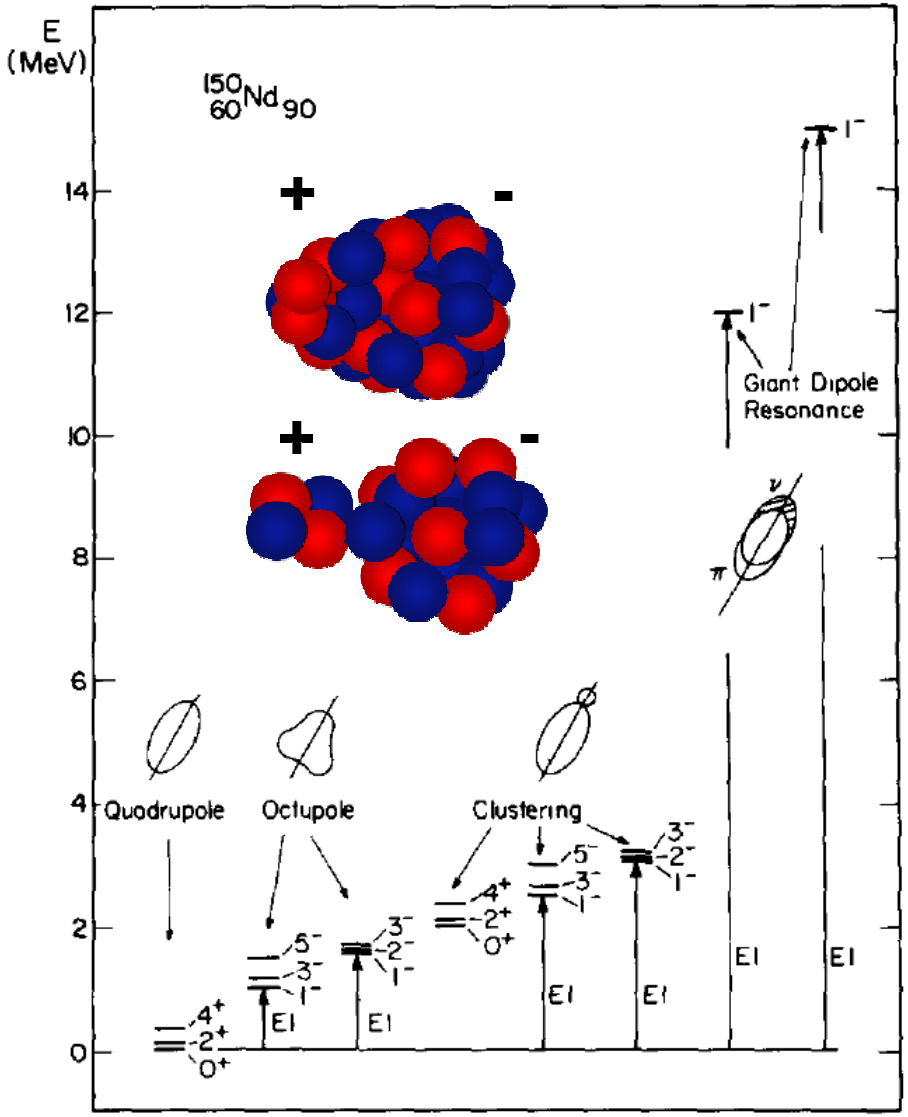

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Two components:

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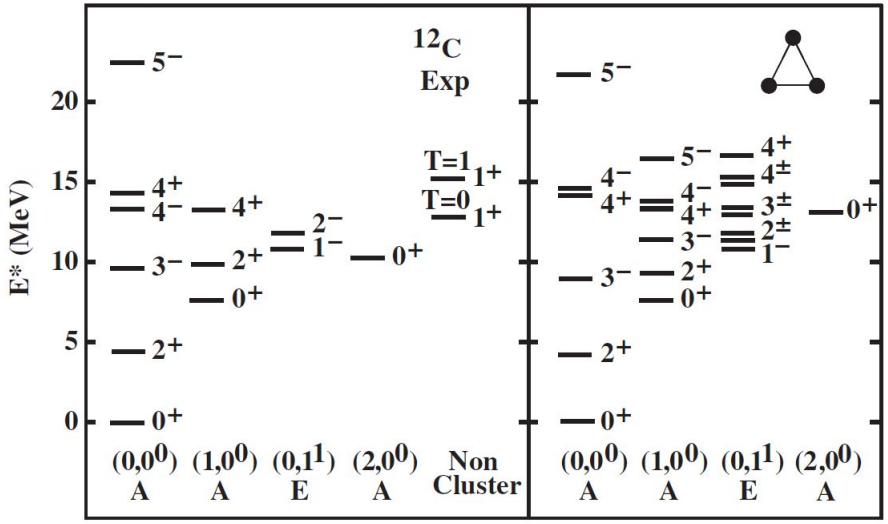
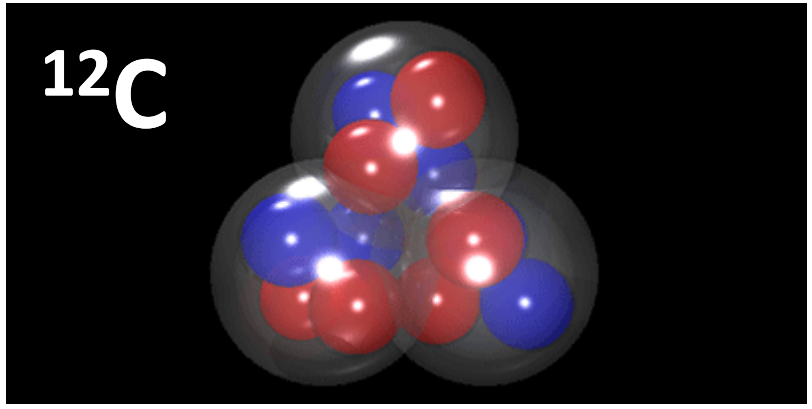
- α-clustering mode

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

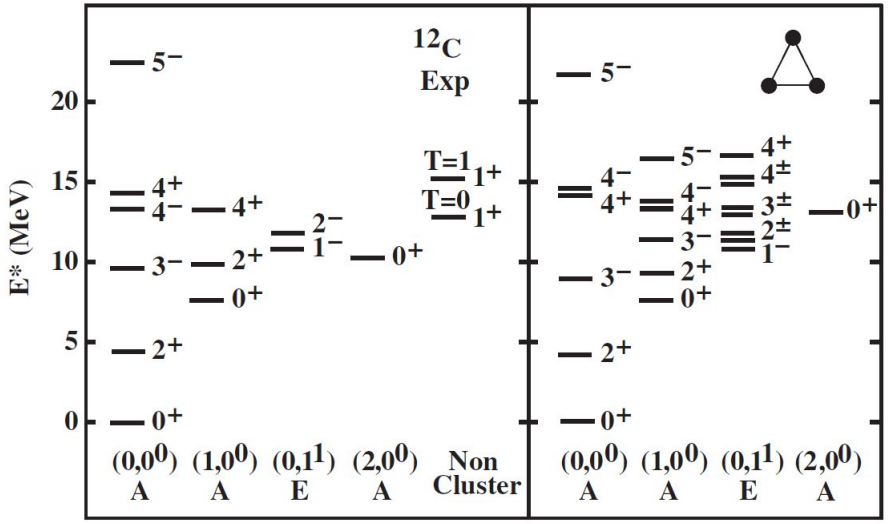
- Cluster states can be explained by the algebra of $U(\nu+1)$, *e.g.*, ^{12}C and ^{16}O!
- $\nu = 3n-3$, where n = #clusters

[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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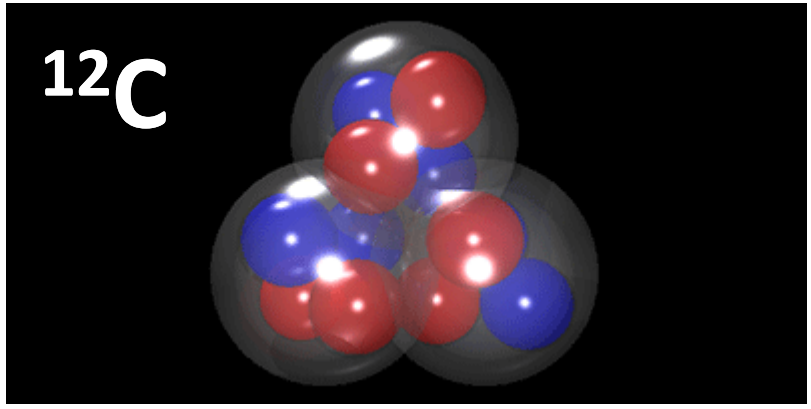

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- U(4) for two-body clusters
- U(4) is the algebra of the *sp* interacting boson model

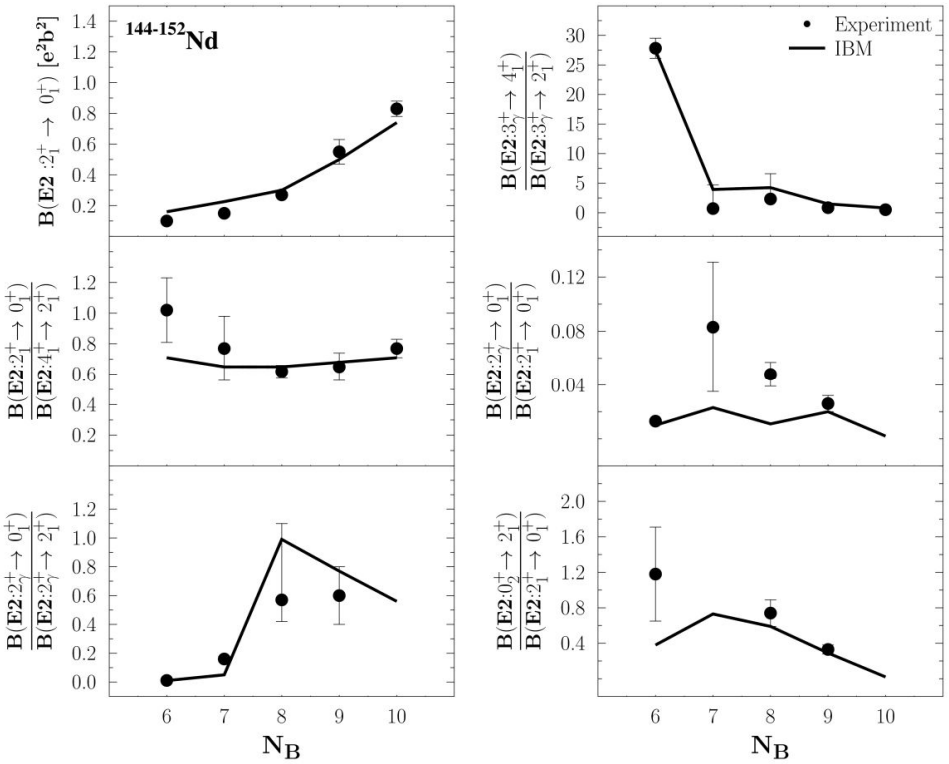
→ ***spdf*** **IBM to describe octupole mode and α-clustering mode!**

spdf interacting boson model – Hamiltonian

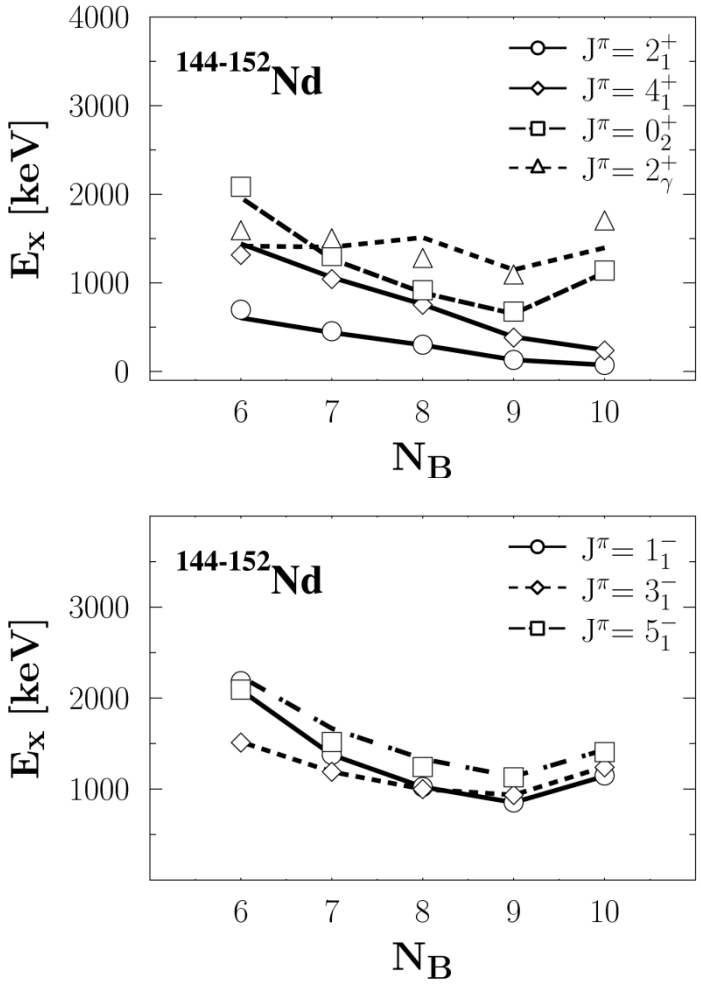
- **Model Hamiltonian:**

$$\hat{H}_{spdf} = \epsilon_d \hat{n}_d + \epsilon_p \hat{n}_p + \epsilon_f \hat{n}_f - \kappa \hat{Q}_{spdf} \cdot \hat{Q}_{spdf} + a_3 \left[\left(\hat{d}^\dagger \tilde{d} \right)^{(3)} \cdot \left(\hat{d}^\dagger \tilde{d} \right)^{(3)} \right]^{(0)}$$

- ***E2* transitions and branching ratios:**



- **Excitation energies:**



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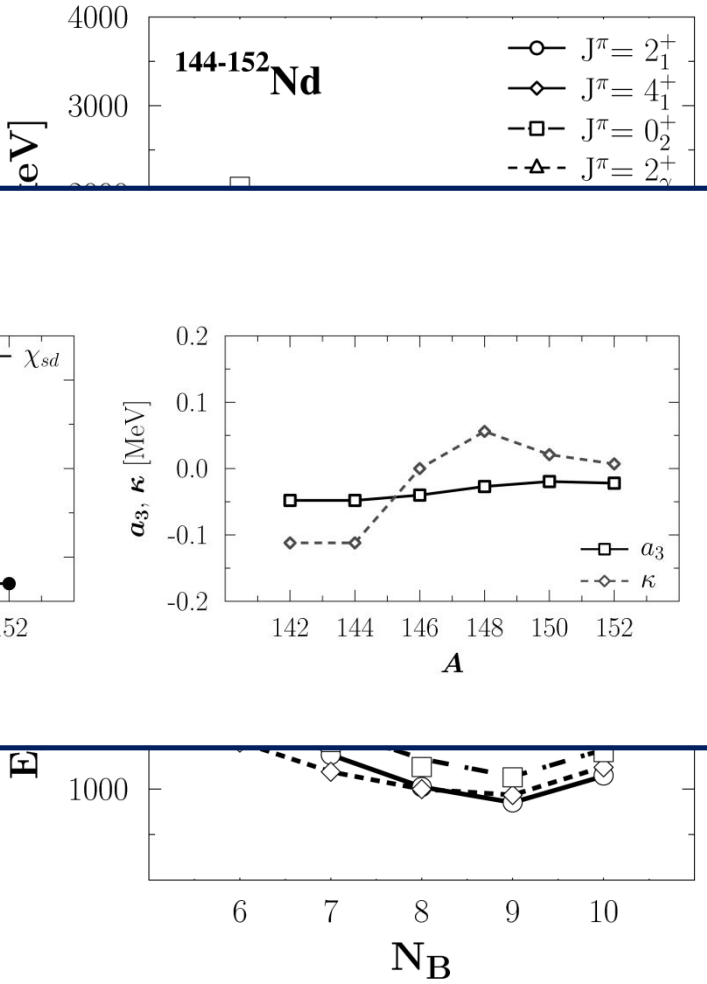
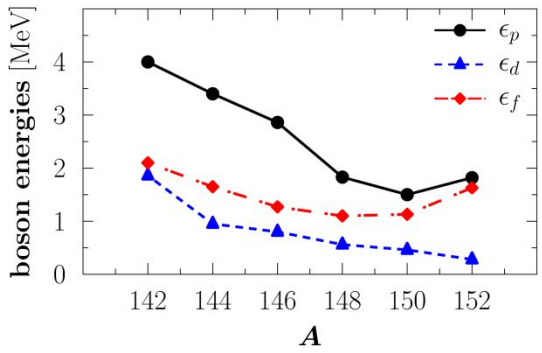
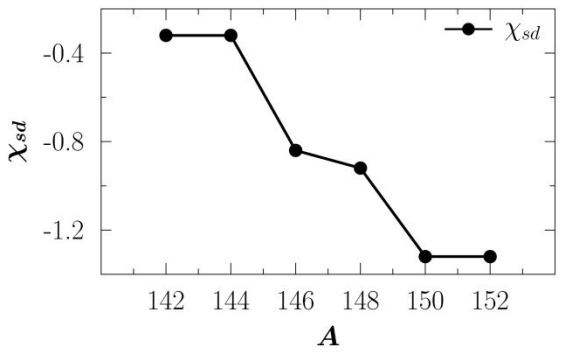
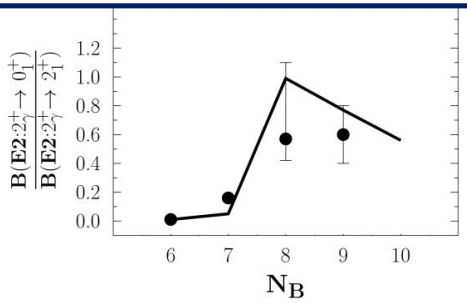
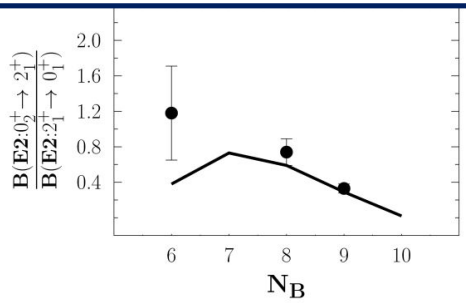


Final parameters for $^{142\text{-}152}$Nd:





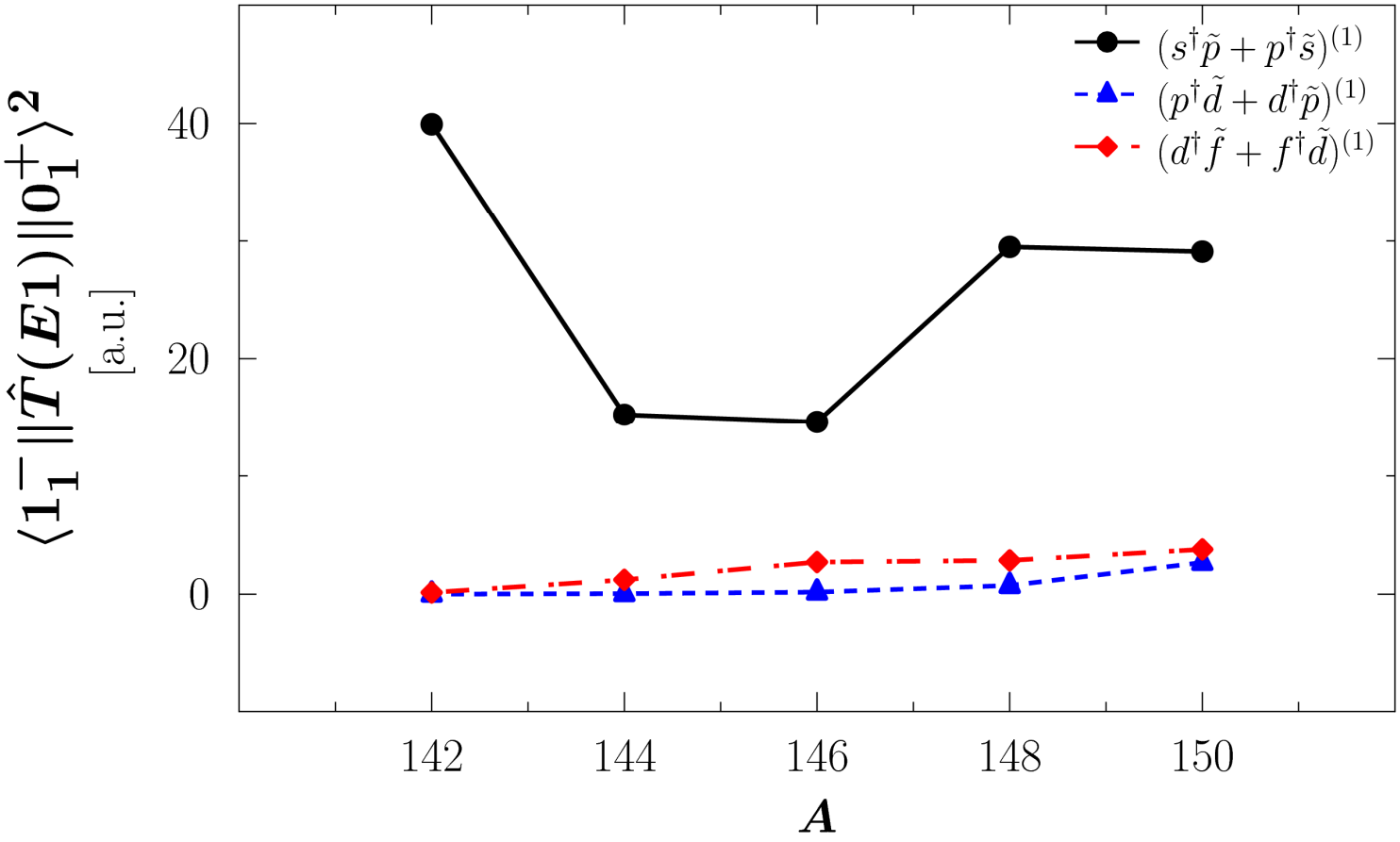




Origin of *E1* strength in Nd isotopes

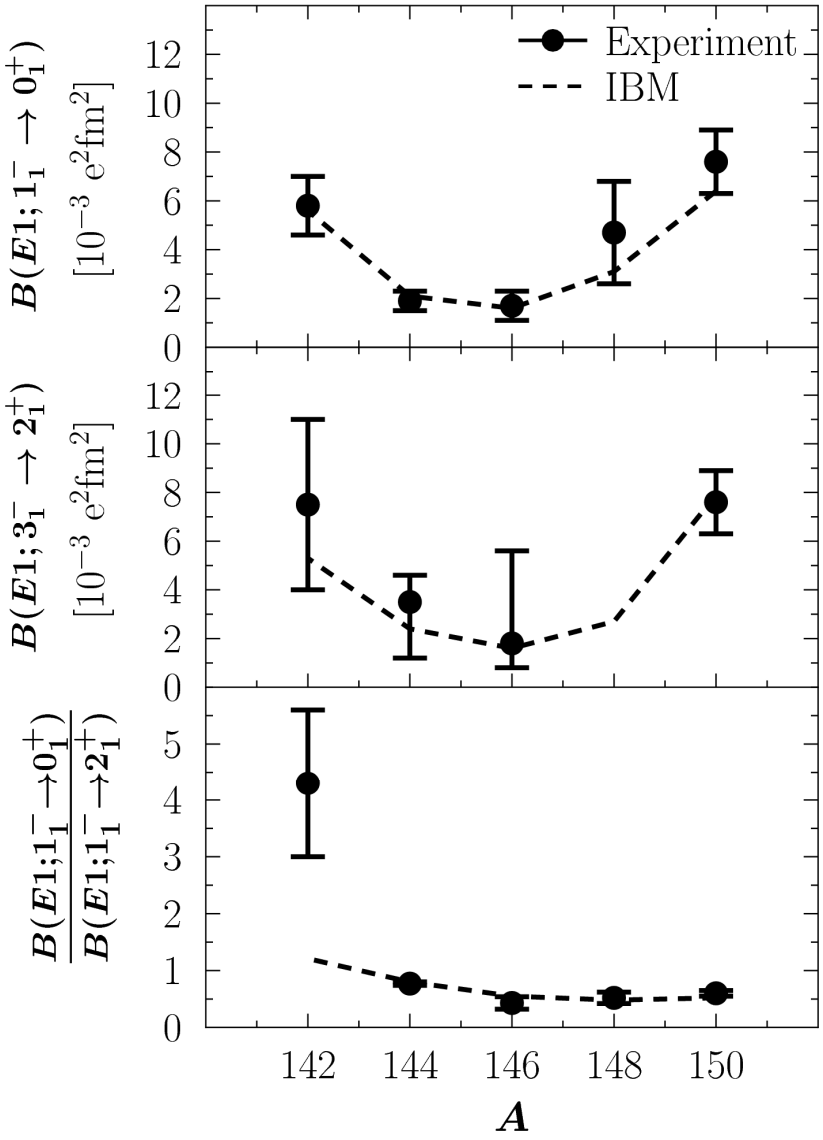
One-body *E1* operator:

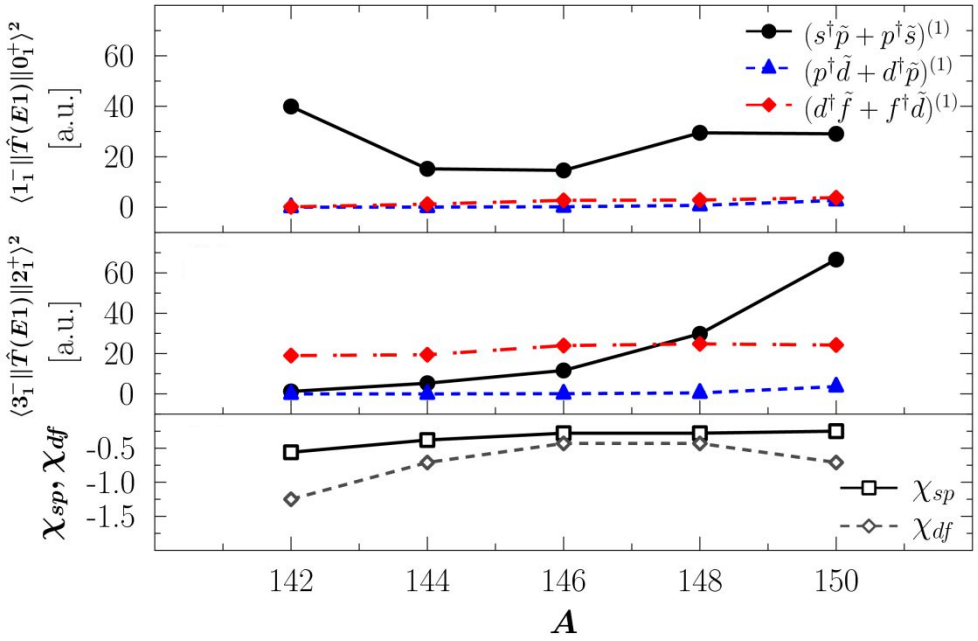
$$\hat{T}(E1) = e_1[\chi_{sp}(s^\dagger\tilde{p} + p^\dagger\tilde{s})^{(1)} + (p^\dagger\tilde{d} + d^\dagger\tilde{p})^{(1)} + \chi_{df}(d^\dagger\tilde{f} + f^\dagger\tilde{d})^{(1)}]$$



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

E1 strength in Nd isotopes



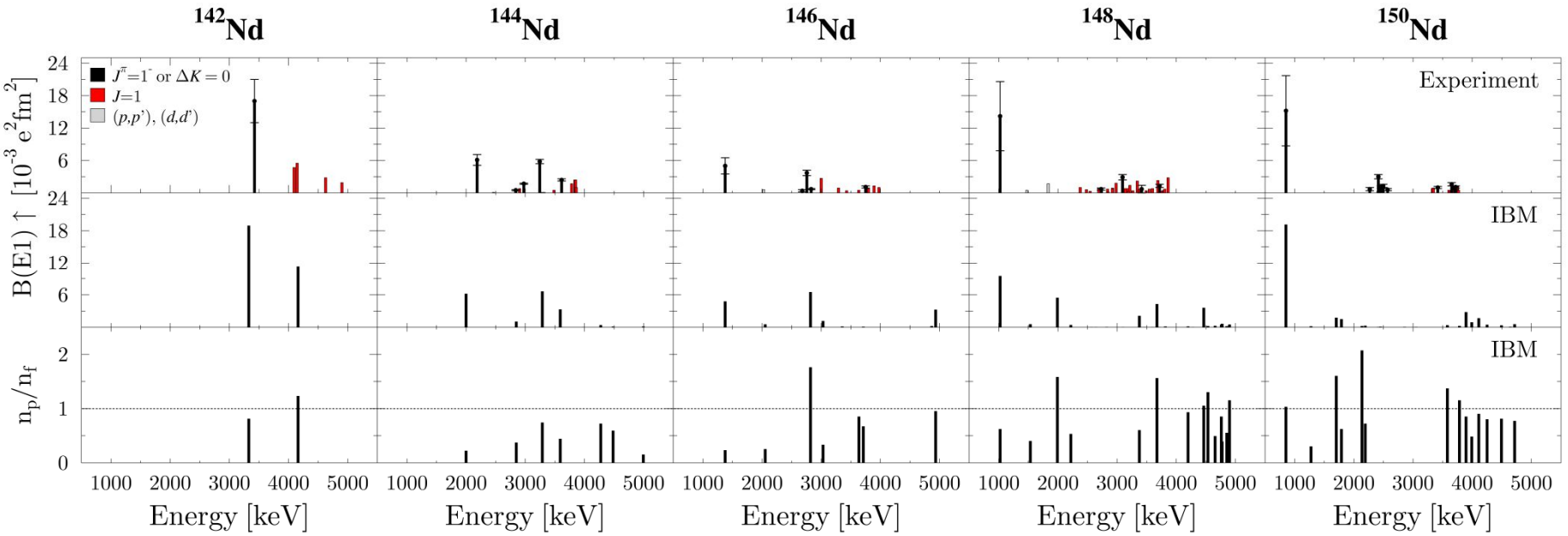


[MS, S. Pascu, A. Zilges, and F. Iachello, PRL **114**, 192504 (2015)]

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)]
[T. Eckert *et al.*, PRC **56**, 1256 (1997)]
[ENSDF, 2015]

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

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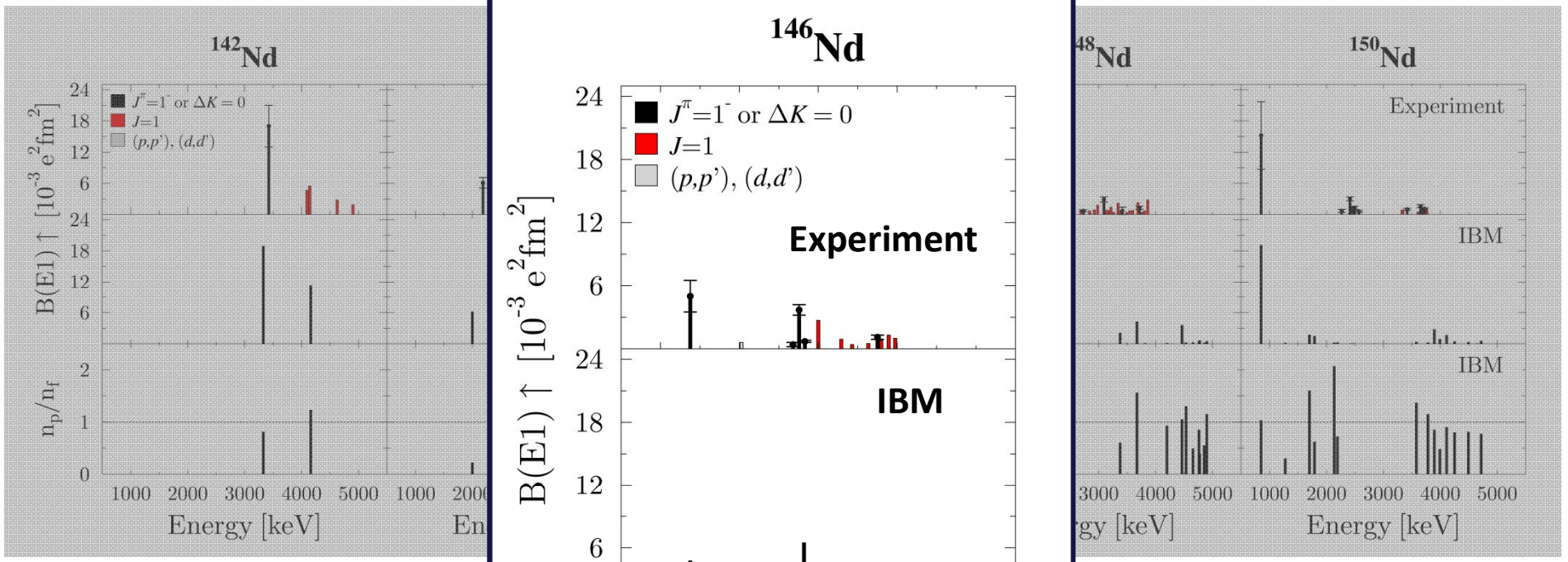

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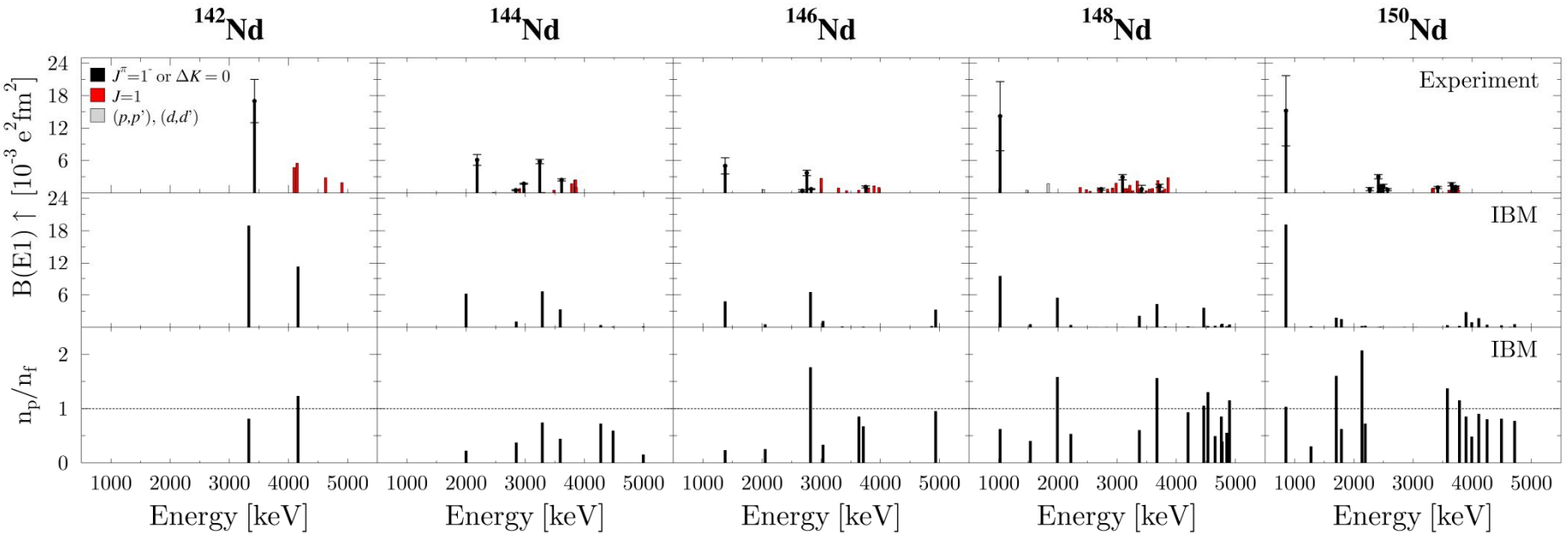

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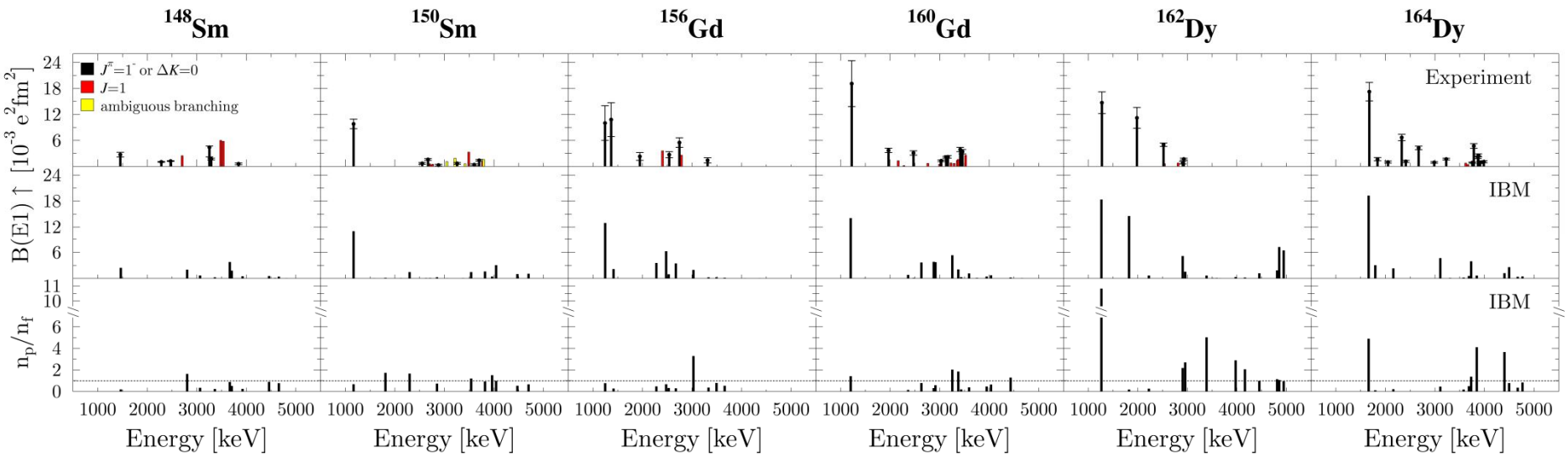
[ENSDF, 2015]

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]

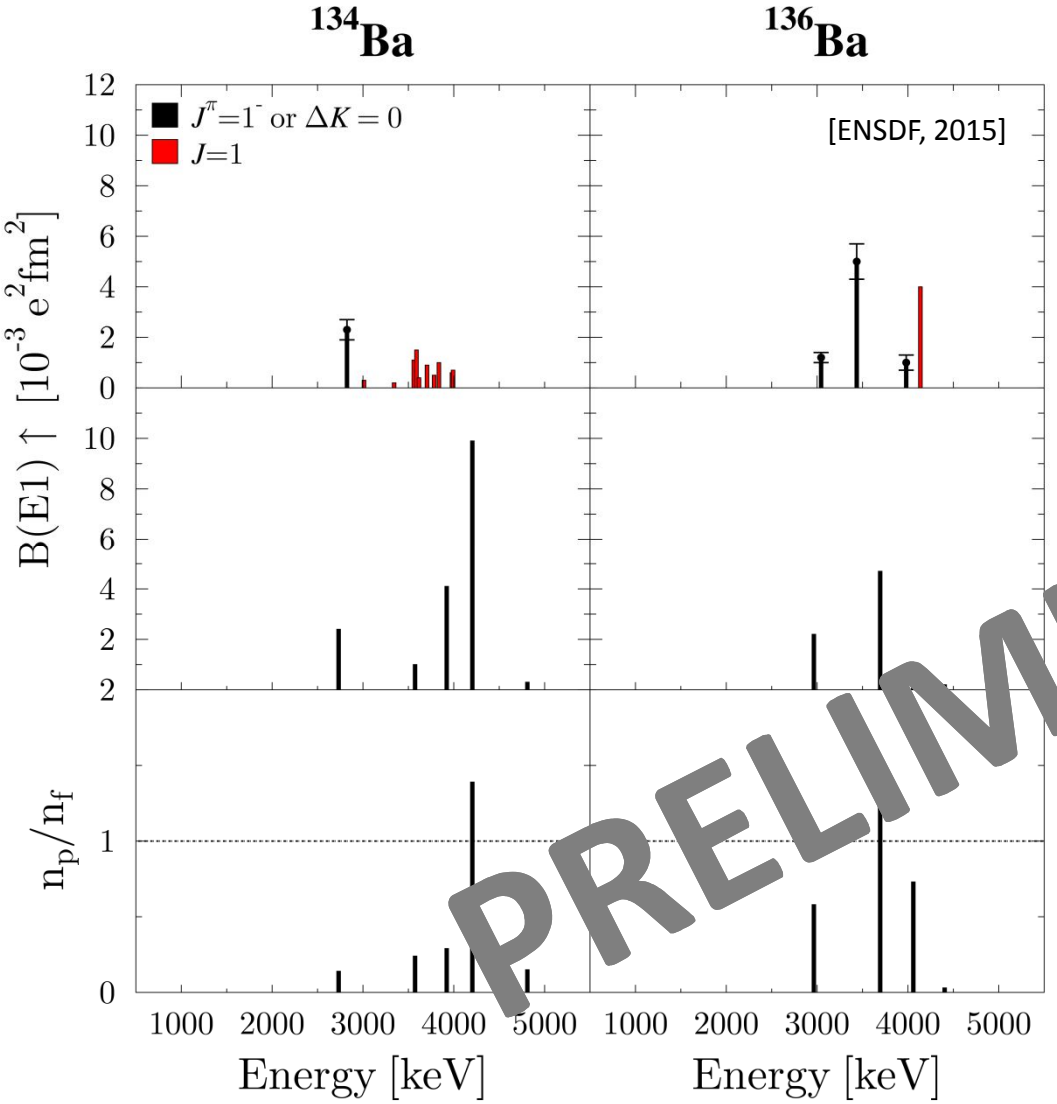
***sd*-IBM parameters for Dy:** [E.A. McCutchan *et al.*, PRC **69**, 064306 (2004)]
(Gd parameters similar)

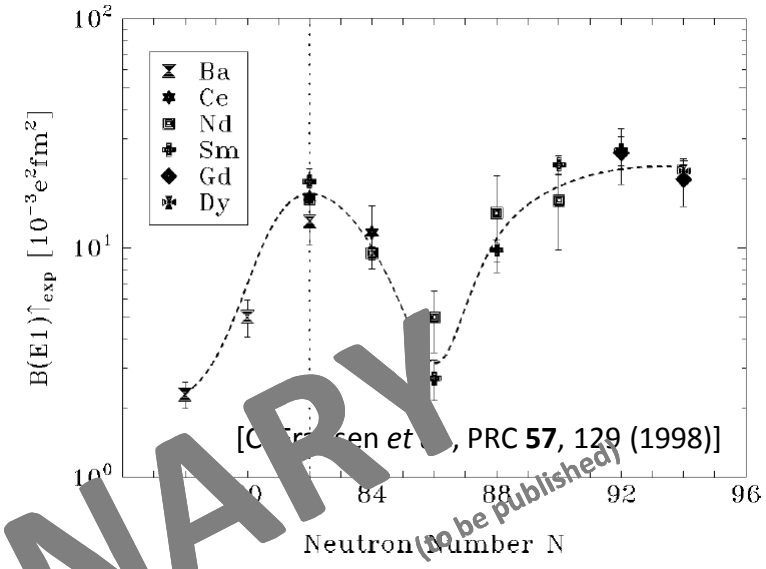
IBM Results: [MS, S. Pascu, A. Zilges, and F. Iachello, PRL **114**, 192504 (2015)]

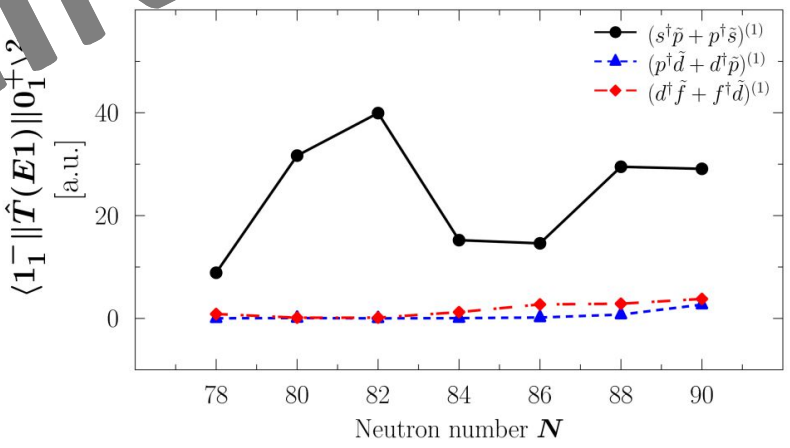
Results:

- *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

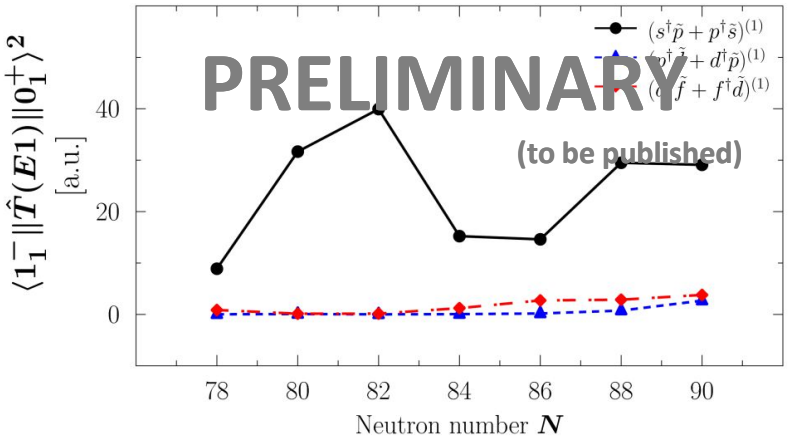


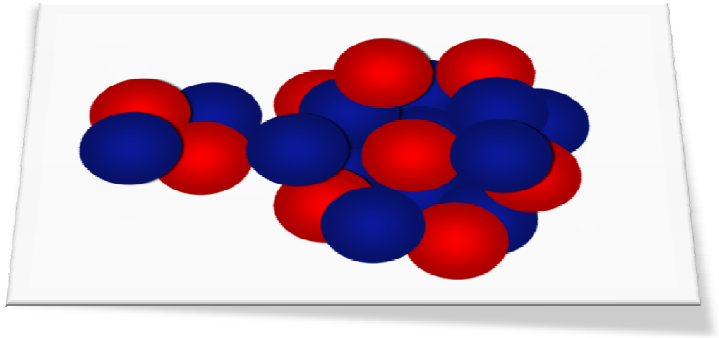




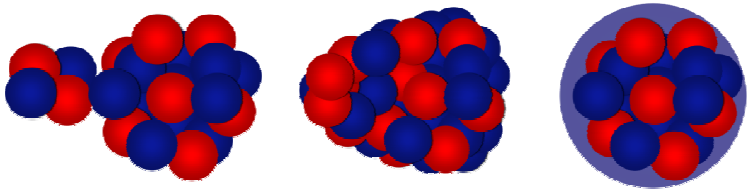
***sd*-IBM parameters:** [S. Pascu *et al.*, PRC **81**, 054321 (2010)]

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?