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Letter of Intent to the ISOLDE and Neutron Time-of-Flight Experiments Committee for experiments with HIE-ISOLDE

Shape Transition and Coexistence in Neutron-Deficient Rare Earth Isotopes

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Abstract

We propose to study static quadrupole moments of excited states and electromagnetic transition rates between them in neutron-deficient rare earth nuclei using projectile Coulomb excitation at energies of ~5 MeV per nucleon. The rare earth nuclei below the N=82 shell closure form one of the few regions of the nuclear chart where oblate shapes are expected to occur near the ground state. Nuclear shapes are expected to change rapidly in this region, with coexistence of oblate and prolate shapes in some nuclei, so that the measurement of electromagnetic matrix elements represents a particularly sensitive test of theoretical nuclear structure models. The higher beam energies of the HIE-ISOLDE post-accelerator will lead to higher cross sections, and therefore significantly increase the number of accessible states and matrix elements, allowing a comprehensive study of nuclear shapes.

1. Physics case

The measurement of dynamic and static electromagnetic moments represents one of the most sensitive probes of nuclear structure and the most direct method to study nuclear collectivity and shapes. The motion of individual nucleons depends critically on the nuclear shape, and conversely the shape can be strongly influenced by a few individual nucleons. The deformation can be described by a multipole expansion, with the quadrupole deformation being the most important deviation from spherical shape. Such quadrupole shapes can either have axial symmetry, in which case one distinguishes elongated (prolate) and flattened (oblate) shapes, or the deformation can be without axial symmetry resulting in a triaxial shape. In particular for heavy nuclei with N,Z>50 a strong dominance of prolate shapes is observed, which has been related to the strength of the spin-orbit interaction relative to the radial term in the nuclear interaction [1]. Oblate shapes are then only expected when a major shell is almost filled due to the strong shape-driving effect of holes in the Ω=1/2 orbitals. In these regions of the nuclear chart the shape is very sensitive to structural effects and can change from one nucleus to its neighbor. In addition the shape can also change with excitation energy or angular momentum within the same nucleus. Such changes are caused by a rearrangement of the orbital configuration of the nucleons or by the dynamic response of the nuclear system to rotation. In some cases configurations corresponding to different shapes coexist at similar energies. The wave functions of such states can then mix according to the laws of quantum mechanics. The experimental observables most closely related to the nuclear shape are quadrupole moments of excited states and electromagnetic transition rates between them. The experimental measurement of these observables represents a stringent test for theoretical models, in particular in the case of shape coexistence and shape mixing. Of particular relevance for the description of nuclear shapes and shape coexistence are extensions of the mean-field approach that take into account configuration mixing, for example using the generator coordinate method (GCM). Figure 1 shows the predicted deformations from such calculations for the ground states of even-even nuclei across the entire nuclear chart [2] and for excited states in ^{138}Nd, ^{140}Sm, ^{142}Gd, and ^{144}Dy. The calculations predict a rapid transition from prolate to oblate shapes for the N=78 isotones between Nd and Dy.

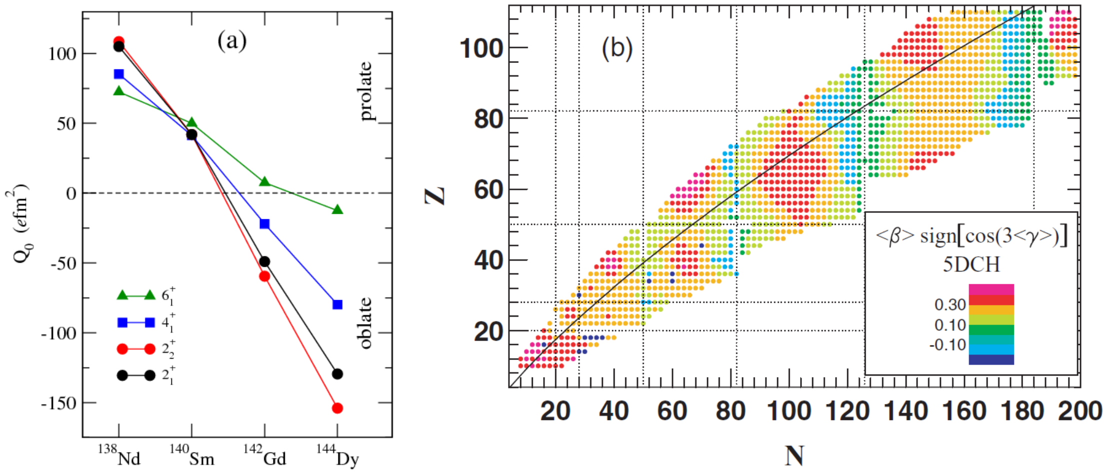

Fig 1: (a) Intrinsic quadrupole moments for excited states in even-even nuclei with N=78 and 60≤Z≤66 from beyond-mean-field calculations with the Gogny D1S force. (b) Nuclear chart showing predictions for the ground-state deformation [2].

The high-spin structure of the neutron-deficient rare earth nuclei is accessible in fusion-evaporation reactions with stable heavy-ion beams. The measurement of transition probabilities between low-lying states, however, is hampered by the occurrence of long-lived isomeric states, which prevent the measurement of lifetimes for the states below. The only means to measure transition probabilities between low-lying states is consequently low-energy Coulomb excitation using radioactive beams. This technique is furthermore sensitive to static quadrupole moments due to the reorientation effect, providing a direct measurement of the nuclear shape associated with a specific state. The measurement of quadrupole moments and transition probabilities in ^{140}Sm is the goal of ISOLDE experiment IS495, which is currently in preparation. At the present maximum beam energy of 3·A

MeV only the first and second 2^+ states and the first 4^+ state can be populated, while the measurement of quadrupole moments is probably limited to the first 2^+ state. At a higher energy of 4.7·*A* MeV, where influences of the nuclear force are still excluded, the cross sections are considerably higher, as illustrated in figure 2. Measurements under these conditions will yield a rather complete set of electromagnetic matrix elements, including diagonal matrix elements for several states, resulting in a comprehensive understanding of shape transitions and shape coexistence in this region. The measurement at higher beam energy will also give access to more exotic N=78 isotones such as ^{144}Dy, which is out of reach today due to the combination of weak beam intensities and low cross sections.

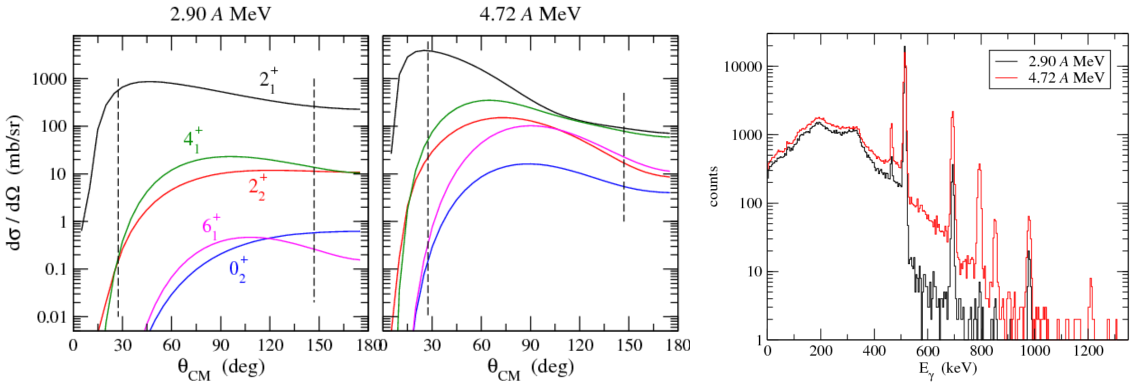

Fig 2: Comparison of cross sections to populate low-lying states in ^{142}Gd by projectile Coulomb excitation on a ^{208}Pb target at 2.90 and 4.72·*A* MeV using experimental excitation energies and matrix elements from the Gogny calculations. The vertical lines indicate the angular range covered by the setup. The cross sections were used to simulate γ-ray spectra for Coulomb excitation of ^{142}Gd on ^{208}Pb at the two different beam energies, assuming a beam intensity of $2 \cdot 10^4$ ions per second and a measuring time of five days.

2. Experimental setup

The measurement can be carried out using the MINIBALL detector array coupled to a highly segmented annular silicon detector. A measurement of the beam composition after the Coulomb excitation setup would be advantageous.

3. Beam requirements

The proposed study is challenging because it aims at measuring electromagnetic matrix elements in a chain of isotones, which requires the production of radioactive beams of different chemical elements. It is a further complication that the rare earth elements have very similar chemical properties, making the use of resonant laser ionization mandatory. Beam development and testing of laser ionization schemes is in progress. The most interesting nuclei to study in this region are the N=78 isotones ^{138}Nd, ^{140}Sm, ^{142}Gd, and ^{144}Dy, with a possible extension of the program to the N=76 isotones. The required beam energy lies in the range between 4.5 and 5.0·*A* MeV. The minimum beam intensity and purity for successful Coulomb excitation experiments are 10^4 per second and 50%, respectively.

4. Safety aspects

Safety hazards are the same as for present REX-ISOLDE experiments.

5. References

[1] Naoki Tajima and Norifumi Suzuki, Phys. Rev. C 64, 037301 (2001).
[2] J.-P. Delaroche et al., Phys. Rev. C 81, 014303 (2010).