Directional Neutron Detection

Peter Fisher, Tim Imholt

April 24, 2011

1 Introduction

We have developed a new kind of particle detector able to locate radioactive materials used in nuclear weapons and power plants. The detector locates fissile materials by measuring the number, energy and direction of neutrons emitted by the radioactive decay of the fissile materials. This new method improves on the current technology that is unable to measure the direction. In addition, this new method is much less susceptible to naturally occurring radiation, giving much greater sensitivity to the presence of fissile materials even when they are inside a container or warhead. This detector will also be able to locate fissionable materials by using a neutron beam to interrogate material.

This detector was developed by Peter Fisher, Steve Ahlen (Boston University) and Hermann Wellenstein (Brandies University) with the aim of detecting dark matter. Dark matter, thought to compose 23% of the mass in the universe, interacts in exactly the same manner as neutrons and the dark matter work we have done translates directly into neutron detection. We have constructed several prototypes and used them to detect neutrons in our lab. In the coming year, we plan to deploy a prototype underground and detect neutrons from naturally occurring radioactive materials. Over the same time, we are working on developing a portable neutron detector.

The work plan for this proposal has two parts: the first part covers the first two years and focuses on building two portable detectors and using them to identify fissile substances in realistic conditions. In the second phase, which covers years three to five, I plan to design and build a ten cubic meter detector (0.5m × 10m × 2m) able to assay a truck-born shipping container in a few seconds.

The next section describes the problem of locating fissile and fissionable materials. The following section describes the detector and how it solves this problem, including engineering challenges, risks and their mitigation. Locating Fissile and Fissionable Materials Nuclear power plants around the world use about 15,000 tonnes of uranium, producing about 6% of the worlds energy. In the US, about 80,000 tonnes of spent fuel rods are stored in cooling ponds near the 100 or so reactors. Terrorists would likely view the plutonium residing in spent fuel rods as a promising weapons material as much less plutonium would be needed to build a weapon than uranium (see Table 1). They would need to steal the fuel rods and process them into weapons grade plutonium (WgPu) and make a crude device. While this procedure is quite difficult, the steps are well known and, aside from the WgPu, readily available. The resulting device would not be as powerful as those used at the end of World War II, but its mere existence would create an unimaginable security and political situation. Clearly, the best means of preventing the creation of a terrorist bomb is to secure the necessary plutonium so that it cannot be diverted to terrorists. However, much of the fissile 15,000 tonnes of uranium used in reactors each year resides outside the United States in country unwilling or unable to exercise due caution in securing and tracking it. Even in the US, there is a 0.1% uncertainty in record keeping, meaning 800 ton of plutonium bearing spent nuclear fuel is unaccounted for. Given this, it is obvious that systems for detecting WgPu, even when hidden inside containers or vehicles, would be very valuable.

Table 11 shows several different models for small nuclear devices for study in Ref. 1. The table shows much less WgPu is needed for a small device than WgU (4 kg v.s 12 kg) and that for any device made with WgPu, the radiation from neutrons far exceeds the gamma radiation. However, gamma ray detection is a very well developed technology while neutron detection is not. The best neutron detectors today are called Bonner Spheres and can only detect neutrons by slowing them down in a moderator and capturing them on He-3.

However, the study carried out in Ref. [1] indicates that the presence of a WgPu device could be detected at a distance of 25 m using neutrons, while gamma ray detection would only work up to 60 cm. Scintillator or germanium detectors both could detect neutrons, but are also very good gamma ray detectors and, as the naturally occurring radiation is largely gamma rays, the neutron signal from the device would be lost at distances over 60 cm. Bonner Spheres will detect only neutrons, but are designed for

Weapon Model		Multiplication Factor	Emission rate at surface of model neutrons/s
Fissile material	Tamper material		
12 kg WgU	tungsten	1.65	30
12 kg WgU	79 kg depleted U	1.30	1,400
4 kg WgPu	tungsten	1.89	400,000
4 kg WgPu	52 kg depleted U	1.94	400,000
Weapon model		Emission rate at surface of model	Gamma ray energy (MeV)
Fissile material	Tamper (γ/s)		
12 kg WgU	tungsten	30	1.001
12 kg WgU	79 kg depleted U	100,000	1.001
4 kg WgPu	tungsten	600	0.662
		1,000	1.6
4 kg WgPu	52 kg depleted U	60,000	1.001

Table 1: Various possible weapon configurations and the associated radiations. The tamper is the material surrounding the fissionable material. From [1].

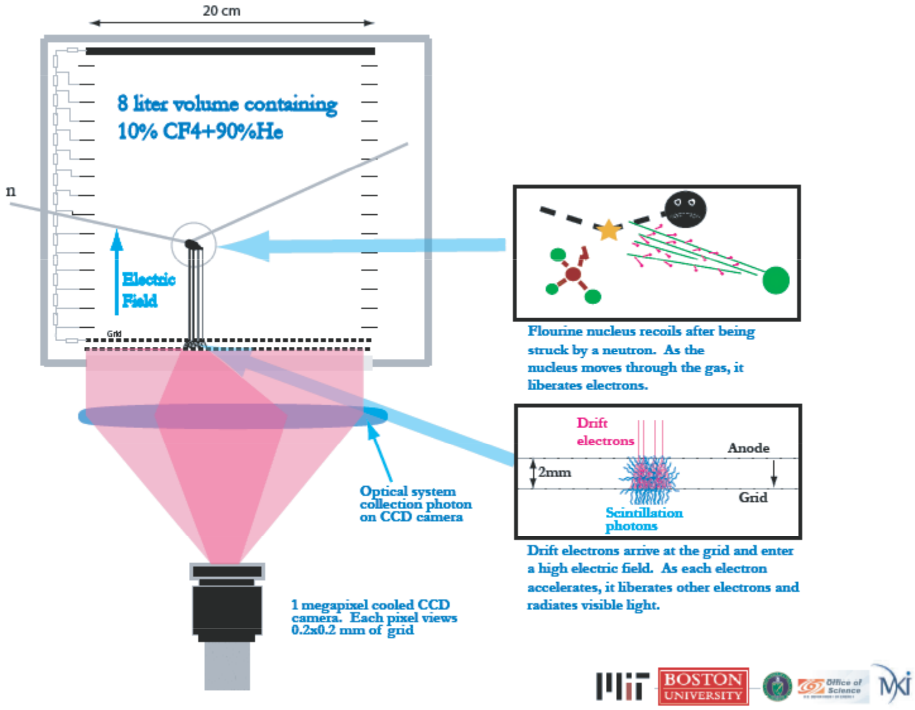
the very low energy thermal neutrons rather than the fast neutrons from WgPu.

Our dark matter detector is an excellent neutron detector because neutrons and dark matter interact in an identical manner and because our detector is designed not to detect gamma rays. Our detector is designed to be sensitive to one dark matter particle interaction per year and this requires that fewer than one in a million gamma rays be identified as a neutron or dark matter type interaction.

2 A CF_4 based neutron detector

Our detector is shown in Fig. 7. When a neutron strikes a helium nucleus, it scatters elastically, transmitting a fraction of its energy to the helium nucleus. For example, a typical neutron from WgPu has an energy of 2 MeV and such a neutron striking a helium nucleus would transmit about 750 keV of energy. As the helium nucleus recoils, it loses energy to the surrounding gas, losing more energy at the start of its trajectory. The energy is lost by librating electrons from the surrounding gas. These electrons drift under the influence of an applied electric field (about 100 V/cm) to the amplification region where a very strong electron field (about 1 MV/cm) causes proportional amplification of the drifting electron, releasing scintillation light (about 3,000 scintillation photons for each drift electron). The CCD camera images this scintillation light giving an image of the trajectory of the nucleus; Fig. 2 shows an example. The incident neutron came from the right, causing the struck nucleus to recoil to the left. The larger energy loss is clearly visible on the right side of the image. The total energy of the recoil nucleus is measured in two ways: the total light output of the track (determined by just summing up the signals in the individual pixels of the image) and the length of the track. The detector itself is relatively easy to construct and made from commercial components. The sensitive volume is enclosed in a pressure vessel with the electronic components (CCD camera, image processor and power supplies) mounted outside.

From Ref. **??**, 4 kg of WgPu warhead emits 400,000 neurons/s, so the neutron flux at 1m is $3.2 \times 10^4/\mathrm{m}-\mathrm{s}$. If we have a $1\mathrm{m}^3$ detector with 1 bar of ^{4}He, there are 2.7×10^{27} (or 45 moles) of target nuclei. Assuming a cross section of 4b , the detection rate is



Flourine nucleus recoils after being struck by a neutron. As the nucleus moves through the gas, it liberates electrons.

Drift electrons arrive at the grid and enter a high electric field. As each electron accelerates, it liberates other electrons and radiates visible light.

Figure 1: Schematic of neutron detector.

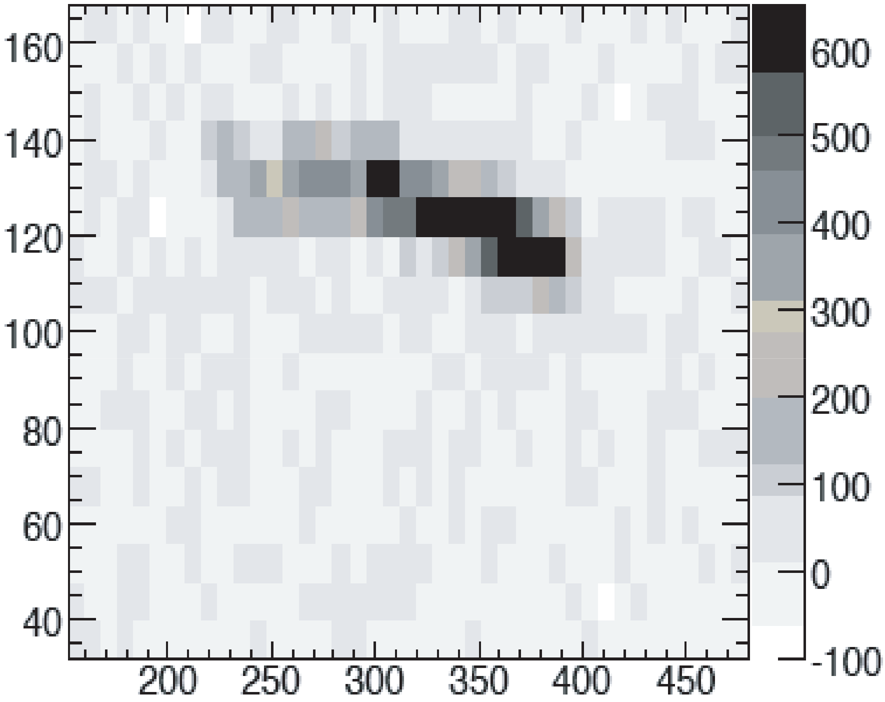


Figure 2: Image of a 700 keV recoiling nucleus in our detector. The total track length is about 3 mm.

$$R = \frac{3.2 \times 10^4}{\mathrm{m}^2\,\mathrm{sec}} \times 4 \times 10^{-28} \times 2.7 \times 10^{25} = 344\,\mathrm{Hz}$$

. We can use this result to make a general scaling for different detector parameters

$$R = 344\mathrm{Hz} \left(\frac{P}{1\,\mathrm{bar}}\right) \left(\frac{V}{\mathrm{m}^3}\right) \left(\frac{1\mathrm{m}}{D}\right)^2 \left(\frac{A}{400,000\,\mathrm{sec}}\right)$$

where A is the source strength, D is the distance from the source to the detector, V is the volume of the detector and P is the pressure of ^{4}He. In the absence of background, as exposure of duration $T = 1/R$ would give a high probability of detecting a neutron, which is all that is needed to detect the source. There are background neutrons from cosmic rays that have a flux of roughly $7/\mathrm{m}^2\,\mathrm{sec}$ in the few MeV range. If we take the range to be 4 MeV, this gives a detected background rate of

$$B = \frac{0.3}{\mathrm{sec}} \left(\frac{V}{\mathrm{m}^3}\right) \left(\frac{P}{\mathrm{bar}}\right)$$

Assuming Gaussian statistics, an exposure of time T gives RT signal counts and BT background counts with a standard deviation of $\sqrt{BT}$. For detection of a source, we want the number of signal counts to be larger that the typical fluctuation of the background

$$RT > f\sqrt{BT} \tag{1}$$

where f is the number of standard deviations required to detect the source. $f = 1$ would give a false positive 16% of measurements, $f = 2$ gives a false positive in 2.3% of measurements and $f = 3$ gives at false positive in 0.23% of measurements. We can quantify the sensitivity to a source by how long we have to measure to gather enough statistics to satisfy Eq.1:

$$T > 2.5 \times 10^{-6}\,\mathrm{sec} \left(\frac{D}{\mathrm{m}}\right)^4 \left(\frac{400,000/\,\mathrm{sec}}{A}\right)^2 \left(\frac{1\,\mathrm{bar}}{P}\right) \left(\frac{1\mathrm{m}^3}{V}\right) f^2 \tag{2}$$

We will use these estimates to make a quantitative assessment of performance in Sections 4 and 5.

Material	Thickness (m)	Attenuation (E_{vis}¡400 keV)	Atten. length (m)
Steel plate	0.00625	0.8	0.02
Clothes	1	0.25	0.7
Computers	1	0.45	1.2
Kitty Litter	0.4 0.25	0.3	

Table 2: Summary of attenuation measurements in different materials. Precision on attenuation lengths is 20%.

3 Attenuation in materials

The attenuation of neutrons in typical materials plays a key role in the performance of any detector. In particular, for this detector, neutrons carry both energy and direction information, so understanding how both energy and angular information is lost through typical materials found in shipping containers will be key to assessing performance. To this end, we have carried out a series of studies using our directional detector. Fig. 3 shows our setup: a ^{252}Cf source is located inside 30 cm of shielding 4 m from the detector. The ^{252}Cf source emits about 40,000 n/s isotropically and the shielding provides a beam that uniformly illuminates the detector. A table between the source and detector holds sample absorber materials. In this run, the detector was operated with CF_4 only; a detector containing both CF_4 and helium would have about a factor of four better efficiency.

We have carried out measurements of the neutron attenuation of several materials commonly found in shipping containers or railroad cars: clothes, kitty litter, computers and steel plates over a spectrum of energies. The results are shown in Fig. 4. Table 2 summarizes the measurements. Typical consumer items have neutron attenuation lengths of 0.3-1.2 m, meaning a neutron can penetrate 0.7-3 m while still leaving a signal 10% of the time had not the material been there. Typical vehicles have surface thicknesses of 0.06-0.25" (0.15-0.6 cm) of steel, so 5-50% of neutrons will emerge from the vessel or vehicle. Overall, it is reasonable to expect a few percent of fast neutrons will be detectable from the outside of a vehicle.

Fig. **??** shows a typical application. If 1 kg of WgPu were hidden inside a railroad car as shown, 3-10% would emerge from the surface of the car and 1 m^2 detectors shown would have 4-40 neutrons per second incident on their surface. A railroad car moving at 5 mph by a pair of sensors would have at

Figure 3: Lab setup. The detector is in the foreground right and the source is located inside the neutron shielding on the cart on the extreme left of the picture. The distance from the source to the center of the detector is 4 m.

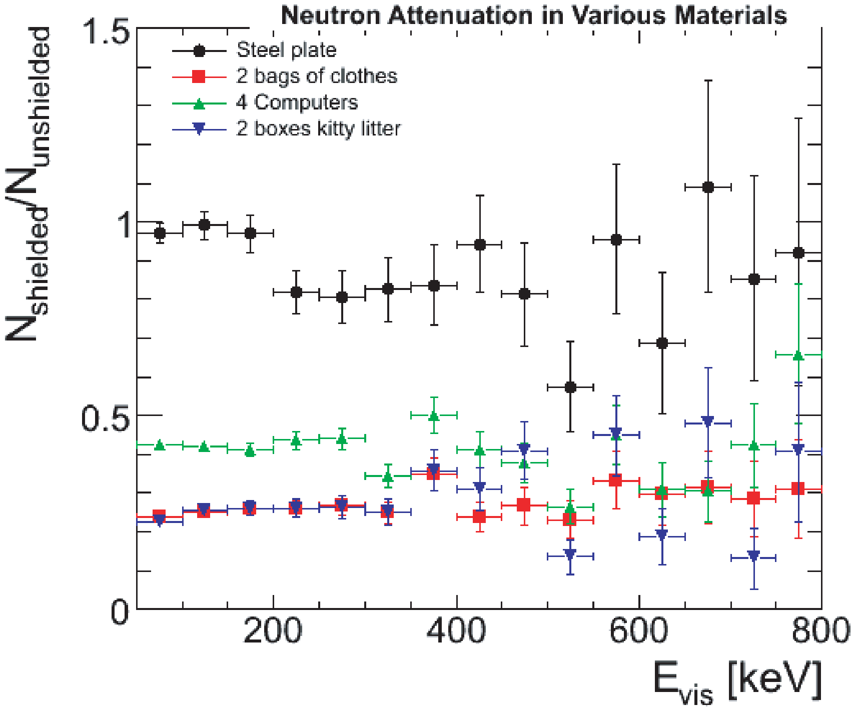


Figure 4: Recoil energy spectra of neutrons with different abosrbers.

least a dozen neutrons per second striking them. The direction of the nuclear recoil would indicate the location of the source. One concern would be that the passage through the material would alter the direction of the neutrons. Fig. 6 shows experimentally there is very little loss of directional information carried by the neutrons. Sections **??** and 5 consider other applications of this means of detecting neutrons.

Of particular concern are fake detections;instances where a positive signal appears with no neutrons present. Detector errors, cosmic ray backgrounds and other backgrounds may cause false positive detections. Fig. **??** shows a measurement we carried out in which we operated the detector for 12.6 days with no neutron source. During that time, we observed 165 single neutron-like events, corresponding to a 0.5 neutron events per hour. From an operational point of view, requiring the observation of two neutron events in a 5 s window would reduce the background rate to 0.0003/hour. An additional requirement that both neutrons come from the same direction further reduces the fake rate.

4 Examples without use of neutron direction

In this section, we consider some concrete examples of the detector performance in various scenairios.

1. For detecting a 4 kg WgPu with tungsten tamper at a distance of 1 m with a 1 m^3 detector at 1 bar, 10^{-5} s would be required for f=1.

2. For detecting 10 g of WgPu at 1 m with the device above, less than a second of counting would be required for f=1, about 1.5s for f=3.

3. At a distance of 30 m, 2s would be needed for 4 kg of WgPu for f=1, 6s for f=3.

4. Suppose we are concerned about scanning containers with hidden sources of A=20,000/s and can scan for 5 s. At what range can we scan? Inverting Eq. 2 gives or 8.4 m for f=1 and 4.8m for f=3.

5. For the detector in Example 4, PV=1000 l-bar, so the same performance could be achieved by a 125 l detector ($50 \times 50 \times 50 \text{cm}^3$) operating at 8 bar.

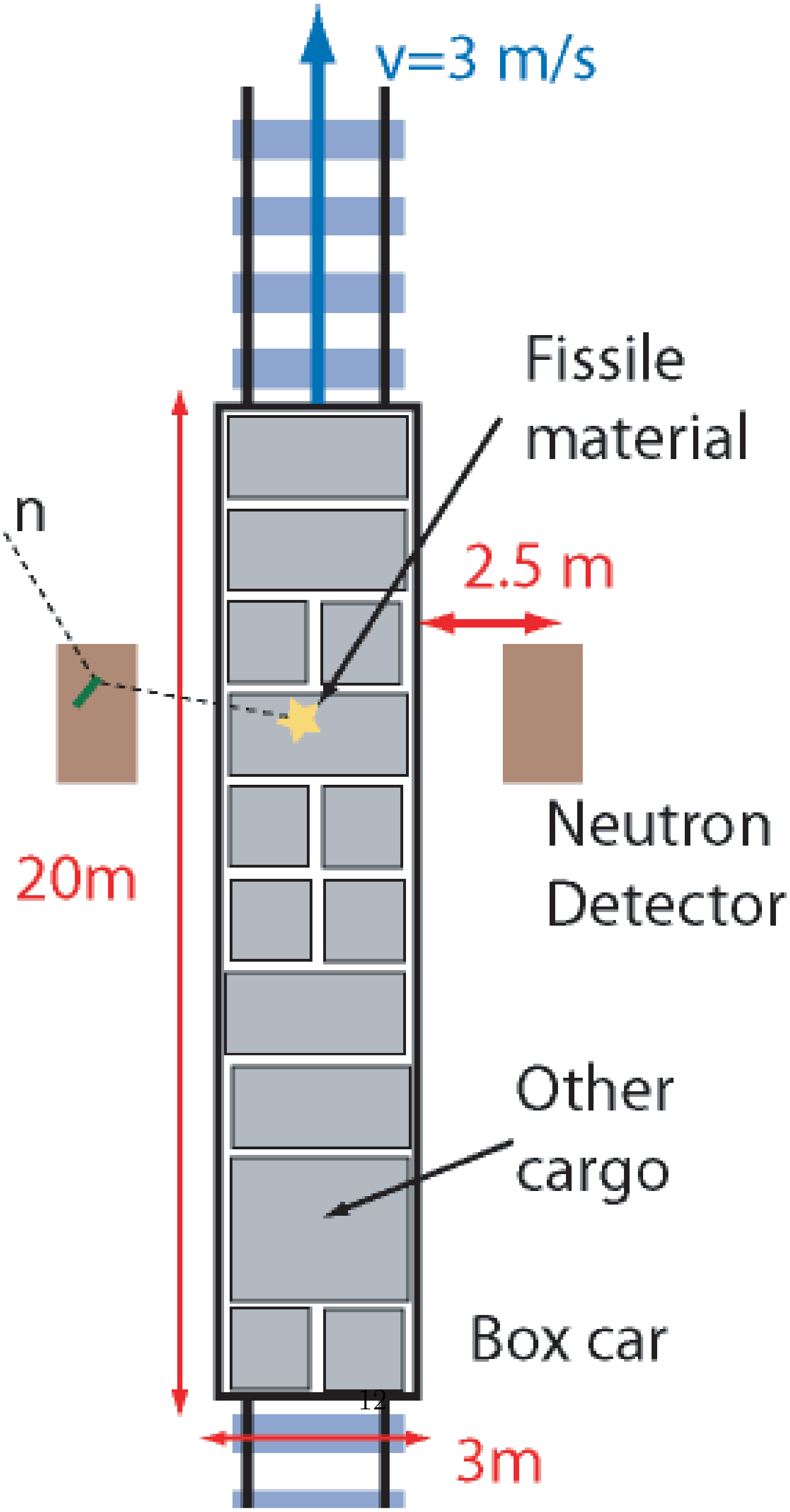


Figure 5: Simple setup for scanning a railroad car.

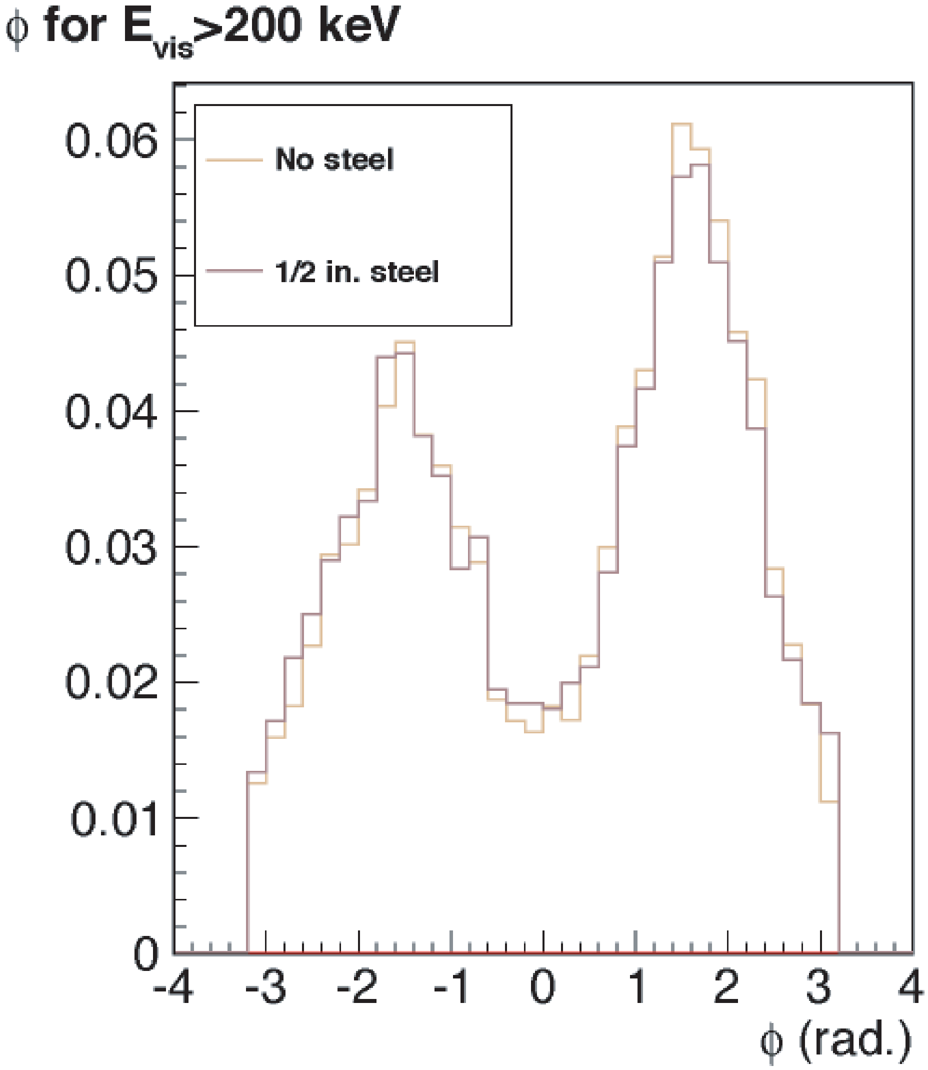


Figure 6: Comparison of measured angle with and without absorber. The data is normalized for comparison.

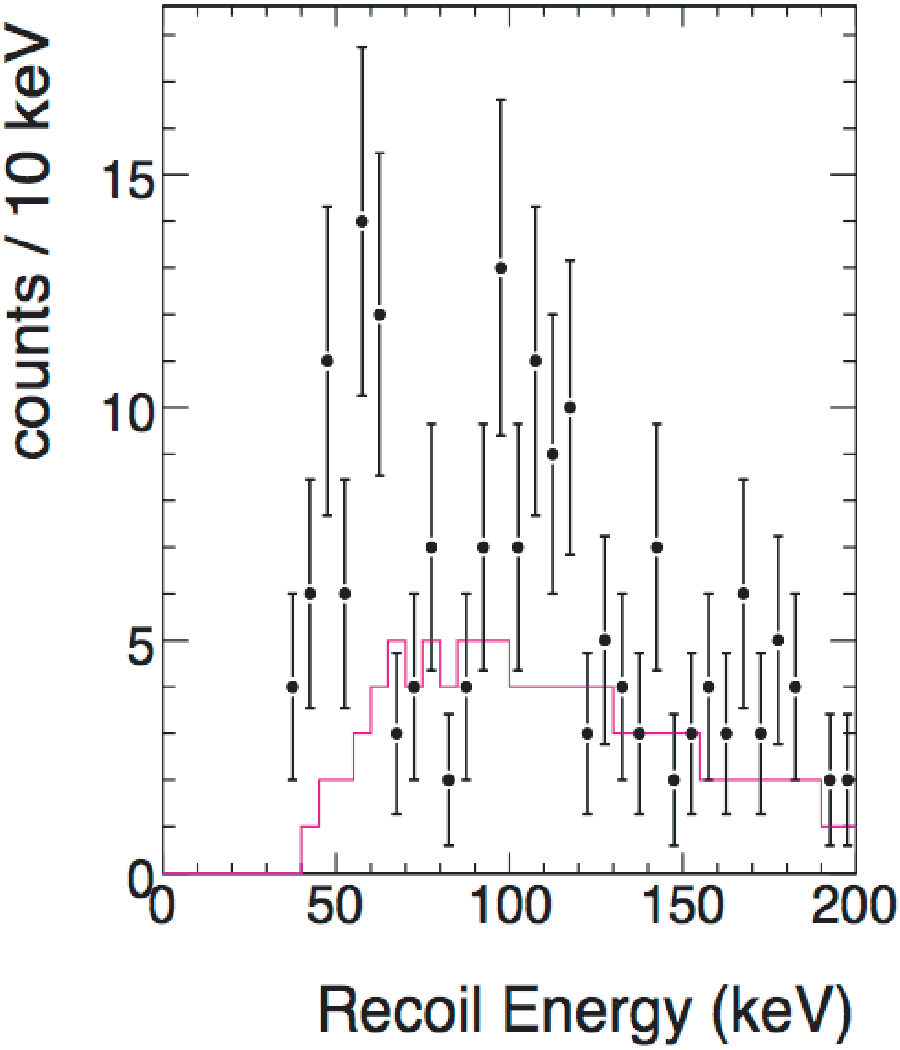


Figure 7: Lab setup.

6. Here is a more complex example: suppose a 4 kg WgPu warhead is hidden in a building 10 m from the street. The building absorbs 90% of the neutrons. A truck with a 1 m^3 detector on it drives down the street at a speed v. Will the warhead be detected if v=2 m/s (=5 mph)? During the 10 s the truck is within 14 m of the location of the warhead (10 m up the street to 10 m down the street), the detector will see 2.7 counts from the warhead with a background of 3 counts from cosmic rays, giving a total of 5.7 counts. For this background rate, there is a 4% chance of observing 6 or more counts , so this would be better than an f=1 detection, but not f=2. Operating at P=5 bar, the numbers become 13.5 counts from the warhead and 15 from background. These numbers are large enough to use Eq. 2 and this gives f=3.5.

7. We consider a ship carrying a 4 kg WgPu warhead passing by a buoy with an 8 m^3 detector at 1 bar. The ship goes 2 m/s (=5 mph) and we require it passes within 10 m of the detector. Suppose the warhead is located 5 m inside the ship, so the warhead itself passes within 15 m of the detector. Assume 90% of the neutrons get lost in the ship. During the 15s of passing, there will be a total of 40 counts: 14 from the warhead and 36 from cosmic ray background. From Eq. 1, this would be a f=2.3 detection.

8. Suppose instead the detector in Example 7 is located in a blimp or UAV that hovers above the ship at a distance of 50 m. How long does it need to stay there in order to detect the warhead? For an f=1 confidence detection, a 200 second dwell time would give 480 background counts and 22 counts from the warhead, which is an f=1 detection. For f=2, the dwell time would need to be almost fifteen minutes.

5 Using directional information to reduce backgrounds

Our detector has the unique feature that it measures both recoil energy and direction and the recoil direction roughly encodes the direction of the incident neutron. From tests so far, ten recoils give the incident neutron direction within about ten degrees. This has the effect of reducing the factor in Eq. 3 by the fraction of background appearing in a ten degree cone around the source direction. For the angular distribution of neutrons at sea level

$$I\left(E,X,\cos\theta\right)=I\left(E,0,0\right)e^{-\Lambda X/\cos\theta}$$

for $\theta < 70°$. In most of the examples above,$\theta = 90°$, which is outside the domain of validity. For air, $\Lambda = 61\mathrm{g/cm}^2$ and at sea level, $X = 1,000\mathrm{g/cm}^2$, so the exponential factor around 70o is 50. To be a little conservative, we take 1% of sea level neutrons in a 20° opening angle cone. Tests we have done indicate 20° is a reasonable cone from a point source, so neutrons from a point source come from 1% of a sphere. This means

$$B=\frac{0.003}{\mathrm{sec}}\left(\frac{V}{1\mathrm{m}^3}\right)\left(\frac{P}{1\mathrm{bar}}\right)$$

. Since B appears in the square root, this has the effect of reducing the measuring time by a factor of ten.

We now revisit the examples of Section 4 including directional information:

1. The measurement time would remain to T=10^{-5}s.

2. The measurement time is reduced to less than 0.2s for f=3.

3. The measurement time is reduced to 0.2 s for f=1 and 0.6 s for f=3.

4. For A=20,000/s and T=5s, we can scan at D=28 m for f=1 and D=7 m for f=3.

5. For the $1\mathrm{m}^3$ operating at 1 bar, in the 10 s the truck is within 14 m of the warhead, there would be 2.7 neutrons with no background neutrons expected. For a detector operating at P=5 bar, 13.5 neutrons would be detected, with a background of 0.02. This would be conclusive.

6. For an 8 m^3 buoy detector, during the 15 s the ship is closest to the buoy, 14 counts would be observed, all from the warhead.

7. In this final case, instead of horizontal, the signal neutrons would be coming up. For this case there is essentially no background, so a dwell time of one minute at 50 m above the ship would give a conclusive signal of seven neutrons.

   Table 3 summarizes these results. We take f=1 as a MARGINAL detection, f=2 as a SIGNIFICANT detection and f=3 as a DECISIVE detection.

Configuration	Not using directional information	Including directional information
4 kg WgPu at 1 m, 1 m^3 at 1 bar	$T = 10^{-5}$ s DECISIVE	$T = 10^{-5}$ s DECISIVE
10 g WgPu at 1 m, 1 m^3 at 1 bar	$T < 1$ s, MARGINAL $T = 2$ s, DECISIVE	$T < 0.1$ s, MARGINAL $T = 0.2$ DECISIVE
4 kg WgPu at 30 m, 1 m^3 at 1 bar	$T = 2$ s, MARGINAL $T = 9$ s, DECISIVE	$T = 0.2$ s, MARGINAL $T = 0.6$ DECISIVE
A=20,000 n/s, T=5s PV=1,000 l-bar	D=8.4 m, MARGINAL D=4.8 m, DECISIVE	$D = 28$ m, MARGINAL $D = 7$ m, DECISIVE
Vehicle mounted 10 m from hidden WgPu warhead, 90% absorption, v=5 mph	During 10 s of passage 3 counts of signal with 3 counts of background MARGINAL-SUBSTANTIAL	During 10 s of passage 2.7 counts, no background SUBSTANTIAL
Previous example with P=5 bar	During 10 s of passage, see 13.5 signal counts plus 15 15 background, DECISIVE	During 10 s of passage see 13.5 counts with no background, DECISIVE
Ship passing a 8 m^3 detector on a buoy 15 m, 4 kg WgPu on board 90% absorption in ship	In 15 s of passge, see 40 counts from warhead, 36 background, SUBSTANTIAL	In 15 s of passage , see 40 counts from warhead no background, DECISIVE
Blimp or UAV mounted detector, 50 m above ship with 90% absorption in ship	T=200 s MARGINAL, 15 min DECISIVE	For T=1 min, see 7 counts from warhead, DECISIVE

Table 3: Summary of examples presented in Sections 4 and 5

.

6 Portable detectors

For a portable version, a sensitive volume of 20 × 20 × 20 cm, the flux of neutrons from a WgPu device (Table 1) 40/s at a distance of 1 m. Of these, 0.6/s would result in recoils as shown in Figure 2. The neutron background from cosmic rays is about 0.1/s, resulting in 0.0015/s detected neutrons. So, at 1 m distance, in one minute of operation, this detector would observe 36 neutrons from the device and 0.1 neutrons background, giving a very clear indication that the device contains fissile material. Carrying out the same argument, at 10 m, an hours operation would result in 22 detected neutrons with 6 background neutrons. However, the ability of our device to determine the direction would mean all of the neutrons from the device would have recoil tracks that point toward the device while the cosmic ray neutrons would have recoil tracks pointing in random directions. Thus, at 10 m, the portable device would also give a clear indication of fissile material.

The portable device described above would weigh about 20-25 kg (this is based on estimates from the actual components), be battery powered (the power consumption is about the same as two laptop computers) and have dimensions of about a foot one each side. A built in processor would carry out the pattern recognition necessary to identify the recoil helium. All of these elements have been demonstrated in our lab [2]. Based on our experience, a portable detector of this type could be built for under $100,000 and part of our plan would be to optimize the most costly components to further reduce the cost.

For screening large cargoes, a large detector would be needed. A larger detector is more sensitive to neutrons so it needs less time to ensure a container or vehicle does not contain fissile material. A large screening detector we plan to design would measure $0.5 \times 10 \times 2m\mathrm{m}^3$ and could be used, for example, to screen trucks passing slowly by. If we go through an analysis similar to the one above, a 4 kg WgPu device in a container on a truck passing 2 m away from the detector wall would have 4,000 neutrons per second passing through the detector resulting in about 120 neutron detections per second, where we have assumed that 90% of all neutrons get absorbed by material in the container or the container itself. The background neutron flux through the detector would be about 30/s, resulting in about 0.5 neutron detections. This calculation tells us this large screening detector could easily identify a 4 kg WgPu device in a truck rolling slowly by the detector. Put another way, if we require as few as 10 neutron detections (with a background of 0.5 neutrons from cosmic rays) to pull a truck over and search it, this system would be sensitive to 300 g of WgPu surrounded by a tungsten or depleted uranium shield and assuming 90% of the neutrons are absorbed by other material.

A detector of this size has not been constructed, but we have demonstrated all the necessary components and understand how the cost and implementation scale to larger sizes. The large detector consists mainly of copies of the portable detector inside a single gas enclosure and, since the gas enclosure is the single most expensive component, we believe the large detector could be constructed for about $2 million.

The optical system and CCD cameras present the primary element of risk in the design of the large detector. For this detector, it will be necessary to image 40 sq. meters of amplification region (see. Currently, our prototypes image about 0.04 sq. meters with optical systems costing about $8,000. This cost is fine for the portable detector; only a single camera is necessary. The large detector would require 1,000 such optical systems, giving a cost of $8 million in cameras alone. One of our principle goals is developing an optical system able to image 1 sq. meter for a cost of $10,000, a factor of twenty improvement over our current system. We would be able to develop a system optimized for this application; an optical system able to image large areas does not exist simply because there is has not been a need for one.

Aside from developing the optical system, the rest of the components are low risk: we have demonstrated the amplification region, measured the light output of the CF_4 avalanche, imaged tracks, demonstrated the ability to reject gamma ray interactions and fabricated all of the internal components. While integrating all of these into the portable system is not trivial, it is primarily incremental engineering. The large detector presents more significant challenges, largely associated with the construction of the very large gas enclosure and the mechanical mounting for the large number of cameras. These are difficult problems, but again addressable by careful engineering and testing

The technical and scientific impact after of this project will the construction of an efficient neutron detector of unprecedented capabilities that can be commercialized and put into widespread use quickly. The focus of this work is the detection of small WgPu devices, but this technology will find very broad application in the remote detection of a wide range of fissile and fissionable materials.

References

[1] Steve A Fetter, Valery A. Frolov, Marvin Miller, Robert Mozley, Oleg F. Prilutsky, Stanislav N. Rodionov, and Roald Z. Sagdeev. Detecting nuclear warheads. *Science and Global Security: The Technical Basis for Arms Control, Disarmament, and Nonproliferation Initiatives*, 1:225 – 253, 1990.

[2] D. Dujmic et al. Charge amplification concepts for direction-sensitive dark matter detectors. *Astropart. Phys.*, 30:58–64, 2008.