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Letter of Intent to the ISOLDE and Neutron Time-of-Flight Experiments Committee for experiments with HIE-ISOLDE

Study of quadrupole-collective isovector valence-shell excitations of exotic nuclei at HIE-ISOLDE

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Abstract

In this letter we express our intention to propose and perform HIE-ISOLDE and MINIBALL experiments to study MSSs of radioactive nuclei from mass $A\approx 130$-140 and 70-80 regions. The main aim of these experiments is to clarify the influence of the underlying single-particle structure on the properties of the MSSs. ***If successful these can be the first identifications of MSSs in radioactive nuclei on the basis of absolute M1 transition rates.***

1. Introduction

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 degree of freedom. The Quadrupole-collective isovector valence-shell excitations, so-called proton-neutron ***mixed-symmetry states*** (MSSs) [1, 2], represent a unique quantum laboratory in which the balance and interplay between the above three phenomena can be studied. A special type of MSSs, the 1^+ scissors mode, was first discovered in nuclei in electron scattering experiments at the TU Darmstadt [3] and subsequently found or suggested to exist in Bose-Einstein condensates [4] and metallic clusters [5]. In this respect, the impact of a deeper understanding of the structure of these states is beyond the field of nuclear structure physics.

The fundamental MSS in weakly-collective vibrational nuclei is the one-quadrupole phonon $2^+_{1,ms}$ 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 [6]. The MSSs are identified experimentally by their unique strong *M1* decay to the low-lying fully symmetric states (FSS) [1, 6].

The nature of MSSs makes them sensitive to both the residual proton-neutron interaction V_{pn} [7, 8] and underlying shell structure [6, 8]. The identification of MSSs of exotic nuclei and their evolution with mass number, especially in neutron-rich nuclei, is of immediate interest. ***No MSSs have ever been identified in unstable nuclei on the solid basis of large absolute M1 strengths.***

2. Physics case

An example for the impact of the shell structure on the properties of MSSs was found in the mass $A\approx 130$ region where a tremendous progress on the study of MSSs has recently been made [8-11]. Using projectile Coulomb excitation reactions and the Gammasphere array at Argonne National Laboratory we have identified the one-phonon MSSs in several low-abundant stable nuclei, namely ^{134}Xe [8], ^{138}Ce [9], ^{136}Ce [10], and ^{130,132}Xe [11]. 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 from absolute $M1$ data. These extensive data sets not only demonstrate the experimental accessibility of MSSs by inverse kinematics Coulomb excitation reactions on a carbon target, but also reveal novel interesting physics phenomena. Examples are given by our data on the N=80 isotones ^{138}Ce [9] and ^{134}Xe [8]. In contrast to the isotone ^{136}Ba [12], the $2^+_{1,\mathrm{ms}}$ state in ^{138}Ce is strongly mixed with a nearby 2^+ FSS with a mixing matrix element of V_{mix} = 44(3) keV, suggesting that the microscopic structure can have a dramatic influence on the properties of MSS. The observed mixing in ^{138}Ce is attributed to the lack of ***shell stabilization*** at the proton $\pi(1g_{7/2})$ sub-shell closure. This hypothesis was partially confirmed experimentally by observing a single, well pronounced MSS of ^{134}Xe [8].

The data on MSSs of stable N=80 isotones and the suggested shell stabilization have initiated theoretical investigations. The properties of MSSs of stable N=80 isotones were studied with the quasiparticle-phonon model (QPM) [13] and the large scale shell model (SM) [14]. 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 [13, 14]. The results from the shell model calculations [14] also show that the experimental information on MSSs provides a tool to determine the pairing matrix elements of realistic interactions.

Though the microscopic models agree on the fact 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, ^{138}Ce, ^{136}Ba and ^{134}Xe cover the transition from the $\pi g_{7/2}$ to the $\pi d_{5/2}$ orbitals, only. To clarify further the shell stabilization, we have to expand our investigations to nuclei beyond the Z=58, *i.e.*, to unstable nuclei ^{140}Nd and ^{142}Sm. The theoretical models do not provide unambiguous predictions for the properties of MSSs of ^{140}Nd and ^{142}Sm. SM calculations predict a single isolated MSS for ^{140}Nd [22], while the QPM predicts a fragmentation [23]. This situation prompts for an experimental identification of MSSs of ^{140}Nd and ^{142}Sm. The first step towards identifying the MSSs in ^{140}Nd and the ^{142}Sm will be taken in the approved experiment IS496 for which the physics case has been reviewed by the INTC and judged as an important issue. The goal of the experiment is to develop RILIS RIBs of ^{140}Nd and the ^{142}Sm nuclei and to measure the transition strengths of the first excited 2^+. The actual search for MSSs in the ^{140}Nd and the ^{142}Sm nuclei will be conducted in Coulomb excitation measurements on a carbon target at beam energies close to the Coulomb barrier. This step is foreseen for the time when the HIE-ISOLDE facility, will become operational.

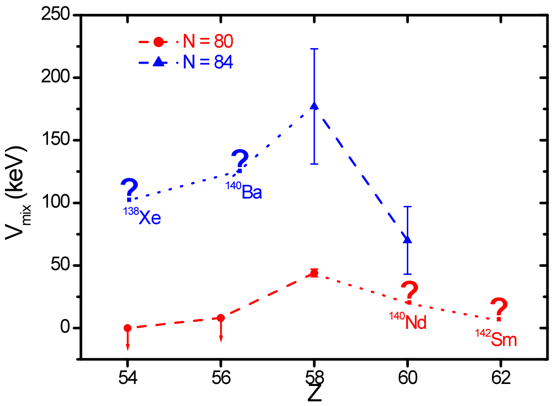

Figure 1: *Evolution of the mixing-matrix elements between FS and MSS in the N = 80 and 82 isotonic chains. The experimental data are taken from Refs. [8,9,15-17]. The dashed lines are drawn to guide the eye. The dotted lines represent the expected be behavior according to the concept of shell stabili-*

Another important question is to what extend the shell stabilization depends on relative contributions of protons and neutrons in the collective wave functions. In the N=80 isotones the proton excitations are in the space above Z=50 (mostly in the $g_{7/2}$ and $d_{5/2}$ orbitals) while the available neutron space is much smaller; the Fermi level for neutrons lies at the top of the $\nu 1h_{11/2}$ orbital. Hence, the collective excitations in N = 80 isotopes have mostly proton particle-like character while the neutrons form a constant hole-like contribution. It is not clear whether and how the effect of shell stabilization will be present when the collective states have more balanced proton-neutron character. A way to address this question is to identify the MSSs in the neutron rich N=84 isotones in the mass 140 region. Candidates for MSSs of ^{140}Ba, ^{142}Ce and ^{144}Nd nuclei have been first suggested by Hamilton *et al.* [15] based on small *E2/M1* mixing ratios. Later on, this unsafe assignment was confirmed in the cases of ^{142}Ce and ^{144}Nd on the basis of Coulomb excitation [16] and lifetime measurements [17]. The available information for the mixing matrix elements V_{mix} for nuclei from N=80 and 84 isotonic chains is summarized in Fig. 1. Even though the data suggest increase in the mixing-matrix element at Z=58, which corresponds to the $\pi(1g_{7/2})$ sub-shell closure, no definitive conclusion on the lack of shell stabilization at Z=58 can be drawn on either side of the N=82 neutron shell closure. This is primarily due to the lack of experimental data on MSSs in ^{138}Xe, ^{140}Ba and ^{140}Nd, ^{142}Sm (see Fig. 1).

Other examples for influence of microscopic structure on the properties of MSS are found in the regions of stable Z=30 zinc isotopes [18] and N=52 isotones [6], where sub-shell closures are present at N=40 (^{68}Ni) and Z=38 (^{88}Sr), respectively. In both cases the energy splitting between the 2^+_1 state and the $2^+_{1,\mathrm{ms}}$ state is reduced. The observed effect is especially pronounced in the case of the zinc isotopes, where the $2^+_{1,\mathrm{ms}}$ state lowers by about 1 MeV from N=36 to N=40 [18]. This unforeseen phenomenon was recently explained as a combined effect of changing both the monopole and quadrupole part of the proton-neutron interaction [19], clearly demonstrating the sensitivity of MSSs to the proton-neutron interaction. From a microscopic point of view this is linked to the rapidly downsloping $\nu(g_{9/2})$ intruder orbital as well as to strong monopole shifts in the proton orbitals. It is of substantial importance to expand our knowledge to nuclei beyond the sub-shells at N=40 and Z=40. ***However, both in the Z=30 chain and the N=52 chain the knowledge on MSSs is limited up to the last stable isotope, namely ^{70}Zn (N=40) and ^{92}Zr (Z=40).*** The study of MSSs in neutron-rich nuclei ^{72}Zn-^{78}Zn, ^{88}Kr, ^{84}Ge and ^{86}Se will be a direct and absolute measure of the residual proton-neutron interaction towards ^{78}Ni.

3. Experimental setup

The MSSs of the nuclei of interest will be identified in Coulomb excitation reactions of RIBs on a carbon target. The γ-ray yield measurements will be performed with the MINIBALL spectrometer while the T-REX array will be used for particle identification. This set-up also allows for performing angular correlation measurements for the cases where multiple mixing ratios are not known. The use of carbon target is dictated by the fact that it favors the one step excitations, *i.e.* the reaction mechanism is selective to one-phonon states of different multipolarities, including the MSSs. The resulting γ-ray spectra are simple and free of target excitations. However, to populate effectively the one-phonon states beyond the 2^+_1 state in Coulomb excitation reactions on a carbon target, the necessary beam energy is close to the respective Coulomb barrier. For the nuclei of interest in the N=52 region and the A=130 region this translates to 3.5 – 4.5 MeV/u. These energies are not achievable at REX-ISOLDE, but they will be well within the capability of HIE-ISOLDE. ***We stress that the future HIE-ISOLDE upgrade is an absolute condition for the search for MSSs in radioactive nuclei.***

4. Beam requirements

Most of the nuclei of interest have already been produced at ISOLDE: ^{72}Zn-^{78}Zn (IS412), ^{138}Xe, ^{140}Ba (IS411, IS415) and ^{88}Kr (IS423). The beam development is under way for ^{140}Nd and ^{142}Sm (IS496). For ^{84}Ge and ^{86}Se beam development will be needed.

- isotopes of interest: $^{72\text{-}78}$Zn, ^{84}Ge, ^{86}Se, ^{88}Kr, ^{138}Xe, ^{140}Ba, ^{140}Nd, ^{142}Sm;
- beam purity: as high as possible; for the $^{72\text{-}78}$Zn, ^{84}Ge, ^{140}Nd, ^{142}Sm beams we would like to use selective ionization (RILIS);
- beam intensity: $\approx 10^6$ pps. Between 5 – 10 days beam time is needed per isotope.
- beam energy: 3.5 - 4.5 MeV/u;
- spatial properties of the beam: 3mm diameter beam spot size at target position;
- time structure of the beam: a slow extraction from the EBIS is mandatory;

5. Safety aspects

During the ^{88}Kr runs in IS423 the intensity was limited due to radiation safety aspects (high dose rates at trap roughing pump and at EBIS-BTS bellow). The long half-life of ^{140}Ba should be taken into account in the experiment scheduling process.

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