α clustering and its connection to the $E1$ response of heavy 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

COMEX5
Krakow (Poland)

Supported by the DFG (ZI 510/4-2)

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)

The nuclear $E1$ response

$E1$ strength due to isospin-symmetry breaking

... are there more generating mechanisms?

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)
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?

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

[12C]

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

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

[Pictures: M. Freer/University of Birmingham]

M. Spieker, University of Cologne, AG Zilges

α clustering and the E1 response of heavy nuclei
Low-lying $E1$ 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?)
- **$\gamma$-decay branching** of strongly excited states
  → $K$ quantum number assignment ($\Delta K=0$ or $\Delta K=1$ excitation?)

Large experimental data base!

[C. Fransen et al., PRC 57, 129 (1998)]
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
  \[ \rightarrow \text{Parity of strongly excited states accessible (E1 or M1 excitation?)} \]
- **$\gamma$-decay branching** of strongly excited states
  \[ \rightarrow \text{K quantum number assignment ($\Delta K=0$ or $\Delta K=1$ excitation?)} \]

Large experimental data base!

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

How to describe these two modes with one “simple” model?
Clustering in atomic nuclei – $U(\nu+1)$

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

[12C]

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

[M. Freer/University of Birmingham]
Clustering in atomic nuclei – \( U(\nu+1) \)

**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 \( n \) = number of 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

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

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

[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

**$E1$ strength in Nd isotopes**

\[
\hat{T}(E1) = c_1 [\chi_{sp} (s^\dagger \tilde{p} + p^\dagger \tilde{s})^{(1)} + (p^\dagger \tilde{d} + d^\dagger \tilde{p})^{(1)} \\
+ \chi_{df} (d^\dagger \tilde{f} + f^\dagger \tilde{d})^{(1)}]
\]

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

[MS, S. Pascu, A. Zilges, and F. Iachello, PRL 114, 192504 (2015)]
E1 strength in Nd isotopes

$^{142}\text{Nd}$  $^{144}\text{Nd}$  $^{146}\text{Nd}$  $^{148}\text{Nd}$  $^{150}\text{Nd}$

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)]
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:
- M. S. Pascu, A. Zilges, and F. Iachello, PRL 114, 192504 (2015)
**E1 strength in Nd isotopes**

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

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)]
**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

M. Spieker, University of Cologne, AG Zilges

\[ ^{134}\text{Ba} \quad ^{136}\text{Ba} \]

\[ J^\pi = 1^- \text{ or } \Delta K = 0 \quad J = 1 \]

\[ \text{B(E1)} \uparrow \left[ 10^{-3} \text{ e}^{2}\text{fm}^2 \right] \]

\[ \frac{n_p}{n_f} \]

Energy [keV] \hspace{2cm} Energy [keV]

\[ 1000 \quad 2000 \quad 3000 \quad 4000 \quad 5000 \]

\[ 1 \quad 2 \quad 2 \quad 2 \quad 1 \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \]

\[ 10^0 \quad 10^2 \]

\[ \text{B(E1)}_{\text{exp}} \left[ 10^{-3} \text{ e}^{2}\text{fm}^2 \right] \]

Neutron Number N

80 \hspace{0.5cm} 84 \hspace{0.5cm} 88 \hspace{0.5cm} 92 \hspace{0.5cm} 96

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

\[ \alpha \text{ clustering and the } E1 \text{ response of heavy nuclei} \]

\[ \text{ENSDF, 2015} \]

\[ \text{C. Fransen et al., PRC 57, 129 (1998)} \]
Neutron-deficient rare earths – Ba isotopes

$^{134,136}$Ba

$B(E1)$ vs. Energy [keV]

$B(E1) \uparrow [10^{-3} e^2 fm^2]$

$J^\pi=1^+$ or $\Delta K = 0$

$J=1$

$\frac{n_p}{n_f}$

ENSDF, 2015

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

$\alpha$ clustering and the $E1$ response of heavy nuclei

M. Spieker, University of Cologne, AG Zilges
The nuclear $E1$ response

$E1$ strength due to isospin-symmetry breaking

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

... are there more generating mechanisms?
... is there a cluster component in the PDR?
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)]
α clusters and the PDR?

\[ \frac{d\sigma}{d\Omega} \text{ [mb/s]} \]

\[ B(E1) \text{ [10}^{-3} \text{ e}^2 \text{fm}^2] \]

\[ n_p/n_f \]

\[ J^T = 1^- \]

\[ J = 1 \]

[S. Volz et al.]
[B. Löher et al.]

\[ ^{140}\text{Ce} \]

\[ \alpha, \alpha', \gamma \]

\[ \gamma, \gamma' \]

[ppnp 70, 210 (2013)]

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

$^{208}$Pb

$\sigma_{(d,p)}$ [µb]

$B(E1) \uparrow$

$[10^{-3} e^2$ fm$^2]$}

$\frac{d\sigma}{d\Omega}$ [mb/sr]

Energy [keV]

(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. Pellegrin et al., PLB 738, 519 (2014)

($\alpha$,\xspace$\alpha'$): J. Endres et al., PRL 105, 212503 (2010)

$^{124}$Sn($\alpha$,$\alpha'\gamma$)

Rel. Str. 1

5-7 7-9 MeV

$^{124}$Sn($^{17}$O,$^{17}$O$'$)$\gamma$)

Rel. Str. 1

5-7 7-9 MeV

$^{124}$Sn($\gamma$,$\gamma'$)

Rel. Str. 1

5-7 7-9 MeV

preliminary
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]
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
  - [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?
    - \[ \rightarrow \text{Microscopic calculations including 4QP } a \text{ priori, } i.e., \alpha\text{-particles needed!} \]

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

---

Connection of different modes?