A flexible and modular fast neutron multiplicity counter for correlated nuclear data research

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Abstract:

We describe a new form of flexible multiplicity counter to address gaps in fission nuclear data by measuring a broad range of correlated neutron and gamma-ray signatures with high angular and energy fidelity. The detector consists of independent modules of ^{6}Li-doped pulse shape discriminating (PSD) plastic scintillator, sensitive to both fast and thermal neutrons. The modules will be between 0.5 and 1 meter in length and with a 5 - 10 cm square cross section. The proposed length scales reflect the intrinsic attenuation lengths achievable in ^{6}Li-doped PSD plastic. The modules will contain no liquid scintillator, will be rugged and easily movable and reconfigurable around a central test fission source. The anticipated position sensitivity within each module is expected to be at the same level as the cross section (~5 - 10 cm). The angular uncertainty will depend on the distance of each module from the test fission source. The modules may be placed at greater distance from a source to optimize for time-of-flight fidelity or adjacent to the source to optimize detection efficiency. Modules may be mixed and matched with gamma-ray detectors or ^{3}He tubes to address different gaps in nuclear data as required. The whole system may be scaled to any number of modules in principle if very high efficiencies are required.

Introduction:

Nuclear fission produces prompt neutron and gamma-ray emission from the resulting excited fission daughters as they return to their respective ground states. Correlations in energy, angular distribution and multiplicity have been observed between these prompt particles, but they are not very well understood [1]. Better models of this process will provide better predictions and telltale clues as to the nucleus responsible, which has applications in Nuclear Nonproliferation and Safeguards. Significant effort has been initiated towards more fully understanding fission parameter correlations. At present the nuclear data libraries (e.g. ENDF) do not accurately predict the behavior of correlations between the many neutron and gamma-ray parameters of interest. Monte Carlo fission models such as FREYA and CGMF have been incorporated into the MCNP code in an effort to better understand the complicated interactions. Better high efficiency data, with minimal systematic uncertainties, is needed to help validate these models.

Despite recent developments in detection methods to improve experimental data on correlated signatures, further improvements may be attainable. Contemporary detectors consist of a series of discrete detectors placed at various angles around a fission source in such a way as to optimize for energy and angular resolution. Examples are the Chi-Nu array [2] at LANL, an array of 24 EJ-309 and 8 NaI scintillators at U. Michigan [3,4], and the DANCE/NEUANCE array at LANSCE which consists of a vast array of gamma-ray detectors together with a smaller array of

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stilbene detectors [5]. Some of these detectors approach 4π solid angle coverage, especially in gamma-ray detection. Reaching neutron detection efficiencies that approach 100% using vast arrays of discrete stilbene or liquid scintillator detectors in this way is doable but expensive.

It may be possible to maximize neutron detection efficiency while maintaining excellent energy, position and angular resolution using one of the new forms of large volume ^{6}Li-doped pulse shape sensitive plastic scintillators presently attainable. The recent development of liter-scale (Figure 1) stable formulations of ^{6}Li-doped PSD plastic scintillator with similar performance characteristics to liquid formulations [6], enables the realization of a large volume neutron multiplicity experiment with a stable, scalable and rugged raw material.

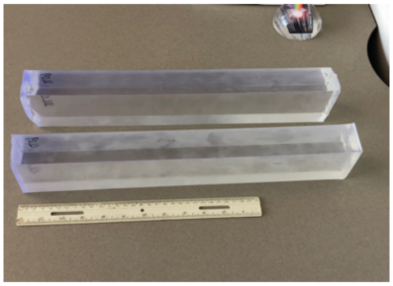

Figure 1: Two recent examples of liter-sized samples of 0.1% ^{6}Li doped PSD plastic scintillator.

Optimal detector configurations for correlated fission parameters:

This paper will focus primarily on neutron detection. The detector concept described here consists of an array of independent neutron detector modules made of ^{6}Li-doped PSD plastic. The array may be arranged in any desired formation around a fission source, fuel element or object of interest. Gamma-ray detectors may also be positioned between the neutron detector components if gamma-ray energy, multiplicity or angular information is needed.

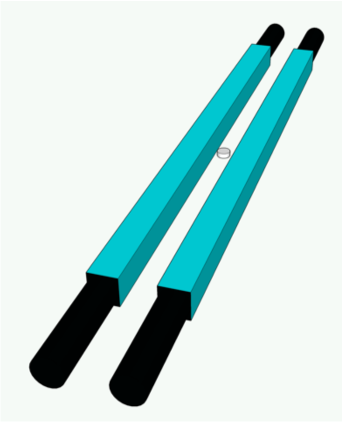

Figure 2: The initial 2 module test configuration shown with a central hypothetical fission source. The photodetectors shown are PMTs, although SiPMs would also be a practical solution.

Each neutron detector module consists of a single long piece of ^{6}Li-doped PSD plastic scintillator, wrapped in a specular reflective cover, read out by photon detectors at either end. The photon collection is most efficient using this kind of module design, maximizing energy resolution and pulse shape sensitivity. The position of each event along each bar will be determined using a combination of relative photon detector timing and charge. The detector module configuration shown in Figure 2, shows a fission source located at the center between two modules. Since the concept is modular and expandable, any number of modules can be arranged at solid angle coverage approaching 4π to maximize efficiency. The motivation for plastic rather than liquid is driven by both practical and scientific considerations. Liquid requires non-scintillating containment materials and expansion volumes to adjust for atmospheric pressure changes, as well as secondary containment and fire mitigation. These factors tend to reduce the flexibility with which the detector configurations can be adjusted. Non scintillating material also reduces efficiency and increases systematic uncertainties. Recently, ^{6}Li-doped plastic scintillator has been produced with attenuation lengths of ~70 cm, so it is realistic to consider modules at the few liter-scale.

A 40 cm long test module with 2.5 cm square cross section was constructed and characterized so as to tune a GEANT4 simulation for predicting the response of larger modules. The module was wrapped in a non-specular reflective material (Teflon tape). Figure 4 (Left) shows an example of

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the response from a ^{137}Cs gamma-ray source collimated at the center of the bar and compared to simulation. Figure 3 (Right) shows how the relative response of the PMTs changes as a function of position along the bar. Figure 4 shows the pulse shape sensitivity observed from a ^{252}Cf source. Two bands corresponding to the gamma-rays (lower band) and fast neutrons can be seen extending across all energies. A high-density region of events in the neutron band at ~0.5 MeVee corresponds to a population of neutron captures on ^{6}Li. After tuning, the simulation showed that the intrinsic attenuation length was consistent with ~70 cm.

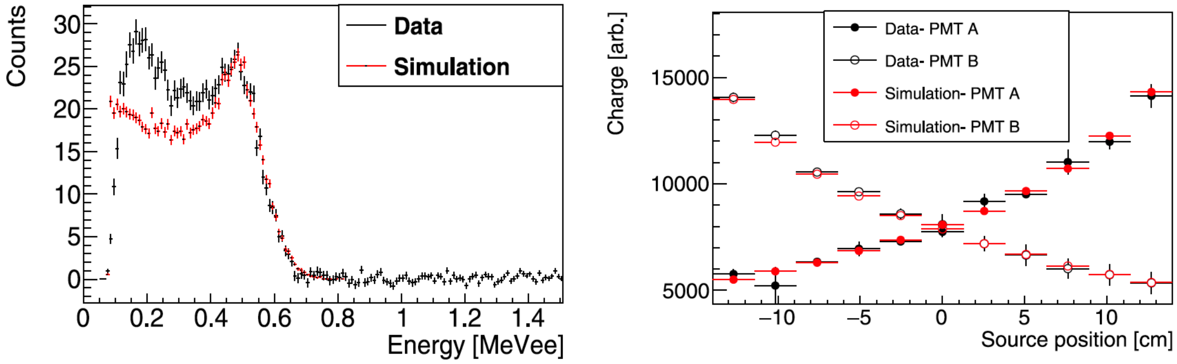

Figure 3: The ^{137}Cs spectrum (Left) obtained from a 2.54x2.54x40 cm bar wrapped in Teflon tape. The simulation matches the ^{137}Cs Compton edge well, but doesn't match at lower energies. The lack of agreement below 0.4 MeV was attributed to an incomplete inclusion of all the surrounding objects in the simulation. The figure to the right shows the relative response of the PMTs on either end of the bar as a function of source position along the bar.

Once tuned, the simulation was used to predict the performance of a single 60 cm long 5x5cm bar wrapped in a specular reflective material (3M DF2000MA), assuming the same 70 cm intrinsic attenuation length. Assuming a Watt spectrum with mean energy of 1 MeV, the intrinsic fast neutron *interaction* efficiency estimated from this simulation was 81±6%. The position resolution for electrons at 1 MeV based on the relative PMT signals was ±1.2 cm, while for protons was ±2.5 cm. The PSD sensitivity can be estimated from the smaller bar tests assuming that the FOM scales proportionally to $\sqrt{N_{PE}}$, where N_{PE} is the number of photoelectrons detected.

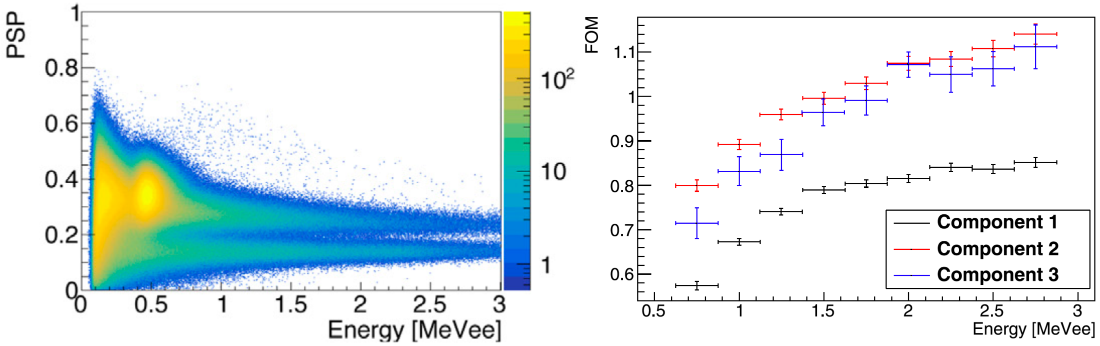

Figure 4: The Pulse shape sensitivity of the 2.5x2.5x40 cm bar as a function of electron equivalent energy (Left) using just the comparison between the gamma-ray candidate band at PSP values ~0.15 and the fast neutron candidate band at PSP ~0.3. The FOM obtained from the Left-hand plot as a function of energy (RED, Right). The blue and black FOM values were obtained for similar bars - a 2.5x5x40 cm bar (Blue),

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and some .5x.5x40 cm long unwrapped rods [7].

Table 1 shows the basic performance metrics predicted by the simulation. A full-scale version of this concept, consisting of an array of 10-20 identical modules can be envisioned as shown end-on in Figure 5. No non-scintillating containment material would be required to support plastic scintillator, though each module would need to be contained within a thin light tight container. The configurations shown are arranged to minimize neutron escape routes, and to achieve solid angle coverages approaching 4π.

The flexibility of the design permits any one or more parameters to be emphasized if desired, depending on the measurement required. Fast neutrons will be detectable on a ~10 ns time scale, while thermalized neutrons can be captured on a 40 μs time scale. The fast neutron energy and position resolutions will afford significant sensitivity to neutron energies and angular correlations over a significant solid angle.

The first phase of the project will consist of building a simple 2 module arrangement (see Figure 2) to determine the performance characteristics we can expect from each module within a full-scale system. A benchmarking campaign will be performed against an existing commercial fresh fuel verification instrument called the CAENSys VeryFuel.

The full-scale multiplicity counter concept is designed to optimize neutron efficiency. High resolution neutron time-of-flight measurements may be accommodated by moving modules further away from the source to improve neutron energy resolution.

Consider a detector comprising modules arranged as shown in Figure 5 (Right). If we assume each module has a cross section of 5 cm x 5 cm, with length 60 cm, the solid angle coverage of the detector will be a little over 3π. For neutrons sampled from a Watt spectrum with mean energy of 1 MeV, the predicted neutron interaction efficiency is 66%. The detection efficiency will be somewhat lower, depending on the detection threshold. An analysis threshold of 0.2 MeVee (~40 PE in both photon detectors), would result in a detection efficiency of 26%, or a 17% total intrinsic detection efficiency (26% x 66%). One complicating factor that may impact efficiencies, energy and position resolutions is the likelihood of multiple correlated neutron interactions occurring within a single bar. We have not included a consideration of this effect in this paper. However, an attempt to quantify this effect will be made when the two module first phase is built.

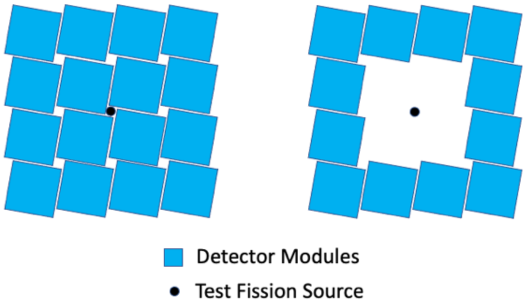

Figure 5: Two examples of arrangements of detector modules around a test fission source at the center. Module rotations as shown permit space for a small source while reducing avenues for neutron escape (left), or reduce avenues for neutron escape (right). thereby maximizing efficiency.

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Table 1: A brief summary of some of the key detector characteristics based on a GEANT4 simulation of early single module tests.

Detector Characteristics	
Detector Medium	^{6}Li-doped PSD plastic scintillator
Module Size	5 cm x 5 cm x 60 cm
Arrangement	Flexible
Position Resolution (electrons @ 1 MeV)	±1.2 cm
Position Resolution (protons @ 1 MeV)	±2.5 cm
Energy Resolution (electrons @ 1 MeV)	±5% (electrons at 1 MeV)
Energy Resolution (protons @ 1 MeV)	±10% (protons at 1 MeV)
Fast Neutron Detection Time	~10 ns
Neutron Capture Time	40 μs

Conclusion:

Nuclear fission produces correlated prompt neutrons and gamma-rays. The timing, energy and angular distributions of these particles are well known. However, the observed parameters are correlated in ways that are complicated and less predictable. Fission models such as FREYA and CGMF have been constructed to better understand these correlations. However further validation is required from data. Large ~4π gamma-ray detector arrays have been built to study the gamma-ray component of these correlations. Here, we describe a large solid angle detector concept to detect the fast and thermal neutron component. The detector arrangement consists of an array of identical "bars" of ^{6}Li-doped PSD plastic scintillator, with specular reflective wrapping and photon detectors coupled at both ends. This arrangement is relatively simple to build using plastic scintillator and far less complicated than similarly sized liquid scintillator modules. The material cost is moderate, especially when compared with stilbene, or other fast neutron sensitive crystals. Most importantly, the arrangement of modules around a central source can easily achieve large solid angle coverage AND competitive energy and position (angular) resolution.

The performance predictions reported here were produced by a simulation tuned to reproduce the performance parameters of a 40 cm long bar (2.5 x 2.5 cm). These results will be tested further with the planned construction of a two-module detector, proposed for 2022. In addition to the performance metrics listed here, the two-module detector will be benchmarked against a CAENSys VeryFuel neutron collar designed for fuel element characterization.

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