EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of the $E2$ excitation strength of ^{154}Nd through Coulomb excitation

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Abstract: With modern theory, e.g., large space shell model calculations, becoming available for detailed predictions of heavy deformed nuclei, there is an increasing interest in the evolution of structure in such regions. In particular, the evolution of $B(E2)$ excitation strengths and excitation energies in the (neutron-rich) rare earth region poses a puzzling situation. Whereas low values of the excitation energies of the first excited 2^+ states in even-even deformed nuclei gives rise to large moments of inertia, hence, large quadrupole deformation, this should be mirrored by large $B(E2)$ transition strength from those states to the ground state. The opposite, however, seems to be the case across the rare earth region toward the ^{170}Dy mid-shell isotope, which to date lacks explanation. ^{154}Nd, at the beginning of this highly-deformed region has an astonishingly small literature value of the $B(E2; 2_1^+ \to 0_1^+)$ strength, and is well accessible at HIE-ISOLDE. We intend to remeasure this $B(E2)$ value, using Coulomb excitation of a ^{154}Nd beam. However, while a laser ionization scheme has previously been developed for the lighter ^{140}Nd, a ^{154}Nd beam has never been produced at HIE-ISOLDE and the achievable purity is uncertain. In addition, the measurement is challenging due to the low excitation energy of the 2_1^+ state. Therefore, we ask for a test of the beam, as well as the thresholds achievable with MINIBALL and the amounts or background produced using targets of different mass regions, in order to prepare for an optimized experiment.

Requested shifts: 4 shifts, (unsplit in 1 run)

1 Physics motivation

One of the largest regions of strongly deformed isotopes is that in the vicinity of rare earth isotopes, centered around ^{170}Dy, which marks the middle of both, the $Z = 50 - 82$ proton and $N = 82 - 126$ neutron shells. In this isotope, neglecting any effects from the underlying orbital structure, the valence space can be expected to be maximum, and in accordance with the N_pN_n scheme [1] collectivity should be largest. This should be manifested in a maximum of quadrupole deformation, hence, a maximum moment of inertia, reflected by a minimal energy of the first excited 2^+ state and a maximum $B(E2; 2_1^+ \rightarrow 0_1^+)$ value. Therefore, one should expect that, coming from the low-A end of the valence shell, 2_1^+ energies drop and their $B(E2)$ strength rise toward mid-shell, and reverse that trend approaching the end of the valence shell at large A.

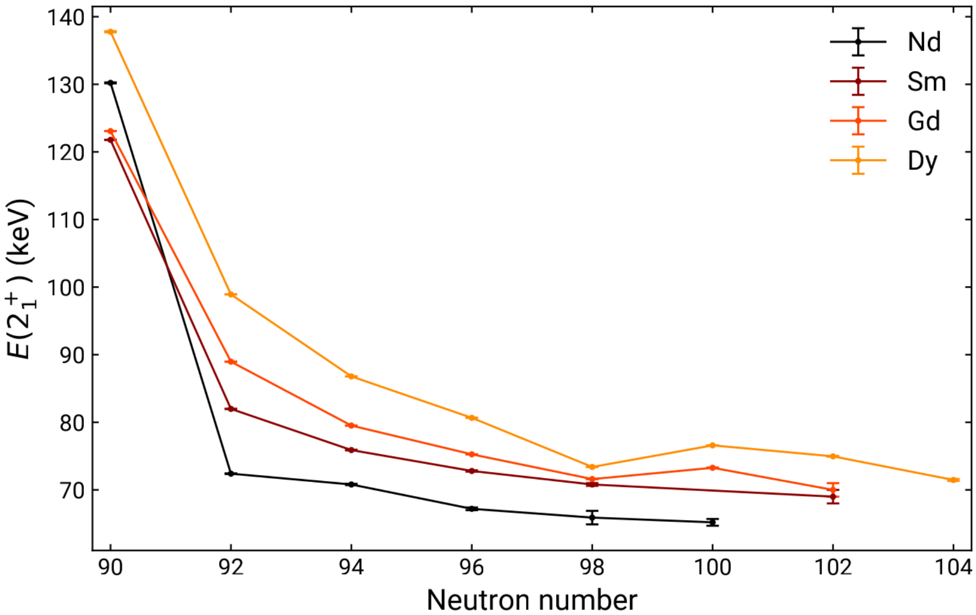

Figure 1: Energies of the first 2^+ states of Nd-Dy isotopes from the onset of deformation toward mid-shell. (Source: NNDC)

This scheme is, exemplarily, depicted in Figs. 1 and 2, showing respective experimental values for Nd, Sm, Gd, and Dy isotopes. Overall, the 2_1^+ energies show the expected behavior along each isotopic chain, minimizing toward mid-shell. It is, however, striking that the 2_1^+ energies of the deformed Nd isotopes are significantly lower than those of the more mid-proton shell isotopes. Overall, there is a minimization of 2_1^+ energies toward lower Z, which yet needs to be understood. $B(E2)$ values of the Sm, Gd, and Dy isotopes show the expected rise toward mid-shell - whether a similar unexpected trend toward the lower-Z isotopes arises as for the 2_1^+ energies is, to date, unknown and will be subject to future rare-isotope beam experiments, in particular of the accepted DESPEC experiment S100 at GSI. ^{154}Nd, in particular, is within the range of ISOLDE at high intensities, hence, HIE-ISOLDE is the facility of choice to give a reliable value for the $B(E2)$ strength of the 2_1^+ state, and to give a reliable anchor point for further studies, e.g., using beams from fragmentation at high energies.

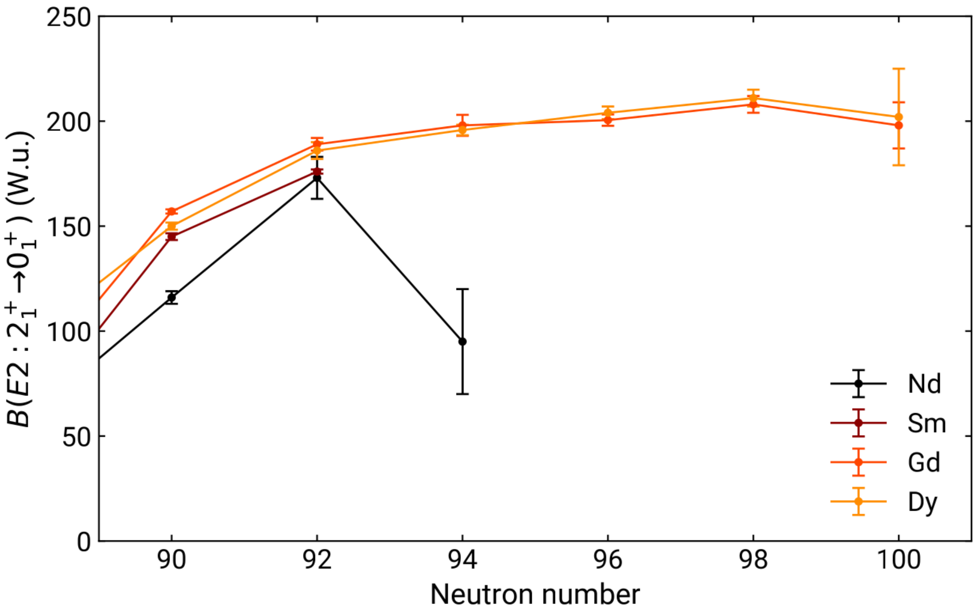

Figure 2: $B(E2)$ values of the first 2^+ states of Nd-Dy isotopes from the onset of deformation toward mid-shell. (Data: NNDC)

However, the trend of $B(E2)$ values in the Nd isotopic chain (see Fig. 2) shows a glaring disagreement with any expectation for the onset of deformation. Namely, the $B(E2)$ value of ^{154}Nd drops by more than 30 % relative to its lighter neighbor ^{152}Nd. Before further exploring the above-mentioned inconsistency of interpretation of the 2_1^+ behavior, this surprisingly low $B(E2)$ value of ^{154}Nd must be scrutinized. The literature value stems from a measurement following fission of a Cf source [2] from 1974. Given the status of γ detection technology at the time, and the multitude of γ-rays in the energy region of interest emitted in spontaneous fission, that value needs to be remeasured using more modern techniques. Should the literature value hold, it would be a challenge to any nuclear theory. The interest in deformed regions is boosted by its increased accessibility by modern theory, including shell model calculation as in Ref. [3]. Based on similar calculations, namely, potential energy surfaces, from the Tokyo group [4], the expected trend for the Nd isotopes is a steady build-up of deformation toward mid-shell, rather than a drop at $N = 94$.

2 Experimental approach

The lifetime of the 2_1^+ state of ^{154}Nd is in the nano-second range and, therefore, in reach for multiple techniques. A fast-timing measurement using fast scintillators would be possible, however, may suffer from the proximity of γ-rays from other isotopes, which, in this deformed region of the nuclear chart, may be too close in energy to be resolved even by modern scintillators. We intend to use Coulomb excitation in combination with HPGe (Miniball) detectors to obtain the $E2$ matrix element of the 2_1^+ state. Although the high electron conversion factor $\alpha = 7.79$ will suppress the γ-ray signal, the Coulomb-excitation

cross section for such a low-energy $E2$ excitation with a $B(E2)$ value in the range of 100 W.u. will more than compensate for the losses from conversion. Furthermore, a Coulomb-excitation experiment is very likely to give complementary information on higher-lying states, in particular the ground-state band, through multi-step Coulomb excitation of ^{154}Nd.
However, the measurement of the 2_1^+ $B(E2)$ value is a challenge for the following reasons:

- A ^{154}Nd beam has so far not been done at HIE-ISOLDE, therefore the available beam intensity and purity needs to be verified. A laser scheme has been developed for the isotope ^{140}Nd [5].
- The 2_1^+ state occurs at an energy of 70.8 keV. Therefore, it must be ensured that the thresholds of the Miniball detectors can be sufficiently low, and detection efficiencies at that energy must be calibrated.
- Depending on beam purity, the influence of eventual contaminating transitions and more importantly of background at that low energy needs to be checked.

On the first point we note that a laser ionization scheme had previously been developed for experiments using a ^{140}Nd beam, which should help in the first extraction of the desired ^{154}Nd beam. However, beam impurities can be much different for this much heavier region. The excitation energies of 2_1^+ state of potential contaminants (typically, isobars) in the beam are at least 10 keV away from that of ^{154}Nd. Therefore, these should not be a problem for the measurement. The background at the low energies will depend on the amount of γ rays at higher energies, hence, their Compton background. This also includes the target excitation. We intend to try multiple targets, for which the excitation energy of the respective 2_1^+ target state is low enough to ensure sufficient excitation yield, to probe for which the balance between statistics in the 2_1^+ decay versus related Compton background at 70 keV is optimal.
On the second point - for the efficiency calibration a ^{133}Ba source can be used for energies down to about 80 keV, and x-rays from a ^{226}Ra source could be used. However, it would be favorable to do off-beam measurements of the ^{154}Nd beam, implanted into a stopper (e.g., Copper) target within Miniball. The decay daughter, ^{154}Pm emits low-energy γ rays at 68 keV and 72 keV, as well as higher energies, which would determine the relative efficiency at these energies. With a half-life of ^{154}Nd of 26 seconds, this measurement could be done with beam-on/beam-off periods.
With the information obtained in this test experiment we will be able to verify the possibility, and ensure the optimum conditions for a longer measurement. We will employ Miniball and a silicon CD detector, in order to gate on outgoing target-like particles. Therefore, the beam and target masses must be sufficiently separated. Through the different Doppler shift for target- and beam-like recoils, narrow peaks can be achieved for both, the 2_1^+ target and beam excitations, allowing for the relative measurement between both. Standard targets available are ^{58}Ni, ^{94}Mo, and ^{112}Cd. The use of heavy targets, e.g. ^{196}Pt or ^{208}Pb is not possible due to their x-rays being in the energy range of interest. The ^{112}Cd target would be most interesting, since it would allow for a simultaneous measurement of the 4_1^+ cross section due to the higher excitation yield.

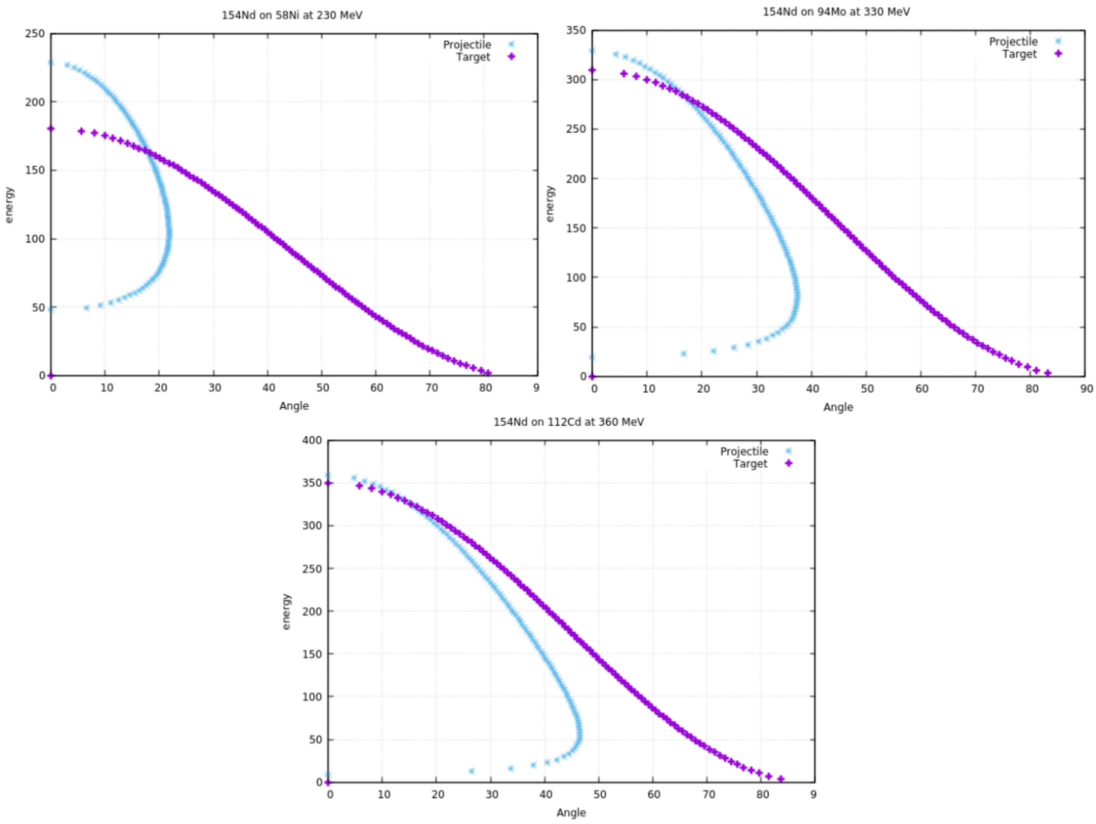

Figure 3: Kinematics of ^{154}Nd on ^{58}Ni, ^{94}Mo, and ^{112}Cd targets at respective energies of 230 MeV, 330 MeV, and 360 MeV.

Beam energies that ensure safe Coulomb excitation at an angular coverage of 20-60° of the particle detector are

- ^{58}Ni - 230 MeV (1.5 MeV/u).
- ^{94}Mo - 330 MeV (2.15 MeV/u).
- ^{112}Cd - 360 MeV (2.34 MeV/u).

The kinematics plots for all three cases, given in Fig. 3, show that a separation of beam- and target-like particle will be possible. In all cases x-rays from the target are below 30 keV, those of Nd are well below 50 keV. Therefore, x-rays do not impose a problem. Assuming the literature value of 95(25) W.u. for the $B(E2)$ strength of the 2_1^+ state of ^{154}Nd, therefore even an (unlikely) lower limit of 75 W.u., we calculate lower limits of the excitation and detection yields of the 2_1^+ state, further assuming 5 % γ efficiency and a beam intensity of 10^5 pps and thicknesses of available targets from the ISOLDE website. Similarly, we also include the 4_1^+ state in the estimates. The resulting yields are:

Target and Energy	State	Energy [keV]	x-section [b]	Yield [γ/d]
2 mg/cm^2 ^{58}Ni	2_1^+	70.8	1.76	1800
230 MeV	4_1^+	233.2	7.5×10^{-3}	68
2 mg/cm^2 ^{94}Mo	2_1^+	70.8	4.69	2950
330 MeV	4_1^+	233.2	0.10	564
2 mg/cm^2 ^{112}Cd	2_1^+	70.8	6.14	3240
360 MeV	4_1^+	233.2	0.20	928
^{112}Cd target excitation	2_1^+	617.0	0.56	2604

We note that, in case that contaminants in the beam are strong, we may switch to a beam-on/beam-off mode. Assuming a ratio of 1 between both modes, the above-mentioned γ-ray yields will be half.
For all three targets the γ-ray yields for the 2_1^+ decay of ^{154}Nd (which take into account the dominating electron conversion) are large enough to ensure observation of a peak within hours, if background conditions and beam purity are favorable. All three targets are listed as available on the ISOLDE website. The ^{112}Cd target we consider the most promising candidate due to its high Z giving the opportunity to also significantly excite the 4_1^+ state which is a secondary goal of the experiment. The ^{112}Cd excitation yield is high enough to allow for good estimates for a future run, based on observed peak areas. The relatively low-Z ^{58}Ni target would only be used for a few hours (less than 1 shift) to check for the background at the 2_1^+ excitation energy and feasibility to extract a reliable peak area. We would then switch for 1 shift to a ^{94}Mo target, in order to probe the excitation of the 4_1^+ state in this medium-Z target resulting in somewhat different background.

Summary of requested shifts:

- **1 shift** for ^{154}Nd stoppe in a 10 mg/cm^2 Cu target for efficiency calibration.
- **1 shift** for ^{154}Nd impinging on a Ni target.
- **1 shift** for ^{154}Nd impinging on a Mo target.
- **1 shift** for ^{154}Nd impinging on a Cd target.

References

[1] R. F. Casten, Phys. Lett. B **152**, 145 (1985); Nucl. Phys. A **443**, 1 (1985).

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[3] T. Otsuka, Y. Tsunoda, T. Abe, N. Shimizu, and P. Van Duppen, Phys. Rev. Lett. **123**, 222502 (2019).

[4] T. Otsuka, *private communication.*

[5] R. Kern *et al.*, Phys. Rev. C **102**, 041304(R) (2020).

DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
If relevant, write here the name of the fixed installation you will be using [Name fixed/present ISOLDE installation: Miniball]	☒ To be used without any modification ☐ To be modified
If relevant, describe here the name of the flexible/transported equipment you will bring to CERN from your Institute [Part 1 of experiment/ equipment]	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	

Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			