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Imaging Carbon and Nitrogen Concentrations and the Interdiction of Concealed Narcotics and Explosives

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ABSTRACT

I describe a new nuclear technique which produces images of elemental carbon (nitrogen) in concentrations and with surface densities typical of concealed bulk narcotics (terrorist explosives.) The signal is the totality of high-energy gamma rays detected with time after irradiation of a target pixel by a ~30 (~50) MeV beam from an electron accelerator. There are no significant interfering signals. I present 180 2 x 2 cm^2 pixel intensity images of a kilo of cocaine (125 grams of SEMTEX).

INTRODUCTION

Postal packages, airline baggage, cargo containers, and vehicles could be effectively screened for illicit drugs if carbon concentrations could be detected, since cocaine and heroin are ~66% carbon by weight. The ubiquity of carbon in our environment requires that images of these concentrations be made since form often indicates function (Sullivan, 1924). Further, quantities of carbon imaged in unusual venues (e.g., automobile fenders, airplane wings, etc.) have a high probability of being contraband. Finally, the addition of conventional transmission x-ray images to those of carbon concentrations would improve the screening efficiency and decrease the number of time consuming hand searches. The Carbon Camera, which is described below, addresses this scenario.

The attack on Pan Am 103 in 1988, which resulted in that plane's destruction and 270 deaths (Report, 1990), momentarily re-energized governmental efforts to develop effective screening technology for explosives concealed in airline passenger baggage. However, none of these incipient "tombstone technologies" have succeeded in detecting, let alone imaging, quantities of explosives as small as the ~300 grams of SEMTEX used in that attack. Equally troubling is Iraqi's reckless, random, and undocumented seeding of the Kuwait desert with land mines which pose a continual hazard to animals, civilians, and demolitions mercenaries. These two faces of terrorism motivated the invention of the Nitrogen Camera described here.

The Carbon and Nitrogen Cameras have much in common. In each a succession of pixels on the surface of an object suspected of concealing carbon or nitrogen concentrations are irradiated intermittently and sequentially by a beam from an electron accelerator. Scintillation detector counts registered between pulses are attributed to the carbon or nitrogen content of the previously irradiated pixel. When aggregated these individual pixel counts form an intensity image. X-rays, produced with the high-energy nuclear-probing photons, detected in transmission produce a conventional mass-density image.

The Carbon Camera differs from the Nitrogen Camera in that it uses a lower energy accelerator beam and has effectively no interfering signals. In the Nitrogen

Camera, carbon produces the sole significant contaminating signal from which the nitrogen signal must be quantitatively untangled.

In what follows, I first discuss the physics on which the Carbon and Nitrogen Cameras are based. I then present experimental proof of the technique as I have demonstrated it to date, clearly indicating what remains to be verified. I end by making a gloss of the enabling technology from which a working prototype can result.

THE PHYSICS

Although the Carbon and Nitrogen Cameras share much with conventional cameras -- photographic, x-ray, and positron -- they rest on different physics. Recall that in the photographic camera visible light with energy of a few eV is scattered by an object, is manipulated by a variety of optical devices, falls onto an aperture, and is recorded on electronic or chemical media. While in the x-ray camera, photons of a few keV are scattered as they pass through an object and fall unmanipulated onto an aperture where they are recorded. In the PET camera, a radioisotope, with a half-life of hour to days, is injected into an object. Decay positrons lose energy by bremsstrahlung in a succession of collisions, finally annihilating into two oppositely-directed half MeV gamma rays whose signals are manipulated to produce a three-dimensional image.

In the Carbon and Nitrogen Cameras, high-energy photons are flashed into a small area of an object in which they create a variety of radioisotopes, many of which give rise to gamma rays. Excited isotopes go to their ground state by emitting gamma rays. Beta decay produces electrons and positrons and in turn a plethora of bremsstrahlung gamma rays, logarithmically increasing in number with decreasing energy. Positrons annihilate into gamma rays. All these gamma rays detected in a brief interval after irradiation constitutes the signal for the Carbon and Nitrogen Cameras.

For the Carbon Camera, the irradiation of all known materials by photons with energies above ~17 MeV but below ~30 MeV produces only one isotope, in appreciable quantity which beta-decays rapidly - its half-life is 20.2 milliseconds. That radioisotope is boron-12, its production and decay reactions are,

$$\gamma + {}^{13}C \rightarrow {}^{12}B + p\,;\ {}^{12}B \rightarrow {}^{12}C\,\nu_e\,e^-,$$

and its cross section increases linearly with photon intensity and dramatically with energy. The bremsstrahlung and de-excitation gamma rays recorded immediately after irradiation is taken as our carbon marker.

A quantitative example confirms the promise of this technique. If we irradiate a graphite block with monoenergetic photons of ~25 MeV only two reactions are induced, each with roughly equal probability: $^{13}C\ (\gamma,\ p\ )\ ^{12}B$ -- the "signal" -- and the "noise" -- $^{12}C(\gamma\ ,\ n)\ ^{11}C$ whose half life is ~1,200 seconds. During the first 20 milliseconds after irradiation, half of the produced boron-12, but only ~0.00002 of the carbon-11 will decay. The signal-to-noise in the first 20 ms will be ~600/1, because carbon-13 constitutes only ~1% of all naturally occurring carbon.

In reality the situation is more complicated. First, these reactions have different cross sections which are only vaguely known. Second, photons produced by an electron beam in a radiator are not monochromatic, their number varying not only with the electron beam energy and intensity, but also with the radiator

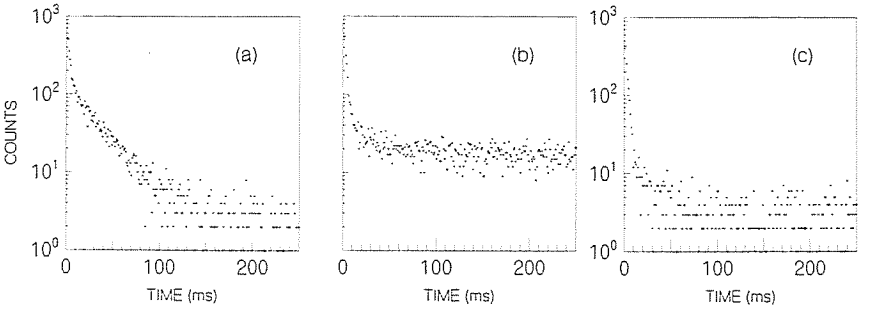

FIGURE 1. Time evolved spectra for 26.7 MeV electrons on (a) graphite, (b) Boraxo, and (c) KNO_3.

geometry and material. Third, extraneous radiation is produced during and immediately after the acceleration process which produce counts in the detectors. Finally, the wide variety of elements present in most material, when irradiated, contribute long-lived "noise" elevating the background on which our signal sits.

THE CARBON CAMERA

A burst of ~30 MeV electrons traversing matter generate neutrons and photons, both virtual and real, which produce a variety of radionuclei. In the first few milliseconds the neutrons are slowed by collisions and captured by nuclei giving rise to gamma rays. After some tens of milliseconds most gamma rays come from the decay of long-lived radioisotopes. In the time interval between these two salient regimes, boron-12 decays ejecting beta rays which bremsstrahlung and some of the time leaves carbon-12 in an excited state. Bremsstrahlung and de-excitation gamma rays constitute the Carbon Camera signal.

I have experimentally verified this scenario at the Alfven Laboratory's 50 MeV electron racetrack microtron of the Royal Institute of Technology in Stockholm, Sweden (Rosander, 1982). The beam, up to ~20 mA of electrons, was delivered in 3 μs-long pulses at a rate of 1.2 Hz. A 1 mm thick tantalum radiator could be inserted in the beam to provide real photons. The detectors, 12.5 cm diameter fast photomultiplier tubes coupled to thick organic scintillators, were located ~50 cm upstream from the targets. Detector signals were energy discriminated, summed and fed into a multiscalar board resident in the back plane of a 486/33 personal computer.

The time evolved spectra of three targets irradiated by multiple (~100) 1 mA bursts of 26.7 MeV electrons are seen in Fig. 1. These spectra share (1) a dominate fast peak, ~1.5 ms half-life, from radiative neutron capture and (2) a small persistent background which increases with the number of beam bursts, the beam current, and the target matter density. What remains after these two features are taken into account is the Carbon Camera signal in Fig. 1(a) which constitutes 65.9 ± 1.1% of the total counts and exhibits a half-life of 20. 13 ± 0.24 ms.

If carbon is to be used as a marker in screening for narcotics there must be few sources of similar signals. A computer search (Brookhaven, 1989) was made for

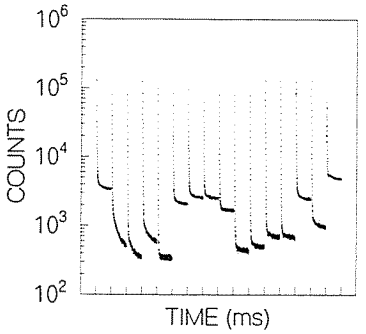

FIgure 2. Time spectra (from left to right) of aluminum, medium plastic mine, small plastic mine, small metal mine, air, granite, earth, sand, KBr, magnesium, $CaSO_4$, $NaBiO_8$, water, iron, Teflon and lead obtained with 50 MeV electrons.

photo-nuclear reactions induced with 30 MeV photons on stable isotopes whose isotopic abundance was >1%. All reactions producing up to four nucleons, as well as those involving radiative neutron capture, were screened for beta emitters which decayed with half-lives < 100 ms. The reactions $^{13}C(\gamma, p)\ ^{12}B$, $^{11}B(n, \gamma)\ ^{12}B$, and $^{14}N(\gamma,2p)\ ^{12}B$ were identified, where the boron-12 half-life is ~ 20.2 ms. The last reaction has a threshold of 25.1 MeV and so is still weakly produced at 30 MeV (see Fig. 1(c)). The second reaction is not troublesome (see Fig. 1(b)) and further the environmental abundance of boron is small (Trower, 1993).

Experimental spectra for a variety of objects, including all but one (titanium) of the ten most abundant elements in the earth's crust (99.48% by weight) as well as 17 other elements, showed only one signal, $^{14}N(\gamma,2n)\ ^{12}N$, in addition to those mentioned above, when a ~ 50 MeV electron beam was used (Trower, 1993). A typical suite of time evolved spectra are shown in Fig. 2, nitrogen being present in the melamine land mine simulants.

These multiple-pulse data had encouraging implications for single-burst excitation needed for imaging: (1) short-time noise is brief so its time domain can be excluded; (2) long-time noise is small and well behaved so can be ignored; and (3) only the carbon signal is appreciable.

For imaging, a bending magnet was inserted into the beam line and its power supply programmed to produce 15 equally spaced vertical sequentially ascending beam spots. A constant speed motor drove a worm screw which moved a 2 cm thick, 25 x 25 cm^2 aluminum plate horizontally and transverse to the beam at a speed of 1 cm/s. The plate supported the targets and provided background counts. About 70% of the electron beam was contained in a ~ 2 cm diameter circle, which increased to ~ 3 cm with the radiator interposed. With this saw tooth scanning pattern 180 pixel images were produced in ~ 2.5 minutes.

Figure 3 shows the response of a 251 g, 3 x 3x 5 cm^3 pyrolytic graphite block viewed end-on by the 30 MeV probing electrons. A clear image of the carbon, ~ 56 counts on a ~ 12 count background, is evident. These data are the raw counts registered in a 30 ms interval beginning 10 ms after irradiation. A similar block of table salt attached to the middle of the left most side of the plate is not in evidence.

A solid 996 g, 24 x 10 x 4 cm^3 block of cocaine (Narkotikaroteln, 1992) was mounted vertically in the middle of the plate and irradiated with 30 MeV electrons. The resulting intensity image, seen in Fig. 4, clearly shows the presence of this drug.

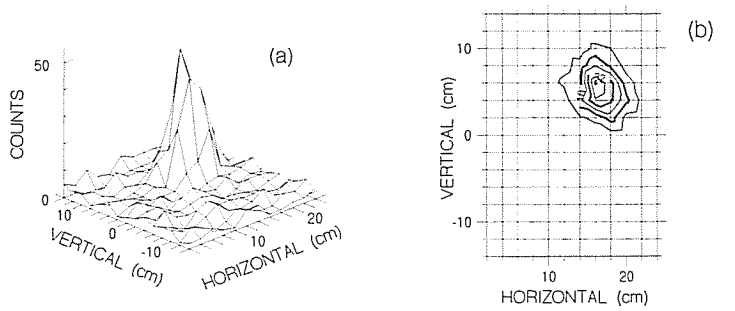

FIGURE 3. Response from graphite (upper right) and salt (mid-far left): (a) intensity image and (b) contour projection.

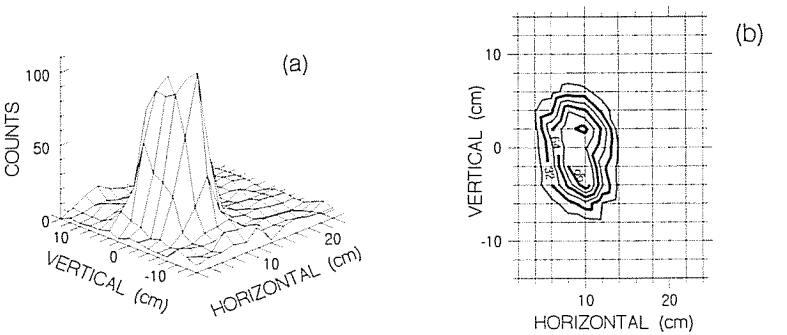

FIGURE 4. A kilogram of a solid cocaine (a) intensity image and (b) contour projection.

The theoretical limit for producing 180 pixel images appears to be ~7.2 seconds. However, at this 25 Hz scanning rate the captured image will be smeared--residual fast decays from previously irradiated pixels will be counted in current pixel count intervals. Desmearing can be accomplished by doubling the current pixel counts and subtracting from subsequent pixels decreasing fractions of the current pixel counts based on the wait-out times, count intervals, and lifetimes involved.

THE NITROGEN CAMERA

Only two additional reactions are produced in appreciable quantity whose products beta decay rapidly, $^{14}N(\gamma,2p)^{12}B$ and $^{14}N(\gamma,2n)^{12}N$, when the accelerator electron energy is increased to 50 MeV. These two reactions together are the nitrogen signal. Nitrogen-12 is a positron emitter with a half-life of 11.0 ms.

To use nitrogen as the marker in screening for explosives, the nitrogen signal must be separated from that of carbon. For samples containing comparable amounts of carbon and nitrogen and excited with 50 MeV electrons each contribute to the signal about equally. For nitrogen-14, the two-proton reaction is ~7

times more probable than the two-neutron reaction (Meyer, Paul, private communication , 1988).

Two promising, but as yet undemonstrated, possibilities for discriminating between carbon and nitrogen reactions are being pursued. The first takes advantage of the differing production thresholds of our three reactions, ~ 17 for the carbon, and 25 and 30 MeV, respectively, for the two nitrogen reactions. Here the target will be irradiated at 50 MeV until a signal is encountered. Then the beam energy will be reduced to 30 MeV and the promising pixel re-irradiated. These counts, suitably corrected, will provide an estimate of the pixel's carbon and nitrogen content.

The second carbon-nitrogen discrimination method relies on energetic differences in the nitrogen-12 and boron-12 pulse height spectra. Only nitrogen-12 produces 1/2 MeV annihilation gamma rays. Further, nitrogen-12 bremsstrahlung spectra is substantially harder (end-point energy is ~17 MeV) than that of boron-12 (~13 MeV) and so has more high-energy gamma rays. Setting discriminator levels on the detector pulse heights, we can obtain three spectra with energy of 0.4-0.6, 1.0-4.0 and >4.0 MeV. The nitrogen reaction will dominate the first and last, while the second will arise from reactions on both carbon and nitrogen. From these three images the relative amounts of carbon and nitrogen will be determined.

Targets of room air and of ~300 grams of melamine ($C_3N_6H_3$) were irradiated by multiple (~1,500) 1 mA bursts of 50 MeV electrons to produce the time spectra seen in Fig. 5. In the melamine spectrum, which displays the features seen for carbon at 30 MeV, the signal constitutes 17.3 ± 0.5% of the counts and implies a half-life of 18.6 ± 0.6 ms, appropriately between that of nitrogen-12 and boron-12.

Figure 6 shows two intensity images of ~225 grams of potassium nitrate contained in a thin-walled aluminum tube attached to the plate by one of its circular surfaces. In the first, the probing radiation is 30 MeV electrons while in the second the electron energy into the tantalum radiator is 40 MeV. At 30 MeV no evidence of the target is seen above a background of ~3 counts, while at 40 MeV a peak of ~56 counts on a ~12 count background is clearly evident.

An intensity image of 125 grams of the plastic explosive, SEMTEX, with similar shape and orientation as the KNO, is irradiated with 50 MeV electrons, and is clearly seen in Fig. 7. This explosive, less than half that responsible for the Pan Am 103 disaster (Report, 1990), contains carbon and nitrogen in about equal amounts.

PROSPECTS

With the physics of the Carbon and Nitrogen Cameras now established, efforts are underway to test their effectiveness for detecting real concealed drugs and narcotics in controlled blind trials in the laboratory.

However, much still remains to be accomplished before the Carbon and Nitrogen Cameras become practical devices. The image desmearing and carbon-nitrogen discrimination strategies described above must be experimentally verified. Our detectors to date have used a variety of photomultiplier tubes, scintillation materials and geometries which now must be optimized and standardized. Data acquisition must be automated and pattern recognition codes

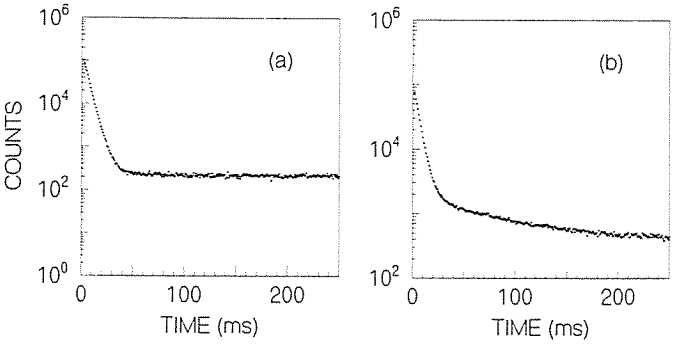

FIGURE 5. Time spectra for 50 MeV electrons on (a) room air and (b) melamine targets.

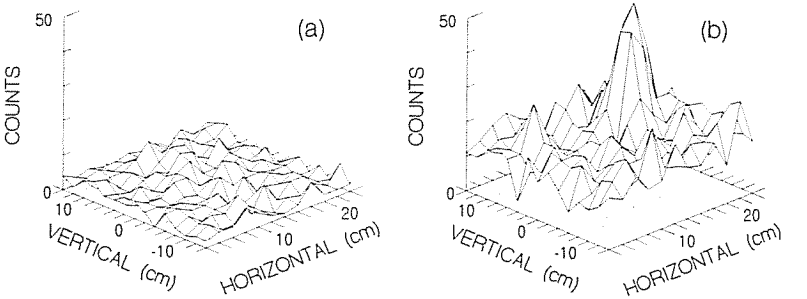

FIGURE 6. Intensity images of a KNO_3 cylinder irradiated at (a) 30 and (b) 40 MeV.

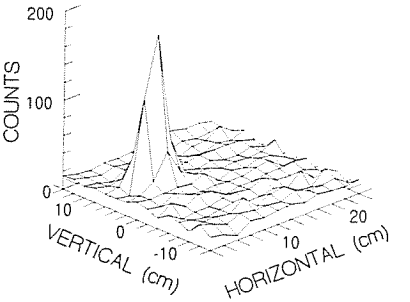

FIGURE 7. Intensity image of a cylinder of SEMTEX irradiated by 50 MeV electrons.

written and evaluated so operator intervention is minimized. The radiation hazard must be re-evaluated and minimized.

The most daunting obstacle to realizing the Carbon and Nitrogen Cameras in a prototype is the lack of an appropriate accelerator with which to produce the photons. No commercial linac has sufficient energy while the sole microtron manufacturer sells sufficiently energetic machines but they are too large and heavy. What is needed is a small, light weight, rugged, reliable microtron which can be vehicle mounted and its operation automated so that it can be controlled remotely. To act as the Nitrogen Camera light source, this machine must be capable of producing 60 MeV pulsed electron beams of 30 mA in 5 μs pulses at a rate of 25 Hz. For the Carbon Camera, the reduced beam energy of 30 MeV makes a small, so-called "shoe-box" accelerator a real possibility. Finally, the cost of these microtrons must be reasonable, more typical of industrial than medical devices. Design studies for such light sources are currently being made with colleagues in Russia (Karev, 1992).

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