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Detection of Neutron Sources in Cargo Containers

J. I. Katz

Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO, USA

We investigate the problem of detecting the presence of clandestine neutron sources, such as would be produced by nuclear weapons containing plutonium, within cargo containers. Small, simple, and economical semiconductor photodiode detectors affixed to the outsides of containers are capable of producing statistically robust detections of unshielded sources when their output is integrated over the durations of ocean voyages. It is possible to shield such sources with thick layers of neutron-absorbing material, and to minimize the effects of such absorbers on ambient or artificial external neutron fluxes by surrounding them with neutron-reflective material.

Terrorist nuclear weapons or special nuclear material may be shipped in cargo containers, and their detection is a matter of serious concern. If the special nuclear material is plutonium then its ^{240}Pu content is a significant source of spontaneous fission neutrons, depending on the quantity of plutonium and its isotopic composition. These spontaneous fission neutrons may be detectable.

In an earlier report[1] we suggested applying ^{10}B-coated photodiode neutron detectors to the outsides of shipping containers to detect any spontaneous fission neutrons emitted inside. Simple analytic estimates showed that, integrated over a 10-day voyage, a 1 cm^2 detector would detect with high statistical significance an unshielded spontaneous fission neutron source in the presence of the background of cosmic ray-induced spallation neutrons. The purpose of this article is to report the results and implications of quantitative Monte-Carlo neutron transport calculations of this problem, including the effects of shielding and the contents of surrounding containers. These calculations used the MCNPX code,[2–4] which is a standard tool used to calculate neutron transport.

In all of these calculations the assumed source was a sphere of 5 kg of δ-plutonium (radius 4.22 cm). A source strength of 4.5×10^5 n/s was chosen (this

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Address correspondence to J. I. Katz, Department of Physics and McDonnell Center for the Space Sciences, Washington University, 1 Brookings Dr., St. Louis, MO 63130, USA. E-mail: katz@wuphys.wustl.edu

is appropriate to 10 percent ^{240}Pu, a compromise between nominal “weapons grade” and “reactor grade” compositions). The results were normalized to the source rate of spontaneous fission neutrons. The plutonium was surrounded by a 50 cm thick spherical shell of nominal “explosive” (composition $C_7N_3O_6H_5$ and density 1.62 gm^{-3}; TNT). This is not meant to be a realistic bomb; rather, it was deliberately chosen as an amateur interpretation of Fat Man (the subject of the Trinity test and dropped on Nagasaki).

The thick “explosive” layer is a fairly effective moderator and reflector and a significant absorber. The assembly is close to thermal neutron criticality (the multiplication factor is 6.0), and for each source neutron there are 20 neutron crossings of the boundary between plutonium and “explosive,” although only 0.24 neutrons cross the outer surface of the “explosive.”

The source was at the center of a 40′ shipping container. The detector was applied to the surface of the container (the container walls were ignored) at a point half-way from bottom to top but 3.29 m displaced from the center of the side of the container along its length, so that the center of the detector was 3.5 m from the center of the source. This location was chosen because three detectors may be applied to the container so that no point within its volume is more than 3.5 m from any detector. Three detectors is a reasonable compromise between the requirements to minimize the number of detectors and to bring every point in the container as close as possible to a detector. In order to obtain accurate statistics with a feasible number of Monte Carlo particles a disc detector of 1 m radius was used in the calculations, and the inferred count rate scaled to the more practical 1 cm^2 detector.

The detector itself consisted of a 2 μ layer of boron enriched to 80 percent ^{10}B. In all cases the detector was assumed to have an area of 1 cm^2. The silicon or gallium arsenide photodiode, perhaps 10 μ thick, is not calculated explicitly, but a (conservative) 0.25 efficiency for detection of (n,α) reactions in the boron is assumed, as discussed by Grober and Katz.[1] This layer is sandwiched between two 1.75 cm thick layers of paraffin or polyethylene (CH_2 of density 0.92 g/cm^3) whose purpose is to thermalize neutrons emitted by a bare source. When the source is moderated the CH_2 acts as a neutron reflector (each slab has a scattering optical depth, at normal incidence, to thermal neutrons of 2.8). The thickness of these layers is constrained by the corrugations of shipping container walls, which are about 3.75 cm deep. If the slabs of CH_2 were not included the detector would be insensitive to an *unmoderated* neutron source. A more sophisticated system would include detectors with and without sandwiching slabs of CH_2.

This baseline calculation produces a reaction rate of 1.5×10^{-5} cm^{-3} (of the boron film) per source neutron. In 10^6 seconds of exposure (typical of a transoceanic voyage) to a source of 4.5×10^5 neutrons s^{-1} a 1 cm^2 detector records 340 events, given the assumed efficiency. This may be compared to the rough estimate[1] of 600 detected events. The results cannot be compared closely because the estimate assumed a bare unmoderated source for the baseline problem.

A number of variations on the baseline calculation were performed (Table 1). For example, surrounding the container containing the neutron source with 26 innocent containers (a $3 \times 3 \times 3$ array of containers, with the neutron source in the central container), with each innocent container filled with a nominal homogeneous cargo of 0.3 g/cm^3 (the known mean density of container loading), taken to be of composition FeH (3.7% hydrogen by mass; only the hydrogen is significant for neutronics so the composition of the remainder of the mass is irrelevant), increases the number of (n,α) reactions detected to 1600. This is a consequence of neutron reflection by the hydrogen in the innocent containers. It is about ten times less than the rough estimate,[1] probably because the latter ignored the reflective effect of the CH_2 slabs around the detector.

The assumption of homogeneous cargo (other than the assumed threat source) is of uncertain validity and may introduce significant error. Neutron transport is very different in a heterogeneous medium, with free passages between regions of comparatively high hydrogen density, than in a homogeneous medium. Some cargoes (for example, a container packed full of clothing) are reasonably homogeneous, whereas others (machinery, dense objects with hydrogenous packing, drums of chemicals) may either contain no hydrogen or have it concentrated into isolated regions. Unfortunately, it is probably not possible to resolve this uncertainty computationally because the hydrogen distribution in real cargo is difficult to characterize. Straightforward experiments in which real neutron sources (D-D accelerators, (α,n) or ^{252}Californium, not plutonium!) are placed in instrumented containers among innocent cargo are probably necessary to resolve these uncertainties.

These count rates should be compared to those produced by cosmic ray spallation neutrons. The chief source of these neutrons is spallation in the cargo (both the threat source and surrounding innocent cargo), rather than in the air, because cargo densities (0.3 g/cm^3, of which very little is hydrogen) are hundreds of times greater than the density of air. The production of neutrons by cosmic ray interactions in surrounding cargo and the ship itself is known as the "ship effect." Solar neutrons are negligible compared to those made by spallation.

Again, the FeH composition was assumed; the spallation neutron production rate is nearly independent of the composition of the non-hydrogenous portion of the material. Therefore, MCNPX calculations were done in which containers containing innocent cargo were irradiated by cosmic rays, and neutron production, transport, and reaction were calculated. The sea-level cosmic ray spectrum from 100 MeV to 100 GeV was taken from Pal,[5] and vertical downward incidence distributed uniformly across the top of the container at a flux of 2.7×10^{-4} cm^{-2} s^{-1} was assumed (this makes it a reasonable approximation to ignore cosmic rays entering the container from the side). The cosmic rays were assumed to be all protons because the more abundant muons rarely produce neutrons.

The result for irradiation of a single container filled with the same model (FeH at 0.3 g cm^{-3}) of innocent cargo, integrated over 10^6 s, with the same detector as before, was 0.6 detected reaction. When an array of 27 similar containers was taken this increased to 1.7 detected reactions, as a result of reflection of neutrons by the surrounding containers. These results are very small compared to the predicted signals of the assumed threats discussed earlier, and indicate that the natural neutron background is not a significant obstacle to detection of spontaneous fission neutrons from the assumed threat. These backgrounds are about two orders of magnitude less than the rough estimates of Grober and Katz,[1] in part because the estimates did not allow for thermal neutron reflection by the CH_2 slabs surrounding the detector, and in part because of differing assumptions regarding the cosmic ray flux (equivalently, geomagnetic latitude).

Unfortunately, anyone capable of building even an improvised plutonium-based nuclear device is probably aware of the desirability of shielding the spontaneous fission neutrons and is capable of doing so. An effective shield is a 50 cm layer of borated polyethylene or paraffin. A series of calculations was run with such a shield, in the form of a spherical shell of inner radius 54.22 cm and outer radius 104.22 cm containing 5% natural boron by mass. The result was to reduce the detected counts in the baseline calculation to 0.08, an effective shielding factor of about 4,000. This is clearly undetectable. If the source is surrounded by 26 containers filled with innocent cargo 0.7 counts are detected, the effective shielding factor is 2,000, and the source would still be undetectable.

Thermal neutron absorbers produce a “hole” in the surrounding distribution of thermal neutrons. Would it be possible to detect the presence of such an absorber (comparatively uncommon in innocent cargo) by measuring the density of thermal neutrons produced by cosmic rays? Two calculations were done to test this. In the first the absorber (with only a void inside) was placed in a container, and the container outside the absorber was filled with the usual assumed FeH innocent cargo. In the second calculation this container was surrounded by 26 containers each filled with innocent cargo.

Table 1: Problems.

No.	Features	Counts in 10^6s
1	Baseline (4.22 cm Pu, 50 cm HE)	340.00
2	Baseline + 26 innocent containers	1600.00
3	Innocent container with cosmic rays	0.60
4	27 innocent containers with cosmic rays	1.70
5	Baseline with 50 cm borated CH_2 shield	0.08
6	Baseline + shield + 26 innocent containers	0.70
7	No. 3 + shield	0.60
8	No. 4 + shield	1.80

The results agreed, to within a few percent, with the results for containers containing innocent cargo but no neutron absorbers. The reason for this is that once neutrons have thermalized (the detector is not sensitive to unthermalized neutrons) their scattering mean free path in the cargo is about 7.5 cm. The detector, about 2.5 m (33 mean free paths) from the absorber, senses a neutron field essentially unaffected by the presence of the absorber. Of course, someone deliberately hiding the presence of absorber would surround it with material of even greater hydrogen density (for example, CH_2, in which the mean free path is about 0.6 cm). Hence thermal neutron detection is not likely to be a feasible method of detecting thermal neutron absorbers if even the most minimal measures are taken to conceal them within a neutron-scattering medium.

Similar conclusions apply to interrogation of containers with fast neutrons. Although they (like the spontaneous fission neutrons calculated here) are much more penetrating than thermal neutrons, it is still possible, within the volume of a cargo container, to moderate and absorb them. Even if fission were induced in fissionable material (by a penetrating interrogation beam, or the natural muon background), that material could be surrounded by enough moderator and absorber to prevent detection of the fission neutrons, and by enough neutron scatterer to prevent detection of the neutron absorber.

It is concluded that boron neutron detectors can be an effective means of detecting the presence of unshielded neutron sources, such as kilogram quantities of plutonium, within cargo containers (uranium, of any isotopic composition, is a negligible source of neutrons). A knowledgeable adversary may shield such sources, and the presence of such shields may be concealed from detection by their effects on the background thermal neutron density if they are surrounded with neutron-reflective material.

NOTES AND REFERENCES

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