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Technical notes

Pillar-structured neutron detector based multiplicity system

John W. Murphy [a,*], Qinghui Shao [a], Lars F. Voss [a], Phil L. Kerr [a], Lorenzo Fabris [b],
Adam M. Conway [a], Rebecca J. Nikolic [a]

[a] Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 95440, USA
[b] Oak Ridge National Laboratory, 1 Bethel Valley Rd, Oak Ridge, TN 37830, USA

ABSTRACT

This work demonstrates the potential of silicon pillars filled with boron-10 as a sensor technology for a compact and portable neutron multiplicity system. Solid-state, semiconductor based neutron detectors may enable completely new detector form factors, offer an alternate approach to helium-3 based systems, and reduce detector weight and volume requirements. Thirty-two pillar-structured neutron detectors were assembled into a system with an active area of over 20 cm^2 and were used in this work to demonstrate the feasibility of this sensor technology as a potential replacement for helium-3 based gas detectors. Multiplicity measurements were successfully carried out using a californium-252 neutron source, in which the source mass, system efficiency, and die-away time were determined. This demonstration shows that these solid-state detectors could allow for a more compact and portable system that could be used for special nuclear material identification in the field.

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Neutron multiplicity counting is a powerful technique for the non-destructive assay of special nuclear materials. During the spontaneous fission process, the number of neutrons emitted can vary from zero to six or more. This technique, which was developed as an extension of neutron coincidence counting, analyzes the distribution of the detected neutron events with respect to time. Whereas neutron counting simply sums all detected neutrons and neutron coincidence counting analyzes pairs of neutrons that are detected within a certain resolving time period or gate width, neutron multiplicity counting sums separately the number of zero, single, double, triple, and higher multiples of neutrons detected within the resolving time. Qualitative and quantitative information can be deduced about the neutron source from this distribution. This technique finds application in materials accountability, verification, and confirmatory measurements, as well as excess weapons materials inspections [1].

Multiplicity counting systems generally utilize ^{3}He gas-based neutron detectors as their sensor element. These detectors are large, resulting in a bulky system that is difficult to transport, require high-voltage, and are subject to interference from microphonics [2]. Solid-state, semiconductor based neutron detectors have received renewed interest in recent years, in part due to the limited supply of ^{3}He. Microstructured Si detectors have been used in conjunction with ^{10}B [2–7] and ^{6}LiF [8–10] neutron converting layers, which absorb neutrons and emit heavy charged particles. There have also been demonstrations of thin-film CdTe detectors used in conjunction with $^{10}B_4C$ to produce low-cost, large-area neutron detectors [11,12], as well as "intrinsic" neutron detecting materials in which the film serves as both the semiconductor and the neutron converting material, such as chemically-vapor deposited ^{10}BN [13,14] and lithium containing chalcogenides, particularly $LiInSe_2$, grown by the vertical Bridgman method [15,16]. For a review of the physics and design considerations of solid-state neutron detectors see the 2010 paper by Caruso [17].

Another approach that has been under investigation recently is the use of neutron scintillator materials coupled to photo-multiplier tubes to directly measure the fast neutron output of fissioning material; this technique allows for much greater accuracy in neutron timing while also providing energy information. This can lead to a greatly reduced assay time, however these systems do suffer some of the same drawbacks as ^{3}He-based systems such as being bulky, relatively delicate, and requiring high voltage [18,19].

The multiplicity system described in this work consists of 32 ^{10}B coated Si pillar-structured neutron detectors which are split into two detector heads; each head contains 16 detectors with a combined detector area of approximately 10.5 cm^2 for a total active area of 21 cm^2. The development of the detectors has been previously reported [2–5]. Here we report, for the first time, the performance of a multiplicity system based on these detectors. The intrinsic thermal neutron detection efficiency of the detectors used in this system, at the optimal shaping time, is up to 35%. Each detector is connected to a custom preamplifier and shaping amplifier [20], the output from the shaping amplifier is discriminated and converted to a transistor–transistor logic (TTL) signal, and the TTL signal is fed into a custom multiplicity digital electronic data acquisition system.

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[*] Corresponding author.
E-mail address: murphy70@llnl.gov (J.W. Murphy).

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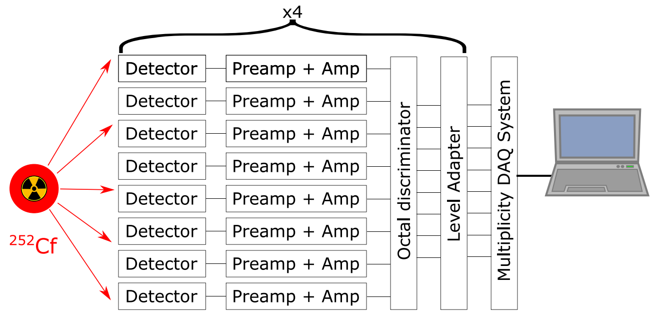

Fig. 1. Block diagram of 8 detectors (full system is 32 detectors—x4 indicates there are 32 detectors and amplifiers, as well as 4 octal discriminators and level adapters) connected to the data acquisition system through a discriminator and level adapter.

The prototype system described herein was tested using a 35 μCi ^{252}Cf source at a distance of approximately 6 cm. This arrangement was chosen to maximize the count rate of the system, so that the mass extraction could be performed quickly. Tests were also conducted in the absence of a source, as well as with the ^{252}Cf source placed at a distance of 50 cm to simulate a Poisson or (α, n) source in which the neutrons are not correlated in time.

The fabrication procedure of the detectors used in this system has been previously described [2–5]. Briefly, the detectors were fabricated on n+ silicon wafers, with a 47 μm thick epitaxial layer of n− Si, and completed with a 3 μm thick epitaxial layer of p+ Si. The silicon pillars were produced by dry etching to a depth of 45 μm to form circular pillars with a diameter of 2–5 μm and a spacing of 2 μm. These pillars were coated by chemical vapor deposition with a layer of ^{10}B. This boron layer was subsequently etched back to expose the top of the pillars, which were then metallized to form the p-type contact, and the backside of the n+ wafer was metallized to form the n-type contact.

The detectors were packaged into two separate detector heads, each containing 16 detectors. They were operated at 0 V applied bias with a custom-made charge-sensitive preamplifier and shaping amplifier, which operated with a 1 μs shaping time [20]. The arrays of amplifiers were coupled to the detector heads using approximately 25 cm of RG-174 coaxial cable for each channel. The system was tested using a 35 μCi (65 ng) ^{252}Cf source. The distance from the source to the center of the detector head was 6 cm; there was 4.5 cm of moderating polyethylene between the source and detector heads, and 5 cm of polyethylene backing the detector heads. Measurements were performed as both a function of the system area and measurement dwell time, and data was averaged over several such measurements.

The signal from the shaping amplifier was passed into a Phillips Scientific Model 710 octal discriminator, where the threshold was set to ensure there were no more than 2 counts per minute per channel in the absence of a source. This dark count rate was found to be sufficiently low that the random background counts did not interfere with the mass extraction, but also did not compromise the efficiency of the system. The discriminated signal was then passed through a Phillips Scientific Model 726 level translator to convert the nuclear instrumentation module (NIM) signal to TTL. Selected channels were summed before passing them into a custom built data acquisition system (DAQ) to capture the registered pulses in list mode format with a time resolution of 10 ns. The channels were summed in such a way as to allow for analyzing the data for an active detector area of 5, 10, and 21 cm^2—21 cm^2 being the full active area of all 32 detectors. A block diagram of the configuration for 8 detectors is shown in Fig. 1.

After collecting the list mode data from the multiplicity DAQ to a computer, the data set was analyzed using the Neutron Multiplicity Analysis Code (NMAC), developed at Lawrence Livermore National Laboratory. The NMAC program uses a standard Feynman moment analysis to extract parameters from the list mode data [21,22]. The data were analyzed by assuming the source neutron multiplication factor was one, the α-ratio was zero, and the source was purely ^{252}Cf.

Table 1
Results of 24-hour multiplicity measurements.

Area (cm^2)	Extracted mass (ng)	Mass error (%)	Extracted efficiency (%)
10	68.2 ± 10.3	13.0 ± 10.0	0.16 ± 0.03
21	69.1 ± 0.8	5.7 ± 1.2	0.30 ± 0.01

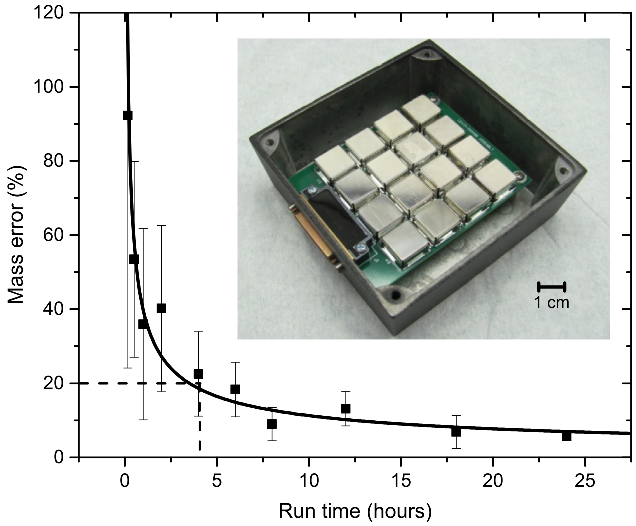

Fig. 2. Extracted mass error versus measurement time for the full 21 cm^2 array of detectors. The dashed lines indicate that the measurement error falls below 20% at approximately four hours. The inset shows one detector head with 16 packaged detectors within.

The data in Table 1 shows averaged results for three 24 h measurements analyzed using 10 and 21 cm^2 of detector area. The die-away time is typically quite high, >200 μs, due to the large amount of moderating HDPE both in front of and behind the detectors. The results for the 5 cm^2 measurement were omitted due to very high uncertainties.

The very high mass error and large uncertainties for the smallest area array, 5 cm^2, indicate that accurate measurement of the source mass is not possible on a reasonable time scale for a detector array area this small. However, because the doubles count rate is proportional to the system efficiency squared [1], and the efficiency scales directly with the active area, the mass can be accurately determined in just a few hours using an area four times as large. It can be seen in Table 1 that the extracted efficiency does scale approximately with the active area of the array. The extracted mass error versus measurement time for the full 21 cm^2 active area, shown in Fig. 2, demonstrates that the mass can be determined to within a 20% error after 4 h, and after 24 h the error is always less than 10%. The averaged data is fit with an exponential and shows that the mass error decreases as approximately $t^{-1/2}$—the exponential factor of the fit is 0.54.

Since the time to determine the source mass within a certain error should scale as the efficiency or the active area squared in this scenario, based on the doubles count rate, then one way to improve the dwell time required to determine the source mass within a certain error is to increase the size of the detector array. It is expected that by increasing the size of the array to 40 cm^2, only a one hour dwell time would be required to determine the source mass of 65 ng of ^{252}Cf to within 20% error. If 80 cm^2 of active area were used, roughly the area of a 4″ silicon wafer, then only approximately 15 min would be necessary for this particular source–detector distance and experimental setup.

In this study, the shaping time of all of the amplifiers was set at 1 μs, which was found to be the best shaping time for the majority of the detectors used in this study. However, it was found that if the shaping time can be optimized for each detector, a significant improvement