EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Determining $\rho^2(E0)$ in ^{150}Nd during LS2

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Abstract: This letter of intent proposes the utilisation of the Miniball spectrometer and stable beams from the HIE-ISOLDE linac to study collective modes in rare-earth nuclei, specifically the stable ^{150}Nd. The aim of the experiment is to determine $\rho^2(0^+_2 \to 0^+_1)$ in ^{150}Nd via the detection of the $E0$ transition depopulating the 0^+_2 state following Coulomb excitation. The experiments would be performed with the SPEDE conversion-electron spectrometer coupled to the Miniball gamma-ray array. This isotope is stable and has a natural abundance of 5.6% meaning that an enriched target foil can be produced for study. Contrary to RIB experiments usually performed at HIE-ISOLDE, this target would provide the nuclei of interest while the beam would be the electromagnetic probe that induces the excitation. This leaves a wide range of possibilities for beam species, energy and intensity that can be used to give good physics results. We estimate that the aims of the experiment on ^{150}Nd can be achieved in 12 shifts, using a medium-mass beam such as ^{84}Kr at a typical energy of 3-5 MeV/u.

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1 Physics case

Electromagnetic properties of non-yrast states at low energy and low spin are required in order to understand the collective structures that near to the ground states of atomic nuclei. This is particularly important when different collective modes compete with each other, either in terms of vibrational and rotational degrees of freedom or coexisting shapes [1]. In even-even nuclei, low-lying excited 0^+ states are often key signatures of shape coexistence [1]. However, the β-vibrational mode in deformed nuclei, described by Bohr and Mottelson, also gives rise to excited 0^+ states and detailed spectroscopy, especially determination of electromagnetic properties, can help to distinguish between them. It has long been debated as to whether the harmonic-vibrator description of nuclei is robust though, given the lack of clear candidates across the nuclear chart. Studies of the cadmium isotopes [2, 3], often considered the best examples of harmonic vibrators, reveals the breakdown of this description on the basis of detailed measurements of electromagnetic properties. That work highlights the need to base the collective description of nuclear phenomena on much more than just the interpretation of level energies. A particularly useful observable in this case is the $\rho^2(0^+_i \to 0^+_1)$ value, which indicates a mixing between configurations with different deformations [4].
In many cases around $N = 90$, excited 0^+ states have long been attributed to β vibrations but doubt has been cast on these assignments [5]. However, there is evidence to suggest that the description of shape coexistence is better suited to $N \approx 90$ nuclei [6, 7]. Along the $N = 90$ isotopic chain, the stable isotopes ^{150}Nd, ^{152}Sm and, in particular, ^{154}Gd have been subject to much experimental scrutiny due to both the suggestion of β vibrations and the critical-point description of Iachello within the Interacting Boson Approximation (IBA) [8]. Recent beyond-mean-field (BMF) calculations in this region [9] show that a quantitive approach to resolve this ambiguity is possible. They reveal that the deformation of excited 0^+ states in the $N = 90$ isotones differ from their ground states [9]. This hints more towards shape coexistence where the $E0$ strength is an indication of the mixing between configurations. On the other hand, systematic calculations within the dynamic pairing-plus-quadrupole model (DPPQM) [10] have recently lead to the conclusion that the description of a β band is a good one, going as far as to rule out shape coexistence [11].
In the $N = 90$ chain, data for the transition strengths is still missing, particularly $\rho^2(0^+_2 \to 0^+_1)$ values beyond the stable isotopes, but also in the stable ^{150}Nd. The next even-Z isotone on the lighter side of this sequence, ^{148}Ce, is radioactive and subject to a Letter of Intent to this committee [12]. The energy systematics of 0^+_2 states in this region are shown in the top part of Fig. 1, where a minimum is approached at $N = 90$ for Sm, Nd and Ce. The two key components in determining $\rho^2(0^+_2 \to 0^+_1)$ are the $E0$ branching ratio and the lifetime of the 0^+_2 state. In the majority of even-even nuclei, the 2^+_1 state lies below the 0^+_2 state allowing for a lifetime measurement via $B(E2; 0^+_2 \to 2^+_1)$, given that the branching ratio is known. In ^{150}Nd, half of this has already been done, only the branching ratio is missing. So far, the $E0(0^+_2 \to 0^+_1)$ conversion-electron decay has not been observed in parallel with the $E2(0^+_2 \to 2^+_1)$ gamma-ray decay due to difficulties in populating this state. The best method of populating the state has been via Coulomb excitation, but previous experiments did not include an electron detector, only gamma-ray and heavy ion detectors.

2 Experimental details

Multiple-step Coulomb excitation is an excellent method of populating low-lying low-spin states in a nucleus. The excitation does not favour the yrast states, but instead states that are close

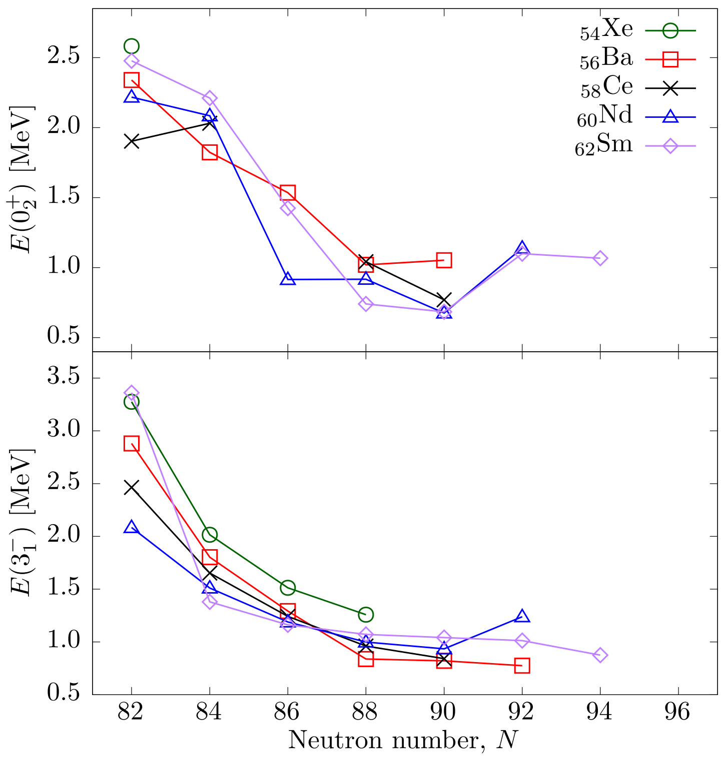

Figure 1: Excitation energy systematics of the first-excited 0^+ (top) and 3^- (bottom) states in the $N = 90$ region. Both the 3_1^- and 0_1^+ energies appear to minimise around $N = 88, 90$. Data is taken from NNDC [13].

in energy and have large matrix elements coupling them. To populate the 0_1^+, one must go via the 2_1^+ state in a two-step process, since $E0$ excitations are forbidden. The cross-section for multiple-step processes increases with the Z and also with the energy of the beam. Using a heavy stable beam from EBIS, such as ^{86}Kr or ^{132}Xe, accelerated to HIE-ISOLDE energies of around 5 MeV/u is therefore preferred, but there is much flexibility in exact choice of beam.
The Miniball Ge-detector array [14] will be used to detect the de-excitation γ rays following Coulomb excitation. This will be coupled to the new SPEDE chamber for Coulomb-excitation experiments, which adds a cooled Si detector in the upstream of the target position for conversion electron detection [15]. A double-sided silicon strip detector (DSSSD) in the forward laboratory angles will be used to detect the scattered projectiles and recoiling target nuclei. The granularity of the Miniball Ge detectors, SPEDE and the CD detector allows for Doppler correction to be applied to γ rays and a kinematic correction to the electrons emitted in flight. The particle-γ-ray coincidence intensities can then be related to the excitation cross-sections in order to extract nuclear-structure information, such as transition strengths and quadrupole moments.
The target foil will be made from isotopically enriched neodymium-oxide in the target laboratory at University of Cologne. It has the potential to oxidise quickly and should be kept under vacuum as much as possible before and during the experiment. However, contamination from different masses or from oxide layers will not affect the results of the experiment since no normalisation is required.

2.1 Beam-time estimates

Gosia calculations have been performed assuming typical REX/HIE beam energies of 3-5 MeV/u and beam species such as ^{12}C, ^{40}Ar, ^{86}Kr ^{132}Xe. In each case, the population of the 0_2^+ state is around three orders of magnitude lower than that of the 2_1^+ state. Assuming an $E0/E2$ branching ratio in the range of 1% and factoring in the relative efficiencies of SPEDE and Miniball, we expect to see more than five orders of magnitude difference between the inten-

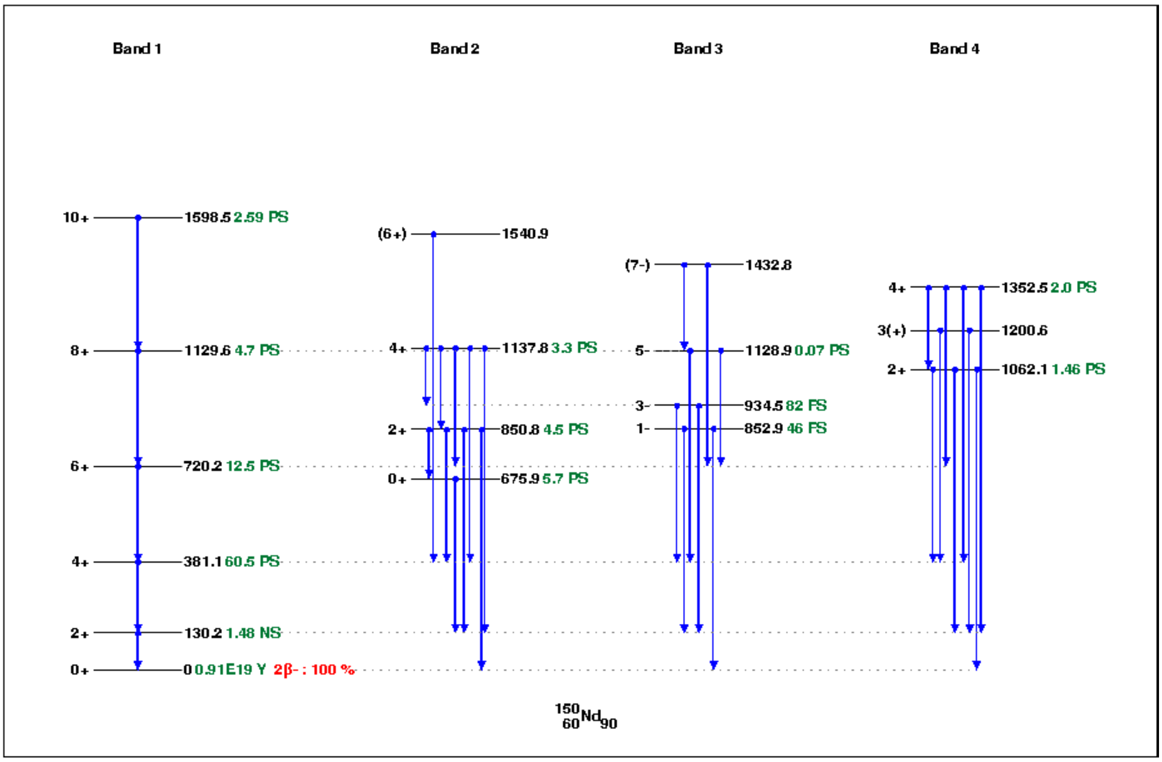

Figure 2: Level scheme of ^{150}Nd, taken from NNDC [13].

sities of the $E2(2_1^+ \to 0_1^+)$ γ-ray transition and the $E0(0_2^+ \to 0_1^+)$ conversion-electron transition. Therefore, we need to collect a large number of statistics to be sensitive to the $E0/E2$ branching ratio and hence $\rho^2(E0; 0_2^+ \to 0_1^+)$. The cross-section for exciting the 0_2^+ state increases with heavier Z beams and higher energies. We are not concerned with the usual "safe" criterion for the beam energy since we are not intending to measure electromagnetic matrix elements via the cross-section, but instead via branching ratios and complementary data. However, we do require good separation of target-like and projectile-like events in the DSSSD detector, in order to perform good Doppler and kinematic corrections. Therefore, we request a beam of ^{86}Kr at 5.0 MeV/u and an intensity at Miniball of 2×10^6 pps, to limit the effects of the δ-electron flux. Under these conditions, we expect to see ≈ 50 counts per day in the $E0(0_2^+ \to 0_1^+)$ conversion electron transition. Simulated spectra (without background) are shown in Fig. 3, which show the expected number of counts after 10 days of beam time. A doublet is present at the energy of the $E0$ transition of interest, which is clear from the larger width of the peak. This can be deconvoluted using fitting procedures and γ-γ or γ-e^- coincidence techniques. To reach a precision of $< 5\%$ and be comparable with the precision on the lifetime of the 0_2^+ state [16], we would like to have at least 500 counts in the $E0$ peak corresponding to 10 days (or 30 shifts) of stable beam.

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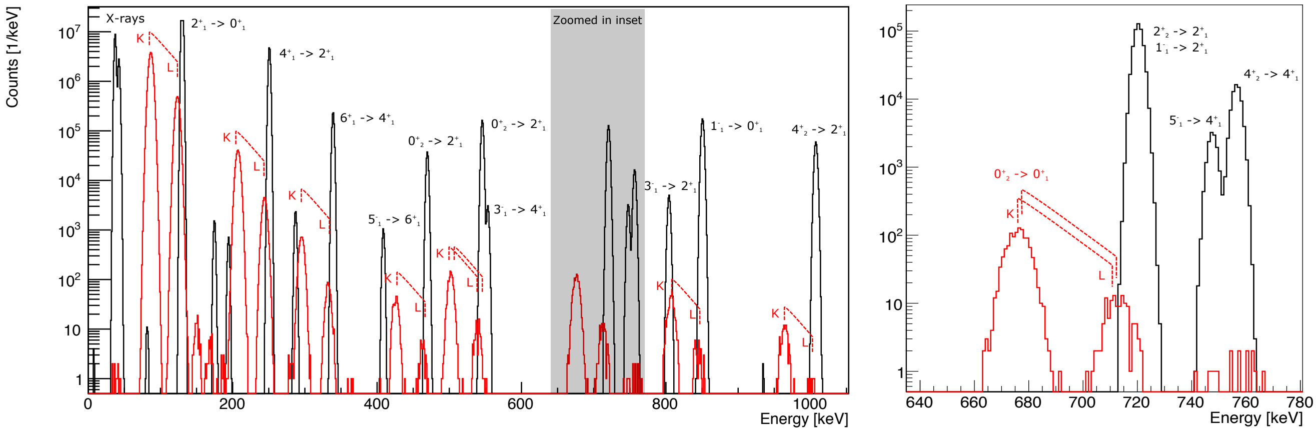

Figure 3: Simulated γ-ray (black) and electron (red) spectra following Coulomb excitation of 2.0 mg/cm^2-thick ^{150}Nd target by a ^{86}Kr beam at 5.0 MeV/u. Ten days of beam on target at an intensity of 2×10^6 pps is assumed. The γ-ray transition have been labelled and their corresponding K and L electon peaks are indicated. The $E0(0_2^+ \rightarrow 0_1^+)$ transition is marked in the expanded spectrum on the right, where contamination from conversion of the $1_1^- \rightarrow 2_1^+$ and $2_2^+ \rightarrow 2_1^+$ peaks is clear.

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