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S. McAlpine, D. Yang, V. Mozin, A. Schmidt

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Monte Carlo Simulations of Neutron Resonance Transmission Analysis with the Dense Plasma Focus

Samuel W. McAlpine,* Dustin X. Yang,† Vladimir V. Mozin, and Andrea E.W. Schmidt
Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550, USA‡

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Simulations were performed using the Monte Carlo radiation transport code MCNP in order to analyze the feasibility of using a dense plasma focus to perform neutron resonance transmission analysis. It was found that the dense plasma focus is well-suited for neutron resonance transmission analysis because of the relatively short pulse duration and large neutron yield. This makes low-energy neutron spectroscopy using time of flight much more accurate, allowing for more detailed assays of smaller quantities of special nuclear material.

I. INTRODUCTION

A dense plasma focus (DPF) has been developed at Lawrence Livermore National Laboratory (LLNL) which can produce 2.45 MeV neutrons from the deuterium-deuterium fusion reaction with a yield of about 10^7 neutrons[1] in a short pulse, simulated to be 20 - 60 ns[2]. The short pulse length, relative to existing pulsed neutron sources, allows for unique applications of the DPF. The applications explored were based around using neutron interrogation in order to identify, characterize, and analyze actinides and other isotopes which constitute special nuclear materials (SNM). MCNP was utilized in order to model the radiation transport characteristics of the DPF. With this information, it was concluded that one technique the DPF might be optimal for is called neutron resonance transmission analysis (NRTA). Because NRTA relies upon time-of-flight (TOF) analysis, the short pulse length of the DPF allows for acceptable energy resolution in measurements using the TOF diagnostic.

NRTA can be used in order to identify actinides, fission products, and other nuclides with large neutron absorption resonances. Not only can isotopes be identified, but relative amounts can be determined as well. Using this technique, several national security objectives can be achieved. For example, NRTA could be used in order to verify treaty-accountable items in an arms control setting. Also, NRTA could be utilized to characterize fuel rod enrichment levels in a safeguards scenario.

A. Dense Plasma Focus

A DPF consists of coaxial electrodes attached to a capacitor bank (with anywhere from tens of joules to 1 MJ of stored energy[3]). The DPF can operate using existing capacitor technology. Using deuterium gas inside of the DPF, fusion neutrons can be produced in a short pulse. The voltage between the electrodes is sufficient to ionize the deuterium, forming a plasma "sheath" at the base of the electrodes. A magnetic field is created by the current running through the plasma. This magnetic field then pushes the plasma down the electrodes. At the end of the electrodes, the plasma "pinches" in on itself, compressed by the immense magnetic field. In the pinch, a large number of neutrons (anywhere from 10^4 - 10^{13} per pulse) are created from fusion in a short amount of time (10 - 100 ns). Although the DPF at LLNL uses pure deuterium, a deuterium-tritium mixture can be used as well. Using newly developed kinetic simulation codes[4] in order to inform design, a DPF can be optimized for the desired yield and pinch length.

Conventional electronic neutron generators (ENGs) can create pulses as short as a few μs[5] with a neutron yield of 10^7 - 10^8 neutrons/s. It is clear that the DPF creates a much shorter, intense burst of neutrons compared to existing ENGs. This means that the DPF enables TOF measurements which are not possible with the relatively low intensity and long pulse provided by an ENG. Furthermore, the DPF would take up a much smaller footprint than previously proposed accelerator-driven sources[6] which would likely require a dedicated facility.

B. Neutron Resonance Transmission Analysis

Many nuclides have neutron absorption resonances, neutron energies which correspond to extremely high neutron absorption cross-sections. These resonances are unique to each nuclide and can be utilized to characterize and assay materials. The resonance region from 1 eV - 50 eV is particularly useful for identifying common isotopes contained in SNM (^{235}U, ^{239}Pu, etc.) and fission products [7]. In order to analyze the resonance absorp-

* Also at the Department of Nuclear Engineering; and the Department of Materials Science & Engineering, University of California, Berkeley
† Also at the Department of Nuclear & Radiological Engineering, Georgia Institute of Technology
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tion signal from these materials, one needs to send an incident spectrum into the material from 1 eV - 50 eV and measure the neutron energy spectrum after passing through the material which is being analyzed. Neutron absorption resonances will produce a "notch" in the spectrum at the energy of the resonance[6]. The locations of the notches indicate which isotopes are present, and the relative amplitude of the notches indicate their relative amounts. The direct measurement of neutron energies in this relatively low energy range is impossible, and thus it is necessary to obtain the energy inferred through TOF, making the DPF a source which is ideal for NRTA.

C. Monte Carlo Simulations With MCNP

The simulations that were performed consisted of interrogating an inspection object to model an arms control scenario. It can be assumed in such a scenario that long stand-off distances would not be required, allowing for a short drift distance. Also, passive background was ignored as the interrogation time (under a second) is relatively short in this scenario, and thus the total number of background counts will be fairly small.

A slab of polyethylene, placed next to the source, was included in the model to moderate the fusion neutrons to the energy range of interest, 1 eV - 50 eV. Then, the spectrum of neutrons was passed through the inspection object and the flux produced was tallied through a detector volume 2m away. 2m is a relatively short drift distance for TOF measurements, meaning that the entire detection system could be compact while preserving a large signal. Furthermore, the dependence of the efficiency of the hypothetical detector (assumed to be ^{3}He) on neutron energy was considered in post processing by using the common neutron absorption scaling law: $\sigma_{abs} \propto \frac{1}{v}$

II. METHODS

The source was modeled as a monoenergetic, isotropic point source, and a 3 cm slab of polyethylene was placed between the source and the inspection object in order to moderate the fusion neutrons to the relevant resonance energies while preserving a large flux through the moderating slab. Different thicknesses of polyethylene were tested, and 3 cm was found to be the best thickness in order to maintain a large flux while sufficiently moderating neutrons. The geometry of the inspection object was held constant throughout the simulations. The inspection object consisted of a thin layer of steel cladding, surrounding a spherical object with a volume of about 180 cm^3.

First, we used MCNP to simulate the energy spectrum in the detector volume, in order to compare with the TOF spectrum. The TOF spectrum was obtained by simulating the flux through the detector volume as a function of time, and using relatively simple TOF calculations to convert this to an energy spectrum. A Gaussian-shaped pulse representative of the DPF was used, with a full-width at half-maximum of 20 ns.

Then we compared the TOF spectrum from a source representative of the DPF with a source representative of conventional ENGs. The DPF pulse was represented with a Gaussian pulse shape with a full-width at half-maximum of 20 ns, while the conventional ENG was represented with trapezoidal pulse 4 μs in length. The purpose of this comparison was to demonstrate the benefits of performing NRTA with the DPF. In all simulations 10^{10} source particles were used.

Finally, we simulated NRTA performed on different materials, using the source representative of the DPF. We compared depleted uranium, highly-enriched uranium, plutonium, and lead. The purpose of simulating NRTA on lead was to show the the signature of a benign material. The volume of interrogated material was held constant throughout the simulations.

III. RESULTS

In figure 1, below, we see that TOF spectrum compared with the actual energy spectrum in the detector volume:

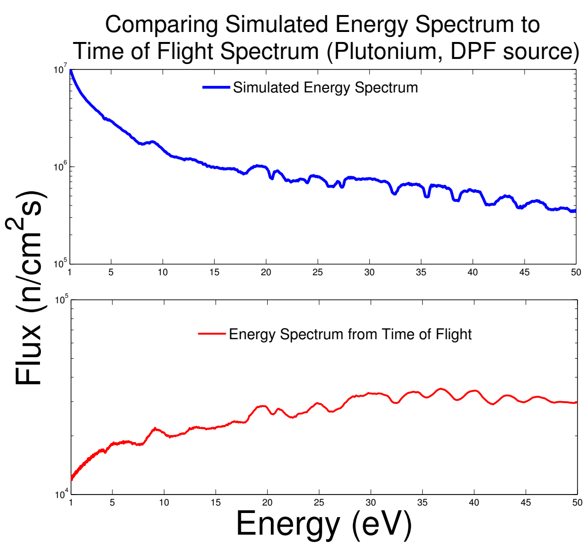

FIG. 1. Comparison of simulated TOF spectrum and simulated true energy spectrum

Figure 1 demonstrates that the TOF diagnostic produces a slight amount of broadening of the resonances, but accurately reproduces the location of the neutron absorption resonances.

Next, we sought to demonstrate the benefits of the shorter pulse of the DPF compared to conventional ENGs for NRTA. This is shown on the next page in figure 2.

In figure 2, many resonances can be seen with the DPF which are undetectable using an ENG. Furthermore, due

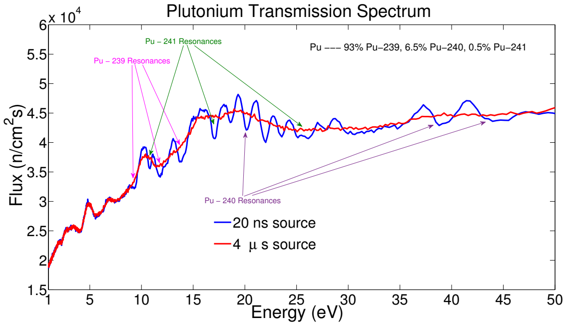

FIG. 2. Comparison of transmission spectrum of plutonium inspection object from different sources

to the low intensity of the ENG, and the number of neutrons needed to resolve the remaining resonances, it would take about a day with an ENG to make a measurement which could be performed with the DPF using a single pulse.

In figure 3 below, we sought to compare the TOF energy spectra from different material, using the source representative of the DPF:

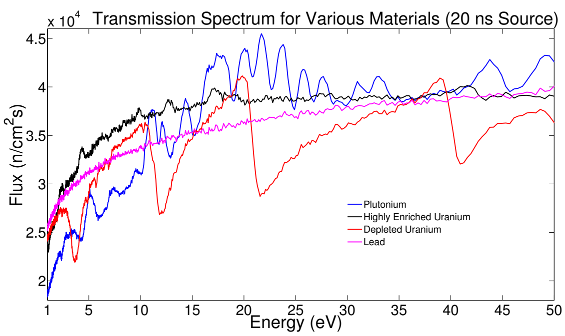

FIG. 3. Comparison of transmission spectra of different materials with the DPF source

Figure 3 demonstrates that SNM such as highly-enriched uranium or plutonium can be distinguished from benign material such as lead. Furthermore, uranium can be distinguished from plutonium, and highly-enriched uranium can be distinguished from depleted uranium.

IV. CONCLUSIONS

The simulations performed with MCNP demonstrate that the unique characteristics, specifically the short pulse, of the DPF enable NRTA to be performed for the detection and characterization of SNM for several national security applications. TOF spectra obtained with the DPF show the desired neutron absorption resonances which cannot be obtained with a conventional ENG source. What resonances can be resolved by the ENG would take about a day to measure, while the DPF can do so with a single pulse. Furthermore, the DPF provides a much more compact, portable system for performing NRTA than alternative accelerator-driven systems which would require an entire facility.

A major advantage of NRTA is that common elements one might expect to be present, such as nitrogen, oxygen, carbon, and iron do not have neutron absorption resonances in the energy range of interest. Another advantage, demonstrated in the simulations performed in this work, is that only 3 cm of polyethylene is needed to moderate fusion neutrons down to the energy range of interest. This means that we can produce the desired spectrum while producing little attenuation of the neutron pulse. Also, use of less polyethylene will mean less “time-blurring” due to non-uniform moderation of fusion neutrons.

The results of the simulations performed in this work demonstrate that the TOF method is an effective diagnostic tool for the NRTA technique, and that this technique can be used for several applications relevant to national security, such as arms control and safeguards. Furthermore, the DPF provides a much higher level of energy resolution in the TOF spectrum when compared with conventional pulsed neutron sources such as ENGs, allowing the analyst to conclude much more about presence of isotopes and their relative amounts in a given material. This can be done using a relatively compact, portable system. Finally, the resonance structure of SNM is seen to be quite unique compared with a benign high-Z material when NRTA is performed with the DPF. Within the classification of SNM, different materials and grades can be determined with a high-degree of accuracy.

V. FUTURE WORK

In order to develop confidence in the simulations in this work, experiments must take place to represent the relevant scenarios. Inspection objects similar to that used in this work exist at LLNL and could be used in said experiments. Should these be successful, further development will be needed to deploy a system using the DPF in the field.

The simulation can also be further developed in order create a more realistic scenario. This might include factoring in the effects of the room and other surroundings into the geometry.

Analysis will be needed to determine the minimum neutron yield, which would allow the system to be more compact. Also, less total irradiation will lead to less concern about the safety effects on the operator of the system.

Finally, the detector response should be factored into the simulations directly. This may require use of different simulation software. Furthermore, novel neutron detector materials could be explored through simulations.

[1] J. Ellsworth, S. Falabella, V. Tang, A. Schmidt, G. Guethlein, S. Hawkins, and B. Rusnak, "Design and initial results from a kilojoule level dense plasma focus with hollow anode and cylindrically symmetric gas puff," *Review of Scientific Instruments*, vol. 85, no. 1, p. 013504, 2014.

[2] A. Schmidt, A. Link, D. Welch, J. Ellsworth, S. Falabella, and V. Tang, "Comparisons of dense-plasma-focus kinetic simulations with experimental measurements," *Physical Review E*, vol. 89, no. 6, p. 061101, 2014.

[3] L. Soto, "New trends and future perspectives on plasma focus research," *Plasma Physics and Controlled Fusion*, vol. 47, no. 5A, p. A361, 2005.

[4] A. Schmidt, V. Tang, and D. Welch, "Fully kinetic simulations of dense plasma focus z-pinch devices," *Physical review letters*, vol. 109, no. 20, p. 205003, 2012.

[5] R. Soule, W. Assal, P. Chaussonnet, C. Destouches, C. Domergue, C. Jammes, J.-M. Laurens, J.-F. Lebrat, F. Mellier, G. Perret, *et al.*, "Neutronic studies in support of accelerator-driven systems: the muse experiments in the masurca facility," *Nuclear Science and Engineering*, vol. 148, pp. 124–152, 2004.

[6] D. L. Chichester and J. W. Sterbentz, "Neutron resonance transmission analysis (nrta): initial studies of a method for assaying plutonium in spent fuel," tech. rep., Tech. Rep., Idaho National Laboratory (INL), 2011.

[7] C. Bowman, R. Schrack, J. Behrens, and R. Johnson, "Neutron resonance transmission analysis of reactor spent fuel assemblies," in *Neutron Radiography* (J. Barton and P. von der Hardt, eds.), pp. 503–511, Springer Netherlands, 1983.