Measurement of the ^{252}Cf Acrylic Source Standard

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I. INTRODUCTION

Neutron calibration sources containing ^{252}Cf have been made by encapsulating the material into small acrylic cylinders [1]. Knowledge of the source standard decay rate is essential for calibrating the neutron capture efficiency in SNO by direct counting methods. Source rate evaluation has been made by George Ewan in September 2000 using direct γ-ray counting [2] in conjunction with α spectroscopy [3] by Geoff Miller. Measurements featuring direct neutron counting using a ^{3}He proportional counter array are reported here for the first time.

The previous work [2] was conducted on Sept. 1, 2000 and used a high-purity Ge detector to observe γ-rays following the ^{249}Cf β-decay. The 388-keV γ-ray line was used to determine the ^{249}Cf decay rate, reported to be 31.0 ± 1.9 s^{-1}. The ratio ^{252}Cf/^{249}Cf was previously determined by α-spectroscopy [3], and was evaluated to be 5.67 on Sept. 1, 2000. The uncertainty in the ratio was not available. The fission branch strength and mean neutron yield per fission used in the previous work were $3.092 \pm 0.008\%$ fissions per disintegration and 3.8 neutrons per fission, respectively. The neutron rate from the strong source was reported as 20.7 n s^{-1}, with at least 6% uncertainty, coming primarily from a 5% γ-ray efficiency uncertainty, and 3% uncertainty on the 388-keV branch strength. The weak source emission was evaluated to be a factor of 19.6 ± 1.6 lower than the strong source. Evaluating the ^{252}Cf source standard by direct neutron counting offers a means to reduce the 6% uncertainty quoted in Ref. [2].

II. DIRECT COUNTING MEASUREMENTS

Two evaluations have been performed using a fission trigger source and platinum (Pt) disks with known fission rate. Both sources feature Cf from the same stock used in the acrylic source. The two techniques are sensitive to the neutron multiplicity under two different conditions: prompt and total neutron multiplicity. The neutron multiplicity from ^{252}Cf spontaneous fission has a component from direct neutron evaporation from prompt fission fragments and a delayed component from β-delayed neutron emission for a small number of Cf fission fragments. The delayed component is evaluated in Ref. [4] to be $0.781 \pm 0.074\%$ of the total neutron yield. The prompt mean neutron value used in the fission trigger source evaluation is 3.7676 ± 0.0047 from Ref. [5]. The total mean neutron value used in these evaluations is 3.797 ± 0.006. These values are summarized in Table I.

Mode	Mean	Sigma
Prompt	3.7676 ± 0.0047	1.57 ± 0.02 [6]
Delay	0.0294 ± 0.0028	–
Total	3.7970 ± 0.0055	

TABLE I: The ^{252}Cf prompt and delay neutron yields.

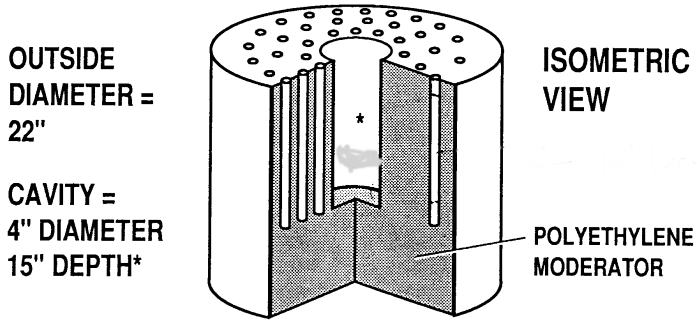

FIG. 1: ^{3}He array illustration.

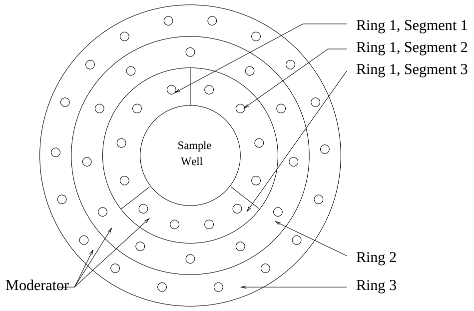

FIG. 2: ^{3}He counter array layout.

A ^{3}He proportional counter array was used to perform the direct neutron measurement. It features 42 ^{3}He proportional counters that are 1.0 inches in diameter and 14 inches in length. They are placed within polyethylene moderator as shown in Fig. 1. The moderator extends below the counters by about 15 cm. The well depth is 15 inches, but in this evaluation a 4 inch polyethylene block was placed in the well to better center the neutron sources. The counters are organized into three rings at constant radius from the center of the well. Data acquisition is organized to readout five counter segments. The 18 outer ring counters are readout as one segment, as are the 12 middle ring counters. The 12 inner ring counters are organized into groups of four and represent three data acquisition segments.

A. Fission Triggered Source Evaluation

The ^{3}He proportional counter array was calibrated for neutron efficiency using ^{252}Cf electroplated onto a Si surface barrier detector and mounted face-to-face with a clean Si surface barrier detector. A trigger signal is extracted by placing a threshold on the dual detector to exclude signals from α-decay. The trigger signal opens a 200 μs gate for observing ^{252}Cf fission neutrons capturing in the array. The detector efficiency is obtained by comparing the observed neutrons (η) to the triggers (T), taking the ^{252}Cf prompt mean neutron multiplicity (N) into account, as shown in Eq. 1.

$$\epsilon_{trig} = \frac{\eta}{TN}. \tag{1}$$

Data was acquired in 92 runs featuring 5001 triggers each. A small fraction of events feature more than 1 trigger in the gate window due to pileup. For this reason only those events reporting identically 1 trigger are assessed. The observed neutrons are extracted from the counts in the two inner rings. The efficiency is found to be

$$\epsilon_{trig} = \frac{397848 \pm 631}{451530 \pm 672 \times 3.768 \pm 0.005} = 23.37 \pm 0.06\%. \tag{2}$$

A correction is made for background events occurring within the gate window. Data was obtained by triggering the array with a pulser at about 10 Hz. The observed background was 474 events during 1115438 pulses.

The efficiency is also extracted from a χ^2 fit to the probability distribution in Eq. 3,

$$\mathrm{P(d)} = \sum_{\mathrm{r=d}}^{\infty} \frac{\mathrm{r}!\epsilon^{\mathrm{d}}(1-\epsilon)^{\mathrm{r-d}}}{\mathrm{d}!(\mathrm{r}-\mathrm{d})!} \frac{1}{\sqrt{2\pi}\sigma} \exp\frac{-(\mathrm{r}-\mu)^2}{2\sigma^2} \tag{3}$$

where d neutrons are observed for r neutrons produced. The normalized Gaussian term describes the neutron multiplicity per fission. The binomial probability term is described in terms of the efficiency for the ^{3}He array to detect a single neutron. A single parameter fit to the efficiency was performed using the MIGRAD minimization and MINOS error estimation routines from the CERN analysis library, implemented in ROOT. The extracted efficiency is $23.47 \pm 0.11\%$. The data and fit values appear in Fig. 3. The agreement between the two methods is encouraging.

Is the multiplicity distribution actually an independent efficiency measurement? Or was that analysis completely constrained to reproduce the efficiency obtained by counting triggers and neutrons by the choice of the timing gate? Our evaluation is that the only degree of independence was to validate that the triggers were a clean ^{252}Cf fission sample. If the fission sample contained spurious signals, e.g. signals from α-decay, the multiplicity fit would not have converged to the same efficiency as the counting method. But the multiplicity analysis is not actually independent because the readout time scale is too short. An analysis similar to that done in SNO, where the probability to observe neutrons *per unit time interval* on time scales long compared to capture time, would have been independent. We therefore rely on the fission trigger integral evaluation.

A correction must be applied to the fission gated evaluation due to the choice of a 200 μsec gate. MMF collected a fission trigger TAC spectrum in October 2000 soon after the triggered source was first assembled. The TAC spectrum was recorded to 500 μsecs. MMF has evaluated this spectrum to find the event fraction falling between 200 and 500 μsecs. The number of events in the 0–500 μsec window is 209520, and 22577 fall in the 200-500 μsec window. The additional neutron fraction observed in that late window (with the neutrons observed in the primary 0–200 μsec window normalized to 100%) is $12.08 \pm 0.09\%$. The 200–500 μsec region is fit to an exponential to estimate the remainder of neutrons missed in the 500–1000 μsec window (stipulating that 1000 μsecs $= \infty$). The calculated value in the 500–1000 μsec window is $4224 \pm 65 \pm 127$ neutrons, where the first error is statistical and the second represents 3% uncertainty extracting the fit parameter. The total correction is then $14.34 \pm 0.12\%$. This correction is to be applied to the number of observed neutrons and results in a reevaluated efficiency of $26.68 \pm 0.23\%$. This is the corrected value for backgrounds in the 1000 μsec gate window.

B. Pt Disk Direct Counting Evaluation

The ^{3}He proportional counter array efficiency has been evaluated by an additional method. Sources have been prepared by electroplating ^{252}Cf solution onto Pt disks. These sources have been calibrated for fission rate using a Frisch grid chamber and then counted for neutron rate in the ^{3}He proportional counter array. The intrinsic Frisch grid efficiency is 100% for fission fragments. Each fission will emit two particles, but only one will emerge into the ionization chamber. The efficiency for detecting fissions is then 100%, excepting a (very?) small correction for losses due to fissions fragments that don't emerge from the Pt disk material and a separate, yet perhaps equally small correction for two fission fragment emission into the ionization chamber. This correction is not yet performed.

The results summarized in Table II are preliminary and do not include systematic errors. The efficiency is $27.55 \pm 0.20\%$, the weighted average of the Pt disk determinations. The energy spectrum from Pt disk cf-09-13-00-01 is shown in Fig. 4. The regions of interest used to determine the α and fission fragment counts are shown with solid and dashed vertical lines, respectively. The α region features a singles band (channels 5–31) and an α sum band (channels 34–59).

Pt Disk ID	Fission Events	Fission Rate	Emitted Neutron Rate	Observed Neutrons	Observed Neutron Rate	Efficiency (%)
9-13-00-01	10939 ± 104.6	2.188 ± 0.021	8.307 ± 0.080	323771	2.262 ± 0.006	27.23 ± 0.27
9-13-00-02	11097 ± 105.3	2.219 ± 0.021	8.427 ± 0.081	197678	2.353 ± 0.008	27.92 ± 0.29

TABLE II: ^{3}He detector efficiency evaluation summary. The efficiency was evaluated using ^{252}Cf electroplated onto Pt disks that were characterized for fission rate by counting with a Frisch grid chamber.

C. Discussion

The Pt disk and triggered source efficiency evaluations agree at only 2σ. Both of these evaluations are preliminary. Here follows a list of issues requiring attention:

- The Frisch grid fission fragment efficiency for the Pt disks should be fully evaluated.
- Additional neutron counting with the Pt disks may also be merited given the statistically significant disagreement (1.2σ) between the present two sample measurements. The disagreement may indicate systematic variations in efficiency due to sample location in the neutron counting well.
- The triggered source should be operated with a longer primary gate to quantify the validity of the TAC corrections. The TAC correction is an interesting problem because the DAQ was organized to readout a 100-μsec delay gate immediately following the primary gate. An evaluation of all the triggered data shows only 111 events detected in the delayed gate. This is far fewer events in the delay gate than observed in the TAC spectrum. Clearly additional work is required here. A new fission triggered source is required to complete this study.
- Finally, there has been speculation that radiation damage to the triggered source may have introduced a systematic into that efficiency evaluation. Consider again the efficiency calculations that were performed. One speculation is that radiation damage has caused the alpha and fission fragment signals to become partially overlapped, so that there were alpha contamination in the trigger. These triggers would have zero neutrons in coincidence within the 200 μsec gate. This artificially lowers the efficiency. Considering the data, the number of fission triggers must be reduced by about 3% to adjust the corrected fission trigger efficiency from 26.68% to obtain 27.55% efficiency. Is this completely unreasonable? It depends on the nature of the radiation damage. Electroplating may lead to localized severe damage, such that charge collection may be limited to relatively small physical regions in the detector, reducing resolution sufficiently such that α and fission fragment separation is compromised. Another possibility is the opportunity for spurious signals to develop due to the non-uniform depletion layer in the severely damaged detector. Either mechanism would act to decrease the efficiency. It does not appear possible for radiation damage to provide a mechanism leading to an *overestimated* detector efficiency.

Accepting that the above points may need to be addressed, the disagreement in the two efficiency evaluations is taken as a systematic uncertainty. The weighted average is obtained and the systematic error is defined by taking the variance of the two measured values from their mean. The systematic error is added linearly to the error from the weighted average. This evaluated value and error are $27.18 \pm 0.15 \pm 0.31 = 27.18 \pm 0.46\%$. The efficiency results are summarized in Table III.

Method	Efficiency	Systematic Error
Fission	0.2668 ± 0.0023	—
Pt Disk	0.2755 ± 0.0020	—
Average	0.2718 ± 0.0015	± 0.0031

TABLE III: Direct counting ^{3}He array efficiency evaluation summary.

D. Additional Data

A first-neutron triggered data set was also obtained, where any signal within the first two detector rings triggered a 200 μs gate. This data is not yet evaluated.

III. SUMMARY AND CONCLUSIONS

The acrylic source rate was established using singles data accumulated for 159,000 s (12-13 June, 2001) with a corresponding 676,000 s background data set (13-22 June, 2001). Data from the two inner rings was evaluated to provide an observed neutron rate of 4.743 ± 0.016 n s^{-1}. The acrylic source neutron flux was then 17.45 ± 0.30 n s^{-1} on June 12, 2001, using the direct counting average efficiency.

The neutron rate predicted for June 12, 2001 based on the previous work is 16.84 ± 1.06 n s^{-1}. The previous work did not include an estimate of neutron yield from the ^{250}Cf activity. The spontaneous fission ratio is 40.2:1 and the activity ratio is 1.203:1 for ^{252}Cf/^{250}Cf on June 12, 2001. The ^{250}Cf average neutron multiplicity is 3.511 ± 0.037 n/f [5]. The additional activity from ^{250}Cf is found by calculating the fractional activity and correcting for the different neutron yields to obtain the following neutron rate correction:

$$2.06\% \times \frac{3.511 \pm 0.037}{3.768 \pm 0.005} = 1.92 \pm 0.02\% 16.84 \pm 1.06 \times 0.0192 \pm 0.0002 = 0.323 \pm 0.021 \mathrm{ns}^{-1} \quad (4)$$

The total prediction from Ewan should then be 17.16 ± 1.06 n s^{-1}. Recall that the original value includes a 3% error on the original estimate of the relative activities but does not evaluate errors on the respective fission branches. The neutron activity from ^{250}Cf does not represent a constant fraction of the total neutron rate, since ^{250}Cf and ^{252}Cf decay at different rates (13.08 and 2.645 y, respectively). The corrections are performed for the neutron rate on September 1 and November 23, 2000, and July 28 and August 28, 2001. These calculations are summarized in the table below.

The acrylic source standard neutron rate is summarized in Table IV. The weighted average neutron rate is reported as a weighted sum of the independent evaluations by γ-ray and direct neutron counting.

	λ (n/s)				
Method	Sept. 1, 2000	Nov. 23, 2000	June 12, 2001	July 27, 2001	Aug. 28, 2001
γ-ray	20.98 ± 1.30	19.78 ± 1.22	17.17 ± 1.06	16.59 ± 1.02	16.25 ± 1.00
direct counting	21.39 ± 0.37	20.16 ± 0.35	17.45 ± 0.30	16.86 ± 0.29	16.51 ± 0.28
weighted average	21.36 ± 0.36	20.13 ± 0.34	17.43 ± 0.29	16.84 ± 0.28	16.49 ± 0.27

TABLE IV: Acrylic source standard summary table.

[1] Malcolm Fowler, Jerry B. Wilhelmy, SNO-STR-99-016, *Preparation of Acrylic Encapsulated Radioactive Calibration Sources for SNO.*

[2] G.T. Ewan, Source strength of ^{252}Cf calibration neutron sources by gamma counting, Sept. 15, 2000.

[3] G. Miller, private communication.

[4] Arthur C. Wahl, *Nuclear-Charge Distribution and Delayed-Neutron Yields for Thermal-Neutron-Induced-Fission of ^{235}U, ^{233}U and ^{239}Pu and for Spontaneous Fission of ^{252}Cf* , Atomic Data and Nuclear Data Tables, **39**, No. 1, pp 1-156 (1988).

[5] E.J. Axton, Nucl. Stand. Ref. Data, p 214 (1985).

[6] Boldeman, J.W., *Prompt Neutron Yield from the Spontaneous Fission of ^{252}Cf* , at Neutron Standards Reference Data Panel Meeting, Vienna, (Nov. 20-24, 1972) IAEA.

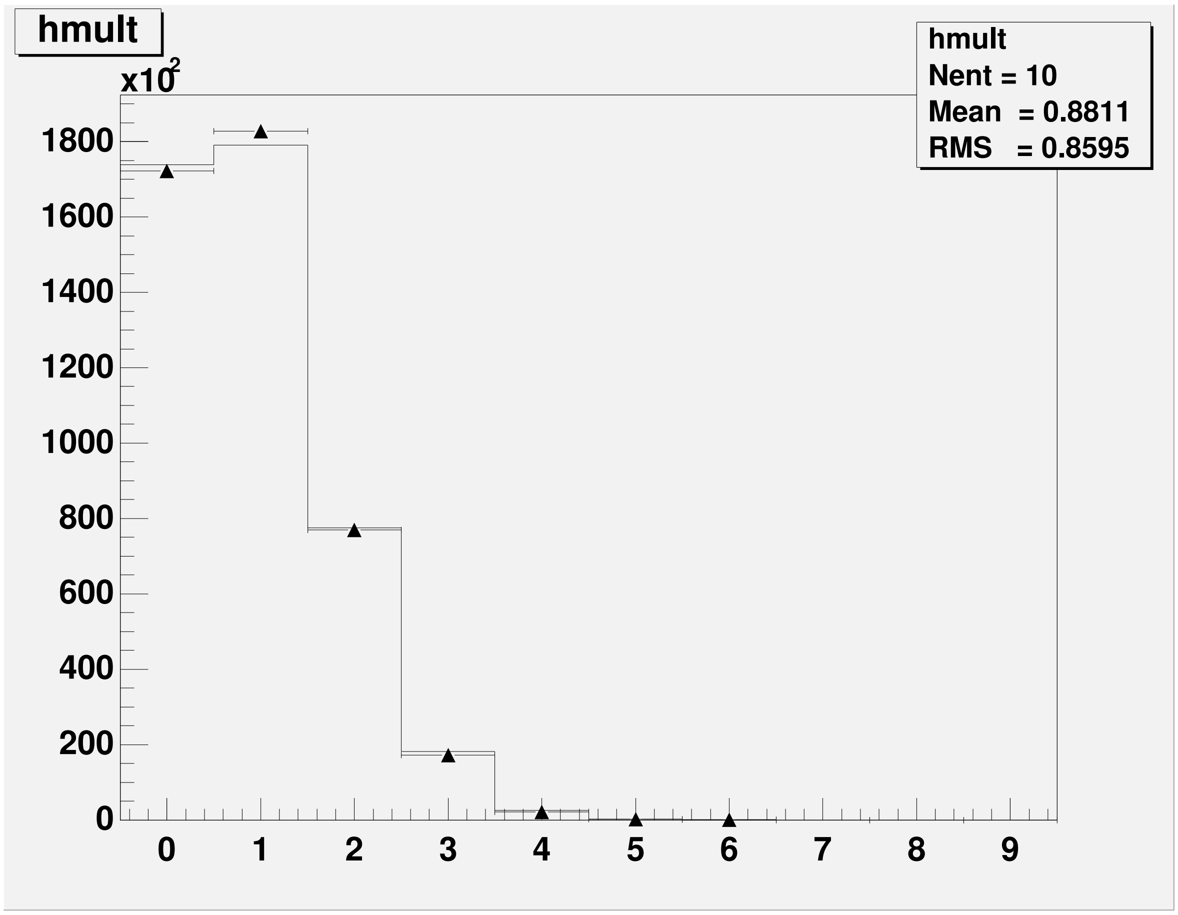

FIG. 3: ^{3}He array multiplicity distribution. The points and error bars represent the data values. The solid histogram represents the fit values for ϵ=23.72%.

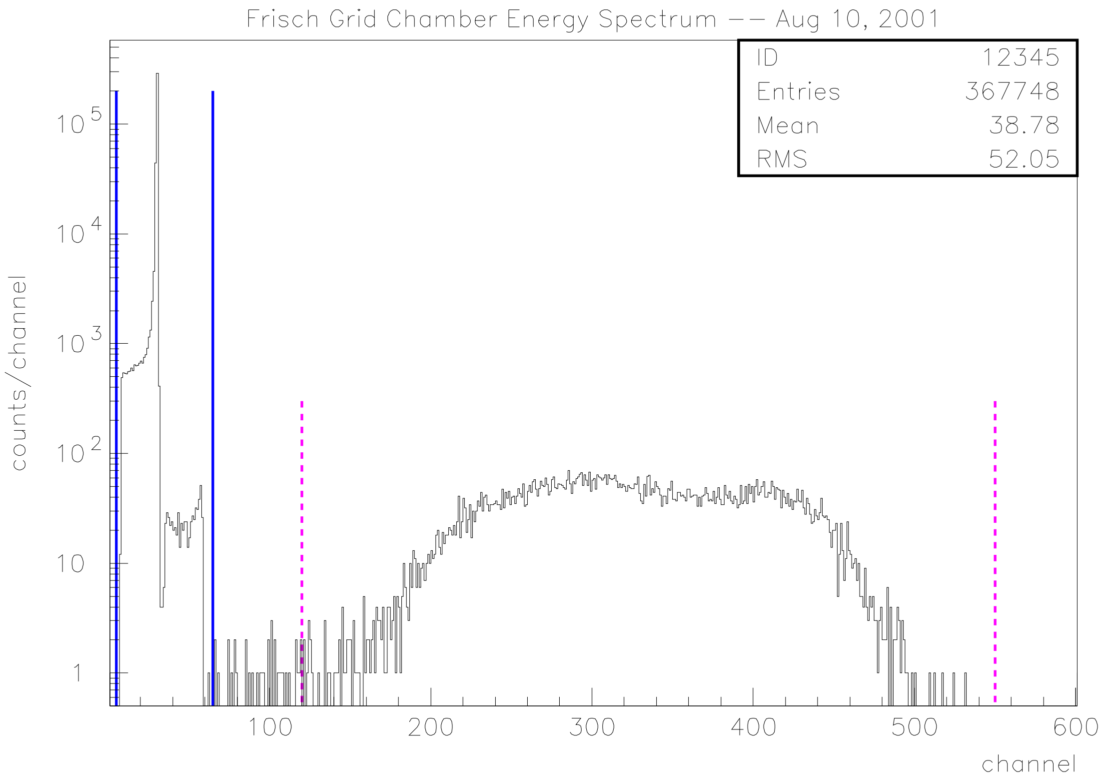

FIG. 4: Frisch grid chamber energy spectrum for Pt disk sample cf-09-13-00-01. The disk is electroplated with Cf from the same stock used for the acrylic Cf source. The spectrum shows the α and fission fragment regions to be well separated.