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

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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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... are there more generating mechanisms?

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Isospin-symmetry breaking in atomic nuclei

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

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

Two components:

- Quadrupole-octupole coupling (static/dynamic)
- $\alpha$-clustering mode

[F. Iachello, PLB 160, 1 (1985)]
Is clustering a general phenomenon in nuclei?

\[ \text{[J.-P. Ebran \textit{et al.}, PRC 90, 054329 (2014)]} \]
Low-lying $E1$ strength in rare-earth nuclei

$E1$ 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
  \[ \rightarrow \]  Parity of strongly excited states accessible ($E1$ or $M1$ excitation?)
- **$\gamma$-decay branching** of strongly excited states
  \[ \rightarrow \]  $K$ quantum number assignment ($\Delta K=0$ or $\Delta K=1$ excitation?)

Large experimental data base!

[C. Fransen et al., PRC 57, 129 (1998)]
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How to describe these two modes with one “simple” model?

[F. Iachello, PLB 160, 1 (1985)]
**Theoretical description of cluster configurations**

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

Theoretical description of cluster configurations

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

$\rightarrow$ *spdf* IBM to describe octupole mode and $\alpha$-clustering mode!

[M. Freer/University of Birmingham]
The interacting boson model (IBM)

- 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


M. Spieker, University of Cologne, AG Zilges  Origin of enhanced \( E1 \) strength in rare-earth nuclei
**E1 strength in Nd isotopes**

First 1- state:
- $p$-boson is responsible for parabolic evolution of the $E1$ strength!

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

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

- **sd-IBM parameters for Dy:**
  - (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

\[ \text{sd-IBM parameters: [S. Pascu et al., PRC 81, 054321 (2010)]} \]

\[ \text{[M. Spieker et al., to be published]} \]
**The nuclear *E1* response**

*E1* strength due to isospin-symmetry breaking

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

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**PDR:** D. Savran, T. Aumann, and A. Zilges, PPNP 70, 210 (2013)  
α clusters and the PDR?

... is there a cluster component in 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)]
[see also: S. Pascu et al., PRC 85, 064315 (2012)]
The diagram shows the behavior of $B(E1)$ and $B(E2)$ transition probabilities for $\alpha$ clusters in $^{140}$Ce. The panels on the left display the $B(E1)$ values as a function of energy, with $B(E1) \rightarrow 10^{-3}$ e fm$^2$. The panels on the right show the $B(E2)$ values in terms of $\sigma$ and $\gamma$ as a function of energy [D. Savran, T. Aumann, and A. Zilges, PPNP 70, 210 (2013)].

The question mark (?) indicates an area of interest, possibly related to the origin of enhanced $E1$ strength in rare-earth nuclei.

[S. Volz et al.]
[B. Löher et al.]
Experimental identification?

M. Spieker et al., to be published

(p,p'):
I. Poltoratska et al., PRC 85, 041304(R) (2012)

(17O,17O'):
F.C.L Crespi et al., PRL 113, 012501 (2014)
L. Pellegrini et al., PLB 738, 519 (2014)

(α,α'):
J. Endres et al., PRL 105, 212503 (2010)
Dipole $\alpha$ vibrations – a universal collective mode?

Centroid energy evolves smoothly as expected for a collective mode!

$E_x = 8.8(19) \cdot A^{-1/3} + 9.9(11) \cdot A^{-1/6}$

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

M. Spieker, University of Cologne, AG Zilges

Origin of enhanced $E1$ strength in rare-earth nuclei
Summary & open questions

- **Summary**
  - Possible signatures of an $\alpha$-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

- **Some open questions**
  - Theory:
    - Unambiguous correspondence of $sp$-IBM, i.e., $U(4)$ with cluster configurations?
      → Microscopic calculations including $4QP a priori, i.e., \(\alpha\)-particles needed!
  - Experiment:
    - Further experimental observables?
    - Parity of dipole states?
    - Link between deformed and spherical nuclei/ connection with PDR?
    - Is there a mass dependence?

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