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Detection of Uranium-Based Nuclear Weapons Using Neutron-Induced Fission*

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Abstract

Although plutonium-based nuclear weapons can usually be detected by their spontaneous emission of neutrons and gammas, the radiation emitted by weapons based entirely on highly-enriched uranium can often be easily shielded. Verification of a treaty that limits the number of such weapons may require an active technique, such as interrogating the suspect assembly with an external neutron source and measuring the number of fission neutrons produced. Difficulties include distinguishing between source and fission neutrons, the variations in yield for different materials and geometries, and the possibility of non-nuclear weapons that may contain significant amounts of fissionable depleted uranium. We describe simple measurements that test the induced-fission technique using an isotopic Am-Li source, a novel energy-sensitive neutron detector, and several small assemblies containing ^{235}U, ^{238}U, lead, and polyethylene. In all cases studied, the neutron yields above the source energy are larger for the ^{235}U assemblies than for assemblies containing only lead or depleted uranium. For more complex geometries, corrections for source transmission may be necessary. The results are promising enough to recommend further experiments and calculations using examples of realistic nuclear and non-nuclear weapons.

I. INTRODUCTION

One important issue facing treaties such as START is distinguishing between nuclear and non-nuclear weapons. Plutonium-based nuclear weapons can be easily detected with passive detectors because plutonium is a prolific emitter of radiation. The isotope ^{239}Pu emits more than 100 gamma-ray lines. The most intense one at high energies has an output of 3.1×10^4 γ/s/g and is at 414 keV, which is very penetrating. The isotope ^{240}Pu has a neutron output of 1000 n/s/g.

Detecting uranium-based weapons may be much more difficult. The isotope ^{235}U emits only one strong low-energy line at 186 keV. These gammas can be easily shielded because their mean free path in lead is only 0.7 mm. The neutron output of 6×10^{-4} n/s/g is also too low to be useful. Thus, passive techniques may not work for such weapons. Based on the measurements described in this report, we can show that an active technique should work.

Our technique involves placing an Am-Li neutron source, which ideally only emits neutrons with energies less than 1.5 MeV, close to the material being studied. The neutrons from the source cause fissions in any ^{235}U present. Fission neutrons with energies greater than 1.5 MeV are detected by a fast-neutron detector. The detector must discriminate between the low-energy source neutrons and the fast fission neutrons.

There are complications in this simple concept. First, Am-Li sources emit a small percentage of neutrons with energies greater than 1.5 MeV because of (α, n) reactions on contaminants in the source, and this source tail might be confused with the high-energy fission neutrons. Second, the fission yield depends on the materials, particularly the moderating materials, and on their geometries. Third, some conventional weapons may contain depleted uranium, which is mostly ^{238}U. The fission cross section for ^{238}U is negligible below 1 MeV but rises rapidly above 1 MeV. In addition, depleted uranium contains a small residual amount of ^{235}U. Thus, an Am-Li source could possibly cause fission in depleted uranium. Our measurements and analyses address these issues.

II. EXPERIMENTAL EQUIPMENT

A. *Layout*

The experimental layout is shown in Fig. 1. The four Am-Li sources provided a total of 1.8×10^5 n/s. Lead sheets around the sources attenuated the intense 60-keV gamma rays from ^{241}Am. Polyethylene blocks 5.1 cm thick served as moderators and were removed for unmoderated measurements. The samples were plates of lead and uranium, each nominally 0.35 cm thick. Each block or plate

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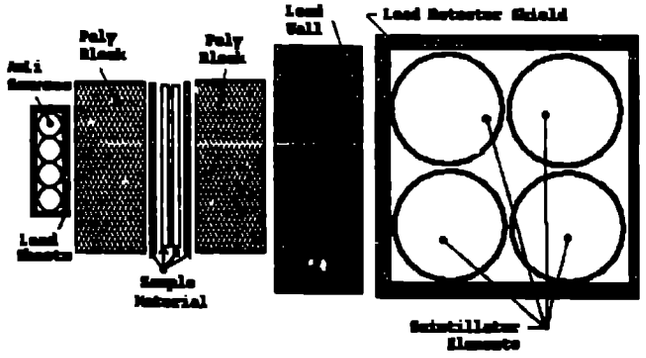

Figure 1: Experiment Layout

was nominally 10.5 × 10.5 cm^2 in area. The mass of the two ^{235}U plates (> 93% enrichment) was 925.85 g total; that of the two ^{238}U plates (depleted to $\leq 0.2\%$ ^{235}U) was 951 g. The thick lead wall shielded the detector from the 1001-keV gamma rays from the depleted uranium.

B. *Detector*

The detector consists of four cylindrical boron-loaded plastic scintillators, each 7.62 cm in diameter × 20.32 cm in length. The detector was originally developed for the Army Background Experiment (ABE).[1] One such detector is now in orbit; we made the present measurements with the backup detector. Being space-qualified assures that it is rugged, low-power, and requires no adjustments.

The principles of operation are described in detail elsewhere,[2] but for completeness we briefly review it here (Fig. 2). An incident neutron deposits all of its energy in a series of collisions within the resolving time of the detector, producing a first pulse. Within a few microseconds the neutron is captured in the reaction $^{10}B(n,\alpha)^7Li$, which produces a second pulse with a characteristic signature (Fig. 3). (The energy units keV_{ee}, meaning "keV electron equivalent," are used because light production in scintillators saturates and becomes nonlinear for recoiling heavy particles, including protons.[1]) The peak at 93 keV_{ee} is caused by the ^7Li and α recoils. The reaction is predominately to the first excited state at 478 keV in ^7Li; the gamma decay of this state produces the tail at high pulse heights. The positions of the recoil peak at 93 keV_{ee} and the Compton edge at 311+93 keV_{ee} from the 478 keV gamma ray give an internal calibration. We used a measured conversion curve[1] to convert to neutron energy in the rest of this paper. Requiring that the first pulse be in coincidence with the second pulse guarantees that, except for accidental coincidences, the first pulse was produced by a neutron that deposited all of its energy. In particular, gamma rays are rejected because they do not produce the characteristic second pulse. The time difference between the two pulses can be used to measure and subtract accidental coincidences. Additional discussion is included in Refs. [1,2] and in another contribution to this conference.[3].

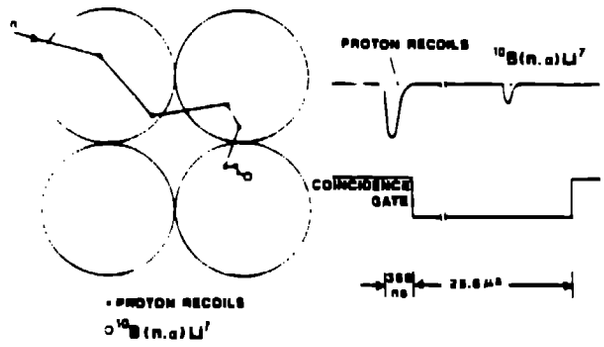

Figure 2: Operation of a Borated-Plastic Neutron Scintillation Detector

III. MEASUREMENTS AND ANALYSIS

A. ^{252}Cf *Test*

We verified that the detector and our analysis techniques were working correctly by measuring a ^{252}Cf neutron spectrum (Fig. 4) and showing that it agreed with a published standard distribution.[5] The sharp cutoff below 0.5 MeV indicates the detector's first-pulse threshold.

B. *Am-Li Source Spectrum*

To determine the Am-Li source spectrum, we placed four lead plates in the four sample positions and removed the polyethylene moderator blocks. As shown in Fig. 5, most of the neutrons are below 1.5 MeV, as expected, but there is a high-energy tail containing about 2.7% of the flux.[4]

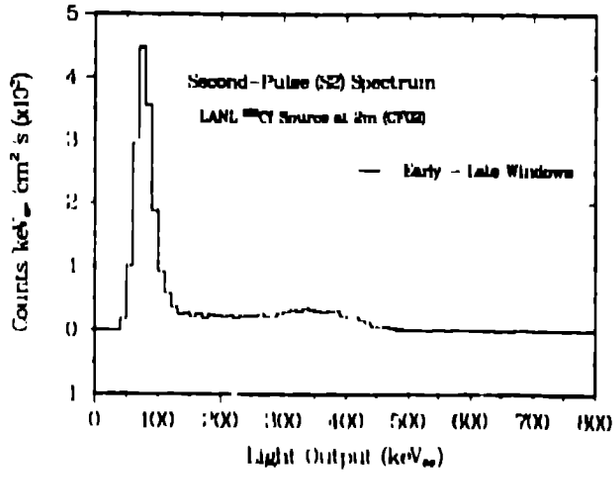

Figure 3: Light Output Spectra for the Capture Pulse

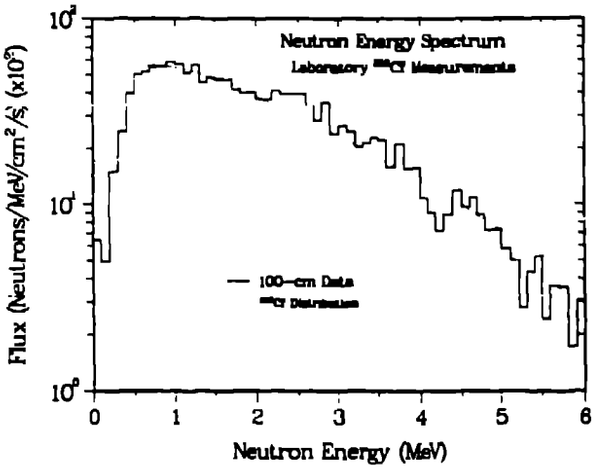

Figure 4: Measured ^{252}Cf Energy Spectrum

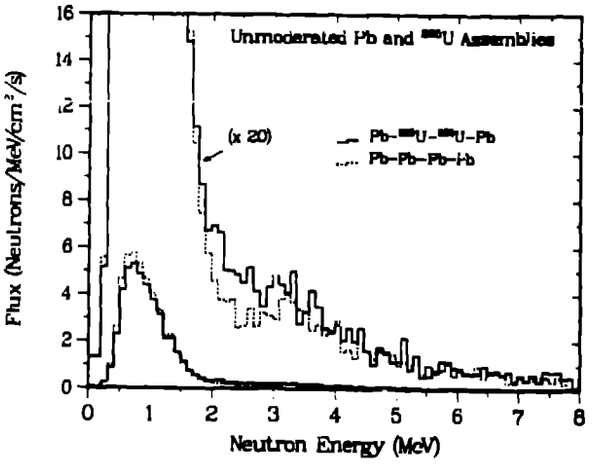

Figure 6: Energy Spectra for Unmoderated Pb and ^{235}U

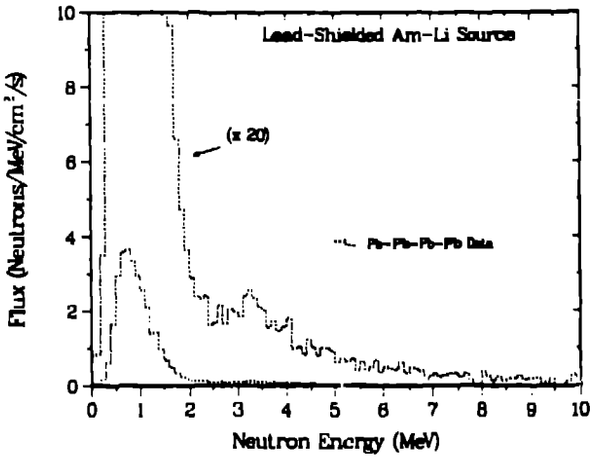

Figure 5: Measured Am-Li Source Spectrum

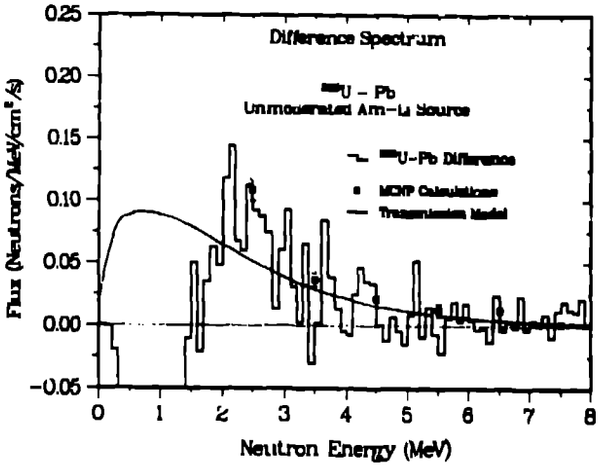

Figure 7: Difference Spectrum for Unmoderated Pb – ^{235}U

There have been suggestions that this tail is produced by (α, n) reactions in the source on beryllium or oxygen contaminants. We are not aware of any success in efforts to remove such contaminants.

C. *Unmoderated ^{235}U*

To determine the induced fission spectrum from ^{235}U, we sandwiched two plates of enriched uranium between two plates of lead, again without the polyethylene moderator blocks. As shown in Fig. 6, the yield at high energy from the enriched uranium sandwich is slightly larger than the yield from the all lead case. The difference between these two spectra (Fig. 7) gives just the fission spectrum without the source contribution. The data at high energy are in good agreement with a transmission model and an MCNP Monte Carlo calculation.

D. *Moderated ^{235}U and ^{238}U Spectra*

To determine the effect of moderation, we repeated the ^{235}U measurements with the two polyethylene blocks in place. We made a similar measurement on depleted uranium by sandwiching two plates of depleted uranium between plates of lead with the polyethylene blocks in place. As shown in Fig. 8, the yield from enriched uranium is enhanced by a factor of two because the fission cross section for ^{235}U is much larger at low neutron energies. There is little difference in the yield between depleted uranium and lead. Subtracting the lead spectrum gives the fission spectra without the source contributions (Fig. 9). Again the data are in good agreement at high energy with transmission models and MCNP Monte Carlo calculations.

E. *Shape Analysis*

It is significant that the energy dependence of the above spectra at high energies were not distorted significantly by the shielding; only their amplitudes were changed. This observation suggests that the source and fission components can be separated by differences in shape, that is, without relying on the subtraction of a "bench mark" spectrum from a similar lead only assembly. We have therefore used the shapes of the ^{252}Cf (Fig. 4) and Am-Li (Fig. 5)

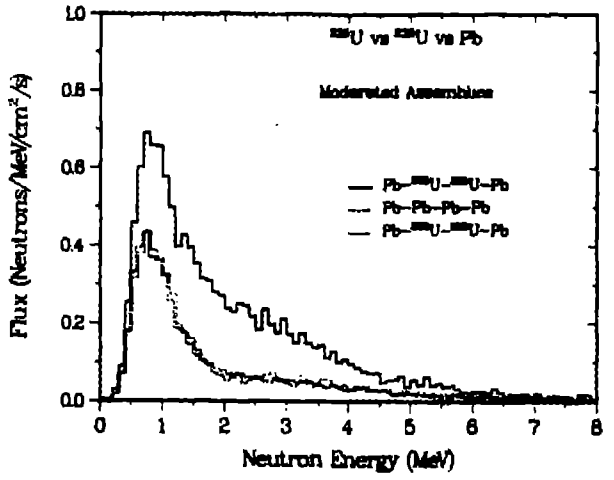

Figure 8: Energy Spectra for Moderated ^{235}U and Pb

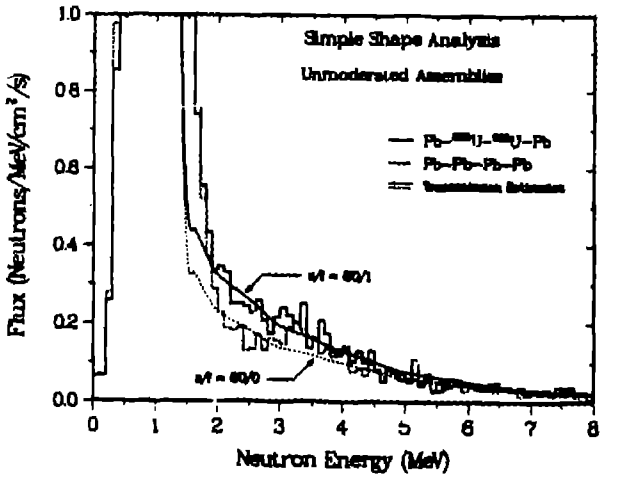

Figure 10: Shape Analysis, Unmoderated Spectra

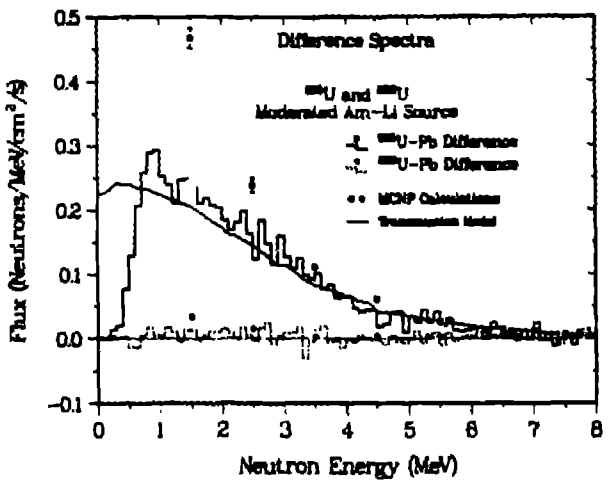

Figure 9: Difference Spectra for Moderated ^{235}U - Pb, ^{238}U - Pb

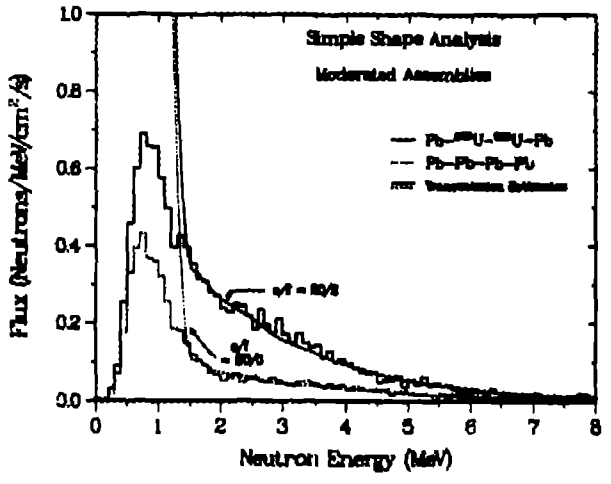

Figure 11: Shape Analysis, Moderated Spectra

spectra to estimate the contributions of each component to the measured spectra. Figs. 10 and 11 show the results for the unmoderated (Fig. 6) and moderated (Fig. 8) cases. The "*s/f*" values give the number of units of each component required to describe the measured spectrum. The the all-lead spectra both require a zero fission component and the 2-to-1 ratio between the moderated and unmoderated ^{235}U components matches the ratio obtained by the above subtraction approach.

IV. CONCLUSIONS

We conclude the following: 1) the ABE detector is an appropriate fast neutron detector for this application; 2) the Am-Li high-energy tail is tolerable; 3) depleted uranium can be easily distinguished from enriched uranium in the geometries studied; 4) bench mark measurements are desirable, because only measurements and not analyses have to be compared, but shape analysis can be used if no bench mark measurements are available. These results suggest that induced-fission measurements may be useful for detecting or characterizing uranium-based nuclear weapons.

ACKNOWLEDGEMENTS

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