EPJ Web of Conferences **62**, 01002 (2013)
DOI: 10.1051/epjconf/20136201002

Lifetime measurements on fission fragments in the A ∼ 100 region

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Abstract. Lifetimes of first 4^+ and 6^+ states have been measured in neutron-rich isotopes of Zr, Mo, Ru and Pd using the recoil distance Doppler shift method at GANIL. The nuclei were produced through a fusion-fission reaction in inverse kinematics. The fission fragments were fully identified in the large-acceptance VAMOS spectrometer and γ -rays were detected in coincidence with the EXOGAM germanium array. Lifetimes of excited states in the range of 1–100 ps were measured with the Cologne plunger. Preliminary lifetime results are presented as well as a discussion on the evolution of the collectivity in this region.

Introduction

The mass region located around A $\sim$ 100 and on the neutron-rich side of the nuclear chart is known for the rapid changes occuring in the properties of the nuclei, especially in their shapes. Between the strongly deformed Sr and Zr isotopes and the γ -soft Cd nuclei, a large variety of shape configurations are expected to appear. Shape transition from prolate to oblate as well as triaxiality have been predicted in this region [1–3]. Here the focus will be on the Zr, Ru, Mo and Pd isotopes where the study of

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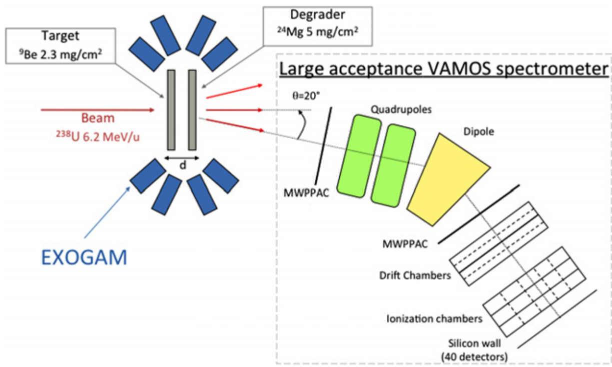

Figure 1. The VAMOS-EXOGAM experimental setup used at GANIL.

their collectivity through lifetime measurement of excited states is expected to bring information on the quadrupole deformation.

This variety of behaviour is already visible from the evolution of the reduced transition probability B(E2) from the first excited 2^+ state to the ground state. An abrupt onset of the collectivity has been established at $N = 60$ in Sr and Zr isotopes [4, 5], indicating an increase of the deformation. This evolution as a function of the neutron number is smoother for higher Z nuclei like in the transitional Mo, Ru and Pd nuclei [6, 7]. For these nuclei, the deformation is less pronounced but the shapes might become more complex.

Although this region has gathered a lot of interest in the past, experimental data on the collectivity are still missing for higher spin levels. The aim of this experiment was to extend the B(E2) experimental values in order to observe the evolution of collectivity with spin.

Experimental method

Neutron rich nuclei were produced by a fusion-fission reaction in inverse kinematics using a ^{238}U beam at 6.2 MeV/u impinging on a ^{9}Be target (2.3 mg cm^{-2} thick) forming a ^{247}Cm compound nucleus with an excitation energy around 45 MeV. The heavy compound nucleus predominantly decays via fission and the fragments are transmitted to the focal plane detection system of the VAMOS spectrometer [8] (see Fig. 1). VAMOS is oriented at 20° with respect to the beam axis to detect one of the fragments. A set of detectors at the focal plane allows to reconstruct the trajectory of the nucleus and to identify its mass, charge and atomic number.

The prompt γ -ray emission in coincidence with the detection of a nucleus in VAMOS is detected by the EXOGAM germanium array [9] composed of 10 segmented clovers mounted at 15 cm from the target and equipped with their complete anti-Compton shield. Three clovers were placed in the backward position at 135° and 7 clovers at 90°.

A degrader foil made of ^{24}Mg (5 mg cm^{-2} thick) is placed after the target and slows down the fission fragments. The Cologne plunger device [10] was used to control the target-to-degrader distance and lifetimes are extracted through the Recoil Distance Doppler Shift Method (RDDS). Data were acquired for 7 different target-to-degrader distances between 37 and 1554 μm for 24 hours per distance.

Data analysis

The different quantities measured in the VAMOS detection system [8] give access to the mass number (M), the charge state (Q) and the atomic number (Z) of every nucleus reaching the focal plane. The time

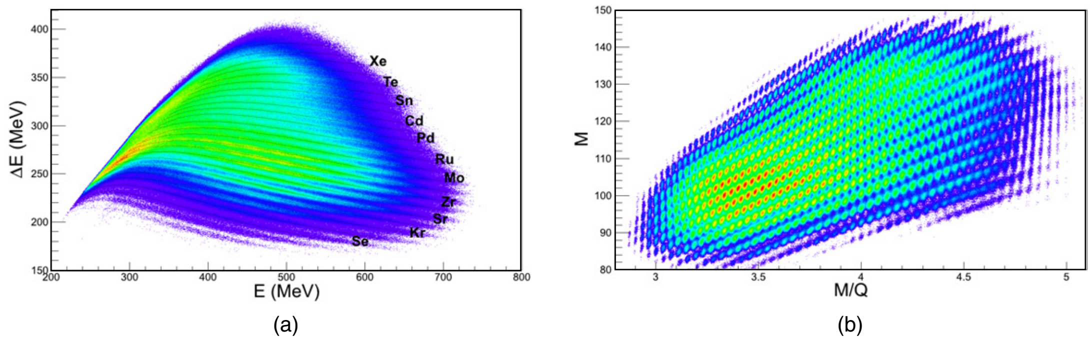

Figure 2. (a) Correlation of the energy loss ΔE measured in the ionisation chambers with the total kinetic energy of the fission fragments used for the Z identification. (b) Correlation of the mass number M with the mass-over-charge state ratio M/Q.

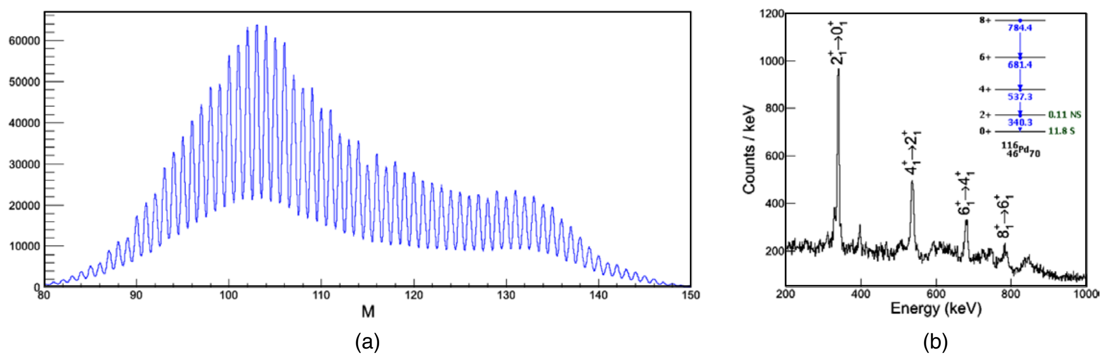

Figure 3. (a) Total mass distribution of the detected nuclei. (b) Example of a γ-spectrum in coincidence with a selection in A and Z in VAMOS, here for the ^{116}Pd. The four first transitions of the yrast band are observable.

of flight (ToF) is the difference between the signal of the two MWPPACs (Multi-Wire Parallel Plate Avalanche Counter). Two drift chambers are used to measure the coordinates (x, y, θ , ϕ) of the nucleus at the focal plane. The energy loss (ΔE) measured in the ionization chamber and the residual energy (E_{res}) measured in the 40 silicon detectors wall provide the total kinetic energy (E). The correlation between ΔE and E as represented on Figure 2a allows to separate the fission fragments depending on their atomic number, from Z = 34 (Se) to 54 (Xe), with a resolution of $\Delta Z/Z \approx 1/60$.

From the coordinates measured at the focal plane, the reconstruction of the trajectory [11] allows to determine the magnetic rigidity Bρ and the velocity of the nuclei, necessary to obtain the mass and the M/Q ratio. After selecting a given charge state through the correlation of M and M/Q (Fig. 2b), the sum of the projection of M/Q*Q gives the total mass distribution (Fig. 3a). Masses from 80 to 150 are well separated with a resolution of $\Delta M/M \approx 1/200$.

Due to the inverse kinematics that focuses the fission fragments towards forward angles and the large acceptance of VAMOS, a large number of nuclei are transmitted and identified in both M and Z. The produced nuclei cover a wide region of neutron-rich nuclei with a maximum yield around ^{100}Zr, and significant statistics up to 10 neutrons beyond stability.

Gamma-spectra for all nuclei identified in VAMOS are Doppler corrected with the velocity measured in the spectrometer (Fig. 3b). The RDDS method [12] is then applied to obtain the lifetimes of

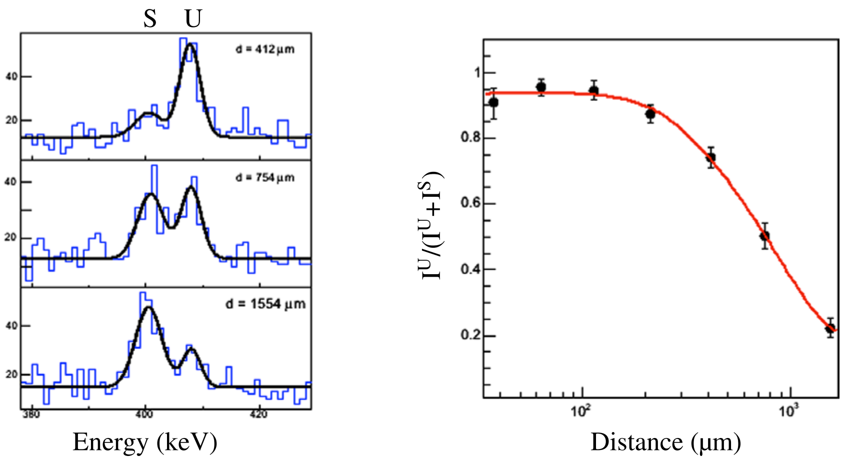

Figure 4. An example of γ-spectra showing the $4_1^+ \to 2_1^+$ transition in ^{112}Ru for different target-to-degrader distances is represented on the left. Two components are visible and labelled as shifted (S) and unshifted (U). The number of counts in each component ($I^{U/S}$) depends on the distance and the ratio $I^U/(I^U + I^S)$ as a function of the distance is the decay curve, shown on the right).

excited states. This method is based on the difference of Doppler shift of the γ -ray emitted by the excited nucleus depending on the position of the recoil at the moment of the emission, before or after the degrader. Two components for one transition are then observed in the spectrum (Fig. 4, left panel). The evolution of the relative intensities of these two components as a function of the target to degrader distance gives the decay curve of the excited level (Fig. 4, right panel). The decay curve is analysed with the differential decay curve method [12] that requires knowledge of the feeding of the level of interest. The feeding from the upper level in the yrast band is always observed and taken into account in the lifetime analysis.

Results

This procedure was applied to levels of spin 4^+ and 6^+ in Zr, Mo, Ru and Pd isotopes and allowed to extract twenty lifetimes. Ten lifetimes have been measured for the first time, in particular in the Pd isotopes and in the most neutron rich Zr, Mo and Ru isotopes.

From these lifetimes, reduced transition probabilities were deduced. They are presented in Figure 5 and compared with previous measurements. In general one can notice a good agreement between the previous values and the present results. The few values that differ from the previous measurements will be studied in more details. In many cases, the uncertainty on the B(E2) values is reduced in our experiment.

These results were compared to the predictions obtained by the Hartree-Fock-Bogoliubov model using the Gogny D1S interaction and extended by the generator coordinate method within the Gaussian Overlap Approximation (HFB+GCM, D1S) [17]. This beyond mean field approach is particularly appropriate for the nuclei in the mass 100 region. The 5 degrees of freedom of the quadrupole deformation that are included in the collective Hamiltonian allow to account for the potential triaxiality and hence the γ-soft character of these nuclei.

In Figure 6 are shown the B(E2) values for the Mo and Ru isotopes from the data set [18] which compiles the results of the HFB+GCM with D1S calculations over the whole nuclear chart. New calculations dedicated to the nuclei studied in this experiment have been performed [19] with the

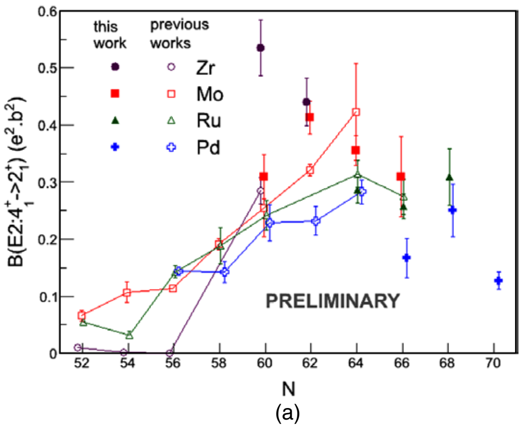

Figure 5. Measured B(E2) values and comparison with previous experiments [5, 13–16] for the $4_1^+ \rightarrow 2_1^+$ transition on the left and the $6_1^+ \rightarrow 4_1^+$ on the right.

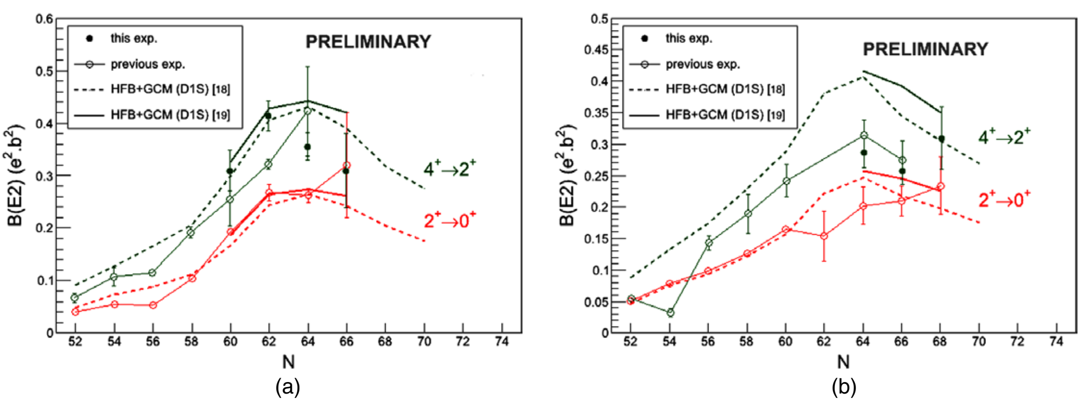

Figure 6. Reduced transition probabilities for the Mo (on the left) and the Ru (on the right) isotopes: comparison between the experimental data and the HFB+GCM (D1S) theoretical predictions.

same model but with an enlarged harmonic oscillator basis to ensure the full convergence. One can note that they do not significantly differ from the ones of Ref. [18]. The theoretical predictions reproduce the evolution of the collectivity in the excited states of the Mo and Ru isotopes. A trend of a maximum of collectivity around N $\approx$ 64 seems to emerge from the measured and theoretical values. The interpretation of these experimental results is still in progress and will be continued.

Conclusion and perspectives

Thanks to this first experiment of lifetime measurement in fission fragments identified in A and Z, the collectivity in more neutron rich nuclei and at higher spins has been studied. The fission reaction and the experimental set-up allow the simultaneous measurement of lifetimes in a wide range of nuclei. Twenty lifetimes have been extracted among which ten for the first time in even-even nuclei from ^{100}Zr to ^{116}Pd. A first comparison with the prediction of the HFB+GCM model with the D1S Gogny interaction shows a good agreement with the experimental data and suggests a maximum of collectivity in Mo and Ru isotopes around N $\approx$ 64. The interpretation of these results will be further developed in order to get more insight on the evolution of the collectivity in this region.

S. Erturk acknowledges the Scientific and Technological Council of Turkey for their support with project number 210T043.

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