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Using anisotropies in prompt fission neutron coincidences to assess the neutron multiplication of highly multiplying subcritical plutonium assemblies

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ABSTRACT

There is a significant and well-known anisotropy between the prompt neutrons emitted from a single fission event; these neutrons are most likely to be observed at angles near 0° or 180° relative to each other. However, the propagation of this anisotropy through different generations of a fission chain reaction has not been previously studied. We have measured this anisotropy in neutron–neutron coincidences from a subcritical highly-multiplying assembly of plutonium metal. The assembly was a 4.5 kg α-phase plutonium metal sphere composed of 94% ^{239}Pu and 6% ^{240}Pu by mass. Data were collected using two EJ-309 liquid scintillators and two EJ-299 plastic scintillators. The angular distribution of neutron–neutron coincidences was measured at 90° and 180° and found to be largely isotropic. Simulations were performed using MCNPX-PoliMi of similar plutonium metal spheres of varying sizes and a correlation between the neutron multiplication of the assembly and the anisotropy of neutron–neutron coincidences was observed. In principle, this correlation could be used to assess the neutron multiplication of an unknown assembly.

1. Introduction

Characterizing the neutron multiplication of unknown assemblies of special nuclear material (SNM) is an important area of research for nuclear arms dismantlement verification. The multiplication of an assembly is defined as the total expected number of neutrons created within the assembly for one incident or source neutron. Sources that do not sustain fission chain reactions, such as AmBe or ^{252}Cf, can be distinguished from sources capable of sustaining fission chain reactions, such as weapons-grade plutonium or highly-enriched uranium, by measurements of the multiplication of the source.

A widely-used technique for measuring the multiplication of an assembly of SNM is neutron multiplicity counting. In this technique, ^{3}He proportional counters surrounded by a neutron moderator such as high density polyethylene are used to measure neutron singles, double coincidences, and triple coincidences. The multiplication of the assembly can be inferred based on these count rates and fundamental nuclear data parameters [1]. Despite the success of this technique, there are several disadvantages to this method. One significant disadvantage is that the neutrons from the source must be thermalized to be detected with acceptable efficiency in the ^{3}He proportional counters. The thermalization process obscures some information about the neutrons emitted by the source, such as their original energies and emission directions.

Here, we propose to use the anisotropy of coincident prompt fission neutrons to assess the multiplication of a subcritical assembly of plutonium. Experimental measurements and simulations will show that the anisotropy of coincident prompt fission neutrons depends on the multiplication of the subcritical assembly. Specifically, it will be demonstrated that the prompt neutron coincidences are anisotropic for bare spheres of weapons-grade plutonium with neutron multiplications below 3, and the coincidences are isotropic for these materials with multiplications above 3.

In nuclear arms dismantlement verification, it is critical to prevent the disclosure of sensitive details about the nuclear material itself, such as its mass, multiplication, or geometry. Other techniques have focused on using information barriers or zero-knowledge proofs [2] to prevent the disclosure of this classified information. However, in this case the information barrier is related to the fundamental physics of the process itself, since any neutron multiplication above a critical value will result in an isotropic coincidence angular distribution. Therefore, the actual value of the multiplication cannot be recovered from measuring the

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coincidence angular distribution; all that will be known to inspectors is that the material had a large neutron multiplication. This physics-based information barrier could be particularly useful for nuclear arms dismantlement verification.

Section 2 describes some of the measurements and theory of the neutron–neutron coincidence anisotropy and projects how this anisotropy might propagate in fission chain reactions. Section 3 discusses an experimental measurement of a highly multiplying subcritical assembly of plutonium. The analysis and results of that experiment, and MCNPX-PoliMi and GEANT4 simulations of the experimental setup, are provided in Section 4. Results from simulations of spherical plutonium assemblies of varying sizes are discussed in Section 5. Finally, conclusions based on the present studies are given in Section 6.

2. Previous work on prompt fission neutron coincidence anisotropy

The angular distribution of coincident prompt fission neutrons was first measured in Ref. [3]. In that experiment, fast neutrons induced fission within a sample of ^{235}U, and the prompt neutron coincidence count rate was measured for two detectors as a function of the relative angle between the detectors. They observed a higher coincidence rate when the detectors were placed at 180° relative to each other than when they were placed at 90°. Since that initial experiment, many additional measurements of the angular dependence of prompt neutron coincidences have been performed for spontaneous fission of ^{252}Cf [4–6] and neutron induced fission of ^{235}U [7]. The general observation of these measurements is that prompt fission neutrons from the same fission event are correlated in angle. They are most likely to be observed at 0° or 180° relative to each other and least likely to be observed at 90° relative to each other. This anisotropy in the neutron–neutron coincidences has a demonstrated applicability in extracting the ratio of the spontaneous fission rate to the (α, n) rate in oxide samples of SNM [8].

The cause of the angular correlation between the neutrons is evident when examining the time scale for the predominant method of generating prompt neutrons. The majority of the prompt neutrons are emitted after the fragments have nearly fully accelerated [9]. It is generally assumed that the neutrons are emitted with no preferred direction in the rest frame of each fragment. However, because the fragments have already nearly fully accelerated, the prompt neutrons tend to travel in the direction of the fission fragments. The fission fragments themselves travel at 180° with respect to each other because they are accelerated due to their mutual Coulomb repulsion. Therefore, the neutrons emitted from the same fragment will tend to appear at angles near 0° relative to each other, and the neutrons emitted from complementary fragments will tend to appear at angles near 180° relative to each other.

The angular dependence of the prompt neutron coincidences also depends on the prompt neutron energies. Neutrons traveling in the same direction as the fission fragment will receive a larger velocity boost into the lab frame, gaining more energy. Therefore, the higher energy neutrons will have a stronger angular correlation than the lower energy neutrons. This effect has been observed in Refs. [4,5] and has been accurately reproduced in an advanced Monte Carlo simulation [10].

While this angular correlation and its energy dependence is a clear signature of a single fission event, the propagation of this anisotropy in a fission chain reaction has not been previously studied. Fundamentally, the propagation of this anisotropy in a fission chain reaction depends significantly on the fission fragment angular distribution for neutron-induced fission. The fission fragment angular distribution has been measured for fast-neutron-induced fission of ^{235}U [11–13] and fast-neutron-induced fission of ^{239}Pu [13]. Those measurements showed that it was slightly more likely, approximately 10–20% depending on the isotope and neutron energy, for the fission fragments to be emitted in the direction of the incident neutron rather than perpendicular to the direction of the incident neutron. This small angular correlation between the incident neutron and fission fragments becomes even weaker when considering the angular correlation between the incident neutron and the prompt neutrons generated from these fission fragments. Based on these angular distributions, it is expected that neutrons from different generations will be largely uncorrelated in angle.

For assemblies of SNM with low multiplication, most of the coincident neutrons will be from single fission events, so they will have a strong anisotropy. However, for assemblies of SNM with high multiplication, a higher proportion of the coincident neutrons will be from different generations of a fission chain reaction, so the anisotropy should decrease significantly. Based on the preceding physical arguments, we have investigated the possibility of using the prompt neutron coincidence anisotropy to assess the multiplication of an assembly of SNM.

3. Description of the experiment

Prompt neutron coincidence anisotropy measurements were performed using a plutonium assembly located at the Device Assembly Facility (DAF) on the Nevada National Security Site (NNSS). The plutonium assembly, hereafter referred to as the BeRP ball, is a 4.5 kg sphere of α-phase plutonium metal. The radius of the BeRP ball is approximately 3.8 cm and it is encased in stainless steel with a nominal thickness of 0.3 mm. It is composed of approximately 93.3% ^{239}Pu, 5.9% ^{240}Pu, and 0.2% ^{241}Am by mass [14]. The primary neutron source is the spontaneous fission of ^{240}Pu within the assembly itself, and this generates approximately 2.8×10^5 neutrons per second which can then induce fission chain reactions. The (α, n) rate from the BeRP ball is negligible. The multiplication of the BeRP ball is 4.5.

The setup of the experiment is shown in Fig. 1. The BeRP ball is located at the center of the figure on top of a small aluminum stand. The data presented in this paper were acquired from two EJ-309 liquid organic scintillators and two EJ-299 plastic organic scintillators. All four of these detectors had active volumes that were 7.6 cm in diameter and 7.6 cm long. The four detectors were

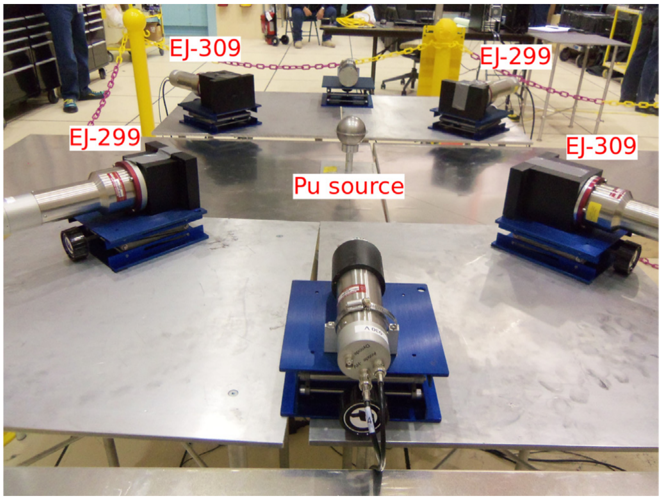

Fig. 1. The experimental setup used to measure neutrons from the BeRP ball.