CERN-INTC-2008-018 / INTC-I-076
20/04/2008

Letter of Intent

Study of oblate nuclear shapes and shape coexistence in neutron-deficient rare earth isotopes

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Motivation

To first order, describing the nuclear potential as a harmonic oscillator, the binding energy is independent of the sign of the deformation, and prolate and oblate shapes should be equally probable. In light nuclei both prolate and oblate shapes occur indeed more or less equally. For heavier nuclei (N,Z>50), where the shell structure changes from a harmonic oscillator type to a Mayer-Jensen type with intruder orbitals, 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 only expected when a major shell is almost filled due to the strong shape-driving effect of holes in the Ω=1/2 orbitals [2]. This effect is confirmed by HFB calculations, which predict a dominance of oblate ground-state shapes for example just below the N=82, N=126, and Z=82 shell closures (see Fig. 1). Apart from the fundamental question where in the nuclear chart oblate shapes can be found, nuclei with oblate ground-state shapes are also the best candidates to study the phenomenon of oblate-prolate shape coexistence, since prolate shapes become rapidly favored with angular momentum due to their higher moment of inertia, so that oblate shapes can only compete at low angular momentum. Oblate ground states are expected in the region of rare earth elements with N≈78 and Z≥62. A similar shape transition from prolate for N>82 to spherical at N=82 to oblate at N=78 and back to prolate for N<78 is also found for rare earth nuclei in calculations using a relativistic mean-field approach [3].

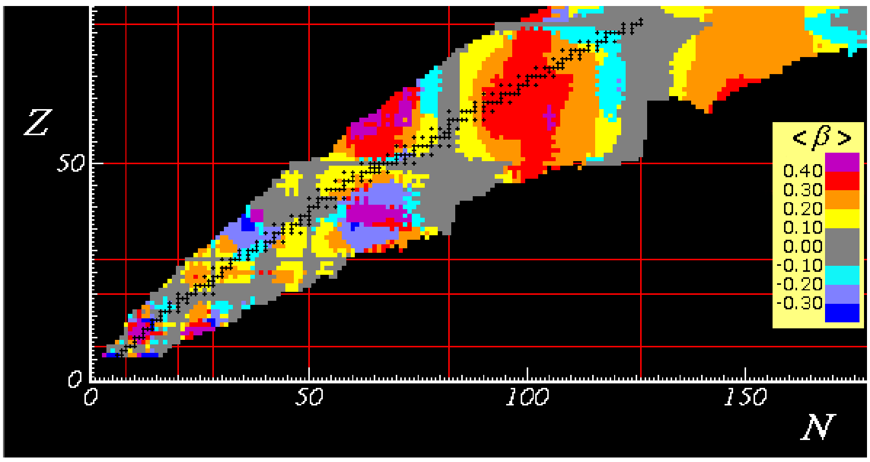

Fig. 1. Expected ground-state shapes from Gogny-HFB (D1S) calculations. Large prolate deformations (β>0) are found above the Z=50 and below the N=82 shell closures, with a small area of oblate shapes (β<0) for Z≥62 and N≈78.

The neutron-deficient rare earth nuclei are accessible via heavy-ion induced fusion-evaporation reactions. Some of them have been studied in great detail up to high spins, where, among other phenomena, superdeformation [4] and magnetic rotational ("shears") bands [5] have been observed. Even for relatively easily accessible nuclides which have been studied in detail at high spin, experimental studies of the shapes near the ground state are lacking completely.

With this Letter of Intent we propose to initiate the investigation of nuclear shapes and shape coexistence in the neutron-deficient rare earth region at the ISOLDE facility by employing Coulomb excitation of rare earth beams from the REX accelerator. The isotopes in the region of interest can be produced e.g. by fragmentation of a Ta target by high-energy protons. Yields have already been measured at ISOLDE mostly with protons from the SC driver. In the case of Dy a laser ionization scheme has been developed [6].

Theoretical predictions

We have performed Hartree-Fock-Bogolyubov based configuration mixing calculations using the Gogny D1S interaction and a five-dimensional collective Hamiltonian comprising both axial and non-axial quadrupole deformations and the rotational degrees of freedom in order to identify the most interesting isotopes for the study of oblate shapes and oblate-prolate shape coexistence. The procedure to calculate the energy spectra, reduced transition probabilities, and quadrupole moments is described in detail in Ref. [7]. The calculations can be compared to experimental data in some selected cases where the low-spin level scheme and transition strengths are known from lifetime measurements, e.g. in ^{134}Nd [8]. The experimental level scheme for ^{134}Nd is shown in Fig. 2 and compared to our configuration mixing calculations. Note that the numbers given for the transitions represent the B(E2;↓) values in e^2fm^4. The observed structures are interpreted as a prolate rotational ground-state band and a gamma-vibrational band. This interpretation is consistent with the quadrupole moments found in our calculations. The agreement for the transition strengths is satisfactory and gives confidence that the calculations yield reliable predictions in this mass region. However, when moving from this region of prolate shapes around ^{134}Nd to the region around ^{144}Dy where shapes are expected to change rapidly, experimental data is scarce. The measurement of transition strengths and in particular of quadrupole moments represents a stringent test of the theoretical predictions.

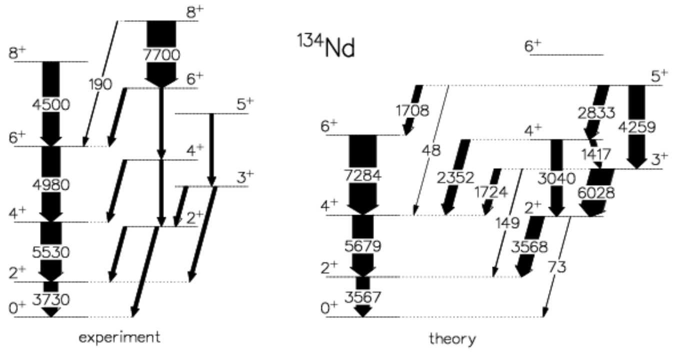

Fig.2. Experimental and theoretical level scheme of ^{134}Nd. The labels of the transitions give the B(E2;↓) values in e^2fm^4, and the width of the arrows is proportional to these values. Experimental transitions without label have been observed, but the B(E2) values are unknown.

The first N=78 isotone where our calculations predict oblate ground-state shape is ^{142}Gd. Despite detailed experimental studies [9,10], the transition strengths between low-lying states remain unknown. Experimental information becomes rapidly scarce for the heavier isotones. In ^{144}Dy the states of the ground-state band have only been tentatively assigned up to spin 8^+ [11]. A low-lying second 0^+ state has been observed in ^{142}Gd at 1368 keV [12]. The calculations find this state consistent with a coexisting prolate state. The excitation energy of the second 0^+ state is predicted to decrease from ^{142}Gd to ^{144}Dy. At the same time, the deformation of the oblate and prolate states is predicted to increase in ^{144}Dy, which hence seems to be the most interesting case to study shapes and shape coexistence in this mass region.

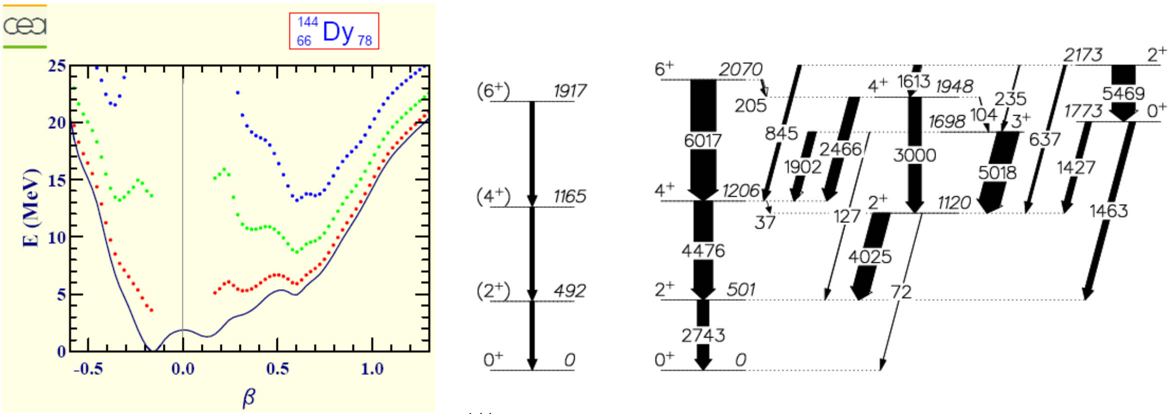

Fig.3. *Left:* Potential energy curves for ^{144}Dy. The full line is for spin 0, the dotted lines for spins 8, 16, and 24, respectively. *Center:* Experimental level scheme. No B(E2) values are known experimentally. *Right:* Calculated level scheme. The labels of the transitions give the B(E2;↓) values in e^2fm^4, and the width of the arrows is proportional to these values. The calculated spectroscopic quadrupole moment of +37 fm^2 for the first 2^+ state indicates oblate shape. The 2_3^+ state above the 0_2^+ state has a large prolate quadrupole moment of −75 fm^2. The 2_2^+ state has negative $Q_s = -44$ fm^2, consistent either with an oblate K=2 gamma vibration or a prolate K=0 band.

Experimental considerations

The predicted oblate shapes can directly be determined from Coulomb excitation experiments utilizing the reorientation effect, even with low intensities of radioactive beams, as has been demonstrated recently [13-15]. We have calculated the Coulomb excitation cross sections using the experimental excitation energies of the states (where known) and the calculated B(E2) values and quadrupole moments. Calculations were performed for a beam energy of 2.9 MeV per nucleon and a ^{208}Pb target, taking into account the angular coverage of the particle detector typically used at ISOLDE. The large cross sections suggest that a reorientation measurement for the 2_1^+ state and population of at least the 2_2^+ and 4_1^+ states should be feasible.

	^{142}Gd	^{144}Dy
2_1^+	6042	7393
2_2^+	89	38
4_1^+	166	238

Table 1: Coulomb excitation cross sections (in mb) for the first excited states in ^{142}Gd and ^{144}Dy, based on the calculated transition strengths and quadrupole moments.

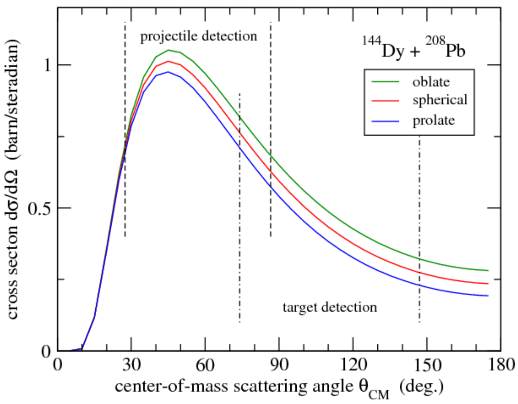

Fig. 4. Differential Coulomb excitation cross section for the first 2^+ state in ^{144}Dy populated on a ^{208}Pb target at 2.9 MeV/u, based on the quadrupole moments and B(E2) values from the Gogny calculation (green curve). If the quadrupole moment is set to zero, the red curve is obtained, if the sign is inversed (to prolate shape), the blue curve is found. This illustrates the sensitivity of the measurement to the reorientation effect. The vertical lines show the angular range covered by the CD detector.

The expected cross sections are very similar to those found in the Coulomb excitation of ^{74}Kr, which was performed at GANIL [13]. In that case is was possible to measure several quadrupole moments with a secondary beam intensity of 10^4 pps. We expect Coulomb excitation experiments in the rare earth region to be feasible at ISOLDE, if similar beam intensities can be achieved. As the region is also accessible via fusion-evaporation reactions, it will be possible to perform complementary lifetime measurements, which has proven useful in order to obtain additional constraints to extract quadrupole moments [14,15].

The yield for ^{142}Gd ($T_{1/2}$=70.2 s) has been measured (using the SC driver) to be $1.2 \cdot 10^6$ ions/μC. Even though this value should be confirmed by a new measurement using the PS Booster, it gives hope that a secondary beam intensity of 10^4 pps could be achieved. No yield information is available for ^{144}Dy ($T_{1/2}$=9.1 s). The measured yields drop from $2.9 \cdot 10^8$ ions/μC in ^{148}Dy to $5.0 \cdot 10^6$ in ^{146}Dy. These measurements were also obtained with the SC driver.

With this Letter of Intent we would like to trigger yield measurements for the relevant Sm, Gd, and Dy isotopes in the region around N=78. If these turn out promising, we hope that the necessary beam developments will be started. Once more reliable data on the beam intensities and purities are available, we intend to submit a full proposal.

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