Electromagnetic transitions as a probe of clustering in nuclei

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Abstract. Clustering in nuclei is traditionally explored through reaction studies but observation of electromagnetic transitions can be of high value in establishing, for example, that highly-excited states with candidate cluster structure do indeed form rotational sequences. A topical example is given of the identification of a candidate super deformed band in ^{28}Si where super deformation in this nucleus has been described as originating from ^{24}Mg+α clustering.

1. Introduction

Alpha-clustering is often suggested in various alpha-conjugate light nuclei on the basis of the location of excited states which appear to form rotational sequences from their energy spacing. Confirmation of such assignments and a deeper understanding of the clustering phenomenon can only come, however, from observation of electromagnetic transitions connecting these states, or indeed electromagnetic transitions between these cluster states and excited states of standard shell model character. Unfortunately, there are very few cases where this has been done in practice. The best example, perhaps, where clustering is observed even in the ground state is the case of ^{8}Be. Datar *et al* carried out a "brute-force" determination of the $4^+ \rightarrow 2^+$ transition strength in ^{8}Be in an experiment at the Tata Institute for Fundamental Research in Mumbai [1]. The measurement comprised a coincidence between a detected gamma ray in an array of BGO detectors with alpha particles from the break-up of the 2^+ state in ^{8}Be. The B(E2) value obtained is 25(8) e^2fm^4. This value is consistent with the predictions of both *ab initio* and cluster model calculations. Recently, Freer *et al* [2] reported the possible existence of a 2^+ state at 9.6(1) MeV in ^{12}C with a width of 600(100) keV. It is argued that this state corresponds to the first member of the rotational band built on the Hoyle state. Locating this state was extremely challenging as it sits underneath an extremely broad 0^+ state at 10.3 MeV. The observation of an E2 transition connecting this 2^+ state to the 0^+ "Hoyle" state and measuring its transition strength would be sensational as it would provide extremely important information regarding the nature of the "Hoyle" state. It would, however, be extremely difficult to realise as the gamma width might be expected to be of the order of 10^{-5} of the width of the state.

In this paper, we describe a recent example where the observation of electromagnetic transitions was studied as a means of probing clustering behaviour in nuclei, specifically, in the context of super deformed bands in light nuclei.

2. Candidate superdeformed band in ^{28}Si

Superdeformed (SD) states in nuclei were first reported in rare-earth isotopes like ^{152}Dy [3], and were later found to exist in several mass regions, including those with A$\sim$150, A$\sim$130, and A$\sim$190 [4, 5]. The identification of these weakly-populated, highly-excited structures came about through a step-change in technology with the advent of highly-segmented, high-resolution gamma-ray detector arrays. These same techniques led to the discovery around ten years ago, of SD bands in the light, alpha-conjugate nuclei, ^{36}Ar [6] and ^{40}Ca [7]. These form fascinating examples of superdeformation since complementary descriptions can be found in terms of particle-hole excitations in the shell model [8, 9], and α-clustering configurations within various cluster models [10, 11, 12]. Key theoretical questions center on whether the clustering is a real feature of the system, or whether it simply corresponds to the appearances but is not a true physical description. In addition, a major question is how such clustered configurations evolve into deformed ones. It is particularly important to locate SD bands in lighter, alpha-conjugate nuclei such as ^{32}S and ^{28}Si for which long-standing theoretical predictions exist and which continue to attract the interest of theory. Recent examples of theory initiatives in this area include AMD calculations for ^{28}Si [13] and ^{32}S [14], and macroscopic-microscopic calculations for both nuclei [15]. In all cases, it is predicted that the SD bands in ^{28}Si and ^{32}S should lie at high excitation energy; *i.e.*, with bandheads around 10 MeV. This has two consequences in terms of the challenge in identifying such states experimentally: firstly, phase space favours high-energy, out-of-band transitions compared to low-energy, in-band ones despite the strong collective character of the latter. Secondly, the bandhead lies on or above the particle-decay threshold meaning that there is competition with particle emission.

Recently, Taniguchi *et al* [13] carried out an extensive study of collective structures in ^{28}Si using the AMD model. They explore clustering degrees of freedom of the type: ^{24}Mg+α and ^{12}C+^{16}O. These studies reveal a rich diversity of rotational behaviors. An SD band is identified in the AMD calculations [13] with a strong ^{24}Mg+α configuration as well as some ^{12}C+^{16}O component. Such a cluster configuration for the SD minimum is supported by recent macroscopic-microscopic potential-energy surface calculations for ^{28}Si [15] as well as by Nilsson model calculations. The AMD calculations [13] suggest that the SD band should have a moment of inertia $\mathcal{J}^{(1)} \approx 6\ \hbar^2/MeV$, related to the large associated deformation, $\beta_2 \approx 0.8$. It is difficult to identify experimental counterparts for the predicted SD states. Taniguchi *et al* [13] compare their predictions for the SD band in ^{28}Si with the properties of a so-called "excited prolate" band identified in the early 1980s by Kubono *et al* [16] using the ^{12}C(^{20}Ne,α)^{28}Si reaction. The experimental assignment of this "excited prolate" band rests on peaks in a charged-particle spectrum, and many of the associated states do not have well-established spin/parity. As shown by Taniguchi *et al* [13], the states identified by Kubono *et al* [16] do not form a smooth sequence characteristic of a rotational band even when making plausible allowance for mixing, and the suggested moments of inertia are higher than the calculated values. Moreover, γ-ray transitions between these states are not observed, and, consequently, transition strengths are unknown. Without the observation of in-band transitions, assigning candidate rotational bands is difficult and potentially ambiguous, although such an approach has been a common procedure in the past for "cluster" bands in light nuclei.

The fact that both recent AMD [13] and other [15, 17] calculations suggest that the SD band in ^{28}Si should have a strong ^{24}Mg+α component, raises the question as to whether the ^{24}Mg(α,γ) radiative capture reaction might prove to be a favoured one to selectively populate SD states in ^{28}Si. Such a possibility was not considered by Taniguchi *et al* [13], but a detailed review of the literature suggests, in fact, that plausible candidates for SD states may already exist. In a series of articles, Brenneisen *et al* [18] collate data from studies they carried out with the ^{27}Al(p,γ)^{28}Si and ^{24}Mg(α,γ)^{28}Si reactions. Of the large number of states identified in this systematic study, a number stand out as having unusual characteristics. In particular, a 6^+ state at 12.86 MeV is identified which is populated in the (α,γ), but not in the (p,γ) reaction. This 12.86-MeV level has decay branches to a number of states including a 4^+ state at 10.945 MeV, via a 1.921-MeV transition. The observation of a relatively intense, low-energy E2 transition, in competition with high-energy γ rays, immediately suggests that it must have a large transition strength. Brenneisen *et al* [18] infer that $(2I+1)\Gamma_\gamma > 0.37$ eV for the 12.86-MeV state which means that the transition to the 10.945-MeV level has an associated B(E2) value exceeding 25 Wu [18]. The unusual character of the 10.94-MeV and 12.86-MeV states becomes clear in conjunction with other work such as the ^{12}C(^{20}Ne,α)^{28}Si reaction studied by Kubono *et al* [16]. In particular, the 10.94-MeV state is the most strongly populated level below 12 MeV (see Figure 1 (a) of Ref. [16]), and it is populated with more than ten times the cross-section of the 4^+ levels in the prolate and oblate ground-state bands. A ^{24}Mg(^{6}Li,d) reaction by Tanabe *et al* [19] also shows a remarkably similar spectra of states with selective population. Again, the 10.94-MeV level is the most strongly populated one below 12 MeV, exceeding the cross-section to the other 4^+ levels by a similar factor. These observations taken together would suggest that the 10.94-MeV state has a dominant ^{24}Mg+α configuration. Indeed, it is interesting to consider this in the light of studies of the ^{32}S(^{12}C,α) reaction by Middleton *et al* [20], where the 0^+ state attributed to the 4p-4h configuration is excited ten times more strongly than the level associated with the 0p-0h configuration. The 8p-8h level is excited 1.5 times more strongly than the 4p-4h one. Indeed, the state most strongly excited in this reaction is at 7.98 MeV in ^{40}Ca which has later been shown to correspond to the 6^+ member of the SD band based on the 8p-8h configuration [7].

A state at 12.8 MeV is strongly excited in both the ^{12}C(^{20}Ne,α)^{28}Si [16] and ^{24}Mg(^{6}Li,d) reactions [19]. Analysis of angular correlations in the ^{12}C(^{20}Ne,α)^{28}Si reaction provides a firm assignment of 6^+ to a 12.8-MeV state [16]. This level is also shown to have a direct proton branch to the $5/2^+$ ground state of ^{27}Al [16], implying L = 4 decay and, hence, there must be an associated $g_{9/2}$ component. This is estimated by Kubono *et al* [21] as corresponding to a spectroscopic factor for the $g_{9/2}$ component of S = 0.3. This result is reinforced by a parallel ^{24}Mg(α,t) study by Kubono *et al* [16, 21] which also indicated a sizable $g_{9/2}$ component in the 12.82-MeV state. In this scenario, a consistent picture emerges where the candidate intruder states discussed by Brenneisen *et al* [18] appear with unusual selectivity in the ^{12}C(^{20}Ne,α)^{28}Si reaction, and with the suggestion of strong deformation, in the case of the 12.86-MeV state.

3. Gammasphere study

Confirmatory information on the presence of candidate super deformed states in ^{28}Si has recently been obtained from analysis of a data-set related to a γ-ray spectroscopy study where ^{28}Si was one of the main channels [22]. The original objective of the experiment was, in fact, the study of mirror symmetry in ^{31}S and ^{31}P, for which results were published some years ago [23]. Excited states in ^{28}Si were populated via the ^{12}C(^{20}Ne,α) reaction using a 32-MeV ^{20}Ne beam from the ATLAS accelerator at Argonne National Laboratory. A self-supporting ^{12}C target of 90 μg/cm^2 was bombarded with a 40 pnA ^{20}Ne beam for a period of two days. The resulting γ decays were detected by Gammasphere, an array of 100 Compton-suppressed germanium detectors [24]. The array was operated in stand-alone mode with a trigger condition of two or more coincident γ rays. Since evaporated alpha particles were not detected, γ rays associated with ^{28}Si were strongly Doppler-broadened, but the use of high-fold coincidence data still permitted a level scheme for ^{28}Si to be produced from the analysis of a γ-γ matrix and a γ-γ-γ cube. The analysis confirms the location and decay branching of the candidate states in the intruder band identified by Brenneisen *et al* [18] (see figure 1).

4. Conclusions and future work

In conclusion, observation of electromagnetic transitions is of high value in probing clustering in nuclei. A concrete example is given of the identification of candidate super deformed states

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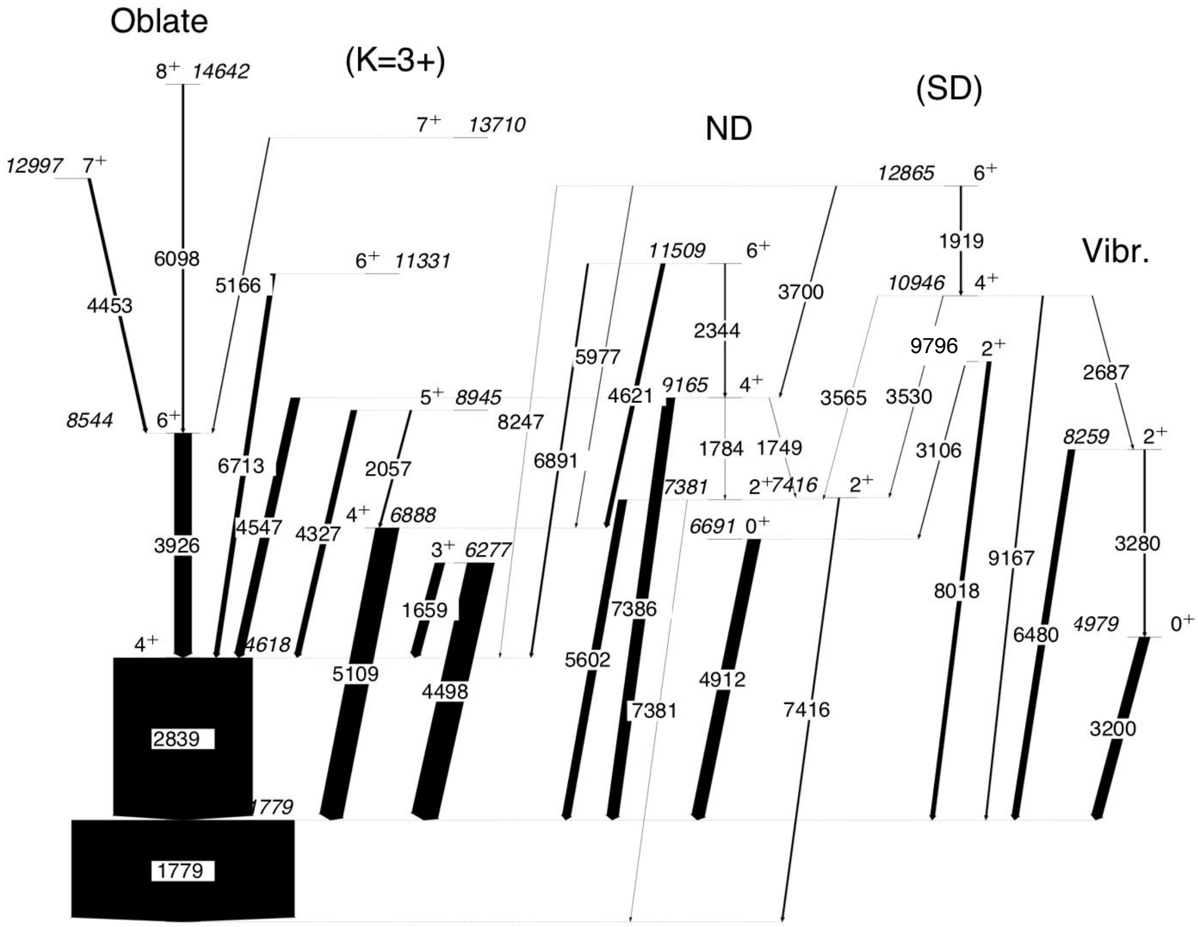

Figure 1. Subset of positive-parity levels in ^{28}Si derived from the analysis of the Gammasphere dataset . Excited states and transition energies are labeled with their energy in keV, while the width of the arrows corresponds to the relative intensity of the observed transitions. The different structures are labeled according to previous assignments as oblate, prolate (ND), vibrational and with different K values.

in ^{28}Si which find various theoretical descriptions including alpha cluster models. Important questions remain outstanding, however. It would be highly desirable to obtain, for example, a precise value for the B(E2) strength of the $6^+ \rightarrow 4^+$ transition rather than a lower limit as at present. It would also be important to locate additional states in such a band and indeed, complete a study of high spin states in ^{28}Si. An experiment is approved at iThemba laboratory and will take place in May 2013. In this experiment, the ^{12}C(^{20}Ne,α)^{28}Si reaction originally employed by Kubono *et al* [16] will be used to produce high spin states in ^{28}Si with selectivity for the candidate super deformed band. The K600 spectrometer at iThemba will be used to detect the reaction alpha particles at zero degrees as a means of selecting the ^{28}Si states of interest. The particle decay of highly-excited states will be examined with a silicon detector system around the target position, while a very large sodium iodide detector and germanium detectors will be used to detect the gamma-ray decay of these states. It is hoped that this experiment may shed fresh light on high spin behaviour and alpha-clustering in ^{28}Si.

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