A focus on shape coexistence in nuclei

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Editorial

A focus on shape coexistence in nuclei

Abstract

The present collection of articles focuses on new directions and developments under the title of shape coexistence in nuclei, following our 2011 *Reviews of Modern Physics* article (K Heyde and J L Wood).

(Some figures may appear in colour only in the online journal)

This collection of articles originated following an invitation extended to JLW from the Institute of Physics to edit a focus issue. The topic of 'shape coexistence in nuclei' was chosen, in discussions between the two of us, in recognition of the significant advances made since our review, completed in 2011 [1]. The authors that we invited to contribute to this focus issue, and to some degree the topics, are the result of where we perceived that significant activity has occurred since 2011. Any failings in the coverage of the focus topic are ours.

The origin of the topic of shape coexistence in atomic nuclei can be well localized to a paper by Haruhiko Morinaga, published in 1956 [2]. In this paper he makes an interpretation of the first excited state in ^{16}O, and its unexpected spin-parity of 0^+, to invoke a multi-nucleon cross-shell excitation with the property that it is deformed. The topic took a surprisingly long time to influence other investigations of nuclear structure. It was not until 1964 that Gerry Brown used Morinaga's idea in an application to a similar state in ^{40}Ca. Our own engagement in the exploration of the topic came about through a meeting in 1978 (in Erice, Sicily) and a discussion of the nature of intruder states in the odd-mass Tl isotopes, see figure 1. This led to our first review in 1983, in collaboration with Michel Waroquier, Piet van Isacker, and Dick Meyer [3]. In this review, which was focused on shape coexistence and intruder states in odd-mass nuclei, we undertook to document the early history of the topic in light-mass, even–even nuclei.

Already, by the time that we carried out our work on the first review, shape coexistence was emerging in the neutron-rich, $N = 20$ region and the neutron-deficient, Hg region. These results depended on the production of highly unstable isotopes and their study 'on-line', which was pioneered at the ISOLDE Facility at CERN in Geneva. An important component of these studies was the determination of ground-state properties, namely masses and differences in mean-square charge radii (isotope and isomer shifts). Isotope shifts have played a very important role in the discovery of shape coexistence through the appearance of sudden changes that herald the intrusion of strongly deformed configurations to dominate ground state structures. The rare determination of isomer shifts provided essentially direct demonstration of shape coexistence.

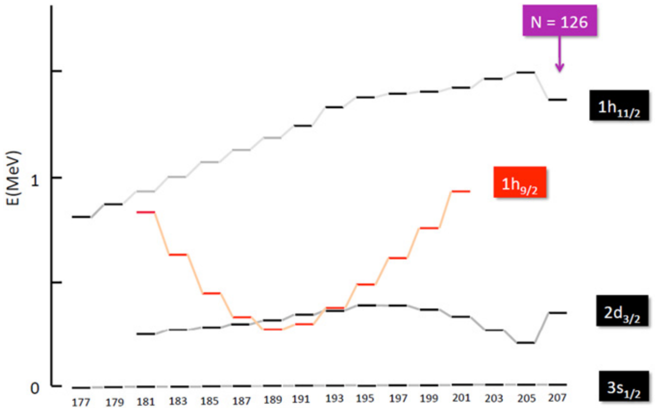

Figure 1. Systematics of the 1h$_{9/2}$ proton intruder states in the odd-mass Tl isotopes. The appearance of this structure below the 1h$_{11/2}$ proton hole state indicates that the correlation energies possessed by the intruder structure dominates over the spin–orbit interaction energy. The complex nature of intruder states is often not recognized with the result that they are erroneously described as examples of the breakdown of the independent-particle shell model. The data are taken from the Evaluated Nuclear Structure Data File.

The challenge of detailed nuclear structure studies in nuclei far from stability is the often-limited information attainable. This has resulted in slow progress in the elucidation of the occurrence and nature of shape coexistence in nuclei. A particularly difficult region has been the nuclei centered on ^{32}Mg (the neutron-rich, $N = 20$ region). It has been termed ‘the island of inversion’ [4], an example of the ‘collapse’ of the shell model or a ‘melting of shells’ [5]. There was the suggestion of a unified view of intruder states and shape coexistence in this region [6] and a shell model description that invoked correlated multi-particle-multi-hole excitations [7]; but this region of shape coexistence has remained rather isolated, conceptually.

The isolated nature of the regions where shape coexistence emerges reflected the fact that it took a long time to recognize that there was a unified view of the topic, even at the time of our second review in 1992, in collaboration with Witek Nazarewicz, Mark Huyse, and Piet van Duppen [8]. This review was focused on shape coexistence in doubly even nuclei, but did not offer a systematic connection to manifestations in odd-mass nuclei. However, some regions were beginning to reveal extended sets of shape coexisting structures, in particular the neutron-deficient Pt, Hg, Pb isotopes. This came about, again, with important contributions from on-line isotope separator facilities, especially ISOCELE in Orsay, LISOL in Louvain-la-Neuve (KU Leuven Group), and UNISOR in Oak Ridge.

The deployment of large arrays of gamma-ray detectors, starting with the TESSA array in Daresbury and leading to Gammasphere, Euroball, and their successors, extended the concept of shape coexistence in nuclei to ‘superdeformed’ bands, observed mainly at high spin. Unfortunately, this topic has evolved in an essentially decoupled mode from shape coexistence at low spin. But, with techniques such as recoil-decay tagging, most notably as carried out in Jyväskylä, extreme limits of regions of shape coexistence have been probed using large arrays of gamma-ray detectors, as shown in figure 2.

Shape coexistence had rather ‘quietly’ been emerging in stable isotopes such as the region around ^{42}Ca/^{43}Sc and ^{72}Se. It appeared dramatically in ^{112,114,116,118}Sn with work by

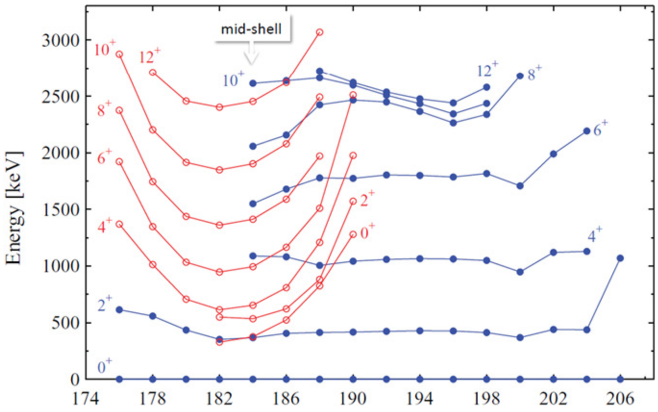

Figure 2. Systematics of low-lying states in the even-mass Hg isotopes. This is shown to illustrate the clear 'parabolic' trend in the pattern of excitation energy of the shape coexisting structures and the similarity to the excitation energy of the intruder structures in the odd-Tl isotopes. The figure is adapted from [10] with permission.

Bron *et al* using the cyclotron at the Vrije Universiteit, Amsterdam. But already there were clues from 10 years earlier in odd-mass In isotopes, from studies by Anders Bäcklin, Birger Fogelberg, and S.G. Malmskog (Uppsala-Studsvik collaboration) that shape coexistence was occurring in the Z = 50 region.

In 2011 we published our third review on shape coexistence in atomic nuclei [1]. We attempted a more unified view of the subject. In so doing, it became evident (at least to us) that shape coexistence probably occurs in (nearly) all nuclei. Thus, in our 30-plus year engagement with the topic, we moved from 'exotic rarity', through 'isolated regions of occurrence', to 'universal occurrence'. It remains to be seen whether or not this view is correct. However, we point to a model, the symplectic shell model [9], where shape coexistence emerges naturally and universally. We also note that constrained mean-field methods are now demonstrating remarkable predictive power for coexisting shapes in nuclei. We further note that large-scale shell model calculations in lighter nuclei are revealing the way that collective structures result.

A feature of shape coexistence that potentially could seem puzzling is the lack of examples for some closed shell regions, particularly N = 82. This appears to be due to the occurrence of a subshell gap at Z = 64. This suppresses the intrusion of shape coexisting configurations such that they do not appear at low energy. By now, this has been demonstrated at N = 50 and Z = 28 as resulting from the N, Z = 40 subshell gaps. It is also occurring at N = 20, because of a Z = 14 subshell gap. Indeed, as we undertook to illustrate in the 2011 review, subshells appear also to support shape coexistence by the same mechanism as major shells, as illustrated in the Z = 40, N = 56 region.

We chose the topics and the invited authors for this Focus Issue on the basis of where new and promising directions are apparent from the recent literature. The balance between theory and experiment is about 50:50. On the theory side, the remarkable advances in mean-field methods and beyond and the increased understanding of how collective structures arise from a nuclear shell-model approach caused us to contact all of the theory groups engaged in exploration of shape coexistence at low spin and low energy.

We were strongly influenced by those colleagues with whom we have had contact, especially those with whom we have collaborated. Some colleagues declined with reasons such as 'nothing new right now' or 'too busy'. We apologize to those who feel that they should have had their say. To younger colleagues we would say 'We have reached the end of the beginning, now begins the middle'. There is an enormous amount of work to be done. Mainly, it is detailed, systematic investigation. We trust that this Focus Issue will inspire the next generation to fully explore what appears to be a fundamental feature of nuclear structure. With some confidence the two of us can say that we will not be writing a fourth review.

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