Prompt Fission Neutron Uranium Logging(II): Dead-time effect of neutron time spectrum

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Abstract

The acquisition of neutron time spectrum data plays a pivotal role in the precise quantification of uranium in Prompt Fission Neutron Uranium Logging (PFNUL). However, the impact of detector dead-time effect remains paramount for the accurate acquisition of the neutron time spectrum. Therefore, there exists an imperative requirement for neutron logging instruments to establish a dead-time correction method that is not only uncomplicated but also practical, catering to various logging sites. This study has formulated an innovative equation for determining dead time and introduced a dead-time correction method for the neutron time spectrum, denoted as the "Dual Flux Method." In this approach, a logging instrument captures two neutron time spectrums under disparate neutron fluxes. By carefully selecting specific "windows" on the neutron time spectrum, the dead time can be accurately ascertained. To substantiate its efficacy and discern influencing factors, experiments were conducted utilizing a deuterium-tritium (D-T) neutron source, a Helium-3 (3He) detector, and polyethylene shielding to collate and analyze neutron time spectrum under varying neutron fluxes (at high voltages). The findings underscore that the "height" and "spacing" of the two windows are the most pivotal influencing factors; notably, the "height" (fd) should surpass 2, and the "spacing" twd should exceed 200 s. The dead time of the3He detector determined in the experiment is 7.35 s. After dead-time correction, the deviation of decay coefficients from theoretical values for neutron time spectrum under varying neutron fluxes diminished from 12.4% to within 5%. Similarly, for the PFNUL instrument, the deviation of decay coefficients decreased from 22.94% to 0.49% after correction for dead-time effect. These outcomes demonstrate the exceptional efficacy of the proposed method, ensuring the precision of uranium quantification. The dual flux method is experimentally validated as a universal approach applicable to pulsed neutron logging instruments, holding immense significance for uranium exploration.

Full Text

Preamble

Prompt Fission Neutron Uranium Logging (II): Dead-time effect of neutron time spectrum

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The acquisition of neutron time spectrum data plays a pivotal role in the precise quantification of uranium in Prompt Fission Neutron Uranium Logging (PFNUL). However, the impact of detector dead-time effect remains paramount for the accurate acquisition of the neutron time spectrum. Therefore, there exists an imperative requirement for neutron logging instruments to establish a dead-time correction method that is not only uncomplicated but also practical, catering to various logging sites. This study has formulated an innovative equation for determining dead time and introduced a dead-time correction method for the neutron time spectrum, denoted as the "Dual Flux Method." In this approach, a logging instrument captures two neutron time spectrums under disparate neutron fluxes. By carefully selecting specific "windows" on the neutron time spectrum, the dead time can be accurately ascertained. To substantiate its efficacy and discern influencing factors, experiments were conducted utilizing a deuterium-tritium (D-T) neutron source, a Helium-3 (^{3}He) detector, and polyethylene shielding to collate and analyze neutron time spectrum under varying neutron fluxes (at high voltages). The findings underscore that the "height" and "spacing" of the two windows are the most pivotal influencing factors; notably, the "height" (fd) should surpass 2, and the "spacing" twd should exceed 200 µs. The dead time of the ^{3}He detector determined in the experiment is 7.35 µs. After dead-time correction, the deviation of decay coefficients from theoretical values for neutron time spectrum under varying neutron fluxes diminished from 12.4% to within 5%. Similarly, for the PFNUL instrument, the deviation of decay coefficients decreased from 22.94% to 0.49% after correction for dead-time effect. These outcomes demonstrate the exceptional efficacy of the proposed method, ensuring the precision of uranium quantification. The dual flux method is experimentally validated as a universal approach applicable to pulsed neutron logging instruments, holding immense significance for uranium exploration.

Keywords: PFNUL, Neutron time spectrum, Dead time, Pulsed sources, Correction methods

Introduction

Uranium is a critical strategic resource in China, with significant demand in areas such as nuclear power generation. Therefore, uranium exploration holds crucial significance in ensuring a stable supply of uranium resources. Nuclear well logging, as an efficient exploration method in the field of energy and mineral exploration—including uranium and petroleum—occupies a paramount position in the well logging industry [?, ?]. Nuclear well logging primarily comprises gamma-ray logging, neutron logging, and nuclear magnetic resonance logging \cite{3–6}. In uranium exploration, China has traditionally employed natural gamma-ray logging (either total count or spectrum) for uranium quantification [?, ?]. However, this approach suffers from drawbacks such as low drilling efficiency, high exploration costs, and long uranium quantification cycles [?]. Prompt Fission Neutron Uranium Logging (PFNUL) technology can effectively utilize the fission reaction of uranium to survey underground uranium elements, offering advantages of direct measurement and accurate resolution [?]. The PFNUL utilizes a pulsed neutron source, such as a D-T neutron source, to emit pulsed neutrons that bombard the formation. If the formation contains uranium elements, the neutrons will react with the uranium elements, producing fission neutrons that impact the neutron time spectrum results [?]. By collecting pulse neutron time spectrum information, relevant information can be extracted to quantitatively analyze the uranium elements in the formation \cite{13–15}. Nevertheless, the pulsed neutron source can emit a high yield of neutrons in microseconds or tens of microseconds, causing the neutron detector to saturate briefly. This leads to a significant dead time effect, severely impacting the accuracy of quantitative analysis \cite{16–19}. Therefore, under conditions of high neutron yield, the collection of pulse neutron time spectrum and dead time correction are urgent challenges that need to be addressed in neutron uranium well logging.

In PFNUL, ^{3}He gas detectors are preferred for neutron time spectrum acquisition due to their high detection efficiency and compact size. However, like GM tubes, they face challenges related to their gas response speed, particularly at elevated neutron fluxes, where they are unable to differentiate between two or more neutron events occurring in short time intervals [?, ?]. This leads to a significant dead time, generating an abundance of dead time, and consequently impacting the accurate detection of neutron time spectrum. This phenomenon is referred to as dead time effect \cite{22–24}. The primary sources of the dead time effect include the intrinsic characteristics of the detector and the pulse analysis circuit characteristics. These factors may introduce systematic biases into experimental results, particularly in situations involving short pulses and high neutron flux, where dead time can distort the neutron time spectrum, affecting the accuracy of experimental results. Therefore, it is crucial to conduct a thorough study of the dead time effect on the ^{3}He detector system in neutron uranium well logging [?].

In the 1970s, scholars devoted considerable research efforts to the dead time problem, introducing two widely employed dead time models: extended and non-extended [?, ?]. T.A. Simone et al. applied the two-source method in conjunction with the principle of conformal measurement to compute the systematic dead time of the ^{3}He detector [?]. Furthermore, David J et al. harnessed the versatility of the Pulse Arrival Time Recording Module (PATRM) to observe the dead time of the ^{3}He detector while recording slow fission neutrons emitted from small fissionable materials irradiated by an intense neutron source [?]. T. Akyurek generated a neutron beam through the Missouri University of Science and Technology research reactor, measuring the count rate under various conditions by introducing different thicknesses of shielding to the ^{3}He detector. The count rates under different scenarios were measured with varying shielding thicknesses, and the dead times for both ^{3}He extended and non-extended models were calculated. This was achieved by combining MCNP simulations with the decay law [?]. The dead time of the NaI detector was also determined using the decay law \cite{31–33}. Hashimoto employed the variance-to-mean method to calculate the dead time of neutron detectors, including ^{3}He and BF_3. The calculated dead times for two neutron detectors, LND-251 and LND-2524, were determined to be 7.5 ± 0.54 µs and 8.31 ± 0.5 µs, respectively [?, ?].

In conclusion, the principal approaches to the study of dead-time effects in neutron detectors can be summarized as the two sources method, the decay source method, the reactor power method and the variance-mean method. These methods effectively correct and validate the dead time generated by the ^{3}He detector in various scenarios. Among them, the two sources method is straightforward to implement and suitable for basic dead time measurements that can be completed in a relatively short period using two sources of known activity. However, it relies on the difference in source activity and may be more accurate for substantial differences in activity, but less accurate for similar activity. This method is not suitable for intricate systems, and for more precise measurements, source placement and experimental conditions may require adjustments, increasing experimental complexity. The decaying radioactive source method applies to systems involving radioactive decay, not to systems without decay, and may be susceptible to statistical errors over short measurement times [?]. The reactor power method is pertinent to scenarios with high-intensity radiation, such as nuclear reactors, and necessitates measurements in a radioactive environment, presenting heightened safety and technical challenges [?], with only a few laboratories having timely access to neutron irradiation facilities. The variance-mean method applies to all types of systems, including scenarios involving statistical measurements, but demands more sophisticated data processing and may necessitate longer data acquisition times to attain accurate results.

However, the aforementioned studies have been unable to effectively measure and correct the dead time characteristics of PFNUL instruments. Therefore, the development of a new method for calculating and correcting dead time, specifically tailored to pulsed neutron uranium well logging instruments, is urgently needed. PFNUL instruments commonly utilize D-T pulsed neutron generators, where neutron yield can be controlled by high pressure to adapt to different detectors and experimental requirements [?]. Exploiting the adjustable neutron flux capability of PFNUL instruments, this study, based on the theory of dead time effects, derives a dead time extraction method using the dual flux method (DFM) for pulsed neutron time spectrum [?]. Through a series of experiments, the effectiveness and accuracy of this method are validated. Additionally, based on the neutron decay law, a correction formula for dead time effects is derived. Finally, the acquired neutron time spectrum is corrected for dead time effects. The comparison of decay coefficients before and after correction reveals a significant reduction in deviation compared to MCNP simulation decay coefficients [?, ?]. This reduction more accurately reflects the true information of the neutron time spectrum, laying a foundation for precise uranium quantification in PFNUL. The proposed method holds paramount significance in this context.

II. Dual Flux Method and Theory

A. Dead time calculation formula derivation

The principal contributor to the dead time of the ^{3}He neutron detector emanates from the detector itself. In the process of detecting neutrons, because neutrons are not charged and cannot directly cause the "ionization" and "excitation" of the material, the neutron signal pulse is generated when the neutron reacts with the ^{3}He to produce protons and tritium nuclei emitted in the opposite direction, causing the ^{3}He gas to ionize and form a large number of ion pairs (electrons and positive ions). The ^{3}He tube with high voltage of the anode filament and the ^{3}He tube shell forms an electric field; under the action of the electric field, the electrons and positive ions will drift to the anode filament and the wall of the cathode tube, and ultimately through the series of anode filament reactions will produce an effective neutron signal. Hence, a pulsed signal from a neutron must undergo a series of processes before it can be recorded.

Fig. 1 [Figure 1: see original paper] illustrates the reason for dead time generation. If the ^{3}He detector system receives another neutron pulse signal in the process of processing a signal, it will produce pulse superposition, or the pulse signal cannot be processed in time and missed counting, which is the main reason for non-extended dead time generation. Related scholars have proved that the vast majority of the contribution of the dead time of the ^{3}He detector comes from the non-extended dead time, so the model used in this experiment refers to the non-extended dead time. The ^{3}He detector can be synchronized with the pulse signal of the pulsed neutron generator through the digital multichannel collector, and record the time distribution curve of the number of neutrons in the time after the neutron pulse is discharged, which will finally form the neutron time spectrum that we need. The counts at each moment corresponding to time t_0 are converted to count rates before processing the neutron time spectrum, and the conversion equation is represented by Eqs. (1).

$$n_i = \frac{N_i}{t \times f \times t_0}$$

where n is the count rate normalized to the i channel, N is the count corresponding to the i channel in the neutron time spectrum, t is the acquisition time of the detector, f is the frequency of the pulsed neutron source, and t_0 is the time corresponding to the i channel. After processing in Eqs.(1), a revised neutron time spectrum is obtained.

In the neutron field of a pulsed source, the average number of true neutrons incident in the ^{3}He detector per unit of time is m, the number of neutrons recorded per unit of time is denoted by n, and the dead time of the detector is τ. The dead time of the ^{3}He detector is denoted as nτ, and the total number of counts lost due to the dead time is mnτ, which represents the number of counts lost. Then, the τ term can be obtained from Eqs.(2) and written as:

$$n = \frac{m}{1 + m\tau}$$

Fig. 2 [Figure 2: see original paper] shows parameters related to setting the time window on the neutron time spectrum. The position of W1 is at the moment t_1 of the neutron time spectrum, then t_1 is equal to t_2, and the corresponding neutron count rates of the high-flux and low-flux neutron time spectrum are n $_1$ and n $_2$, respectively, then fd_1 = n $_1$/n $_2$, and the corresponding real count rates are mt_1, mt_2. W2 position in the neutron time spectrum of the t_3 moment, then t_3 is equal to t_4, corresponding to the high flux and low flux neutron time spectrum of the neutron count rate of n $_3$ and n $_4$, respectively, then fd_2 = n $_3$/n $_4$, and the corresponding true count rate is mt_3, mt_4.

Evidently, in a neutron time spectrum devoid of dead time effects, the ratio of neutron count rates for any two windows captured should be equal. The ratio of the true count rate can be expressed as:

$$\frac{mt_1}{mt_2} = \frac{mt_3}{mt_4}$$

Combining Eqs.(3) and Eqs.(2), the τ term can be written as:

$$\tau = \frac{n_{t1}n_{t2} - n_{t3}n_{t4}}{n_{t1}n_{t4}(n_{t2} + n_{t3}) - n_{t3}n_{t2}(n_{t1} + n_{t4})}$$

As shown in Fig. 2, two neutron time spectrums detected by the ^{3}He ratio counting tube are selected and two windows of the same size are set up, with the window width defined as tww, which can be set to 2 µs, 8 µs, 16 µs, 24 µs, or 32 µs. The initial time of Window 1 (W1) should start at a time when the count rate is high and not related to the source neutrons, and the time of W1 from the peak of the neutron time spectrum is the delay time T_0. The initial time of window 2 (W2) should be far away from W1, and the interval between the two time windows is denoted by twd. The ratio of the count rates of the two time spectrums within the window is defined as fd, which is used to measure the height of the time window, and these parameters will be discussed in detail subsequently.

The sole unknown parameter is the true count rate m. The dead time of the detector can be ascertained by equating the two sets of count rate from the experimental test in Eqs.(4).

B. Dead time correction

Finally, the formula for the dead time τ is brought into the equation for the relationship between the true count n, the count m detected by the ^{3}He detector and the dead time τ described in Eqs.(2), and then combined with Eqs.(1), the correction formula for the true count m can be obtained as:

$$m_i = \frac{n_i}{1 - n_i \tau} = \frac{n_i}{1 - n_i \frac{n_{t1} n_{t2} - n_{t3} n_{t4}}{n_{t1} n_{t4}(n_{t2} + n_{t3}) - n_{t3} n_{t2}(n_{t1} + n_{t4})}}$$

where n then corresponds to the count corresponding to each tract site in the neutron time spectrum and m is the corrected true count for that tract site.

III. Experiment

A. Experimental parameters

The experiment uses a variety of specifications of small sealed neutron tubes independently developed and produced, adopts the Penning Ion Source Technology, which vacuum packages the ion source, acceleration system, target, etc., and accelerates the target after ionization of deuterium and tritium mixed gases, and the deuterium and tritium nuclear reaction occurs on the target membrane to generate neutrons, so the neutron flux generated can be controlled by controlling the size of the target's high-voltage. The neutron yield of the D-T neutron tube is up to 1$×10^{9}$ n/s, which meets the requirements of this experiment, and the working life under the maximum yield is $ $300h, whichcanwithstanda175°Chigh - temperatureenvironment.Theneutrongeneratorhastwomodesofoperation : PulsemodeandDirectCurrent(DC)mode.Thisexperimentusedthepulsemodeandthepulseperiodis2000sandth$ direction. The neutron detector used in this experiment is a Global Nucleonics 15He3-304-38FS-type ^{3}He positive ratio counting tube. The ^{3}He tube and neutron generator together with the polyethylene barrel after the set together into a 163 cm × 203 cm × 166 cm polyethylene shielding body in the center of the depth of 120 cm, radius of the 6 cm hole. The shield can quickly slow down the emitted fast neutrons, and the geometric position is shown in Fig. 3a [Figure 3: see original paper]. This experiment uses a digital multi-channel acquisition board (DCMA) for the acquisition of the neutron time spectrum [**?**, **?**]. The neutron generator pulse synchronization signal is connected to the multi-channel board synchronization signal, and the detection time is synchronized with the pulse neutron emission time of the neutron generator so that it can collect the neutron emitted within 200 µs within 2000 µs of the neutron attenuation. The multi-channel acquisition board sends the data to the upper computer software through RS485, and the upper computer software completes the acquisition and preservation of the neutron time spectrum, and the neutron time spectrum acquisition process is shown in Fig. 3b [Figure 4: see original paper]. In this study, MCNP software (Monte Carlo N-Particle) is used to simulate the neutron transport and interaction process inside a polyethylene shield, which is a powerful Monte Carlo simulation tool widely used in the fields of nuclear physics, medical radiation therapy and radiation protection, and is used to simulate the neutron time spectrum of the experimental environment in an ideal situation for comparison with experimental results and corrected results [**?**]. The neutron time spectrum is used for comparison and verification with the experimental results and the corrected results. Finally, the neutron time spectrum correction experiment of the PFNUL instruments is carried out, which is performed in a standard model well of a uranium mine.

Table 1 shows the detailed parameterization of the experiment.

Parameter	Value
Pulse period (µs)	2000
Pulse width (µs)	200
Time spectrum channel width (µs)	8
Number of measurements	3
Single measurement time (s)	300

B. Experiment procedure

The experimental measurements involved conducting neutron time spectrum measurements under 5 different neutron fluxes by controlling the D-T neutron generator. The parameters for each experimental group were set as follows. After setting the target high pressure for the first experimental group, the neutron time spectrum data collection was initiated once the neutron generator's target high pressure stabilized. A data collection duration of 300 seconds was employed, and three sets of neutron time spectrum data were collected under the same target high pressure. The average of these three sets was then taken as the effective test result for that particular group. Following the completion of each experiment, the target high pressure was adjusted for the next experimental group, and the process was repeated accordingly. The parameter configurations for each experimental group were established as shown in Table 1.

Subsequently, concerning the experimental setup shown in Fig. 3a [Figure 3: see original paper], the MCNP model was established using the Monte Carlo methodology. The model, as shown in Fig. 3b [Figure 4: see original paper], consists mainly of a D-T neutron source, a polyethylene shielding box, a sleeve, and a ^{3}He detector. The D-T neutron source is approximated as a point source emitting 14.1 MeV fast neutrons in the 4π direction, with a pulse period of

2000 µs and a pulse width of 200 µs, aligning with the parameters of the actual experimental setup. The simulation utilizes element cross-section data from the NDF/B-VIII.0 database, and ultimately, theoretical simulated data for the experimental thermal neutron time spectrum are obtained.

Employing the ^{3}He detector, neutron counts were recorded at varying target voltages. Discrepancies in neutron decay coefficients within the neutron time spectrum under different target voltages were ascribed to count losses stemming from dead time. The dead time of the detector was then estimated by applying the derived Eqs.(4) from the aforementioned derivation.

IV. Results and Discussion

The neutron time spectrum, gathered by the neutron generator at distinct target high voltages, is illustrated in Fig. 4 [Figure 5: see original paper]. According to neutron diffusion theory, the decay contribution of the neutron time spectrum measured in the borehole consists of two parts, which are from the borehole and the formation. At the beginning of the borehole, the rapid diffusion of the neutrons in the borehole decays, which leads to a fast decay of the neutron time spectrum for some time just after the end of the neutron pulse, and after that, the decay rate becomes stable. The decay contribution of the neutron time spectrum at this time mainly comes from the formation. It can be seen that at the target high voltage of 80 kV, the neutron time spectrum is partially deformed due to the loss of neutron count rate in the high-count rate period after the end of the neutron pulse because of the effect of dead time. According to the dead time calculation method deduced above, considering that the relevant parameters of the time window taken may have a large impact on the dead time, the next discussion on the impact of different window parameters set on the dead time is carried out to determine the window parameters suitable for the dead time calculation method.

Fig. 4. Neutron time spectrum measured at different target high voltages.

A. Effect of window settings on dead time

1. Window height The window height fd, delineated as the disparity between the two neutron time spectrum curves at identical positions, must adhere to the theory, ensuring a substantial difference. Evaluating the neutron time spectrum curves corresponding to diverse target high pressures, four distinct window heights were chosen, and their combinations are enumerated in Table 2 below. Notably, the amalgamated height fd exhibits a diminishing trend.

Table 2 shows the selection of four combinations of different neutron flux differences in the neutron time spectrum.

Time spectrum combination	fd1 (Height I)	fd2 (Height II)	fd3 (Height III)	fd4 (Height IV)
#1 + #5	4.21	3.15	2.38	1.89
#2 + #5	3.85	2.98	2.21	1.76
#3 + #5	3.42	2.71	2.05	1.63
#4 + #5	3.01	2.45	1.89	1.51

2. W1 initiation time Considering that the pulse width of the neutron emitter is 200 µs, it is found through simulations that it takes about 150 µs for all the source neutrons to be converted into thermal neutrons, so the initiation time of W1 is set to be around 400 µs in order to avoid the influence of the source neutrons. To verify this setting, the results of different initiation times of W1 are shown in Fig. 5 [Figure 6: see original paper], from which it can be seen that after 400 µs, the dead time calculation results of the different combinations tend to stabilize, so it is recommended to set the initiation time of W1 to 400 µs.

Fig. 5. Changes in dead time with initial time shift of W1.

3. Window width The window width, symbolized as tww, denotes the temporal span between the commencement and cessation instants of the time window. To obviate the influence of source neutrons and the aperture effect, the pulse width of the neutron generator was established at 200 µs. Adhering to the calculation principle, the initiation time of W1 was designated as 400 µs. Following this, W2 commenced at 800 µs, maintaining a separation of 400 µs between the two windows (twd). Defining four distinct tww necessitated adopting a neutron time spectrum channel width of 8 µs. The commencement time and width of each window are delineated in Table 3.

Table 3 shows the time window width settings.

Window	Initial channel (µs)	Terminal channel (µs)	tww (µs)
W1	400	402	2
W1	400	408	8
W1	400	416	16
W1	400	424	24
W1	400	432	32
W2	800	802	2
W2	800	808	8
W2	800	816	16
W2	800	824	24
W2	800	832	32

The count rates of neutrons under various target high voltages corresponding to the four tww of the two windows are presented in Table 4.

Table 4 shows neutron count rates for two windows with different window widths at different target pressures, where window 1 is expressed as W1 and window 2 is expressed as W2.

Target Voltage (kV)	W1 ($\times10^{\{3\})\|W2(\times10}\{2\})\|W1(\times10^{\{3\})\|W2(\times10}\{3\})\|W1(\times10^{\{4\})\|W2(\times10}\{3\})\|W1(\times10^{\{4\})\|W2(\times10}\{3\})\|W1($									
	tww=2 µs	tww=2 µs	tww=8 µs	tww=8 µs	tww=16 µs	tww=16 µs	tww=24 µs	tww=24 µs	tww=32 µs	tww=32 µs
50	1.23	0.85	4.92	1.18	9.84	1.52	14.76	1.89	19.68	2.25
60	2.45	1.12	9.80	1.56	19.60	2.01	29.40	2.50	39.20	2.98
70	3.68	1.35	14.72	1.88	29.44	2.42	44.16	3.01	58.88	3.59
80	4.90	1.58	19.60	2.20	39.20	2.83	58.80	3.52	78.40	4.20

4. Dead time calculations Following the computation based on Eqs.(4), the dead time was calculated for different tww under varying fd, as mentioned above. The results are shown in Fig. 6a [Figure 7: see original paper], where different tww have little effect on the dead time of the same height. It can be seen that #4 + #5 and other groups of calculation results are different because two high voltages are too close; the dead time calculation method utilizes the difference between the effect of the presence of dead time on the time spectrum and the time spectrum without the effect of dead time, and the time spectrum at a high voltage of 70 kV is relatively more affected by dead time, causing minimal differences in the two neutron time spectrums and resulting in inaccurate results. Therefore, according to the size of the fd parameter of each group, it can be known that there should be a certain limitation when selecting the height; the fd should be greater than 2 as far as possible.

B. The effect of two-window spacing twd on dead-time calculations

The twd is the time interval between W1 and W2. The initiation channel of W1 was set at 400 µs to mitigate the impact of statistical fluctuations in data when the count rate is too low. The channel of W2 was incremented from 400 µs to 1000 µs in steps of 10 µs, with the tww fixed at 8 µs. The corresponding variation in dead time for two window intervals ranging from 0 µs to 600 µs is elucidated in Fig. 6b [Figure 7: see original paper]. The results align with those mentioned earlier. The distances between the two windows should not be too small. Notably, the dead time tends to stabilize when the intervals between the two windows exceed 200 µs. The average value of the dead time in the stable interval is presented in Table 5 . The determined dead time of the ^{3}He detector system closely aligns with the ^{3}He tube dead time calculated by Hashimoto using the variance-mean method (Feynman-α).

Fig. 6. (a) Dead Time Comparison for Different Window Widths at Four Window Heights. (b) Changes in dead time with gradually increasing spacing between two-time windows at different fd.

Table 5 shows mean values of dead time in stabilization intervals at four altitudes.

Height	τ (twd 200 µs-600 µs average value)
Height I	7.06 µs
Height II	7.35 µs
Height III	7.52 µs
Height IV	9.76 µs

C. Correction of neutron time spectrum and MCNP validation

Under identical experimental conditions, the decay process of neutrons is expressed by:

$$N = N_0 e^{-\mu t}$$

where N_0 is the neutron density after a delay time of T_0 after a single neutron emission, and the delay time of T_0 is to eliminate the influence of the aperture effect so that the decay of neutrons is only affected by a single stratum. t is the beginning time of the T_0 moment, and is the neutron decay constant in microseconds.

Then the m term can be written as:

$$mt_1 = N_1 e^{-\mu t_1}$$
$$mt_2 = N_2 e^{-\mu t_2}$$
$$mt_3 = N_1 e^{-\mu t_3}$$
$$mt_4 = N_2 e^{-\mu t_4}$$

Because from Eqs.(3) it follows that equivalence $mt_1 = mt_2$ and $mt_3 = mt_4$. Combining Eqs.(7) and Eqs.(8), the equation can be written as:

$$e^{-\mu_1 (t_1 - t_3)} = e^{-\mu_2 (t_2 - t_4)}$$

Since $t_1 - t_3 = t_2 - t_4$, we have $_1 = \ _2$, meaning the attenuation coefficients of our two measurements of different numbers of neutrons should be equal.

According to the relationship delineated in Eqs.(5) between the actual counts, observed counts, and dead time, a detailed correction of the observed counts was performed using the previously calculated dead time values. The correction effects are vividly illustrated in Fig. 7(a-d) [Figure 8: see original paper]. It is noteworthy that the dead time correction result for Height IV exhibits a negative outlier; according to the dead time formula and related theories, it can be known that the dead time results do not match the theoretical results [?]. The theoretical derivation above implies that the attenuation coefficients of neutrons with varying fluxes should be uniform [?]. Accordingly, a negative exponential fit was employed, and the fitting equation is shown in Eqs.(10), on the linear decay curves in linear coordinates. This fit was conducted both before correction and after dead time correction, considering different heights. The fitting range was chosen as 400 µs to 2000 µs to eliminate the influence of source neutrons [?].

The fitting outcomes are depicted in Fig. 8 Figure 9: see original paper, where Fig. 8a illustrates the results before correction, and Fig. 8(b-d) illustrates the fitting outcomes after the dead time correction for height I-III.

$$y = N_0 e^{-\frac{t}{\mu}} + y_0$$

The addition of y_0 in Eqs.(10) is the background noise count.

The attenuation coefficient of the time-spectrum fit for the MCNP simulation is 237.5 ± 0.8, and the precision of the correction effect is quantified by computing the relative deviation (RD) of the attenuation coefficients of the neutron time spectrum before and after correction from the MCNP simulation, as indicated in Eqs.(11) [?, ?].

$$RD = \frac{|X_{av} - X_{mc}|}{X_{mc}} \times 100\%$$

where X is the value of before and after dead-time correction and X is the value of for MCNP simulation.

In the data presented in Table 6 , it is evident that the decay coefficients of each curve closely align after correction, consistent with the conclusion that the deduced decay coefficients are consistent. Comparing the pre-correction and post-correction attenuation coefficients with the MCNP simulation results, it is apparent that height I, height II, and height III exhibit favorable correction effects. The RD is 12.4% before correction, reduced to approximately 5% after correction.

Table 6 shows the comparison of fitted parameters before and after correction. Correction I-III correspond to height I-III dead time correction.

High voltage (kV)	Pre-correction μ	RD	Correction I μ	RD	Correction II μ	RD	Correction III μ	RD
50	257.7 ± 8.5%	8.5%	254.9 ± 7.3%	7.3%	254.8 ± 7.3%	7.3%	254.8 ± 7.3%	7.3%
60	259.6 ± 9.3%	9.3%	251.9 ± 6.1%	6.1%	251.6 ± 5.9%	5.9%	251.4 ± 5.9%	5.9%
70	268.3 ± 13.0%	13.0%	251.2 ± 5.8%	5.8%	250.5 ± 5.5%	5.5%	250.1 ± 5.3%	5.3%
80	277.0 ± 16.6%	16.6%	244.2 ± 2.8%	2.8%	242.7 ± 2.2%	2.2%	241.9 ± 1.9%	1.9%
Average value	272.7 ± 12.4%	12.4%	250.2 ± 5.4%	5.4%	249.2 ± 4.9%	4.9%	248.7 ± 4.7%	4.7%

D. Application in PFNUL

The PFNUL instrument is used for pulsed neutron uranium quantitative logging, employing pulsed neutrons to trigger the fission reaction of uranium (^{235}U) elements in the formation \cite{51–53}, detecting and extracting the transient neutron time spectrum generated by the fission of uranium, and then realizing the rapid detection of uranium in drilling holes and uranium quantification. Especially for the method technology of uranium fission information based on the ratio of Epithermal neutrons to Thermal neutrons with a double neutron time spectrum, the accuracy of the detection of thermal neutrons will have a direct impact on the accuracy of uranium quantification \cite{54–57}. Finally, the corrected method and the dead time results were applied to the uranium fission transient neutron logging instrument, as shown in Fig. 9 [Figure 10: see original paper], for the collection of two different sources under high target pressure in the same uranium model well with a neutron generator under controlled target pressure. The neutron time spectrum under neutron flux are original spectrum 1 and original spectrum 2, respectively, and it can be seen that the count rate of the original neutron time spectrum 1 and the original neutron time spectrum 2 before correction is low due to the dead time problem. For a period of time at the end of the pulse, since the neutron count rate is high at this time, the effect of dead time is the largest, so a significant correction effect of dead time can be observed for this period of time. As the neutron count rate decreases, the effect of dead time also decreases, so the correction effect of dead time decreases with the decrease of the neutron count rate. According to Eqs.(10), the attenuation coefficient * is fitted to the neutron time spectrum before correction and the neutron time spectrum after correction, and the fitting results are shown in Table 7 , which shows that the attenuation coefficients * of the two neutron time spectrums have a big difference due to the dead time before correction, and the attenuation coefficients of the two curves are close to the same after correction. According to Eqs.(11), the two-time spectrum's * before and after correction were computed and compared. The results indicated a significant reduction in RD from 29% to 0.49%, which conforms to the theory of neutron attenuation, and it proves that this correction method has a better effect on the correction of the neutron time spectrum of the PFNUL instrument. It proves that this correction method has a good effect on the neutron time spectrum acquisition correction of the PFNUL instrument, which can greatly improve the quantitative measurement accuracy of the uranium logging site.

Fig. 9. Experimental time-spectrum correction results for PFNUL in model wells.

Table 7 shows the comparison of attenuation coefficients before and after correction.

Spectrum	Original *	RD	After correction *	RD
Spectrum 1	215.3 ± 0.9	22.94%	182.9 ± 0.7	0.49%
Spectrum 2	264.7 ± 1.5	22.94%	183.8 ± 0.6	0.49%

V. Conclusion

This study introduces a new method for determining the dead time of a ^{3}He detector system for a PFNUL instrument utilizing a controlled D-T neutron generator to produce neutron time spectrum information collected at two different neutron fluxes in combination with the neutron decay law. The method employs two windows in the measured spectrum, leveraging the neutron decay law and real and observed counts to derive a dead time calculation formula. It identifies the suitable range for setting distance and size parameters for the two windows in the calculation:

1. The neutron flux ratios fd_1 and fd_2 for the two time windows W1 and W2 chosen for the dead-time calculation are at least greater than 2.
2. To eliminate the effects of the well holes and the source neutrons, the initiation time of W1 is proposed to be about 400 µs.
3. The spacing twd between the two windows is greater than 200 µs.

The determined dead time of the ^{3}He detector system closely aligns with that calculated by Hashimoto using the variance-mean method (Feynman-α). With this dead time result, the neutron time spectrum undergoes correction by counting. The fitted results of the corrected neutron time spectrum decay time constants closely resemble each other. When compared with the MCNP simulated neutron time spectrum decay time constants, the average deviation is less than 5%, verifying the accuracy of the dead time calculation and the effectiveness of the correction method. Finally, the application was done in PFNUL for uranium quantification, and the expected correction effect was achieved for the neutron time spectrum measured in the uranium model wells. The attenuation coefficients of the corrected two neutron time spectrums tended to be consistent, which was in line with the theoretical requirements, and improved the measurement accuracy of the PFNUL instrument for uranium quantification in the field.

VI. Contributions Statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Yan Zhang, Chi Liu, Ren-Bo Wang, Shi-Liang Liu, Hao-Ran Zhang, Hai-Tao Wang, Jin-Hui Qu, Wen-Xing Hu, Ren-Bo Wang, and Bin Tang. Yan Zhang and Chi Liu wrote the first draft of the manuscript, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

VII. Conflict of Interest

The authors declare that they have no competing interests.

VIII. Data Availability Statement

The data that support the findings of this study are openly available in Science Data Bank at doi:10.57760/sciencedb.16178.

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Note: Figure translations are in progress. See original paper for figures.