EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

(Following HIE-ISOLDE Letter of Intent INTC-I-106)

Study of the effect of shell stabilization of the collective isovector valence-shell excitations along the N=80 isotonic chain

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Abstract: It is proposed to investigate the microscopic mechanism which leads to a concentration or a fragmentation of the quadrupole-collective isovector valence-shell excitations, the so-called mixed-symmetry states (MSSs), an effect called *shell stabilization* of MSSs. This aim will be achieved by identification of MSSs of the unstable nuclei ^{140}Nd and ^{142}Sm. The first steps of this program have been undertaken in two subsequent REX-ISOLDE experiments (IS496) in which we have measured the $B(E2; 2^+_1 \rightarrow 0^+_1)$ transition strengths in the radioactive nuclei ^{140}Nd and ^{142}Sm. By using these data and the higher beam energy of HIE-ISOLDE we propose now to identify the MSSs of these nuclei by measuring their relative populations with respect to the population of the first 2^+ states in Coulomb excitation (CE) reactions.

Requested shifts: 42 shifts (can be split into 2 runs (18+24 shifts) over 2 years)
Installation: [MINIBALL + CD-only] or [MINIBALL + T-REX]

1 Physics case - shell stabilization phenomenon in the mass A $\approx$ 130 region

Atomic nuclei are examples of mesoscopic two-fluid quantum systems. The physics of these systems is determined by three main properties: the many-body aspect, the quantum nature, and the two-fluid character. Nuclear phenomena that reflect these three properties are collectivity, shell structure, and the isospin degrees of freedom. The Quadrupole-collective isovector valence-shell excitations, so-called mixed-symmetry states (MSSs) [1, 2], represent a unique quantum laboratory in which the balance and interplay between the nuclear collectivity, the shell structures, and the isospin degree of freedom can be studied. The structure and the characteristics of MSSs are determined by the effective proton-neutron (p-n) correlations in the valence shell of collective nuclei. Their excitation energies are directly related to the proton-neutron symmetry energy in the valence shell. The most distinct feature of MSSs is the existence of allowed $M1$ transitions to fully-symmetric states (FSSs). This is of importance because the $M1$ transitions are forbidden between FSSs and can, thus, very well serve as a unique signature for MSSs. The fundamental MSS in weakly collective vibrational nuclei is the one-quadrupole phonon $2^+_{1,\mathrm{ms}}$ state [1] which is the lowest-energy isovector quadrupole excitation in the valence shell.
Available information on MSSs of vibrational nuclei has recently been summarized in a review article [3]. MSSs have been observed so far in stable nuclei only except for the case of ^{132}Te [4]. The best examples are found in the mass A$\approx$90 regions [3, 5–13]. Until recently only a few cases have been known in mass A$\approx$130-140 region [14–17]. An unambiguous identification of MSSs can be done only on the basis of measured large absolute $M1$ strengths. To obtain this experimental information, one needs to perform several experiments [3]. Projectile Coulomb excitation reactions in combination with a large γ-ray array was suggested recently as a solution for this methodological problem [18]. Even though this technique was exploited before to study MSSs [5], its full potential was revealed in the past few years; by using projectile Coulomb excitation reactions and the Gammasphere array at Argonne National Laboratory, the one-phonon MSSs were identified in several low-abundant stable nuclei [18–22]. This experimental technique can straightforwardly be applied to radioactive ion beams (RIBs). The data yield the $E2$ and $M1$ strength distributions between low spin states which reveals the $2^+_{1,\mathrm{ms}}$ state.
These data also reveal novel interesting physics phenomena. Examples are given by the data on the N = 80 isotones ^{138}Ce [18], ^{134}Xe [19], and ^{136}Ce [20, 21]. In contrast to the isotone ^{136}Ba [17], the $2^+_{1,\mathrm{ms}}$ state of ^{138}Ce is strongly mixed with a nearby 2^+ (see Fig. 1). This dramatic change in the properties of MSSs when only two protons are added to the system, suggests for the first time that the strength concentration of collective-isovector excitations in the valence shell reflects the underlying single-particle structure through a mechanism dubbed *shell stabilization* [18]. The observed mixing in ^{138}Ce is attributed to the lack of *shell stabilization* [18] at the $\pi g_{7/2}$ subshell closure. This hypothesis was partially confirmed by observing a single well-pronounced one-phonon MSS of ^{134}Xe [19]. On the other hand the observation of single isolated one-phonon MSS of ^{136}Ce [21] has indicated the importance of neutron degrees of freedom for fragmentation of MSSs. All these experimental data lead to the conclusion that **a direct experimental**

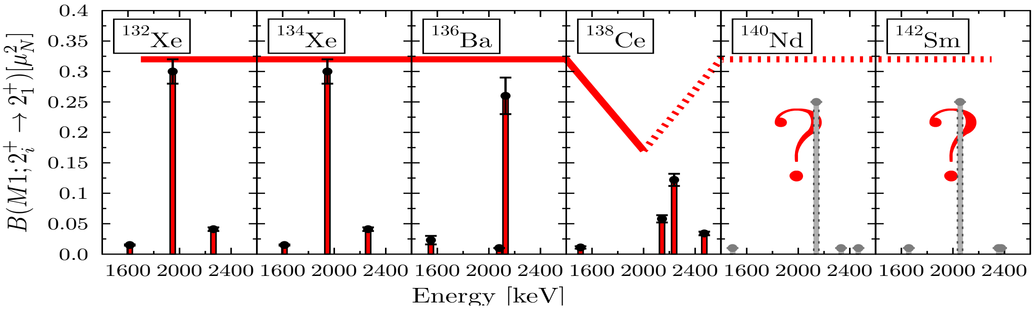

Figure 1: Systematics of the $B(M1; 2_i^+ \rightarrow 2_1^+)$ strength in the N=80 isotones. In contrast to the $2^+_{1,\mathrm{ms}}$ states in the neighboring isotones the $2^+_{1,\mathrm{ms}}$ state of ^{138}Ce is strongly mixed and it is not clear at all how the trend continues in ^{140}Nd and ^{142}Sm.

confirmation of the mechanism of shell stabilization in the $N = 80$ isotones, which is a phenomenon related to the proton structure, should be sought for by identifying the MSS in ^{140}Nd and ^{142}Sm [21].

The data on MSSs of stable $N = 80$ isotones and the suggested mechanism of shell stabilization have also initiated theoretical investigations. The properties of MSSs of stable $N = 80$ isotones were studied with the quasiparticle-phonon model (QPM) [23] and the large-scale shell model (SM) [24]. Both models have demonstrated that the splitting of the $M1$ strength in ^{138}Ce is *a genuine shell effect caused by the specific shell structure and the pairing correlations* [23, 24].

Although the microscopic models agree that the stability of MSSs is related to the single-particle structure and some parts of the nucleon-nucleon interaction, the generic nature of the shell stabilization is not yet proven even for the $N = 80$ isotones. The stable nuclei in this isotonic chain, $^{134}_{54}$Xe$_{80}$, $^{136}_{56}$Ba$_{80}$ and $^{138}_{58}$Ce$_{80}$, cover the sequential filling of the $\pi g_{7/2}$ orbital at proton number $Z = 58$, only. To fully demonstrate the shell stabilization mechanism, the investigation of MSSs in the $N = 80$ isotonic chain has to be extended beyond the proton number $Z = 58$, *i.e.*, to the unstable nuclei $^{140}_{60}$Nd$_{80}$ and $^{142}_{62}$Sm$_{80}$ (see Fig. 1). The theoretical models do not provide unambiguous predictions for the properties of MSSs of ^{140}Nd. SM calculations with a modified pairing matrix elements predict a single isolated MSS for ^{140}Nd [24], while the QPM predicts a fragmentation [25]. Moreover, the available theoretical microscopic calculations for ^{140}Nd [25, 27, 28] neither can provide unambiguous predictions for the energy of the main fragment of the one-phonon MSS of ^{140}Nd nor can describe the sudden increase of collectivity observed through the $B(E2; 2_1^+ \rightarrow 0_1^+)$ [28]. This is evident from the comparison of the available experimental data and the QPM calculations [25, 28] presented in Table 1. This situation prompts an experimental identification of MSSs of ^{140}Nd. In an attempt to identify candidates for one-phonon $2^+_{1,\mathrm{ms}}$, ^{140}Nd was investigated in a $\gamma\gamma$-angular-correlation experiment following the ϵ/β^+ decays of ^{140}Sm and ^{140}Pr [26]. This measurement shows that the 2_3^+ and the 2_4^+ states of ^{140}Nd at 2140 keV and 2332 keV, respectively, decay predominantly by $M1$ transitions to the 2_1^+ state [26].

Hence, both states have to be considered as candidates for the one-phonon $2^+_{1,\mathrm{ms}}$ of ^{140}Nd [26]. As a result, neither the available experimental information, nor the theoretical predictions allow for any decisive conclusion on whether and how the effect of shell sta-

Table 1: Properties of the low-lying 2^+ states of ^{140}Nd predicted by the microscopic QPM [25, 28]. The calculations were performed using the same parameters as in Ref. [23].

E_{level}(keV)		J^π	$B(M1; 2_i^+ \to 2_1^+)(\mu_N^2)$		$B(E2; 2_i^+ \to 2_1^+)$ (W.u.)^{2,3}	$B(E2; 2_i^+ \to 0_1^+)$ (W.u.)^3	
EXP.^{1}	QPM ^{2}		EXP.	QPM^2		EXP.	QPM^2
773	757	2_1^+				$34(3)^4$	21
1489	1570	2_2^+		0.005	26		1.1
2140	2153	2_3^+	$> 0.07^{+0.055}_{-0.02}$	0.02	3.2	$> 0.6^5$	10^{-4}
2332	2267	2_4^+		0.17	4.5		9.3

^{1}Experimentally observed levels. From Refs. [26, 29].
^{2}QPM calculations from Ref. [25, 28]
^{3}1 W.u. = 43.2 e^2fm^4
^{4}From the Coulomb excitation experiment IS496 [28]
^{5}From the effective lifetime reported in Ref. [29]

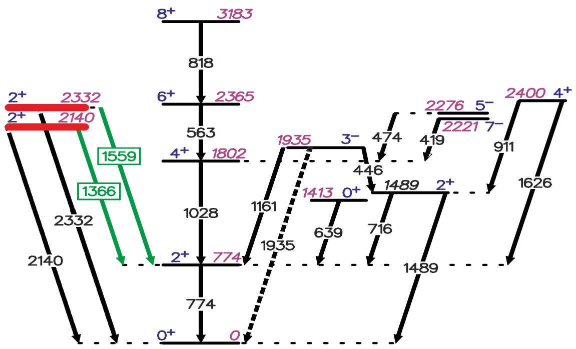

Figure 2: Partial level scheme of ^{140}Nd, candidates for the one-phonon MSS [26] given in red.

bilization is present in ^{140}Nd. Apparently, this can be resolved only by measuring the absolute $M1$ strengths of the 1366.2-keV and 1558.6-keV transitions. Such an attempt has been made by using the DSA method in the reaction ^{140}Ce (^{3}He,3n)^{140}Nd [29]. An effective lifetime of 220(90) fs has been measured for the 2_3^+ state at 2140 keV of ^{140}Nd (see Fig. 2). This fast $M1$ decay identifies the 2_3^+ state at 2140 keV, at least, as a fragment of the one-phonon MSS of ^{140}Nd. However, the data are not conclusive on whether this decay exhausts the total $M1$ strength and whether the one-phonon MSS of ^{140}Nd is fragmented or not. From a methodological point of view the study presented in Ref. [29] has clearly demonstrated the limitation of the experimental techniques based on beams of stable nuclei on studies of MSSs in radioactive nuclei. It has proven that *the only reliable experimental technique which can reveal all properties of the MSS of radioactive nuclei is Coulomb excitation reactions.*

2 Experimental details

The present proposal aims to identify the one-phonon MSSs of the unstable nuclei ^{140}Nd and ^{142}Sm. This identification will reveal the microscopic structure of MSSs which should provide quantitative answers to the following questions:

- Is the effect of shell stabilization of the MSSs of such a general nature that can be expected to be present in ^{140}Nd and ^{142}Sm in the same way as observed in the stable $N = 80$ isotones [18]?

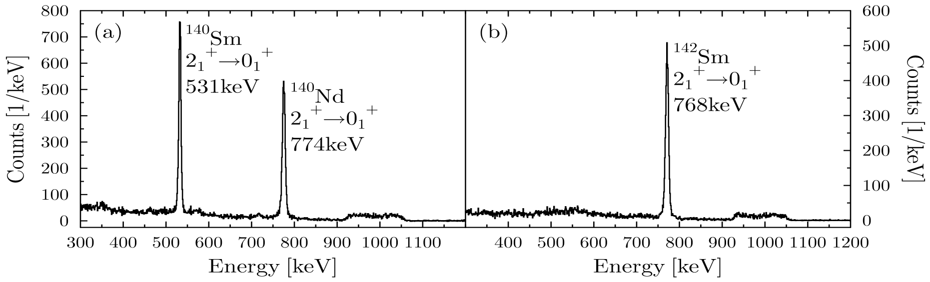

Figure 3: Background-subtracted particle-γ coincidence spectra applying Doppler-correction with respect to the projectiles from our IS496 experiments. The observed $2_1^+ \to 0_1^+$ transitions in (a) ^{140}Nd at 774 keV (2011, ^{140}Sm contaminant at 531 keV) and in (b) ^{142}Sm at 768 keV (2012) are shown. Both spectra are taken just with lasers on and a 1.4mg/cm^2 ^{48}Ti target.

- Is the microscopic description of the MSSs of the stable N=80 isotones obtained in the framework of the QPM [23] and large-scale SMs [24, 27] also applicable to the MSS of ^{140}Nd and ^{142}Sm?
- How the sudden increase of collectivity in ^{140}Nd and ^{142}Sm which is observed through the $B(E2; 2_1^+ \to 0_1^+)$ values [28] influences the properties of one-phonon MSSs in these nuclei?

As discussed above the only clear approach to these questions is via the identification of the MSSs of ^{140}Nd and ^{142}Sm which is possible in Coulomb excitation reactions. In the REX-ISOLDE experiment IS496 the RILIS radioactive ion beams of ^{140}Nd and ^{142}Sm have been developed. These beams were successfully delivered to the MINIBALL set-up for Coulomb excitation yield measurements and γ spectra from these experiments are shown in Fig. 3. The beam intensity was estimated to be about 4×10^5 pps for both isotopes. The RILIS ionization scheme has proven to be quite efficient in both measurements. The ^{142}Sm beam was essentially free of contaminants (Fig. 3 (b)) while the ^{140}Nd beam was contaminated up to 40 % with ^{140}Sm (Fig. 3 (a)). Here, we propose to perform analogous measurements at HIE-ISOLDE for these two nuclei, but at higher beam energy which will allow us to populate the MSSs of ^{140}Nd and ^{142}Sm. Instead of the ^{48}Ti target we intend

Table 2: Coulomb excitation (CE) yields for the 2^+ states of ^{140}Nd using the code CLX [30]. The CE cross-sections result from integration over the angular range of interest (22°-52°) and the γ-ray yields are presented for 3 shifts (1 day) running time, laser-on mode. This calculations represents an extrapolation from our measurements in 2011 at 2.85 MeV/u (^{48}Ti, first column) to 3.62 MeV/u for the ^{52}Cr target and 4.5 MeV/u for the ^{208}Pb target, corresponding to 85% of the Coulomb barrier in the latter 2 cases to ensure "safe" CE.

E_{level} (keV)	J^π	1.4mg/cm^2 ^{48}Ti		2.0mg/cm^2 ^{52}Cr		2.0mg/cm^2 ^{208}Pb	
		σ (mb)	γ-ray yields	σ (mb)	γ-ray yields	σ (mb)	γ-ray yields
774	2_1^+	296	5000	714	17228	2242	54114
1490	2_2^+	1.76	30	14	328	100	2421
2140	2_3^+	0.01	0.2	0.3	7.4	2.8	68
2267[1]	2_4^+	0.44	**7.4**	6.1	**147**	8.1	**196**
2468[1]	2_5^+	0.01	0.2	0.4	8.6	3.0	72

[1]QPM predictions for the level energies

to use ^{52}Cr due to the fact that the γ-rays from the target excitation of ^{52}Cr interfere less with the γ-rays from the projectile excitation. We propose to start these measurements with an experiment devoted to the identification of the one-phonon MSS in ^{140}Nd since in this nucleus there are states that are suspected to be the one-phonon MSSs (see Fig. 2). The multipole mixing ratios and the branching ratios for the γ-decays of these states have already been measured in Ref. [26].

The Coulomb excitation (CE) population of the one-phonon MSS is estimated based on the QPM calculations presented in Table 1. The necessary beam time is estimated by scaling the CE yields from the ^{48}Ti(^{140}Nd, ^{140}Nd*) reaction at 2.85 MeV/u (IS496 experiment) to the ^{52}Cr(^{140}Nd, ^{140}Nd*) reaction at 3.62 MeV/u (85 % of Coulomb barrier). The result is presented in Table 2 and clearly indicates the dependency of the CE cross-sections on energy and Z. The calculations are based on the standard setup of MINIBALL and CD in forward direction. The numbers for a ^{208}Pb target are included to present an alternative target using regular kinematics. At 630 MeV, however, the beam energy is above the fusion/fission threshold for lighter material in the chamber (Al/Fe). We expect from the experience of the first runs at HIE-ISOLDE to learn if this can be a problem in terms of too high count-rates in MINIBALL or contaminated γ-ray spectra. The kinematics plot for the ^{52}Cr(^{140}Nd, ^{140}Nd*) reaction at 3.62 MeV/u is presented in Fig. 4. We will normalize the observed CE yields to the one of the 2^+_1 state in ^{140}Nd which will allow us to extract the absolute excitation strengths to higher-lying states by using the already measured $B(E2; 2^+_1 \rightarrow 0^+_1)$ value which is the main result from the experiment IS496 [28]. This experimental approach allows the whole experiment to be performed in laser-on mode only. Based on the scaling in Table 2 and the measured branching ratios it is clear that the necessary statistics (3-4 % statistical uncertainty in the peak area of the $2^+_{1,\mathrm{ms}} \rightarrow 2^+_1$ transition) can be accumulated for about 6 days. We assume that the case of ^{142}Sm is similar, but since the branching and the multipole mixing ratios are not known in this case we will need additionally 2-3 days in order to accumulate statistics that will allow for performing γ-particle angular-correlation analysis.

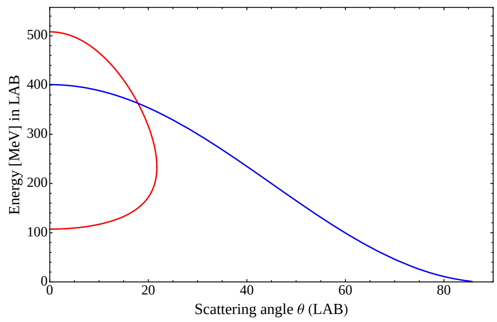

Figure 4: Kinematics of the ^{52}Cr(^{140}Nd, ^{140}Nd*) reaction at 3.62 MeV/u. Projectiles are indicated in red, target recoils in blue.

Summary of requested shifts: 42 shifts (18 for ^{140}Nd, 24 for ^{142}Sm) without setup

- **18 shifts** for CE yield measurements of ^{140}Nd beam at 3.62 MeV/u on a 2.0 mg/cm^2 ^{52}Cr target in laser on mode (+3 shifts setup);
- **24 shifts** for CE yield measurements of ^{142}Sm beam at 3.62 MeV/u on a 2.0 mg/cm^2 ^{52}Cr target in laser on mode (+3 shifts setup);

Installation: [MINIBALL + CD-only] or [MINIBALL + T-REX]

Our calculations consider the standard Coulex setup with MINIBALL and the CD in forward direction. In case of the T-REX setup we can compensate the small loss in γ-ray efficiency by the larger range of covered scattering angle by the T-REX particle detectors.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
[MINIBALL + only CD] or [MINIBALL + T-REX]	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

No additional hazards are mentioned here because the fixed-ISOLDE installations are used.