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The results of a detailed analysis performed on the data obtained in the ^{248}Cm(^{48}Ca,4*n*)^{292}116 reaction is presented. This analysis is independent of the original data analysis performed in Dubna in which three separate decay chains were found. Each decay chain began with an evaporation residue followed by three α decays and ended in a spontaneous fission event, all correlated in time and position. The analysis presented confirms that the three events are present in the data. A summary of the three events will be given as well as a description of the analysis performed.

I. INTRODUCTION

In 2000, a ^{248}Cm + ^{48}Ca bombardment was performed at Flerov Laboratory of Nuclear Reactions (FLNR), Joint Institute for Nuclear Research (JINR), in Dubna in the hope of observing the decay of ^{292}116 [1]. Earlier experiments with ^{244}Pu targets resulted in the observation of ^{288}114, the α-decay daughter of ^{292}116 [2,3]. It was believed that ^{292}116 decayed via α decay to ^{288}114, and if ^{292}116 could be produced, a decay chain similar to the ones already observed would be seen, solidifying both discoveries by providing a consistent picture of their decay properties. Over the course of a year, an accumulated beam dose of 2.3×10^{19} ^{48}Ca ions was obtained and three ^{292}116 events were observed. A summary of the three decay chains is given in Fig. 1. The energies and positions from Fig. 1 were calculated using calibrations performed in Dubna.

In an attempt to confirm the results of the original data analysis, a separate, independent analysis was performed on the 116 data. This marked the first time that the full calibration and subsequent data analysis was performed at Lawrence Livermore National Laboratory (LLNL), which resulted in a more complete understanding of the data. Any discrepancies observed between the LLNL and FLNR analysis were minor.

II. CALIBRATION

To begin the independent analysis of the 116 data, the calibration parameters for all of the detectors were established. Each focal plane detector strip was calibrated for 9 parameters: slopes and intercepts for energy alpha, energy fission, position alpha, position fission and a correction factor for the fission energy. Each side detector was calibrated for 4 parameters: slopes and intercepts for energy alpha and energy fission.

The $^{206}Pb(^{48}Ca,2n)^{252}No$ reaction was used to obtain the calibration parameters in both the a and fission ranges. ^{252}No ($T_{½}$=2.30±0.22 s) has a 73.1±1.9% a-decay branch and a 26.9±1.9% spontaneous fission (SF) branch [4]. ^{252}No a decays with an energy of 8415±6 keV (~75%) and 8372±8 keV (~25%) to ^{248}Fm. ^{248}Fm ($T_{½}$=36±3 s) a decays (93±7%) with an energy of 7870±20 keV (80%) to ^{244}Cf. ^{244}Cf ($T_{½}$=19.4±0.6 m) a decays (70±20%) with an energy of 7213±2 keV (75±3%) to ^{240}Cm. In addition to the three a decay peaks, a pulser set on two voltages, one exactly twice the voltage of the other, was used to obtain a more accurate calibration.

The energy alpha slopes and intercepts for each focal plane strip were calculated using information obtained from the a decay and pulser spectra and the following formulas,

$$energy\_alpha\_slope = \frac{\sum_{i=1}^{k} knownenergies_i}{\sum_{i=1}^{k} alphacentroids_i - k\left(2eapulser_{low} - eapulser_{high}\right)},$$

$$energy\_alpha\_intercept = energy\_alpha\_slope\left(eapulser_{high} - 2eapulser_{low}\right)$$

where k is the number of a peaks used, *knownenergies* are the energies of the a peaks used in keV, *alphacentroids* are the centroid values of a Gaussian fit in channels, and $eapulser_{low}$ and $eapulser_{high}$ are the two energy alpha pulser centroids. Once the energy alpha slope and intercept were obtained, the energy associated with the two pulser peaks was determined using the following equation:

$$eapulserenergies_{low,high} = eapulser_{low,high} \times energy\_alpha\_slope + energy\_alpha\_intercept\ .$$

A simple linear fit using the position alpha pulser peak centroids in channels as the x-values and the energy alpha pulser peak energies (*eapulserenergies*) from the above equation as y-values establishes the position alpha slope and intercept. The energy alpha pulser peak energies in keV were multiplied by a known ratio (14/120, derived from the pulser magnitude settings) to obtain the energy fission pulser peak energies in MeV (*efpulserenergies*):

$$efpulserenergies_{low,high} = eapulserenergies_{low,high} \times \frac{14}{120}\ .$$

Again, a simple linear fit of the energy fission pulser peak energies and the energy fission pulser peak centroids resulted in the energy fission slope and intercept. Finally, a simple linear fit of the energy fission pulser peak energies and the position fission pulser peak centroids resulted in the position fission slope and intercept.

The side detectors were calibrated in a similar manner to the focal plane detectors. In this particular experiment, only one known energy appeared in the spectrum, that of ^{238}Pu ($T_{½}$=87.7±0.3 yr) with a energies of 5499.03±0.20 keV (70.91±0.10%) and 5456.3±0.3 keV (28.98±0.10%). Therefore only one alpha peak and two energy side pulser peaks were used in the determination of the energy side alpha slope and intercept. Once they were determined, the energy side fission slope and intercept were determined in a similar manner as with the focal plane detectors. In general, the resolution of the side detectors was poorer than the focal-plane detector.

Finally, two correction factors were determined. The first correction factor deals with fission energies and the second deals with a correction to the a energy based on the position of the a's in the strip. The energy of the recoils that make it through the separator is well known, and therefore can be used as a measure of how accurate the fission energy is. For this experiment, the ^{48}Ca ions had an energy of 195.09 MeV in the focal plane detector. The fission energy correction can then be determined from the ratio of this known energy to the value established in the energy fission slope and intercept calibration. The second correction factor is determined by examining the energy of the ^{238}Pu a particles that pass through 5 slits in a mask that is placed over the focal plane detector. These ^{238}Pu a particles are detected with different energies based on their location on the focal plane detector. The five positions of the slits in the focal plane mask are known (17.227 mm, 8.614 mm, 0.000 mm, -8.614 mm, and –17.227 mm) as measured from the vertical center of the detector strip. These positions are then multiplied by the a decay energy for ^{238}Pu, which has been corrected for recoil energy loss (5406.7765 keV), and is used as the x-values in the determination of the slope correction factor. The y-values are the difference in energy between the ^{238}Pu a particle from five slits experiment and the true ^{238}Pu a-particle energy of 5406.7765 keV. The determination of the slope gives rise to the energy correction based on the position in the strip.

There were calibration runs performed several times during the course of the experiment and thus the calibration parameters changed slightly as the experiment progressed. The results of the first calibration using the $^{206}Pb(^{48}Ca,2n)^{252}No$ reaction are shown in Figs. 2 and 3.

III. DATA ANALYSIS

The most effective data analysis technique was to search for SF events that occurred above a certain energy, because the expected decay chains of a 116 isotope were predicted to terminate with a SF and the overall number of SFs was low (11 total fissions greater than 170 MeV in 164.7 days). Previous analysis deduced the $^{292}116$-decay chain ended in the spontaneous fissioning isotope $^{280}110$. The SF of $^{280}110$ would occur with fission-fragments of energies totaling more than 170 MeV. Once a SF event with energy greater than 170 MeV was observed, the data preceding this event would be searched for position correlated α decays and an evaporation recoil (EVR) implantation event. As the exact decay signature of these new isotopes was unknown, the exact time and energy requirements were determined from systematics and the Geiger-Nuttal relationship between an isotope's α-decay energy and lifetime [5] and generous gates were established.

After performing a couple of searches looking for various correlations, we observed that the position of an event would need to be corrected based on three effects noticed in each strip. First, the centroid of the difference in position between an EVR and an α event or SF event ($\delta P_{EVR-\alpha}$ or δP_{EVR-SF}) should be zero. This was not observed. Second, the difference in position between an EVR and an α event or SF event shouldn't vary as the position of the EVR varies ($\delta P_{EVR-\alpha}$ vs. P_{EVR}). A small variation was seen in the data. Finally, the energy implanted in the focal-plane detector has a significant influence on the accuracy of the position determination ($\delta P_{EVR-\alpha}$ vs. E_α). Specifically, position signals tended to get worse as the energy implanted into the focal-plane detector decreased.

To correct for these problems, we chose a reference point for the true position to be the EVR event and applied some correction factors. The α and SF positions would then be modified by the corrections based on the three effects discussed above. It was noted that the correction due to the centroid value for the difference in position between the EVR and α ($\delta P_{EVR-\alpha}$) was already present in the EVR-α position difference vs. EVR position correction. Therefore, only two corrections to the position information were needed. To obtain the correction factor for the position difference vs. EVR position correction ($\delta P_{EVR-\alpha}$ vs. P_{EVR}), a plot was made of the differences in position vs. position of the EVR. A quadratic fit to the correlation data was performed and the parameters from the quadratic fit were used to correct the position of the α events. To obtain the position difference vs. energy correction ($\delta P_{EVR-\alpha}$ vs. E_{α}), various focal-plane energy gates were set and an exponential fit to the resulting data was performed and the parameters were used to correct for the focal-plane energy. In most cases, the $\delta P_{EVR-\alpha}$ vs. P_{EVR} correction was much larger than the correction due to the $\delta P_{EVR-\alpha}$ vs. E_{α} effect.

This method for correcting the positions was different from the one used in the original Dubna analysis. In that analysis, the SF event position was considered the reference point, and the *a* and EVR positions were corrected based on that reference point. The final positions reported for each event from the two methods might be different by some constant value, but the overall interpretation that the events are correlated will remain the same.

The search began looking for SF's with a focal plane signal only, or with both a focal plane and side detector signal with energy greater than 170 MeV. Eleven such fissions, three of which had both a focal-plane and side detector signal were found. The events that occurred previous to the fission event were searched, in the same strip, within a position window (±1 mm) of the fission event, and with *a* energies greater than 8 MeV. The search was performed on events that occurred one hour before the fission event. The results of this search are discussed below for each of the 11 SF events. Each SF event description begins with a header containing the file name and the total energy (focal plane energy + side detector energy, if applicable) for the observed fission event.

SF Event 1, file: tsy1026, energy: 171.65 (119.91+51.74) MeV

Looking through the data that occurred before the fission event (δt = 2.64 days), we found only one *a* with energy greater than 8.6 MeV. This *a* event had an energy of 10.392 MeV, but the nearest correlated EVR occurred more than 869 seconds before the *a* event. An *a* event with this energy would have a half-life much shorter than this according to Geiger Nuttal systematics. For this particular file, based on the length of time for the file, the number of EVRs (7-18 MeV) in the same strip as the SF, and the number of possible position pixels (10), one would have expected approximately 2 EVRs in 869 seconds. Because only one was seen, it was assumed that this was not a good event.

SF Event 2, file: tsy1094,energy: 174.43 (161.92+12.51) MeV

This event is possibly a $^{293}116$-correlation chain fission event from the 3n-evaporation channel. A considerable amount of time was spent looking at this event and although it has some promise, without another correlation chain to compare to, it is left as only a possibility and nothing more definitive.

EVR: 7.196 MeV, 18.37 mm
α_1: $\varnothing$
α_2: 9.632 MeV (2.383+7.249), 17.73 mm, 161.0 s
α_3: 8.586 MeV (4.784+3.802), 16.74 mm, 611.7 s
α_4: 8.704 MeV, 18.38 mm, 544.735 sec
SF: 174.43 MeV (161.92+12.51), 18.13 mm, 1465 s

SF Event 3, file: tsy1100, energy: 194.80 MeV

This event is the first of the previously reported $^{292}116$ events. Aside from obvious minor differences in energy and position that arise from the different calibrations, this event is definitely a $^{292}116$ event, and matches the original analysis.

EVR: 10.799 MeV, 27.78 mm
α_1: 10.570 MeV, 27.86 mm, 46.9 ms
α_2: 9.820 MeV, 28.27 mm, 2.4172 s
α_3: 9.090 MeV (?+8.545), 53.8656 s
SF: 194.80 MeV, 28.06 mm, 6.928 s

No position is recorded for the third a, as all of the energy has been deposited into the side detector. No detectable signal was observed in the focal plane detector meaning the a decay left an energy signal below the thresholds in the focal plane detector of approximately 0.7 MeV. Because of this, the error on the third a-decay energy is approximately 0.5 MeV.

SF Event 4, file: tsy120, energy: 171.83 MeV

Looking through the data that occurred before the fission event (δt = 15.53 hrs), we found only one a with energy greater than 8.8 MeV. This a event had an energy of 13.568 MeV, but the closest correlated EVR occurred more than 76 seconds before the a event. An a event with this energy would have a half-life much shorter than this. This is not a good event and was rejected based on Geiger Nuttal systematics. The expected number of EVRs in 76 seconds within the specific position window was 0.61.

SF Event 5, file: tsy139, energy: 187.83 MeV

No correlated EVRs were found in the preceding 2.19 days from the fission event. The TOF gate was examined and was set up correctly; just a small number of EVRs were recorded. This is not a good event.

SF Event 6, file: tsy263, energy: 183.44 MeV

Looking through the data that occurred before the fission event (δt = 2.43 days), we found seven *a*'s with energy greater than 8.0 MeV. Two *a*'s had energies between 10 and 11 MeV (10.977 and 10.145), both being the sum of a focal plane and a side detector signal. Both of these *a*'s were correlated to EVRs with times of (509.6783 and 59.3444 seconds, respectively). These correlation times are much to long for an *a* decay of element 116 with those energies. This is not a good event.

SF Event 7, file: tsy393, energy: 171.72 MeV

Looking through the data that occurred before the fission event (δt = 4.278 days), we found numerous (>10) *a*'s with energy greater than 8.0 MeV. However, only five EVRs are present. None of the *a*'s with energies greater than 8.0 MeV were suitably correlated to those EVRs. This is not a good event.

SF Event 8, file: tsy548, energy: 221.74 MeV

This SF ends the second of the three previously observed ^{292}116 correlated chains. The correlated events are extremely clear and do not need any further explanation.

EVR: 13.261 MeV, 18.24 mm
α1: 10.478 MeV, 18.85 mm, 125.5 ms
α2: 9.799 MeV, 18.56 mm, 306.4 ms
α3: 9.139 MeV, 18.26 mm, 88.5430 s
SF: 221.74 MeV, 18.55 mm, 23.0363 s

SF Event 9, file: tsy567, energy: 177.36 MeV

This SF ends the third of the three previously observed ^{292}116 correlated chains. The correlated events are extremely clear and do not need any further explanation.

EVR: 9.732 MeV, 20.60 mm
α1: 10.538 MeV, 20.20 mm, 55.0 ms

α2: 9.806 MeV, 20.73 mm, 10.9733 s
α3: 9.110 MeV, 20.50 mm, 152.6197 s
SF: 177.36 MeV, 20.59 mm, 3.1511 s

SF Event 10, file: tsy588, energy: 206.27 MeV

No correlated EVRs were found in the preceding 1.046 days from the fission event. The TOF gate was examined and was set up correctly; just a small number of EVRs were recorded. This is not a good event.

SF Event 11, file: tsy667, energy: 170.15 (117.04+53.11) MeV

Looking through the data that occurred before the fission event (δt = 1.66 days), we found ten a's with energy greater than 8.0 MeV. None of the a's with energies greater than 8.0 MeV were suitably correlated to an EVR. This is not a good event.

IV. CONCLUSIONS

The current data analysis confirms what was discovered during the original data analysis in Dubna. Three extremely good 116 events were found in the data. All three events have an EVR (E_{EVR}>7 MeV) correlated in position (±2mm) to three a decays (E_a>7 MeV) followed by a SF event (E_{SF}>170 MeV). A summary of the details of each correlation can be found in Fig. 4.

The current data analysis also discovered a possible decay chain originating from the decay of ^{293}116. In agreement with the original data analysis performed in Dubna, there is not enough for this decay chain to be conclusively believed.

The original data analysis found a total of 16 SF events with energies greater than 170 MeV. 11 of those SF events were found in this analysis while five were not. After comparing the results, it was discovered that the fission energy for the five events not discovered by this analysis were all close to the 170 MeV limit imposed by the SF search. The differences in the calibrations between the two analyses can explain why the additional four SF events were not discovered in this analysis. The additional eight, non-element 116 SF events found in this analysis can be attributed to fissioning isotopes produced in transfer reactions with the ^{248}Cm target as well as fission from the target.

V. UPDATE

Since this paper was originally written, numerous additional experiments with ^{48}Ca beams have been performed [6-7]. Based on the findings of those experiments, the mass number assigned to the 116 isotope from the three event chains discussed in this paper has been changed [6] from 292 to 293. Therefore, the mass numbers for all the isotopes discussed in this paper that result from the decay of ^{292}116 or ^{293}116 should all be increased by one. This has been done only in Figure 4. The authors felt changing the original text would be too confusing when dealing with the original work [1].

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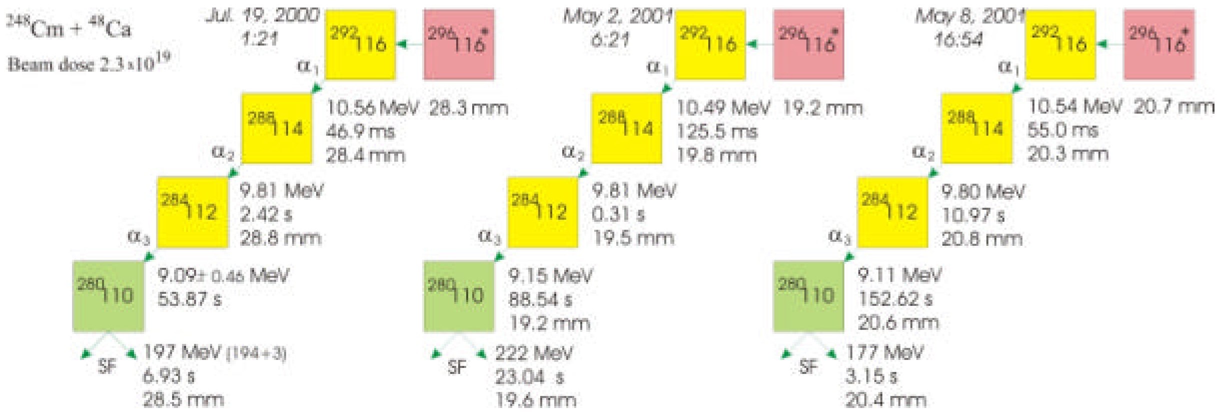

FIG. 1. Three decay chains from the ^{248}Cm(^{48}Ca,4n)^{292}116 reaction performed in Dubna [1].

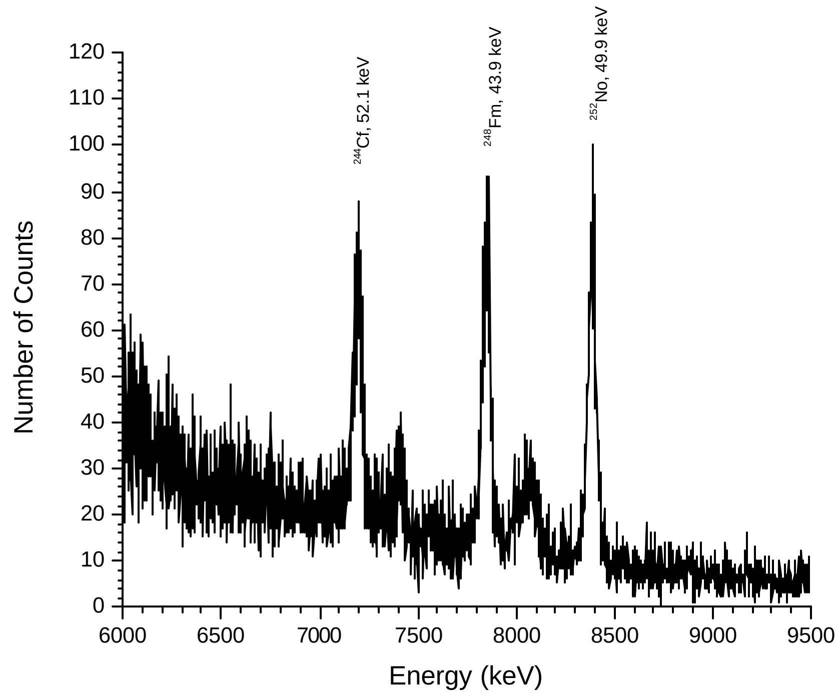

FIG. 2. The *a* particle spectrum from the ^{206}Pb(^{48}Ca,2*n*)^{252}No reaction. The peaks resulting from the decay of ^{252}No, ^{248}Fm, and ^{244}Cf are noted as well as the resolution (FWHM) of those peaks.

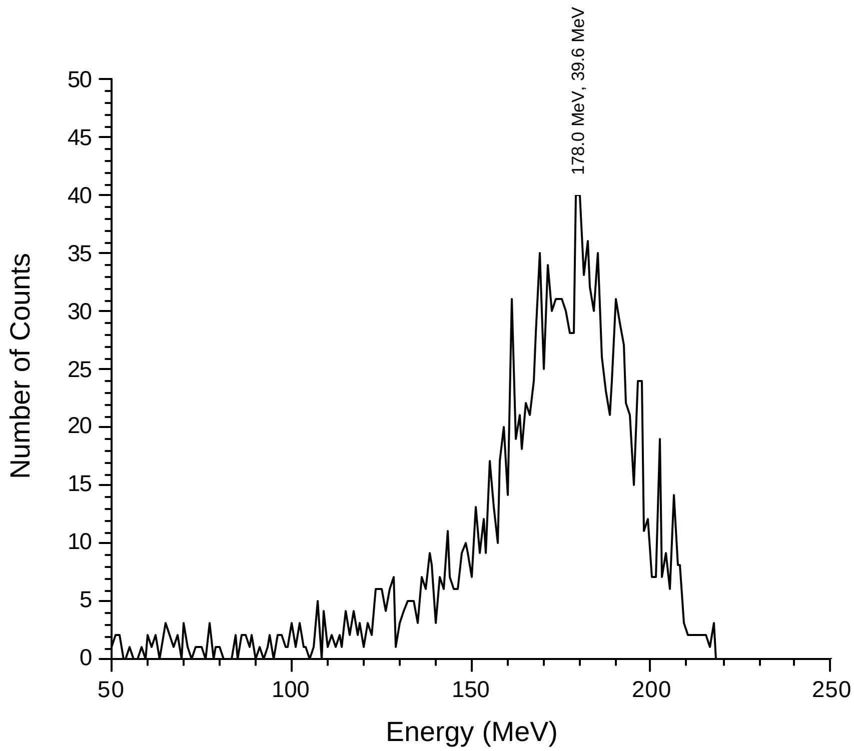

FIG. 3. SF decay spectrum from the ^{206}Pb(^{48}Ca,2n)^{252}No reaction. The fission-fragments are a result of the SF decay of ^{252}No. The centroid energy and resolution (FWHM) from a Gaussian fit to the peak are noted.

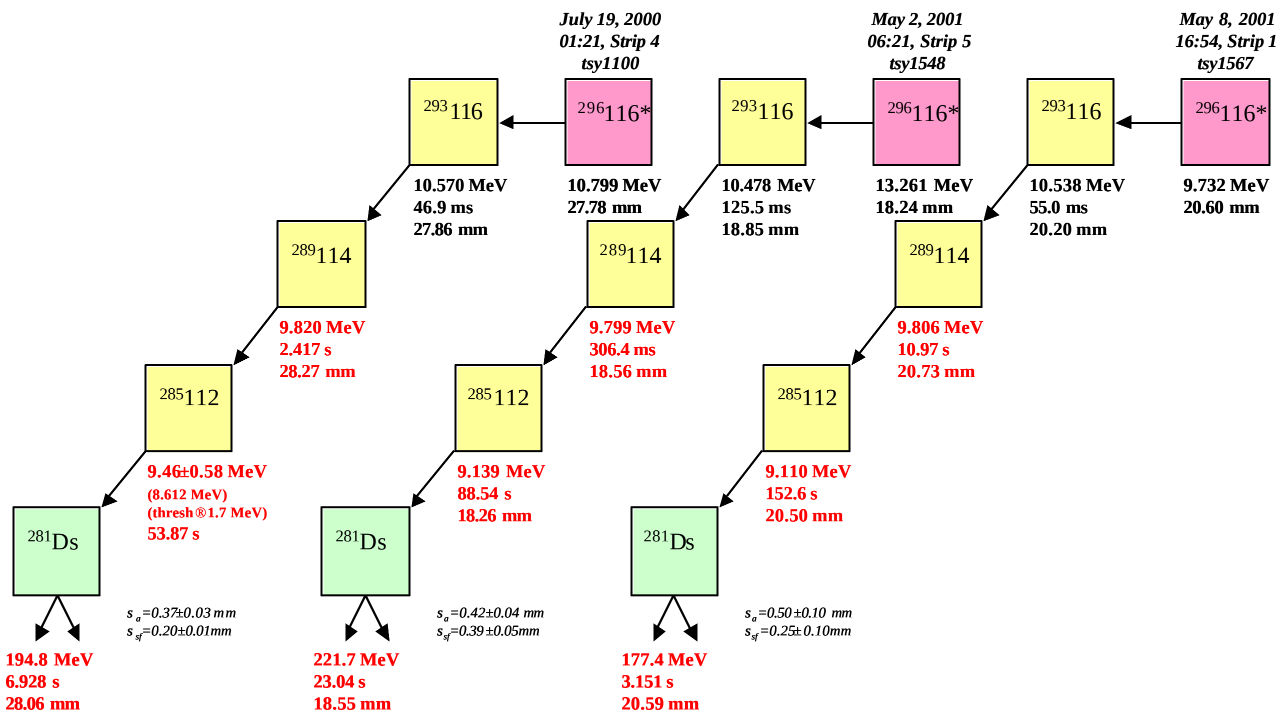

FIG. 4. Summary of the $^{293}116$ decay correlations found in the current data analysis (see Section V). Values in red correspond to data seen in beam-off conditions. Standard deviations (σ) for position differences are given for a and SF decay for each correlation chain.