One-sided Imaging of Large, Dense Objects Using the 511 keV Photons from Induced Pair Production

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The use of annihilation photons from photon-induced electron-positron pair production as a means of inspecting objects when only one side is accessible is described. The Z^2 dependence of the pair production cross section and the high penetration of 511 keV photons suggest that this method should be capable of localizing high- Z materials in lower- Z matrices. The experimental results for the dependence of the back-streaming photon yield on Z indicate that dynamic ranges of the order of 20 may be obtained for materials with $4 < Z < 82$. Results for point-by-point "images" obtained in line scans of representative geometries are also shown. Simulation studies based on the EGS4 Monte-Carlo code were also performed and their results show an agreement with experimental data of the order of 5%.

I. INTRODUCTION

In situations where access to an object is limited or the dimensions limit conventional transmission radiography, an imaging technique based on a one-sided approach is necessary in order to generate information about the internal structure of the object. In the one-sided approach both the interrogating radiation source and the detector are located on the same side of the object. The methods that have been developed to overcome this situation are usually based on the use of Compton back-scattered radiation or neutron-activated gamma-ray emission.

The underlying physics for imaging methods based on Compton scattering, as well as a review of the several developments in the field, have been discussed in detail [1]. The simplest concept of Compton imaging employs a collimated beam viewed by a single detector which is shielded to accept only scattered radiation from a small region of the interrogating beam. The energy of single-scattered photons from the volume element (voxel) of interest, neglecting binding effects, is related to the energy of the primary beam by means of simple relationship (expression 2-17 of [2]). The kinematics of the "billiard ball" approximation between incoming photons and electrons in the medium limit the energy of photons single scattered in the backward directions to a maximum of 255 keV. The high quality of 3-D images obtained using this technique has resulted in the development of systems like the Automated Inspecting Device for Explosive Charge in shells (AIDECS) [3,4] and the commercially available Compton Scattering Scanner (ComScan) [5].

Another one-sided imaging technique is based on the detection of gamma rays produced in neutron reactions. The interrogated object is placed in either a flux of thermal neutrons [6,7] or a high-energy [8,9] neutron beam. Characteristic gamma rays are emitted from excited nuclear states resulting from either thermal neutron

capture or by inelastic neutron scattering. The gamma rays are characteristic of the different elements present in the interrogated object. Neutron techniques are used to image illicit substances and explosives in passenger luggage [6,10] and cargo containers [11], to characterize radioactive waste in containers [12] and to analyze biological samples [13]. In some instances, such as treaty verification and assurances, the use of well-defined elemental signatures may pose a major drawback to implementation.

In this paper we explore an alternative approach based on the detection of the 511 keV photons resulting from induced electron-positron pair production by high energy incident radiation. Although introduced some time ago for the purposes of probing deep beneath surfaces [14] using the bremsstrahlung spectra from 24 MeV electron beams, this concept has not received much attention over the last few years. More recently [15], the potential of this method for inspecting the position and condition of rebars inside steel-reinforced concrete structures was assessed, highlighting the advantages of this somewhat novel procedure.

Experimental data for the Z -dependence of annihilation photons yields and line scans of representative geometries are described in this communication. Simulation studies based on the widely used Electron Gamma-Shower, version 4 code system [16] are also presented.

II. RATIONALE

The interaction of photons with energies above the 1.022 MeV pair production threshold in all materials results, to some extent, in the creation of electron-positron pairs. Any excess kinetic energy above the threshold is shared quasi-randomly by the created particles which slow down and, for moderate energies of a few MeV, stop near their point of creation as annihilation in flight is unlikely to occur at these energies. The thermalized positron rapidly annihilates, giving rise to two 511 keV photons which are emitted back-to-back, as required by momentum conservation.

Near the 1.022 MeV threshold, the pair production cross section rises sharply with energy, and, above ~5 MeV, assumes the larger fraction of the total attenuation cross section in media with high atomic numbers ($Z > 70$). Moreover, the production is strongly dependent on the atomic number of the material, increasing approximately with Z^2 . Since photon absorption is also proportional to ρ/A , where ρ is the physical density and A the mass number of the sample, images of dense, high- Z materials can be expected to stand out in high contrast against less dense, low- Z backgrounds. In typical situations where the distances travelled by the positrons before annihilation are small, good spatial resolution may also be achieved.

The requirement for radiation sources with gamma-ray energies in excess of 1.022 MeV may present some experimental difficulties. However, with the substantially greater penetration of the 511 keV photons and the Z^2 dependence of the pair production cross section, it is possible to overcome some of the

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limitations of Compton imaging, where the cross sections rises linearly with Z and the energy of the back-scattered photons is kinematically limited to a maximum of 255-keV which restricts the depth that can be probed.

III. METHOD

A. Experimental

The measurements were performed using the arrangement depicted in Figure 1. Both the interrogating source and the photon detector were housed in lead collimators; additional lead and tungsten carbide absorbers were positioned between the source and detector in order to further reduce any backgrounds that are transmitted through their respective collimators.

Figure 1: Experimental set-up

The interrogating radiation used throughout the measurements was the 2.615 MeV gamma ray from ²³²U. The decay chain of this isotope, illustrated in Table I, eventually leads to the formation of ²⁰⁸Tl, a b- emitter that produces 2.615 MeV gamma rays. It is a fortuitous circumstance that in the decay chain of ²³²U, the only gamma ray with energy above the pair production threshold of 1.022 MeV is the 2.615 MeV gamma ray from ²⁰⁸Tl. For the purpose of inducing pair production, ²³²U may be considered a monoenergetic source of gamma rays. Secular equilibrium is established approximately 10 years after ²³²U is “purified”, and the ²⁰⁸Tl behaves as a long-lived source with a 70-year half life.

Two cylindrical ²³²U sources (with a total activity of 397 mCi) were positioned inside a 20-cm long, 3-cm diameter, lead collimator. The front surface of the source collimator was positioned (measured along its central axis 28 cm from the sample surface and, as shown in Fig. 1, directed at an angle of 40o with respect to the detector axis. With the help of a light source, the beam spot of the incident photons at the sample surface was estimated to be an ellipse with approximate dimensions of 11.2 cm by 7 cm.

Table I
Decay chain of ²³²U

Isotope	T _{1/2}	Main decay mode	Gamma-Rays emitted (keV)
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²³² U	70 y	α	58; 129
↓			
²²⁸ Th	1.91 y	α	84; 116; 132
↓			
²²⁴ Ra	3.66 d	α	293; 646
↓			
²²⁰ Rn	55.6 s	α	550
↓			
²¹⁶ Po	0.15 s	α	805
↓			
²¹² Pb	10.64 h	β ⁻	239; 300
↓			
²¹² Bi	60.6 min	β ⁻ (63.8%); α(36.2%)	727
↓			
²⁰⁸ Tl	3.1 min	β ⁻	227; 508; 511; 583; 860; 2615

The coaxial hyper-pure germanium detector (HPGE) used in our experiments consisted of a 6.77-cm long, 5.62-cm diameter, Ge crystal that was collimated with a 5-cm long, 5.75-cm diameter collimator. The front surface of the collimator was positioned 43 cm away from the interrogated object. The signals from the detector were shaped and amplified in an Ortec 673 spectroscopy amplifier. This is a high rate system with a transistor reset preamplifier and gated integrator amplifier, with a resolution of 2 keV at 1333 keV. The multi-channel analyzer was an Ortec 921 Spectrum Master MCA running on a PC-based machine using Ortec Maestro MCA software.

(a) Copper

(b) Lead

Figure 2: Energy spectrum of backstraming photos

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The pulse-height distributions obtained from copper and lead samples in ~200 s counting periods are presented in Figure 2 (a) and (b), respectively. In the first example, the peaks corresponding to the annihilation radiation (511 keV) and the single-scattered photons (~270 keV) can be easily identified; the well defined peak located at an energy of the order of 200 keV corresponds to the mean energy of incident photons that are first scattered through an angle of 180° (the maximum of the Klein-Nishina differential cross section in the backward direction) and then scattered again into the detector acceptance solid angle. The pulse-height distribution for lead, on the other hand, shows a substantial suppression of the Compton edge and the appearance of characteristic X-rays from lead. This is due to the fact that photons with energies of the order of hundreds of keV are highly attenuated via the photoelectric effect and in reality, for the 511-keV annihilation photons, this becomes the main form of interaction in materials with $Z > 80$.

B. Simulation

The experimental results derived from the apparatus described in the previous section were simulated with a program based on the EGS4 code system. EGS4 is an efficient and flexible software tool developed for the purpose of simulating the coupled transport of photons, electrons and positrons. The transport of particles is performed using a "class II algorithm" [17] where a detailed simulation of events involving energy transfers above a given threshold is combined with the use of the continuous slowing down approximation (csda) in those events which result in small-energy transfers.

The simulations were performed using the standard EGS4 code, together with the improvements of PRESTA algorithm [18], the low-energy photon transport LSCAT [19], the implementation of L-shell photoabsorption and L X-Ray fluorescence emissions [20], and the updated bremsstrahlung [21] and pair production angular distributions [22]. Since the measured signal consisted of 511 keV photons, the energy value below which photons were considered to be locally absorbed and consequently ignored was selected to be 510 keV. Positrons and electrons were, respectively, transported down to kinetic energies of 80 keV and 1022keV (above this value bremsstrahlung photons can still induce pair production). Although inefficient from the point of view of computational time, these values were chosen so that the accuracy of the results was not affected by neglecting the migration of positrons before annihilation (the csda range of 80 keV positrons in graphite is of the order of 1.5 microns [23]). For the sake of accuracy, the value below which charged-particle interactions were treated in terms of their specific energy loss (EGS4 variables AE and AP) was selected to be 10 keV.

(a) Source (b) Detector

Figure 3: Collimators

To realistically reproduce the experimental set up, the finite size of the radiation source as well as the dimensions of its collimator were modelled. As illustrated in Fig. 3(a), a photon emitter of cylindrical shape was considered to be positioned at the back of the 20-cm long collimator: for the sake of simplicity, the

thickness of the source was neglected and the its radius considered

to be identical to the collimator. The detector was defined to be encapsulated within a collimator with dimension shown in Fig.3(b); in order to reduce the required computational time, detector efficiency was considered to be 100% so that every photon emitted within the solid angle defined by the geometry, was considered to be detected (on pg. 431 of [Knoll], the full energy peak intrinsic efficiency at 511 keV of a Ge detector similar to that used is estimated to be of the order of 19%). The size of the incident beam spot at the interrogated object was determined to be approximately 11cm x 7 cm, values that agree well with the experimental values (11.2cm x 7.2 cm).

Although the simulation geometry was similar to Fig. 1, no particle transport was actually performed outside the material objects. The position and direction cosines of each photon striking the surface of the object were calculated from the geometry and EGS4 transport began at this point. Similarly, of all backward-emitted photons escaping from the sample, only those geometrically within the solid angle of the detector were accepted and considered detected. This simplification (neither the additional shielding between the source and detector nor the intervening air were considered) resulted in a more efficient code with no significant loss in accuracy.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Since we intend to apply this technique to the location of high- Z inclusions in less dense, low- Z , matrices, we first evaluated the Z -dependence of the annihilation photon yield. Then, point-by-point "images" were generated by scanning representative geometries.

Table II
Annihilation photon yields

Material	Z	t (cm)	No. of 511 keV photons	
			Experimental	Simulation
Beryllium	4	14.4	202 ± 22	239 ± 15
Polyester	5.3*	10	204 ± 23	221 ± 15
Graphite	6	6	252 ± 29	319 ± 18
Aluminium	13	9.8	711 ± 31	909 ± 30
Iron	26	4.5	1602 ± 45	2031 ± 45
Copper	29	3.5	1766 ± 47	2212 ± 47
Cadmium	48	3.6	2389 ± 43	3571 ± 60
Tungsten carbide	70*	11	2590 ± 58	4096 ± 64

A list of the different samples available, together with their thicknesses and the 511 keV photon yields are presented in Table II. The experimental values correspond to the number of photons obtained over a 300 s counting period, with the background subtracted. Background was considered to be the number of photons obtained per 300 s with the sample removed. The simulation results correspond to the number of detected annihilation photons per 40 million incident 2.615 MeV gamma rays.

Figure 4: Annihilation photon yields from different samples: experimental and simulation results.

Although the number of incident particles in the simulations was selected so that the 511 keV photon output was of the same order of magnitude as the experimental results, a direct comparison of simulated with experimental data can only be made after normalizing the data sets. Normalization would not be necessary if one could be absolutely confident that the number of incident gamma rays in the simulations was exactly the same as the number that reached the samples during the 300-s counting period and that detector response had been taken into account. It is reasonable to assume that the detection efficiency of the HPGe detector was constant throughout the measurements. In this case to normalize the data only requires the determination the ratio of the number of photons used in the simulation to what, on the average, struck the samples during the 300 s counting period. This variable, C , can be determined by means of a least square fit between the experimental and C times the simulation data, for the different materials considered. When using all the data points shown in Table II, the value of C was found to be $C = 0.747218$. However, the rather poor fit ($\chi/\nu = 14.2$; $r = 0.975$) led us to exclude the data for cadmium and tungsten carbide and this clearly improved the fit ($\chi/\nu = 1.23$; $r = 0.999$, now with $C = 0.834908$). The motivation

for excluding these two experimental points has to do with the fact that the sample of cadmium used was not a compact block but an assembly of different sheets and any "gaps" between the layers would results in a sample whose density is much different from solid cadmium; in the case of tungsten carbide, neither the purity nor the density were known to a great degree of accuracy. Experimental and simulation results (these were previously multiplied by C) are presented in Figure 4 where, for the sake of clarity, error bars are omitted. The agreement between the two sets of results is quite remarkable: the average difference obtained is of the order of 5%, with a maximum value of the order of 10% (in cadmium and tungsten carbide differences of the order of 25% are observed).

Figure 5: Schematic diagram of the object scanned.

Using the same experimental arrangement, a scan across an assembly of different materials was performed. The arrangement of the samples is shown in Fig. 5 and, referring now to Fig. 1, the scan was performed in the direction perpendicular do the plane of the paper. The size of the beam in the direction of the scan was 7 cm. The results for the number of 511 keV photons per second are shown in Fig. 6.

Figure 6: Relative number of 511 keV photons obtained in a line scan.

Finally, a scan across a test "phantom" consisting of a block of polyester with inclusions positioned 10 cm (~ 1.2 means free paths for 511 keV photons) below its surface was simulated. The geometry considered of the test object used in the scan is presented

in Fig. 7, and the inspecting radiation was considered to be an infinitely narrow beam of 2.615 MeV photons perpendicular to the entrance surface. The total back-streaming of 511 keV photons obtained in the scan per 1.8×10^5 photons is shown in Fig. 8.

V. CONCLUSIONS

Experimental and simulation results of photon-induced positron annihilation radiation have been presented. The results demonstrate that the signal from high atomic number materials appear in high contrast against, low atomic number, less dense materials and lead us to conclude that the technique may play an important role in the future whenever it is necessary to locate large, high-Z, dense objects in less dense matrices. Moreover, the possibility of combining this information with Compton scattered radiation and, where possible, fluorescence photons, may result in a powerful and unique method to locate and identify substances. In the future, the sensitivity and ultimate spatial resolution of this technique will be explored. The good agreement between experimental data and the results from EGS4 simulations clearly indicate that this code is well suited for the modelling of this imaging technique, and can, with a reasonably high degree of confidence, be used to perform a wide variety of calculational studies.

Figure 7: Schematic diagram of the object scanned.

Figure 8: Number of 511 keV photons obtained in a simulated scan.

VI. REFERENCES

- [1] G. Harding, "Inelastic photon scattering: effects and applications in biomedical science and industry", *Rad. Phys. Chem.*, Vol. 50, No. 1, pp. 91-111, 1997.
- [2] Glenn F. Knoll "Radiation Detection and Measurement", Second Edition, John Wiley & Sons, 1989.
- [3] A.P. Trippe and M.B. Marlowe J.A. Stokes, "AIDECS- Second Generation System", *Systems*, Vol. 5, No. 3, pp. 3-6, IRT Corp San California.
- [4] J.A. Stokes, K.R. Alvar, R.L. Costello, D.G. John, S. Kocinski, N. Lurie, D.D. Thayer, A.P. Trippe and J.C. Young, "Some new applications of collimated photon scattering for 'nondestructive examination'", *Nucl. Instrum. Meth.*, vol. A193, pp. 261-267, 1982.
- [5] G. Harding and J. Kosanetzky, "Scattered X-Ray beam nondestructive testing", *Nucl. Instrum. Meth.*, vol. A208, pp. 511-528, 1989.
- [6] P. Shea, T. Gozani and H. Bozorgmanesh, "A TNA explosives-detection system in airline baggage" *Nucl. Instrum. Meth.*, vol. A299, pp. 444-448, 1990.
- [7] W.C. Lee, D.B. Mahood, P. Ryge, P. Shea and T. Gozani, "Thermal neutron analysis (TNA) explosive detection based on electronic neutron generators", *Nucl. Instrum. Meth.*, vol. B99, pp. 739-742, 1995.
- [8] T. Gozani, "Novel applications of fast neutron interrogation methods", *Nucl. Instrum. Meth.*, vol. A353, pp. 635-640, 1994.
- [9] T. Gozani, "Understanding the limitations of PFNA - the nanosecond pulsed fast neutron analysis", *Nucl. Instrum. Meth.*, vol. B99, pp. 743-747, 1995.
- [10] W. Lee, J. Bendahan, P. Shea and V. Leung, "Technical updates from the TNA operations program" *Nucl. Instrum. Meth.*, vol. A353, pp. 641-645, 1994.
- [11] D.R. Brown and T. Gozani, "Cargo inspection system based on pulsed fast neutron analysis", *Nucl. Instrum. Meth.*, vol. B99, pp. 753-756, 1995.
- [12] E.A. Pentaleri and T. Gozani, "Complete characterization of containerized waste using a PNFA-based inspection system", *Nucl. Instrum. Meth.*, vol. A353, pp. 489-493, 1994.
- [13] C.L. Hollas, L.E. Ussery, K.B. Butterfield and R.E. Morgado, "Analysis of biological samples using prompt gamma-radiations induced by 14.7-MeV neutrons", *Biological Trace Element Research*, vol. 26-7, pp. 103-110, 1990.
- [14] M.D. Silver J.W. Erker, M.Z. Duncan, T. J. Hartford, E.A. Sivers and J.F. Hopkinson, "Detector for high energy photon backscatter, X-Ray Detector Physics and Applications-II", SPIE vol. 2009, pp. 168-178, 1993.
- [15] W.B. Gilboy, G. Harding, L.M.N. Távora and B. Ulmer, "On the Potential of Photon Induced Annihilation Photons for Inspection of Engineering Structures", accepted for publication in *Appl. Rad. and Isotopes*.
- [16] W. R. Nelson, H. Hirayama and D.W.O. Rogers, "The EGS4 code system", Stanford Linear Accelerator Center Report SLAC-265, 1985.
- [17] M.J. Berger, "Monte-Carlo calculation of the penetration and diffusion of fast charged particles", *Methods in Computational Physics*, vol. 1, pp. 135-215, 1963.
- [18] A.F. Bielajew and D.W. O. Rogers, "PRESTA: The Parameter Reduced Electron-Step Transport Algorithm for Electron Monte-Carlo Transport", *Nucl. Instrum. Meth.*, vol. B18, pp. 165-181, 1987. Also available as *National Research Council of Canada Report PIRS-0042*, October 1986.
- [19] Y. Namito, S. Ban and H. Hirayama, "Implementation of the Doppler broadening of a Compton-scattered photon into the EGS4 code", *Nucl. Instrum. Meth.*, vol. A349, pp. 489-494, 1994. Also available as "LSCAT: Low Energy Photon Scattering Expansion for the EGS4 Code", *KEK Internal Report 95-10*, August 95.
- [20] H. Hirayama, Y. Namito and S. Ban, "Implementation of an L-Shell Photoelectron and an L X-ray for Elements in the EGS4 Code" *KEK Internal Report 96-10*, August 96.
- [21-43] A.F. Bielajew, R. Mohan and C.-S. Chui, "Improved bremsstrahlung photon angular sampling in the EGS4 code system", *National Research Council of Canada Report PIRS-0203*, November 1982.
- [22-43] A.F. Bielajew, "Improved angular sampling for pair production in the EGS4 code system", *National Research Council of Canada Report PIRS-0287R1*, October 1994.
- [23-43] M.J. Berger and S.M. Seltzer, National Bureau of Standards Report NBSIR 82-2550 (Washington, 1982). Also available as, "ICRU Report 37: Stopping powers for Electron and Positrons", ICRU, October 1984.

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