Tagging fast neutrons from a $^{252}$Cf fission-fragment source

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Abstract

Coincidence and time-of-flight measurement techniques are employed to tag fission neutrons emitted from a $^{252}$Cf source sealed on one side with a very thin layer of Au. The source is positioned within a gaseous $^4$He scintillator detector. Together with $\alpha$ particles, both light and heavy fission fragments pass through the thin layer of Au and are detected. The fragments enable the corresponding fission neutrons, which are detected in a NE-213 liquid-scintillator detector, to be tagged. The resulting continuous polychromatic beam of tagged neutrons has an energy dependence that agrees qualitatively with expectations. We anticipate that this technique will provide a cost-effective means for the characterization of neutron-detector efficiency in the energy range 1 – 6 MeV.

Keywords: californium-252, fission fragments, fast neutrons, time-of-flight, tagging

1. Introduction

We recently reported on our efforts to “tag” fast neutrons from an $^{241}$Am/$^9$Be source $^1$ as the first step towards the development of a source-based fast-neutron irradiation facility. Here, we report on our investigation of a $^{252}$Cf
fission-fragment fast-neutron tagging technique very similar to that reported on by Reiter et al. [2]. In contrast to Reiter et al. who employed a thin layer of plastic scintillator to detect the fragments, we use a gaseous $^4$He-based scintillator detector. The corresponding fission neutrons are detected in a NE-213 [3] liquid-scintillator detector. This effort represents our first step towards the development of an apparatus for the measurement of absolute neutron-detection efficiency at our facility.

2. Apparatus

2.1. Californium fission-fragment source

$^{252}$Cf is an intense source of fast neutrons. With an overall half life of 2.645 years and a specific activity of 0.536 mCi/µg, it decays by both α-particle emission (96.908%) and spontaneous fission (3.092%) [4]. The weighted average α-particle energy is $\sim 6111.69$ keV. The prompt-neutron yield is $\sim 3.75$ neutrons per fission event [5, 6]. The resulting fast-neutron energy spectrum follows the Watt distribution [7] and is very well known, with a most-probable energy of 0.7 MeV and an average energy of 2.1 MeV. Our californium source [8] has an active diameter of 5 mm and is mounted a capsule that has a thick platinum-clad nickel backside and a thin 50 µg/cm$^2$ sputtered-gold front side which allows both α particles and fission fragments to escape. The (nominal) activity is 3.7 MBq [9]. While trace activity comes from $^{249}$Cf (<0.2%) and $^{251}$Cf (<0.04%), the majority comes from $^{250}$Cf ($\sim 7.5\%$) and $^{252}$Cf ($\sim 92.3\%$). We estimate a neutron emission rate of $\sim 4 \times 10^5$ neutrons per second.

2.2. Gaseous $^4$He fission-fragment detector

The noble gas $^4$He is a good scintillator with an ultra-violet light yield of about the same magnitude as intrinsic (non Tl-doped) NaI crystals [10-13]. In this measurement, we employed a gas cell built originally as a prototype active target for recent $^4$He photoreaction measurements [14]. The cell was machined from a solid aluminum block and has a cylindrical interior volume measuring 72 mm long $\times$ 58 mm $\phi$, for an inner volume of $\sim 0.35$ liters (see Fig. 1).
Figure 1: A drawing of the gas cell. Left panel: Section Side View. The cell is filled with 5 bar of gaseous $^4$He scintillator and 500 ppm gaseous $N_2$ wavelength shifter. Right panel: Front View. The photomultiplier tube is attached via a fused-silica window from the top.
The interior of the gas cell was sandblasted and then treated with two layers of water soluble EJ-510 reflective paint \[15\]. A fused-silica optical window 10 mm thick \(\times\) 60 mm \(\varnothing\) is pressed against the body of the cell and allows the scintillation light produced by the \(\alpha\) particles and fission fragments to escape. A rubber O-ring provides the pressure seal. The cell was filled with 5 bar 99.99999% pure \(^4\)He (scintillator) gas together with 2.5 mbar 99.99999% pure \(\text{N}_2\) (scintillation-wavelength shifter) gas. A photograph of the assembled cell is shown in the left panel of Fig. 2. A 5.08 cm XP2262B photomultiplier tube (PMT) \[16\] was attached to the optical window and EJ-550 optical grease \[17\] was employed at the boundary. A photograph of the assembled detector (gas cell and PMT) is shown in the right panel of Fig. 2.

The californium source described above was positioned at the center of the gas cell so that the thin front side through which the \(\alpha\) particles and fission fragments could escape faced away from the PMT. The distance from the cal-
Figure 3: Typical pulses associated with the decay of $^{252}$Cf obtained with the $^4$He gas cell. Top (red) trace: $\alpha$ particles. Middle (green) trace: heavy fission fragments. Bottom (blue) trace: light fission fragments. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

ifornium source to the center of the fused-silica optical window was $\sim 65$ mm. Operating voltage for the PMT was $-1750$ V and the discriminator threshold was set at $-60$ mV. Typical signal risetime was 5 ns, while the falltime to $<10\%$ of the original amplitude was $\sim 10$ ns. Figure 3 shows some typical detector pulses obtained with the $^4$He gas cell. The top traces with amplitudes of about $-350$ mV correspond to $\alpha$ particles. The middle traces with amplitudes of about $-1600$ mV correspond to heavy fission fragments. The bottom traces with amplitudes of about $-2200$ mV correspond to light fission fragments. We note that the average $\alpha$-particle energy is $\sim 6.1$ MeV, while the average heavy fission-fragment energy is 80 MeV and the average light fission-fragment energy is 104 MeV [25]. See also the histogram presented in Fig. [6].
2.3. NE-213 fast-neutron and gamma-ray liquid-scintillator detector

NE-213 is an organic liquid scintillator that has been employed for decades as a fast-neutron detector. The NE-213 liquid-scintillator detector used here has been reported upon earlier [1, 18, 19]. It consisted of a 62 mm long $\times$ 94 mm $\varnothing$ cylindrical aluminum “cup” fitted with a borosilicate glass optical window [20]. The filled cell was dry-fitted against a cylindrical PMMA UVT lightguide [21] and coupled to a $\mu$-metal shielded 7.62 cm ET Enterprises 9821KB PMT and base [22]. Operating voltage was set at about $-1900$ V, and the energy calibration was determined using standard gamma-ray sources together with a slightly modified version of the method of Knox and Miller [23] as described in Ref. [19]. The detector threshold was set at 150 keV electron equivalent (keV$_{ee}$), corresponding to a neutron depositing an energy of about 1 MeV.
2.4. Configuration

A block diagram of the electronics is shown in Fig. 5. α particles and fission fragments were detected in the $^4$He scintillator detector and corresponding neutrons (and gamma-rays) were detected in the NE-213 detector. The analog signals from the NE-213 detector were passed to a Phillips Scientific (PS) 715 NIM constant-fraction timing discriminator (CFD). The analog signals from the $^4$He scintillator detector were fanned out (FO) and passed to a PS 715 NIM CFD as well as a CAEN V792 12-bit (DC-coupled 60 ns gate) VME QDC. The CFD signals from the $^4$He scintillator detector were used to trigger the data-acquisition (DAQ) and thus provided start signals for a CAEN 1190B VME multihit time-to-digital converter (TDC) used for the neutron time-of-flight (TOF) determination. The NE-213 detector provided the corresponding stop signal. A SIS 1100/3100 PCI-VME bus adapter was used to connect the VMEbus to a LINUX PC-based DAQ system. The signals were recorded and processed using ROOT-based software [24].

3. Results

Figure 6 shows a deposited-energy spectrum measured using the $^4$He scintillator detector. The top panel is plotted on a logarithmic scale to better illustrate the overall features of the spectrum, while the bottom panel is plotted on a linear scale to emphasize certain of these features. The very sharp leftmost peak in the figure located at about channel 80 is the pedestal or zero-energy bin in the QDC. Just to the right of the pedestal is the edge corresponding to our hardware threshold located at about channel 140. Recall that this discriminator threshold was $-60$ mV. The α particles which dominate the spectrum and correspond to the red trace in Fig. 3 correspond to the peak centered at about channel 190. Note that the entire α-particle distribution is not shown as the hardware threshold cuts into it. A distribution corresponding to heavy fission fragments (green trace in Fig. 3) is shown here centered at channel 950, while that corresponding to light fission fragments (blue trace in Fig. 3) is centered at channel 7.
Figure 5: A simplified overview of the experimental setup (not to scale). The $^4$He scintillator detector (which contains the $^{252}$Cf source) and the NE-213 detector are shown together with a block electronics diagram illustrating the time-of-flight concept employed.
channel 1310). Separation of fission fragments and α particles is not completely clean, as seen in the grey shaded area of Fig. 6 between channels 230 and 540. This could result from non-uniform scintillation-light collection, different energy losses of different particle types in the source as well as the thin Au source window, non-linearity of the scintillation, or even fission fragments striking the source holder. This will be examined in more detail in a future publication.

Recall that the average α-particle energy is ~6.1 MeV, while the average heavy fission-fragment energy is 80 MeV and the average light fission-fragment energy is 104 MeV. If we calibrate our QDC based upon the average energy deposition of the two types of fission fragments and then apply this calibration to the α-particle distribution, we reconstruct the α peak at ~12 MeV. 4He is often assumed to be a linear scintillator, while this preliminary analysis suggests an apparent non-linearity. However, as outlined above, there are several factors which will affect the apparent scintillation-pulse height. The degree of non-linearity in the scintillation (if any) requires an in-depth study. Note that for the data presented subsequently in this paper, a software fission-fragment cut located at channel 520 was employed.

Figure 7 shows a fission-neutron TOF spectrum obtained using the signal in the 4He scintillator detector to start a TDC and a signal from the NE-213 detector to stop it. Note that the spectrum shown corresponds to events lying above the software fission-fragment cut at channel 520 shown in Fig. 6. After this cut, interpretation of the resulting TOF spectrum is straightforward. The sharp peak to the left of the spectrum centered at about 5 ns and labeled “gamma-flash” corresponds to the detection of a fission fragment in the 4He scintillator detector and a correlated fission-event gamma-ray in the NE-213 detector. The ~1.8 ns FWHM of the gamma-flash distribution is consistent with the observed timing jitter on our PMT signals and the slight tail in the distribution is possibly due to time walk in the electronics. Note that 4He scintillator is highly insensitive to gamma-rays [14, 18] and any electrons produced via Compton scattering or pair production will result in only a very small scintillation signal. These events will be entirely suppressed by the relatively high software
Figure 6: Deposited-energy histogram measured using the $^4$He fission-fragment detector. Both panels present the same data set. The pedestal (leftmost blue peak), hardware discriminator threshold, software fission-fragment cut, and distributions corresponding to $\alpha$-particles (dominant peak), heavy fission fragments (green dashed line), and light fission fragments (blue dot-dashed line) are all shown. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)
Figure 7: Fission-neutron TOF spectrum. The gamma-flash and fission-neutron distribution are shown. The flat background is due to random events.

cut we have applied on the signals from the $^4$He scintillator detector. Thus, the present apparatus is almost completely insensitive to fission-associated multiple gamma-ray events. The broad bump centered at about 55 ns corresponds to the fission-neutron distribution. The underlying background distribution corresponds to random coincidences. It was measured to be flat as expected by breaking the line-of-sight between the $^4$He scintillator detector and the NE-213 detector using a stack of lead (∼15 cm) and polyethylene (∼10 cm).

Figure 8 shows the fission-neutron TOF spectrum from Fig. 7 converted to a neutron kinetic-energy spectrum. To convert from TOF to neutron kinetic energy, we used the 5 ns position of the gamma-flash shown in Fig. 7 and the 106 cm distance between the $^{252}$Cf source and the center of the NE-213 liquid-scintillator cell. The data were then rebinned linearly in kinetic energy. Also shown are three representations of the neutron-kinetic energy distribution constructed using the information presented by Thomas in Ref. [26]. We
Note that there are small differences between the representations, so a normalization factor has been applied to each so that they coincide with our data at 1.5 MeV. It should be emphasized that the present data have not been corrected for neutron-detection efficiency and that, with the present hardware neutron-detector threshold, neutron energies below 1 MeV cannot be corrected for reliably. At 1 MeV, the agreement between all three representations is essentially exact. Between 1 MeV and 4 MeV, the Maxwellian approximation and the ISO 8529-1 representation both lie below the ENDF/B-VII suggestion by 2% and 1%, respectively. By 5 MeV, the agreement between all three is again essentially exact. Above 6 MeV, a divergence between the representations begins and by 8 MeV, both the Maxwellian and the ISO 8529-1 representations lie above the ENDF/B-VII suggestion by about 9% and 4%, respectively. The ±1% level of agreement between all three representations of the $^{252}\text{Cf}$ fission-neutron energy spectrum over the energy region from 1 to 6 MeV is well within any systematic uncertainty that we are likely to obtain in measurements of neutron-detection efficiency using the tagging technique presented here. Thus, they provide an excellent benchmark from which it will be possible to evaluate the neutron-detection efficiency.

4. Summary

As a first step towards the development of an apparatus for the measurement of neutron-detection efficiency at our source-based fast-neutron irradiation facility, we have employed coincidence and time-of-flight measurement techniques to “tag” neutrons emitted by a $^{252}\text{Cf}$ source. The spontaneous-fission fragments are detected in a gaseous $^4\text{He}$ scintillator detector. The neutrons are detected in a NE-213 liquid-scintillator detector. The resulting continuous polychromatic beam of tagged neutrons has a measured energy dependence that agrees qualitatively with expectations. This preliminary study strongly suggests that the method of neutron-energy tagging will work well and future investigations will concentrate on quantifying systematic effects in order to optimize the perfor-
Figure 8: Fission-neutron kinetic-energy spectrum for $^{252}$Cf. The grey histogram is measured data. Also shown are the ISO 8529-1 recommendation (filled blue circles), a Maxwellian approximation (green triangles), and the ENDF/B-VII suggestion (open red circles) for the fission-neutron spectrum. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)
mance. We anticipate that the technique will provide a cost effective means for the characterization of neutron-detector efficiency, and note that this technique will work equally well for all spontaneous-fission neutron sources.

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