Eur. Phys. J. A **35**, 167–170 (2008)
DOI 10.1140/epja/i2007-10534-y

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Lifetime measurement of the six-quasiparticle isomer in ^{140}Nd and evidence for an isomer above the $19/2^+$ state in ^{139}Nd

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Received: 21 November 2007 / Revised: 21 January 2008
Published online: 11 March 2008 –
Communicated by R. Krücken

Abstract. The lifetime of the recently discovered six-quasiparticle (6-qp) isomer in ^{140}Nd has been measured using the ^{126}Te(^{18}O, 4n) reaction and the pulsed-beam technique at the Institut de Physique Nucléaire (IPN) Orsay. The deduced lifetime of the 6-qp isomer in ^{140}Nd of 1.23(7) μs supports the 20^+ spin-parity assignment to the isomeric state which is based on a spherical configuration that coexists with the triaxial bands observed in this spin range. Evidence for delayed components for the transitions below the $19/2^+$ state in ^{139}Nd was observed, with an apparent half-life of 272(4) ns.

PACS. 27.60.+j $90 < A < 149$ – 21.60.-n Nuclear structure models and methods – 21.10.Tg Lifetimes, widths

1 Introduction

The nuclei around the $N = 82$ shell closure are a fertile field of spectroscopic investigations both at low and high spins: at low spins the presence of isomers based on simple particle-hole configurations helps to establish the active quasiparticle configurations in a specific nucleus and test the suitability of various nuclear potentials [1], whereas at high spins the combined contribution of neutron holes and proton particles drives the nuclear shape toward a stable triaxial shape with $\gamma \approx +30°$ [2,3]. New experimental data were recently published for the ^{140}Nd nucleus, which has two neutron holes with respect to the $N = 82$ shell closure and therefore presents several isomeric states, with configurations involving up to six quasiparticles [4]. In the odd-even ^{139}Nd, the existence of an isomeric state was reported long time ago [5], but its position in the level scheme and the lifetime could not be established.

In this article we report on the lifetime measurement in a pulsed-beam experiment of the 20^+ isomeric state in ^{140}Nd and on the apparent half-life of the transitions below the $19/2^+$ state in ^{139}Nd.

2 Experimental details

High-spin states in ^{140}Nd and ^{139}Nd have been populated in the reaction ^{126}Te(^{18}O, xn) with a 75 MeV ^{18}O beam delivered by the Tandem accelerator of IPN Orsay. The ^{126}Te target with a thickness of 400 μg/cm^2 was deposited on a 10 mg/cm^2 thick Au backing. Gamma-ray coincidences were measured with one Clover and three coaxial Ge detectors with BGO Compton-suppression shields. The four detectors were positioned in the horizontal plane, around the reaction chamber, at angles of $\pm 45°$, and $\pm 135°$ with respect to the beam axis.

The reaction channel leading to ^{139}Nd is (^{18}O, 5n) and to ^{140}Nd is (^{18}O, 4n), with nearly equal cross sections of around 200 mb as calculated with CASCADE [6]. The recoiling residual nuclei were stopped by the thick Au backing in the center of the array to measure the isomeric decay. The beam pulsing was realized using a chopper-buncher system which produced Gaussian beam pulses with FWHM of 1.8 ns and FWTM of 5 ns. A repetition rate of 10 μs was chosen between the beam pulses, a time interval sufficient to study isomers with lifetimes in the range from tens of nanoseconds to several microseconds. We have measured single γ-rays and their detection time with respect to the beam pulse to deduce the lifetime of the isomeric states.

Events were written on disk employing the NARVAL program. The data were collected using the Orsay acquisition system based on COMET-6X cards [7], designed to be used as high-resolution ADCs. A COMET-6X card consists of a 32 bits 40 MHz Digital Signal Processor (DSP) which realizes part of the data processing *in situ*, producing an event composed of the absolute time coded on

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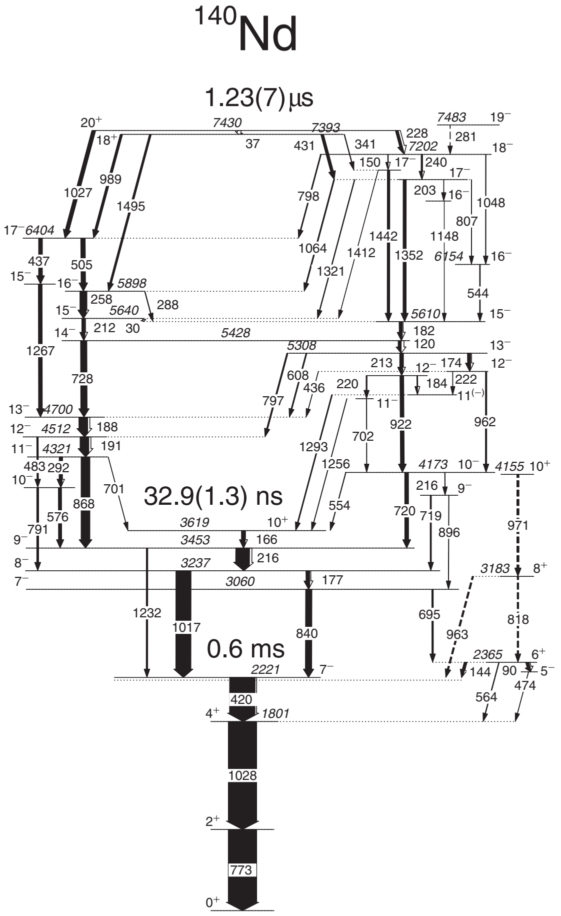

Fig. 1. Level scheme of ^{140}Nd below the 20^+ isomer resulting from the analysis of the delayed coincidences reported in ref. [4].

47 bits with a resolution of 400 ps, allowing any off-line coincidence between the input signals within a time range of ≈ 15.6 hours, the amplitude coded on 15 bits (32768 channels) and a bit pattern. The events are transferred event by event via the linkport of the DSP in the concentrator (20 Mo/s), then to the resource manager of the VXI chassis, and finally to the acquisition system through a 1 Gbits/s ethernet link.

The recorded coincidence events were sorted in various two-dimensional arrays, as follows: E_γ-E_γ coincidences with a prompt time gate to study the cascades above the isomers, E_γ-E_γ coincidences with a delayed time gate to study the cascades below the isomers, and E_γ-E_γ prompt-delayed coincidences to study the connections between cascades above and below the isomers. To deduce the lifetime of the populated isomeric states we sorted two-dimensional E_γ-t_γ arrays.

Contour lines on the γ-rays of interest can be defined and projected on the time axis to deduce the lifetimes, or on the energy axis to obtain spectra at different times after the beam pulse. A total of 5×10^{11} events with a γ-ray fold $f \geq 1$ and 5×10^8 events with a γ-ray coincidence fold $f \geq 2$ were obtained from the data.

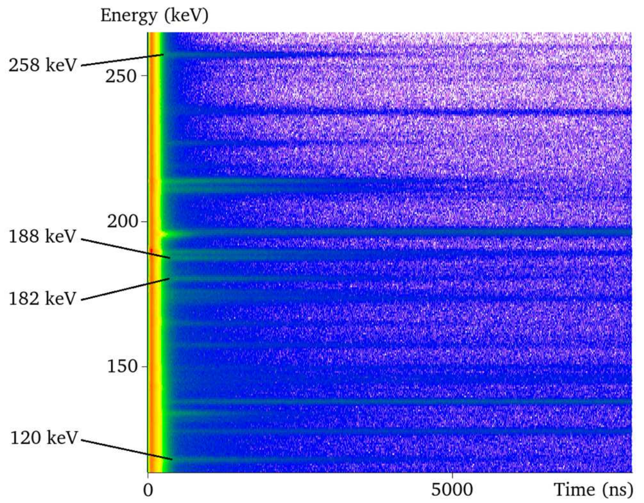

Fig. 2. Zoom on the E_γ-t_γ matrix showing the decay of the transitions used to deduce the lifetime of the 20^+ isomer in ^{140}Nd.

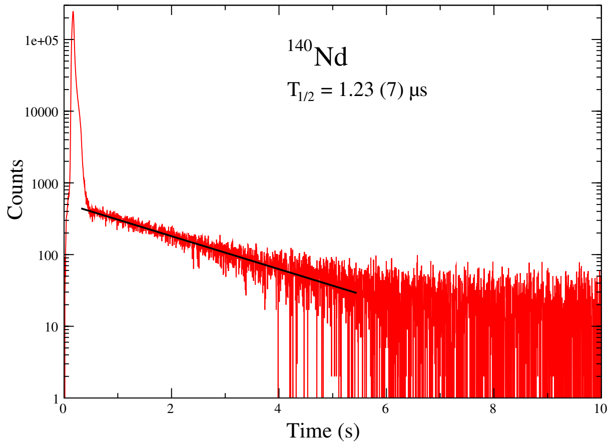

Fig. 3. The sum of time spectra of the 120, 182, 188 and 258 keV transitions from the two main cascades de-exciting 20^+ isomer in ^{140}Nd. The solid line shows the fitted exponential decay with a half-life of 1.23(7) μs.

3 Results

3.1 The ^{140}Nd nucleus

The partial level scheme of ^{140}Nd showing the transitions which de-excite the investigated isomeric state is shown in fig. 1.

The spectra of the 228 keV transition de-exciting the 20^+ isomer and the 341, 431, 989 and 1495 keV transitions de-exciting the 18^+ state are all similar, indicating the same apparent lifetime. Their statistics was too poor to be useful in the determination of the lifetime of the 20^+ isomer, which was instead determined by fitting an exponential decay to the sum of time spectra of the clean 120, 182, 188 and 258 keV transitions placed in the two main cascades de-exciting the isomer. A zoom on the E_γ-t_γ array in the energy range of interest is shown in fig. 2, while fig. 3 shows the projected time spectrum and the exponen-

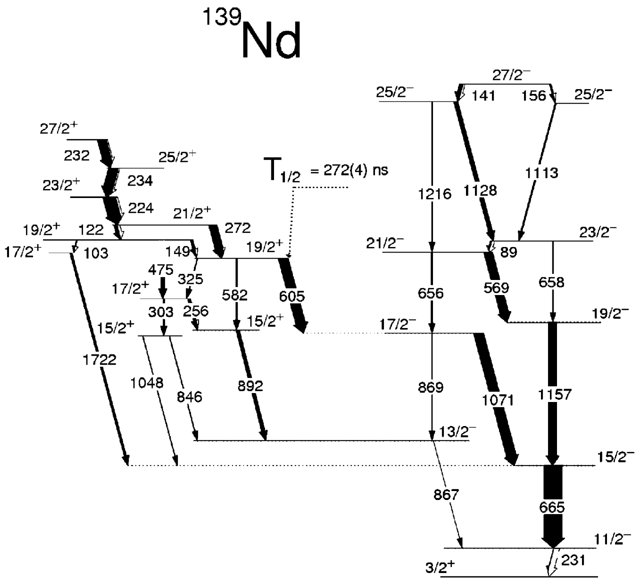

Fig. 4. Partial level scheme of ^{139}Nd around the $19/2^+$ state resulting from the data of the experiment reported in ref. [3] and from the delayed-coincidence data reported in ref. [4].

tial fit. A half-life of 1.23(7) μs was obtained. We have also analysed the prompt-delayed concidences, but no γ-rays populating the 20^+ isomer could be identified.

3.2 The ^{139}Nd nucleus

A partial level scheme of ^{139}Nd around the $19/2^+$ state is shown in fig. 4.

From the delayed-coincidence relationships and the analysis of the time spectra, it is clear that only the transitions below the $19/2^+$ state have a delayed component. Spectra with a delayed time gate ($t \geq 50$ ns) obtained by gating on the three intense transitions of 605, 665 and 1071 keV below the $19/2^+$ state are shown in fig. 5. However, we could not observe any delayed transition populating the $19/2^+$ state, nor the characteristic K X-rays of Nd. Therefore, we could not establish the excitation energy of the isomeric state.

To determine the apparent lifetime of the isomer above the $19/2^+$ state in ^{139}Nd, we can use the three intense transitons of 605, 1071 and 665 keV connecting the $19/2^+$ state to the $11/2^-$ isomer. However, only the 1071 keV transition is sufficiently clean to be used in the determination of the lifetime. The region of interest around the 1071 keV transition in the E_γ-t_γ matrix is shown in fig. 6. The time spectrum and exponential fit for the 1071 keV transition is shown in fig. 7, from which we deduced a lifetime of 272(4) ns. We have also analysed the prompt-delayed concidences, but no γ-rays populating the isomer above the $19/2^+$ state in ^{139}Nd could be identified.

During our lifetime measurement the beam was also hitting the target frame made of aluminium, populating high-spin states in ^{43}Sc through the ^{27}Al(^{18}O, 2n) reaction. The time spectra of the 136, 1157 and 1830 keV

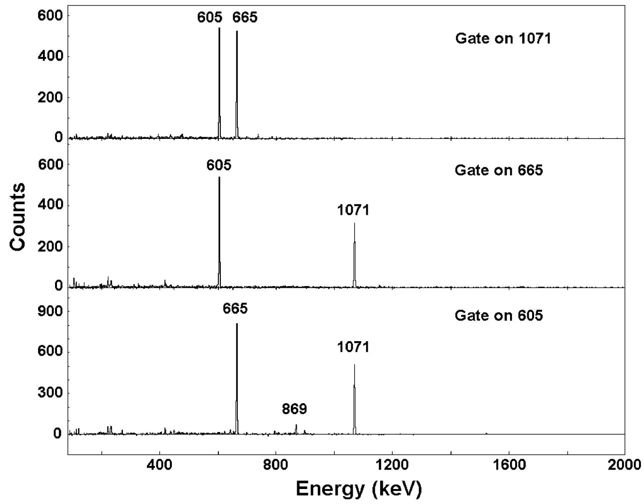

Fig. 5. Spectra obtained by gating on the delayed 605, 665 and 1071 keV in ^{139}Nd.

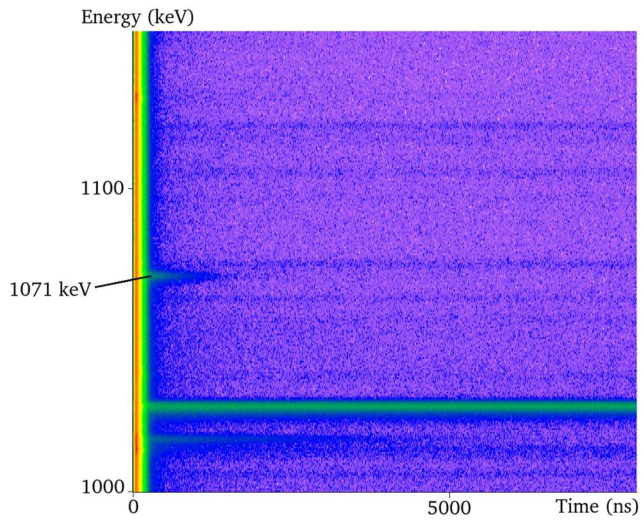

Fig. 6. Zoom on the E_γ-t_γ matrix showing the decay of the 1071 keV transition used to deduce the lifetime of the new isomeric state in ^{139}Nd.

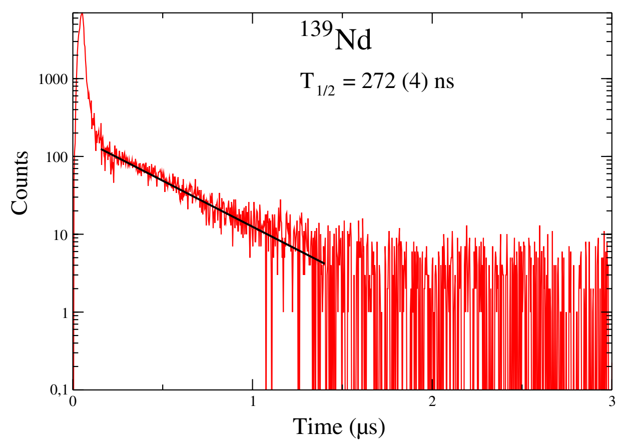

Fig. 7. The time spectrum of the 1071 keV $17/2^- \to 15/2^-$ transition in ^{139}Nd. The solid line shows the fitted exponential decay with a half-life of 272(4) ns.

γ-rays de-exciting the known $19/2^-$ isomer at $E_x = 3123\,\mathrm{keV}$ in ^{43}Sc with $T_{1/2} = 469(4)\,\mathrm{ns}$ [8] were analyzed, from which we deduced a half-life of 481(9) ns. The agreement, within the error bars, between the present and the previously reported values can be considered as a validation of the method we used to deduce the presently reported lifetimes.

4 Discussion

In order to understand the observed de-excitation patterns of the isomeric state, we have used the single-particle Weisskopf estimates for the lifetimes. The 20^+ state, with $E_x = 7430\,\mathrm{keV}$, decays by means of the 228 keV and 1027 keV transitions, and an unobserved low-energy 37 keV transition towards the state with $E_x = 7393\,\mathrm{keV}$. The single-particle Weisskopf estimates are $1.9\,\mu$s for the 228 keV $M2$ transition, $0.84\,\mu$s for the 1027 keV $E3$ transition and $186\,\mu$s for the 37 keV $E2$ transition. To compare the measured lifetime with the total lifetime of the isomeric state resulting from the partial lifetimes, one needs the relative intensities of the de-exciting transitions. Unfortunately, we could not deduce the intensities of the 1027 and 37 keV transitions: the 1027 keV γ-ray is strongly contaminated by the delayed 1028 keV transition below the 7^- isomer with $T_{1/2} = 0.6\,\mathrm{ms}$, while the 37 keV transition is not observed because the K-conversion is not energetically possible and the L-conversion leads to the emission of X-rays with energies lower than 6 keV, which are below the electronic threshold of the detectors. Therefore, we could not determine the relative intensities of the transitions de-exciting the 20^+ isomer and estimate the total lifetime.

The four transitions de-exciting the $I^\pi = 18^+$ state have estimated Weisskopf partial lifetimes smaller than 1 ns. Their time spectra are all similar to that of the 228 keV transition, and therefore are due to the delayed population from the $I^\pi = 20^+$ isomer. As mentioned in ref. [3], the $E1$, $M2$ and $E3$ transitions towards the negative-parity states involve the jump of one neutron between the negative-parity orbital $\nu h_{11/2}$ and one of the positive-parity orbitals $\nu d_{3/2}$, $\nu d_{5/2}$ and $\nu g_{7/2}$, and therefore are not strongly inhibited.

As a final comment on the obtained results, one could say that the presence of an isomeric state with lifetime of the order of $1\,\mu$s at spin 20^+ in ^{140}Nd, in the range of the Weisskopf estimates for the partial lifetimes, strongly support the predicted coexistence of spherical and triaxial states at medium high-spins in nuclei close to the $N = 82$ shell closure and the proposed 6-qp configuration [3,4]. In fact, as one can see in fig. 7 of [4], calculated spherical and triaxial configurations nicely agree with the observed yrast maximum aligned states, among which there is also the investigated 20^+ isomer whose caculated shape is spherical.

In conclusion, we have measured a lifetime of $1.23(7)\,\mu$s for the 6-qp isomeric state in ^{140}Nd and found evidence for an isomer above the $19/2^+$ state in ^{139}Nd with an apparent half-life of 272(4) ns. The qualitative agreement of the measured lifetime of the 20^+ isomeric state in ^{140}Nd with the Weisskopf estimates confirms the spin-parity assignment.

The authors are grateful to the technical staff of the Tandem accelerator of IPN Orsay for the high quality of the delivered beam.

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