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Search for one-phonon mixed-symmetry states in the radioactive nucleus ^{140}Nd

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Low-spin excited states of ^{140}Nd have been studied via the ^{140}Ce(^{3}He,3n)^{140}Nd reaction. The data show that one of the candidates for the one-phonon mixed-symmetry state (MSS) of ^{140}Nd, namely, the 2_3^+ state at 2140 keV with an effective lifetime of 220(90) fs, exhibits a fast $M1$ decay to the 2_1^+ state. Thus, this state can be considered, at least, as a fragment of the one-phonon MSS of ^{140}Nd. This is the first example where mixed symmetry character is tentatively assigned to a state of an unstable nucleus from the mass $A \approx 140$ region based on the data on absolute $M1$ transition rates. However, the data are not conclusive on whether this decay exhausts the total $M1$ strength or whether the one-phonon MSS of ^{140}Nd is fragmented.

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Shell structure, collectivity, and the isospin degree of freedom are the three key aspects that define the dynamics of atomic nuclei. In many cases, the properties of excited nuclear states are predominantly determined by one of them. Therefore, each of them is separately widely studied. The interplay between these three key aspects of nuclear structure is an intriguing subject and far from being fully understood. The primary reason for this is that there are not many nuclear excitation modes that depend strongly on the mutual balance between them. In even-even nuclei the quadrupole-collective isovector valence-shell excitations, the states with so-called mixed proton-neutron symmetry (MSS) [1,2], are the only low-lying states whose structure reflects in full the mesoscopic two-fluid quantum nature of the nuclear matter. In this respect the MSSs represent a unique quantum laboratory in which the balance and interplay between the nuclear collectivity, shell structures, and isospin degree of freedom can be studied.

The MSSs are defined [1] in the framework of the interacting boson model with proton-neutron degree of freedom (IBM-2). The concept of proton-neutron mixed symmetry is formalized by the F-spin quantum number [3], which is the isospin analog for bosons. Within this concept the lowest states in a given nucleus have the maximum F-spin quantum number $F_{\max} = (N_\pi + N_\nu)/2$ and are called full symmetry states (FSSs) ($N_{\pi,\nu}$ denote the proton and neutron boson numbers), while MSSs are those states with $F = F_{\max} - 1$ [3]. In other words, the F-spin quantum number counts the number of proton and neutron pairs which are in phase in the quantum state. With little modification, the MSSs in the IBM-2 repeat the multiplet structure observed for the FSSs, albeit at higher energy and with different decay properties. The most distinct feature of MSSs is the existence of allowed F-vector ($\Delta F = 1$) $M1$ transitions to FSSs. This is of importance because $M1$ transitions are forbidden between FSSs and can, thus, very well serve as a unique signature for MSSs [1].

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 [4]. The best examples of MSSs in stable nuclei are found in the mass $A \approx 90$ region [4–7]. Until recently there were only a few MSSs identified in the mass $A \approx 130$ region [8–10]. The main reason for the small number of studied cases comes from the fact that the stable open-shell even-even isotopes in this mass region have relatively low abundance. This comprises an experimental problem because 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 [4], which in the case of low-abundant or unstable isotopes is not possible. Projectile Coulomb excitation reactions in combination with a large γ-ray array was suggested recently as a solution for this methodological problem [11]. Even though this technique was exploited in the past to study MSSs [6], 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, namely, ^{134}Xe [12], ^{138}Ce [11], ^{136}Ce [13], and ^{130,132}Xe [14]. 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 extensive data not only demonstrate the experimental accessibility of MSSs by inverse kinematics Coulomb excitation reactions on a light target, but also reveal novel interesting physics phenomena. Examples are given by the data on the $N = 80$ isotones ^{138}Ce [11] and ^{134}Xe [12]. In contrast to the isotone ^{136}Ba [6], the $2^+_{1,\mathrm{ms}}$ state of ^{138}Ce is strongly mixed with a nearby 2^+, probably FSS, suggesting that the microscopic structure can have a dramatic influence on the properties of the MSSs. The observed mixing in ^{138}Ce is attributed to the lack of *shell stabilization* [11] 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 [12]. 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) [15] and the large-scale shell model (SM) [16]. 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 [15,16]. The results from the SM calculations [16] also show that the experimental information on MSSs provides a tool for determining the pairing matrix elements of realistic interactions.

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, $^{134}_{54}\mathrm{Xe}_{80}$, $^{136}_{56}\mathrm{Ba}_{80}$, and $^{138}_{58}\mathrm{Ce}_{80}$, 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 $Z = 58$, that is, to the unstable nuclei $^{140}_{60}\mathrm{Nd}_{80}$ and $^{142}_{62}\mathrm{Sm}_{80}$. 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 [16], while the QPM predicts a fragmentation [17]. 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 recently investigated in a $\gamma\gamma$-angular-correlation experiment following the ϵ/β^+ decays of ^{140}Sm and ^{140}Pr [18]. This measurement shows that the 2^+_3 and the 2^+_4 states of ^{140}Nd at 2140 and 2332 keV, respectively, decay predominantly by $M1$ transitions to the 2^+_1 state [18]; the measured $E2/M1$ mixing ratios for the corresponding 1366- and 1559-keV transitions (see Fig. 1) are $\delta = -0.08(8)$ and $\delta = -0.19(9)$, respectively. Hence, both states have to be considered as candidates for the one-phonon $2^+_{1,\mathrm{ms}}$ of ^{140}Nd [18]. 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 stabilization is present in ^{140}Nd. Apparently, this can be resolved only by measuring the absolute $M1$ strengths of the 1366.2- and 1558.6-keV transitions (see Fig. 1). Such measurements are possible by using projectile Coulomb excitation of the RIB ^{140}Nd. However, taking into account the high demand for beam time at RIB facilities and the fact that ^{140}Nd is not a very exotic nucleus, it is wise first to show to what extent the present physics problem can be solved by using experimental techniques which are based on stable beams. It has been the purpose of this study to determine the lifetimes of the states that are candidates for one-phonon $2^+_{1,\mathrm{ms}}$ of ^{140}Nd (see Fig. 1) by means of the Doppler-shift attenuation method (DSAM) in a light-ion fusion-evaporation reaction, induced by an accelerated stable beam. With respect to the latter, the study also shows to what extent conventional techniques can be used to unambiguously identify the MSSs of unstable nuclei.

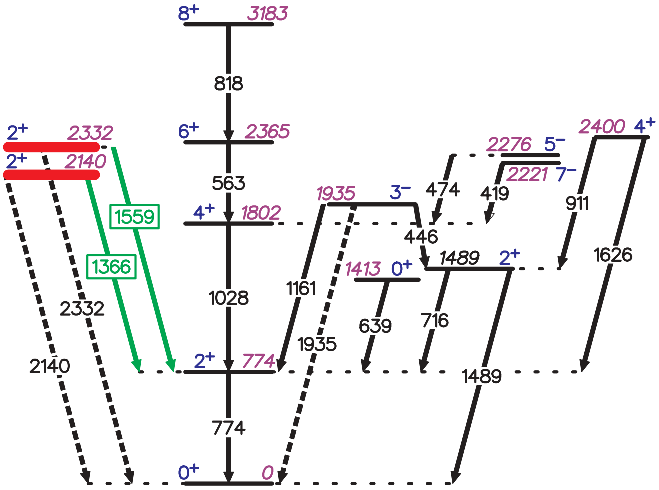

FIG. 1. (Color online) Partial level scheme of ^{140}Nd. The candidates for the one-phonon MSS [18] and the transition that were analyzed to extract the lifetimes are indicated. The ground-state decays that were not observed in the present experiment but are known to exist from Ref. [18] are given by dashed lines.

The experiment was performed at the FN Tandem facility of the University of Cologne. Excited states of ^{140}Nd were populated using the $^{140}\mathrm{Ce}(^{3}\mathrm{He},3n\gamma)^{140}\mathrm{Nd}$ reaction at a beam energy of 19.8 MeV. The ^{3}He beam and the beam energy were chosen as a compromise between the requirements to populate the low-spin nonyarst states and to provide sufficient recoil velocity for DSAM measurements of lifetimes in the range of 100 fs or shorter. The target consisted of a 0.8 mg/cm^2 natural Ce layer deposited onto a 2.0-mg/cm^2-thick Ta foil. The usual Cologne setup for recoil distance Doppler shift measurements [19] was used. The setup consisted of one EUROBALL cluster Ge detector [20] positioned along the beam axis after the target chamber and five large volume coaxial HPGe detectors. The six outer detectors of the cluster were grouped into a ring with a polar angle of 19° with respect to the beam axis. The inner segment corresponded to a central angle of 0°. The five single HPGe detectors formed a ring at a polar angle of 143°. γ-ray spectra, gated on the 774- and 1028-keV transitions in the total coincidence matrix are shown in Fig. 2. The low-spin level scheme of ^{140}Nd is not very well known. Most of the γ rays observed in our experiment connect energy levels of ^{140}Nd that are known from previous studies [18,21]. However, we have also observed several γ rays that are in strong coincidence with the γ rays from low-spin states of ^{140}Nd but cannot be placed unambiguously in the level scheme. For example, the 1491-keV transition is in coincidence with the 774-keV transition and with a new 1888-keV transition. The 1888-keV transition is in coincidence only with the 1491-keV transition. This suggests that the 1888-keV transition represents a decay to the ground state of a new level that is fed by the 1491-keV transition. However, we have not observed any transitions whose energies add up to 1114 keV, which is the energy difference between the new level at 1888 keV and the first 2^+ state at 774 keV. Besides these ambiguities, the spectra in Fig. 2 clearly demonstrate that the previously known 1366- and 1559-keV transitions directly feed the 2^+_1 state, representing

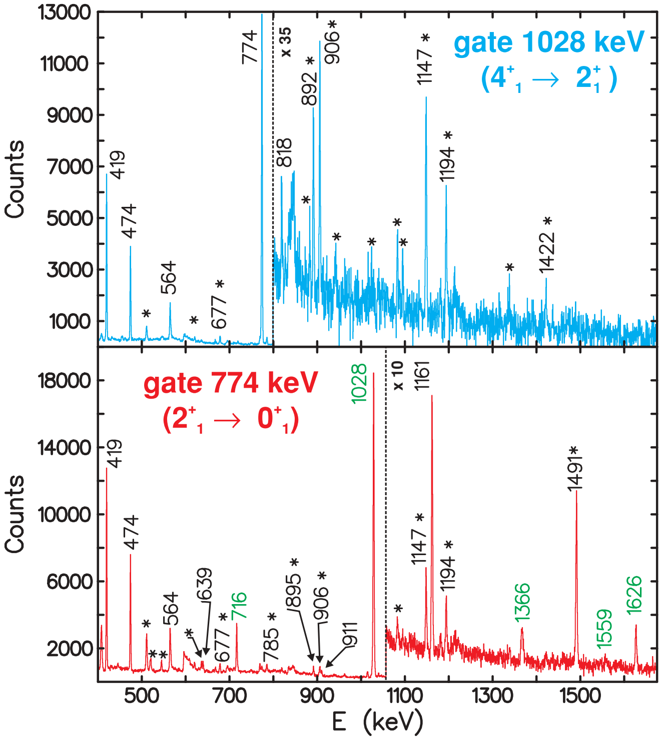

FIG. 2. (Color online) Gated γ-ray spectra from the total $\gamma\gamma$ matrix. The known transitions of ^{140}Nd are marked with their energies, new transitions which most likely belong to ^{140}Nd are labeled with their energies and stars, while possible contaminants are labeled with stars only. The transitions directly feeding the 2^+_1 state are indicated.

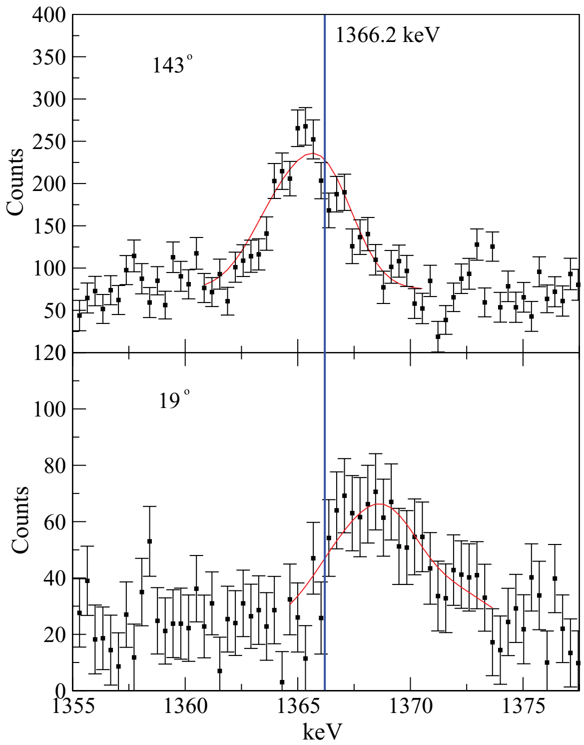

FIG. 3. (Color online) Line-shape analysis of the 1366.2-keV transition at backward (top) and forward (bottom) angles with a gate set on the fully stopped 774-keV transition. The vertical blue line indicates the position of the 1366.2-keV decay transition in the rest frame of ^{140}Nd.

the $M1$ decay of the candidates for the one-phonon MSS of ^{140}Nd [18].

The main aim of our study was to measure the lifetimes of the 2140- and 2332-keV states (see Fig. 1) by means of the DSAM (cf. Ref. [22] and references therein). Owing to low statistics, only the effective lifetime of the 2^+_3 state at 2140 keV could be deduced. To describe the slowing down of the recoiling nuclei, we used a Monte Carlo (MC) simulation by means of a modified [23,24] version of the program DESASTOP [25]. The electronic stopping powers used were obtained from the Northcliffe and Schilling tables [26] with corrections for the atomic structure of the medium as discussed in Ref. [27]. An empirical reduction of $f_n = 0.7$ was applied [28] to downscale the nuclear stopping power predicted by the theory of Lindhard, Scharff, and Schitt [29]. According to the calculations performed, the recoils needed in average 430 fs to come to rest. The evaporation of neutrons was also taken into account in the MC simulation. The database of about 10 000 velocity histories was additionally randomized with respect to the experimental setup by taking into account the positions of the detectors and their finite size. More details of our approach for the Monte Carlo simulation can be found in Refs. [23,24].

Because of the small yield of the states of interest, we had to work in a "singles"-like regime where the coincidence gate for purifying the spectra is set on a transition deexciting a level fed by the transition under analysis. In the case of the 2140-keV state the line shape of the 1366.2-keV transition was analyzed in the γ-ray spectra obtained by gating on the 774-keV transition which does not show any shifted component. A simultaneous fit of the line shapes of the 1366.2-keV transition at forward and backward angles, obtained by using the described approach is presented in Fig. 3. The gating procedure used leads to uncertainties related to the unobserved feeding of the level of interest. We did not observe any discrete feeding, and under these circumstances the lifetime deduced is an effective one, setting an upper limit for the level lifetime and lower limits for the transition strengths. More details of the analyzing procedure can be found, for example, in Ref. [30]. An error propagation calculation was performed to take into account the effect of the background subtraction on the errors of the gated line shapes. The lifetime of the 2140-keV level was determined to be

$$\tau_{\mathrm{eff}}(2140\ \mathrm{keV}) = 220(90)\mathrm{fs}.$$

Taking into account the previously measured multipole mixing ratio of the 1366-keV transition and the estimated branching ratio for the decay of the 2140-keV transition [18] one obtains

$$\mathrm{B}(M1;2^+_3, 2140\ \mathrm{keV} \rightarrow 2^+_1) > 0.07^{+0.05}_{-0.02}\mu^2_{\mathrm{N}}.$$

This lower limit for the $M1$ strength clearly identifies the 2^+_3 state of ^{140}Nd as a rapidly decaying fragment of the one-phonon MSS. For comparison, the $M1$ strength from the weaker fragment of the one-phonon MSS of ^{138}Ce, the 2_3^+ state at 2143 keV, is 0.058(6) μ_N^2 [11]. However, the question whether the decay of the 2_3^+ state of ^{140}Nd accounts for the total $M1$ strength remains unclear. Nuclear structure models predict a total $M1$ strength of about 0.3 μ_N^2 [16,17] for the decay of the $2_{1,\mathrm{ms}}^+$ state of ^{140}Nd. This value can be in agreement with our observation if a finite feeding time from above is included in the fitting procedure for the lifetime. The data do not allow for the extraction of the lifetime of the 2^+ state at 2332 keV excitation energy. Its 1559-keV decay transition barely can be observed at forward angles but a small centroid shift of about –0.9(4) keV can be estimated for this transition at backward angles. This is an indication that the 2332-keV state also undergoes a fast $M1$ decay. While the data are too poor for any quantitative estimate, they certainly do not exclude such a scenario and this leaves unanswered the main question of whether the one-phonon MSS of ^{140}Nd is fragmented.

In summary, we have attempted to identify the one-phonon MSS of ^{140}Nd using the DSAM in the reaction ^{140}Ce(^{3}He,3n)^{140}Nd. An effective lifetime of 220(90) fs was measured for one of the candidates for the one-phonon MSS of ^{140}Nd. 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. The present work clearly demonstrates the limitation of the experimental techniques based on beams of stable nuclei on studies of MSSs in radioactive nuclei. For the moment, the only reliable experimental technique that can reveal all properties of the MSS of radioactive nuclei seems to be Coulomb excitation reactions of RIB on carbon targets.

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