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## LIFETIME MEASUREMENTS OF LOW-LYING STATES IN $^{73}\text{Ga}$ AND $^{70,72,74}\text{Zn}$ ISOTOPES\*

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Lifetimes of low-lying states in  $^{73}\text{Ga}$  and  $^{70,72,74}\text{Zn}$  were measured using the Recoil Distance Doppler Shift (RDDS) method. These nuclei were produced in deep-inelastic reactions in inverse kinematics with a  $^{208}\text{Pb}$  beam impinging on a  $^{76}\text{Ge}$  target. Prompt  $\gamma$  rays were detected using the AGATA tracking array coupled to the VAMOS++ spectrometer. Lifetime of the  $5/2^-$  state in  $^{73}\text{Ga}$ , measured for the first time, provides additional evidence for the existence of a  $1/2^-$ ,  $3/2^-$  ground-state doublet. The lifetimes of the  $4^+$  states in  $^{70,72,74}\text{Zn}$  were remeasured in an attempt to understand the discrepancies observed between earlier measurements. Our results are in agreement with those of previous plunger experiments.

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## 1. Introduction

One of the main goals of nuclear structure studies around  $^{68}\text{Ni}$  is to understand the onset of collectivity when adding or removing particles from this core. In odd- $A$  gallium isotopes, with three protons outside the  $Z = 28$  core, the observed magnetic moment of the ground state (g.s.) in  $^{71}\text{Ga}$  reveals its single-particle (s.p.) nature since it is close to the effective s.p. moment of  $g_{\text{eff}}(\pi p_{3/2})$ , while for  $^{75,77}\text{Ga}$ , they indicate a more mixed configuration. Contrary to the rest of odd- $A$  gallium isotopes between  $A = 67$  and  $A = 79$ , which have a  $3/2^-$  g.s., the g.s. spin and parity of  $^{73}\text{Ga}$  was found to be  $1/2^-$ . The fragmented wave function of the  $1/2^-$  g.s. in  $^{73}\text{Ga}$ , obtained in shell-model calculations, indicates its possible collective structure [1].

Transfer reactions [2–4] indicate that in  $^{73}\text{Ga}$ , the  $3/2^-$  and  $1/2^-$  states are close in energy. This suggests the possibility of a  $1/2^-$ ,  $3/2^-$  ground state doublet [5]. A 199-keV transition associated to the  $5/2^- \rightarrow 1/2^-$  decay has been observed in a Coulomb-excitation experiment at ISOLDE [6]. The Doppler broadening of this peak indicates that the lifetime of the  $5/2_1^-$  state has to be much smaller than 3.5 ns, while the extracted experimental  $B(\text{E}2; 5/2^- \rightarrow 1/2^-)$  value gives 13(2) ns if it were a pure E2 transition [6]. The presence of a fast component in this transition would further support the existence of a  $1/2^-$ ,  $3/2^-$  g.s. doublet. Diriken *et al.* [6] suggest an energy difference of  $< 0.8$  keV between these two states, while Vedia *et al.* [7] give 0.3 keV. Both experiments could only provide an upper limit for the  $5/2^-$  state lifetime.

In order to firmly establish and characterize the onset of collectivity in  $^{73}\text{Ga}$ , we performed lifetime measurements using deep inelastic reactions. In addition, low-lying states in  $^{70,72,74}\text{Zn}$  were populated, allowing us to measure lifetimes of the first  $4^+$  states, for which strong and systematic discrepancy between the Coulomb excitation and plunger measurements exists.

## 2. Experimental setup

The experiment was performed at the Grand Accélérateur National d'Ions Lourds (GANIL) using the AGATA tracking array [8] coupled to the VAMOS++ mass spectrometer [9]. The nuclei of interest were produced using a deep-inelastic reaction in inverse kinematics with a  $^{208}\text{Pb}$  beam at 6.63 MeV/ $A$  impinging on a 0.95 mg/cm<sup>2</sup> thick  $^{76}\text{Ge}$  target deposited on a 1.2 mg/cm<sup>2</sup> Cu backing. The nuclei of interest were identified on an event-by-event basis at the focal plane of the VAMOS++ mass spectrometer, used in dispersive mode. VAMOS++ was rotated at 45° with respect to the beam axis. In coincidence with the detected recoils, the emitted  $\gamma$  rays were detected by the AGATA array, consisting of 29 HPGe crystals, in compact configuration, with the detectors placed at 13 cm from the target.

Lifetimes in the picoseconds range were measured by applying the Recoil Distance Doppler Shift (RDDS) method [10] with the use of a differential plunger device developed at the University of Cologne [11]. A  $3\text{ mg/cm}^2$  thick Mg degrader foil was mounted at close distance after the target. The purpose of the degrader is to slow down the recoiling nuclei and provide the possibility to measure the difference in the intensity of  $\gamma$  rays decaying before (unshifted component) and after degrader (shifted component) as a function of target–degrader distance. In this experiment, six target–degrader distances were used:  $119\ \mu\text{m}$ ,  $218\ \mu\text{m}$ ,  $918\ \mu\text{m}$ ,  $2398\ \mu\text{m}$ ,  $5035\ \mu\text{m}$  and  $9948\ \mu\text{m}$ . The relative intensity evolution of the shifted and unshifted components for the  $2^+ \rightarrow 0^+$  transition in  $^{76}\text{Ge}$  is shown in Fig. 1.

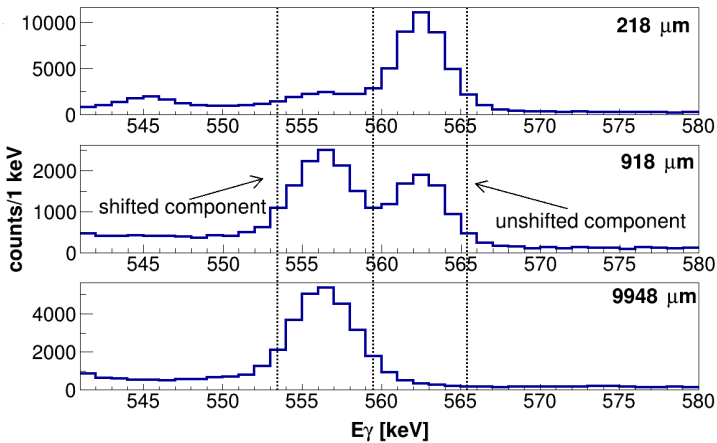


Fig. 1. Evolution of the  $2^+ \rightarrow 0^+$  transition peak in  $^{76}\text{Ge}$  for three different target–degrader distances:  $218\ \mu\text{m}$ ,  $918\ \mu\text{m}$  and  $9948\ \mu\text{m}$ .

The lifetime for the  $2_1^+$  state in  $^{76}\text{Ge}$  is very well-known ( $25.93 \pm 0.29\text{ ps}$  [12]) and we could acquire a large statistics allowing us to validate our method. Our measurements yielded a value of  $26.27 \pm 0.30\text{ ps}$ , in excellent agreement with the adopted one. For the  $4^+$  state, we obtained a lifetime of  $3.14 \pm 0.06\text{ ps}$ , which is in agreement with the literature values of  $2.6(6)\text{ ps}$  [12] and  $3.2(1)\text{ ps}$  [13].

### 3. Results and discussion

In order to achieve our main goal, confirming the existence of a ground-state doublet in  $^{73}\text{Ga}$ , the lifetime of the  $5/2^-$  state was determined from the measured intensities of the 199-keV transition ( $5/2^- \rightarrow \text{g.s.}$ ). The  $\gamma$ -ray energy spectra, showing the 199 keV peak for three different target–degrader distances and the partial level scheme of  $^{73}\text{Ga}$  obtained using data from this experiment, are presented in the left and right panel of Fig. 2, respectively.

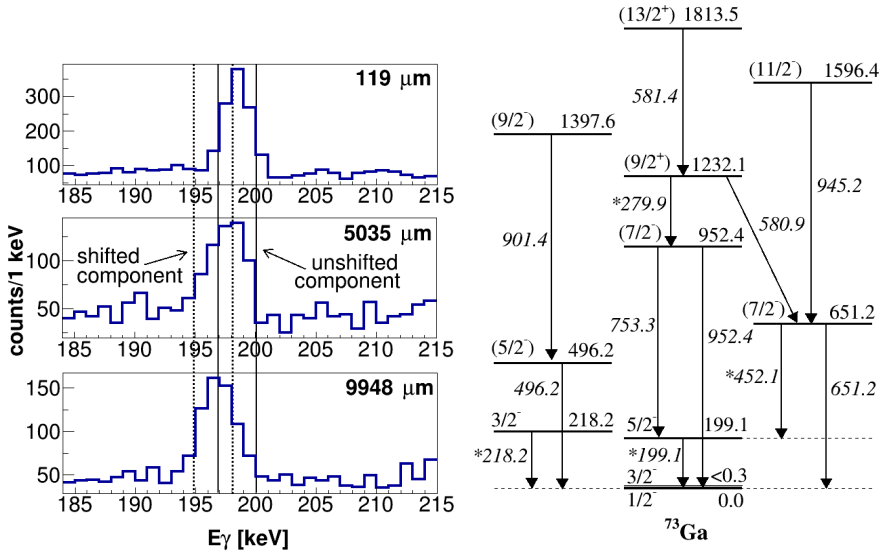


Fig. 2. The 199-keV peak for 119  $\mu\text{m}$ , 5035  $\mu\text{m}$  and 9948  $\mu\text{m}$  target–degrader distances (left). Both unshifted and shifted components appear at two target–degrader distances: 5035  $\mu\text{m}$  and 9948  $\mu\text{m}$ . On the partial level scheme of  $^{73}\text{Ga}$  (right) obtained from this experiment, transitions for which we were able to obtain lifetimes are marked with a star. Energy splitting between  $1/2^-$  and  $3/2^-$  states of  $< 0.3$  keV is taken from Ref. [7].

Both unshifted and shifted components appear only at 5035  $\mu\text{m}$  and 9948  $\mu\text{m}$  target–degrader distances. The lifetime was deduced from these two target–degrader distances by fitting the decay curve with an exponential curve (Fig. 3) and correcting it for the feeding using the standard formula [10]. The measured lifetime of the  $5/2^-$  state is  $224 \pm 24$  ps. Corresponding

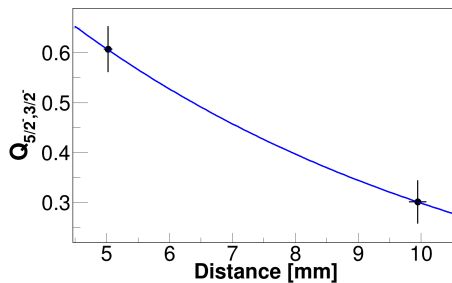


Fig. 3. Decay curve of the  $5/2^- \rightarrow 3/2^-$  transition in  $^{73}\text{Ga}$ , obtained from the intensity ratios of unshifted component over the total peak intensity ( $Q_{5/2^-,3/2^-}$ ) on two distances.

reduced probabilities when assuming a pure M1 or a pure E2 transition are  $B(\text{M1}; 5/2^- \rightarrow 3/2^-) = 0.018 \pm 0.002$  W.u. and  $B(\text{E2}; 5/2^- \rightarrow 3/2^-) = 640 \pm 70$  W.u., respectively. The measured E2 strength is beyond typical values for this mass region, further supporting the argument that the decay of the  $5/2^-$  state is of dominant M1 nature.

In addition, we were able to extract lifetimes for the  $3/2_2^-$  and  $7/2_1^-$  states, and limits for the  $9/2^+$  state. Lifetimes of the  $5/2^-$  and  $7/2_1^-$  states were measured for the first time, while the lifetime of the  $3/2_2^-$  state was previously measured as 67(9) ps, using the advanced time delay (ATD)  $\beta\gamma\gamma(t)$  method [7]. These results are presented in Table I.

TABLE I

Measured lifetimes of low-lying states in  $^{73}\text{Ga}$ .

Isotop	Transition	$E_\gamma$ [keV]	$\tau_{\text{exp}}$ [ps]
$^{73}\text{Ga}$	$5/2^- \rightarrow 3/2^-$	199.1	$224 \pm 24$
	$3/2_2^- \rightarrow 3/2^-$	218.2	$40 \pm 14$
	$(7/2^-) \rightarrow 5/2^-$	452.1	$202 \pm 68$
	$(9/2^+) \rightarrow (7/2_2^-)$	279.9	$33 \leq \tau \leq 180$

We have measured the following lifetimes of the  $4^+$  states in Zn isotopes:  $6.0 \pm 0.8$  ps ( $^{70}\text{Zn}$ ),  $8.3 \pm 0.8$  ps ( $^{72}\text{Zn}$ ), and  $20.8 \pm 2.2$  ps ( $^{74}\text{Zn}$ ) corresponding to  $B(\text{E2}; 4^+ \rightarrow 2^+)$  values of  $229 \pm 30 e^2\text{fm}^4$ ,  $226 \pm 22 e^2\text{fm}^4$  and  $111 \pm 12 e^2\text{fm}^4$ , respectively. These results, although pointing to slightly lower collectivity, are in agreement with the ones previously measured using RDDS methods: VAMOS-EXOGAM [14] and PRISMA-AGATA [15], as shown in Fig. 4. Systematic discrepancy between the  $B(\text{E2}; 4^+ \rightarrow 2^+)$  values obtained from the RDDS and Coulomb-excitation measurements [16] is strongest at  $N = 44$ .

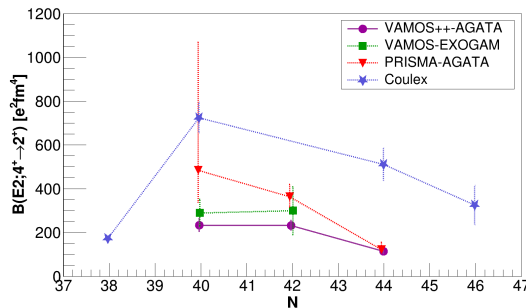


Fig. 4. Experimental  $B(\text{E2}; 4^+ \rightarrow 2^+)$  values for zinc isotopes around  $N = 40$ , obtained in this experiment (VAMOS++-AGATA) and previous experiments.

#### 4. Conclusion

Lifetimes of low-lying states in  $^{73}\text{Ga}$  and  $^{70,72,74}\text{Zn}$  were measured using the Recoil Distance Doppler Shift method. The lifetime of the  $5/2^-$  state in  $^{73}\text{Ga}$  was determined for the first time and its value of  $224 \pm 24$  ps indicates the presence of a strong M1 component in the transition to the ground state, which firmly establishes the ground state as a doublet. Lifetimes of several other low-lying states in  $^{73}\text{Ga}$  were measured for the first time. More detailed analysis of these results, and of the nature of low-lying states in odd- $A$  gallium isotopes, is in progress. In the  $^{70,72,74}\text{Zn}$  isotopes, the lifetimes of the  $4^+$  states were measured and the results are in good agreement with the previous values measured by the RDDS method. However, in order to resolve the strong discrepancy observed between the  $B(E2; 4^+ \rightarrow 2^+)$  values obtained from the Coulomb-excitation and lifetime measurements, a careful  $\gamma$ - $\gamma$  coincidence analysis for the plunger experiment should be performed.

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