Recoil-distance lifetime measurement in ^{138}Nd

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Abstract
We propose to measure lifetimes of low-lying states in ^{138}Nd using the recoil-distance Doppler shift technique. The rare earth nuclei just below the N=82 shell closure belong to one of the few regions of heavy nuclei in the Segrè chart where oblate shapes are expected near the ground state. Calculations predict a transition from prolate to oblate ground-state shape with increasing proton number for the N=78 isotones. The ^{138}Nd nucleus is transitional with a γ-soft character at low excitation. Prolate and oblate shapes are expected to coexist at medium spins, and recent experiments suggest a more stable triaxial shape at higher spins. The measurement of electromagnetic transition rates, completely unknown so far, and their comparison with theoretical calculations is important for the understanding of the various structures in this nucleus and the evolution of shapes in the mass region.

Present experimental knowledge and theoretical predictions

The shape is one of the most fundamental properties of an atomic nucleus. To first order the binding energy is independent of the sign of the deformation, and prolate and oblate shapes should be equally probable. In light nuclei 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 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. This effect is seen for example in HFB calculations with the Gogny D1S interaction, shown in Fig.1. The calculations predict strongly deformed prolate shapes in the deformed region above Z=50 and below N=82, except for a small region of oblate shapes for the most proton-rich N=78 and N=76 isotones. Relativistic mean-field (RMF) calculations [2] with the NL-SH Lagrangian predict a similar island of oblate shape for N=78.

To account for possible configuration mixing, correlations beyond the mean field have to be considered in the calculations. HFB-based configuration mixing calculations using the Gogny D1S interaction and the generator coordinate method (GCM) with Gaussian overlap approximation (GOA) comprising axial and non-axial quadrupole degrees of freedom were used to calculate quadrupole moments and transition strengths for the chain of N=78 isotones [3]. The calculated quadrupole moments suggest a gradual transition from prolate shapes in ^{138}Nd to oblate shapes in ^{144}Dy (see the right-hand part of Fig.1). The shape transition and possible shape coexistence in this region has been addressed recently in measurements of transition probabilities and quadrupole moments for ^{140}Sm using Coulomb excitation of a radioactive beam at ISOLDE and RDDS lifetime measurements in Warsaw. Similar experiments are also planned for ^{142}Gd. With the present proposal we aim at extending the systematic study towards the lighter isotone ^{138}Nd.

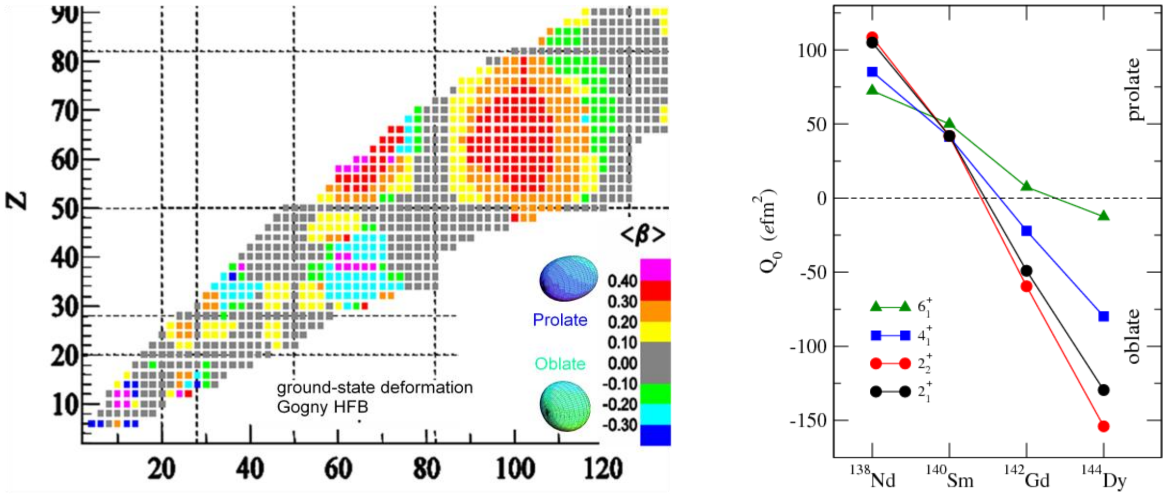

Fig.1. Left: Nuclear chart showing the ground-state shapes predicted by a Hartree-Fock-Bogolyubov (HFB) calculation with the Gogny D1S effective interaction [3]. Shell closures are marked by dotted lines. Large prolate deformations (β>0) are found above the Z=50 and below the N=82 shell closures, with a small area of oblate shapes (β<0) for Z≥62 and N≈78. Right: Quadrupole moments for several excited states in N=78 isotones from GCM(GOA) calculations with the Gogny D1S interaction.

The level scheme of ^{138}Nd is known in great detail from investigations following β^+ decay of ^{138}Pm [4] and fusion-evaporation reactions [5-9]. Most previous studies focused on high-spin spectroscopy and gave evidence for strongly deformed rotational bands [7] and structures that can be associated with stable triaxiality [6,8]. A common feature of the N=78 isotones is the occurrence of isomeric 10^+ states based on $\pi(h_{11/2})^2$ and $\nu(h_{11/2})^{-2}$ configurations. The rotational bands built on the 10^+ states can be associated with prolate and oblate shapes, respectively [5]. In ^{138}Nd only the state based on the $\nu(h_{11/2})^{-2}$ configuration is isomeric, whereas the 10^+ state based on the $\pi(h_{11/2})^2$ configuration decays prompt via a negative-parity structure (see Fig.3). The sequence comprising the 2_2^+, 3_1^+, and 4_2^+ states is interpreted as a γ-vibrational band, and very recently candidates for states belonging to a two-phonon γ vibration were reported [9]. Except for the isomeric 10^+ state at 3175 keV excitation energy, the lifetimes of excited states in ^{138}Nd are completely unknown. We propose to measure the lifetimes of several low-lying states and compare the resulting transition probabilities with theoretical calculations. Fig.2 compares the experimental level scheme for the lowest states of the ground-state and γ bands in ^{138}Nd with the Gogny calculations. Measuring transition strengths in the ground-state band is important to understand the evolution of nuclear shapes within the chain of N=78 isotones. Transition strengths from states of the presumed γ-vibrational band will help to clarify the nature of this structure. A further goal of the proposed experiment is to measure B(E2) values for the rotational bands built on top of the two 10^+ states, which can confirm their interpretation as proton particle and neutron-hole excitations of the $h_{11/2}$ shell, and their prolate and oblate character, respectively.

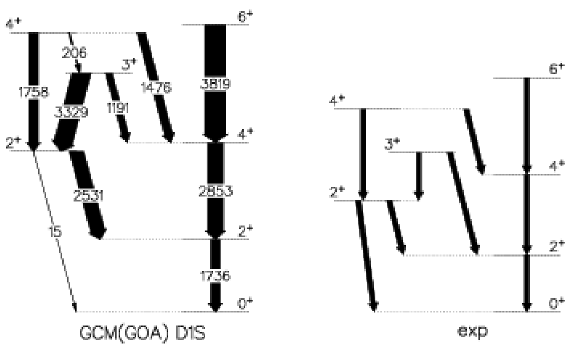

Fig. 2. Calculated and experimental level schemes for the ground-state and γ-vibrational bands in ^{138}Nd. The transitions in the calculated level scheme are labeled with their B(E2) values in e^2fm^4. Experimental transition strengths are unknown. The calculated excitation energies overestimate the experimental values by ~20%.

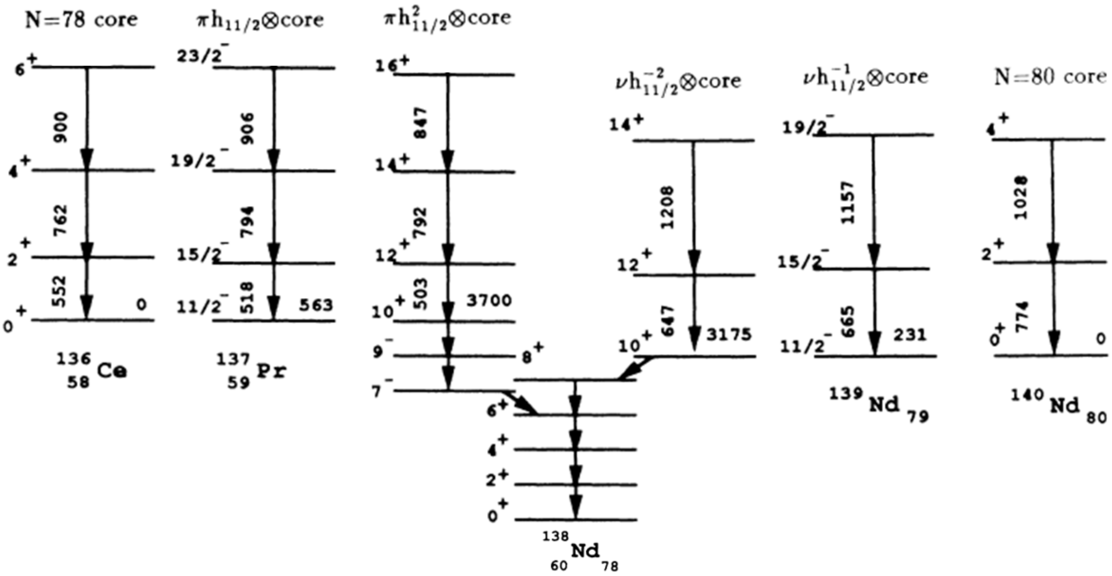

Fig. 3. Energies of the rotational structures built on the 10^+ states in ^{138}Nd compared with the $h_{11/2}$ bands in the odd-mass neighbors and the ground-state bands in the even-even neighbors with Z–2 and N+2, respectively.

Details of the proposed experiment

We propose to measure the lifetimes of several excited states in ^{138}Nd using the recoil distance Doppler shift (RDDS) technique with the Bucharest Plunger device coupled to the γ spectroscopy array comprising 15 HPGe and 10 $LaBr_3$(Ce) detectors. The $LaBr_3$(Ce) detectors will be used for the direct measurement of lifetimes for longer-lived states. With the combination of the RDDS and fast timing techniques, the setup is sensitive to lifetimes over a wide range from picoseconds to nanoseconds. The differential decay curve method [10] will be used in combination with the RDDS measurement in order to eliminate effects due to unobserved feeding. This requires analyzing γ-γ coincidences and gating on flying components of transitions feeding the state of interest. The Compton-suppressed Ge detectors will be arranged with five detectors in each of the rings at 37° and 143° with respect to the beam axis, with the remaining Ge and $LaBr_3$(Ce) detectors distributed over the rings at 70°, 90°, and 110°.

Based on the theoretical prediction for the B(E2) values from the Gogny calculations, we expect a lifetime in the range of 12 ps for the 2_1^+ state, and approximately 1.5 ps for the 4_1^+ state. From systematics we expect the lifetimes of the 12^+ states with $h_{11/2}$ proton-particle and neutron-hole configuration also to be in the range 10 – 15 ps. These lifetimes are within the range of the RDDS technique and their measurement is feasible with the proposed experiment. The 7^- state at 2322 keV excitation energy is likely to be built on the $\nu(h_{11/2}^{-1}\otimes d_{3/2}^{-1})$ configuration and expected to be long-lived with a lifetime of up to several hundred picoseconds. This lifetime can be measured directly using the fast $LaBr_3$(Ce) detectors.

Two reactions are suitable for the proposed lifetime measurement in ^{138}Nd: ^{124}Te(^{18}O,4n) and ^{123}Sb(^{19}F,4n). Our recent lifetime measurement in ^{140}Sm with the Bucharest Plunger at the Heavy Ion Laboratory in Warsaw successfully used a ^{124}Te target, which consisted of a 0.7 mg/cm^2 thick layer of ^{124}Te evaporated onto a 5 mg/cm^2 thick Au foil. The target was stretched onto the plunger frame and mounted with the Au layer facing the beam. RDDS spectra from the Warsaw experiment are shown in Fig.4. The fact that a ^{124}Te target was proven suitable for a RDDS lifetime measurement speaks in favor of the ^{18}O induced reaction. However, the required beam energy is at the limit of what the Bucharest Tandem can deliver. Calculations using the code PACE suggest a projectile energy of 68 MeV in the Te layer of the target, resulting in a cross section of 292 mb for the 4n evaporation channel, out of a total fusion cross section of 438 mb. With an energy loss of 9 MeV in the preceding Au layer of the target, a beam energy of 77 MeV is needed, which requires the fully-stripped 8^+ charge state and a terminal voltage of 8.6 MV. The ^{124}Te(^{18}O,4n) reaction can only be the first choice after a successful beam test.

Alternatively the reaction ^{123}Sb(^{19}F,4n) can be used with a projectile energy of 72 MeV in the center of the target. The use of stretched Sb targets in a plunger has not been tested, but should be possible if a Au backing is used. Assuming a thickness of 4 mg/cm^2 for the Au backing, a beam energy of 80 MeV is required, allowing the use of the (Z−1) charge state 8^+. A beam intensity of 0.5 pnA should be feasible in this case, so that the experiment will only be limited by the maximum count rate of 10 kHz in the Ge detectors. With an estimated cross section of 190 mb for the ^{19}F induced reaction and an assumed target thickness of 0.5 mg/cm^2, We expect to produce 1400 ^{138}Nd recoils per second, which should be sufficient to perform the proposed lifetime measurement with an average beam time of 36 hours per distance. The recoil velocity is calculated to be 3.6 μm/ps. To cover a sufficient range of lifetimes and to obtain lifetimes with high precision we propose to measure at 8 distances ranging from 5 to 500 μm, which in total requires **12 days of beam time**.

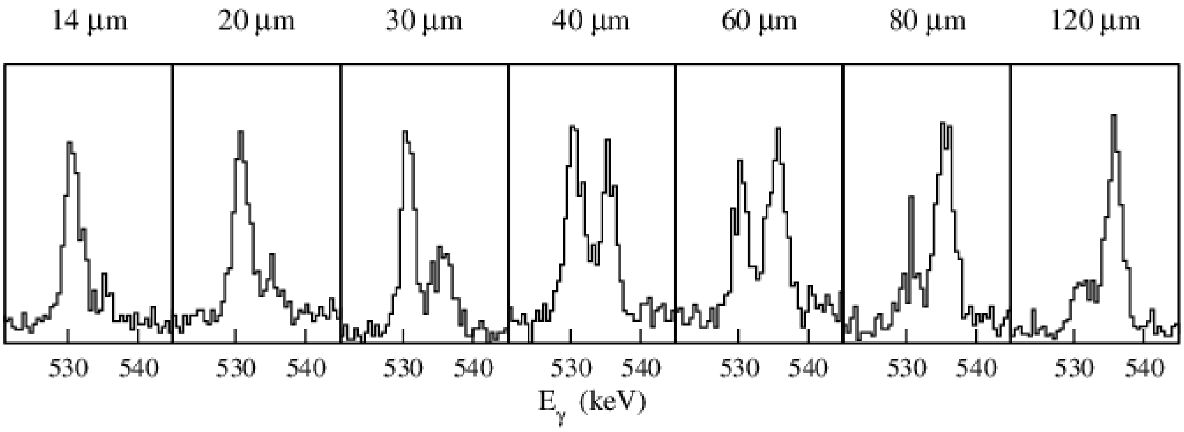

Fig.4. Preliminary spectra from the recent RDDS lifetime measurement in ^{140}Sm with the Bucharest plunger at the Heavy Ion Laboratory in Warsaw. The spectra show the flying and stopped components of the $2_1^+ \rightarrow 0_1^+$ transition, observed at 37° with respect to the beam axis and gated on the flying component of the $4_1^+ \rightarrow 2_1^+$ transition. The experimental conditions during the ^{140}Sm experiment were similar to those expected for the proposed experiment in ^{138}Nd.

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