α clustering and its connection to the $E_1$ response of heavy nuclei

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Abstract. The generation of the collective nuclear $E_1$ response is intimately connected to the breaking of proton-neutron symmetry. In this contribution, we present our recent results on a possible $\alpha$-cluster dipole mode, which were obtained in the framework of the $spdf$ interacting boson model. These extended studies of the low-lying $E_1$ response support the general occurrence of $\alpha$-cluster dipole states in atomic nuclei.

1. Introduction

The generation of the collective nuclear $E_1$ response is intimately connected to the breaking of proton-neutron symmetry. Especially the low-lying $E_1$ strength (LES) or so-called pygmy dipole resonance (PDR), a dipole-strength accumulation below and around the particle-emission thresholds has attracted a lot of interest during the last two decades, see the review articles [1, 2]. Besides other generating mechanisms, the dipole-type oscillation of the neutron-skin has been discussed frequently. Of course, it is interesting to ask the question, whether other mechanisms can account for the experimental systematics. In this contribution, the $\alpha$-cluster dipole mode will be discussed, which was investigated in the framework of the $spdf$ interacting boson model (IBM). First results for the low-lying $E_1$ strength in rare-earth nuclei have already been presented and a close connection of the origin of $E_1$ strength with the collective $p$ boson was established [3]. The $p$ boson is geometrically identified with a two-body cluster configuration, see, e.g., Refs. [4, 5], where the $\alpha + (A-4)$ configuration might be considered as the energetically most favored. Therefore, a successful extension of the rare-earth studies to other regions of the nuclear chart might help to establish the $\alpha$-cluster dipole mode as a possible generator of collective $E_1$ strength and, furthermore, contribute to the question as to whether $\alpha$ clustering is a general feature of atomic nuclei.

2. The $spdf$ interacting boson model (IBM)

The full one-body $E_1$ operator of the $spdf$ IBM [6] was adopted to calculate $E_1$ transitions.

$$
\hat{T}(E_1) = e_1 [\chi_{sp} (s^\dagger \tilde{p} + p^\dagger \tilde{s})^{(1)} + (p^\dagger \tilde{d} + d^\dagger \tilde{p})^{(1)}] + \chi_{df} (d^\dagger \tilde{f} + f^\dagger \tilde{d})^{(1)}$$

(1)
and the spd f further strengthens the claim of Ref. [3], that $E_{100}$ nuclei. In this contribution, the examples of $A < 40$ for $\alpha$ fragmentation and total strength for experimentally firmly assigned $1^-$ to disentangle the different structures of the $1^-$ states. The general agreement in terms of $B(E1)$ strength could serve as a sensitive measure for $\alpha$ clustering and might, thus, support the general occurrence of $\alpha$ clustering in nuclei. In

![Figure 1. The origin of $E1$ strength in the $N = 78 - 90$ nuclei of the rare-earth region. (a) Respective contributions to the $(1^+ \parallel T(E1)\parallel 0^+)2$ matrix element predicted by the IBM with Eq. (1). (b) Experimental data taken from Refs. [7, 8]. Note that the same experimental states have been chosen in (b) as in the original figure of Ref. [8].](image)

This operator allows in a very intuitive manner for a clear identification of the most important matrix elements. In the rare-earth nuclei, the $(s^1p + p^1s)1^+$ matrix element could be identified as the most collective and accounted in a natural way for the evolution of the experimental $B(E1; 1^+ \rightarrow 0^+_1)$ strength. The other matrix elements evolved as expected for decreasing quadrupole deformation when approaching the $N = 82$ shell closure. The results are shown in Fig. 1. Note, that the spd f IBM allows for the discrimination of $p$ boson and $df$-coupled $1^-$ states in terms of the $n_p/n_f$ ratio, which is a measure for the $p$-boson and $f$-boson content of the wave function, respectively. Furthermore, the mixing between these different structures can be accessed. See Ref. [3] for more information.

3. The low-lying $E1$ response of $A < 100$ nuclei
As pointed out in the introduction, it is very interesting to test if the conclusions of the rare-earth region [3] could be extended to other mass regions. For this test, the three nuclei $^{48}$Ti, $^{74}$Ge, and $^{94}$Mo have been chosen. While, on the one hand $^{48}$Ti is located between the $N = 20$ and $N = 28$ shell closures with a quadrupole deformation parameter $\beta_2$ of about 0.25 [9], $^{74}$Ge, on the other hand, is on the edge of the transition from a $\gamma$-soft to a $\gamma$-rigid nucleus [10, 11]. Furthermore, the vibrational nucleus $^{94}$Mo has been the prime laboratory for so-called mixed-symmetry states for decades, see, e.g., the review [12], and an $\alpha + (A - 4)$ structure has already been discussed [13]. For all these nuclei extended information on the $E1$ response up to the particle-emission thresholds is available [7, 14, 15, 16].

The comparison of the experimental data and the IBM predictions for the $B(E1)$ strength is shown in Fig. 2. As in the case of the rare-earth nuclei, the $n_p/n_f$ ratios were also studied to disentangle the different structures of the $1^-$ states. The general agreement in terms of fragmentation and total strength for experimentally firmly assigned $1^-$ states is encouraging. Strong $p$-boson states are observed in all three nuclei. These are states, for which $n_p/n_f$ exceeds one. In contrast to some rare-earth nuclei, very large ratios are observed, which might point at less fragmented $\alpha$-cluster structures.

4. Conclusion
Our studies of enhanced $E1$ strength due to an $\alpha$-cluster dipole mode have been extended to $A < 100$ nuclei. In this contribution, the examples of $^{48}$Ti, $^{74}$Ge, and $^{94}$Mo were presented and the spd f IBM was able to account for the $E1$ strength distribution as in the case of the rare-earth region. The general applicability of the model to the $E1$ strength of atomic nuclei further strengthens the claim of Ref. [3], that $E1$ strength could serve as a sensitive measure for $\alpha$ clustering and might, thus, support the general occurrence of $\alpha$ clustering in nuclei. In
Figure 2. $E_1$ distribution in $^{48}$Ti, $^{74}$Ge, and $^{94}$Mo. The experimental data have been taken from Refs. [7, 14, 15, 16]. Firm spin-parity assignments in black, while ambiguous assignments are presented in red.

the future, our studies will be extended and more experimental $E_1$ data will be considered. To this end, the isoscalar $E_1$ strength constitutes another very promising probe for $\alpha$ clustering [17].

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References
[1] Savran D, Aumann T and Zilges A 2013 Prog. Part. Nucl. Phys. 70 210
[2] Bracco A, Crespi F C L and Lanza E G 2015 Eur. Phys. J. A 51 99
[3] Spieker M, Pascau S, Zilges A and Iachello F 2015 Phys. Rev. Lett. 114 192504
[4] Iachello F and Jackson A D 1982 Phys. Lett. B 108 151
[5] Daley H and Iachello F 1983 Phys. Lett. B 131 281
[6] Kusnezov D F 1988 Nuclear Collective Quadrupole-Octupole Excitations in the U(16) spdf Interacting Boson Model, PhD Thesis, Princeton University
[7] NNDC Online Data Service, ENSDF database, 2016 http://www.nndc.bnl.gov/ensdf/
[8] Fransen C et al 1998 Phys. Rev. C 57 129
[9] Pritychenko B, Birch M, Singh B and Horoi M 2016 At. Data Nucl. Data Tables 107 1
[10] Toh Y et al 2013 Phys. Rev. C 87 041304
[11] Sun J J 2014 Phys. Lett. B 734 308
[12] Pietralla N, von Brentano P and Litsetskiy A 2005 Prog. Part. Nucl. Phys. 60 225
[13] Souza M A and Miyake H 2015 Phys. Rev. C 91 034320
[14] Degener A et al 1990 Nucl. Phys. A 513 29
[15] Jung A et al 1995 Nucl. Phys. A 584 103
[16] Romig C et al 2013 Phys. Rev. C 88 044331
[17] Chiba Y, Kimura M, Taniguchi Y 2016 Phys. Rev. C 93 034319