Nuclear shapes studied with low-energy Coulomb excitation

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Abstract. Coulomb excitation is one of the rare methods available to obtain information on static electromagnetic moments of short-lived excited nuclear states, including collective non-yrast levels. It is thus an ideal tool to study shape coexistence and shape evolution throughout the nuclear chart. Historically, these experiments were limited to stable isotopes, however the advent of new facilities, providing intense beams of short-lived radioactive species, has opened the possibility to apply this powerful technique to a much wider range of nuclei. Here, we present some recent complex Coulomb-excitation studies and use the example of superdeformed states in ^{42}Ca to demonstrate the sensitivity of the method to second-order effects such as relative signs of electromagnetic matrix elements and quadrupole moments.

1 Introduction

One of the most fundamental properties of the atomic nucleus is its shape, which is governed by the interplay of macroscopic, liquid-drop like properties of the nuclear matter and microscopic shell effects. While closed-shell nuclei always exhibit spherical shapes in their ground states, nucleons residing in open shells tend to deform the mass distribution, with quadrupole deformation being the most important degree of freedom. In some cases, configurations corresponding to different shapes may coexist at similar energies, which results in the wave functions of these states mixing. Experimental observables, such as electromagnetic transition rates between excited states and static quadrupole moments, are closely related to the nuclear shape. The experimental determination of these observables, therefore, represents a stringent test for predictions of the theoretical models.

Coulomb excitation has been shown to be a highly successful method to study nuclear collectivity and deformation. In the scattering of two nuclei, the electromagnetic field that acts between them causes their excitation. At low beam energy (typically 2-5 MeV/A) this process is dominated by the well-known electromagnetic interaction, while contributions from the nuclear force are negligible. This technique has been pioneered in the 1950s and was extensively used during the 1960s and 70s when heavy-ion accelerators and high-resolution germanium detectors became readily available. However, it was limited to stable or very long-lived nuclei. A recent renaissance of this method was related to the advent of ISOL-based RIB facilities, making possible experiments on short-lived radioactive nuclei.

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Coulomb-excitation cross sections depend in a complex way on signs and magnitudes of electromagnetic matrix elements between the states involved in the excitation process. A given state may be populated directly, or via one or more intermediate states. This leads to appearance of interference terms between possible excitation paths, which can increase or decrease the population of the state in question, depending on the relative signs of the matrix elements involved, see Ref. [1]. Consequently, sophisticated computer codes are needed to extract nuclear structure parameters from the measured cross sections. Among them, the GOSIA code [2] seems to be most widely used as it is the only Coulomb-excitation code able to perform a multi-dimensional χ^2 fit of electromagnetic matrix elements to experimental data. The existing analysis methods have been refined to address common issues present when studying exotic nuclei [1], and currently Coulomb excitation is one of the most important experimental methods used to study nuclear shapes and collectivity, in particular on the neutron-rich side of the nuclear chart. In the present paper, we show some recent examples of complex multi-step Coulomb-excitation studies and illustrate the influence of second-order effects on measured cross sections with the example of superdeformed states in ^{42}Ca.

2 Recent examples of shape coexistence studies using Coulomb excitation of exotic nuclei

The potential of low-energy Coulomb excitation applied to short-lived exotic nuclei was demonstrated in a pioneering experiment on ^{74,76}Kr [3], which was the first to utilise the reorientation effect to measure quadrupole moments with radioactive beams. Opposite signs of the spectroscopic quadrupole moments were found for the states in the ground-state bands and those built on the shape isomers, confirming the shape coexistence scenario. The coexistence of a prolate ground-state band with an excited oblate band built on the low-lying 0^+_2 state for A = 74, 76 and the inversion of oblate and prolate configurations below A = 74 was found to be well described by HFB calculations using the Gogny D1S interaction with configuration mixing (GCM/GOA) [3]. Later, it was shown that allowing for triaxial degrees of freedom is crucial in this mass region to properly reproduce the experimental results [4].

Another region, where important nuclear structure information was obtained using Coulomb excitation of exotic beams, is that of A$\sim$100 neutron-rich nuclei. A sudden onset of quadrupole deformation, observed at N = 60 in the neutron-rich Zr and Sr isotopes, triggered an important experimental and theoretical effort to explain the origin of this dramatic shape change. The boundaries of the deformed regions have been firmly established in low-energy Coulomb-excitation experiments at REX-ISOLDE. Regular rotational ground-state bands were observed in for the first time in ^{97,99}Rb [5], and the obtained transition probabilities show that the deformation of these nuclei is essentially the same as that observed inside the well-deformed region. On the other hand, the B($E2$; $2^+_1 \rightarrow 0^+_1$) value measured for ^{96}Kr [6, 7] is significantly lower than those for ^{98}Sr and ^{100}Zr, and only slightly higher than that for ^{94}Kr [6, 7]. The recent Coulomb-excitation study of ^{96,98}Sr [8, 9] demonstrated important similarities in terms of transition probabilities and spectroscopic quadrupole moments between the ground-state band in ^{96}Sr and the structure built on the 0^+_2 state in ^{98}Sr. This confirmed the scenario of two distinct configurations associated with different nuclear shapes interchanging at N = 60. However, while in other regions of shape coexistence a strong mixing of underlying structures is the rule, the analysis of the obtained $E2$ matrix elements in ^{98}Sr using the two-state mixing model points to very low mixing between prolate and spherical configurations in the wave functions of the two 0^+ states, in spite of their proximity in energy. This has been related [8] to the abrupt transition at N = 60, in contrast to a smooth evolution of ground-state properties, 2^+_1 energies and B($2^+_1 \rightarrow 0^+_1$) transition strengths observed, for example, in $^{182-188}$Hg [10] and ^{74,76}Kr [3].

3 Second-order effects in Coulomb excitation of ^{42}Ca

Recently, the Coulomb-excitation technique has been applied for the first time to study superdeformed states [11, 12]. In the very first experiment using the AGATA array [13], the superdeformed structure in ^{42}Ca was populated following Coulomb excitation of the ^{42}Ca beam on ^{208}Pb and ^{197}Au targets. From the measured γ-ray intensities a complete set of electromagnetic matrix elements between the observed states was obtained, including spectroscopic quadrupole moments and relative signs of transitional $E2$ matrix elements. Those, in turn, were interpreted using the quadrupole sum rules formalism [14] leading to the conclusion that the spherical ground state of ^{42}Ca exhibits large fluctuations into the β-γ plane, while the excited structure has a large quadrupole deformation of β = 0.43(4) for 0^+_2, comparable to those measured for other superdeformed bands in this mass region. Additionally, the triaxiality parameter $\langle\cos(3\delta)\rangle$ obtained for the 0^+_2 state provided the first experimental evidence for non-axial character of superdeformed structures around A$\sim$ 40.

The level scheme of ^{42}Ca, taken into account in the Coulomb-excitation analysis, is presented in Fig.1. Transitions observed in the experiment are marked in blue. The analysis yielded two key pieces of information regarding the deformation of the side band, highlighted in red in Fig.1: the $\langle 2^+_2||E2||0^+_2\rangle$ matrix element, as well as the spectroscopic quadrupole moment of the 2^+_2 state, are both consistent with a large quadrupole deformation of this band. In the present paper, we analyse the sensitivity of the experimental data to these two observables, as well as to the relative signs of transitional $E2$ matrix elements.

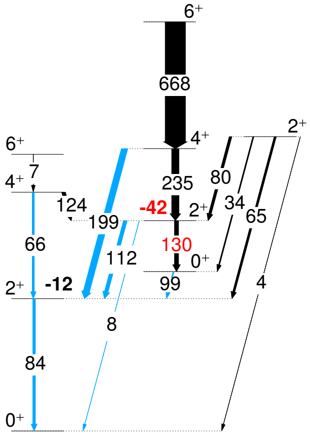

Figure 1. Low-lying excited states in ^{42}Ca, considered in the analysis described in Refs. [11, 12]. Transitions observed in the Coulomb-excitation experiment are marked in blue. The widths and labels of the arrows represent the experimental B($E2$,↓) values in e^2fm^4. Spectroscopic quadrupole moments, expressed in $e$fm^2, are given in bold. Red colour is used to highlight the observables which have been determined for the first time.

The following sign convention has been imposed: the signs of all in-band transitional $E2$ matrix elements, both in the ground state band and in the side band, were assumed to be positive, as well as that of $\langle 0^+_2||E2||2^+_1\rangle$. Signs of all other $E2$ matrix elements have been determined relative to those. The signs of two matrix elements, coupling the states of low spin and realtively low excitation energy, strongly influenced the observed excitation cross sections: $\langle 0^+_1||E2||2^+_2\rangle$ and $\langle 2^+_1||E2||2^+_2\rangle$. Figure 2 presents the influence of the signs of these matrix elements on intensities of γ-ray transitions following Coulomb excitation of ^{42}Ca on ^{208}Pb. The calculations were performed for the magnitudes of all matrix elements obtained in Refs. [11, 12] and all possible combinations of signs of the two matrix elements. It should be noted here that the magnitudes of transitional matrix elements were strongly constrained by known lifetimes of all excited states in ^{42}Ca included in the analysis, measured with precision ranging from 2% (0^+_2) to about 20% (4^+_2, 2^+_3). As shown in Fig. 2, the effect of interference terms on Coulomb-excitation cross section is much larger in the range of scattering angles covered by the particle detector (105-142°), and corresponds to changes of the population of excited states by a factor of two or more. Under these conditions, the sensitivity of the data to the relative signs of matrix elements is undeniable. These signs, obtained for the first time for transitions de-exciting a superdeformed structure, were crucial for the quadrupole sum rules analysis presented in Refs. [11, 12].

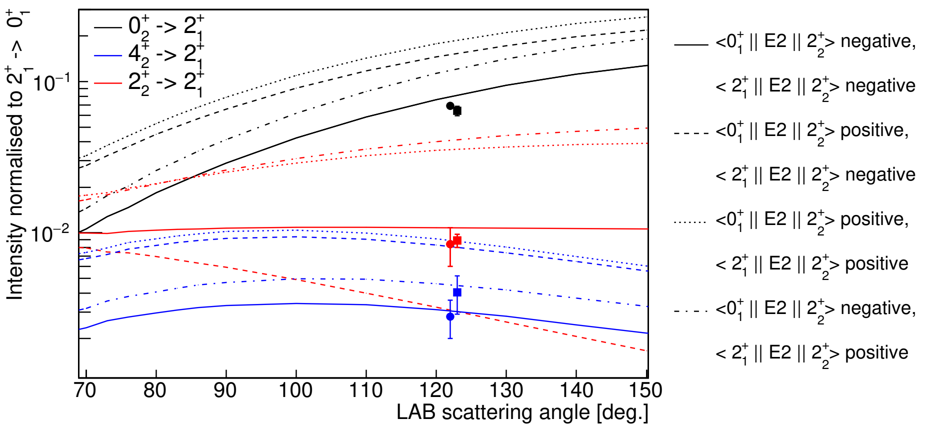

Figure 2. Transition intensities in ^{42}Ca normalised to that of $2^+_1 \to 0^+_1$, following Coulomb excitation of ^{42}Ca on ^{208}Pb in the experimental conditions of the measurement described in Refs. [11, 12]. The solid lines denote the calculations using the final set of matrix elements obtained in the analysis, while for the other lines different signs of the $\langle 0^+_1 \| E2 \| 2^+_2 \rangle$ and $\langle 2^+_1 \| E2 \| 2^+_2 \rangle$ matrix elements were used. The experimental intensity ratios are also shown; those measured for ^{197}Au, denoted by squares, are rescaled to take into account the difference in cross sections, and, for clarity, slightly offset on the x axis.

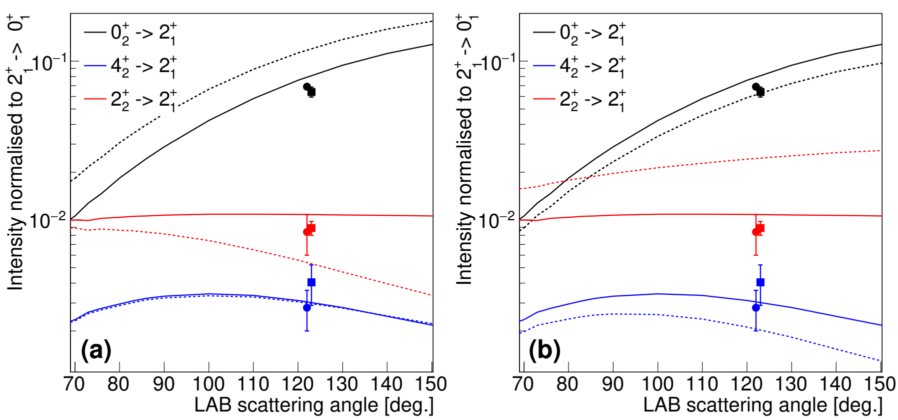

Figure 3. Same as Fig. 2, but the dotted lines correspond to: (a) $\langle 2^+_2 \| E2 \| 0^+_2 \rangle$ equal to zero, (b) quadrupole moment of the 2^+_2 state equal to zero.

Figure 3 illustrates the influence of the $\langle 2^+_2 \| E2 \| 0^+_2 \rangle$ matrix element (a) and the spectroscopic quadrupole moment of the 2^+_2 state (b) on measured γ-ray intensities. Clearly, although the $2^+_2 \to 0^+_2$ transition is too weak to be observed and prior to the present study only an upper limit for the branching ratio has been known, the corresponding matrix element strongly affects excitation cross sections of observed states and hence it could be determined from the intensities of other transitions measured in the Coulomb-excitation experiment. The effects of the $\langle 2_2^+\|E2\|0_2^+\rangle$ and $\langle 2_2^+\|E2\|2_2^+\rangle$ matrix elements on the population of both the 0_2^+ and 2_2^+ states are opposite, and consequently an increase of $\langle 2_2^+\|E2\|0_2^+\rangle$ could be compensated by a larger value of $\langle 2_2^+\|E2\|2_2^+\rangle$, leading to an equally good reproduction of the $2_2^+ \rightarrow 2_1^+$ and $0_2^+ \rightarrow 2_1^+$ transition intensities. The population of the 4_2^+ state, however, is sensitive only to the latter, thus making it possible to extract both matrix elements independently. The existing correlation between them is reflected in relatively large uncertainties of the two matrix elements ($\langle 2_2^+\|E2\|0_2^+\rangle = 26\,^{+5}_{-3}$ $e$fm^2, $\langle 2_2^+\|E2\|2_2^+\rangle = -55\,^{+15}_{-15}$ $e$fm^2 [11]). Their values confirm the superdeformed character of the excited structure in ^{42}Ca at low spin. In particular, the measured spectroscopic quadrupole moment of the 2_2^+ state corresponds to β=0.48(16). It should be noted here that improving the precision on the 4_2^+ lifetime would better constrain the magnitude of all matrix elements related to the deexcitation of this state, which would help to evaluate the role of second-order effects more precisely and thus increase the sensitivity to the $\langle 2_2^+\|E2\|0_2^+\rangle$ and $\langle 2_2^+\|E2\|2_2^+\rangle$ matrix elements.

4 Summary

The Coulomb-excitation technique can be used to explore many facets of nuclear shape evolution, from the mechanism driving the onset of quadrupole deformation, the development of exotic deformations, such as superdeformed or triaxial shapes, to the coexistence of different shapes in the same nucleus. The sensitivity of Coulomb-excitation data to second-order effects, such as influence of static quadrupole moments or relative signs of matrix elements that are critical for the sum-rule analysis, can be greatly enhanced by precise complementary data, in particular lifetimes and branching ratios. If lifetimes of excited states are unknown, which is often the case for exotic nuclei, integral measurements of Coulomb-excitation cross sections may lead to transition probabilities involving non-yrast states over- or underestimated by as much as a factor of two when a wrong combination of relative signs of matrix elements is assumed. This shows the importance of differential cross-section measurements that are sensitive to relative signs.

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