

LIFETIME MEASUREMENTS OF Zn ISOTOPES AROUND $N = 40$ *

I. ČELIKOVIĆ^{a,b}, A. DIJON^a, E. CLÉMENT^a, G. DE FRANCE^a
 P. VAN ISACKER^a, J. LJUNGVALL^c, C. FRANSEN^d, G. GEORGIEV^c
 A. GÖRGEN^e, A. GOTTARDO^f, M. HACKSTEIN^d, T.W. HAGEN^e
 C. LOUCHARTE^g, P. NAPIORKOWSKI^h, A. OBERTELLI^g, F. RECCHIAⁱ
 W. ROTHER^d, S. SIEM^e, B. SULIGNANO^g, P. UJIĆ^{a,b}
 J.J. VALIENTE-DOBÓN^f, M. ZIELIŃSKA^g

^aGrand Accélérateur National d'Ions Lourds (GANIL) CEA/DSM-CNRS/IN2P3
 Boulevard H. Becquerel, 14076 Caen, France

^bInstitute of Nuclear Sciences "Vinča", University of Belgrade
 11000 Belgrade, Serbia

^cCSNSM, CNRS/IN2P3, 91400 Orsay, France

^dInstitut für Kernphysik, Universität zu Köln, 50937 Köln, Germany

^eDepartment of Physics, University of Oslo, 0316 Oslo, Norway

^fLNL (INFN), Laboratori Nazionali di Legnaro, 35020 Legnaro, Italy

^gCEA Saclay, IRFU, SPHN, 91191 Gif-sur-Yvette, France

^hHeavy Ion Laboratory, University of Warsaw, 02-097 Warszawa, Poland

ⁱDipartimento di Fisica dell'Università and INFN, 35131 Padova, Italy

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Lifetimes of the low-lying states in Zn isotopes around $N = 40$ have been measured using the Recoil Distance Doppler Shift method. The nuclei of interest were populated in deep-inelastic reactions in inverse kinematics. The ratios $B(E2; 4^+ \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+)$ measured for the Zn isotopes follow a systematics consistent with a seniority classification.

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1. Introduction

The region in the vicinity of ^{68}Ni and the question of the $N = 40$ sub-shell closure have attracted much attention in the recent years. The high excitation energy of the 2^+ state in ^{68}Ni [1], the low $B(E2; 2^+ \rightarrow 0^+)$ value [2] as

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well as the low 0_2^+ excitation energy [3] are indications of the doubly magic character of ^{68}Ni while mass measurements show that the $N = 40$ sub-shell gap is not well pronounced [4]. Several other experimental results [5–8] established a local magicity around $N = 40$ with the observation of a rapid onset of collectivity when adding a few particles/holes to the ^{68}Ni core.

From the systematics of the first 2^+ states energy and several $B(E2)$ values in the $^{74-80}\text{Zn}$ isotopes, measured by Coulomb excitations at low energy, the maximum collectivity for Zn isotopes was suggested to be at $N = 44$ [9]. Recent measurements, performed using a plunger device indicated rather a maximum at $N = 42$ [10, 11]. Moreover, the measurement of $B(E2)$ values between higher-lying states above the first 2^+ in ^{74}Zn , produced by multi-nucleon transfer induced by ^{76}Ge beam on ^{238}U target, pointed out a surprising non-collectivity of the yrast structure [11].

At the GANIL, we have performed an experiment with the goal to confirm the evolution of the collectivity in even neutron-rich Zn isotopes beyond $N = 40$. This has been done by measuring the lifetimes of the low-lying states above the 2^+ level using the plunger technique and a different reaction channel than the one reported in [11]. Since the spectroscopy of the odd nuclei around the $N = 40$ sub-shell allows us to probe the role of a hole or a particle in the single-particle orbitals of interest, another aim was to investigate the collectivity of excited states in $^{69,71}\text{Zn}$.

2. Experimental setup

The experiment was performed at GANIL by applying the Recoil Distance Doppler Shift (RDDS) method [12]. The nuclei of interest were produced using deep-inelastic reactions in inverse kinematics with a ^{238}U beam at 6.76 A MeV impinging on a $800\text{ }\mu\text{g}/\text{cm}^2$ ^{70}Zn target deposit on a $550\text{ }\mu\text{g}/\text{cm}^2$ of Mg backing. Target-like reaction products were detected and identified (Fig. 1) on an event-by-event basis using the focal-plane detectors in the large acceptance VAMOS spectrometer [13]. The optical axis of the spectrometer was rotated by 45° with respect to the beam axis, close to the grazing angle of the reaction. Prompt γ -rays were detected with the segmented germanium clover detectors of the EXOGAM array [14] in coincidence with the recoil nuclei identified in VAMOS.

The differential plunger device developed at the University of Cologne was used for the lifetime measurements of excited states in the picoseconds range. An Mo degrader foil with a thickness of $6.13\text{ mg}/\text{cm}^2$ was mounted at close distance after the target in order to slow down the recoiling nuclei. The Doppler correction of γ -rays emitted before and after the degrader was applied using the recoil velocity measured after the degrader by VAMOS which resulted in two peaks for the same transition. The γ -rays emitted after

the degrader had the proper transition energy corresponding to the unshifted component, while the γ -rays emitted before the degrader appeared at a lower energy corresponding to the shifted component of the peak (Fig. 1). The two components are well separated if they are detected in clovers located at angles larger than 135° . The evolution of the γ -ray spectra for one transition as a function of the target to degrader distance (33 and 99 μm) is shown in the right panel of Fig. 1. Following the recipe of the RDDS method [12], we measured the lifetimes of the states applying a correction for the feeding.

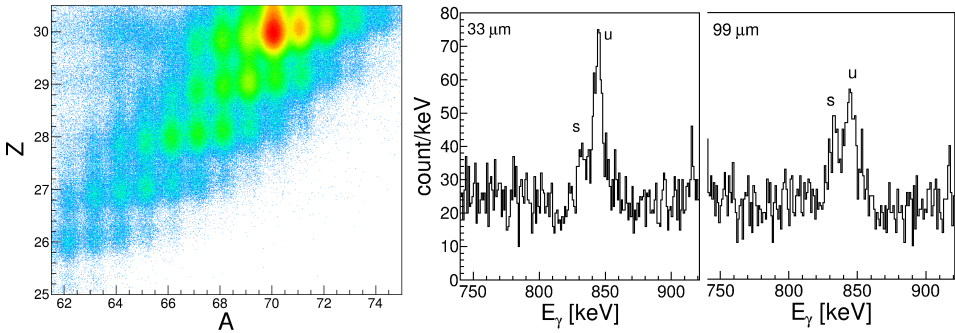


Fig. 1. Particle identification spectra in Z versus A collected for one distance (left). Evolution of the γ -ray spectra obtained for the 4^+ to 2^+ transition in ^{72}Zn as a function of the distance between the target and the degrader (right). The peak marked with u corresponds to the unshifted component, while s corresponds to the shifted component.

3. Results and discussion

The measured lifetimes and extracted $B(E2)$ values of the low-lying states populated in ^{70}Zn and ^{72}Zn are given in Table I and compared with the existing experimental data and theoretical predictions.

The major contribution to the error bars comes from the statistical uncertainty of peak intensities. The extracted $B(E2; 2^+ \rightarrow 0^+)$ values for ^{70}Zn and ^{72}Zn are in agreement with the previous results obtained using different techniques. Conversely, the $B(E2; 4^+ \rightarrow 2^+)$ value for ^{70}Zn significantly differs from the one measured using the Doppler shift attenuation method [15]. Our results obtained for $^{70,72}\text{Zn}$ are in agreement with those reported by Louchart *et al.* [11], where the same RDDS method was used, but with a different reaction. A similar discrepancy between the results obtained with the RDDS method and those using Coulomb excitations has been observed for $B(E2; 4^+ \rightarrow 2^+)$ values for ^{74}Zn [9, 11] which are not fully understood.

TABLE I

Measured lifetimes and $B(E2; J \rightarrow J - 2)$ values for low-lying states in ^{70}Zn and ^{72}Zn , compared with previous experiments and shell-model calculations.

		This experiment		Previous work	SM [16] JUN45 [17]
	J^π	τ [ps]	$B(E2; J \rightarrow J - 2)$ [$e^2\text{fm}^4$]		
^{70}Zn	2^+	5.2 ± 0.5	289 ± 28	286^{+131}_{-68} [11] 283 ± 17 [18] 305 ± 15 [19]	302
	4^+	4.9 ± 1.1	276 ± 61	475^{+584}_{-147} [11] 720 ± 70 [15]	394
^{72}Zn	2^+	19.4 ± 5.5	354 ± 100	392^{+34}_{-29} [11] 348 ± 42 [20]	336
	4^+	6.4 ± 2.4	292 ± 110	361^{+57}_{-47} [11]	349
	6^+	3.0 ± 1.2	133 ± 51	134^{+57}_{-31} [11]	228

We performed shell model calculations with the ANTOINE code [16]. The JUN45 [17] interaction in the $pf_{5/2}g_{9/2}$ valence space with the effective charges $e_\pi = 1.5e$, $e_\nu = 1.1e$ was used. The theoretical results are in agreement with the experimental values for 2^+ states, while the shell-model calculation overestimates $B(E2)$ values for higher-lying transitions.

The energy ratio $E(4^+)/E(2^+)$ along the Zn isotopic chain gives a qualitative idea of the collective properties of those nuclei. For all Zn isotopes this ratio is in the range between 2 and 2.5 which is a typical value for nuclei that exhibit a vibrational character. Additional information about the collective properties of nuclei can be extracted from the $B(E2)$ ratio, $B_{42} = B(E2; 4^+ \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+)$ which, for collective excitations, is expected to be larger than one. Moreover, for nuclei with vibrational character, this ratio is equal to two, while for rotors it is equal to 1.43. The B_{42} values obtained for ^{70}Zn and ^{72}Zn are 0.95 ± 0.23 and 0.82 ± 0.39 respectively, which is the benchmark for nuclei where the seniority is a good quantum number [21]. The B_{42} values measured and calculated for the Zn isotopes are plotted in Fig. 2.

The Zn isotopes lie in the region where it was precisely proposed that seniority is a good quantum number [22]. Moreover, the $B(E2; J \rightarrow J - 2; J > 2)$ values obtained for ^{72}Zn , decrease from $4^+ \rightarrow 2^+$ to $6^+ \rightarrow 4^+$ transition, following the expected behaviour for such nuclei as indicated in Fig. 2 of Ref. [22].

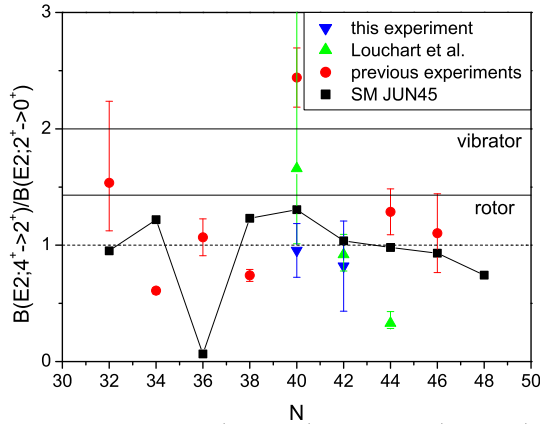


Fig. 2. Systematics of the $B(E2; 4^+ \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+)$ ratio for the Zn isotopes.

From the γ spectrum of ^{71}Zn , the lifetime of the state tentatively assigned to $1/2^-$ or $3/2^-$ [23] decaying to the $1/2^-$ g.s. with a 490 keV γ -ray was found to be $\tau = 7.3 \pm 2.0$ ps. According to the Weisskopf estimates $\tau_w(M1) = 2.73 \times 10^{-13}$ s, $\tau_w(E2) = 1.67 \times 10^{-9}$ s, one can reasonably assume that the transition is mainly $M1$ with a corresponding $B(M1) = 0.066 \pm 0.018 \mu_N^2$. In order to check the nature of this state, we have applied a particle-core coupling approach by calculating the spectroscopic factors and occupancies as was done by Dijon *et al.* [24]. Assuming this state to be the first calculated $3/2^-$, we obtained wave functions where the major component (around 60%) comes from a neutron hole in $\nu p_{3/2}$ coupled to the 0^+ ground state of ^{72}Zn while $1/2^-_{\text{g.s.}}$ is dominantly a neutron hole in $\nu p_{1/2}$ coupled to the ground state of ^{72}Zn , which supports the assumption of an $M1$ transition and indicates the single particle nature of the $3/2^-$ state. If we now assume that the state is the first excited $1/2^-$ calculated by the SM, its major component (just 30%) is a neutron hole in $\nu p_{1/2}$ coupled to the 0^+ of ^{72}Zn , indicating more a collective nature of the $1/2^-$.

From the γ -ray spectrum of ^{69}Zn we were able to identify the shifted component of the $3/2^-$ state which allowed us to extract an upper limit for its lifetime found to be smaller than 0.44 ps. Again, the Weisskopf estimates give: $\tau_w(M1) = 5.52 \times 10^{-14}$ s, $\tau_w(E2) = 1.21 \times 10^{-10}$ s. Therefore, we assume a dominant $M1$ character for this transition. In the framework of the particle-core coupling approach, the $3/2^-$ state is mainly a neutron hole in $\nu p_{3/2}$ coupled to the ground state of ^{70}Zn (48%), while $1/2^-_{\text{g.s.}}$ is mainly a neutron hole in $\nu p_{1/2}$ coupled to the ground state of ^{70}Zn (48%). This is also consistent with the assumption of an $M1$ transition and indicates its single-particle nature.

4. Conclusion

Lifetimes of the low-lying states in Zn isotopes around $N = 40$ have been measured using the Recoil Distance Doppler Shift method. The nuclei of interest were populated in deep-inelastic reactions in inverse kinematics. The results obtained for $^{70,72}\text{Zn}$ are in agreement with those reported by Louchart *et al.* [11], where the same RDDS method was used, but with a different reaction. The $B(E2)$ ratios between $B(E2; 4^+ \rightarrow 2^+)$ and $B(E2; 2^+ \rightarrow 0^+)$ as well as the systematics of the $B(E2; J \rightarrow J - 2; J > 2)$ values obtained for ^{72}Zn , show a surprising absence of collectivity which might indicate that the seniority is a good quantum number in the Zn isotopes. Lifetimes of the odd $^{69,71}\text{Zn}$ isotopes were measured and discussed in the framework of a particle-core coupling approach.

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