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New Technology for Detecting 235U in Cargo

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Abstract

The probability and the consequences of a nuclear detonation in a major US city are shown to justify deploying newly developed technology that can radiographically detect shielded ^{235}U in cargo at border crossings. The doses for both radiography and active interrogation are compared to natural background rates and are shown to be negligible. It is estimated a system of active and passive charged particle radiography that could radiograph all licit cross border traffic would cost ~ $\$6\times10^9$.

Introduction

The destruction of the world trade center buildings in an attack on 9/11/2001 demonstrated that some extremist groups are will to inflict massive death and destruction. The large number of deaths and the economic damage caused by two jet airliners flying into the world trade towers pales in comparison to the number of deaths, the direct economic damage, and the disruption of the world economy that would be caused by the explosion of even a small atomic weapon in a major urban area. The explosion of an atomic bomb over Hiroshima at the end of World War II caused ~10^5 prompt deaths .[1] The US government values preventable deaths at ~$\$10^7$.[2] The direct cost in deaths of a nuclear explosion in a major city would likely be on the order of a trillion dollars. The cost of casualties and the economic costs would exceed this considerably.

Estimates of the likelihood of such an event found in the literature[3] range from ~0.01/year to 0.1/year. Since there has not been such an event in the past 65 years, the lower number appears more credible. A simple cost benefit analysis based on these numbers suggests that investing ~$\$10^{10}$ annually to eliminate the likelihood of a terrorist nuclear detonation in a US city is warranted.

Nuclear explosives can be broken into two classes, thermonuclear weapons that make up the nuclear stockpile of the major nuclear armed state, and atomic weapons that are far simpler and less powerful and are the weapons of the minor nuclear states. It is the latter that pose the terrorist nuclear threat, because of the simple and well know principles for their operation.

Atomic explosions are created by generating a supercritical mass (a mass of material that supports a chain reaction because it is larger than the critical mass of about 10 kg for a bare sphere of ^{239}Pu and 52 kg of ^{235}U) of fissile materials and injecting neutrons to start a fast fission chain reaction that releases large amounts energy in 100's of nsec, before the energy released causes the critical mass of materials to disassemble. Two fissile materials, ^{235}U and ^{239}Pu, can be made on a scale that allows sufficient amounts to be produced for making atomic bombs. ^{235}U occurs with an abundance of 0.7% in natural Uranium and is produced in industrial scale separation facilities. ^{239}Pu doesn't occur naturally in any significant amount but is made by neutron capture on ^{238}U in the neutron flux in a nuclear reactor, and needs to be chemically separated from the irradiated reactor fuel.

Large quantities of these materials have been created in the past 65 years. Most are tightly controlled by the major nuclear nations. Indeed this is the first line of defense in preventing terrorists from obtaining nuclear explosives. However, the frightening prospect of some material being available to terrorists either through theft or intentional release has been the subject of many studies over the past couple of decades.

The higher specific activity and neutron radiation produced by some of the plutonium isotopes in reactor produced plutonium makes its use in atomic explosions more complicated than uranium. Plutonium requires implosion assembly of a supercritical mass in order to obtain any efficiency in a nuclear explosion because of neutrons produced by spontaneous fission. If neutrons are released into the assembly too early the fission energy released causes the device to disassemble without an explosive yield-a so called fizzle. Another import aspect of the neutrons released by spontaneous fission is that they are hard to shield and easy to detect.

Articles in the popular literature point to the difficulty of detecting highly enriched uranium using currently deployed technology. Recent work has shown that an effective border defense can be mounted against the transport of such devices through border crossings. In this paper we describe how this can be accomplished and argue that it is cost effective.

A simple Test

A simple experiment with a high purity germanium (HpGe) counter and 20 kg uranium cubes (1 liter) of depleted (DU) and 20% enriched(LEU) uranium illustrates the difficulty detecting shielded highly enriched uranium. Gamma-ray spectra were measured with the detector 3 m from the center of the targets for 5 configurations ; background, bare DU, Bare LEU, Shielded DU, and Shielded LEU. By forming the quantity:

$$\frac{dN}{dE}(^{235}U) = \left[\frac{dN}{dE}(LEU) - \frac{dN}{dE}(background)\right] - 0.8\left[\frac{dN}{dE}(DU) - \frac{dN}{dE}(background)\right],$$

$\frac{dN}{dt}$?

for both the bare and shielded configuration, the gamma ray signature due only to the 235U was extracted. The signal would be 5 times larger for highly enriched uranium. The results are shown in Figure 1 for 1000 seconds of counting time. Although there is a clear and strong signal from bare ^{235}U there is no detectable signal from shielded ^{235}U. **With 2.5 cm of lead shielding, threat quantities of ^{235}U are undetectable with the best practical gamma detection technology**[4] in 1000 seconds of counting time.

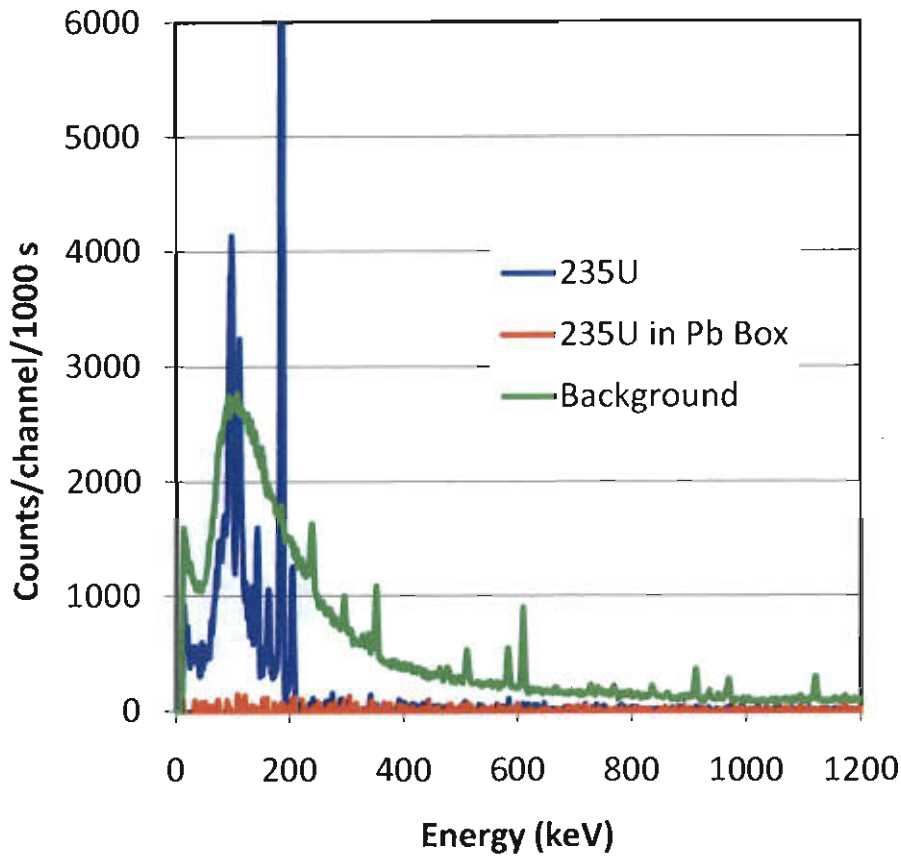

Figure 1) Subtracted signal from an enriched uranium sample showing the gamma ray signal from 235U for a 1000 second counting time. The background signal is also shown.

These objects could be easily transported in a small automobile. The lead shield weighs 17 kg and the uranium weighs 20 kg. Three 37 kg packages would contain enough fissile material to create a Hiroshima sized explosion-about 100 kg total including the shielding. Radiation monitors cannot be relied upon to detect the threat of a ^{235}U based fission bomb carried in a light vehicle. **The absence of an alarm from a radiation monitor does not prove that ^{235}U is not present--it only proves that no unshielded threat is present.** In order to mount a robust

border defense, the first level of screening needs to be based on something other than the passive radiation signal, and it needs to screen all transport vehicles including automobiles.

The scale of the problem is daunting. Approximately 20,000,000 shipping containers enter the county by air, sea, and land annually.[5] In addition about 100,000,000 personal vehicles enter the country annually from Mexico and Canada.[6] Any of these could be a delivery vehicle for an atomic weapon. **The hardest problem in providing a robust border defense is screening the 10^8 personal vehicles in a safe and effective fashion.**

Radiography

X-ray radiography can detect dense objects in complex scenes with high reliability if care is taken to reduce scatter backgrounds and more than one axis is used.[7] Although radiography can detect dense objects it cannot provide a positive identification of fissile materials. Positive radiographic identifications need to be checked by direct examination which may involve unloading the cargo.

Unfortunately, the dose needed for conventional x-radiography is too large to be applied to human occupants of vehicles. Since 90% of cross border traffic is occupied personal vehicles, x radiography can only address a small fraction of the problem. A new form of radiography that uses the multiple scattering of charged particles (see Figure 2) that are transmitted through the object can provide a solution that is both safe and effective.[8-10] Other types of radiography with charged particle beams have been studied previously, and should be considered given the urgency of a solution to this problem. Proton energy loss[11] or range radiography,[12] particularly, in view of a new class of low cost compact proton accelerators that are currently or expected to be available soon[13] may be attractive when compared to x-radiography.

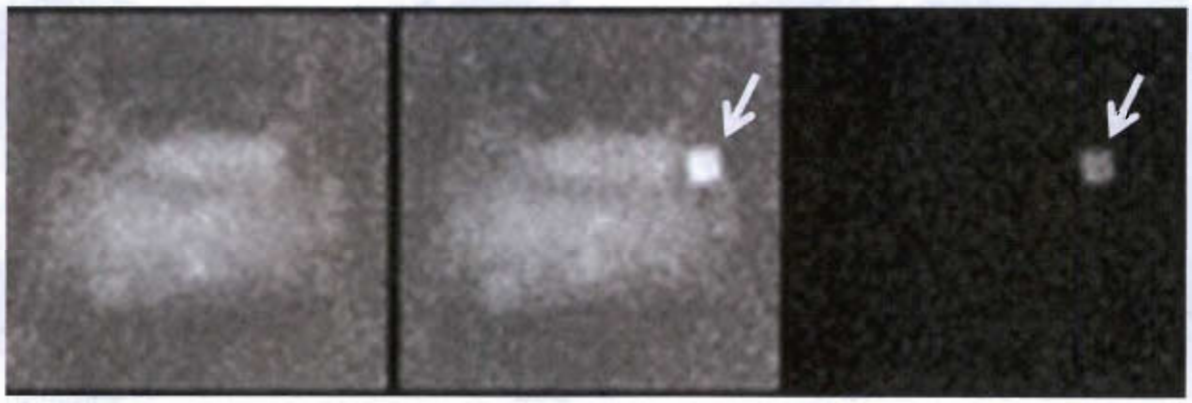

Figure 2) One slice of a cosmic ray muon tomography of an engine (left) an engine with 10x10x10 cm^3 depleted uranium sample (marked with an arrow) above it (middle) and the difference (right). The data are from reference 10.

A figure of merit for comparing different types of radiography for radiography aimed at detecting nuclear threats is the dose required to achieve a given precision. A suitable figure of merit is $\frac{\Delta l}{l} = 1$ for a 1cm^2 10 cm thick uranium object. This dose would provide a 10 standard deviation signal for detection averaged over the 100 cm^{2}area of the uranium object used for the gamma ray tests.

Figure of Merit

X-ray transmission through an object depends on measuring the attenuation of the incident beam in order to obtain density information. The attenuation is given by Beers law:[14]

$$\frac{N}{N_0} = e^{-\frac{l}{\lambda}}$$

Where N is the transmitted flux, N_0 is the incident flux, λ is the mean free path for the incident X-rays, and l is the thickness through the object being radiographed. This can be inverted to obtain : $l = -\lambda \ln\left(\frac{N}{N_0}\right)$. If one assumes mono-energetic x-rays so that λ is a constant and perfect counting of the x-rays, the uncertainty is given by the Poison statistics of the transmitted flux: $\Delta l = \frac{\lambda}{\sqrt{N}}$. In a simple approximation where the X-ray energy is assumed to be deposited at it's interaction point. The dose is given by the energy deposited per unit mass in the beam: $D_X = \frac{E_X}{\lambda}$.

The maximum mean free path of x-rays in Uranium occurs near 4 MeV and is 22 g/cm^2. The long mean leads to best figure of merit for thick object radiography.[15] The dose of 4 MeV x-rays needed to measure a 10 cm thickness of uranium with an uncertainty of 10 cm (1 sigma detection) is about 2 nSv. If one considers the dose from a bremsstrahlung source, which is not mono energetic, and detector efficiency, this increases this by ~5. This corresponds to 2.4 minutes of the average person's exposure to natural background radiation.

Cosmic ray muon radiography relies on measuring the difference of the incident and outgoing angles of cosmic ray muons that pass through a scene (multiple scattering radiography). The uncertainty is given by: $\frac{\Delta l}{l} = \frac{1}{\sqrt{2N}}$.[9] Because the mean free path of muons is large $N_0 \cong N$. muons loss energy at a nearly constant rate of ~2MeV/(g/cm^2) In this case the dose needed is 0.16 nSv, more than ten times lower than the idealized x-ray dose. The disadvantage of muon tomography is the low rate of arrival of cosmic ray muons. This exposure takes ~1 minute, but has the advantage that no external source of radiation is required.

Multiple scattering radiography can be performed using any charged particle with sufficient penetration. The exposure time for charge particle radiography can be reduced by using an artificial source of radiation, i. e., a proton accelerator. In this cast the dose need to obtain a given transmitted flux would be increased because of the nuclear attenuation of protons in the object, and because of the radiation weighting factor for protons which is about 2 compared to 1 for muons and x-rays.[16] This leads to a dose of ~1 nSv. A beam energy of 600 MeV would be sufficient to penetrate nearly all cargo containers.

One can take advantage of a source of monoenergetic protons to perform energy loss radiography.[11] Here one measures the energy loss of protons that have passed through the scene. Since energy loss is approximately linear with material thickness, a single particle provides a measurement of the thickness to a precision of the straggling width. The distribution in the energy loss of charged particles is given by the Landau distribution[17] and its width is only a small fraction of the energy loss. For the thickness of a cargo container, the straggling is typically a few percent of the energy loss. This is illustrated in Figure 3 where calculations [18] of the Landau distribution for 1 GeV protons passing through the amount of iron presented by a cargo container uniformly loaded with iron to its weight limit (green) and the iron plus 10 cm of ^{235}U are shown. The widths of the distributions are several percent. The dose required for energy loss radiography to measure the thickness of 10 cm of 235U is only 4 pSv, 400 times less than x-rays. This is not realistic since it is less than a single proton, but it does demonstrate the power of energy loss radiography. This is equivalent to 57 ms of average background radiation.

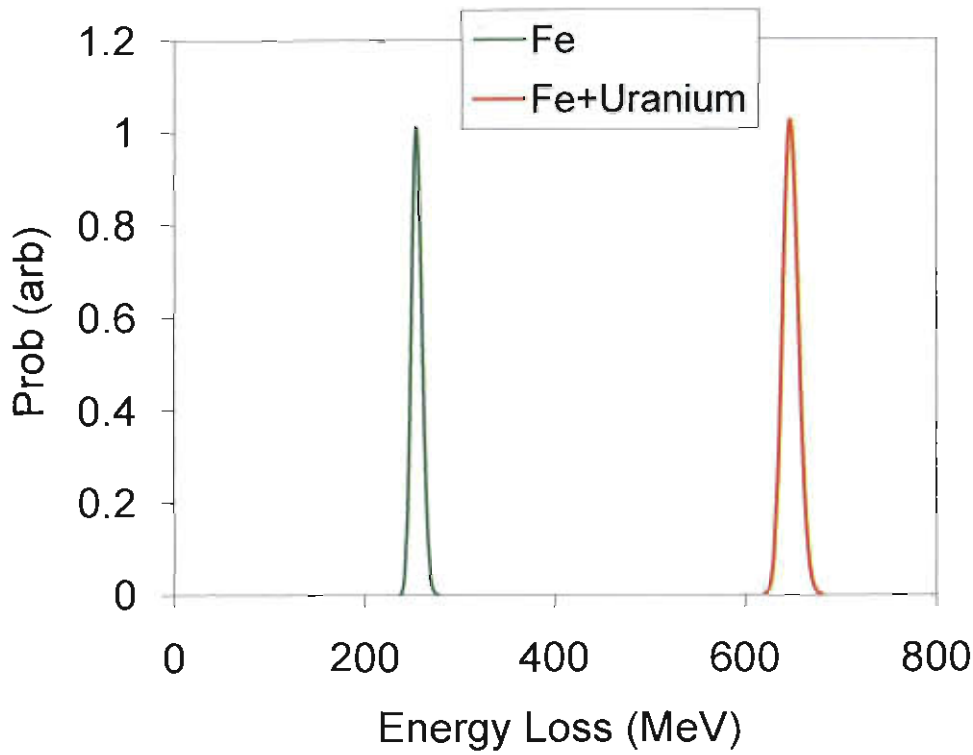

Figure 3) The Landau distribution for 1 GeV protons passing through 149 g/cm^2 of iron (the areal density presented by a cargo container loaded uniformly to its weight limit with iron) and 149 g/cm^2 of iron plus 200 g/cm^2 (10 cm) of ^{235}U. The separation is sufficient so that a single transmitted proton provides a 40 standard deviation detection.

The risk of even large scale human exposure to dose of this size is negligible. Furthermore, with a proton accelerator such a dose can be applied in very short times. This opens up the possibility of radiography to detect nuclear threats at highway speed traffic.

Active interrogation

None of the forms of radiography discussed above can discriminate fissile material from other heavy dense material such as gold or tungsten at low dose. Although radiography can provide primary screening, identification of fissile material requires secondary screening. In personal vehicle traffic at a border crossing, cosmic ray muon tomography could provide primary screening with no added radiation dose while inspection could be used for secondary screening. Where higher screening rates are desirable one could use accelerator produced proton beams and energy loss radiography for primary screening. The same proton accelerator could be used for targeted active interrogation of any threats that were identified by the radiography.

Recent work has shown that the long mean free path of protons provides advantages over other probes for active interrogation because although the fission cross sections are large protons both penetrate material well and also generate secondary particles which also induce fission an fissile material.[19] In a 20 kG ^{235}U cube, incident protons produce fissions at the rate of about 2 fissions/proton. About 1% of fissions produce delayed neutrons 10 sec or more after the irradiating proton pulse. A 20 kg cube of 235U has a k_{eff} of about 0.8. This leads to a neutronic gain of about 5 for both the prompt and delayed neutrons. A single incident neutron will produce about 0.5 delayed neutrons. A pulse of 10^4 protons spread over the 100 cm^2 of the target would produce about 10^4 delayed neutrons, a distinctive signature of fissile material. This fluence corresponds to a dose of 64 nSv, the equivalent of 14 minutes of natural background radiation.

Economics

The cost of a commercial produced cosmic ray muon scanner is ~$\$2\times10^6$. Assuming a scan time of 60 s, a yearly flow of personal vehicles of 1×10^8, and an efficiency of 10% to account of traffic ebbs and peaks, 2000 scanners at a cost of $\$4\times10^9$ would cover the borders, a modest cost when compared to the consequences of a nuclear explosion.

For commercial traffic, where higher speed scanning is essential to avoid disrupting commerce, a very low power 600 MeV synchrotron accelerator built using conventional technology, beam transport system, and a spectrometer for energy loss radiography would cost ~$\$5\times10^7$. This system would be capable of 10 times (or more) higher scanning speeds than a cosmic ray muon scanner and could provide integrated active interrogation. If these were used at high traffic ports for cargo scanning perhaps only 40 would be needed at a cost of $\$2\times10^9$.

These are only very rough estimates of costs and do not include operating costs. Never the less, the actual cost of a robust radiography based border detection system would be far less than the annual cost of an unprotected border.

Conclusions

Existing technology can be deployed to detect enriched uranium in cargo and personal vehicles with high reliability and at low radiation doses. A cost benefit analysis shows that the research and cost of deployment are justified. A solution that employs a mix of cosmic ray radiography coupled with inspection to resolve positive signals, and active radiography and active interrogation would be cost effective well providing reliable detection. Research into low dose radiography and detection techniques is surely warranted.

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