1 Tests of a novel method to assay SNM using polarized
2 photofission and its sensitivity in the presence of
3 shielding

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12 **Abstract**

A novel method to identify Special Nuclear Material was recently developed [1]. This method relies upon using a linearly polarized γ -ray beam to induce photofission of a sample and then comparing the prompt fission neutron yields in and out of the plane of beam polarization. The present paper will describe experimental tests of this new technique and assess its sensitivity in the presence of shielding. The capability of this technique to measure the enrichment of uranium was tested by using combinations of thin ^{235}U and ^{238}U foils of known enrichments. The sensitivity of this assay to shielding by lead, steel, and polyethylene was experimentally measured and simulated using GEANT4. These tests show that the measured asymmetry can indeed be used to determine the enrichment of materials composed of an admixture of ^{235}U and ^{238}U , and this asymmetry is relatively insensitive to moderate amounts of shielding.

13 **Keywords:** Active interrogation; Fission; Enrichment; Assay; Polarized
14 beams; Neutron detectors

15 **1. Introduction**

16 Non-destructively identifying the presence of shielded Special Nuclear Ma-
17 terial (SNM), or attempting to measure the enrichment of SNM, is sufficiently

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difficult that many potential solutions have been proposed. These solutions are typically divided into passive measurements, which rely on the natural radioactivity of the material of interest, and active measurements which use a beam to interrogate a sample. Many solutions which might work for one subset of SNM, such as ^{235}U and ^{238}U , may not work for other types of SNM, such as plutonium isotopes.

In passive measurements, natural emissions from a sample are used to detect or assay SNM. These natural emissions could be α particles or γ rays from α -decay, or neutrons or γ rays from spontaneous fission. Many passive techniques have been developed to detect γ rays following α -decay to measure the enrichment of $^{235,238}\text{U}$ [2, 3, 4, 5] and $^{239,240}\text{Pu}$ [6]. However, it may be difficult to use these techniques to measure the enrichment of samples composed of an admixture of ^{233}U and ^{232}Th because of the long half-life of ^{232}Th and the absence of γ rays emitted from its decay. Passive measurements of α -particles produced by α -decay could be used to assay samples of ^{232}Th and $^{233,235,238}\text{U}$ [7]. Unfortunately, this technique is more difficult to use with $^{239,240}\text{Pu}$ since their α -particle decay energies are very close. There is, however, some progress on unfolding measured spectra to assay plutonium samples [7, 8]. Passive measurements of α particles are also complicated by the fact that the α particles will straggle or stop in the sample itself and in any casing or shielding, so sample preparation is typically required. Another possible passive measurement to identify ^{240}Pu takes advantage of its relatively short spontaneous fission half-life and looks for spontaneous prompt fission neutrons. These neutrons are sufficient to discover samples of ^{240}Pu , but the spontaneous fission half-lives of $^{235,238}\text{U}$ are long enough that this technique is less practical to identify these nuclides [9].

In active measurements, a beam is used to interrogate a sample. This beam is typically composed of either neutrons or high-energy γ rays [10]. Thermal neutrons, either moderated at the neutron generator or moderated within the sample, are a particularly sensitive probe of the presence of fissile nuclear material. After interrogating the sample with thermal neutrons, one could detect either prompt neutrons such as with the differential die-away technique [11, 12]

49 or delayed γ rays [13] to identify the presence of fissile material. However, active
 50 interrogation with thermal neutrons is not sensitive to the presence of non-fissile
 51 but fissionable material such as ^{238}U or ^{232}Th . Therefore active interrogation
 52 with thermal neutrons cannot be easily used to measure the enrichment or iso-
 53 topics of SNM. Fast neutron beams are sensitive to the presence of fissile and
 54 non-fissile materials, and Ref. [14] has found that ^{232}Th , ^{237}Np , and ^{238}U could
 55 be distinguished by detecting differences in the yields of specific delayed γ rays.
 56 These differences fundamentally arise from variations in the mass distribution
 57 of the daughters following fission, so when the fission mass distributions are
 58 similar, such as for ^{237}Np and ^{238}U , the sensitivity of this technique decreases
 59 [14].

60 Active measurements with γ -ray beams can also be used to measure the
 61 enrichment or isotopics of a sample. Delayed γ rays from fission could be used
 62 to measure the isotopics of samples in a technique similar to that of Ref. [14], but
 63 this again becomes more difficult when the fission product mass distributions
 64 are similar. Nuclear Resonance Fluorescence (NRF) in principle is the most
 65 sensitive technique, since in principle it could be used to quantify the amount of
 66 each nuclide present in a sample of SNM [15, 16]. The NRF technique seems to
 67 be the most versatile method to distinguish different isotopes in SNM, though
 68 it is still under development.

69 A new technique has recently been proposed to measure the fissile versus
 70 non-fissile, but fissionable, content of SNM [1]. This technique relies upon a 6
 71 MeV, linearly polarized γ -ray beam to induce fission of actinide nuclei within
 72 a sample. Ref. [17] demonstrated that the relative number of prompt neutrons
 73 in the plane of beam polarization compared to those perpendicular to the plane
 74 of beam polarization varies depending on the fissile nature of the sample. For
 75 non-fissile samples, such as natural uranium or thorium, a factor of roughly 2-3
 76 more prompt neutrons are emitted parallel to the plane of beam polarization
 77 compared to those emitted perpendicular to the plane of beam polarization.
 78 However, for fissile samples, such as nearly pure ^{235}U or ^{239}Pu , about the same
 79 neutron yield is observed in and out of the plane of beam polarization.

80 One advantage of this proposed technique is its generality. The fundamental
81 cause of this polarization asymmetry in the prompt neutrons is the even-A or
82 odd-A character of the fissioning nuclide. With a 6 MeV γ -ray beam, we expect
83 that all even-A nuclei should have a significant polarization asymmetry, and all
84 odd-A nuclei should have almost no polarization asymmetry. The even-A nuclei
85 in general are not fissile, while the odd-A nuclei generally are either fissile or
86 are otherwise of special interest, such as ^{237}Np . Therefore, this technique might
87 be able to measure the fissile versus non-fissile content of an arbitrary mix of
88 actinide isotopes.

89 However, before that potential is considered, additional experiments must
90 be performed to assess the viability of this technique. No previous work has
91 ever attempted to use the polarization asymmetry to measure the fissile versus
92 non-fissile content of SNM. In the present paper, we report measurements of the
93 polarization asymmetry for combined foils of ^{235}U and ^{238}U as direct tests of
94 the ability of this technique to determine the enrichment of the combined foils.
95 In particular, this could be of interest as a new way to distinguish natural or
96 reactor-grade uranium from weapons-grade uranium.

97 Additionally, photofission has been considered as a method to identify clan-
98 destinely transported shielded SNM in an active interrogation environment. By
99 measuring the polarization asymmetry of the prompt neutrons, in principle one
100 could not only identify the presence of shielded SNM, but also simultaneously
101 measure the enrichment of the shielded SNM. However, this capability depends
102 on how shielding affects the prompt neutron polarization asymmetry. We re-
103 port here novel measurements of the dependence of the polarization asymmetry
104 on the thickness and orientation of common shielding materials: high density
105 polyethylene, steel, and lead.

106 2. Description of the experiment

107 The experimental techniques used were similar to those in Refs. [1, 17, 18], so
108 only a short description of the experimental setup and analysis is provided here.

109 A nearly 100% linearly-polarized, high-intensity ($\sim 10^7 \gamma/\text{s}$), pulsed γ -ray beam
 110 was generated using the High Intensity γ -Ray Source (HI γ S) located at Duke
 111 University [19, 20]. The γ -ray beam was created by colliding a high-power Free
 112 Electron Laser (FEL) beam with an electron beam in a storage ring, and a quasi-
 113 monoenergetic γ -ray beam of 6.1 MeV was generated. The energy spread of the
 114 γ -ray beam was approximately 3% (FWHM). The beam was pulsed at a rate of
 115 5.58 MHz, and the duration of each beam pulse was significantly shorter than
 116 our timing resolution. This beam repetition rate, with 179 ns between beam
 117 bursts, is well suited to fast neutron detection using time of flight methods.

118 At the HI γ S facility, there are two ways to produce linearly polarized γ -
 119 ray beams: using either horizontal undulators, or using a technique similar to
 120 that described in Ref. [21]. In previous experiments [1, 17, 18], the FEL was
 121 generated using the first method. This technique of producing an FEL allowed
 122 for the generation of well-collimated γ -ray beams with nearly 100% polarization.
 123 Therefore, in our previous work, the γ -ray beam polarization was assumed to be
 124 100% with no systematic uncertainty. This technique of polarized γ -ray beam
 125 production was used for the present shielding measurements with lead, steel,
 126 and some of the measurements with polyethylene.

127 In the rest of the experiments presented here, such as the tests with multi-
 128 ple target foils and the other shielding measurements with polyethylene, a new
 129 method of FEL production was used to generate linearly polarized γ -ray beams.
 130 This new technique is conceptually similar to Ref. [21], where a buncher mag-
 131 net was used to controllably switch the beam polarization. The resulting γ -ray
 132 beam was found to be highly polarized, but the polarization was not longer
 133 consistent with 100%. In the work described here, the γ -ray beam polarization
 134 was continuously monitored with a separate experimental setup upstream of
 135 the actinide target. The polarimeter consisted of a D₂O target and four liquid
 136 scintillator detectors filled with BC-501A. The D₂O was kept in a 5.03 cm long
 137 and 3.18 cm diameter cell composed of thin plastic walls. The neutron detec-
 138 tors were 12.70 cm in diameter and 5.08 cm thick. The outgoing neutrons from
 139 the $d(\gamma, n)$ reaction were detected by the liquid scintillators. Two detectors were

140 placed in the horizontal plane at a scattering angle of 90° , and the other two de-
 141 tectors were placed in the vertical plane at a scattering angle of 90° . The $d(\gamma, n)$
 142 reaction has a large polarization asymmetry in the outgoing neutrons for beam
 143 energies below 20 MeV, as indicated by theoretical calculations [22, 23, 24, 25]
 144 and experimental measurements [26, 27, 28, 29]. At a beam energy of 6.1 MeV,
 145 the predicted polarization asymmetry for the $d(\gamma, n)$ reaction at a scattering an-
 146 gle of 90° in a pointlike geometry is 0.972 according to Ref. [23, 30]. According
 147 to Ref. [25, 31], the asymmetry is 0.966 with a calculated uncertainty of ap-
 148 proximately 1%. Because of the good agreement between these two predictions,
 149 0.972 has been used as the theoretical polarization asymmetry, and a systematic
 150 uncertainty of 1% was assumed. Based on this prediction and a GEANT4 [32]
 151 simulation, the linear polarization of the beam was determined to range from
 152 96.5 to 98.0%, with a statistical uncertainty of less than 0.2% per measurement
 153 and a global systematic uncertainty of 1.0% across all measurements. The sys-
 154 tematic uncertainty is dominated by the uncertainty assigned to the theoretical
 155 prediction of the $d(\gamma, n)$ asymmetry.

156 After traversing the D_2O cell, the γ -ray beam was incident on a set of ura-
 157 nium foils located several meters downstream of the D_2O cell. A set of ^{235}U
 158 and ^{238}U foils was used to test the enrichment measurement capabilities of our
 159 aforementioned technique [1]. The three ^{235}U foils each had thicknesses of ap-
 160 proximately 0.24 g/cm^2 , masses of approximately 1.5 g, and enrichments of
 161 93.7%. The different ^{238}U foils were approximately 0.11, 0.40, and 1.18 g/cm^2
 162 thick with masses of 0.72 g, 1.5 g, and 6.16 g respectively and enrichments of
 163 0.7% (natural uranium).

164 Some of the uranium foils were visibly nonuniform, so it was not possible
 165 to calculate the enrichment of the combined foils by simply measuring their
 166 thicknesses. Therefore, the enrichment of each foil combination was determined
 167 by the measured counting rates. For example, one of the ^{238}U foils would be
 168 inserted into the beam, and the count rate relative to the D_2O polarization
 169 monitor was measured. Then, without moving the ^{238}U foil, a ^{235}U foil was
 170 placed approximately 1 cm downstream of the ^{238}U foil, and the polarization

171 asymmetry and the new count rate relative to the polarization monitor was
 172 measured. The count rate due to the ^{235}U foil was calculated by subtracting off
 173 the measured pure ^{238}U count rate. The measured ^{235}U and ^{238}U count rates,
 174 weighted by the photofission cross sections (σ_f) and average prompt neutron
 175 multiplicities ($\bar{\nu}$) for each isotope, were proportional to the amount of ^{235}U and
 176 ^{238}U in the beam. Previous measurements have found the ratio of $\sigma_f\bar{\nu}$ for ^{235}U
 177 to that of ^{238}U to be 1.02 ± 0.09 at a beam energy of 6.1 MeV [33, 34]. The
 178 uncertainty in this value was treated as a systematic uncertainty. In addition
 179 to this systematic uncertainty in the enrichment, there was also a statistical
 180 uncertainty present in the measured enrichment from the statistical uncertainty
 181 in each measured counting rate.

182 A series of measurements was also performed using only ^{238}U foils and var-
 183 ious shielding materials. For these measurements, the combined thickness of
 184 the ^{238}U foils was approximately 6.9 g/cm². One shielding test was performed
 185 with a 2.45 cm thick copper block inserted about 45 m upstream of the target.
 186 This distance was chosen to significantly reduce the probability of scattered
 187 γ rays reaching the target, simply from the small solid angle of the target as
 188 viewed from the block. The copper block was located upstream of the primary
 189 γ -ray beam collimator, which removed any large-angle scattered γ rays from
 190 the copper block and prevented them from reaching the neutron detectors. An-
 191 other series of tests was performed using blocks of lead, steel, and high density
 192 polyethylene. In these tests, each block was 7.62 cm tall, 7.62 cm wide, and
 193 2.54 cm thick. Figure 1 shows the different shielding scenarios tested with these
 194 shielding materials. First, one block of each type was inserted approximately 2
 195 cm directly upstream of the uranium foil. This type of shielding will be referred
 196 to as “F” for “front” shielding. The beam had to pass through the 2.54 cm
 197 thick side of the block to reach the target. Then, four blocks of each type of
 198 shielding material were placed around the uranium target to shield the target
 199 from the neutron detectors. These blocks were again located approximately 2
 200 cm from the target and completely shielded the target from all of the neutron
 201 detectors. The neutrons had to pass through the 2.54 cm thick side of the block

Figure 1: The different shielding scenarios with lead, steel, and high density polyethylene blocks are shown. The leftmost illustration is without any shielding materials. The γ -ray beam is indicated by the arrow and is incident on the target. The following illustration, indicated by (F) for front shielding, shows a shielding block (red) in front of the target. The next illustration, labeled (S) for side shielding, shows shielding blocks between the target and neutron detectors. The final schematic, labeled (A) for all shielding, shows shielding blocks in front of and on the sides of the target. Shielding materials and neutron detectors above and below the plane of the figure are in the same configuration and are omitted for clarity. The illustration is approximately to scale except for the target which was enlarged for the figure.

202 to reach a detector. This scenario will be referred to as “S” for “side” shielding.
 203 Finally, the front and side shielding scenarios were combined so that the front
 204 face and four sides of the target were shielded with 2.54 cm of each shielding
 205 material. This configuration is called “A” for “all” shielding. All of these tests

206 were performed using the original method of polarized γ -ray beam production.

207 As a final shielding test using only high density polyethylene, the amount of
208 shielding on the sides of the target was varied. Measurements were taken with
209 2.54, 5.08, 10.16, 15.24, and 20.32 cm of high density polyethylene shielding on
210 the sides of the target. The shielding began approximately 4 cm from the target.
211 In these cases, blocks of various dimensions were used in order to completely
212 shield the target. However, the width of each block was always 15.24 cm. This
213 width was chosen to ensure the 12.70 cm diameter detector was shielded by
214 the polyethylene. All of these tests were performed using the new method of
215 polarized γ -ray beam production.

216 All of the experimental setups described above used the same neutron de-
217 tection method. The prompt fission neutron yields were measured using four
218 liquid scintillator detectors filled with BC-501A. These detectors had the same
219 dimensions as the BC-501A detectors used in the D₂O polarimeter. Two detec-
220 tors were placed in the horizontal plane at a scattering angle of 90°, and the
221 other two detectors were placed in the vertical plane at a scattering angle of
222 90°. The detectors were placed approximately 70 cm from the target. Pulse
223 shape discrimination was used to eliminate γ -ray backgrounds. The energies
224 of detected neutrons were determined based on their time-of-flight, and neu-
225 tron energy thresholds were set at $E_n = 1.5$ MeV. This threshold was chosen
226 to eliminate potential backgrounds from the (γ, n) reaction. The neutron back-
227 grounds from delayed fission neutrons from earlier events were subtracted from
228 the prompt neutron events by measuring the yield out-of-time with the beam
229 pulse. The background-subtracted prompt fission neutron yield was integrated
230 over all neutron energies above the energy threshold, and the polarization asym-
231 metry Σ at a scattering angle of 90°:

$$\Sigma(90^\circ) = \frac{1}{P} \frac{L + R - U - D}{L + R + U + D} \quad (1)$$

232 was measured. Here L is the prompt neutron yield in the beam left detector, R
233 is the yield in the beam right detector, U is the yield in the beam up detector,
234 and D is the yield in the beam down detector. The fractional beam polarization

235 P was measured for each run independently using the D₂O polarization monitor
 236 setup as previously discussed.

237 **3. Simulations of shielding measurements**

238 Simulations using GEANT4 were performed for all of the different shield-
 239 ing configurations. In the simulations, neutrons were generated at the target
 240 according to the measured angular distribution with no shielding. This proce-
 241 dure ensured agreement between the measurements without shielding and the
 242 simulated results. It was assumed that the beam polarization did not degrade
 243 when passing through shielding materials between the target and the beam.
 244 This assumption is supported by the experimental measurement using copper
 245 shielding as shown in Fig. 4a, and is ultimately validated by the ability of the
 246 simulation to reproduce the measured values. Blocks of shielding were added
 247 in the simulation using the same geometries, dimensions, and orientations as in
 248 the experimental measurements. After the simulations were completed, one cor-
 249 rection to the simulation was made. In simulations with shielding between the
 250 target and the beam, the simulated count rate was scaled down by the known
 251 attenuation factor of the shielding material [35], since this was not taken into
 252 account previously in the simulation.

253 **4. Experimental results: enrichment assay**

254 Figure 2 shows the experimental measurements of the polarization asymme-
 255 try as a function of the enrichment of a sample composed entirely of ^{235,238}U.
 256 The solid line is an interpolation between two measurements: one on natu-
 257 ral uranium and one on 93.7% enriched ²³⁵U. This interpolation is based on
 258 the measured asymmetries and $\sigma_f \overline{\nu}$ for each isotope using only those two data
 259 points, and is not fit to any of the other points. The dashed lines indicate the
 260 expected uncertainty in the interpolation.

261 The mixed-sample points of varying enrichments show good agreement with
 262 the interpolation. The mixed-sample points were taken with the new method

Figure 2: The polarization asymmetry at a scattering angle of 90° is shown as a function of the enrichment of a sample composed entirely of $^{235,238}\text{U}$. The red points indicate experimental measurements. The error bars on the points are statistical and systematic combined. The solid black line is an interpolation between the two data points with smallest and largest enrichments. The dashed black lines indicate the combined statistical and systematic uncertainties on the interpolation.

of polarized γ -ray beam production, so their systematic uncertainties are larger than the other points. Despite the larger uncertainties, these measurements indicate that this technique can distinguish samples of different enrichments, and that the simple interpolation between the two points is reasonable.

A procedure was developed to fit the new experimental measurements to improve the interpolation and more reliably establish its uncertainty. First, a fit was performed using the same functional form as the interpolation function and only the statistical uncertainties in the data points. The statistical uncertainties in the fitted curve were calculated using the change in χ^2 as the parameters were adjusted to neighboring values. Then, the points were moved systematically according to their correlated systematic uncertainties many times, and each time they were moved another fit was performed. The systematic uncertainty in the interpolation was calculated based on the variation in the interpolation

Figure 3: The polarization asymmetry at a scattering angle of 90° is shown as a function of the enrichment of a sample composed entirely of $^{235,238}\text{U}$. The red points indicate experimental measurements. The error bars on the points are statistical and systematic combined. The solid black line is a fit to the data points. The dashed black lines indicate the combined statistical and systematic uncertainties on the fit.

over these many fits. Figure 3 shows the results of fitting the interpolation curve to all of the data points. The statistical uncertainty on the fit is negligible and the error bands are dominated by the systematic uncertainties.

5. Experimental results: shielding

Figure 4a shows the measured prompt neutron polarization asymmetry in the presence of the copper, lead, and steel shielding, and a subset of the results with polyethylene shielding. Overall, the polarization asymmetries are relatively robust to this amount of shielding. The largest reduction in the asymmetry is found using 2.54 cm of lead surrounding the target, which reduces the measured asymmetry by about 15%.

It is clear that 2.45 cm of copper shielding between the beam and the target does not degrade the beam polarization (Fig. 4a). If the beam polarization were degraded by the shielding, the measured polarization asymmetry would be lower

(a) The polarization asymmetry at a scattering angle of 90°

(b) The counting rate relative to the unshielded counting rate

Figure 4: The polarization asymmetry at a scattering angle of 90° (4a) and the counting rate relative to the unshielded counting rate (4b) are shown as a function of the location of copper, lead, steel, or polyethylene shielding. “F” indicates shielding between the target and the beam, “S” indicates shielding between the target and the detectors, and “A” indicates “F” and “S” shielding combined. All shielding materials were 2.54 cm thick, except for copper which was 2.45 cm thick and only placed in the front of the target. The red points are the experimental measurements, while the black lines are the simulated results. The error bars are statistical and systematic uncertainties combined.

(a) The polarization asymmetry at a scattering angle of 90°

(b) The counting rate relative to the unshielded counting rate

Figure 5: The polarization asymmetry at a scattering angle of 90° (5a) and the counting rate relative to the unshielded counting rate (5b) are shown as a function of the thickness of high density polyethylene shielding placed on the sides of the target. The thickness of the shielding material is indicated in centimeters. The red points are the experimental measurements, while the black lines are the simulated results. The error bars are statistical and systematic uncertainties combined.

289 than the measurement without shielding. The copper shielding was far upstream
 290 of the target, so no neutron multiple scattering off of the copper could occur
 291 within the neutron timing cuts. A small reduction in the measured asymmetry is
 292 predicted for the lead shielding in front of the target. This reduction is caused
 293 by multiple scattering of the neutrons off of the lead. In this configuration,
 294 the shielding was only ~ 2 cm away from the target, so neutrons were able to
 295 reach the detector within the timing cuts after scattering off of the lead. All of
 296 the measurements shown with lead and polyethylene agree with the simulated
 297 results.

298 Figure 4b shows the relative counting rate for the different shielding config-
 299 urations. The count rate without any shielding was approximately 100 detected
 300 prompt neutrons per minute per detector averaged over the in-plane and out-
 301 of-plane detectors. The largest reduction in the count rate is found with 2.54
 302 cm of lead in front of the target. This amount of lead attenuates the beam by
 303 approximately 71%. Steel in front of the target reduces the beam intensity by
 304 a smaller amount, and polyethylene in front of the target only slightly reduces
 305 the beam intensity. When the shielding is placed on the sides of the target, the
 306 opposite trend occurs; polyethylene provides the largest reduction, while lead
 307 provides the smallest reduction. All of the measured count rates with lead and
 308 polyethylene shielding show good agreement with simulated results.

309 There is a minor discrepancy present between the simulated and experimen-
 310 tal results for the steel shielding. The measured count rates for steel in front
 311 of and on the sides of the target are slightly below the predicted values. The
 312 asymmetries for steel in front of the target and on the sides of the target are also
 313 lower than the predicted values. These slight disagreements could be caused by
 314 the uncertainty in the precise elemental composition of the steel. In the simula-
 315 tion, it was assumed the steel was 1018 cold rolled steel, which is approximately
 316 99.1% iron, 0.2% carbon, and 0.7% manganese. However, a small admixture of
 317 other elements, such as tungsten, would reduce the count rate and asymmetry.
 318 No attempt was made to determine the precise composition of the steel sample
 319 that was used since the disagreements are small.

Figure 5a shows the measured prompt neutron polarization asymmetry in the presence of additional high density polyethylene shielding. Overall, the polarization asymmetries are relatively robust to even large amounts of shielding; the largest reduction seen is from 20.3 cm of polyethylene on the sides of the target, which reduces the measured asymmetry by approximately 15%. The agreement between the simulated and experimental results is good, though there appears to be a small, systematic difference between the simulated and measured results. This difference could be due to small inaccuracies in the GEANT4 $^1\text{H}(\text{n},\text{n})$ cross sections or angular distributions. Overall, however, the agreement is good; the disagreement in most points is within the combined statistical and systematic uncertainties in the measurements.

The behavior of the asymmetry with increasing shielding is somewhat unexpected. For small shielding thicknesses, the polyethylene preferentially out-scatters the prompt neutrons traveling in the horizontal plane. This out-scattering increases the yield measured in the vertical plane, which slightly decreases the polarization asymmetry. However, it appears that after approximately 10 cm of shielding is inserted, any additional shielding does not significantly reduce the asymmetry. One cause of this behavior is the dependence of the asymmetry on the neutron energy. The polyethylene shielding preferentially scatters the lower energy prompt neutrons ($\sim 1\text{-}2$ MeV), since the $^1\text{H}(\text{n},\text{n})$ cross section is larger there than at higher prompt neutron energies [36]. Therefore, as shielding is added, the higher energy neutrons constitute a larger fraction of the measured neutron yield. Previous measurements have shown that the higher energy prompt neutrons have larger polarization asymmetries than the lower energy neutrons [17]. This correlation may be one explanation of the observed behavior of the asymmetry for large amounts of shielding. Another cause of the observed dependence of the asymmetry is the specified timing window. Neutrons that scatter off of the outer layers of the shielding may not have time to reach a detector within the neutron timing cuts. Therefore, the outer layers of shielding may reduce the count rate observed in all detectors in an approximately equal way, which would not affect the polarization asymmetry.

Figure 5b shows the relative counting rate for the different shielding configurations. It is clear from both the experimental and the simulated results that high density polyethylene can significantly scatter outgoing neutrons. Each 2.54 cm of polyethylene between the target and the detectors reduced the counting rate by approximately 37%. Despite the significant reduction in count rate for large amounts of polyethylene shielding, the polarization asymmetry is relatively unchanged.

6. Conclusions and future work

A previously reported novel method of assaying SNM [1] has been tested. This method uses a linearly-polarized γ -ray beam to induce fission of actinide nuclei within a sample, and the asymmetry between the in-plane and out-of-plane prompt neutron yield is measured. An extended study of this new method involved using different combinations of multiple ^{235}U and ^{238}U foils to imitate samples of uranium with different enrichments. The agreement between the measured prompt neutron polarization asymmetries for these combined foils and the interpolation based on the measurements of highly enriched ^{235}U and natural uranium demonstrates the precision of this new technique. The accuracy of the interpolation was improved by fitting to these new results.

In addition to these experiments, novel tests were also performed with different shielding materials blocking either the beam from the target, the target from the detectors, or both of these scenarios combined. When shielding was placed between the beam and the target, no degradation in the beam polarization was observed for the materials and thicknesses used. Overall, the measured asymmetries and count rates agree with known γ -ray attenuation factors and simulations based on GEANT4 using the unshielded case as a baseline. The reduction in the measured asymmetries is typically less than 15% for shielding thicknesses of 2.54 cm. It is interesting to note that the reduction in asymmetry makes non-fissile material look like fissile material, but it does not make fissile material look like non-fissile material. Therefore, in an active interrogation en-

380 vironment where one is searching for shielded SNM, the shielding would increase
381 the rate of false positives but not the rate of false negatives other than from the
382 simple reduction in the count rate.

383 There still remain many challenges to using this technique in the field.
384 One significant challenge is the difficulty in making a portable intense quasi-
385 monoenergetic linearly polarized γ -ray beam. Our current facility, HI γ S, has a
386 footprint of several thousand square meters and is immobile. Therefore, HI γ S or
387 a HI γ S-like facility for SNM detection or identification in the field is impractical.
388 However, we hope that our measurements may be used to guide the development
389 of future γ -ray beam sources, such as those made by Compton backscattering
390 off of Wakefield accelerators [37], which have the potential to be more compact
391 and mobile. Another potential challenge is the impact of neutron multiplica-
392 tion within the sample. The samples used here were all thin, rendering neutron
393 multiplication negligible. However, in thicker samples of SNM, there may be sig-
394 nificant neutron multiplication, which could reduce the measured polarization
395 asymmetry. The impact of the neutron multiplication within a sample should
396 be carefully studied in future experiments. A final challenge is the fact that
397 all of the fissile nuclides studied have the same polarization asymmetry. Our
398 previous results have demonstrated that the polarization asymmetry for all of
399 the fissile actinides is close to zero at a beam energy of 6.1 MeV. Therefore, one
400 disadvantage of using the polarization asymmetry to perform enrichment mea-
401 surements is that different fissile actinides cannot be distinguished from each
402 other.

403 In future experiments, it may be interesting to measure the prompt photofis-
404 sion neutron-neutron coincidence count rate on several actinides such as $^{233,235,238}\text{U}$,
405 ^{237}Np , and ^{239}Pu . It is possible that the average prompt neutron multiplicities
406 will be different for these different isotopes, and therefore, the different isotopes
407 may have different prompt neutron-neutron coincidence count rates in photofis-
408 sion. Additional information about the specific composition of a sample may
409 be gained by simultaneously measuring both the polarization asymmetry and
410 the neutron-neutron coincidence rate, and this additional information may be

411 sufficient to determine the fissile versus non-fissile content in addition to the
 412 specific fissile isotopes within a sample. There would be no loss in sensitivity in
 413 simultaneously measuring the polarization asymmetry with the neutron-neutron
 414 coincidence counting rate, since the neutron-neutron coincidence counting rate
 415 measurements could be performed with the same detectors and beam configura-
 416 tion. Therefore, in future work, it may be useful to measure the neutron-neutron
 417 coincidence count rate in photofission of these fissile actinides.

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