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First Results from Griffin: The Half-lives Of $^{128-130}$Cd

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Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN) is a new high-efficiency γ-ray spectrometer for decay spectroscopy research with low-energy (20-60 keV) stopped radioactive beams from the Isotope Separator and Accelerator (ISAC) facility at TRIUMF in Vancouver, Canada. GRIFFIN is comprised of 16 HPGe clover detectors and hosts a suite of auxiliary detection systems for tagging β particles, neutrons, and internal conversion electrons in coincidence with γ rays. GRIFFIN is a powerful new tool for studying the nuclear structure of exotic short-lived isotopes far from stability, and for measuring weak γ-ray branches that are important in tests of fundamental symmetries and nuclear astrophysics. In this work, first results from the GRIFFIN physics program will be discussed, including a recent measurement of the half-lives of the neutron-rich $^{128-130}$Cd and ^{131}In isotopes.

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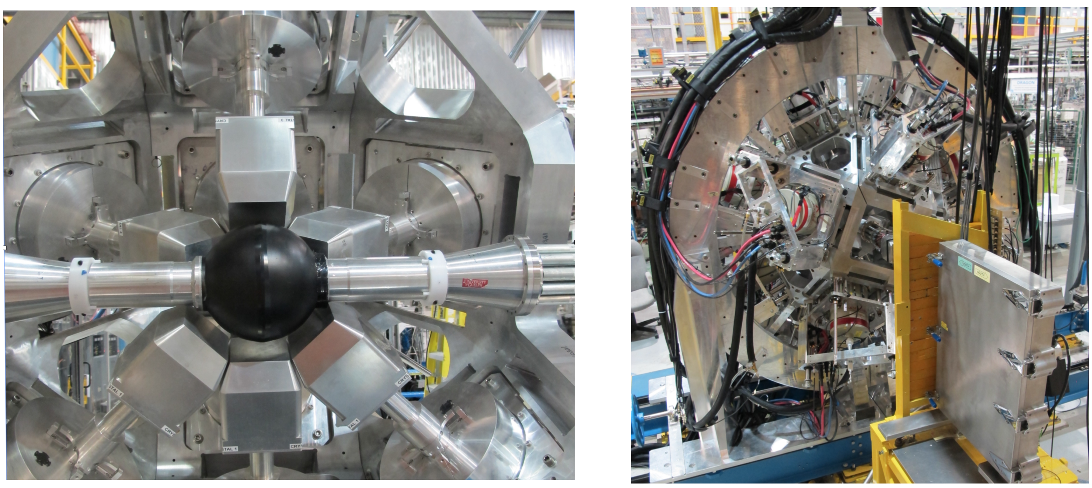
1. GRIFFIN

The Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN) is a state-of-the-art γ-ray spectrometer located at the Isotope Separator and ACcelerator (ISAC) at TRIUMF in Vancouver, Canada (Fig. 1). The GRIFFIN array consists of 16 close-packed high-efficiency HPGe clover detectors and is designed to do very sensitive nuclear β-decay studies [1, 2]. The GRIFFIN spectrometer is compatible with a suite of auxiliary detector systems such as: the 20 plastic scintillator β detectors of the SCintillating Electron Positron Tagging Array (SCEPTAR) [3], the 5 Si(Li) conversion electron and α detectors of the Pentagonal Array of Conversion Electron Spectrometers (PACES), 8 LaBr detectors and the zero degree scintillator (ZDS) β detector for fast timing experiments, and the new 70-element DEuterated SCintillator Array for Neutron Tagging (DESCANT) [4] neutron detector array that provides β-delayed $n-\gamma$ coincidence detection capability. An example of the impressive sensitivity that can be achieved when adding these auxiliary detection systems to GRIFFIN is shown in Fig 2 where the selectivity of a SCEPTAR β-tag combined with the large photo-peak efficiency of GRIFFIN allowed the measurement of the β decay of the very-neutron-rich ^{132}Cd ($T_{1/2}$ = 97 ms). The radioactive ion beam (RIB) of ^{132}Cd was delivered at a rate of approximately 0.1 pps. This is to be compared with the lowest rate measurement performed with the 8π at ISAC of the β decay of ^{32}Na with a beam rate of approximately 4 pps [5]. There is very little known about the decay of the ^{132}Cd isotope, and a γ ray has yet to be observed in ^{132}In following the β decay of ^{132}Cd. Even at these very low rates, GRIFFIN is able to obtain a dataset that should provide insights into the structure of this neutron rich In isotope. The analysis of these data are still in progress.

The large photo-peak efficiency of the GRIFFIN spectrometer allows for the study of two different aspects of β decay. These include high-precision measurements of nuclear structure and



(a) One hemisphere of GRIFFIN (b) The GRIFFIN array when closed

Figure 1: The GRIFFIN Array. (a) shows one hemisphere of the GRIFFIN array with the HPGe detectors centered around the implantation site within a delrin vacuum chamber. (b) shows GRIFFIN from the outside when the array is closed around the implantation chamber. At the end of a cycle the tape is moved into the almuminium collection box behind the yellow lead-shielded wall.

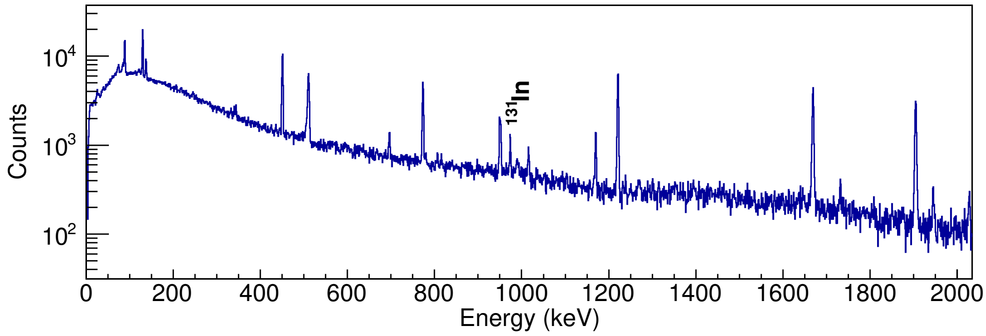


Figure 2: The beta-coincident γ-ray spectrum detected by GRIFFIN during ^{132}Cd β-decay experiment. The ^{132}Cd RIB was delivered at a rate of approximately 0.1 pps. Even at these very low rates, the GRIFFIN spectrometer was able to detect the characteristic γ-rays following the β-decay of ^{132}Cd. The previously observed 988 keV γ-ray in ^{131}In following the $\beta - n$ decay of ^{132}Cd [6] is marked with ^{131}In.

fundamental symmetries, as well as the study of the exotic isotopes very far from stability with very low production yields. To this end, the GRIFFIN spectrometer uses a customized digital data acquisition (DAQ) system that is designed to accommodate large data-throughput of up to 50 kHz/crystal and event traceability [1].

1.1 Tape System

In a typical GRIFFIN experiment, a RIB containing the isotope of interest is implanted into a mylar tape of a moving tape collector at the center of GRIFFIN array. Using the tape system at GRIFFIN has several advantages. The longer-lived background activity, either from isobaric contaminants in the beam or from daughters following the decay of the isotope of interest, can be removed by moving the tape behind a lead-shielded wall following a measurement (Fig 1). A typical cycle consists of a background measurement, followed by two collection periods, the first one (beam-on), with the beam being implanted into the tape, and the second (beam-off), with the beam blocked by the ISAC electrostatic beam kicker downstream of the mass separator. Once the measurement is complete, the tape is moved into a lead-shielded position outside of the array and a new cycle begins. The allocated time for each portion of a cycle is generally chosen to optimize the signal-to-background for the particular measurement.

1.2 Summing Corrections

The clover design of the GRIFFIN detectors allows the option to use add-back algorithms, where the detector energy in multiple crystals are summed together in order to increase the photo-peak efficiency of GRIFFIN, as well as reduce the contribution of Compton background to the γ-ray spectrum [1, 2]. However, one must be careful when dealing with high-efficiency, large-volume, HPGe detectors as γ-ray coincidence summing can become significant. An increased photo-peak efficiency, primarily from an increase in geometric coverage, leads to an increased probability that two γ-rays will deposit their full energy in a single detector and results in the false

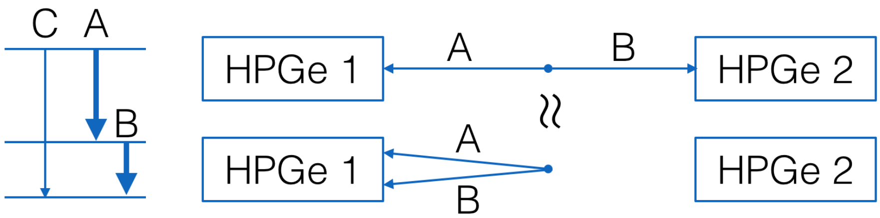


Figure 3: A schematic showing the equivalence of γ-ray coincidence detection in 180° detectors and the summing of γ rays in the same detector. See text for details.

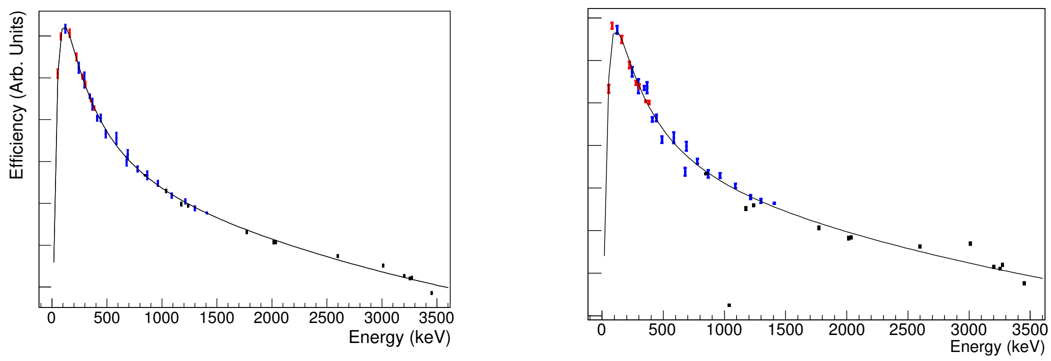
detection of a γ-ray with an effective energy of the sum of the two simultaneous γ rays as well as the nondetection of the two individual simultaneous γ rays. An increased volume, or cross-section, results in the increase of the probability that the full energy deposition of a single γ ray and the Compton scatter of another γ ray take place simultaneously resulting in the nondetection of the two individual simultaneous γ rays. This is especially true in decays with a large γ-ray multiplicity where the probability of multiple γ-rays interacting in the same detector are further increased.

We have developed methods to overcome summing effects by taking advantage of the parity symmetry of emitted γ-rays following the de-excitation of a nucleus by constructing coincidences between detectors located at 180° (Fig 3). The nondetection, due to summing, of the γ-ray of interest can be estimated by counting the total number of detected events in 180° coincidence with that γ ray. The same number of γ rays should have been detected in the 0° detector due to symmetry. The complete photo-peak summing of γ ray C can be estimated by gating on photo peak A and measuring the number of counts in photo peak B at 180°, where the sum of the energy of photo peak A and B equals the energy of photo peak C. The area measured in photo peak B in this case would be equal to the number of times the two γ rays corresponding to photo peak A and B had full energy deposition in the 0° detector. This method has the advantage that it can also estimate the summing contributions from the characteristic X rays that are emitted following β decay which in general are difficult to correctly reproduce in simulation.

As an example of the impact of these summing corrections, the relative efficiency curve for the GRIFFIN spectrometer in add back is shown in Fig. 4. Without applying the corrections due to summing there is a general scattering of the calibration points about the fitted curve. A clear improvement in the fit is seen when the summing correction is applied. On average, there is approximately a 5% correction to the calibration points due to a fully deposited photo-peak summing with a Compton scattered γ ray, although this correction can be as high as 15% for γ rays that have large γ-ray cascade multiplicities.

2. $^{128-130}$Cd Decay

The β-decay half-lives of nuclei below doubly-magic $^{132}_{50}Sn_{82}$ (i.e. $N \approx 82$, $Z < 50$) are key input parameters for any astrophysical rapid neutron capture process (r-process) scenario as they play an important role in the formation and shape of the second abundance peak at $A \sim 130$ [7]. In r-process scenarios like neutron star mergers [8, 9], the reaction path is driven towards the neutron drip-line, into regions that will only be partially accessible to experiments at the new generation of



(a) Summing correction applied

(b) No summing corrections

Figure 4: The relative add-back efficiency curves (a) after the summing corrections were applied and (b) before the summing corrections were applied. The color of the points represent the source used: ^{133}Ba (Red), ^{152}Eu (Blue), ^{56}Co (Black). See text for more details.

radioactive beam facilities and one has to rely heavily on the predictive power of theoretical models for the β-decay of these nuclei. Discrepancies in the available models can have a significant impact on the uncertainty in the calculated abundances and it is therefore imperative that we constrain these theoretical models.

For example, shell-model calculations for the waiting-point nuclei near the $N = 82$ neutron shell closure [10, 11] have been performed by adjusting the quenching of the Gamow-Teller (GT) operator to reproduce the ^{130}Cd half-life reported in Ref. [12]. However, recent measurements of the half-life of ^{130}Cd [13, 14] showed that the half-life measured in Ref. [12] was too large by roughly a factor of 1.3. Consequently, the calculated half-lives of the waiting-point nuclei near the $N = 82$ neutron shell closure were also systematically larger when compared to experiment by roughly a factor of 1.3 [11]. These new, shorter, half-lives for ^{130}Cd resolve this discrepancy by scaling the GT quenching by a constant factor for all of the nuclei in this region.

Many of the nuclei in this neutron-rich region have complicated decay chains, including significant β-delayed neutron-emission branches and β-decaying isomeric states. To reduce the complexity of this background, we take advantage of the large γ-ray detection efficiency of the GRIFFIN spectrometer by measuring the temporal distribution of characteristic γ-rays emitted following the β-decay of the parent isotope.

The following results were obtained using GRIFFIN clover add-back. The isotopes of interest were produced by impinging a 500 MeV proton beam from the TRIUMF main cyclotron incident on a UC_x target. The ion-guide laser ion source (IG-LIS) [15], was used to suppress surface-ionized isobars such as In, while the neutral Cd atoms of interest were extracted and selectively laser ionized in a three-step-excitation scheme, before being delivered to GRIFFIN.

^{128}*Cd Decay* – The 857-keV ($I_{\gamma,rel} = 95(10)\%$) and the 925-keV transition ($I_{\gamma,rel} = 12.4(12)\%$) in the daughter nucleus ^{128}In [16] were used to determine the half-life. The data were grouped into 10-ms bins and fitted with an exponential plus constant background, as shown for the 857-keV γ-ray in Fig. 5. The re-binning of the data was investigated as a source of systematic uncertainty and showed no significant change in the measured half-life. In order to investigate the presence

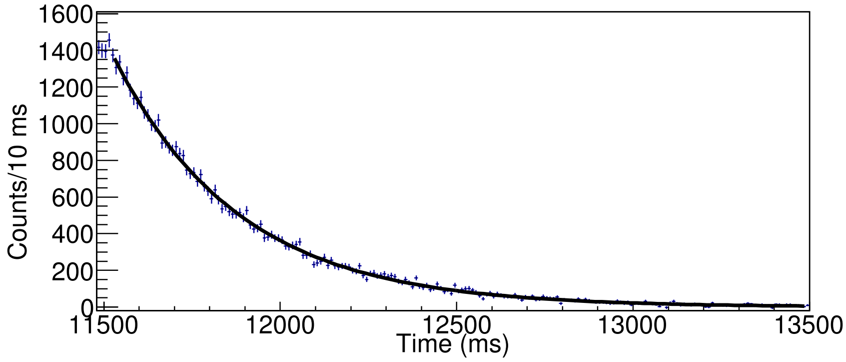


Figure 5: The fit to the activity spectrum of the 857 and 925 keV γ-rays in ^{128}In following the β-decay of ^{128}Cd resulting in a half-life of 246.2(21) ms.

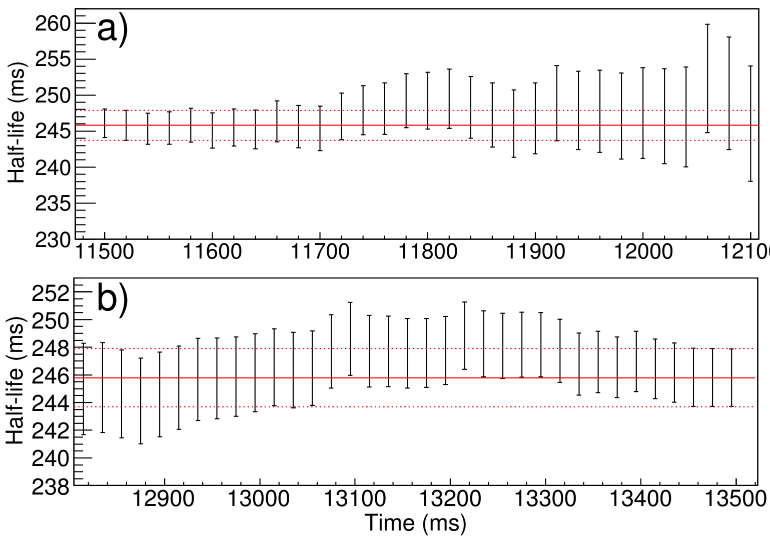


Figure 6: Results from the "chop analysis" on the half-life of ^{128}Cd. a) The measured half-life as a function of the first bin included in the fit. b) The measured half-life as a function of the last bin included in the fit. The horizontal band corresponds to the half-life determined in this experiment with the associated uncertainty.

of any potential rate-dependent effects such as dead-time and pile-up, a "chop analysis" [17, 18] was performed by changing the fit region that was used. In principle, the presence of these rate-dependent effects can be observed by using different start times for the fit region. The chop-analysis for ^{128}Cd is shown in Fig. 6 where it is observed that any potential rate-dependent effect is statistically insignificant. The half-life measured using the sum of the 857 and 925 keV γ rays was 246.2(21) ms, which is an improvement in precision of 2.4 [13].

^{129}Cd Decay – The decay of the ^{129}Cd isotope is complicated somewhat by the presence of two known β-decay isomers. These isomers are known to have spins of $3/2^{+}$ and $11/2^{-}$, although the absolute energies of these states are still unknown. The large photo-peak efficiency of GRIFFIN made it possible to extract the half-life of the $11/2^{-}$ state from just the 359, 1796 and 2156 keV

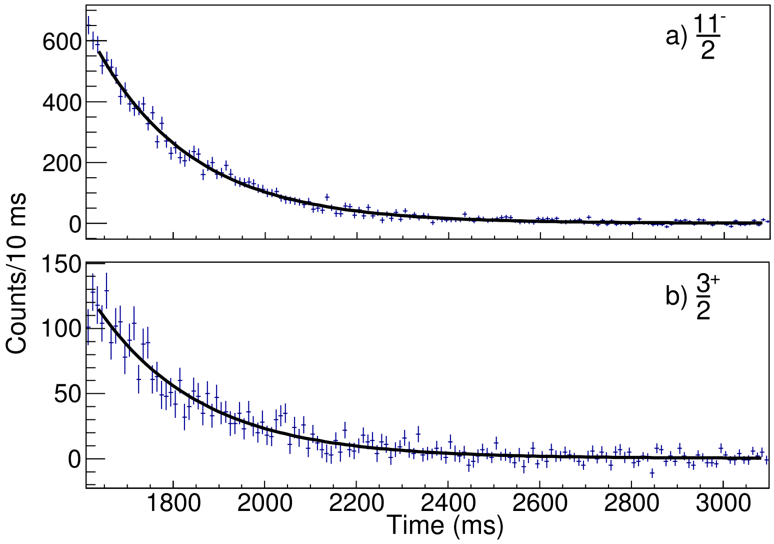


Figure 7: The fit to the activity spectrum of the characteristic γ-rays in ^{129}In following the β-decay of ^{129}Cd. (a) shows the fit to the activity of the $11/2^-$ state of 147(3) ms while (b) shows the fit to the activity of the $3/2^+$ state of 157(8).

transitions, yielding $T_{1/2}(11/2^-) = 147(3)$ ms. The importance of using only these γ rays is that they appear to be fed directly from the decay of the $11/2^-$ isomer, with zero contribution from the $3/2^+$ isomer. For the half-life of the $3/2^+$ state, the two transitions at 1423 and 1586 keV were used resulting in $T_{1/2}(3/2^+) = 157(8)$ ms (Fig. 7 b). The measured half-lives of the β-decaying ^{129}Cd states in this work disagree with the measurements of Ref. [19, 20, 21] which claim that the half-lives differ by roughly a factor of 2.

^{130}*Cd Decay* – The 451.0- ($I_{\gamma,rel} = 88.6(36)\%$), 1170.3- ($I_{\gamma,rel} = 20.0(2)\%$), and 1669.2-keV ($I_{\gamma,rel} = 100\%$) γ-rays following the decay of ^{130}Cd [22] were used to measure the half-life yielding 123(5) ms, 138(20) ms and 126(6) ms, respectively. A partial γ-ray spectrum is shown in Fig. 8. The sum of these three γ rays yield a half-life of 126(4) ms for the decay of ^{130}Cd (Fig. 9), in excellent agreement with the value of 127(2) ms reported in Ref. [14], and in strong disagreement with the half-life measurement of 162(7) ms [12].

The confirmation of the shorter half-life for the $N = 82$ isotope ^{130}Cd has significant implications for nuclear structure calculations in this region, as well as for r-process nucleosynthesis simulations. As discussed in Refs. [13, 14], the scaling of the Gamow-Teller quenching to the half-life of ^{130}Cd reported in Ref. [12] leads to a systematic overestimation of the half-lives for the other $N = 82$ isotones below ^{132}Sn. The newly adopted, shorter half-life value for ^{130}Cd would increase the GT quenching factor from 0.66 to 0.75. This decreases the calculated half-lives for the unmeasured $N = 82$ isotones below ^{132}Sn and has been shown to have a major influence on the shape of the rising wing of the $A \sim 130$ r-process abundance peak [14]. However, as pointed out in Ref. [14], although this rescaling of the GT quenching has resolved the systematic difference in the calculated half-lives, the calculated half-life for ^{131}In is now too short by roughly 40%. This discrepancy between the measured and theoretical half-life for this waiting-point nucleus could have a significant impact on the r-process flow and has prompted a new measurement of this half-life

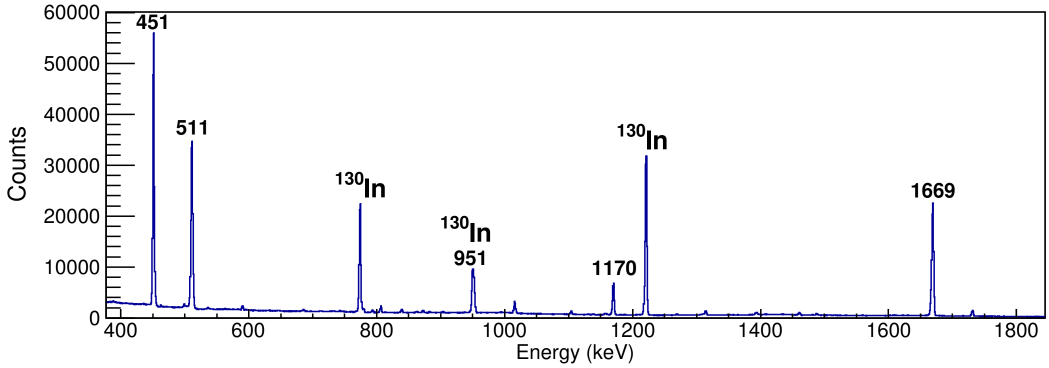


Figure 8: A portion of the β-gated γ-ray energy spectrum for the ^{130}Cd decay. The strongest γ-rays in the spectrum are labeled including the γ-rays at 451, 1170, and 1669 keV that were used for the half-life analysis.

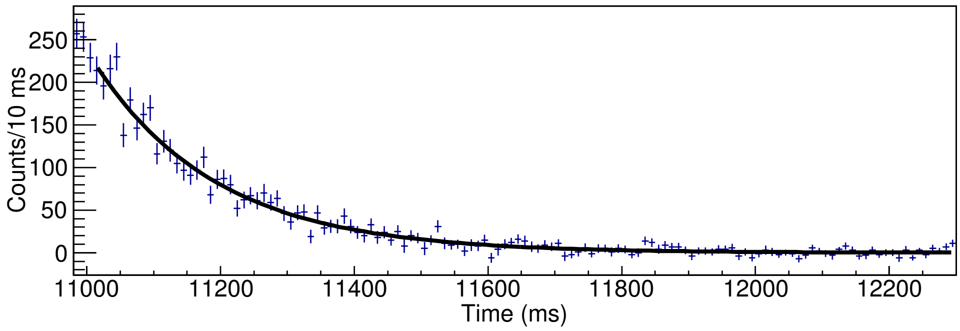


Figure 9: The fit the to activity spectrum of the characteristic γ-rays in ^{130}In following the β-decay of ^{130}Cd. The measured half-life is 126(4) ms in excellent agreement with the value of 127(2) ms reported in Ref. [14].

using the GRIFFIN γ-ray spectrometer. A study of the β decay of ^{131}In is currently in progress where we are taking advantage of the large photo-peak coincidence efficiency of GRIFFIN. This will allow the expansion of the level scheme in an attempt to understand the discrepancy between the measured and calculated β-decay half-life values.

3. Conclusion

The GRIFFIN γ-ray spectrometer at TRIUMF-ISAC has been used to study the β-decay of nuclei in the region just below ^{132}Sn. The decay properties of these nuclei are important in understanding the size and shape of the r-process abundance peaks around $A \sim 130$. Using GRIFFIN, we have been able to measure the γ rays which are emitted following the β decays of $^{128-132}$Cd and ^{131}In. The high efficiency of GRIFFIN has allowed for the detection of γ-rays emitted following the decay of the ^{132}Cd implanted at a rate of 0.1 pps. The ability to make measurements of very weak beams creates the potential to push γ-ray spectroscopy into unexplored regions of neutron richness which is very important for the study of the r-process. The ^{128}Cd half-life of 246.2(21) ms [13] is in excellent agreement with the previous measurement of Ref. [14], but a factor of 2.4 more precise. The measured half-lives of the two known β-decaying states in ^{129}Cd, 157(8) ms for the $3/2^+$ state and 147(3) ms for the $11/2^-$ state are found to be in agreement with the work of Ref. [23], but in disagreement with the results of Refs. [19, 20, 21]. The half-life of ^{130}Cd was measured to be 126(4) ms, in excellent agreement with the half-life of 127(2) ms reported in Ref. [14] but in strong disagreement with the measurements of 162(7) ms and 195(35) ms from Refs. [24, 12]. This resolves the discrepancy in the calculated half-lives of many of the other $N = 82$ waiting point nuclei by providing a new scaling for the GT quenching, but creates a new discrepancy for the calculated half-life of ^{131}In. The discrepancy is currently being investigated with data that was recently taken with the GRIFFIN γ-ray spectrometer.

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