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Properties of the ^{256}Db Decay Chain

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Experiments were performed at Lawrence Berkeley National Laboratory's 88-Inch Cyclotron Facility to study the decays of neutron-deficient dubnium isotopes. These isotopes were produced in the ^{206}Pb(^{51}V, xn)^{255,256}Db reaction, and excitation functions were measured. This article reports on the observed properties of the ^{256}Db decay chain. The produced ^{256}Db nuclei were separated from unreacted-beam material and reaction byproducts with the Berkeley Gas-filled Separator (BGS) before being implanted into a double-sided silicon strip detector at the BGS focal plane. Decay properties of ^{256}Db and its daughters were then extracted from the analysis of correlations between implanted Db nuclei with α decay chains and spontaneous fission (SF) events. In total, 86 decay chains and 38 SF events were observed, giving increased statistics as compared to previous studies. Improved decay data are presented for ^{256}Db and its daughter isotopes ^{252}Lr, ^{252}No, ^{248}Md, ^{248}Fm, ^{244}Es, and ^{244}Cf.

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I. INTRODUCTION

As the community sets its sights on generating new isotopes of SuperHeavy Elements (SHE, Z > 103), it is still necessary to conduct detailed measurements on those already identified [1]. These studies serve as important benchmarks for theoretical frameworks, facilitating our comprehension of the fundamental properties of the nucleus. Furthermore, such studies will contribute to refining predictions of the properties of SHE that remain undiscovered.

Research on more accessible SHEs, characterized by cross-sections in the range of nanobarns (nb) rather than femtobarns (fb), plays a pivotal role in enhancing our comprehension of the entire SHE region. An illustrative case is the investigation of the production of neutron-deficient dubnium (Db, Z = 105) isotopes, which serves as a reference for understanding both the production of SHE with beams beyond ^{48}Ca, as well as a metric of expected decay properties [2–4]. These inquiries are important, especially as the scientific community endeavors to create new elements beyond Z=118. Further systematic exploration of nuclear reactions for producing isotopes in this region will serve as benchmarks of reaction theory, while decay studies will provide structural insight.

Experiments were performed at the Lawrence Berkeley National Laboratory's (LBNL) 88-inch cyclotron facility to investigate the decay properties of neutron-deficient isotopes of the Db. The isotopes ^{255,256}Db were produced in the nuclear reaction ^{206}Pb(^{51}V, xn)$^{255-256}$Db. The observation and decay properties of ^{255}Db are reported in Ref. [5]. In this article, we report on the decay properties of ^{256}Db and its decay chain members, ^{252}Lr, ^{252}No, ^{248}Md, ^{248}Fm, ^{244}Es, and ^{244}Cf as observed at the focal plane of the Berkeley Gas-filled Separator (BGS) [6]. The results of this work are compared to previous studies. Additionally, the excitation functions for the production of Db in a ^{51}V induced reaction are discussed.

II. EXPERIMENT

A beam of $^{51}V^{12+}$ ions was produced from natural metal material in the VENUS (Versatile ECR for Nuclear Science) ion source [7, 8] and then accelerated with the LBNL 88-inch cyclotron. The $^{51}V^{12+}$ beam was accelerated to Center-Of-Target (COT) energies in the range of of 241 to 253 MeV to map out the ^{51}V + ^{206}Pb excitation function. It is assumed that these energies have a 2 MeV uncertainty. The beam impinged upon a target wheel rotating at ≈30 Hz, positioned just upstream of the Berkeley Gas-filled Separator (BGS). The target wheel was 4.8 inches in diameter, containing four target segments of ^{206}Pb with an average thickness of ≈0.5 mg/cm^2. Each of these segments had been prepared by vapor deposition onto 2.1-μm thick titanium backing foils. To monitor the integrated beam intensity and target thickness during the measurements, two silicon pin diode detectors were positioned in the target chamber at angles of ±27.2° relative to the beam axis to detect Rutherford scattered beam particles.

When the produced Db ions, or EVaporation Residues (EVRs), recoiled out of the target they were then separated from un-reacted beam and unwanted nuclear-

*Present affiliation: Department of Chemistry, Simon Fraser University, 8888 University Drive, Burnaby, British Columbia, V5A 1S6, Canada reaction products within the BGS [6]. For these measurements, the BGS was filled with ≈0.4 torr high-purity helium gas and was tuned to a magnetic rigidity of 2.15 Tm. Upon exiting the BGS, the Db EVRs implanted into a double-sided silicon-strip detector (DSSD) at the BGS focal plane. This detector was comprised of 32×32 strips with an active area of 65.18 mm × 65.17 mm. The position of a detected EVR or decay event is given by the horizontal and vertical strip number in which the event was detected. Energies for the detected α events were calibrated using a source containing ^{239}Pu, ^{241}Am, and ^{244}Cm. The observed energy resolution was ≈47 keV FWHM in the 7 - 10 MeV range. Note that the source was always "active" during the experiment, such that any potential changes in calibration during a measurement could be corrected. For these studies, the data acquisition was triggered by an event detected in the DSSD with an energy threshold of ≈1 MeV.

III. DATA ANALYSIS

After the EVRs are produced in the nuclear reaction and separated by the BGS, they are implanted into a pixel of the DSSD. Then any subsequent decays originating from the implanted EVR will occur within the same DSSD pixel and can be identified. For these studies, the accumulated data was analyzed to identify both potential α-decay chains and Spontaneous Fission (SF) events correlated in time and position with an implanted EVR. The characteristics of these events are then studied to extract the decay properties of the produced Db nuclei. This analysis is discussed further in the subsequent sections.

A. α Correlations

The implantation DSSD was instrumented with linear-logarithmic pre-amplifiers. These pre-amplifiers operated on a dual scale, where lower-energy events (≈ < 10 MeV) registered on a linear scale and higher-energy events (≈ > 12 MeV) were recorded on a logarithmic scale. The linear scale was calibrated with sources, as described previously, the logarithmic part was not calibrated and was analyzed in ADC channel. The data was analyzed to search for EVR-α_1-α_2 correlations, where α_1 and α_2 denote the first and second α particles observed within the same pixel as the detected EVR, respectively. The EVR selection criteria adopted here required implantation events to be between 2400 - 3300 channel numbers. The validity of this selection is confirmed in Fig. 1(Top), where there is a clear coincidence between EVRs and ≈9 MeV α_1 events. In these data, a maximum EVR-α_1 correlation time of < 10 s was adopted as is shown in Fig. 1(Bottom).

The analysis conditions for subsequent α decays, following the detection of an α_1 event, were determined by taking into account the previously reported decay properties of the ^{256}Db daughters. The chosen parameters included a maximum correlation time of 150 s and an energy range selected to be 7 - 10 MeV. These criteria would allow the observation of events originating from the decay of ^{252}Lr ($t_{1/2} = 0.36^{+0.11}_{-0.07}$ s [3]), ^{248}Md (13^{+15}_{-4} s [9]), ^{248}Fm (34.5(12) s [10]), and ^{244}Es (37(4) s [11, 12]). Additionally, it could be possible to observe the decay of ^{244}Cf, but given its longer half-life of 19.4(6) min [13], few events would likely be observed within the 150 s cor-

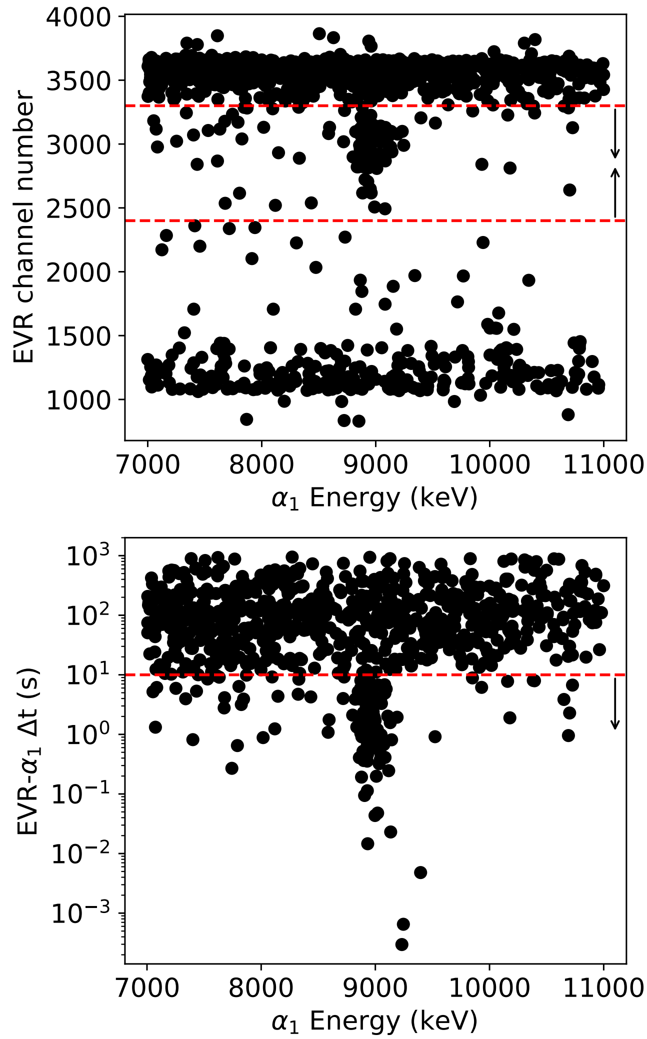

FIG. 1: Gate selection for EVR-α correlation events. (Top) Correlations shown for α events and potential EVR events. The selected EVR gate for further analysis corresponds to channel numbers 2400 - 3300, exhibiting a distinct cluster of correlations. Red dashed lines indicate the chosen upper and lower EVR bounds. (Bottom) EVR-α_1 correlations extending up to 1000 s. There is a clear cluster of α_1 events at approximately 9 MeV and EVR-α_1 Δt < 10 s. Beyond correlation times of 10 s, a notable increase in random correlations is evident. Therefore, EVR-α_1 Δt < 10 s was chosen as the maximum correlation time for EVR-α_1 and is denoted by a red-dashed line.

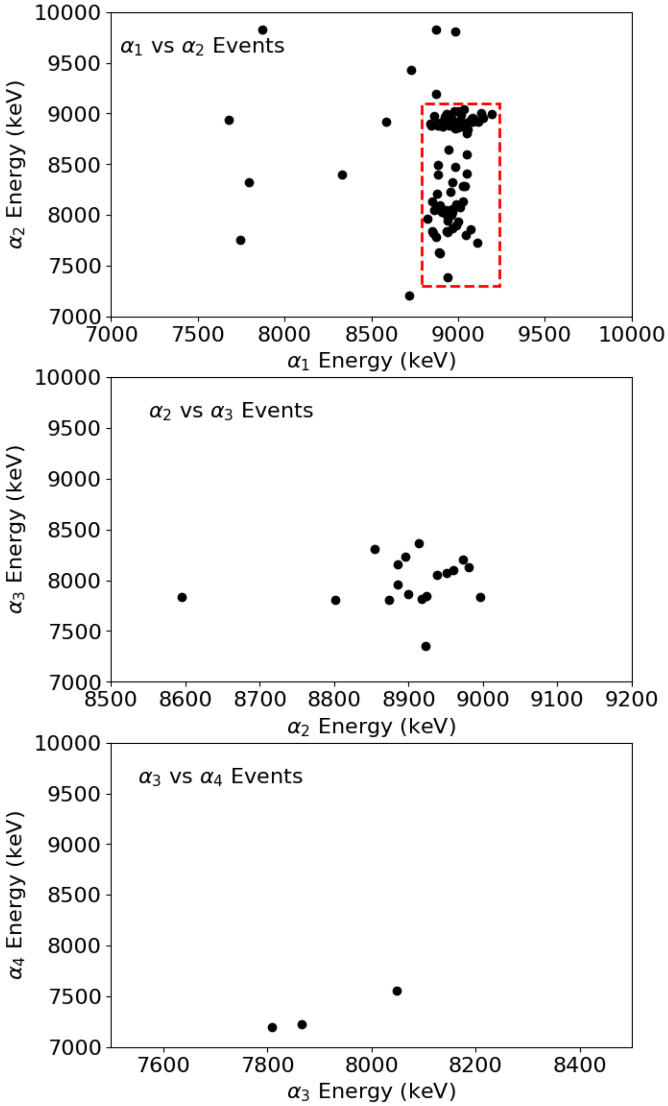

FIG. 2: A scatter plot of decay chains detected at the BGS focal plane. There were observed two-, three-, and four-α correlations. (Top) The α energies of the α_1 vs. α_2 events for the observed decay chains. There is a clear cluster around $\alpha_1 \sim 9$ MeV (indicated by the dashed box) that is consistent with the expected energy range for ^{256}Db or ^{252}Lr decay. The remaining 11 events outside the dashed box are likely random correlations, supported by a random-rate analysis. (Middle) The α energies of the α_2 vs. α_3 events for the observed decay chains. (Bottom) The α energies of the α_3 vs. α_4 events for the observed decay chains. Energies are reported in keV.

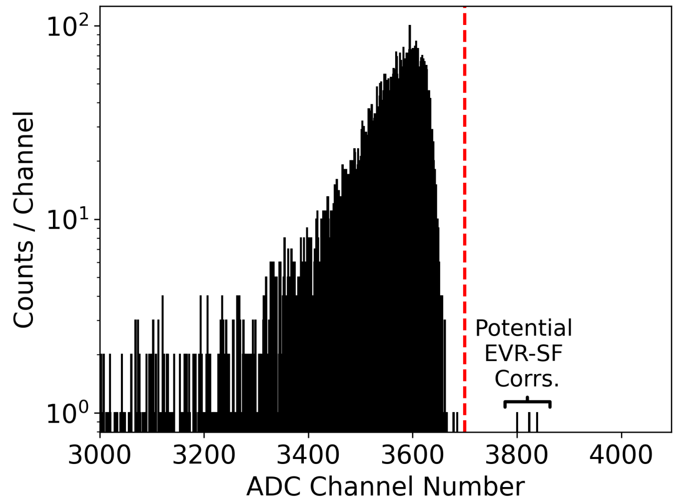

FIG. 3: An example of how potential EVR-SF correlations were selected. Depicted here are the counts of events detected per ADC channel for a single strip of the DSSD. As SF events would be much greater in energy than any other detected event. Therefore, events were selected that were detected at ADC channels beyond the bulk of the other events. The selected events are indicated.

relation window.

Over approximately 12 days of total running time, 100 EVR-α_1-α_2 correlation events were gathered. Among these events, three were identified as decay chains originating from ^{255}Db. These events are discussed in more detail in Ref. [5]. The remaining 97 correlations are shown in Fig. 2. In looking at the energies of α_1 versus α_2 events, there is a distinct cluster around $\alpha_1 \sim 9$ MeV, as highlighted by the dashed box. This aligns closely with the energy range observed in previous measurements for either a ^{256}Db or ^{252}Lr decay. Consequently, these 86 events were attributed to the decay of ^{256}Db. A discussion of the properties of these decay chains follows in Section IV B. The 11 events lying outside the dashed box are considered probable random correlations. To validate this assumption, a random-rate analysis was conducted using uncorrelated data. In this analysis, the total number of EVR-like events detected during the measurement were counted and the rate of 7-10 MeV α events per DSSD pixel was determined. Then these data were used to determine how many random EVR-α events would be expected across the entire DSSD. This analysis found that 11.4 random events would be expected. Therefore, assigning these 11 events as random is well-founded.

B. Fission Correlations

The data was also analyzed looking for potential EVR-SF correlations. The same EVR criteria were used as in the α analysis. SF events were registered on the logarithimic part of the ADC, so will be discussed in ADC channel numbers. To identify possible SF events, it was assumed that its channel number would be higher than that of any other detected event, such as scattered beam particles or transfer reaction products. Therefore, events detected at higher ADC channel numbers beyond the bulk of detected events were considered as potential EVR-SF correlations. An example of the selection of these events for a single detector channel is shown in

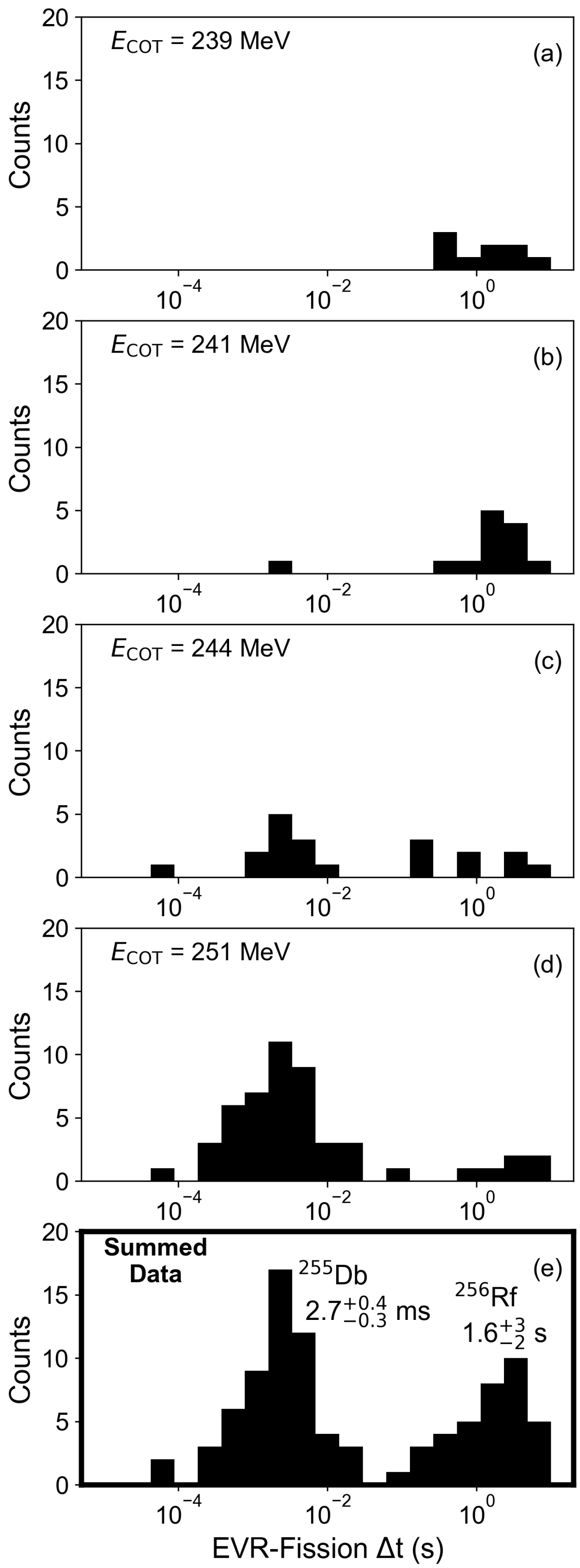

FIG. 4: The correlation times of the EVR-SF events are shown for each investigated beam energy in (a) - (d). The data is showed summed in (e). The 1.6 s SF events are assigned as belonging to the ^{256}Rf, populated via EC of ^{256}Db. The 2.7 ms SF events are assigned to belong to the decay of ^{255}Db.

Fig. 3. The EVR-SF correlation times for all such events are shown in Figs. 4(a-d) for each beam energy studied. Fig. 4(e) shows a summed spectrum over all energies. This analysis was also sensitive to the identification of EVR-alpha-SF correlations, however none were observed.

In looking at Fig. 4(e), there are two primary clusters of potential EVR-SF correlations with correlation times < 10s, that likely correspond to implantations of Db nuclei. The "longer-lived" cluster of 38 events has a half-life of 1.6^{+3}_{-2} s and the shorter-lived cluster of 55 events has a half-life of 2.7^{+4}_{-3} ms. As is shown in Fig. 4(a-d), the longer-lived events are more dominant at lower-COT energies, and the shorter-lived events are more prominent at higher-COT energies. A random rate analysis, similar to that described in Section III A, was performed and it was determined that only 0.5 random correlations would have been expected with a maximum correlation time of 10 s. Therefore, these events are likely not random. The 1.6 s SF events are assigned as belonging to the ^{256}Rf, populated via EC of ^{256}Db. Note that the observed correlation time here contains both the EC decay of ^{256}Db in addition to the SF decay of ^{256}Rf. These events will be discussed in more detail in Section IV C. The 2 ms SF events are assigned to belong to the decay of ^{255}Db. These are discussed in more detail in Ref.[5].

IV. RESULTS AND DISCUSSION

A. The ^{51}V + ^{206}Pb Excitation Function

As the community looks towards producing new elements with $Z > 118$, there is considerable interest in understanding SHE production utilizing beams beyond ^{48}Ca. Two potential candidates are ^{50}Ti and ^{51}V. Therefore it is of great interest to measure the cross-section of reactions utilizing these beams. The experimental excitation functions for the ^{51}V + ^{206}Pb reaction from this work are shown in Fig. 5. The production of the ^{256}Db and ^{255}Db isotopes, via $1n$ and $2n$ exit channels were investigated over the E_{COT} range of 241 to 253 MeV. The energy loss of the beam passing through the titanium-target backing and the first half of the target material was estimated to be ≈19 MeV from Stopping and Range of Ions in Matter (SRIM) calculations [14]. The cross-sections were computed given a 60% transportation efficiency for EVRs through the BGS and using the Rutherford rates observed for each measurement. Error bars on these cross-sections are given based on the Poisson statistical error on the number of events observed.

The maximum cross-section observed for the $1n$ channel, for the production of ^{256}Db was observed to be $\sigma(1n,\text{max}) = 0.5(2)$ nb at $E_{COT} = 243(2)$ MeV. A gaussian curve were also fit to the $1n$ experimental values. From the fit, the $1n$ curve's maximum cross-section is located at $E_{COT} = 243.0(2)$, MeV, with a fitted value of 0.49(7) nb. The maximum cross-section observed here for the $2n$ channel, for the production of ^{255}Db, was

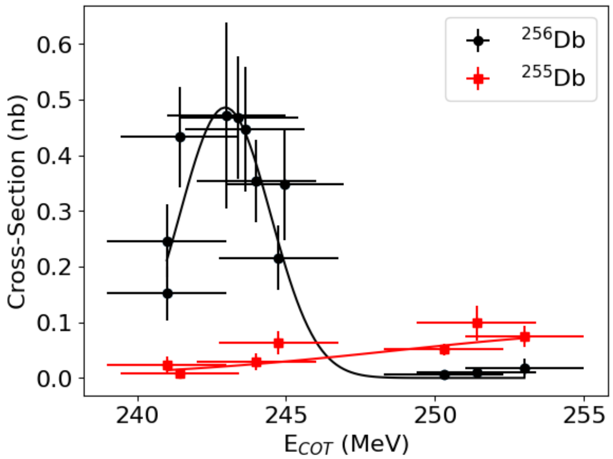

FIG. 5: Experiment excitation functions for ^{51}V + ^{206}Pb. The results for the production of the isotopes ^{256}Db and ^{255}Db are displayed. These data are shown fit to gaussian distributions, the results of which are discussed in the text. When not visible, the error bars are smaller than the point.

$\sigma(2n,\text{max}) = 0.099(31)$ nb at $E_{COT} = 251(2)$ MeV.

These results are compared to previous work to further elucidate the application of ^{51}V versus ^{50}Ti beams in nuclear reactions. Previously, ^{256}Db was produced from the $3n$ exit channel of the ^{50}Ti + ^{209}Bi reaction [3, 4]. There, Heßberger *et al.*, reported a maximum cross-section of ≈0.19(4) nb [3], less than half what is reported here for the ^{51}V + ^{206}Pb reaction. This is interesting as previous studies comparing cross-sections for Db isotopes produced with ^{50}Ti and ^{51}V beams incident on ^{209}Bi and ^{208}Pb targets, respectively, observed drops in production for the same species produced with the ^{51}V beam induced reactions by more than half [2]. There, this was attributed to the relative capture cross-sections of the two reactions [2].

It is also useful to compare the cross-sections observed here to the previous measurements of the ^{51}V + ^{208}Pb reaction by J.M. Gates *et al.* [2]. There, it was reported that the $1n$ and $2n$ channels similarly produced Db isotopes at a cross-section of ≈2 nb [2]. Now, compared to this current results, it appears that there is is an overall drop in cross-section when transitioning from the use of a ^{208}Pb target to a ^{206}Pb target with the use of a ^{51}V beam, roughly by factor of six for the $1n$ production channel. Notably, this drop in production was not observed for similar studies of ^{50}Ti induced reactions on ^{208}Pb and ^{206}Pb targets [15].

B. Properties of the ^{256}Db Decay Chain

The 86 decay chains originating from the decay of ^{256}Db are depicted in Fig. 2. From these, 65 events were EVR-α_1-α_2 correlations, 18 were EVR-α_1-α_2-α_3 correlations, and three were EVR-α_1-α_2-α_3-α_4 correlations. Subsequent analysis focused on extracting the decay properties of ^{256}Db and its daughters. The decay of ^{256}Db has been observed in two previous studies, Heßberger *et al.* observed 16 α decay chains and nine SF events when ^{256}Db was populated directly in the ^{50}Ti + ^{208}Bi reaction [9]. S.L. Nelson *et al.* observed six α decay chains and two fission events when ^{256}Db was populated via the α decay of ^{260}Bh. The previously reported properties of the ^{256}Db decay chain, juxtaposed with the properties of the three four-α correlations observed in this measurement are shown in Fig. 6. The present work significantly improves the level of statistics measured for the decay of ^{256}Db. The energies and decay times of the observed α events are detailed in Table I. Further discussion of assignments and comparisons to previous work are provided in the subsequent sections.

TABLE I: Summary of decay data for the ^{256}Db-decay chain obtain from these studies. In instances where less than 10 events were observed for a given isotope, relative intensities (i_{rel}) are reported as approximations. Note that it was not possible in all instances to report values for the half-lives ($t_{1/2}$) and α-branching ratios (α-BR) for all isotopes. This is discussed further in the text.

Isotope	E_α (keV)	i_{rel} (%)	$t_{1/2}$ (s)	α-BR (%)
^{256}Db	8890(47)	≈20	$1.4^{+0.3}_{-0.2}$	90(4)%
	8930(47)	≈20		
	8980(47)	≈30		
	9020 - 9200	≈30		
^{252}Lr	8884(47)	≈25	$0.41^{+0.07}_{-0.05}$	70-90%
	8929(47)	≈45		
	8987(47)	≈30		
^{252}No	8595 (47)	≈100		
^{248}Md	8050(47)	≈45	13^{+3}_{-2}	61(16) - 68(22)%
	8120(47)	≈20		
	8200-8600	≈30		
	8643(47)	≈5		
^{248}Fm	7830(47)	≈70		
	7950(47)	≈30		
^{244}Es	7550-7650			
^{244}Cf	7180-7400			

C. The Decays of ^{256}Db and ^{252}Lr

The previously-observed α-decay energies and lifetimes of ^{256}Db and ^{252}Lr are quite similar. In order to disentangle the α events correlated to each, only a subset of the total correlations were considered. This subset included events where the energies of the α_1 and α_2 events were both greater than 8750 keV, such that α_1 would be the decay of a ^{256}Db nucleus and α_2 would be the decay of a ^{252}Lr nucleus. Here the α energies of all subsequent chain members are less than 8.5 MeV. The data set contained 43 correlations meeting these conditions. A statistical analysis on the data, given these same selection criteria, revealed that only 0.5 random correlations would be expected. The decay properties of ^{256}Db were then de-

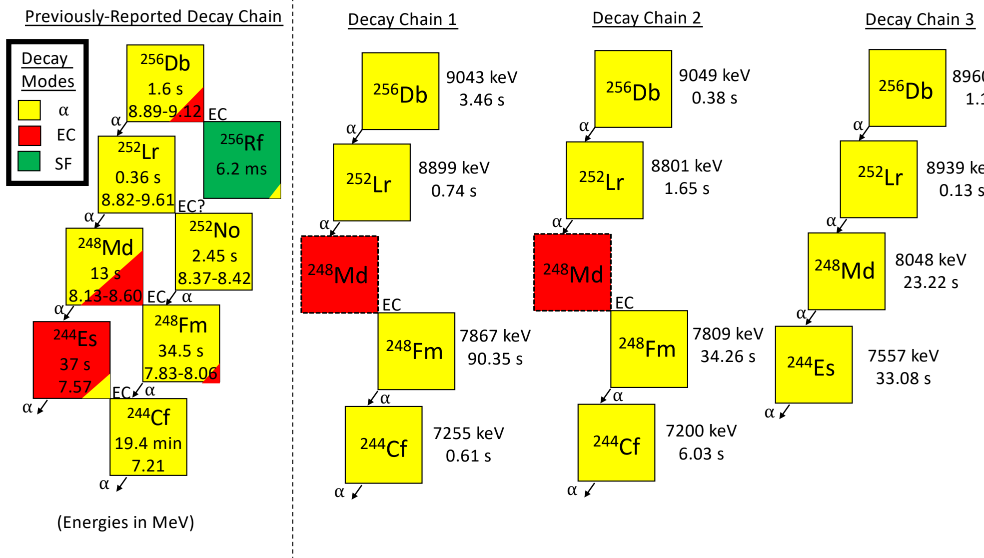

FIG. 6: The previously reported decay chain for ^{256}Db is shown side-by-side with the three four-α correlations observed in this experiment. Previously reported data are taken from Refs. [3, 9, 11–13, 16, 17]. The decay times of the ^{256}Db events are relative to the observed EVR implantation. The decay times of the other isotopes are relative to the previous decay in the chain.

termined from the α_1 events and the decay properties of ^{252}Lr were determined from the α_2 events of these 43 chains. Note that this subset of correlations was analyzed to disentangle the extraction of the properties of ^{256}Db and ^{252}Lr. To determine the properties of all subsequent daughters in the decay chain, all of the collected decay chains were considered.

The energies of the α events assigned to the decay of ^{256}Db are presented in Fig. 7(a) and the decay times of these events, relative to the EVR-implantation time, are plotted in Fig. 7(b). The average half-life of these events was determined to be $1.4^{+0.3}_{-0.2}$ s. This is in good agreement with the previously reported value of $1.6^{+0.5}_{-0.3}$ s [3]. To determine the energies of the observed α-transitions, the correlations were analyzed in 20-keV binned histograms. In looking at Fig. 7(a), it is apparent that several α transitions are present between ≈8880 - 9200 keV. There are three α lines that can be identified at 8890(47) 8930(47), and 8980(47) keV. Additionally, there is a group of α events observed in the energy range 9020-9200 keV. The relative intensities of the these groupings are given in Table I. In the previous work, four α-decay transitions had been reported with energies of 8891(20), 9014(20), 9075(20), and 9120(20) keV [3]. The properties observed here are in the range of those previously reported, though are not in exact agreement. Here we report on the properties of 43 events, where as Heßberger *et al.* was only able to deduce properties from 16 events [3].

In the previous studies, ^{256}Db was observed to undergo electron-capture (EC) to populate ^{256}Rf. After being populated, ^{256}Rf can then undergo SF with a half-life of $t_{1/2} = 6.67(10)$ ms [21]. From the two previous measurements, the ^{256}Db EC branch was reported to be 36(12)% [3] and 30(11)% [9]. Note that in this experiment, a ^{256}Rf SF event would be observed as an EVR-SF correlation. In this instance, the observed correlation time of such an event would be dominated by the half-life of the ^{256}Db EC decay to ^{256}Rf, which would be lower than SF by one to two orders of magnitude. In this work, 38 EVR-SF correlations were observed with an average half-life of 1.6^{+3}_{-2} s. In the previous works, 9 [3] and 2 [9] of such events were observed. Assuming a 100% detection efficiency of SF events and the $> 98\%$ SF branch of ^{256}Rf, the EC branch deduced in the current data is 10(4)%.

The energies of the α events assigned to originate from the decay of ^{252}Lr are presented in Fig. 7(c) and their correlation times are plotted in Fig. 7(d). The average half-life of these ^{252}Lr events, relative to the decay of a ^{256}Db nucleus, is $0.41^{+0.07}_{-0.05}$ s. This is in good agreement with the previous measurement of $0.36^{+0.11}_{-0.07}$ s [3]. Given the level of statistics and distribution of events, it was possible to fit the α spectrum with gaussians. Here, three α-decay transitions were identified with energies of 8884(47) keV, 8929(47) keV, and 8987(47) keV, and relative intensities of 0.25, 0.45, and 0.30, respectively.

There is general agreement on the properties of ^{252}Lr in comparing to previous data. In the work of Heßberger *et al.*, two α lines were reported with energies of 8974(20) and 9018(20) keV with relative intensities of 0.25 and 0.75, respectively [3]. In the work of S.L. Nelson *et al.*, four transitions are reported with energies of 8820, 8990, 9020, and 9610 keV [9]. S.L. Nelson *et al.* note that the 9610 MeV transitions is 500 keV greater than the Q-value. No such high-energy decay was observed for ^{252}Lr

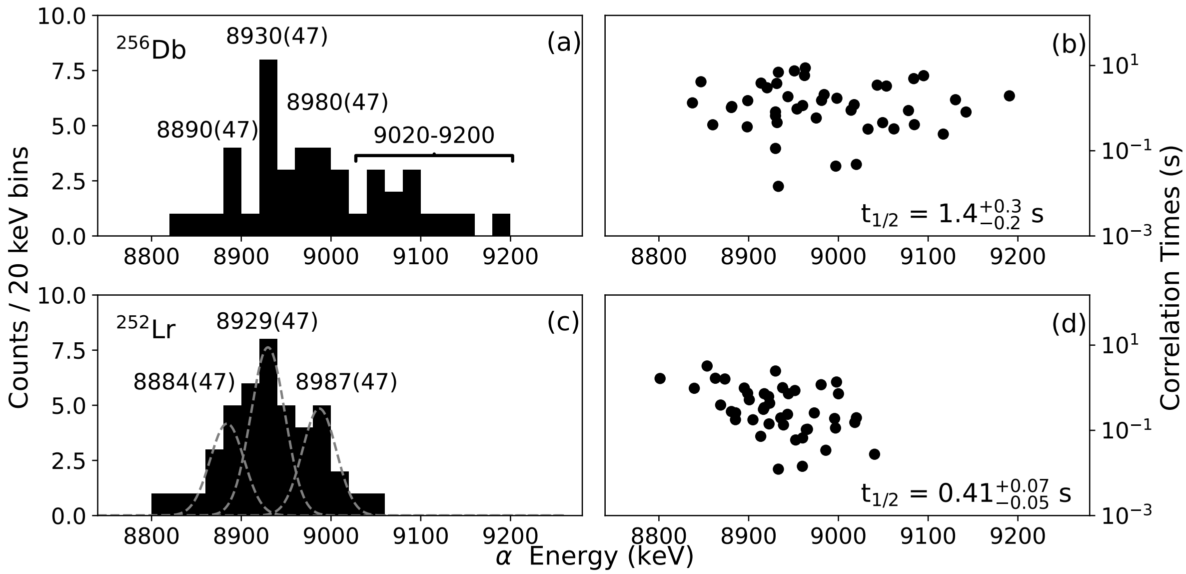

FIG. 7: Observed properties of ^{256}Db and ^{252}Lr. (a) α-decay transitions assigned to the decay of ^{256}Db with respective decay times shown plotted in (b). (c) α-decay transitions assigned to the decay of ^{252}Lr with decay times shown plotted in (d).

in this work.

There has been an open question as to whether or not ^{252}Lr undergoes EC to populate ^{252}No ($t_{1/2} = 2.44(4)$ s [18]. In the previous measurements, no such EC branch was observed [3, 9]. If populated, ^{252}No would decay via a 70.70% α branch with energies of 8372(8) and 8415(6) [19]. Unfortunately, the decay properties of ^{252}No are very similar to those of ^{248}Md. The isotope ^{248}Md has a half-life of $t_{1/2} = 13^{+15}_{-4}$ s and reported α decays in the range of 8130 - 8460 keV [9]. Also, the similarity in the decay properties of ^{256}Db and ^{252}Lr adds complexity to distinguishing whether a potential ^{252}No decay would be preceded by one or the other.

In this study, there was one EVR-α_1-α_2-α_3 correlation observed that could be unambigously assigned as evidence of the EC decay of ^{252}Lr. The chain, shown in Fig. 9, shows the α decay of ^{256}Lr, followed by the α decay of ^{252}No, and the α decay of ^{248}Fm. In this instance, the second α is unambiguously assigned as ^{252}No, as opposed to ^{248}Md, as it is directly followed by the α decay of ^{248}Fm. Here, the energy of the ^{252}No decay, $E_\alpha = 8595$ (47) keV, is higher than what has been reported from previous studies. Perhaps it is possible that a different state is being populated from the EC decay. Given the probability of detecting this three α correlation, considering the previously-reported α decay branches of ^{252}No and ^{248}Fm, and a 50% α detection efficiency, we report the EC branch of ^{252}Lr to be on the order of 10-30%. Additionally, this study observed 4 EVR-α_1-α_2 chains where assignments of α_2 as either ^{252}No or ^{248}Md are ambiguous. The properties of these events are shown in Fig. 10. Interestingly, the average half-life of these α_2 events is 3^{+4}_{-1} s, which does align nicely with that of ^{252}No. However, there is not enough information from these events alone to make an absolute assignment.

In a previous study of the decay of the odd-odd Db isotope ^{258}Db and its daughter ^{254}Lr, α-decaying isomeric states were observed for each isotope from the analysis of α-α and α-γ correlations [20]. The presence of these isomeric states has been explained due to the expected large angular momentum differences between the low-lying states of these two isotopes manifested from coupling the single-particle states of the odd proton and neutron. It would be expected that similar behavior would be observed for ^{256}Db and ^{252}Lr. However, as is apparent from the data shown in Fig. 8, there is no obvious presence of any isomeric states given this level of statistics. Here, the data is shown for the subset of 43 correlations where α_1 is ^{256}Db and α_2 is ^{252}Lr. In Fig. 8(a) the energies of ^{256}Db versus ^{252}Lr for each correlation are plotted and the respective decay times are plotted in Fig. 8(b). In the future, studies with higher statistics also utilize α-γ spectroscopy may further elucidate the matter.

D. The Decays of ^{248}Md and ^{248}Fm

The isotope ^{248}Md is populated from the α decay of ^{252}Lr. In this study, ^{248}Md was observed to decay both by α emission, populating ^{244}Es, and by EC, populating ^{248}Fm. In previous measurements, ^{248}Md was reported to decay with E_α in the range of 8130 - 8460 keV [9, 16] and ^{248}Fm was reported to decay with E_α falling in one of two transitions at 7830(20) keV and 7870(20) keV [17].

From the 86 collected ^{256}Db decay chains, 30 were assigned as including the α decay of ^{248}Md. The energies and decay times for these events are shown in Figs. 11(a) and 11(b), respectively. The average half-life of 13^{+3}_{-2} s

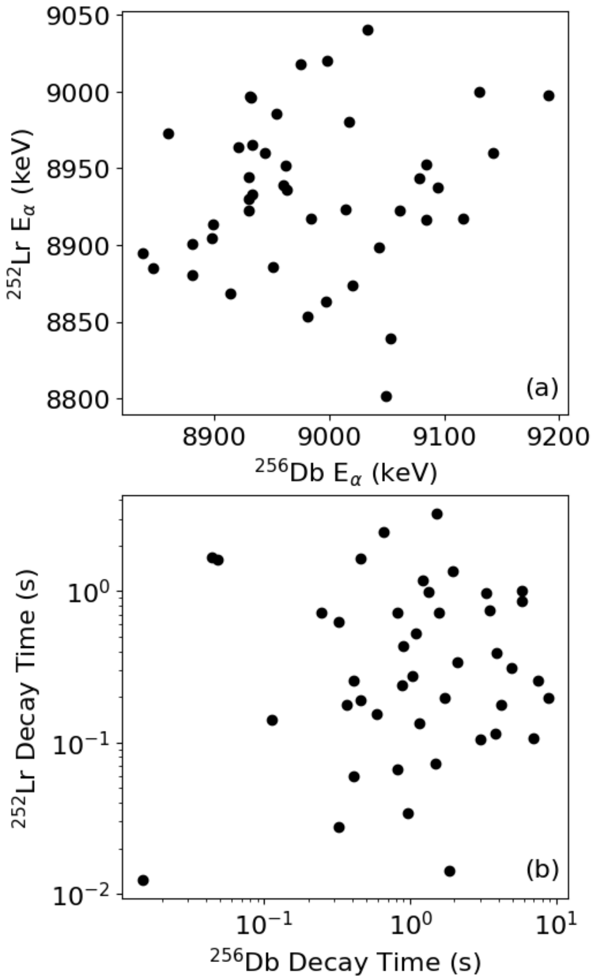

FIG. 8: An examination of the ^{256}Db and ^{252}Lr correlations. (a) The observed α energies for correlations where α_1 is ^{256}Db and α_2 is ^{252}Lr. (b) The observed decay times of ^{256}Db versus correlated ^{252}Lr events. Given the level of statistics, there is no obvious presence of any isomeric states.

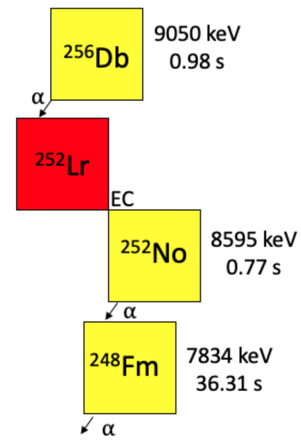

FIG. 9: Properties of the observed EVR-α_1-α_2-α_3 correlation assigned as the α decay of ^{256}Lr, followed by the α decay of ^{252}No, and the α decay of ^{248}Fm. This correlation is evidence of the EC decay of ^{252}Lr.

is in good agreement with the previously reported values of 13^{+15}_{-4} s [9] and $\approx$10 s [3]. Here, two α-decay transitions were observed with energies of 8050(47) and 8120(47) keV. Additionally, there is a broad distribution of α events between 8200 - 8400 keV and a single event detected at 8643(47) keV. The relative intensities of these events are given in Table I.

The population of ^{248}Md was observed in the two previous studies of the ^{256}Db decay chain by Heßberger *et al.* and S.L. Nelson *et al.* [3, 9]. Additionally, ^{248}Md was populated directly in the ^{12}C + ^{241}Am reaction by P. Eskola [16]. In the work of Heßberger *et al.* 7 events where observed in the range of range of 8.2 - 8.6 MeV, in the work of S.L. Nelson *et al.*, three events were observed in the range of 8.1 - 8.5 MeV, P. Eskola observed α-decay energies of 8320(20) and 8360(20). When comparing to the previous works, it is evident that different states in ^{248}Md were likely populated in the different production

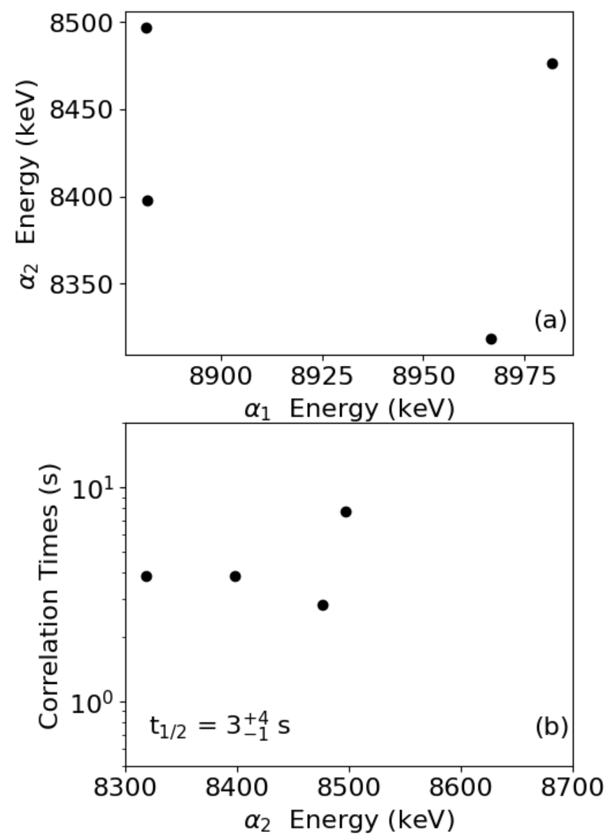

FIG. 10: The 4 ambiguous EVR-α_1-α_2 chains were assignments of α_2 as either ^{252}No or ^{248}Md are possible. (Top) The observed α_1 versus α_2 energies. (Bottom) Correlation times of the α_2 events. The average half-life of these events is 3^{+4}_{-1}s.

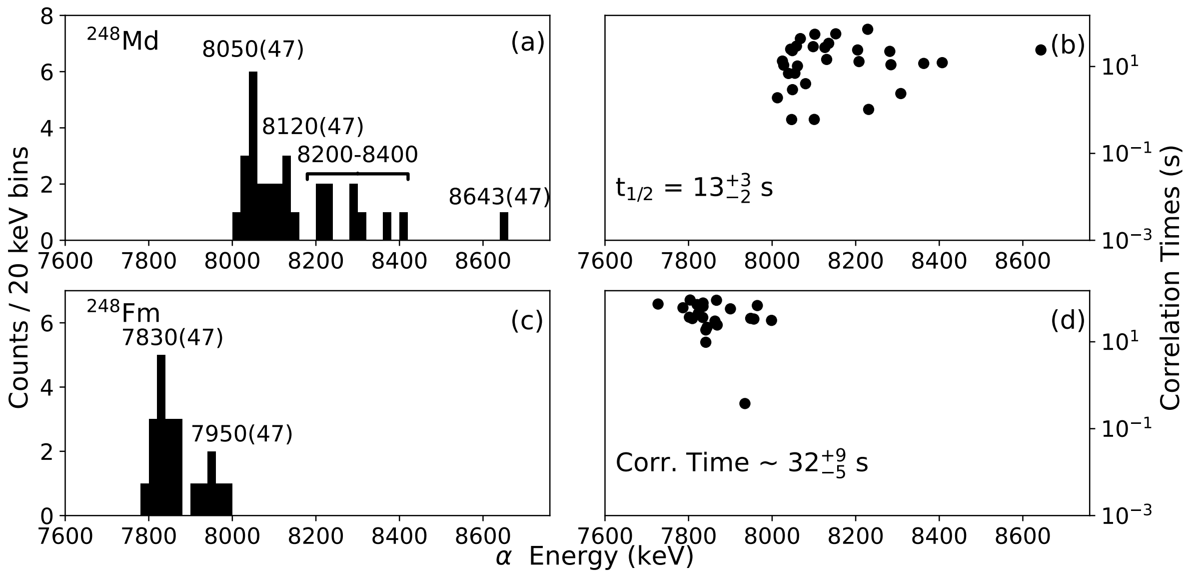

FIG. 11: Observed properties of ^{248}Md and ^{248}Fm as members of the ^{256}Db decay chain. In analyzing the data, it was decided that α events from 8000 - 8600 keV would be considered as decays of ^{248}Md and that events from 7800 - 8000 keV would be considered as decays of ^{248}Fm. (a) α-decay transitions assigned to the decay of ^{248}Md with respective decay times shown plotted in (b). (c) α-decay transitions assigned to the decay of ^{248}Fm with decay times shown plotted in (d).

modes. The energies measured here agree generally with the previous works. In particular there is agreement with the broad-range of energies reported in Refs. [3, 9].

In this study, 22 events were assigned as including the decay of ^{248}Fm. The α-decay energies and decay times for these events are shown in Figs. 11(c) and 11(d), respectively. Two α transitions were observed for the decay of ^{248}Fm with energies of 7830(47) keV and 7950(47) keV. The relative intensities of these transitions are 0.70 and 0.30, respectively. Note that the half-life for ^{248}Fm could not be determined directly, as the experimentally-observed decay time for ^{248}Fm α events would also include the ^{248}Md EC-decay time. The average decay time of these events was observed to be 32^{+9}_{-5} s, and includes the lifetime of the ^{248}Md parent. The previously reported half-life for ^{248}Fm is 34.5(12) s [10]. Given that the ^{248}Md half-life was measured to be $\approx$12 s, we find agreement with the previously-reported value within error. In previous works, Heßberger *et al.* observed five decays in the range of 7750 - 8000 MeV [3] and S.L. Nelson *et al.* observed two decays with 7850 and 8060 keV [9]. This is in agreement with what is reported here. However, S.L. Nelson *et al.* assigned the 8.06 MeV transition as belonging to ^{248}Fm whereas here it is assigned as the decay of ^{248}Md. The average half-life of the 10 such $\approx$8.05 MeV events observed here is 10^{+4}_{-2} s, supporting a ^{248}Md assignment.

Previous studies disagree on the α-decay branch of ^{248}Md, with P. Eskola reporting 20(10)% [16] and S.L. Nelson *et al.* reporting 58(20)% [9]. Here, there is some ambiguity as to which events should be assigned as ^{248}Md or ^{252}No and as to which events of ^{248}Fm were populated either via α decay of ^{248}Md or ^{252}No. If we assume a 10% or 30% ^{252}Lr EC branch to ^{252}No then the ^{248}Md α branch would be 61(16)% or 68(22)%, respectively. This range of values in more in line with what was reported by S.L. Nelson *et al.*.

E. The Decays of ^{244}Es and ^{244}Cf

In the ^{256}Db decay chain, ^{244}Es is populated following the α decay of ^{248}Md. In these data, three α events were observed and assigned as the decay of ^{244}Es. The energies of these events are 7556, 7622, and 7628 keV and are plotted in Fig. 12(a). The α decay of ^{244}Es was not observed as a component of the ^{256}Db decay chain in the two previous works [3, 9]. However, the decay properties of ^{244}Es have been reported from its direct production in the ^{12}C + ^{237}Np reaction [11]. There, an α energy of 7570(20) keV and half-life of 37(4) s was reported. This is in line with what has been observed here. However, it is also important to note that in Ref. [11], higher-energy transitions would have been obscured by the 7.73 MeV ^{245}Es transition that was also present. Therefore, a direct comparison to the α-decay energies of ^{244}Es when populated from ^{248}Md cannot be made. In regards to determining the ^{244}Es half-life, only one of the three collected events directly followed the observed-α decay of ^{248}Md. This event had a decay time of 33.08 s, consistent with the previous measurement.

It has been previously reported that ^{244}Es undergoes EC to populate ^{244}Cf with a 96% branch [12]. In these data, four α events were assigned as the decay of ^{244}Cf,

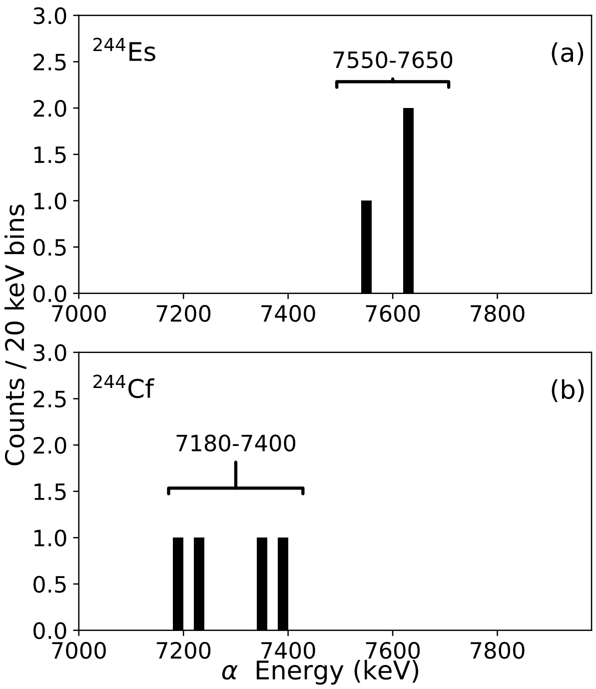

FIG. 12: Observed properties of ^{244}Es and ^{244}Cf as members of the ^{256}Db decay chain. (a) α-decay transitions assigned to the decay of ^{244}Es. (b) α-decay transitions assigned to the decay of ^{244}Cf.

with energies of 7200, 7225, 7349, and 7382 keV. These are shown plotted in Fig. 12(c). In the previous study of Heßberger *et al.*, seven decays of ^{244}Cf were observed with energies ≈7200 keV [3]. This is in agreement with what is reported here. Note that the study of S.L. Nelson *et al.* did not observe the decay of ^{244}Cf.

In regards to the half-life of ^{244}Cf, it has been previously measured to be 19.4(6) min [13]. This is much longer than our α-correlation window of 150 s. Note that extending the correlation window beyond 150 s leads to the introduction of significantly more random correlations. Therefore, it is not possible to comment on the half-life of ^{244}Cf from these data. However, it will be pointed out that two of the observed ^{244}Cf events were proceeded by the α-decay of ^{248}Fm, such that the correlation time would be reflective of the ^{244}Cf decay. These events are the terminal members of two of the EVR-α_1-α_2-α_3-α_4 correlations featured in Fig. 6. It is interesting to note that the correlation time for these two decays are quite short at 0.61 and 6.02 s. This strange observation is considered to be merely a statistical anomaly.

V. CONCLUSIONS

Experiments were performed to study the production of neutron-deficient dubnium isotopes in the ^{206}Pb(^{51}V, $1-2n$)$^{255-256}$Db reactions. The production of the ^{255}Db and ^{256}Db isotopes was investigated over the E_{COT}-energy range of 241 MeV to 253 MeV to measure the excitation functions of the $1n$ and $2n$ exit channels for the ^{51}V + ^{206}Pb fusion reaction. The maximum observed cross-sections for the $1n$ and $2n$ channels were 0.5(2) nb at E_{COT} = 243(2) MeV, and 0.099(31) nb at E_{COT} = 251(2) MeV, respectively. In total, 86 decay chains were assigned to originate from the decay of ^{256}Db. This greatly improves the level of events observed compared to previous studies. Improved decay properties were found for ^{256}Db and its daughters.

VI. ACKNOWLEDGEMENTS

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