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Direct observation of the ^{114}Ba → ^{110}Xe → ^{106}Te → ^{102}Sn triple α-decay chain using position and time correlations

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The triple α-decay chain ^{114}Ba → ^{110}Xe → ^{106}Te → ^{102}Sn has been directly observed for the first time, following the ^{58}Ni(^{58}Ni,$2n$) reaction. Implantation of ^{114}Ba nuclei into a double-sided silicon-strip detector has allowed their α decays to be correlated in position and time with the α decays of the daughter (^{110}Xe) and granddaughter (^{106}Te) nuclei. In total, 17 events have been assigned to the ^{114}Ba → ^{110}Xe → ^{106}Te → ^{102}Sn triple α-decay chain. The energy of the ^{114}Ba α decay has been measured to be $E_\alpha = 3480(20)$ keV, which is 70 keV higher than the previously measured value, and the half-life of ^{114}Ba has been measured with improved accuracy, to be 380^{+190}_{-110} ms. A revised $Q_{^{12}C}$ value of 19 035(45) keV for ^{114}Ba is presented.

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I. INTRODUCTION

The study of the different decay modes of the proton-rich nuclei immediately northeast of ^{100}Sn can be a valuable source of information about nuclear structure and nuclear properties at the boundary of nuclear existence. The island of α-particle and proton emitters in the light $52 \leqslant Z \leqslant 56$ nuclei [1] is particularly significant in this regard. Excited states of some of these nuclei have been studied by using characteristic α and proton decays as a tool to select and identify the nuclei of interest using the method of recoil-decay tagging [2–5]. α decays themselves are also a valuable source of information. For example, the energy of an α particle (E_α) can give the difference in mass of the mother and daughter nuclei. Energies, half-lives ($T_{1/2}$), and α-decay branching ratios (b_α) can be used to extract reduced widths; in the $N \simeq Z \simeq 50$ region, reduced widths are particularly interesting since the neutrons and protons near the Fermi level can occupy identical $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ orbitals leading to the possibility of superallowed α decay [6]. Another interesting aspect in this region is the prediction of cluster radioactivity [7]. It has been widely reported that the most promising candidate for this type of decay in the region is the ^{12}C decay ^{114}Ba → ^{102}Sn [8–10], and that the theoretical predictions of the partial half-life depend very sensitively on the Q value for ^{12}C emission ($Q_{^{12}C}$) [8]. The value of $Q_{^{12}C}$ is therefore an important quantity in the design of experiments to search for this novel decay mode.

Recent experimental developments, such as triggerless data acquisition [11] and digital signal processing, have enabled significant progress in the study of α decay in the $N \simeq Z \simeq 50$ region. For example, the ^{109}Xe → ^{105}Te → ^{101}Sn decay chain has recently been studied despite the very short half-life of 620(70) ns for ^{105}Te [12]. Further study of this decay chain in Ref. [13] has revealed interesting information on the ordering of single-particle states in ^{101}Sn. The known α-emitting nuclei in the $A = 100$–110 region are shown in Fig. 1. In total, there are about 20 nuclei in this region which decay by α-particle emission. In many cases, the daughters of the α emitters are also themselves α emitters, leading to a number of two-α-decay chains. Experimentally, time and position correlations between two α decays can act as a very sensitive selection tool, particularly when one of the α decays has a short half-life. Indeed, because this region of α emitters spans five Z values ($52 \leqslant Z \leqslant 56$) it is possible to have three-α-decay

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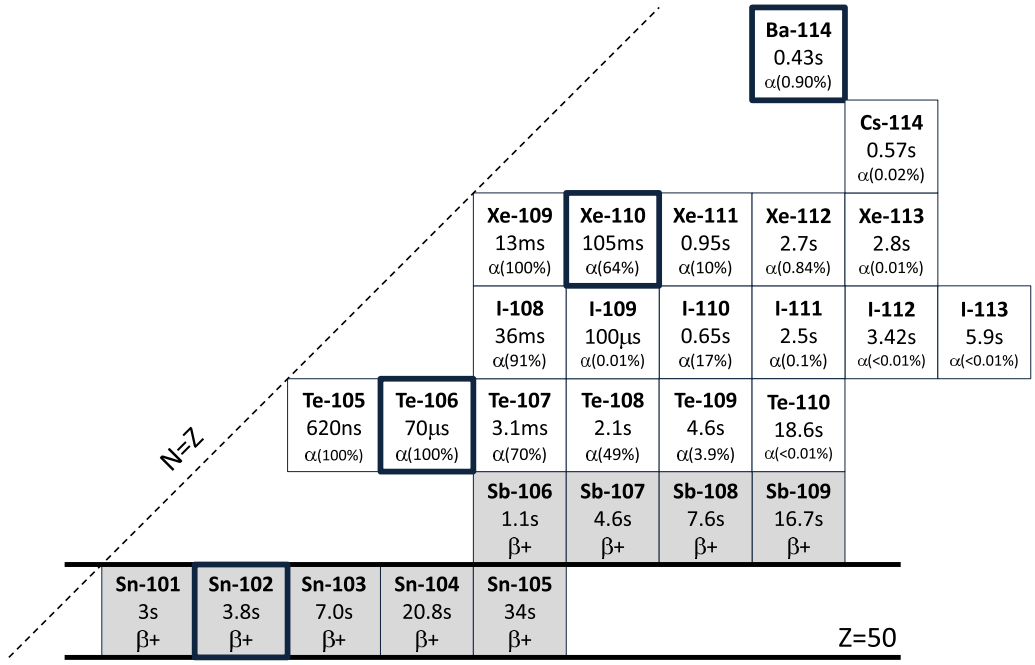


FIG. 1. A chart showing the α-emitting $_{52}$Te, $_{53}$I, $_{54}$Xe, $_{55}$Cs, and $_{56}$Ba nuclei in the region above the $N \simeq Z \simeq 50$ shell closures. For each nucleus, the half-life and the α-decay branching ratio are given. The shaded $_{50}$Sn and $_{51}$Sb nuclei represent the end points of the α-decay chains; these nuclei decay by β^+ emission. Nuclei in the $^{114}\text{Ba} \rightarrow {}^{110}\text{Xe} \rightarrow {}^{106}\text{Te} \rightarrow {}^{102}\text{Sn}$ decay chain, of interest in this work, are marked with thick black borders. The proximity to $Z = 50$ and to the $N = Z$ line is shown.

chains starting from isotopes of barium ($Z = 56$). Presently, the only barium isotope which has been shown to decay by α-particle emission is ^{114}Ba [14].

II. PREVIOUS STUDIES

The nucleus ^{114}Ba has been the subject of a number of experimental studies in the past 20 years, all of which have used the ^{58}Ni(^{58}Ni ,$2n$) reaction. With stable beams, this reaction offers the only viable possibility of producing ^{114}Ba with a cross section sufficient for study. In 1993, Oganessian *et al.* [15] reported on an experiment performed using the Dubna U400 cyclotron to search for ^{12}C emission from ^{114}Ba. The ^{58}Ni beam had energy of 280 MeV and polycarbonate track detectors were used to identify the emitted ^{12}C particles. Several candidate tracks were identified, but the results were inconclusive. However, an upper limit on the ^{12}C branching ratio ($b_{^{12}\text{C}}$) of 10^{-4} was put forward. Subsequently, two experiments were performed using the online mass separator at the GSI UNILAC by Guglielmetti *et al.* [9,10,16,17]. In that work, a ^{58}Ni beam with 4.9 MeV/A (284 MeV) was used, for which the cross section was reported to be $0.2^{+0.13}_{-0.09}$ μb. The experiments used the ISOL technique with the reaction products stopped in a hot catcher, evaporated, ionized, accelerated, and magnetically mass separated. Separation of Ba and Cs ions was achieved using a fluorination technique, in which Cs is suppressed as it does not form fluoride ions. The BaF^+ ions were caught on a stopper foil at the center of an array of ΔE-E silicon-plus-plastic-scintillator telescopes. In the initial experiment [9,10], the observation of three ^{12}C decay events was reported, but following the second experiment [16,17] with improved background subtraction, these claims were retracted. In that work, the half-life of ^{114}Ba was reported to be $0.43^{+0.30}_{-0.15}$ s and an upper limit of $b_{^{12}\text{C}} \leqslant 3.4 \times 10^{-5}$ was given. The α decay of ^{114}Ba was reported by Mazzocchi *et al.* in Refs. [14,18]: a dedicated experiment was performed at the GSI UNILAC using the fluorination technique, and the α-particle energy was reported to be 3410(40) keV, with an α-decay branch of 0.9(3)%. Also, in that work, the half-life of the daughter nucleus ^{110}Xe was measured to be 160^{+290}_{-60} ms. It should perhaps be noted here that although the α decays of ^{114}Ba, ^{110}Xe, and ^{106}Te were observed, the reaction products were collected on a passive catcher foil, and no position correlations were recorded. Time correlations used to measure the lifetime of ^{110}Xe were reliant on the purity of the BaF^+ beam.

In the present work, the ^{114}Ba nucleus has been produced and the three-α-decay chain, starting with ^{114}Ba and ending at ^{102}Sn, has been studied using both position and time correlations between the α decays of ^{114}Ba, ^{110}Xe, and ^{106}Te.

III. EXPERIMENTAL DETAILS

This work reports on results from an experiment carried out using the K130 cyclotron at the Accelerator Laboratory of the University of Jyväskylä Department of Physics. The primary aim of the experiment was to study the excited states and α decay of ^{111}Xe, and the experimental conditions were optimized for that purpose; details of the experiment and the results concerning ^{111}Xe are reported elsewhere [19,20]. A beam of ^{58}Ni ions, with energy 210 MeV, was incident upon a 500-$\mu g/\text{cm}^2$ ^{58}Ni target. Prompt γ rays, emitted at the reaction

site, were detected by the Jurogam-II γ-ray spectrometer [21]. Recoiling reaction products were separated from the primary beam by the RITU gas-filled recoil separator [22]. On exit from RITU, the reaction products passed through a multiwire proportional counter (MWPC) before being implanted into one of two adjacent double-sided silicon strip detectors (DSSDs), each of thickness 300 μm and with 40 horizontal (front) strips and 60 vertical (back) strips, giving a total of 4800 DSSD pixels. A planar HPGe detector and three Clover HPGe detectors were placed around the DSSDs. The MWPC, DSSDs, planar HPGe and (focal plane) Clover HPGe detectors are part of the GREAT spectrometer [23]. The Total Data Readout data-acquisition system was used [11], in which a 100-MHz clock provided a time stamp on each detector signal, accurate to the nearest 10 ns. Data were recorded for all detector signals received within a fixed time window around either (a) a signal in the DSSDs (implant or decay) or (b) $\geqslant$2 prompt signals in the Jurogam-II spectrometer. The beam intensity was limited to an average value of 2 pnA for the duration of the experiment in order to keep the implantation rate in the DSSD appropriate for implant-decay correlations of ^{111}Xe ($T_{1/2} \simeq 800$ ms). In total, approximately 1 TB of data were written to disk. The data were analyzed using the GRAIN data analysis package [24]. For the ^{114}Ba decay results presented here, data from γ-ray detectors were not used; the data are from analysis of the DSSD and MWPC signals.

The DSSDs were initially gain matched using a mixed source of ^{239}Pu, ^{241}Am, and ^{244}Cm, which emit α particles with energies in the range of 5 to 6 MeV. In addition to use of the source data, an internal calibration of the DSSDs was performed using the ^{58}Ni beam, with energy 235 MeV, incident on a natural molybdenum target; the known energies of protons and α particles emitted by the proton-rich $_{66}$Dy, $_{68}$Er, and $_{70}$Yb nuclei implanted into the DSSD were then used to calibrate the individual DSSD strips.

IV. DATA ANALYSIS AND RESULTS

Implantation events in the DSSDs were identified by demanding a time correlation with a signal from the MWPC (with no energy constraint) or an energy $\geqslant$7 MeV. Conversely, decay events were those with no time-correlated MWPC signal and with energy $<$7 MeV. This resulted in 9×10^8 implantation events (henceforth referred to as *implants*) and 2×10^7 decay events (*decays*) in the DSSDs. In order to identify the implanted nuclear species, a decay with the correct energy was required in the same DSSD pixel as the implant, within a search time period of three or four half-lives. Within three half-lives, 88% of the implants decay; within four half-lives, 94% decay. Consideration was also given to false correlations: a longer half-life gives a higher likelihood of false correlations, in which successive implants occur before the initial implants have decayed. In this work, the average time between implants in each pixel was found to be $\sim$1.1 s, but the implantation rate is dependent on position in the DSSD with the highest rates in the central strips and lower rates at the edges. Any search time close to 1 s, or longer, will therefore be susceptible to false correlations, and the number of false correlations will be dependent on position in the DSSD.

The half-lives of nuclei in the ^{114}Ba $\rightarrow$ ^{110}Xe $\rightarrow$ ^{106}Te $\rightarrow$ ^{102}Sn α-decay chain have previously been measured to be $T_{1/2}(^{114}\text{Ba}) = 430^{+300}_{-150}$ ms [14], $T_{1/2}(^{110}\text{Xe}) = 105^{+35}_{-25}$ ms [25], and $T_{1/2}(^{106}\text{Te}) = 70^{+20}_{-10}$ μs [25]. The relatively long half-lives of ^{114}Ba and of its daughter ^{110}Xe mean that any attempts to identify ^{114}Ba using single ^{114}Ba or ^{110}Xe α decays are difficult due to the large number of false correlations.

As stated earlier, the α emitters in the $A = 110$ region span the range $52 \leqslant Z \leqslant 56$ (Fig. 1), so any chain of three α decays in this region must start from an isotope of barium ($Z = 56$). The nucleus ^{113}Ba has so far not been observed experimentally. The nucleus ^{115}Ba was identified by Janas *et al.* [17] but in that work no α-decay branch was identified. In the present reaction, it is very unlikely that ^{115}Ba will be produced, as this would require $1n$ evaporation which is expected to be at or below the interaction barrier. The nucleus ^{113}Ba has been the subject of a dedicated search using the ^{58}Ni(^{58}Ni,$3n$) reaction, as described in Ref. [14], but no evidence for this nucleus was reported. It can therefore be initially assumed that any observed chain of three α decays following the ^{58}Ni(^{58}Ni) reaction is likely to originate from ^{114}Ba. A three-α requirement can thus be used as an initial filter to select ^{114}Ba implants; subsequently, unambiguous identification can be achieved using the characteristic α-decay energies and half-lives. Of particular importance in the identification of the ^{114}Ba α-decay chain is the short half-life (relative to the neighboring nuclei and to the time between implantation events) of the granddaughter nucleus ^{106}Te.

In the search for ^{114}Ba, it was required that an implant (r_1) occurred, followed by three successive decays (α_1, α_2, and α_3) in the same pixel of the DSSD, and that all signals (implant plus three decays) were received within a 6-s period. It was initially required that α_1 was emitted within 1.6 s [$\sim 4 \times T_{1/2}(^{114}\text{Ba})$] of r_1, α_2 decay within 400 ms [$\sim 4 \times T_{1/2}(^{110}\text{Xe})$] of α_1, and α_3 within 0.3 ms [$\sim 4 \times T_{1/2}(^{106}\text{Te})$] of α_2. However, it was found that the selectivity was entirely based on the short (0.3-ms) time condition between α_2 and α_3, so this condition alone was ultimately used. With this requirement between the times of α_2 and of α_3, and with no conditions placed on the decay energies, a total of 17 events were selected. For these events, the energies of the first (α_1), second (α_2), and third (α_3) α decays recorded by the DSSD are shown in Figs. 2(a), 2(b), and 2(c), respectively. The spectrum for α_1, which has been assigned to be the decay of ^{114}Ba, exhibits a clear peak at energy 3480(20) keV. In the spectrum for α_2, assigned to be the decay of ^{110}Xe, several channels with two counts and a channel with four counts form an apparent peak with a centroid at 3720(20) keV. The spectrum for α_3, assigned to the decay of ^{106}Te, has counts that are more widely distributed, but with a number of counts between 3800 and 4200 keV: there are two counts in the channel corresponding to 3940 keV (10 keV per channel) with a cluster of counts at higher energy. The centroid of these counts is at 4100(60) keV.

The times between successive events in the chain $r_1\alpha_1\alpha_2\alpha_3$ can be used to investigate the half-lives of each of the decays. Figures 3(a), 3(b), and 3(c) show the distributions of times between (r_1 and α_1), (α_1 and α_2), and (α_2 and α_3), respectively. Application of the maximum-likelihood method [26,27] to

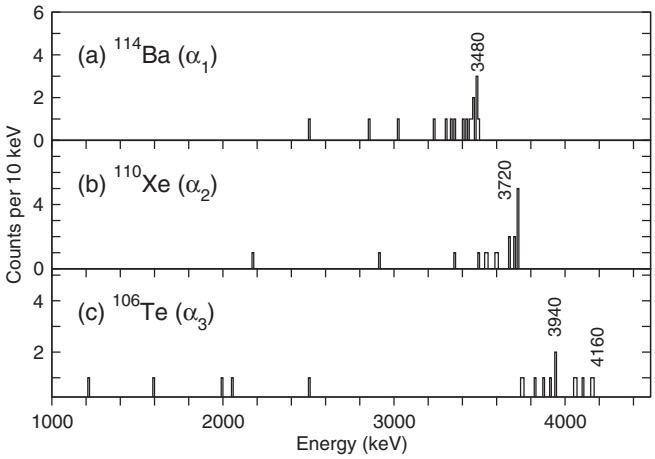


FIG. 2. Energy spectra from the DSSDs. Panels (a), (b), and (c) show the energies of the first (α_1), second (α_2), and third (α_3) decays when it is required that the decays occur following an implant, in the same pixel, and that α_3 occurs within 0.3 ms of α_2. The values written vertically on the panels give the energies associated with selected channels, not the centroids.

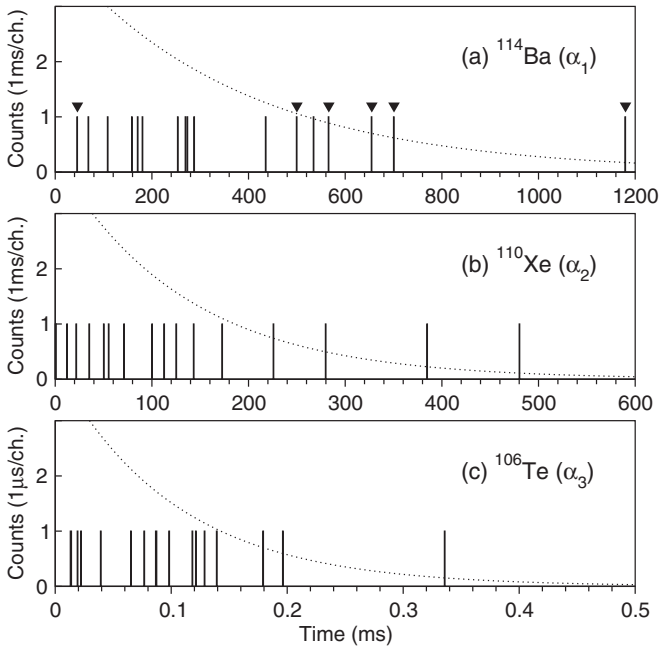


FIG. 3. The distributions of time differences between successive events in the DSSDs. Panel (a) shows the time differences between the implanted recoil (r_1; ^{114}Ba) and the first decay (α_1). Panels (b) and (c) show the time differences between the first (α_1) and second (α_2) decays and between the second (α_2) and third (α_3) decays, respectively. The triangles on panel (a) label the data points which have been subjected to the condition that there must be a time difference of at least 1.6 s between the two implantation events immediately prior to the decay events, as described in the text. The dotted lines are calculated using the extracted half-lives, intended to show the decay behavior; they are not fits to the data.

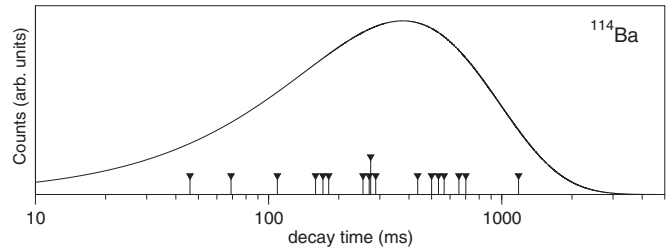


FIG. 4. The logarithmic decay-time distribution of all 17 events attributed to the ^{114}Ba $\rightarrow$ ^{110}Xe α decay. The curve shows the calculated logarithmic decay-time distribution as defined in Ref. [28] and the units on the vertical axis are arbitrary.

these data has allowed values for the half-lives to be extracted. For ^{110}Xe (α_2) the half-life is measured to be 95^{+25}_{-20} ms and for ^{106}Te (α_3), the half-life is 70^{+20}_{-15} μs. Measurement of the half-life of ^{114}Ba (α_1) is complicated by the possibility that α_1 is *not* emitted from r_1, but that it is emitted from a previous implant in the same pixel (r_0), with r_1 decaying by some mode other than α decay. If this happens, the half-life extracted from the time between r_1 and α_1 will give an incorrect value. In order to reduce this possibility, a condition has been applied such that the time between r_0 and r_1 must be greater than four times the (previously measured) half-life of ^{114}Ba, or $\sim$1.6 s. In this case, if r_0 is the ^{114}Ba implant, then there is a 95% probability that it will decay before r_1 occurs. This then significantly increases the probability that α_1 is indeed emitted from r_1. With this condition, there are 6 three-α events in the data, as marked by the triangles on Fig. 3(a). Subsequently, the half-life of ^{114}Ba (α_1) is extracted from these events to be 380^{+190}_{-110} ms. It should be noted that the energy spectra of Fig. 2 do not use the condition on the time between r_0 and r_1. However, this does not mean that the spectra are invalid; the three α decays are still attributed to the most recent α-decaying implant in the same pixel, but this is not necessarily the most recent implant. In order to test whether a set of data points from radioactive decay originate from a single radioactive species, a procedure has been defined by Schmidt which is described in Ref. [28]. In that work, the parameter $\sigma_{\Theta\,\mathrm{exp}}$ is defined, and limits on this parameter are given within which there is a 90% confidence level that the events originate from the same single species. For the 17 events recorded here, $\sigma_{\Theta\,\mathrm{exp}}$ is calculated to be 0.84, which lies within the limits of 0.78 and 1.74 for a data set of 17 events. This suggests that they do indeed arise from decay of the same radioactive species. Figure 4 shows the logarithmic decay-time distribution of all 17 events, plotted as suggested in Ref. [28]. For comparison, the half-life was also estimated from all 17 events, without the time condition between r_0 and r_1, but with the correction defined by Leino *et al.* in Ref. [29]. The resulting half-life of $\sim$400 ms is very similar to that obtained here.

The number of ^{114}Ba α-decay events, together with information about the beam intensity, target thickness, and detection efficiencies, has been used to estimate the production cross section for ^{114}Ba. The transport efficiency of RITU was estimated by comparing the intensities of the same γ rays (from the $2p$ and $3p$ evaporation channels) in the $\gamma\gamma\gamma$ and in

TABLE I. Properties of the α decays of ^{114}Ba, ^{110}Xe, and ^{106}Te measured in the present work compared to previously measured values. The symbols $T_{1/2}$, E_α, and Q_α represent the half-life, α-particle energy, and α-decay Q value, respectively. The data from this work are given as the first row for each nucleus. References are given for the previously measured values in subsequent rows.

Nucleus	$T_{1/2}$ (ms)	E_α (keV)	Q_α (keV)
^{114}Ba	380^{+190}_{-110}	3480(20)	3610(20)
	430^{+300}_{-150} [17]	3410(40) [14]	3540(40) [14]
^{110}Xe	95^{+25}_{-20}	3720(20)	3860(20)
	105^{+35}_{-25} [25]	3717(19) [4]	3856(20) [4]
^{106}Te	$0.070^{+0.020}_{-0.015}$	4100(60)	4260(60)
	$0.070^{+0.020}_{-0.010}$ [25]	4128(9) [31]	4290(9) [31]

the $\gamma\gamma\gamma$-recoil spectra. Here, it was necessary to use high-fold γ-ray spectra to meet the γ-ray fold requirement for data collection, and hence circumvent the bias that would be caused by the requirement of a DSSD signal. Using this method, the RITU transport efficiency was estimated to be around 30(5)%. In estimating the cross section, it was assumed that none of the α particles emitted from the implanted nuclei escaped from the detector. Given the expected implantation depth and α-particle ranges, this will be a reasonably good assumption. However, it is likely that a small percentage of the α particles will escape, meaning that the estimate for the cross section is a lower limit. Taking all of this information into account, the cross section for ^{114}Ba in this work was estimated to be 0.15(9) μb. The cross section reported in Refs. [16,17], with a higher beam energy of 284 MeV, is $0.2^{+0.13}_{-0.09}$ μb, which is consistent with that reported here. Statistical-model calculations [30] predict that $2n$ evaporation will be maximized for a beam energy of ~215 MeV, with a cross section of 5 μb. It should be stated, however, that such calculations are notoriously unreliable in reproducing absolute cross sections in this region.

V. DISCUSSION

A. Comparison to previous work

The α-decay energies and half-lives measured in this work are presented in Table I, and are compared to previously measured values. The E_α values measured here are 3480(20), 3720(20), and 4100(60) keV for the α decays of ^{114}Ba, ^{110}Xe, and ^{106}Te, respectively. The E_α value for ^{114}Ba measured in this work has a smaller uncertainty and is 70 keV higher than that measured in Ref. [14]. The E_α value for ^{110}Xe from this work is very similar to that measured in Ref. [4]. For ^{106}Te, the value measured here has a larger uncertainty than the previously measured value from Ref. [31]. This is due to the wider distribution of counts in the spectrum. However, within uncertainties, the value measured here is consistent with that from Ref. [31].

It can be seen from Fig. 2 that the distributions of counts in the DSSD energy spectra increase when going down the decay chain. This can perhaps be explained by a consideration of the implantation depth and the ranges of the α particles in the DSSD. Calculations with the code SRIM [32] suggest that the recoils are implanted at a depth of ~15 μm into the DSSD, and that the range of a 3.5 MeV α particle is ~13 μm, whereas that for a 4-MeV α particle is close to 17 μm. It would therefore be expected that higher energy α particles are more likely to escape from the silicon without depositing their full energy, which would contribute towards the wider distributions of counts in Fig. 2. Another effect that can contribute to the wide distribution of energies in the DSSD is the failure of the amplifier to return to the baseline following the preceding signal in the same DSSD strip; this effect has been shown to be significant for fast decays following an implantation event. In the present work, the possibility that the signal from the reasonably fast α decay of ^{106}Te (70 μs) could be affected by the preceding α decay (^{110}Xe) was excluded by studying the correlations between α-decay energies and decay times.

The half-lives are presented in Table I. For ^{114}Ba, the value of half-life of 380^{+190}_{-110} ms measured in the present work is lower than the value of 430^{+300}_{-150} ms measured in Ref. [14], but is consistent within the large uncertainty of that value. For ^{110}Xe the half-life measured here is 95^{+25}_{-20} ms; this is consistent with the value of 105^{+35}_{-25} ms from Ref. [25]. For ^{106}Te, the half-life measured here is 70^{+20}_{-15} μs, which is similar to the value of 70^{+20}_{-10} μs from Ref. [25].

It should be noted that in the present data, it was not possible to measure the α-decay branching ratios (b_α) of ^{114}Ba and ^{110}Xe, since the observations of the α-decay chains were necessary to select and identify these nuclei. Therefore, only the ^{114}Ba and ^{110}Xe nuclei that decayed by α-particle emission were identified in the present work.

B. Q values for α and ^{12}C emission

The Q values for α decay (Q_α) deduced from this work are presented in Table I, in comparison to values from earlier work. A thorough discussion of the Q_α value of ^{114}Ba was presented in Ref. [14] in comparison to several different theoretical models. For example, the finite-range droplet model (FRDM) [33] predicts the Q_α value of ^{114}Ba to be 3550 keV, which is 60 keV lower than the value measured here but 10 keV higher than that of Ref. [14]. As pointed out in Ref. [14] the agreement between FRDM values and experimental values is progressively worse for ^{110}Xe and ^{106}Te, where the calculated values are 750 and 1750 keV too high, respectively.

The nucleus ^{114}Ba has been identified as the most promising candidate in this region from which to observe ^{12}C emission [8]. The calculated half-life for ^{12}C emission depends sensitively on the Q value for this decay mode ($Q_{^{12}\mathrm{C}}$): an increase of 1 MeV in $Q_{^{12}\mathrm{C}}$ results in a half-life that is shorter by two orders of magnitude [34]. The value of $Q_{^{12}\mathrm{C}}$ can be deduced from the Q_α values for the three successive α decays that lead to the same final nucleus, with corrections for the binding energies of the three α particles and of ^{12}C. Using the data in Table I, a $Q_{^{12}\mathrm{C}}$ value of 19 035(45) keV is deduced for ^{114}Ba in this work. This is slightly larger than the value of 19 000(40) keV from Refs. [14,18], as would be expected from the larger value of E_α

TABLE II. Reduced α-decay widths (W_α) for ^{114}Ba, ^{110}Xe, and ^{106}Te, together with data used in their calculation. References to previous work are given in square brackets; where no reference is given, the data are taken from the present work.

Nucleus	E_α (keV)	Q_α (keV)	b_α(%)	$T_{1/2}$ (ms)	W_α
^{114}Ba	3480(20)	3610(20)	0.9(3) [14]	380^{+190}_{-110}	6^{+4}_{-3}
^{110}Xe	3720(20)	3860(20)	64(35) [14]	95^{+25}_{-20}	4^{+2}_{-2}
^{106}Te	4128(9) [1]	4290(9) [1]	100 [14]	$0.070^{+0.020}_{-0.015}$	$4.4^{+1.2}_{-0.9}$

for ^{114}Ba from the present work. The calculations presented in Ref. [34] suggest that this increase in the value of $Q_{^{12}\mathrm{C}}$ will reduce the half-life for ^{12}C emission by about one month.

C. Reduced widths

The reduced width for α decay can be expressed by the quantity δ^2, in units of MeV, as

$$\delta^2 = \lambda_\alpha h / P, \tag{1}$$

where h is Planck's constant, λ_α is the partial decay constant for α decay, and P is the α-particle barrier penetrability, calculated using the method of Rasmussen [35]. The quantity δ^2 is often given relative to that for ^{212}Po, as the dimensionless quantity W_α which is defined as

$$W_\alpha = \frac{\delta^2}{\delta^2(^{212}\mathrm{Po})}. \tag{2}$$

The values of W_α calculated in the present work are given in Table II together with the data used in the calculations, assuming s-wave α-particle emission. The value of E_α for ^{106}Te measured by Page *et al.* in Ref. [1] has a lower uncertainty than that measured here and has been adopted in the calculations. The values of W_α for ^{114}Ba, ^{110}Xe, and ^{106}Te are all consistent within uncertainties. The value from the present work has an improved precision compared to the value of W_α of 16^{+12}_{-7} for ^{114}Ba reported in Ref. [14], and in general there is a better overlap of the three W_α values in the decay chain. The relatively large uncertainties on these values mean, however, that it is difficult to draw any firm conclusions regarding the predictions of superallowed α decay.

VI. SUMMARY

In summary, the nucleus ^{114}Ba has been produced in an experiment at the Accelerator Laboratory of the University of Jyväskylä Department of Physics, using the ^{58}Ni(^{58}Ni$,2n$) reaction, with a beam energy of 210 MeV. Following implantation into DSSDs at the focal plane of the RITU recoil separator, position and time correlations have been used to identify 17 events in the $^{114}\mathrm{Ba} \rightarrow {}^{110}\mathrm{Xe} \rightarrow {}^{106}\mathrm{Te} \rightarrow {}^{102}\mathrm{Sn}$ triple α-decay chain. The energy of the ^{114}Ba α decay has been measured to be 3480(20) keV, which is 70 keV higher than the previously measured value [14]. The half-life of ^{114}Ba has been measured to be 380^{+190}_{-110} ms; this is consistent with the previous measurement, but with improved accuracy. A revised value for $Q_{^{12}\mathrm{C}}$ of 19035(45) keV is put forward. The cross section for the reaction has been estimated to be 0.15(9) μb. This cross section suggests that it may be possible to successfully identify the low-lying excited states of ^{114}Ba in a future dedicated experiment. Such an experiment would benefit from A/q separation of the reaction products as will be available using, for example, the MARA vacuum-filled recoil separator [36], which is presently under development at the University of Jyväskylä.

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