Using exotic atoms to keep borders safe

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Abstract. Muons, created by a particle accelerator, can be used to scan cargo for special nuclear materials (SNM). These muons have a sufficiently long lifetime and are penetrating enough that they can be used to actively scan cargo to ensure the non-proliferation of SNM. A set of “proof-of-concept” experiments have been performed to show that active muon analysis can be used. Experiments were performed at high intensity, medium energy particle accelerators (TRIUMF and PSI). Negative muons form exotic atoms with one electron replaced by the muon. Since the muon is captured in an excited state, it will give off x-rays which can be detected by high purity germanium detectors. The characteristic x-ray spectrum can be potentially used to identify nuclides. The muonic x-rays corresponding to the SNM of interest have been measured, even with the use of various shielding configurations composed of lead, iron, polyethylene, or fibreglass. These preliminary results show that muon scanning systems can be successfully used to find shielded SNM, helping to ensure the safety of all citizens.

1. Introduction

For nuclear non-proliferation, it is important to determine if materials being transported contain special nuclear materials (e.g. Uranium). To determine this, a material-specific signature is necessary. One material-specific signature can be found through the use of a beam of negative muons. Muons are suitable probe because, for a given energy, they penetrate a given material farther than protons (whose strong interactions limit their range) and electrons (whose light mass causes radiative losses). Muons can be implanted deep into materials. Furthermore, when a negative muon stops in a material, it becomes atomically captured in a high n and l orbital state, forming an exotic atom. The muon then cascades down to 1s1/2 state. As this occurs, muonic x-rays and Auger electrons are given off. These muonic x-rays have energies which are element-specific and for large mass muonic atoms, they can be isotope-specific [1]. When a negative muon captures on U, it produces highly energetic muonic x-rays of order 6.5 MeV, which can be used to distinguish ²³⁸U from ²³⁵U. These high energy x-rays are
much higher in energy than photons that one measures in terrestrial environmental radioactivity [2]. Also, when a muon atomically captures on an actinide, muon-induced fission occurs, which produces prompt and delayed neutrons, which can also be measured directly or indirectly from neutron-capture gamma rays.

The proposed system consists of a compact proton or electron accelerator, a pion-production target placed within a pion-capture solenoid that provides acceptance near 1 sr, and a muon linac to accelerate the low-energy beam (below 100 MeV) up to 1-GeV energy [3]. The muons’ energy is tuneable, which can be used to change the depth of the muon stop. A Ge cluster detector [4] will be used to detect muonic x-rays of several MeV with high efficiency at a high event rate.

1.1. The TRIUMF M20 muon beam line.
TRIUMF is Canada’s national laboratory for particle and nuclear physics. It is a multidisciplinary laboratory where research is performed on particle physics, nuclear physics, solid state physics, medical physics, material sciences, and life sciences. The heart of the TRIUMF National Laboratory is a 500 MeV cyclotron which accelerates H+ (hydrogen with 2 electrons) to a desired energy, determined by placement of a stripping foil, which then removes the two electrons and changes the charge and direction of the beam, allowing it to be extracted from the cyclotron. This is done to perform experiments with a proton beam directly or with secondary beams or other particles or atoms.

The beamline 1a at TRIUMF uses the the main proton beam to produce beams of muons or pions for various research projects. This is done by the main proton beam hitting a target at the start of a channel, whence pions from this target are collected and formed into a beam through the use of quadrupole magnets. The momentum of these pions can be selected through the use of dipole magnets on the channel. The M20 channel at TRIUMF has been designed to collect these pions and be long enough, so that the pions decay in flight into muons, which can then be used for experiments. For this project, the M20 channel was setup for negative muons.

Figure 1: Diagram of the experimental setup after the end of the M20 channel (Muon Source), including plastic scintillators (S1, S2, and eVeto), the target location (source), Compton suppressor (BGO) and High-Purity Germanium detector (HPGe).
2. Experimental Setup

The beam from the end of the M20 channel was then sent through a collimator (shown in figure 1) which was made out of lead with a polyethylene liner. This was to improve the quality of the beam. If a muon stopped in the collimator’s polyethylene liner, it would most likely produce high energy electrons from the muon decaying in orbit. Whereas, without the liner, the muons capture on Pb and then produce gamma rays and neutrons. After the collimator, the beam passes through two plastic scintillators (S1 and S2) before finally stopping on the target. The beam was tuned to maximize the number of muons stopped on target. The size of S1 and S2 were chosen to be smaller than the target.

An Ortec GEM 140P4-ST High Purity Germanium detector (HPGe) was used to measure the muonic x-rays and background photons. This HPGe detector was surrounded by a BGO Compton suppressor and a plastic scintillator which provided a charge particle veto in front of the HPGe.

A similar arrangement was used in an earlier experiment at the muE1 line of the Paul Scherrer Institut. Here we did not perform time resolved experiments but investigated a wide variety of materials relevant to interrogation scenarios [5][6].

![Figure 2: Schematics of the electronics for the experiment.](image)

2.1. Electronics

The electronics were setup as in figure 2. The thresholds on the discriminators for the S1 and S2 detectors were set to be above the beam-related electrons. Then a coincidence was formed between these two detectors to ensure the beam was on target. A 40 µs gate was then formed from the S1.S2 coincidence and when this gate was in coincidence with either the HPGe detector or a neutron detector, a master gate was formed. This master gate was then used to start a VME-based data-acquisition system. The signals from the HPGe and the Compton suppressor were sent through a timing filter amplifier to improve the timing before the signals were sent into a CFD (Constant fraction discriminator). The HPGe signal was also put into a spectroscopic amplifier which was then sent into an ADC (analog to digital converter). The timing signals from the S1.S2 coincidence, the
HPGe detector, the Compton suppressor, and the electron veto were all sent to a multi-hit TDC (time to digital convertor). The TDC did not use a common start, but was kept running; it only kept data records when the trigger signal was present. The time window was then selected in software.

2.2. Acceptance of the system.
To determine the acceptance of the HPGe detector (acceptance is the efficiency of the detector multiplied by solid angle) a few radioactive sources were used and some other well known muonic x-rays. The sources were placed at the target location to preserve the solid angle. The sources used were $^{133}$Ba, $^{22}$Na, $^{60}$Co, and $^{152}$Eu. Also a run was taken using muons stopped in Au to extend the acceptance curve up to 5 MeV.

The acceptance was determined in multiple steps, because the total number of muon stops was not known. First, the gamma rays from the radioactive sources were used to make a preliminary acceptance curve. Then this curve was fitted to a phenomenological function. Because the yield per muon stop of the 400 and 405 keV x-rays from muon atomic capture in gold are well known [7][8], those peaks were measured in our spectrum and they were used with the first acceptance function to determine the number of muon stops. Then, by knowing the number of muon stops in that run and by measuring the 5 MeV x-rays in Au in the same spectrum, the acceptance at 5 MeV was determined. The acceptance of the detector as a function of energy is shown in figure 3.

![Figure 3: The HPGe acceptance as a function of energy.](image)

3. Results.
Measurements where done with a bare DU target in place, and with various shielding configurations. Figure 4 shows the measurements of a steel canister of U, taken at PSI, for two different muon momenta. At low momenta, the muons are stopped in the casing of the can and no muonic x-rays from U are present. At higher momenta, the muons are stopped in the U in the can, and the muonic x-rays
can be observed, namely the $2p_{1/2} \rightarrow 1s_{1/2}$ transition and the $2p_{3/2} \rightarrow 1s_{1/2}$ transition. This simple experiment, illustrates the concept of how one could use a muon beam to scan for special nuclear materials.

Also since the acceptance of the system is known, the yield of bare-DU-target x-rays was measured and compared to the yields from previous measurements. This is shown in Table 1. The results in this table are within $2\sigma$ and are reasonable, considering the set up was not optimized to measure these yields.

![Energy spectrum of muon capture on U in a can for two momenta.](image)

Figure 4: Energy spectrum of muon capture on U in a can for two momenta.

4. Conclusion.
These measurements were done to illustrate a proof-of-concept experiment, namely, using negative muons to scan for special nuclear materials. This simple illustration indicates that muons can be used to scan materials, by changing the momentum of the beam and measuring the energy of the resultant x-rays. Future research on the design of new more-efficient muon beam lines is needed to transform this “proof-of-concept” experiment into a usable technology to search for special nuclear materials. The experience gained by this experiment will help in the development of novel muon-beamline technology for this purpose.

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Table 1: Comparison of muon capture yields and energies for 6 MeV x-rays from U.

| This work Eγ (keV) | This work Yield | Literature[1] Eγ (keV) | Literature[1] Yield |
|-------------------|-----------------|------------------------|---------------------|
| 6044.8(29)        | 0.022(15)       | 6047.36(49)            | 0.024               |
| 6097.24(45)       | 0.071(28)       | 6096.58(32)            | 0.056               |
| 6123.05(18)       | 0.152(55)       | 6122.10(30)            | 0.163               |
| 6142.03(18)       | 0.232(84)       | 6122.10(30)            | 0.220               |
| 6150.23(38)       | 0.067(26)       | 6149.03(32)            | 0.089               |
| 6167.99(60)       | 0.029(12)       | 6167.41(35)            | 0.0310              |
| 6382.2(12)        | 0.0121(60)      | 6379.26(47)            | 0.0150              |
| 6410.88(28)       | 0.142(54)       | 6409.44(34)            | 0.112               |
| 6420.2(11)        | 0.0172(90)      | 6416.50(50)            | 0.0290              |
| 6455.71(18)       | 0.124(46)       | 6454.14(35)            | 0.113               |
| 6462.62(63)       |                | 6462.62(63)            | 0.021               |
| 6483.34(42)       | 0.035(14)       | 6480.93(36)            | 0.0330              |
| 6520.21(30)       | 0.050(19)       | 6518.36(33)            | 0.0640              |
| 6565.19(70)       | 0.047(23)       | 6563.70(50)            | 0.032               |

SUM 1.000