High Sensitivity Portable Neutron Detector for Fissile Materials Detection

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***Abstract*— Efforts to contain weapons of mass destruction have recently intensified, in response to increasing terrorist activities worldwide. The ultimate scenario for nuclear terrorism involves the smuggling of nuclear weapons, or the material to make them, and subsequent detonation in densely populated cities. Widespread monitoring in ports of entry is part of the solution proposed by experts. We propose a portable, economical monitor with high sensitivity for both neutron and gamma detection. It consists of a close-packed array of many thin-walled copper straws, lined with a 1 μm thick coating of enriched boron carbide ($^{10}B_4C$). Neutrons are converted in ^{10}B, while gammas are converted in Cu. We present performance tests for a prototype monitor that has dimensions of 40×5×5 cm^3 and weighs 3.6 kg. Results show a neutron background of 0.03 cps, a thermal neutron sensitivity of 36 cps/nv (18% efficiency), and an angular resolution of 40 degrees (FWHM). We estimate that a monitor of the proposed design (with enriched boron carbide), traveling at 3 mph, can positively detect 230 g of ^{240}Pu, from a distance of 2.5 m, with 90% sensitivity and with fewer than 1 false alarms every two hours.**

***Index Terms*— security, boron-lined proportional counters, long-range neutron detection, directional neutron detection, straw detectors**

I. Introduction

A PRIMARY need of U.S. national security is the ability to detect fissile radioactive sources, such as plutonium, that can be used for the construction of weapons of mass destruction. Historically, the goals of these efforts have been nuclear weapons non-proliferation and international treaty verification. In light of the greatly increased threat of terrorism, and heightened terrorist activity around the world, illegal smuggling of nuclear materials is an even greater current concern. Since other emissions (α particles, X-rays, γ-rays) can be easily shielded and/or have low abundance, detection of spontaneous fission neutrons offers the most viable approach to locating nuclear weapons materials. Current neutron detectors, such as ^{3}He tubes have significant practical limitations, including high cost and substantial weight and bulkiness, and are dangerous in portable use due to the high pressure required. Therefore, a compelling need has emerged for alternative detectors with more favorable characteristics.

We propose a portable, lightweight and economical monitor with high sensitivity for both neutron and gamma detection. It consists of a close-packed array of many thin-walled copper straws, lined with a 1 μm thick coating of enriched boron carbide ($^{10}B_4C$), as shown in Fig. 1. Neutrons are converted with the $^{10}B(n,\alpha)^7Li$ reaction, while gammas are converted in Cu. Each straw contains counting gas and an anode wire running through its center, and it is operated in proportional mode, providing counting of either gamma or neutron events. The proposed detector draws upon low-cost technology developed by the high energy physics community for large particle detectors such as ATLAS, currently under construction at CERN. This and other straw detector designs are being commercially explored for both neutron and gamma imaging applications [1], [2].

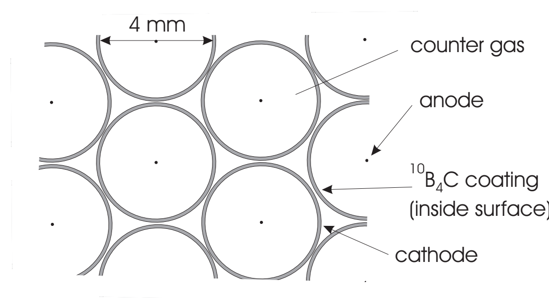

Fig. 1. A close-packed array of copper-walled straws, lined with $^{10}B_4C$, is proposed for the detection of thermal neutrons.

Boron-lined proportional detectors have been employed for many years, but achieve at most a few percent efficiency, due to the fact that, if the foil thickness exceeds the range of reaction products, no escape occurs. Thus only conversions in the very thin layer near the surface are detected. This very thin layer captures only a small percentage of the incident neutrons. The proposed design employs a close-packed array of $^{10}B_4C$-lined straw tubes, and removes the low efficiency barrier, by providing many layers of very thin converters, each providing efficient reaction product escape. Using a stack of such detectors, of reasonable depth, high neutron detection efficiency can be achieved.

It is useful to compare the stopping power of the proposed detector, with the commonly employed ^{3}He medium. The atomic density of ^{10}B in a close-packed array of straws, where each straw is 4 mm in diameter, and incorporates a 1 μm thick $^{10}B_4C$ lining, is 1.0×10^{20} atoms/cm^3. At one atmosphere, the atomic density of ^{3}He (or any gas) is 0.269×10^{20} atoms/cm^3.

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Correcting for the relative thermal neutron cross sections of ^{3}He and ^{10}B, the straw array has the linear stopping power of ^{3}He gas at a pressure of 2.7 atm. It is difficult to achieve this pressure safely in portable detectors of the dimension required for long range detection.

We present a series of experiments that establish the performance of a prototype monitor that incorporates non enriched B_4C. The expected performance of such devices ultimately employing enriched $^{10}B_4C$ (5 fold more ^{10}B per unit volume) can be easily extrapolated.

II. Methods

The prototype detector consisted of 136 copper straws, as shown in Fig. 2, each 40 cm long and 4 mm in diameter. Straw material was made by winding two thin strips of copper, the inner strip incorporating a 1 μm thick layer of vapor-deposited, non-enriched boron carbide (B_4C). A thin wire, 20 μm in diameter, was tensioned in the center of each straw. The sensitive volume of the detector was $40{\times}5{\times}5$ cm^3.

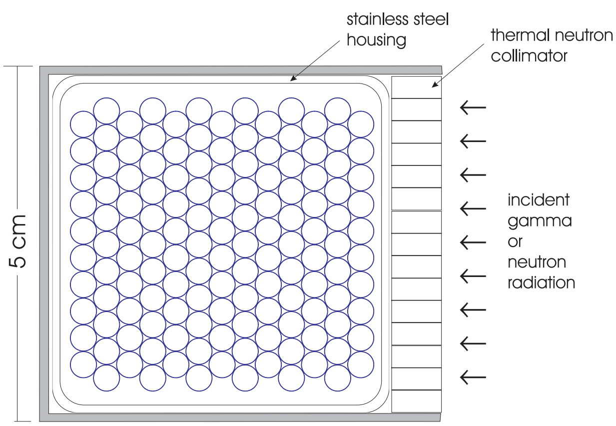

Fig. 2. Cross-sectional diagram of prototype monitor, showing the straw detector array, stainless steel housing, thermal neutron shield and collimator.

The straw array was sealed inside a stainless steel housing that was subsequently evacuated and filled with a gas mixture of 90% argon and 10% methane, at 1 atm. A 2 mm thick thermal neutron shield made of borated aluminum (4.5% boron, ^{10}B-enriched to >95%) was installed on all sides of the housing, except the side where a collimator was fitted, as shown in Fig. 2. The collimator, shown in Fig. 3, consisted of 1086 aluminum straws, each 10 mm in length, and incorporating a 10-15 μm thick layer of enriched boron carbide (>96% ^{10}B enrichment). The ^{10}B areal density was 22 mg/cm^2 for the shielding material and 1.8-2.5 mg/cm^2 for the collimator straws.

The monitor was read out with a single charge sensitive amplifier (all straw wires were connected together), shaper and discriminator, all sealed inside the detector housing, and an external, dual counter, that incorporated a digital display and control buttons. A built-in high voltage supply biased the straw wires (anode) to 1000 V. A 9 V rechargable lithium-ion battery powered all electronics and the detector.

The weight of the prototype monitor was 3.6 kg (8 lbs).

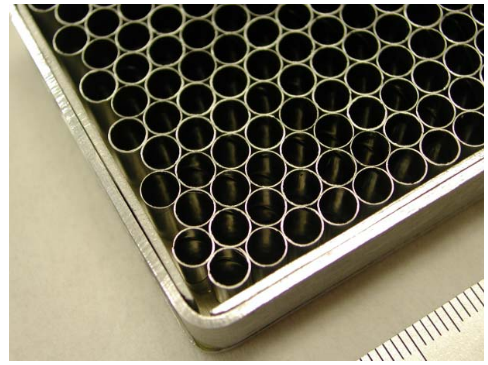

Fig. 3. One centimeter long straws, each lined with a thin layer of $^{10}B_4C$, are close-packed to form a neutron collimator.

A. Energy resolution and gas lifetime

When operated in neutron-counting mode, the monitor discriminates against pulses generated by gamma ray interactions. Neutron and gamma ray events deposit different amounts of energy in the detector, with most neutron events depositing energies significantly higher than those of gamma ray events. Gamma ray discrimination is achieved by setting an energy threshold above the gamma tail. Since the two spectra overlap over a limited range of energies, an adequate level of energy resolution is required for optimal discrimination.

A ^{241}Am gamma ray source was used to collect an energy spectrum in the prototype monitor. Photons emitted by this isotope, primarily with an energy of 60 keV, interact with the copper walls of the straw array. At this energy, most interactions in copper are of the photoelectric kind, resulting in the absorption of the incident photon, and prompt emission of a characteristic X-ray photon, with energy equal to the electron binding energy of 8 keV. This X-ray photon sometimes escapes into the gas volume, where it deposits all its energy. The 8 keV energy peak is useful in gaging energy resolution, and for accurate measurement of gas gain, for example to track gas purity over the lifetime of the detector.

B. Sensitivity

The sensitivity for detection of thermal neutrons was measured by placing the monitor in a thermal neutron field, generated by 0.63 μg of ^{252}Cf. The source was moderated with a solid polyethylene cylinder, 10.5 cm in diameter and 14 cm tall (1.2 liters). The intensity of the field 1 m from the source was 1.7 nv, as characterized with a commercially available BF_3 proportional counter (Lnd Inc., Oceanside, NY, model no. 20126).

C. Background

Background count rates were measured with the monitor at various indoor and outdoor locations, on the ground and off the ground, in front of obstructions such as walls, and in large open spaces. Measurement times were 60 min for neutrons and 10 min for gamma rays.

D. Directionality

The neutron collimator was mounted on the front face of the detector, while all other sides where shielded with borated aluminum. The monitor was placed 1 m above a concrete floor, oriented horizontally, and rotated through a range of angles, from 0° (facing source) to 90° (facing away). The measurement was done at a distance of 3 m from the moderated ^{252}Cf source, and repeated at 12 m.

E. Detection limits

A 0.63 μg ^{252}Cf neutron source was used to identify detection limits for common fissile materials. The source emitted 1.45×10^6 neutrons/s, a rate equal to that of 1.6 kg of ^{240}Pu, or that of 26 kg of weapon-grade plutonium (WgPu), assuming WgPu contains only 6% ^{240}Pu. In order to simulate thermalization of neutrons, the source was supported 1 m above the ground, and was placed inside a polyethylene cylinder, described above. The monitor was placed a specified distance away from the source, and the measured count rate was averaged over a time of several minutes. Detection limits were calculated using the theory presented in [3], assuming that the false alarm rate was 1 alarm every 2 hours, and that the detection sensitivity was 90%.

F. Traveling monitor

Experiments were conducted with the monitor traveling at the speeds of 1 and 3 mph (0.45 and 1.3 m/s). The detector was held by an operator, while he was driving a small electric cart, as shown in Fig. 4, past the moderated ^{252}Cf source, which was placed at 2.5 m. The total path traveled was 15 m. The number of counts measured was recorded versus time, over the entire length of the path. A total count was then computed as the maximum of the moving average, over a specified integration time.

Fig. 4. Testing with the monitor carried by the cart operator, traveling at various speeds. The neutron source is visible in the foreground, mounted on a tripod and inside a thermalizing polyethylene cylinder.

III. Results & Discussion

A. Energy resolution and gas lifetime

Fig. 5 shows the energy spectra collected with the ^{241}Am gamma ray source. The energy resolution is 13% (FWHM) for the 8 keV peak. A resolution of 4% is estimated at 75 keV, where the neutron threshold is set. This resolution should be adequate for successful gamma ray discimination.

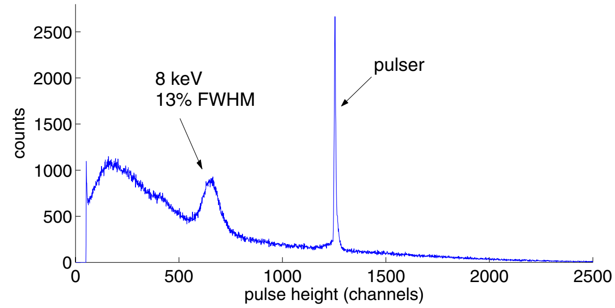

Fig. 5. Pulse height spectra collected in the prototype monitor, operated at 1000 V, and irradiated with a ^{241}Am source.

Fig. 6 shows the pulse height spectra obtained with the ^{252}Cf neutron source. An amplitude threshold set as shown in the figure can successfully discriminate between neutron and gamma ray events.

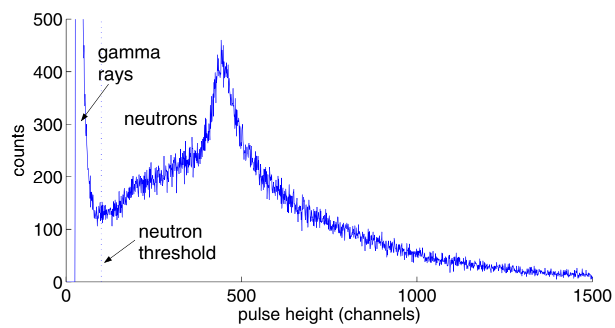

Fig. 6. Pulse height spectra collected in the prototype monitor, operated at 1000 V, and irradiated with a ^{252}Cf neutron source.

Fig. 7 shows the trend in the gas gain, tracked using the 8 keV peak of the ^{241}Am energy spectrum (see Fig. 5). Gain fluctuations on the order of ±5% are observed. However, overall gain stability is good over a timespan of 200 days, indicating that gas purity is maintained and that the monitor can be operated reliably over long periods of time without the need for refilling.

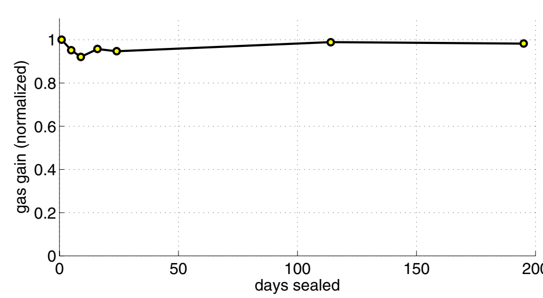

Fig. 7. Gas amplification was tracked in the prototype monitor using the 8 keV full energy peak of the ^{241}Am energy spectrum (see Fig. 5). On day 1, the amplification factor was 2200.

B. Sensitivity

The measured thermal neutron sensitivity was 36 cps/nv, corresponding to a detection efficiency of 18% (given a sensitive area of 200 cm^2). The predicted detection efficiency of the device for thermal neutrons is shown in Fig. 8, and matches the measurement well, assuming a B_4C layer thickness close to 1 μm. The final design will incorporate ^{10}B-enriched B_4C, and in that case, a maximum efficiency of 67% is obtained for a B_4C thickness of 1 μm. The corresponding neutron sensitivity will be approximately 130 cps/nv, 3.7 times higher than the prototype detector.

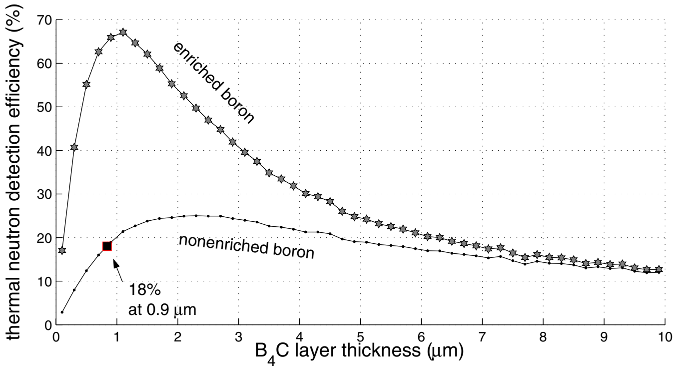

Fig. 8. Predicted thermal neutron detection efficiency, for a natural and ^{10}B-enriched boron carbide layer of increasing thickness. The two curves reach their maxima at different layer thicknesses. The efficiency measured in the prototype monitor is indicated by the square symbol.

By comparison, the neutron sensitivity of a commercially available ^{3}He detector (LND, Inc, Oceanside, NY, model no. 25380), 31 cm in length and 5.0 cm in diameter, is 195 cps/nv. That detector is pressurized to 2.7 atm, which makes it unsafe for handheld operation in the field.

C. Background

The recorded rates were 0.03 cps for neutrons, and 23 cps for gamma rays. No significant variation was observed, despite the multitude of locations tested.

D. Directionality

Fig. 9 shows the measured angular response. The angular resolution was 40° (FWHM) at 3 m, and 70° at 12 m. The neutron count level at 90° is not zero due to thermal neutrons scattering in the ground and nearby objects, and subsequently entering through the collimator; and epithermal neutrons that penetrate the shield and result in detection. Still the aligned count rate is 5 times the misaligned rate at 3 m.

E. Detection limits

The minimum detectable amount for ^{240}Pu is plotted in Fig. 10 for integration times of 8 and 16 s. The prototype monitor can confidently detect in 16 s a ^{240}Pu amount of 94 g, at a distance of 2.5 m (8.2 ft). For a monitor using enriched boron carbide, we estimate that this amount drops to 25 g, as indicated in the figure.

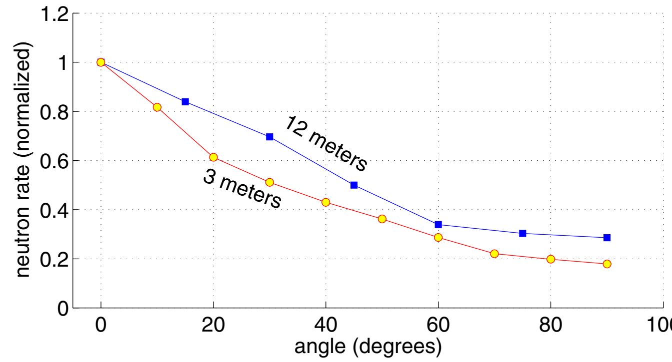

Fig. 9. Angular response measurements.

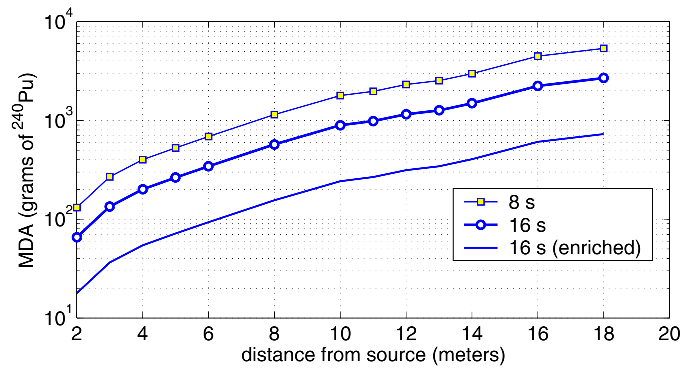

Fig. 10. Estimate of the minimum amount of ^{240}Pu detectable in the proposed monitor, for the integration times indicated. Results were based on measurements using a moderated ^{252}Cf source. The lower curve corresponds to a prediction for enriched boron carbide. The false alarm rate was less than 0.5 alarms/hour, and the sensitivity was 90%. MDA: minimum detectable amount.

F. Traveling monitor

Fig. 11 shows the minimum amount of ^{240}Pu, detectable in the proposed monitor, traveling at the speed indicated, and with the travel path a distance of 2.5 m from the ^{240}Pu source. At both speeds, the amount decreases for increasing integration times, then jumps up at T=7 s as the alarm threshold increases (in order to limit false positives). At 1 mph, 320 g of ^{240}Pu can be confidently detected, with an integration time of 16 s. At 3 mph, and with an integration time of 9 s, the minimum detectable amount is 840 g.

The lower curve shows the minimum detectable amount estimated for a monitor that incorporates enriched $^{10}B_4C$. It is about 3.7 times smaller than the amount detectable with natural boron, due to the increased detection efficiency. Thus, at 3 mph, and with a measurement time of 9 s, the minimum detectable amount is lowered to 230 g of ^{240}Pu.

IV. Conclusion

Measurements with a prototype monitor (see Table I for a summary) indicate that the proposed design, incorporating enriched boron carbide, can confidently detect ^{240}Pu amounts, as small as 230 g, while moving at a speed of 3 mph, from a distance of 2.5 m. This distance equals the width of a

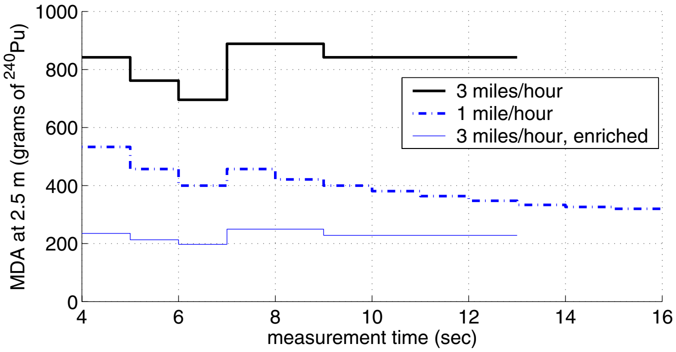

Fig. 11. Estimate of the minimum amount of ^{240}Pu at 2.5 m, detectable in the proposed monitor, traveling at the speed indicated. Results were based on measurements using a ^{252}Cf source. The lower curve corresponds to a prediction for enriched boron carbide. The false alarm rate was less than 0.5 alarms/hour, and the sensitivity was 90%. MDA: minimum detectable amount.

TABLE I

PROTOTYPE MONITOR PERFORMANCE SPECIFICATIONS

	unit	value
neutron counting mode		
background rate	cps	0.03
neutron sensitivity	cps/nv†	36
neutron detection efficiency	%	18
angular resolution (FWHM)	degrees	40
gamma detection efficiency, 662 keV	%	$<$0.000014
gamma counting mode		
background rate	cps	23
gamma sensitivity, 662 keV	cps/(mrem/hr)	4190
gamma detection efficiency, 662 keV	%	2.7

†nv : neutrons/(cm$^2 \cdot$ s)

typical cargo container, and thus, the proposed monitor can efficiently, and confidently scan a large number of containers in a reasonable length of time. Alternatively, the monitor can be used at a stationary point, while containers travel past it at the specified speed. The neutron false alarm rate arising from the natural background rate of 0.03 cps in such moving detection processes is less than 1 every 2 hours. The ability of the monitor to detect and count gamma rays simultaneously can potentially be used to reduce neutron false positives, or as an alert prompting longer neutron counting times.

REFERENCES

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