Characteristics and Performance of an Integrated Portable High Efficiency Neutron Multiplicity Counter for Detection of Illicit Neutron Sources

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Abstract
In the interdiction of illicitly trafficked Special Nuclear Material (SNM) the neutron signal is a valuable adjunct to the gamma-ray signature. Neutrons are not attenuated by heavy metal shielding which might be used to shield the gamma rays emitted by the source. However, "gross-counting" neutron detectors are unable to distinguish neutrons in the environmental background from those emitted by a neutron source. The most challenging interdiction situation for neutron detection is the case where the neutron count rate is up to ten times the average background. Count rates higher than this are readily detectable with gross counting instruments. Below this level however, gross counters have major problems due to innocent alarms.

A portable instrument has been developed which incorporates 30 moderated ^{3}He tubes, multiplicity counting electronics and software capable of discriminating against non-correlated neutron events, thereby greatly increasing the sensitivity of detection of SNM. The instrument is packaged in a way that is easily transported in a motor vehicle and to be rapidly deployed as needed. The instrument is described and performance data are presented.

Introduction
Neutron Multiplicity counting is a technique familiar to those in the business of nuclear materials assay, but less so to those engaged in homeland security applications. The fact that SNM emits multiple (coincident) neutrons is a big factor in its utility as reactor fuel or a nuclear weapon. In nuclear materials assay, the fact that SNM emits multiple neutrons simultaneously can be used to derive equations which allow for the determination of sample mass without requiring an absolute efficiency calibration for the neutron coincidence counter.

Less well known is that the time-coincident or correlated nature of neutrons emitted from SNM can be used as a way of discriminating from non-correlated sources or sources correlated differently, thereby helping greatly in the identification of threat neutron sources which might be encountered by security organizations.

The most challenging interdiction situation is the case where the neutron count rate is between average background and about ten times average background, although the higher neutron fluxes are readily detectable with a portable instrument such as the ORTEC Detective-EX. This "slightly-elevated" count-rate regime is challenging because legitimate, non-fissile cargo can cause increases in background. This change is due to the interaction of cosmic rays with nearby metal such as iron and can increase the background by a factor of 10, making the detection of fission sources for example on board a ship extremely difficult.

Because of these variations, attempts to detect the presence of a man-made neutron source based on an increase in count rate above background are not very effective, unless the source is so strong that the count rate increases to many times background. It is clearly a challenge to discriminate man-made neutron sources from background when the overall count rate is less than ten counts per second. Ten counts per second may represent an increase over the typical background of about three times, but is still difficult to discriminate with the typical handheld or backpack search instrument, because of the lower efficiency of these instruments.

A transportable instrument is reported here which, through the use of multiplicity counting, is able to separate cosmic from non-cosmic neutron sources. It can provide supplemental data to expert teams who can use more sophisticated analysis techniques to fully characterize suspicious neutron sources encountered at a border crossings or searches.

Neutron Multiplicity Distributions

There are several explanations of neutron multiplicity in the literature (see e.g. reference (1)); a very short review is given here.

The key neutron signature for SNM results from the fact that the spontaneous fission process emits multiple neutrons in closely spaced temporal groupings. The number of neutrons emitted in spontaneous fission can vary from zero to six or more. The process is random, or statistical, in nature, and the probability distribution of the number neutrons is referred to as the "neutron multiplicity distribution".

Total neutron counting counts all the emitted neutrons without further analysis. Neutron coincidence counting looks for pairs of neutrons within a small time window. Multiplicity counting counts separately the number neutrons detected within a time gate (e.g., none, 1, 2, 3, 4, 5, 6, 7…).

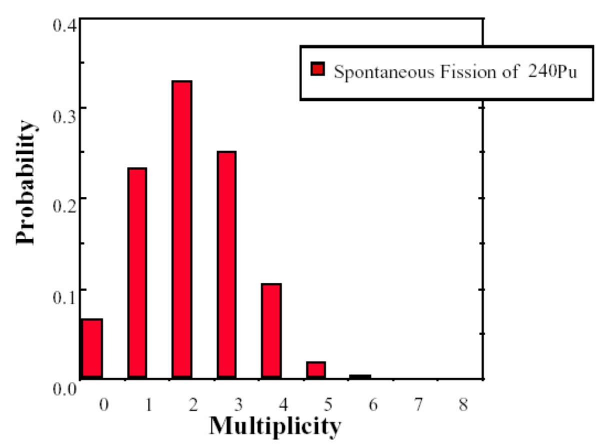

Figure 1 Multiplicity distribution of spontaneous fission neutrons in ^{240}Pu

The average spontaneous fission multiplicity associated with ^{240}Pu is reported to be about 2.16 and is characteristic of the material. In an actual ^{240}Pu source, there is also the possibility of induced fission which changes the observed multiplicity. The observed multiplicity depends on the efficiency of detection.

Figure 2 (from ref 1) shows the count distribution of an AmLi random neutron source. The AmLi source emits uncorrelated neutrons because they are produced by (α,n) reactions where the α-particles emitted by the ^{241}Am source expel neutrons from the Li target. The count distribution for uncorrelated neutrons follows Poisson statistics.
The observed distribution is assumed to be the sum of the individual distributions contributing to the neutron flux. A simple way to characterize a count distribution is the variance-to-mean ratio[2], R, given by

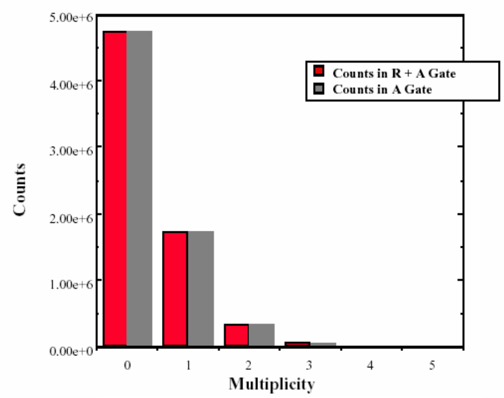

Figure 2 Count Distribution of an AmLi random neutron source

$$R = \frac{\overline{C^2} - \overline{C}^2}{\overline{C}}$$

where $\overline{C}$ is the first moment and $\overline{C^2}$ is the second moment of the count distribution. For a random (Poisson) distribution the ratio is unity. If correlation is present, the ratio, R, is not 1. (The Feynman Variance (Y2F), is defined as (R-1)/2.) To determine the presence of an SNM source therefore it is required that we determine if R can be distinguished from random (Poisson) background or from correlated, but not SNM, sources such as are produced in cosmic ray showers. If the multiplicity distribution can be unfolded from the other interferences in the distribution, then the identity of the fission source can be determined or at least an "educated guess" can be made.

Description of the Instrument

The purpose of the instrument is to identify when a small increase above background in the neutron count rate of the detector due to man made sources by recording the single and multiple neutron counts. The design objective was to be sensitive enough to see the correlation in natural background in a reasonable count time. The system, "Fission Meter™"[3], is designed to achieve high neutron detection efficiency in an instrument which is reasonably portable. Time-correlation is used as a way of distinguishing the different types of neutrons present in the flux on the detector. The instrument had to be large enough to provide reasonable efficiency for detection of multiple time-correlated, but not spatially correlated, neutrons.

The instrument is arranged in a folding format so that it can be "wrapped around" a suspect package for optimum counting geometry. Each panel has a "thin side" and a "thick side" HDPE moderator, giving optimal detection of fast or partially thermalized neutrons. The ^{3}He tubes are 1 inch diameter with 19 inches active length and 7.5 ATM gas pressure. Each panel contains 15 ^{3}He tubes specially selected for low microphonics.

Figure 3 Instrument hardware showing 3He tubes

Figure 4 Instrument hardware, moderators in position

The detector sub-system includes the HV supplies for the He tubes and the preamplifier/discriminator units required to record the neutron events.

Figure 5 Instrument Front Panel

Figure 6 Instrument being carried

Located at the top of one of the two detector panels, the integrated electronics subsystem is powered by readily available D-Cell alkaline batteries. The multiplicity electronics provides 512 time gates. System software operates on an associated ruggedized hand-held computer included with the instrument. In addition to software control, the system may be controlled manually from the front panel. The instrument weights 57 lbs and may be carried on a shoulder strap (Fig 6).

Instrument Software

Mobile Search Mode

Mobile Search Mode (Fig 7) is a survey mode to monitor total neutron count rate above a sliding background. Both the standard deviations and the Feynman variance, Y2F, which is zero for a Poisson source and non-zero for a correlated source, are monitored. The two parameters are displayed with their own "strip charts," showing the values as a function of time, and a "barometer" that gives instantaneous values compared to an alarm threshold. Persistently high values of count rate over background and/or of Y2F indicate a material with correlated neutrons.

Static Search Mode

If the Mobile Search Mode shows a potential fissionable source, or other information indicates a suspicious package, the static search mode (Fig 8) is used to collect data for 15 to 20 minutes or at least 30,000 counts to better characterize the object. The background is not updated in this mode. During the count, the software tells the operator to continue counting to improve the coincident counts. If a consistently high and

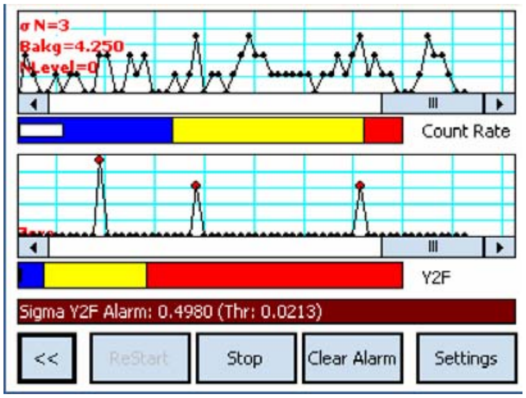

Figure 7 Mobile Search Mode

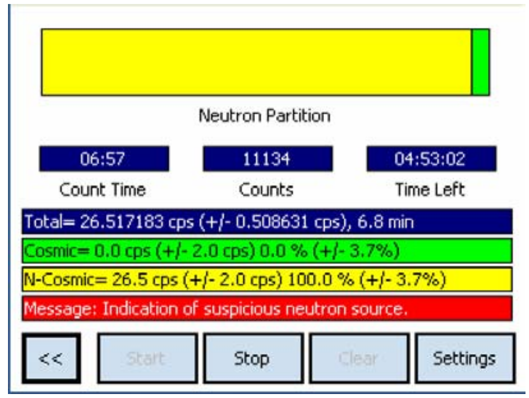

Figure 8 Static Mode Search

statistically valid reading is obtained for the non-cosmic fraction, a red message bar confirms the presence of a suspicious neutron source. This would normally be the point at which an operator would send data to an expert team for in-depth analysis.

Experimental Instrumental count distributions

The performance of the instrument is based on it being a Multiplicity Counter. This allows the determination of the fission source component from the flux from other correlated sources. Multiplicity or coincident neutrons can come from 1) random coincidences (based on count rate and neutron pulse width), 2) multiple neutron cosmic events, 3) fissioning sources. The distribution of the singles vs doubles vs triples (and higher) is different for each of these. Fitting the measured distribution by these functions will give the fraction of each contributing to the total.

A count distribution is made up of the number of times a particular neutron count is observed in a 512 micro-second time interval. This short time interval is repeated typically several million times. The count distributions presented here give the number of times zero counts and one count and two counts and three counts were observed in the time slots, in this order. To illustrate the operation, two examples will be discussed: 1) typical background, 2) californium source, 3) fissioning source.

Example 1 “Typical Background”

Typical background consists of single neutrons and neutron groups from multiple neutron events caused by cosmic rays. The Poisson distribution of the events will cause some “random” coincidence events. Using the observed singles count rate and the device characteristics, the random coincidences can be calculated. The background count distribution in table 1 below was obtained by collecting for about one hour. Total counts collected were 8552 in 61.59 minutes. This is a count rate of 2.31 cps.

Multiplicity	0	1	2	3
"Actual" background	7209176	8463	43	1
expected background	7209166	8481	34	0
Poisson	7209136	8541	5	0

Table 1 Background Multiplicity Distributions

The instrument display shows 100 +/- 4.6% cosmic fraction and 0 +/- 4.7% non cosmic fraction. The "expected" background count distribution for this count rate is given in the second line. The "expected count rate" is derived from an empirical model which takes account of correlation in the cosmic background itself. If at the same count rate the source were 100% Poisson, the count distribution expected would be as line 3.

The data from table 1 is plotted in Fig. 9. Correlation is indicated by the presence of events with higher order multiplicity in the distribution. As can be seen from the table or from the figure, the actual background is slightly more correlated than the expected background, but both are much more correlated than the pure Poisson distribution. Our "expected background" model is underestimating the amount of correlation in the actual background.

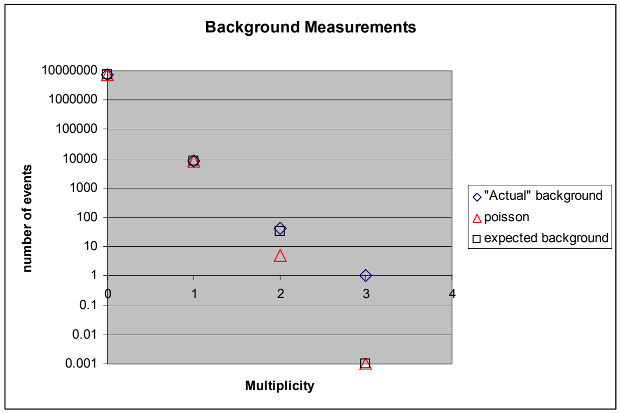

Figure 9 Log plot of data from table 1.
(Note: zeros are plotted as 10^{-3})

Example 2 "Weak Californium source", 10 to 15 meters distant

A man-made neutron source was used to increase the count rate seen by the instrument. The source needed to be many meters distant before the count rate increment was low enough to be near that of the background rate. The data are tabulated in Table 2 and plotted in figure 10.

Multiplicity	0	1	2	3
Weak Cf-252 10m distance	1559722	6299	20	0
expected background	1559736	6269	34	0
pure fission	1559716	6310	13	0
Poisson	1559714	6313	12	0

Table 2 Distant ^{252}Cf source**.**

The data for a 13 minute count consists of 6339 counts, at an observed rate of 7.9 cps. The multiplicity distribution is in the upper line of the table. The background distribution expected for this count rate is in line 2. In line 3 the pure fission source count distribution expected for this count rate is given. For a fission source, the observed count distribution is fit to a fission count distribution where the efficiency is a free parameter in fitting the data. The Bottom line of Table 2 shows, the expected Poisson distribution for

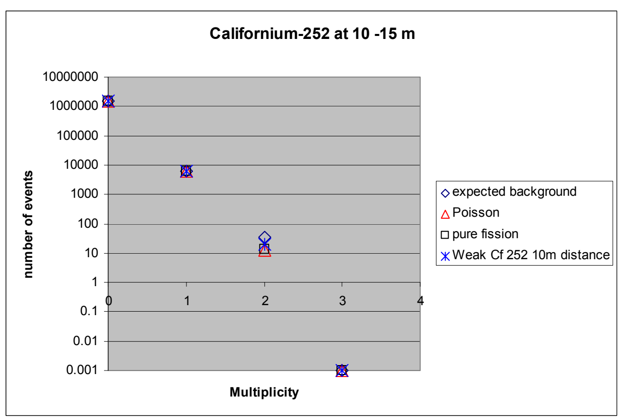

Figure 10 Log plot of data from table 2.
(Note: zeros have been plotted as 10^{-3} for display purposes)

this count rate. These data are plotted in Figure 10.Note that the Fission and Poisson distributions are very similar. This is because the Fission Meter Software observes that a hypothetical fission count distribution can only be similar to the data if the efficiency is very low, in this case this is because of the 10-15 meter distance between source and detector. Very low efficiency fission source measurements look Poisson. A higher efficiency fission count distribution would have a larger tail (more higher-order coincidences).
By inspection, the measured data is somewhere between the expected background shape and the Poisson or fission distribution. A fit of the data to the two count distributions works out to a split of 5.6 cps for the distant ^{252}Cf source and 2.3 cps for background. Note the background count rate for this instrument is about the same as the prior example. Both measurements were made in the same environment. Because the count time is short, the error bar on the count partitions is about 1 cps. At this point in time, the non-cosmic portion is confirmed. The non-cosmic fraction is about 70 +/-11% providing a strong indication of a distant man made neutron source.

Example 3: Measurement of a low count-rate Depleted-uranium billet
This example measurement is of particular interest is given because it is the expected situation where a container is to be shipped somewhere and shows the close proximity, or "near" static-search measurement. The question is whether there is a fission source in the package. Depleted uranium is a fission source, so the instrument should indicate fission.

The count rate from a typical Mo^{99} isotope generator with a DU shield is no more than a few counts per second above typical background, when the Fission Meter is close to the generator (neutron source). For the instrument to be most effective, an increase in count rate of at least 20% over background needs to be obtained. Multiplicity events are well detected with a measurement distance of up to 50 cm or a little more. The example measurement of the DU billet was 5.9 cps, with the detailed count data as shown in Table 3 and graphically in Figure 11.

Multiplicity	0	1	2	3	4
Low count rate DU billet	6979006	20843	149	1	0
expected background	6878961	20930	105	0	
Poisson	6978886	21080	31	0	

Table 3 Depleted uranium Billet

The Fission Meter makes two calculations with the data based upon internal constants. One assumes the source is far away and one that the source is near. The far result for this data shows the measured count distribution to be 100% cosmic. The near result shows a non-cosmic fraction of 5 cps. The operator knows the source is near so he selects the near result.

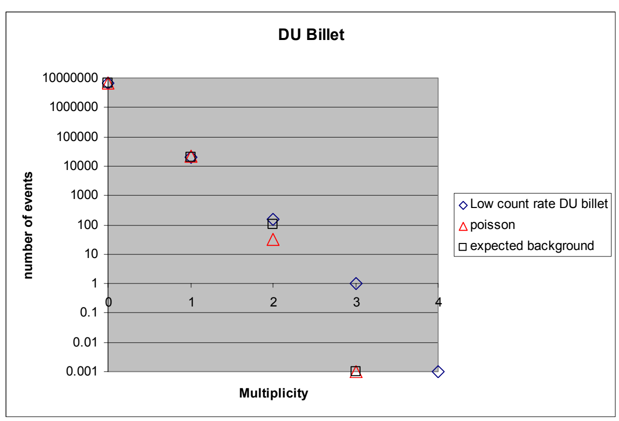

Figure 11 Log plot of data from table 4.
(Note: zeros are plotted as 10^{-3})

By comparison, the measurement is clearly more correlated than the expected background shape, and far more correlated than a Poisson expectation. This excess in correlation is correctly recognized by the user when making a near measurement with the instrument, by using the near result of 5 cps. The quoted fission neutron sensitivity limit for the instrument is about 20% of the total count rate and accounts for the deviation from the expected count rate of about 4 cps. This positive “near” result indicates a fission source is present and further investigation of the package and the data is needed.

The Fission Meter Plot is of great value to the user or to a DOE Triage Program. It helps identify high multiplication in the data. This plot is an overlay of the measured data and the expected Poisson count distribution, normalized for the same count rate as the measured data making visual comparison between the non-fission source expectation and multiplication, which causes the count distribution tail to noticeably diverge from the Poisson data. The larger the deviation from Poisson, the higher the multiplication. Figure 12 shows the Poisson distribution for a typical Fission Meter plot in red and a measurement where shown in blue, the multiplication is much higher than the previous depleted uranium example. The vertical axis is the number of counts for each multiplet (zero to 4). When there is a noticeable deviation from Poisson as in this case, the data must be further analyzed.

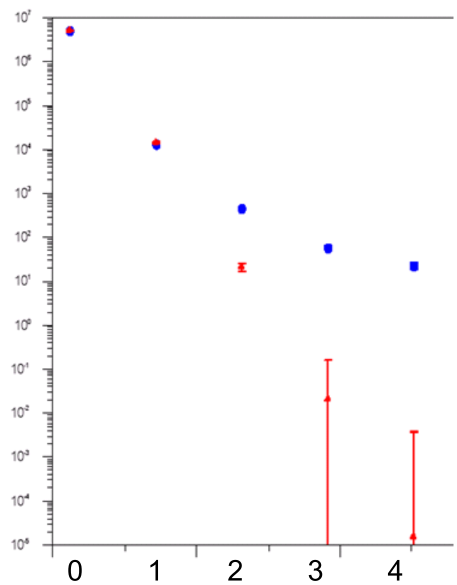

Figure 12 High multiplication sample (blue) compared to Poisson (red)

Conclusion:
A portable neutron detection instrument has been developed which employs multiplicity analysis on a hand held computer to identify fission sources, as part of the process of interdiction of nuclear materials trafficking. It has been shown that the instrument can segregate fission sources much more effectively than can be done with other techniques.

References
[1] N. Ensslin,W. C. Harker, M. S. Krick, D. G. Langner, M. M. Pickrell, J. E. Stewart, “Application Guide to Neutron Multiplicity Counting,” LA-13422-M Manual UC-700, 1998
[2] D Reilly, N. Ensslin, H.Smith Jr, S Kreiner, “Passive Nondestructive Assay of Nondestructive Materials”, LA-UR-90. 1991.pp 465-466
[3] LLNL license TL-01962-0.0