EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Investigation of the evolution of collective isovector valence-shell excitations in the N=84 isotones

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Abstract: It is proposed to investigate the evolution of collective isovector valence-shell excitations in the N=84 isotonic chain by identifying the first mixed-symmetry 2^+ state of ^{138}Xe and ^{140}Ba. The $2^+_{\mathrm{ms},1}$ can be identified by the determination of the $B(M1; 2^+_{\mathrm{ms},1} \rightarrow 2^+_1)$ transition strength in a Coulomb-excitation experiment. Therefore, ^{138}Xe and ^{140}Ba radioactive ion beams with an energy of 500 MeV provided by HIE-ISOLDE will impinge on a ^{206}Pb target. This reaction will ensure the population of the 2^+_3 state which is the most probable candidate for the first mixed-symmetry 2^+ state in both isotopes. The MINIBALL array will be used for gamma-ray detection and a double-sided silicon-strip detector will be placed in forward beam direction to set particle-gamma conditions.

Requested shifts: 36 shifts, (split into 2 runs over 2 years)

1 Motivation and physics case

Atomic nuclei, mesoscopic two-fluid quantum systems, exhibit complex dynamics governed by collectivity, shell structure, and isospin degrees of freedom. The interplay and balance of these three nuclear phenomena can be studied through quadrupole-collective valence-shell excitations, which result from the mixture of the underlying pure proton and neutron excitations. The isoscalar part of the quadrupole-collective excitations can be described by an in-phase combination of proton and neutron contributions. The corresponding configuration is called fully symmetric. An isovector configuration, in which the oscillation of protons and neutrons is out of phase, is called mixed-symmetric configuration [1, 2]. The interaction of protons and neutrons in the valence shell of even-even nuclei determines the structure and characteristics of mixed-symmetry states (MSSs) and the proton-neutron symmetry for even-even nuclei can be quantified in algebraic models, such as the Interacting Boson Model 2, by the F-spin [1, 3]. MSSs create a whole new class of collective excitations, with the one-quadrupole phonon $2^+_{\mathrm{ms},1}$ state representing the lowest lying configuration for heavy vibrational nuclei [1]. This $2^+_{\mathrm{ms},1}$ state can be experimentally identified by it's distinct signatures [4]. The most unique feature is a strong M1 transition to the lowest-energy fully-symmetric state (FSS), the 2^+_1 state. The weakly collective E2 ground-state transition is another distinct observable of the $2^+_{\mathrm{ms},1}$ state.
MSSs have been observed in stable and radioactive nuclei, most commonly in the mass A≈90 region [5–11], and most recently in the mass A≈208 region [12–14]. Furthermore, in the region around the doubly-magic ^{132}Sn, the evolution of the $2^+_{\mathrm{ms},1}$ state has been investigated in the N = 80 isotonic chain for Z = 52-60 [15–19]. Most recently, new results on the B(M1;$2^+_{\mathrm{ms},1} \rightarrow 2^+_1$)value of ^{132}Te have been obtained by our group. The M1 transition strength of the $2^+_{\mathrm{ms},1}$ state of ^{132}Te was previously determined in a Coulomb-excitation experiment at Oak Ridge National Laboratory by an evaluation of a low-intensity transition and therefore had a large uncertainty in the B(M1;$2^+_{\mathrm{ms},1} \rightarrow 2^+_1$)strength [15]. This key value in ^{132}Te has now been precisely determined through a direct lifetime measurement with the Doppler shift attenuation method in a two-neutron transfer reaction at the 9-MV tandem accelerator at IFIN-HH in Bucharest. On the other side of the so-far investigated N = 80 isotones, the $2^+_{\mathrm{ms},1}$ state of ^{142}Sm has been identified for the first time through the measurement of the B(M1;$2^+_{\mathrm{ms},1} \rightarrow 2^+_1$)strength in a Coulomb-excitation experiment performed at HIE-ISOLDE by our group [20]. A β-decay experiment to obtain the missing multipole mixing ratio of this transition from $\gamma\gamma$ angular correlations measurements is currently under analysis by our group. The experiment was performed at the Heavy Ion Laboratory in Warsaw, Poland and the current status of the analysis strongly points to an almost pure M1 transition and therefore confirms the 2^+_3 state as the main component of the $2^+_{\mathrm{ms},1}$.
One reason for the search for the first mixed-symmetry 2^+ state in the N = 80 isotonic chain is to probe the restoration of F-spin symmetry above Z = 58. Breaking of the F-spin symmetry can be observed in ^{138}Ce, where the $2^+_{\mathrm{ms},1}$ state is strongly mixed with a nearby 2^+ state. Experimentally, this fragmentation of a MSS can be observed by the distribution of the M1 transition strength over several excited 2^+ states. In comparison with the neighbouring isotopes in the N = 80 isotonic chain, in which a single well-pronounced one-phonon MSS has been observed for ^{132}Te [15], ^{134}Xe [16], ^{136}Ba [17],

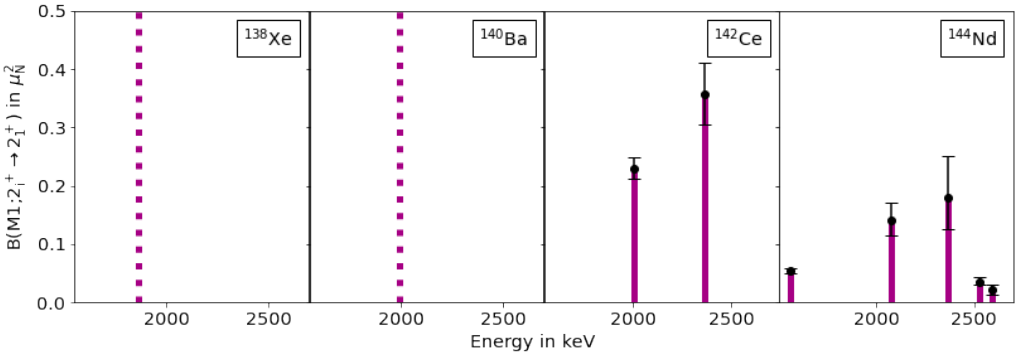

Figure 1: The B(M1;$2_i^+ \rightarrow 2_1^+$) of N=84 isotones is shown. The $2^+_{ms,1}$ state of ^{142}Ce and ^{144}Nd is clearly fragmented. The position for the expected energy of the $2^+_{ms,1}$ state in ^{138}Xe and ^{140}Ba is marked by the dashed lines. Values for ^{142}Ce have been taken from Ref. [28], values for ^{144}Nd have been taken from Ref. [29].

^{140}Nd [19], and most recently ^{142}Sm [20], the dramatic change in the properties of the $2^+_{ms,1}$ state at the $\pi\nu$ subshell closure, when only one proton boson is added to the system, has lead to the assumption, that the underlying single-particle structure is reflected by the strength concentration of the quadrupole-collective isovector valence-shell excitation [18]. This phenomenon is known as shell stabilization. Different theoretical approaches, with the quasiparticle-phonon model (QPM) [21], and with the large-scale shell model [22] have shown, that the fragmentation of the first mixed-symmetry 2^+ state in ^{138}Ce is caused by the underlying shell structure. The observation of only one 2^+ state with the decay behavior that is expected for the $2^+_{ms,1}$ state in ^{136}Ce indicates that the neutron degrees of freedom strongly influence the fragmentation of the $2^+_{ms,1}$ state [23, 24].
Turning to the other side of the neutron shell closure at N = 82, MSSs of ^{142}Ce have been investigated extensively [25–27], most recently through inelastic neutron scattering [28]. The latest experiment has shown, that the M1 strength of the $2^+_{ms,1}$ state of ^{142}Ce is split over the 2^+_3 and 2^+_4 state [28]. Within the same experiment, the MSSs of ^{144}Nd have also been investigated [29]. Here, a fragmentation of the $2^+_{ms,1}$ state can also be observed, as shown in Figure 1. Assuming the fragmentation of the $2^+_{ms,1}$ state of ^{142}Ce is mainly a result of the underlying proton sub-shell structure, the fragmentation of the $2^+_{ms,1}$ state of ^{144}Nd indicates no restoration of the isotonic shell stabilization. To further study the relation between the stability of the $2^+_{ms,1}$ state and the underlying shell structure, the investigation of the $2^+_{ms,1}$ state in the N = 84 isotones has to be extended below ^{142}Ce, to the unstable ^{140}Ba and ^{138}Xe.
In the case of ^{140}Ba, the 2^+_3 state has been proposed as the main fragment of the $2^+_{ms,1}$ state [25, 30, 31]. However, no measurement of the M1 transition strength to the first excited 2^+ state has been made to confirm this. Multipole mixing ratios of $2^+_i \rightarrow 2^+_1$ transitions of ^{140}Ba have been determined for low-lying 2^+ states [30] and are listed in Table 1 together with the corresponding branching ratios. The 2^+_2 and 2^+_4 states do not show mixed-symmetry character due to their multipole mixing ratio of the $2^+_i \rightarrow 2^+_1$ transitions. The multipole mixing ratio and the high branching ratio of the $2^+_4 \rightarrow 2^+_1$ transition could

Table 1: Multipole mixing ratios of $2^+_\mathrm{i} \rightarrow 2^+_1$ transitions of ^{140}Ba and their branching ratios are listed [30].

	$E(2^+_\mathrm{i})$ in keV	$I_{2^+_\mathrm{i}\rightarrow 2^+_1}/I_\mathrm{tot}$	δ $(2^+_\mathrm{i} \rightarrow 2^+_1)$
2^+_2	1510.7	1.00	$-6.0^{+0.18}_{-0.17}$
2^+_3	1993.7	0.78	$0.18^{+0.05}_{-0.06}$
2^+_4	2004.2	0.60	$0.55^{+0.23}_{-0.15}$
2^+_5	2237.2	0.44	$1.00^{+0.02}_{-0.02}$

suggest a fragmentation of the $2^+_{\mathrm{ms},1}$ state, however due to the observed low-energy $2^+_4 \rightarrow 3^-_1$ and $2^+_4 \rightarrow 2^+_2$ transitions at 400.8(5) keV and 693.4(5) keV, respectively, it is unlikely, that the 2^+_4 state is a fragment of the $2^+_{\mathrm{ms},1}$ state. Based on this information of low-lying excited 2^+ states, the 2^+_3 state is the only possible candidate to carry the main portion of the M1 strength of the $2^+_{\mathrm{ms},1}$ state.
In the N = 80 isotones, the M1 strength of the $2^+_{\mathrm{ms},1}$ state of ^{136}Ba is clearly isolated in the 2^+_3 state [17]. Information about MSSs in the Ba isotopes is only available for one more isotope, ^{134}Ba [32, 33]. Here, a splitting of the M1 transition strengths of the $2^+_{\mathrm{ms},1}$ state is observed. Both the 2^+_3 and 2^+_4 state share the MSS character. An identification of the $2^+_{\mathrm{ms},1}$ state in ^{140}Ba is therefore crucial for a thorough understanding of the behavior of MSSs when neutrons are added. Recently, one of us (Prof. G. Rainovski and his group) and his group performed an experiment at the tandem accelerator at the IKP, Cologne with the goal of investigating off-yrast states in ^{140}Ba, populated in 2-neutron transfer. However, after several days no population of off-yrast states could be observed in the measurement. This shows the superiority and therefore, need, of Coulomb excitation experiments in the investigation of MSSs.
MMSs in ^{138}Xe have not been extensively experimentally investigated so far. Nevertheless, information about the $2^+_{\mathrm{ms},1}$ state in ^{138}Xe is of utmost importance for the investigation of shell stabilization in the N=84 isotonic chain. The 2^+_2 has been investigated in a β-decay experiment at ILL, France [34]. Results from this experiment show a predominant E2 character of the $2^+_2 \rightarrow 2^+_1$ transition and it can therefore be concluded, that the 2^+_2 state of ^{138}Xe is not the $2^+_{\mathrm{ms},1}$ state. Due to the low-energy $2^+_4 \rightarrow 2^+_2$ transition at 439.04(23) keV and the weak branching ratio to the 2^+_1 of $I_{2^+_4\rightarrow 2^+_1}/I_\mathrm{tot} \approx 0.35$, the 2^+_4 state can also be ruled out as the main fragment of the $2^+_{\mathrm{ms},1}$ state of ^{138}Xe. Based on this information and the comparison to ^{140}Ba, it is suspected that the $2^+_{\mathrm{ms},1}$ character of ^{138}Xe is predominantly located in the 2^+_3 state.
In Figure 2 the evolution of the excitation energies of the 2^+_1 and the known $2^+_{\mathrm{ms},1}$ states of even-even Xe isotopes are shown. It can be seen that the energy difference between the two states decreases with the increase of neutron pairs. Furthermore, a drop in excitation energy of the first excited 2^+ state can be seen at A=138, in comparison with A=134 at the other side of the neutron shell closure. To understand the effect of the underlying shell structure to the systematics of MSSs, information on the $2^+_{\mathrm{ms},1}$ state has to be extended for the Xe isotopes beyond the N=82 neutron shell closure. Due to the inert-gas nature of xenon, an experiment to populate low-lying excited 2^+ states of ^{138}Xe has to be performed at a radioactive ion beam facility, where the beam can be produced

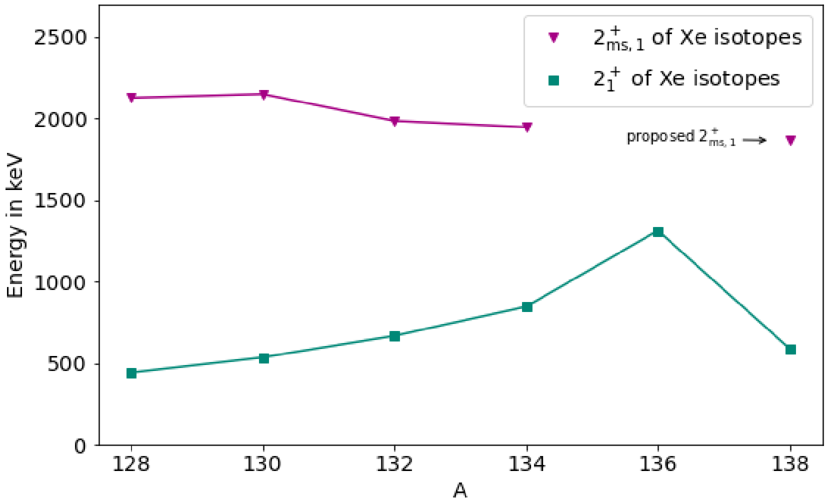

Figure 2: The evolution of the excitation energies of the 2^+_1 and the $2^+_{\mathrm{ms},1}$ states of even-even Xe isotopes are shown. The figure is adapted from Ref. [35].

with sufficient intensity.
Due to their significant E2 matrix element to the ground state, the 2^+_3 states of the neutron-rich unstable ^{138}Xe and ^{140}Ba are well accessible through Coulomb excitation. The intense radioactive ^{138}Xe and ^{140}Ba ion beams necessary for this measurement have been used at HIE-ISOLDE before. In combination with the high-resolution detector array MINIBALL we will be able to measure the excitation strength of the MSSs candidates through observation of the two decays to 0^+_1 and 2^+_1.

2 Experimental details

Summary of requested shifts: 36 shifts (15 for ^{140}Ba and 21 for ^{138}Xe), split into two runs over two years
We propose to use the well-established technique of sub-barrier Coulomb excitation to extract the electromagnetic matrix elements of transitions between the excited states in ^{140}Ba and ^{138}Xe. Both isotopes will be produced with a standard U Carbide target. Both beams have been well-developed and used in previous REX-ISOLDE experiments [36], [37]. The ions will be extracted from the target with intensities of 5.7e+8 and 3.4e+8 ions/μC, respectively. They will be charge-bred by EBIS and accelerated by HIE-ISOLDE to energies of 3.6 MeV/u. Intensity of around 10^6 ions/s can be expected at MINIBALL for both beams. We plan to use a 2 mg/cm^2 ^{206}Pb as a secondary target. Both projectile and target nuclei will be excited via Coulomb excitation in the scattering process. The scattered nuclei will be detected by the DSSD, placed roughly 20 mm behind the target, which will cover angles between 24 and 62 degrees. Safe Coulex is ensured for all angles, covered by the particle detector. Kinematics of the two reactions can be seen on Figure 3. Deexcitation gamma-rays will be detected by the MINIBALL array.
The electromagnetic matrix elements will be extracted from a fit of the experimentally

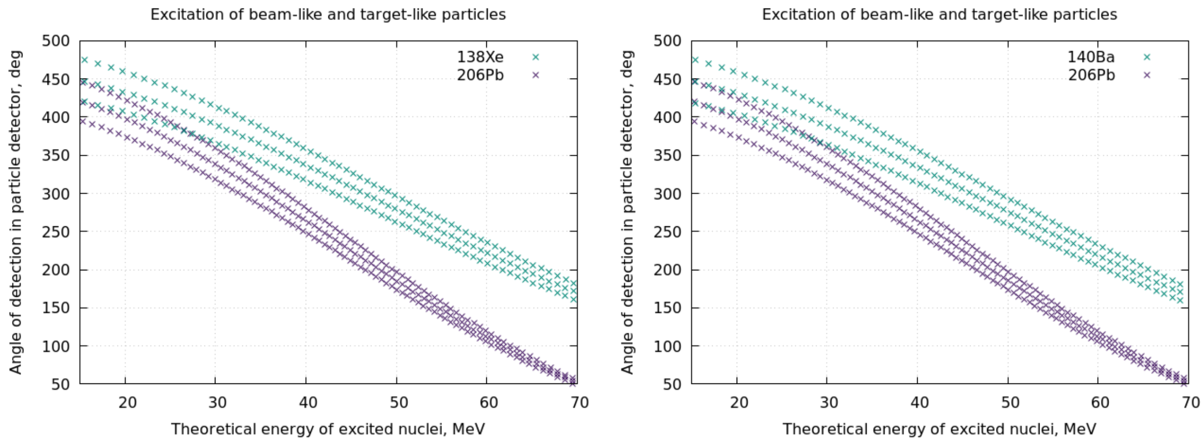

Figure 3: Kinematics of ^{140}Ba and ^{138}Xe at 500 MeV on a ^{206}Pb target. Excitation is assumed at the surface, middle and back of the target.

observed gamma-ray yields. The target ^{206}Pb has a 2^+ first excited state at energy of 803 keV, which has a precisely known reduced transition probability to the ground state, which will be used for normalization.

We want to identify the one-phonon MSS in the N=82 isotopes of Ba and Xe by extracting the M1 transition probabilities for the B(M1;$2^+_{\mathrm{ms},1} \rightarrow 2^+_1$)from the experimental yields. In ^{140}Ba multipole mixing ratios and branching ratios for the 2^+_2 and 2^+_3 states are already known. This means the only piece of information missing to identify the MSS is the B(M1) transition strength. In ^{138}Xe this information is not available for the $2^+_{\mathrm{ms},1}$ candidate 2^+_3. We plan on measuring angular correlations to determine the multipole mixing ratio of the transition of interest. Estimations of the expected yields in the 2^+ states of ^{138}Xe and ^{140}Ba can be found in Table 2 and Table 3.

Table 2: Yield estimations for population of the 2^+ states of ^{138}Xe in Coulomb excitation on a 2 mg/cm^2 ^{206}Pb target. Reaction in the middle of the target is assumed. Gamma-ray efficiency is taken to be 5% and beam intensity of 10^6 pps is used for the calculation.

Excited state	Energy, keV	σ(mb)	Yield/day
2^+_1	588	2.1E+03	5.3E+05
2^+_2	1463	2.2	560
2^+_3	1866	7.6E-01	192

Table 3: Yield estimations for population of the 2^+ states of ^{140}Ba in Coulomb excitation on a 2 mg/cm^2 ^{206}Pb target. Reaction in the middle of the target is assumed. Gamma-ray efficiency is taken to be 5% and beam intensity of 10^6 pps is used for the calculation.

Excited state	Energy, keV	σ(mb)	Yield/day
2^+_1	602	2.5E+03	6.3E+05
2^+_2	1510	8.6E-02	22
2^+_3	1993	2.9E-01	73

In the case of Xe we request 4 days or 12 shifts of data taking to achieve statistical uncertainty of around 3-4% in the peak area. Since no multipole mixing ratio is known, we will try to obtain this by angular correlation measurement. We request an additional day or 3 shifts for beam setup and tuning. For the case of Ba, since less statistics is expected, we request 6 days or 18 shifts for data taking and 1 day or 3 shifts for beam setup and tuning.

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DESCRIPTION OF THE PROPOSED EXPERIMENT
Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
Miniball + CD only	☒ To be used without any modification

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			