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Search for μs-isomers in $^{251-254}$No

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ABSTRACT

Nuclear isomers are one of the main probes for exploring the underlying nuclear structure. In heavy nuclei, especially in nobelium isotopes, many isomers are known and have been intensively studied both experimentally and theoretically. This revealed their shell structure, which primarily defines stabilities of the heaviest nuclei against spontaneous fission. In the present work, we revisited the isotopes $^{251-254}$No and their daughters by searching for hitherto unknown isomers with half-lives on the order of μs using the fast digital electronics. In ^{253}No and ^{254}No, we did not find evidence for new μs-isomers. In ^{251}No, we observed the isomeric state with a half-life of 4^{+6}_{-2} μs, which confirms the previously reported ≈ 2 μs-isomer. In ^{252}No, we observed evidence for the presence of a new 9^{+13}_{-4} μs isomeric state, in addition to the known 110 ms two-quasiparticle K-isomer.

1. Introduction

Studies of nuclear excited states, which deexcite to lower-lying ones via retarded electromagnetic transitions are one of the key tools for exploring the underlying nuclear structure [1,2]. The heaviest nuclei are of special interest as their nuclear structure is responsible for their stability against spontaneous fission [3–5]. The region of deformed heavy nuclei with proton and neutron numbers near $Z = 100$ and $N = 152$, respectively, is rich in different isomeric states [2]. Two types of isomers constrained by quantum selection rules for the total spin (J) and/or its projection onto the axial symmetry axis (K) quantum numbers were observed [6]. The latter, typically referred to as K-isomeric states and formed by couplings of up to several quasiparticles (qp), are of particular importance [6–9]. Decay of a high-K state is not only retarded via electromagnetic transitions but also via fission [10–13]. Moreover, high-K states in very neutron-deficient heavy and superheavy nuclei have been predicted to have longer partial fission half-lives than the ground states [12,14]. To date, experimentally known cases occur in ^{250}No, ^{254}Rf and ^{252}Rf [9,15]. The exploration of this unique property of high-K states in the superheavy nuclei, referred to as “clouds of stability”, is one of the intriguing topics in the field [14].

The most extensively studied cases of K-isomers occur in various No isotopes, which can be produced with sufficiently large statistics in the fusion-evaporation reactions of ^{48}Ca + Pb [16]. Thus, the experimental data on No isotopes represent valuable input for the theoretical description of the shell structure of heaviest nuclei [2,6,12,17–19]. Significant progress in the study of K-isomers has been achieved through the detection of conversion electrons (CEs) emitted during the deexcitation [20–22]. Thanks to this approach, many isomers in various No isotopes were discovered, studied, and continue to be investigated [23–29]. Moreover, multiple

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new μs-isomers have recently been discovered in ^{255}No [30,31] and ^{256}No [32]. This technique, which is however very sensitive to experimental conditions (low-energy threshold, background, etc.) is particularly well suited for studying isomers with half-lives $\gtrsim$10 μs when conventional analog electronics are used.

In recent years, the detection of CEs from isomeric decays has been shown to benefit greatly when the shapes of signals are stored with fast digital electronics [33–35]. This so-called triggerless measurement of CEs has become a powerful tool for studying isomers with half-lives ranging from ≈0.1 to 80 μs [34,36] and has been successfully applied for isomer studies in Rf and Es isotopes [33,34, 36–38]. Recently, the use of this technique was pushed to its limit by discovering the shortest-lived (≈60 ns) known rutherfordium isotope (^{252}Rf), detected thanks to its longer-lived K-isomeric state [15]. Furthermore, the advantage of this technique has most recently been demonstrated in the observation of evidence for the presence of a μs-isomer in ^{259}Sg [39]. All these results show that the K-isomer phenomenon still needs to be explored in heavier nuclei, ideally by applying the triggerless measurement of CEs, which, to our knowledge, has not yet been applied for the study of No isomers except for ^{250}No [35,40]. In the present work, we present experimental data on the isomers in ^{251}No, ^{252}No, ^{253}No, ^{254}No and their daughter isotopes, aimed at searching for the presence of hitherto unknown μs-isomers in addition to the known cases.

2. Experiment

The experiment was performed at the gas-filled TransActinide Separator and Chemistry Apparatus (TASCA) at GSI, Darmstadt, Germany [41]. The Universal Linear Accelerator UNILAC accelerated a pulsed ^{48}Ca^{10+} beam, which had 5-ms long pulses and a repetition rate of approximately 5 Hz, to an energy of 218.9 MeV. Targets of ^{204}Pb (with enrichment of 99.94%), ^{206}Pb (99.8%), ^{207}Pb (98.0%), and ^{208}Pb (99.0%) with average thicknesses of about 0.5 mg/cm^2 were used. PbS targets were evaporated on carbon foils with average thicknesses of about 40 μg/cm^2 and mounted on a wheel rotating synchronously with the beam macro-structure [42]. The beam energy in the middle of the targets was ≈215 MeV for all used targets and corresponded to the dominant production of the 2n channel from the fusion-evaporation reactions [16].

For separation and collection of evaporation residues (ERs) in the focal plane detector, TASCA was operated with helium gas at 0.8 mbar pressure and with a magnetic rigidity ($B\rho$) of 2.08 Tm [43,44]. The efficiency of TASCA to guide ERs to the focal plane was estimated to be 60% [43,45]. The focal plane detector consisted of a 300 μm-thick double-sided silicon strip implantation detector comprising 144 vertical (X) and 48 horizontal (Y) strips on the front and back sides, respectively. The focal plane detector was cooled by liquid alcohol circulating at a temperature of -20° C. Signals from the X and Y strips of the stop detector were shaped with pre-amplifiers with different gains to provide two energy branches up to about 20 MeV and 200 MeV [36].

All amplified and shaped signals were digitized by 100 MHz-sampling FEBEX4 14-bit ADCs developed by the GSI experiment electronics department [46,47]. The shape of each signal was stored in 30, 60 or 80 μs-long traces when the data acquisition system was triggered by signals with energies above ≈0.3 MeV and ≈0.8 MeV detected in the low-energy (X) and high-energy (Y) branches, respectively. Relatively large threshold values were set, resulting in a reasonably low average counting rate of about 40 Hz at the average beam intensity on the target of about 4×10^{11} particles per second. Under such conditions, the readout data rate was about 1 MByte per second when 8000 samples corresponding to 80 μs-long traces were stored.

Energy resolutions (FWHM) of both X and Y strips were about 40 keV for measurements of external α particles with 5.8 MeV. Energy calibrations were made using α decays of implanted nuclei produced in the "calibration" reaction ^{48}Ca + ^{176}Yb. A multi-wire proportional counter (MWPC) was mounted in front of the focal plane detector and was used to discriminate events passing through TASCA, e.g., No isotopes.

3. Results and discussions

Fig. 1 shows the low-energy spectra of α-like events measured during beam-off periods for all four ^{48}Ca + $^{204,206-208}$Pb reactions. Well-pronounced α peaks were identified based on the known decay properties of $^{251-254}$No and their daughter products [48]. In all runs, the background α events originating from ^{211}Po, which was produced as an EC-decay product of the long-lived ^{211}At (7.2 h, [48]) and ^{211}Rn (14.6 h, [48]) are visible. These long-lived isotopes were produced in the α-decay chains of Ra-Th isotopes, which were directly produced in the "calibration' reaction ^{48}Ca + ^{176}Yb prior to No runs.

The isotopes ^{252,253,254}No were produced in the 2n evaporation channels of the fusion reactions of ^{48}Ca + $^{206-208}$Pb. In the case of the ^{48}Ca + ^{204}Pb reaction, its 2n fusion-evaporation channel product, ^{250}No, decays exclusively by spontaneous fission, and the results were published in Ref. [40]. Accordingly, in the low-energy spectrum from this reaction, we observed the α decay of ^{251}No, which was produced in the 1n evaporation channel.

In Fig. 1, the variation of shapes of α-peaks corresponding to various No isotopes is due to the energy summing, which is a side effect of the implantation technique that significantly influences the detector response and adds uncertainty in the interpretation of the measured data [50]. To highlight this variation the Gaussian-shaped peaks with $\sigma = 20$ keV corresponding to the energy of α particles originating from the dominant transitions in No isotopes [48] are shown.

The broadest or higher-energy-tailed α peak, measured for ^{253}No, is due to the sum of energies of α particles (8.02 MeV) populating the excited 280 keV state and CEs originating from the deexcitation of this state [50]. The α peaks of ^{252}No and ^{254}No are narrower than that of ^{253}No. On the other hand, these α-peaks, mainly corresponding to ground-to-ground 0$^+$ state transitions, should still be affected by the α-decay fine structure, i.e., the α transition to the 2$^+$ excited state with an energy of ≈50 keV and a population probability of ≈15 % [48]. In fact, this effect may contribute to the lower-energy-tail visible in α peaks of both ^{252}No and ^{254}No. Eventually, such a fine structure can also be present in cases of odd-A nuclei, e.g., in ^{253}No (cf. Fig. 1a–c). In contrast, despite the low

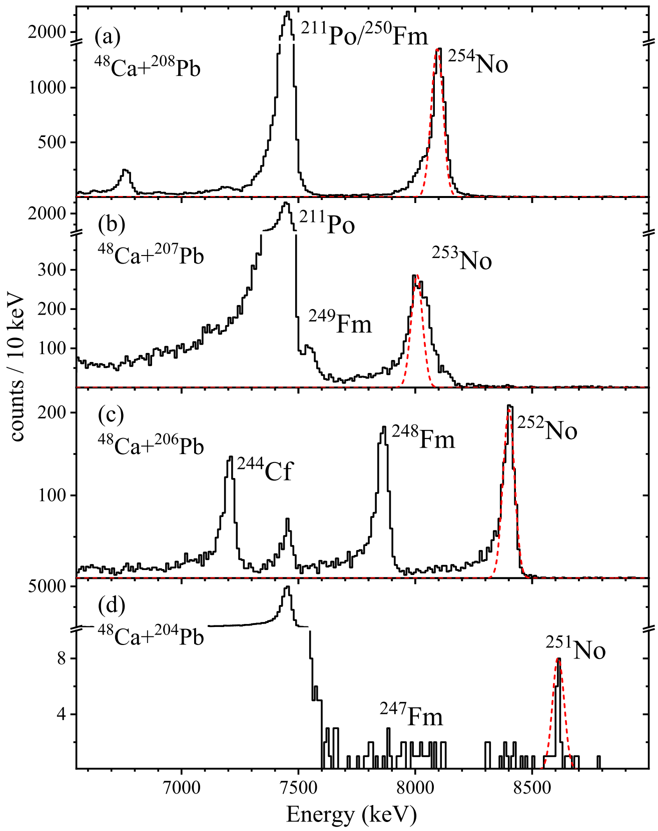

Fig. 1. Energy spectra of beam-off events measured in the low-energy branch (X-strips) from the ^{48}Ca-induced reactions with various lead targets. Identified products from the different reactions are marked. The anticipated Gaussian-shaped peaks (with the $\sigma = 20$ keV) for the α particles originating from the dominant transitions in No isotopes [48] are shown by dashed lines. For details, see text.

statistics, ^{251}No shows a very sharp α peak. This indicates that the corresponding α transition proceeds without populating promptly decaying excited states in the daughter nucleus as is the case of ^{253}No.

To identify the isomeric states in No isotopes, we searched for implantation signals (ER) for all detected α and fission events. Since, the energies of ER, α and fission signals are sufficiently large to be detected in both low-energy and high-energy branches the correlation analysis was performed by requiring the same X and Y strips. Once the ERs were found, delayed small-energy signals were searched for each ER in two ways. First, we searched for self-triggered small-energy signals, i.e., signals with energies above the low-energy detection thresholds. Since we used threshold values of about 0.3 MeV and 0.8 MeV for the X and Y strips, respectively, CEs from the decay of isomeric states can generally be detected only in the low-energy branch. Therefore, for CE correlation only one position, X, was required to be the same as for the ER. The rates of randomly correlated small-energy signals occurring during beam-on and beam-off periods were then estimated. For this, we searched for the nearest preceding small-energy signal (< 1.5 MeV) occurring before any event detected during the beam-on period with an energy < 1.5 MeV. Since the counting rate of beam-off events was small, a correlation time up to 10 s was used for searching the beam-off CE-like signal. The resulting time distribution of random events is shown in Fig. 2(a). The average time for finding at least one random self-triggered beam-off event was about 1.1 s. The probability of observing such a randomly correlated beam-off event was about 0.019. In the case of beam-on CE-like events, the correlation time was limited to 5 ms, implying that both the ER and CE had to be detected within the same beam pulse. The result is also shown in Fig. 2(a), where the maximum for the random peak is not yet reached due to the 5 ms-long pulse length. Nevertheless, this indicates that on an average one random self-triggered low-energy beam-on event can be found for every one thousand ER-like events with an average correlation time of ≈1 ms. The total energy distribution of beam-off and beam-on random low-energy events is shown in Fig. 2(b).

A search for μs-isomers was performed by visually inspecting the trace (after filtering with appropriate parameters [36]) of each ER signal assigned as an implantation signal of a No isotope for the presence of small-energy signals.

To estimate the expected random rates in such cases, we searched for low-energy signals in ≈4000 beam-on α events of ^{215}Ra produced in the ^{48}Ca + ^{176}Yb reaction. To avoid the misassignment of noise signals as low-energy signal each trace was filtered to the trapezoidal shape with different parameters [51]. In Fig. 3, the results from two filters are shown. With the optimized filter the level of the noise band was reduced down to an average of ±20 keV at the confidence level of 95 %. True small-energy events were

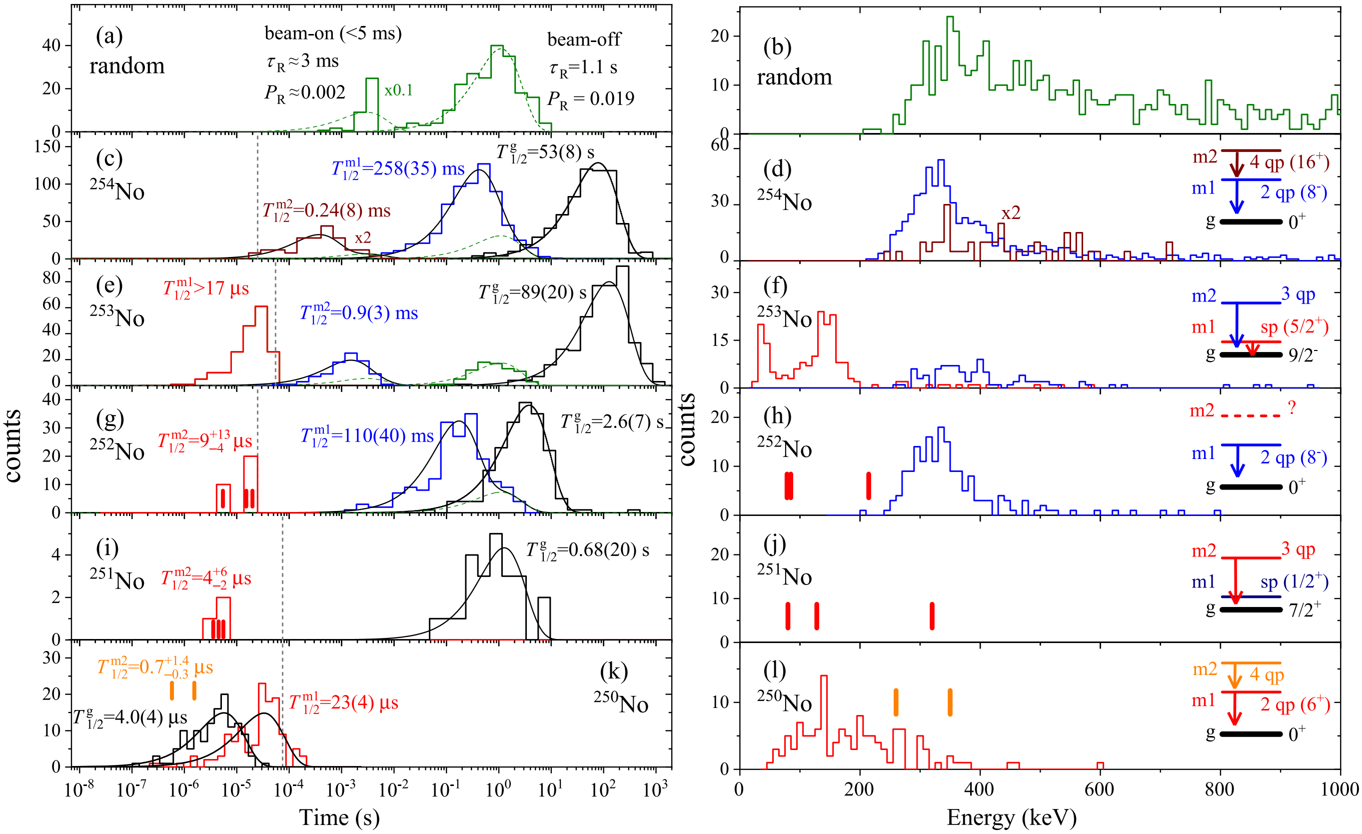

Fig. 2. (color online) The time and energy distributions of events found in various correlation analyses are shown in left and right panels, respectively. The experimental data for ^{250}No are from Ref. [40]. The legends on isotopes and half-lives for the corresponding states are given in each sub-panel. Curves represent the extracted time distributions of events according to Ref. [49]. Vertical dashed lines mark the time coverage of the ER traces for the detection of delayed CEs. Simplified decay schemes of states with half-lives > 1 μs in No isotopes are shown in insets in the right panels. The data corresponding to a particular decay are marked by the same colors except in the case of the μs-isomer in ^{253}No, where a part of the CEs corresponds to the 0.9-ms isomer. For details, see text.

required to have a reasonable trapezoidal shape and a roughly flat-topped signal with an energy above ≈30 keV. Among the ≈4000 beam-on α events no low-energy signal within 30 μs trace-length was observed. This results in a random probability of $< 3 \times 10^{-4}$ when the total beam-on event rate was ≈5.2 kHz.

By taking into account the total beam-on counting rate of 1.6 kHz for all present ^{48}Ca + Pb reactions, the random probability to observe at least one low-energy signal in each ER trace is calculated to be $< 8 \times 10^{-5}$.

All estimated random rates were considered in the extraction of half-lives and in the discussion of the identified isomers. The summary of experimental data on isomers in $^{251-254}$No is shown in Fig. 2, together with the previously reported results for ^{250}No [40], to highlight the prevalence of isomeric states in neutron-deficient nobelium isotopes.

3.1. Isomers in ^{254}No

The time distributions of self-triggered CE and α events found as ER–CE–α(^{254}No) sequences are shown in Fig. 2(c). Fits of the time distributions according to Ref. [49] are also shown. The extracted half-life of 53(8) s for the α events is consistent with the literature value for the ground state of ^{254}No [48].

The low-energy events, consisting of both beam-on and beam-off ones, show two distinct groups. Their total time distribution, however, was fitted with four components, including contributions from random events, as shown in Fig. 2(c). The CEs with half-lives of 258(35) ms and 0.24(8) ms originate from the two well-known K-isomeric states in ^{254}No [48]. The energy spectra of CEs from the decays of the two isomers, shown in Fig. 2(d), are different from that of the random events. It should be noted that a significant fraction of CEs is missing in the present data due to the relatively high detection threshold of ≈ 0.3 MeV.

Additionally, we observed also ER–CE1–CE2–α(^{254}No) sequences, confirming the deexcitation of the higher-lying 0.24(8) ms state into the lower-lying K-isomeric state.

During the ^{48}Ca + ^{208}Pb reaction, only about 30% of the total data were recorded with trace. The trace-length of 30 μs enables registering the CEs decaying within 25 μs after the implantation of ^{254}No. Inspection of about 4000 ER traces resulted in the

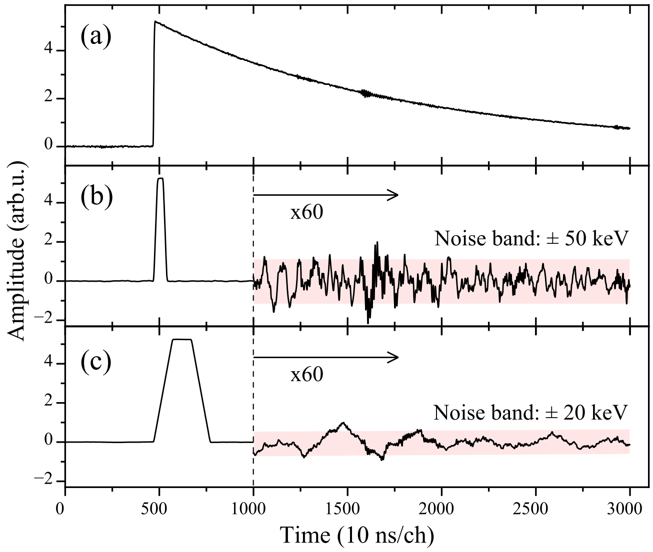

Fig. 3. (a) The trace of a beam-on α event with an energy of 8.7 MeV, which was used to estimate the random probability for observing a low-energy signal. (b,c) The same trace after applying the trapezoidal filters with the two different parameters. Amplitudes of signals in the time range above 10 μs are multiplied by a factor 60 in order to highlight the noise reduction. Calculated noise-bands at the 95% confidence levels are shown by dashed regions and the values are given.

observation of five low-energy events, one of which is shown in Fig. 4. The expected number of random events was < 0.3. These events are attributed to belong to the decay of the 0.24(8) ms K-isomeric state. Therefore, within the present statistics, no signature of a new μs-isomer was observed in ^{254}No.

Inspection of all correlated CE traces showed no evidence of any additional secondary low-energy signals in the time range of ≈0.3-25 μs.

3.2. Isomers in ^{255}No and ^{251}Fm

Recently, several μs-isomers have been reported in ^{255}No [30,31]. In the ^{48}Ca + ^{208}Pb reaction, ^{255}No was expected to be produced as the product of the 1n evaporation channel. However, identifying the α decay of ^{255}No with a half-life of 3.52 min is challenging because its α-particle energies are similar to those of ^{254}No, making correlation analysis difficult. On the other hand, the α-decay fine structure of ^{255}No results in the population of the low-lying single-particle isomeric state in ^{251}Fm with a half-life of 23 μs [48,52–54]. This can easily be identified among the α events detected within the energy range of (7.6–8.2) MeV once their traces are inspected for the presence of delayed CEs.

Among the ≈ 5000 α-traces, we found sixteen cases with delayed CEs. Energies and time distributions of the α events are shown in Fig. 5(a). An α trace of such an event is shown in Fig. 4(b) and the time distribution of CEs relative to the preceding α signal is shown in Fig. 5(b). The half-life of these events is estimated to be >20 μs because only a part of the time distribution of CEs were detected in the 25 μs trace-length. The CE energies, shown in Fig. 5(b), can roughly be assigned to form three groups at energies of ≈60, 170 and 200 keV. These events are consistent with the expected CEs from the K (58 keV) and $LMN+$ (173-200 keV) shells originating from the deexcitation of the 200 keV isomeric state [53]. The $M2+E3$ nature of this $5/2^+$ isomeric state is well established [53] including the lighter $N = 151$ isotones [48]. Nevertheless, it is evident that the triggerless electron measurement is well suited for studying single-particle isomeric states.

Finally, we inspected the ER traces correlated with the α decay of ^{255}No and did not find any delayed CEs. Apparently, only 16 events of ^{255}No are statistically insufficient for observing the recently reported μs-isomers in ^{255}No [31].

3.3. Isomers in ^{253}No

The time distributions of CEs (both self-triggered and found in the ER trace) and α events associated with the decay of ^{253}No are presented in Fig. 2(e). The measured α-decay half-life of 89(20) s agrees well with the literature value of 1.62 min [48].

The time distribution of both beam-on and beam-off self-triggered low-energy events shows two groups of activities. The "longer-lived“ component is consistent with the expected beam-off random-event contribution. Therefore, only one activity with a half-life of 0.9(3) ms was attributed to ^{253}No. The corresponding CE energy distribution, shown in Fig. 2(f), is similar to that observed for the two K-isomers in ^{254}No (see Fig. 2(d)). These results are in agreement with the known 3qp K-isomeric state in ^{253}No [48].

During this run, all signal shapes were stored with a trace-length of 60 μs, allowing the detection of delayed CEs up to 55 μs. In total, 186 cases with low-energy signals were observed; one representative trace is shown in Fig. 4(c) as an example. The time

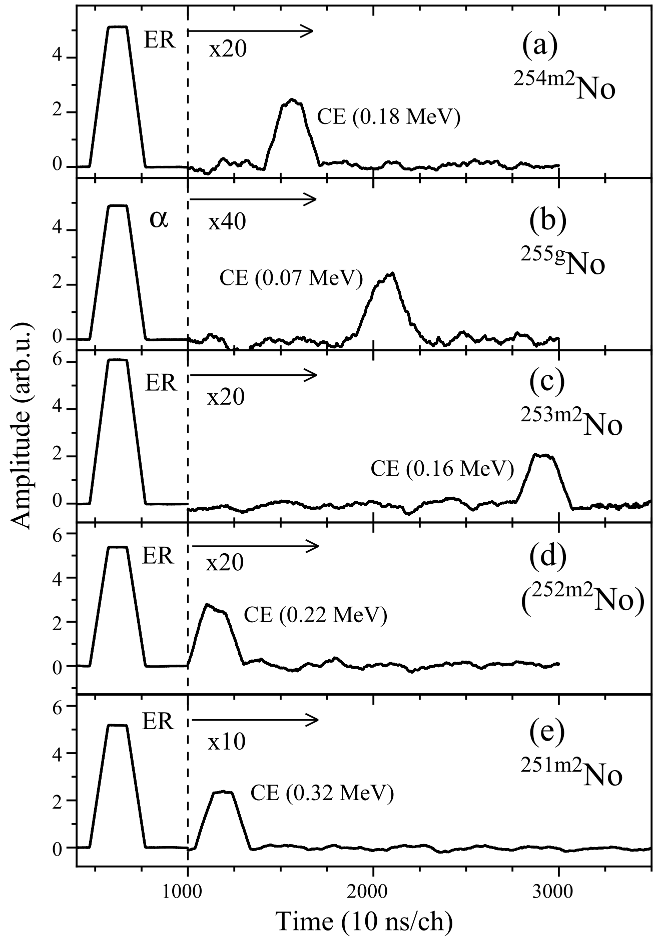

Fig. 4. Examples of trapezoidal filtered ER and α traces from X strips, where delayed CEs originating from μs-isomers from No and Fm isotopes are shown. To highlight the low-energy CE signals, the amplitudes after ERs are shown with different amplification factors.

and energy distributions of these CEs are shown in Fig. 2(e) and (f), respectively. Most of them form a broad peak at ≈140 keV (134 events), a second group is in the 25 – 50 keV range (36 events) and 16 events are at higher energies of >200 keV. The latter ones detected with times close to the end of 55 μs trace are attributed to the 0.9(3) ms isomer. The other events are attributed to originate from the known 30 μs low-lying single-particle $5/2^+$ isomeric state in ^{253}No [48]. Only a lower limit of 17 μs can be deduced for the half-life of this isomer since the 55 μs trace-length covers the time distribution of the 30 μs isomer only partially.

The origin of this isomer is the same as that discussed in ^{251}Fm (see the previous section) and has been well studied [25,48,55]. The well-pronounced broad peak at ≈140 keV is in good agreement with the expected energy distribution of CEs from the $LMN+$ shells following the deexcitation of the 167 keV isomer [56]. The CEs with energies of 25 – 50 keV likely correspond to K-shell electrons with an energy of 17.7 keV ([56]) but summed with the energies of the subsequent Auger electrons and/or L X-rays.

Within the accumulated data, we did not observe any correlation between the CEs from the 0.9(3) ms-state and from the 30 μs-state. This indicates that the deexcitation of the higher-lying isomer bypasses the lower-lying isomeric state with $5/2^+$ single-particle configuration, which is likely not involved in the formation of the 3qp isomeric state.

3.4. Isomers in ^{252}No

^{252}No was identified via its α decay and spontaneous fission [48]. The time distributions of self-triggered CEs and α/fission events attributed to ^{252}No are shown in Fig. 2(g) and (h), respectively. The half-life of 2.6(7) s deduced from the total number of α and fission events agrees well with the literature value for ^{252}No [48].

The time distribution of CEs was fitted by taking into account the random contribution and a single activity with a half-life of 110(40) ms was extracted. The energy distribution of CEs is similar to that measured for the low-lying 258-ms K-isomer in ^{254}No [cf. Fig. 2(d) and (h)]. Again, these results agree with the known 2qp K-isomer in ^{252}No [23].

In total, about 3000 ERs assigned to the implantation of ^{252}No were inspected for the presence of delayed CEs. Three cases were observed, one of them is shown in Fig. 4(d). We expected to observe < 0.3 random events, which indicates that at least two of them

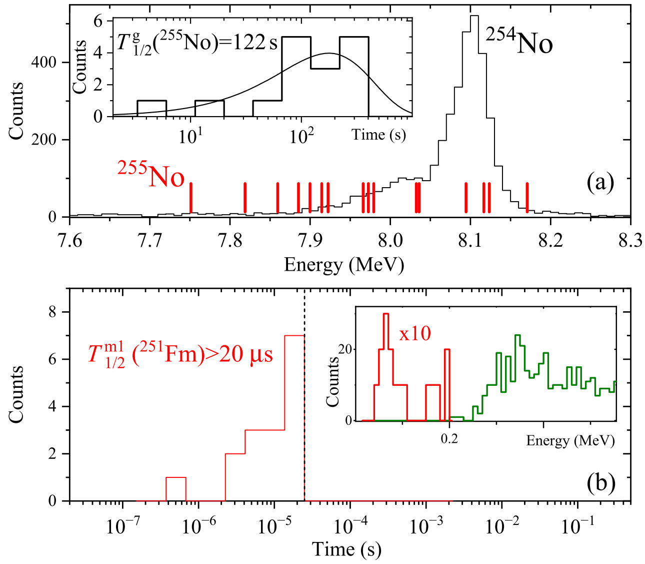

Fig. 5. (a) The energies of α events observed in coincidence with delayed CEs, and thus assigned to originate from ^{255}No, are shown alongside the total beam-off α spectrum from the ^{48}Ca + ^{208}Pb reaction. The time distribution of these α events correlated with ERs, along with the corresponding fit, is presented in the inset of panel (a). Panel (b) also shows the time distribution of CEs relative to the preceding α signals. A comparison of the CE energy distribution with that of random events is shown in the inset of panel (b). For details, see text.

are likely real CEs. Times and energies of these events are given in Fig. 2(g) and (h), respectively. The energies are relatively small compared to the ones of CEs from a 2qp K-isomer. However, energies of CEs from the decay of a K-isomeric state are defined by its particular deexcitation pattern [36,57]. Therefore, we cannot exclude that these three events may originate from the decay of a hitherto unknown K-isomeric state with a half-life of 9^{+13}_{-4} μs in ^{252}No. A very low population probability of this isomer would indicate its possible origin as a 4qp configuration [36,40]. Theory, indeed, predicts different high-K configurations for ^{252}No [17,19]. However, more statistically enhanced experimental data are required to confirm this isomer.

3.5. Isomers in ^{251}No

As mentioned above ^{251}No was produced alongside with ^{250}No in the ^{48}Ca + ^{204}Pb reaction.

The time distribution of 23 α events correlated with the ERs is shown in Fig. 2(i). We did not observe any self-triggered CEs in between the ER and α events.

A half-life of 0.68(20) s was deduced from the total number of α events assigned to ^{251}No. As discussed above, the energies of the α particles resulted in a narrow peak at an energy of 8.61(2) MeV suggesting that they originate from a single α transition. This is, in fact, in full agreement with the α-decay properties of the well-established $7/2^+$ ground-state of ^{251}No.

Among the total 23 ER-traces of ^{251}No we observed three cases with delayed CE-like signals and one of them is shown in Fig. 4(e).

Times and energies of these events are shown in Fig. 2(i) and (j), respectively. The times of these events suggest the decay of an isomeric state with a half-life of 4^{+6}_{-2} μs. In fact, the existence of an isomeric state with a half-life of ≈2 μs was reported in Ref. [27]. Therefore, the presently detected three events confirm the isomeric data on ^{251}No. According to [27], the excitation energy of the isomer was estimated to be > 1.7 MeV that should correspond to a high-K state decaying to the $7/2^+$ ground state via the $9/2^-$ level. Our data confirm this scenario.

In [27], a K-isomer was observed when ^{251}No was produced in the 3n channel of the ^{48}Ca + ^{206}Pb reaction at 30 MeV excitation energy. It is worth noting that, presently, ^{251}No was produced in the ^{48}Ca + ^{204}Pb reaction through the 1n channel, where the excitation energy of the compound nucleus ^{252}No was about 22 MeV. On the basis of CEs measured down to the energy threshold of ≈30 keV, we estimated the population probability of the K-isomeric state as ≈0.13 (= 3/23), which is comparable to typical values observed for 2qp K-isomeric states in No and Rf [36,40].

4. Summary and conclusion

In this work, we presented the experimental study of the various types of isomeric states in ^{251}No, ^{252}No, ^{253}No and ^{254}No. By applying the fast digital electronics with recording the shapes of signals within the time ranges of (30–80) μs, we searched for previously unknown isomeric states.

In the cases of ^{253}No and ^{254}No, we did not find evidence for any hitherto unknown μs-isomeric states. For ^{251}No, we confirmed the previously reported ≈2 μs-isomer Ref. [27]. We measured a half-life of 4^{+6}_{-2} μs. In ^{252}No, we observed a signature for the presence of a new 9^{+13}_{-4} μs isomeric state in addition to the known 110 ms 2qp K-isomer. The single-particle isomeric states in ^{251}Fm and ^{253}No located at energies of 200 keV and 167 keV, respectively, were observed by detecting electrons with energies down to ≈30 keV that are originating from internal conversion.

The present experimental data show the great potential of the triggerless conversion electron measurement for the detection of both K-isomeric and single-particle isomeric states in heavier nuclei. Further development of triggerless CE measurements, including an expanded time range for detecting delayed CEs, will be essential for future studies.

CRediT authorship contribution statement

J. Khuyagbaatar: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization; **R.A. Cantemir:** Writing – review & editing, Software, Investigation; **Ch.E. Düllmann:** Writing – review & editing, Investigation; **F.P. Heßberger:** Writing – review & editing, Investigation; **E. Jäger:** Writing – review & editing, Investigation; **B. Kindler:** Writing – review & editing; **J. Krier:** Writing – review & editing, Investigation; **N. Kurz:** Writing – review & editing, Investigation; **B. Lommel:** Writing – review & editing; **P. Mosat:** Writing – review & editing, Investigation; **B. Schausten:** Writing – review & editing, Investigation; **A. Yakushev:** Writing – review & editing, Validation, Investigation, Conceptualization.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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