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

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Abstract. Low-spin excited states of ^{140}Nd have been studied via the ^{140}Ce(^{3}He,3n)^{140}Nd reaction. The results from the data analysis show that one of the candidates for the one-phonon mixed symmetry state of ^{140}Nd, namely the 2^+_3 state at 2140 keV with an effective lifetime of 220(90) fs, decay with a fast $M1$ transition to the 2^+_1 state. Therefore consequently this state can be treated as, at least 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.

1. Introduction

The isovector states with mixed proton-neutron character, the so called mixed symmetry states (MSSs) are currently of interst because their properties allow some parts of the proton-neutron interaction to be studied[1]. Available information on MSSs of vibrational nuclei is summarized in a recent review article [2]. The best examples of MSSs in stable nuclei are found in the mass $A \approx 90$ region [2, 3, 4, 5]. However, there are only a few MSSs identified in the mass $A \approx 130$ region [6, 7, 8]. The main reason for the small number of studied cases originates from the fact that the stable open-shell even-even isotopes in this mass region have relatively low abundance. This comprises an experimental problem since an unambiguous identification of MSSs can only be done on the basis of measured large absolute B($M1$) values. This experimental information can be obtained through series of experiments [2] which in the case of low-abundant or unstable isotopes is not always possible. Projectile Coulomb excitation reactions in combination with a large γ-ray array detectors were suggested as a solution to this methodological problem [9]. By using projectile Coulomb excitation reactions and the Gammasphere array at the Argonne National Laboratory, the one-phonon MSSs in several low-abundant stable nuclei were identified, namely ^{134}Xe [10], ^{138}Ce [9], ^{136}Ce [11], and ^{130,132}Xe [12]. This experimental technique can also be applied to radioactive ion beams (RIBs). The measured $E2$ and $M1$ strength distributions between the lowest 2^+ states allow for direct and unambiguous identification of the $2^+_{1,\mathrm{ms}}$ state.

These extensive data demonstrate not only the experimental accessibility of MSSs by inverse kinematics Coulomb excitation reactions on a light target, but also reveals novel interesting physics phenomena. Examples are given by the data on the $N = 80$ isotones ^{138}Ce [9] and ^{134}Xe [10]. In contrast to the isotone ^{136}Ba [4], the $2^+_{1,\mathrm{ms}}$ state of ^{138}Ce is strongly mixed with a nearby 2^+ state, probably full symmetry states (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* [9] at the $\pi g_{7/2}$ sub-shell closure. This hypothesis has been partially confirmed by the observation of a single, well pronounced one-phonon MSS in ^{134}Xe [10]. 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) [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. To fully demonstrate the shell stabilization mechanism, the investigation of MSSs in the $N = 80$ isotonic chain have to be extended beyond the proton number $Z = 58$, *i.e.*, to the unstable nuclei $^{140}_{60}$Nd$_{80}$ and $^{142}_{62}$Sm$_{80}$. The theoretical models differ in their predictions for the properties of MSSs of ^{140}Nd. SM calculations predict a single isolated MSS for ^{140}Nd [14], while the QPM predicts a fragmentation [13]. This situation prompts for an experimental identification of MSSs in ^{140}Nd. An experiment [15] was performed recently in an attempt to identify the candidates for the one-phonon $2^+_{1,\mathrm{ms}}$ in ^{140}Nd. The measurement showed 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. The measured $E2/M1$ multipole mixing ratios for the 1366-keV and the 1559-keV transitions are $\delta = -0.08(8)$ and $\delta = -0.19(9)$, respectively. Both states have to be considered as candidates for the one-phonon $2^+_{1,\mathrm{ms}}$ of ^{140}Nd [15]. As

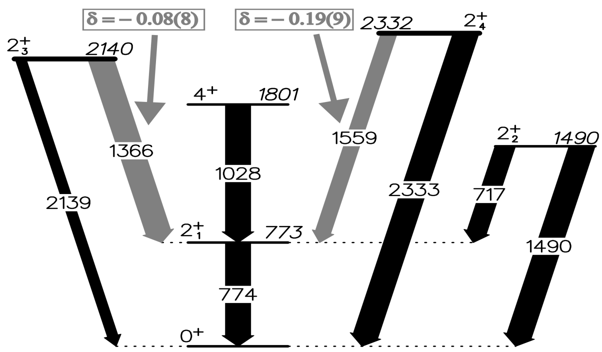

Figure 1. Partial level scheme of ^{140}Nd. The candidates for the one-phonon MSS [15] and the transition which were analyzed in order to extract the lifetimes are indicated.

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-keV and 1558.6-keV transitions (see figure 1). Such measurements are possible by using projectile Coulomb excitation of the radioactive ion beam ^{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 first should be examined to what extent the present physics problem can be solved by using experimental techniques which are based on stable beams. The purpose of this study is to determine the lifetimes of the states, that are candidates for one-phonon $2^+_{1,\mathrm{ms}}$ of ^{140}Nd (see figure 1) in a light-ion fusion-evaporation reaction, induced by an accelerated stable beam.

2. Experimental details

The experiment was performed at the FN Tandem Facility in Cologne (Germany). The excited states of ^{140}Nd were populated using the ^{140}Ce(^{3}He, $3n$)^{140}Nd reaction. The beam of ^{3}He was accelerated to energy of 19.8 MeV and then delivered to the target consisting of 0.8 mg/cm^2 thick ^{140}Ce layer deposited on 2 mg/cm^2 thick Ta foil (the stopper). The ^{3}He beam and the beam energy were chosen as a compromise between the requirements to populate the low-spin non-yrast states and to provide sufficient recoil velocity for DSAM measurements of lifetimes in the range of hundred femtoseconds or shorter. The emitted γ-rays were detected by five coaxial high purity Germanium (HPGe) detectors arranged in a ring at angle $\theta = 143°$ with respect to the beam axis and one EUROBALL HPGe cluster detector build up of seven segments and positioned at forward angle so that its central segment laid on the beam axis and the other six formed a ring at angle $\theta = 19°$ (see figure 2).

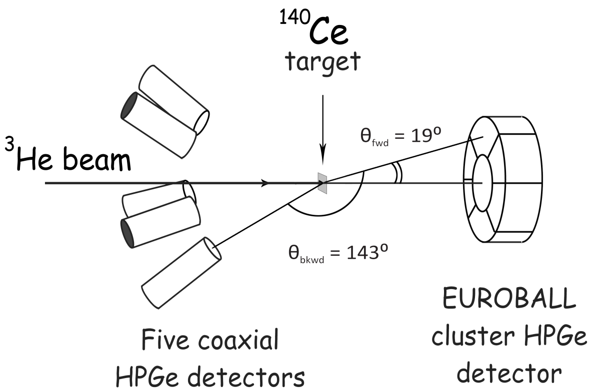

Figure 2. Schematic drawing of the experimental setup.

The three polar angles at which the detectors were positioned formed three rings. R_0 is the ring to which the center segment of the EUROBALL cluster detector belongs ($\theta_0 = 0°$), R_1 contains the six outer segments of the EUROBALL cluster detector ($\theta_1 = 19°$) and R_2 is formed from the five coaxial HPGe detectors at angle $\theta_2 = 143°$. For this arrangement of the detectors, eight types of $\gamma\gamma$-coincidence matrices were sorted. The full (or the total) matrix was used in the analysis for the identification of the observed transitions. Gates were set on the 774 keV and 1028 keV transitions (see figure 1 and figure 3) and so the excited states populated in the reaction were determined (see figure 1). Most of the observed γ-rays connect energy levels of ^{140}Nd which are known from previous studies [15, 16]. However, there are several γ-lines which are in strong coincidences 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 which is fed by the 1491-keV transition. Unfortunately, no transitions were observed with energies that 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 figure 3 clearly demonstrate that the previously known 1366-keV and the 1559-keV transitions (which represent the $M1$ decay of the candidates for the one-phonon MSS of ^{140}Nd [15]) directly feed the 2_1^+ state.

The lifetime analysis was performed in "singles"-like regime because of the small yield of the states of interest (2140 keV and 2332 keV), and the coincidence matrices R_1R_2 and R_2R_1 were

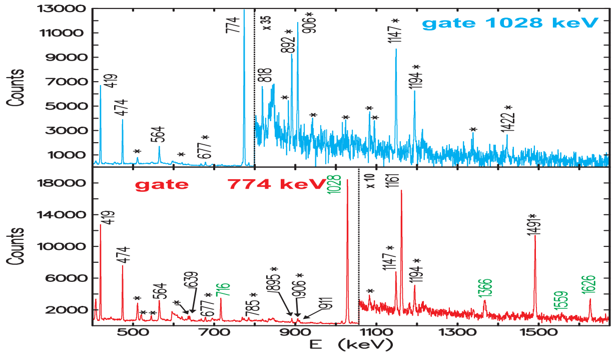

Figure 3. Gated γ-ray spectra from the total $\gamma\gamma$ matrix. The known transitions of ^{140}Nd are marked with their energies, new transitions which most likely belong to ^{140}Nd are labelled with their energies and stars while possible contaminants are labelled with stars only. The transitions directly feeding the 2_1^+ state are indicated.

used for purification of the spectra. A gate was set on the transition de-exciting the 2_1^+ state, namely the 774-keV transition, for which no Doppler-shifted component was observed.

From the obtained spectra the line-shape of the 1366-keV transition ($2_3^+ \rightarrow 2_1^+$) was analyzed. The slowing-down process of the recoiling nuclei was simulated with a modified version [17, 18] of the program code DESASTOP [19]. According to the calculations performed, the recoils needed in average 430 fs to come to rest. This time is longer than the expected lifetime of the state of interest meaning that the Doppler-shift method is applicable for the determination of the line-shape. The results from the fitting at forward and backward angles are presented in figure 4. The evaporation of neutrons was also taken into account in the MC simulation. The database of about 10000 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.[17, 18].

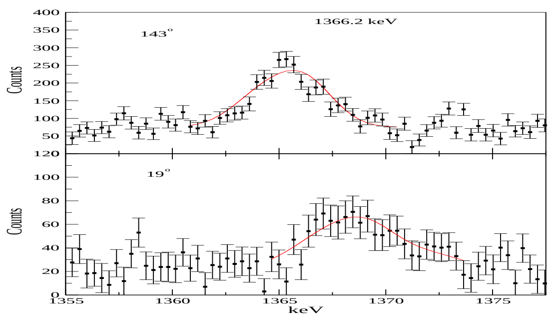

Figure 4. Line-shape analysis of the 1366.2-keV transition at backward (top panel) and forward (bottom panel) angles with a gate set on the fully stopped 774-keV transition.

The used gating procedure introduces uncertainties related to the unobserved feeding of the level of interest and for this reason the deduced lifetime is an effective lifetime.

$$\tau_{\text{eff}}(2140 keV) = 220(90)\, fs \tag{1}$$

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 [15] the B($M1$) value is determined:

$$B(M1; 2_3^+ \rightarrow 2_1^+) > 0.07^{+0.05}_{-0.02}\, \mu_N^2 \qquad (2)$$

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 [9]. 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 [14] for the decay of the $2^+_{1,\mathrm{ms}}$ state of ^{140}Nd. This value can be in agreement with the present observation if a finite feeding time from above is included in the fitting procedure for the lifetime. The data did not allow for the extraction of the lifetime of the 2^+ state at 2332 keV excitation energy. Its 1559-keV decay transition was barely observed at forward angles. However, a small centroid shift of about -0.9(4) keV was estimated for this transition at backward angles. This is an indication that 2332-keV state also undergoes a fast $M1$ decay.

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.

2.1. Acknowledgments

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