A proposal for detecting hidden explosives to high distance

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Abstract: In this paper author describes a proposal for an apparatus utilising nuclear physics techniques to identify hidden explosives to a distance of several tenth of meters. The apparatus uses a modified PFNA (Pulsed Fast neutron Analysis) with the gamma ray detector similar to those used for gamma ray telescopes as INTEGRAL or GLAST.

Key-Words: Explosives detection, electronic instrumentation, application of nuclear physics, security apparatus

1 Introduction

In the last years many news from several countries have pointed out the problem to defend both civilian and military targets by terrorist attacks. Now these strikes happen by several ways (landmine, car bomb, suicidal attacks) but utilising always hidden explosives. Now several methods to identify hidden explosives have been studied and some of these utilise nuclear methods. Up to now these technologies have been successfully tested in several cases in which, however, there was a short distance (dozen of centimetres) between detector and explosive, for example in airport controls or in cars inspections.

The question is if it's possible to improve the detection range until 50-100 meters. In several real cases this improvement (hereafter the aim) would be of great importance. For example let consider three cases. First it's the control of cars gone nearer to a possible fixed target (an hotel, a government office, a road block and so on) going along a road.

Second: the same situation but we want to control people.

Third: there is a convoy going along a road and it's needed to control road to avoid landmines.

Author has started a work to answer to this question and here it's showed the first stage of this work.

2 Actually used techniques

Actually there are several techniques [1], let's see Fig. 1, to detect hidden explosive. Some of these identify directly the explosive by an inspecting radiation (X ray, gamma ray or neutrons) that interacts with the explosives. Others try to detect traces of explosive (gas produced by vapor tension of explosive or particulate).

Let's focus on nuclear techniques and in particular on neutrons analysis. The working of this is simple. A source (radioactive source or portable accelerator) creates a neutrons beam. Neutrons hits object to control and interact with the atoms being in the explosive. These nuclear reactions generate gamma rays that escape from object and were detected by a detector able to distinguish them from other gammas produced by other sources (as cosmic rays and natural radioactivity). But if the principle of operating is simple there are several difficulties to put this method into practice.

First of all the behaviour of neutrons in matter depends strongly on their kinetic energy. And we have to distinguish between fast neutrons (energy of some Mev, speed 1/3 of light speed) and slow neutrons (E<0.5 eV, speed some tenth of kilometres to second). Thermal neutrons are a special type of slow neutrons, whose kinetic energy distribution is in equilibrium with their surrounding (with a typical energy of 0.025 eV at room temperature and a speed of some kilometres to second). They move on irregular paths like a gas through matter, neither accelerating nor slowing down, scattering quite a number of times until they are absorbed (captured in the nucleus). In detail, neutrons can interact with matter in the following ways:

Elastic scattering with nuclei (similarly to the collision of two billiard balls). The kinetic energy loss (speed loss) per collision depends strongly on the mass of the nucleus the neutron is hitting: if the latter is large, the incoming neutron will practically not loose energy, if it is small (like for hydrogen) the incoming neutron can loose up to its entire kinetic energy. Hydrogen rich materials such as polyethylene or paraffine are therefore often used to slow down fast neutrons. Note that the target nucleus is not excited (i.e. stays in the ground state). The reaction is therefore of the X(n,n')X type.

Elastic scattering dominates for slow neutrons.

Inelastic scattering with nuclei: when the incoming neutron has a sufficient kinetic energy (usually > 100 keV for heavy nuclei and > some MeV for light nuclei) it can put the nucleus being hit in an excited state, which decays in a very short time to its ground state (say less than 10^{-12} sec), releasing the energy difference as a gamma ray of characteristic energy. The latter is also called a "prompt" gamma ray as it is emitted so shortly after the collision.
incoming fast neutron continues with a reduced kinetic energy. The reaction is therefore of the \( X(n,n'g)X \) type.

Nuclear reactions with the production of charged particles or additional neutrons, usually starting from a given energy (a threshold), often a few \( \text{MeV} \), as they "consume" energy which has to be taken from the incoming neutron's kinetic energy. A nuclear reaction has often as consequence an activation of the material, i.e. the nucleus which has been hit becomes radioactive. This radioactivity can be short lasting (e.g. milliseconds or seconds). If the nuclei decay emitting gamma rays, these will be called delayed gamma rays (in contrast to the prompt ones mentioned above). Examples are nuclear reactions of the \( X(n,g)Y \), \( X(n,p)Y \), or \( X(n,2n)Y \) type.

Neutron capture does preferentially take place when the neutron has sufficiently low energy, i.e. for slow neutrons, and is particularly important for certain nuclei at one or more specific energies ("resonances"). The resulting nucleus can decay in a number of ways, according to the type of target nucleus and energy of the incoming neutron, including by emission of a prompt gamma ray, again characteristic of the target nucleus; this type of reaction is therefore of the \( ^{A}Z(n,\gamma)^{A+1}Z \) type. Concerning the orders of magnitude of the physical processes involved, fast neutrons are thermalised (slowed down to thermal energies) on a microsecond timescale, whereas neutrons diffuse on a msec scale.

Now explosive have different chemical composition but in every type of these substances there are the same elements: Carbon (C), Hydrogen (H), Nitrogen (N) and Oxygen (O). With these elements neutrons interact via the following reactions

<table>
<thead>
<tr>
<th>Element</th>
<th>Reaction</th>
<th>Neutron Energy</th>
<th>Reaction Type</th>
<th>Gamma energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>( 1H(n,n'g)2H )</td>
<td>Thermal</td>
<td>Prompt</td>
<td>2.223</td>
</tr>
<tr>
<td>C</td>
<td>( 12C(n,n'g)12C )</td>
<td>Fast ( &gt; 5 MeV)</td>
<td>Prompt</td>
<td>4.43</td>
</tr>
<tr>
<td>N</td>
<td>( 14N(n,n'g)15N )</td>
<td>Thermal</td>
<td>Prompt</td>
<td>10.8</td>
</tr>
<tr>
<td>N</td>
<td>( 14N(n,n'g)14N )</td>
<td>Fast ( &gt; 3 MeV)</td>
<td>Prompt</td>
<td>1.63 e 2.3</td>
</tr>
<tr>
<td>N</td>
<td>( 14N(n,2n)13N )</td>
<td>Fast ( &gt; 14 MeV)</td>
<td>Activation (9.9 min)</td>
<td>5.1</td>
</tr>
<tr>
<td>O</td>
<td>( 16O(n,n'g)16O )</td>
<td>Fast ( &gt; 7 MeV)</td>
<td>Prompt</td>
<td>3.84</td>
</tr>
<tr>
<td>O</td>
<td>( 16O(n,p)16N )</td>
<td>Fast ( &gt; 9 MeV)</td>
<td>Activation (7.3 sec.)</td>
<td>6.13</td>
</tr>
<tr>
<td>Cl</td>
<td>( 35Cl(n,g)36Cl )</td>
<td>Thermal</td>
<td>Prompt</td>
<td>10.6</td>
</tr>
</tbody>
</table>

Because of variety of nuclear reactions involved, there are several sub - methods of neutrons analysis such as Thermal Neutron Analysis (TNA) or Fast Neutron Analysis (FNA) but every employing at least a neutron source to produce the neutrons that have to be directed into the target, and a gamma rays detector to characterise the outgoing radiation. The neutrons source can be either a radioactive source or an accelerator, possibly moderated (exploiting hydrogen rich substances to slow down fast neutrons using elastic scattering):

Typical radioactive sources are Californium-252 (252Cf), with a half-life of about 2.6 years (one mg \( ^{252}Cf \) produces about \( 2.3 \times 10^6 \) n/s), or Americium-Beryllium (AmBe), which produces neutrons via the \( ^{9}Be(a,n)^{12}C \) reaction \( ^{241}Am \) has a half-life of 458 years. \( ^{252}Cf \) neutrons produced by spontaneous fission have a lower energy spectrum (average energy of 2.1 MeV, most probable energy of 0.7 MeV); this source is therefore more indicated to produce thermal neutrons.

Neutrons generators (small accelerators) can also be used as sources, usually either of the D-D (deuterium-deuterium, D(D,n)\( ^{3}He \)) or D-T (deuterium-tritium, T(D,a)n) type; the first produce fast neutrons of 2.5 MeV, the second fast neutrons of 14 MeV. The \( ^{6}Be(D,n)^{10}B \) reaction can also be used Note that these generators do emit isotropically, i.e. in all directions (4p). They can work in either a continuous mode, or in bursts (pulsed operation) as short as a few microsec. The possibility to operate with bursts is very important for our aim, because it permits to use Time Of Flight (TOF) technique. By this way it is possible to determine interval between start of neutrons beam and arrival of gamma rays and then distance to which the inspected object is, or vice versa, it can be controlled whether detected gamma came from area inspected by our apparatus. The D-D generator has the advantage of not containing any radioactive material, whereas the D-T contains tritium (which is radioactive) and this can complicate its acquisition and transport. Work is ongoing on different types of generator, such as the so-called plasma focus, which will be able to produce very short pulses (in the nsec range).

Radioactive sources have the advantage of being cheaper and smaller than accelerators, but can obviously not be "turned off". They are more "portable" but have to be transported in special containers (for the shielding) and might require quite some paperwork, according to the actual source strength, as well as dedicated personnel; on the other hand it is true that they are routinely used in a number of applications. They have to be changed at regular intervals, say after one or two half-lives (e.g. max 5 years for the \( ^{252}Cf \)
Finally other important component is gamma detector. Gamma rays interact with matter by three ways: photoelectric effect, Compton scattering and electron-positron pairs production. At energies we are interested (some Mev) gamma interact both by Compton scattering and by pairs production. However, except for high atomic mass number materials such as lead, the main effect to be considered is Compton scattering. Practically gamma hits object, loses energy by several Compton scatterings and finally was absorbed by photoelectron effect. It’s crucial to project a gamma detector, to know how much detector itself has to be thick to absorb gamma. It’s crucial to know weight of detector too. It’s possible to utilise the following formula giving the thickness of material needed to absorb the 98% of incoming gamma energy

\[ 3 \times (\log(E/(550/Z)) + 1.2) \times \lambda_r, \]

where \( E \) is energy in Mev, \( Z \) is atomic number and \( \lambda_r \) is the so-called radiation length, typical of an element, given by [2]

\[ 1/\lambda_r = \frac{(4 \times Z^2 \times N)/137}{r_0^2} \times \log(183/Z^{1/3}) \]

Where \( N \) is number of atoms in unit of volume and \( r_0 \) is the so-called classical radius of electron.

Let suppose element is Germanium with \( Z=32 \) and density \( 5323 \text{ Kg/m}^3 \). Its radiation length is 2.28 cm. and with a gamma energy of 6 Mev we have a thick of 10.01 mm needed to our aim.

Because of density of germanium and supposing detector is a cylinder whose base has radium of 25 centimetres, we have a weigh of 10.56 kg compatible with the portability of apparatus (also if there isn’t hand-portability).

In the commercially available apparatus, detectors used are counters (for their description let’s see Ref. [1]) and they have problems with a very low signal, but this is the case when there are distances of tenth of meters between object to inspect and detector. Then we have to utilise a very different kind of detector.

3 Our proposal

Let imagine a rotating platform with diameter of 50 centimetres (this number and other below cited are purely as an indication) and on it there are a neutron generator and a gamma detector. Neutrons generator is an accelerator producing 14 Mev neutrons. It is just like commercially produced generators. In front of the point where neutrons came out there is a shutter made by paraffine (or other material able to thermalize neutrons). The accelerator is turned on for two seconds. During the first second there are 10 microsecond neutrons bursts every 50 microsecond, shutter is open and neutrons are fast. In the following second bursts are every 50 millisecond, shutter is closed and neutrons are thermal. Then area to be inspected is hit by two different types of neutrons and gamma rays produced are of different energies. Gamma detector is a small size of detector used in gamma rays telescopes as CRO, INTEGRAL [4] or GLAST [5]. They have used or are using, several detectors and among them the most suitable for our purpose is SPI detector operating in INTEGRAL [6]. This detector measures the direction of coming gamma with a precision of 2° (we will see this precision can be sufficient for our aim and in GLAST there will be also more precise detectors). To measure gamma incident direction a coded mask technique is used. This is an acquired technique utilising a plate in which opaque and transparent (to gamma rays) areas follow one another according to precise pattern. The mask is in front of detector and when gamma rays beam hits it, the shadows generated by mask are cast on detector. From location of shadow it’s possible to determine the direction of gamma rays.

Because of high penetration capacity of gamma opaque area of mask have to be made by a high density and high-Z-number element. SPI utilise Tungsten (\( Z=74 \), density 19 gm/cm\(^3\)) 14 mm. thick. For our aim it can be calculated by already used formulas, that a thickness of 9 mm is sufficient and then it involves a weight of 14.9 kg. compatible with portability of apparatus.

SPI is also capable to measure gamma ray energy by traces of Compton electrons inside detector because of it is made by a semiconductor (Germanium) and in the range 20 keV-8 MeV its energetic resolution is 0.2% fully capable to distinguish every energy of our interest. In particular this precision is sufficient to distinguish between 10.8 MeV gamma from reaction in third line of Table 1 (interesting) and 10.6 MeV gamma from reaction of last line of same Table (a noise for our aim).

Now let imagine to be in the first of situation cited at the beginning of paper. We are in the entry of possible target, for example an hotel. We put the platform on which apparatus is at the side of entry and consider a distance (20 meters for example) to which we want to detect a possible suicide bomber. This distance will be used by apparatus software to calculate time of flight. The platform is going to rotate such a way neutrons beam can “sweep” area in front of hotel.
Aparatus software will perform the following operations

To turn on accelerator for two seconds setting shutter as above mentioned and in this time for each neutrons burst controls whether there are gamma rays of "fair" energy coming after a time of flight agreeing with the distance we have chosen. If there are, stores area of detector they have hit.

Ended the two seconds software turn off accelerator and reconstructs the direction of gamma comings. If the direction is the same which the accelerator points to, it turn on an alarm, for example an acoustic alarm.

It's important the fact to know the direction with the same precision of SPI, or of similar apparatus. Let think that at distance of 20 meters a precision of 2° can permit to see clearly an object 80 cm large, more little than suicide bombers. Similar considerations can be done for the cases of car bomb and landmine.

3 Conclusions

As it has been stated above, this paper represents only the first stage of a complex work because it explain how an apparatus works. To pass from an operating scheme to an operating apparatus there are several problems to solve.

Problems can come from
1) Obstacles present between accelerator and explosive or between explosive and gamma detector. These obstacles, as for example shielding, can absorb neutrons or gamma reducing the signal. It's true too that obstacles absorbing fast neutrons don't stop thermal neutrons and vice versa and we operate with both kind of neutrons.

2) Lying signals from substances having same chemical composition of explosive (elements present in explosives there are in human body too). However this problem can be over both by precisely locating the coming direction of gamma and comparing received signal with a sample signal.

3) Danger to radiate many people if apparatus works in crowded environment. Let remember neutrons are a very carcinogenic radiation.

4) Lying signals came from natural radioactivity elements situated very near to explosives. However these radioactive isotopes emit gamma having characteristic energies very different from our interest energies.

A discussion of these problems and of their possible solutions is out the aim of this paper. In the author's intentions is, however, a deeper study by Geant4 simulations to test apparatus in the three real cases above mentioned.

References:
[7] tabella radionuclidi