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Multiple fast neutron and gamma-ray beam systems for the detection of illicit materials

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Abstract Neutron and photon sources have been combined in order to assess the performance of these combinations to discriminate between materials of similar composition. The evaluation has been carried out on the basis of the maximum and minimum ratio values of the relative transmissions of high-energy gamma- or X-ray and neutrons. The number of materials with similar ratio values was used as an indicator of the effectiveness of each source combination. The use of three sources, instead of two, significantly improves the capability of neutron/photon combination to separate similar in composition materials.

Keywords FNGR radiography · Dual beam system · Triple beam system · Fourfold beam system · Illicit materials

Introduction

Acts of terrorism, such as the destruction of Pan Am Flight 103, the Oklahoma City bombing, the destruction of the twin towers in New York, and the recent Oslo bombing, have increased the necessity of the timely detection of explosive materials. Hence, security could be improved in potential targets of such acts, for example in buildings, events, offices, aviation, and train premises. Moreover the transportation of illicit drugs have shown an increasing trend during the last decade requiring immediate action in order to combat the crime. Places where a search for hidden illicit materials is necessary include airports, border crossing points, cargo transport [1, 2].

Today, the majority of inspection systems are based on the well known dual beam method in order to scan hand luggage and cargo containers [1–7]. In this sense, X-rays or gamma rays with different energies are used to identify materials based on their difference in attenuation as they pass through an object. With this method, it is easy to discriminate not only metals from organic materials, but also high-atomic number metals such as lead and uranium from common metals such as iron and aluminium. However, they are practically impossible to differentiate a wide range of organic materials. The replacement of one X-ray energy with fast energy neutrons offers valuable added information in the characterisation of materials [3, 4, 6, 7].

The aim of the present simulation study is to evaluate whether the use of more than two beams would improve, through their combination, the capability of the method to differentiate very similar in composition illegal and non-illegal materials. In this context, two different neutron sources and five different photon sources, have been considered. The required simulations have been carried out using the MCNPX Monte Carlo code [8].

Materials and methods

Dual beam radiography

An object can be characterised by means of the transmission of neutrons and γ-rays through it, as it is the case of an

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FNGR system [3, 4, 6, 7]. In the case of narrow-beam geometry, the transmission of monoenergetic fast neutrons and γ-rays through the object can be calculated by means of the relationships:

$$\frac{I_n}{I_n^0} = e^{-\mu_n \rho x} \Rightarrow R_n = \ln(I_n/I_n^0) \quad (1)$$

and

$$\frac{I_g}{I_g^0} = e^{-\mu_g \rho x} \Rightarrow R_g = \ln(I_g/I_g^0) \quad (2)$$

where ρ and x are the density and thickness of the object, μ_n and μ_g are the neutron and γ-ray mass-attenuation coefficients, respectively, I_n and I_g are the transmission intensities through the object I_n^0, I_g^0 are the intensities of the neutron and γ-ray beams. The logarithmic ratio R, of the neutron and γ-ray attenuation coefficients is:

$$R = \frac{R_n}{R_g} = \frac{\mu_n}{\mu_g} = \frac{\ln\left(I_n/I_n^0\right)}{\ln\left(I_g/I_g^0\right)} \quad (3)$$

Hence, the ratio R, while independent of the thickness, depends on the material of the unknown object and its accurate determination is essential in order to characterise the object [9]. Then, one would simply infer the material of the object through the comparison of the measured R value with the corresponding ones for a range of possible candidate materials. In the absence of sufficient experimental data, R values are created through simulations.

An uncertainty on each R value has been established on the basis of the uncertainties of 1 and 0.1 % on the R_n and R_g values, respectively [6]. Hence, the R ($=R_n/R_g$) values have been calculated together with their associated maximum and minimum values [$R_n \pm 1\ \%\ R_n$, $R_g \mp 0.1\ \%\ R_g$] for the different materials. The R values, with their upper and lower limits are compared in order to establish any overlaps between the different materials. The extend to which these overlaps occur would determine how efficiently one can separate and identify close materials in composition.

Sources

Deuterium–deuterium (DD) or deuterium–tritium (DT) neutron generators with average energy 2.5 and 14 MeV, respectively, were considered as the neutron sources. The three gamma ray sources considered in the simulations were ^{60}Co ($E_\gamma = 1.17$ and 1.33 MeV), ^{137}Cs ($E_\gamma = 0.662$ MeV) and ^{88}Y ($E_\gamma = 0.898$ and 1.836 MeV), as well as two X-rays sources with 4 and 9 MeV end point energies with Bremsstrahlung spectra. The combination of these sources gives 10 dual (D1–D10), 25 triple (T1–T25) and 10 quadruple (Q1–Q10) FNGR source systems, with two, three and four sources, respectively (Tables 1, 2, 3).

Results and discussion

The different combinations of the sources, employed in the dual (D), triple (T) and quadruple (Q) source systems, are shown in Tables 1, 2 and 3. These systems comprise two, three and four sources, respectively. The corresponding ratios R are included in the tables. In the case of the dual system, one ratio per source combination is observed (Table 1). Two and four ratios per source combination are obtained in the case of the triple and quadruple systems, respectively (Tables 2, 3). These two systems, and hence the R values, stem from combining the dual systems D1–D10 (Table 1), in a way that the emerging triple and quadruple systems comprise the three and four sources, respectively. Hence, 25 source combinations (T1–T25), yielding pairs of the ratios R_1–R_{10} are obtained in the dual source case. Ten source combinations are obtained in the quadruple case (Q1–Q10), with the ratios R_1–R_{10} combined in four for each of the systems D1–D10.

The R_1–R_{10} values have been calculated for a wide range of materials. Owing to the numerous materials, the R values, the densities and the chemical formulae of the investigated materials are given as a supplementary file. Compositions and properties of illicit and non-illicit materials have been obtained from the literature [10–41]. For comparison purposes, everyday common materials such as plastics, metals, food, organic materials and fabrics in addition to nuclear materials have been considered [42–51]. In the supplementary Table, explosives are underlined, drugs and stimulants are in italics, chemical weapons are in bold and non-illicit materials are in normal letters. Based on these R values and their associated variable error, their overlap is sought for the materials

Table 1 The 10 FNGR dual beam systems which studied in the present work

Combination	Sources		*R* values
D1	DD	^{60}Co	R_1
D2	DD	^{137}Cs	R_2
D3	DD	^{88}Y	R_3
D4	DD	4 MeV X-ray	R_4
D5	DD	9 MeV X-ray	R_5
D6	DT	^{60}Co	R_6
D7	DT	^{137}Cs	R_7
D8	DT	^{88}Y	R_8
D9	DT	4 MeV X-ray	R_9
D10	DT	9 MeV X-ray	R_{10}

Table 2 The 25 FNGR triple beam systems which considered in the present study

Combination	Sources			*R* values
T1	DD	^{60}Co	^{137}Cs	R_1, R_2
T2	DD	^{60}Co	^{88}Y	R_1, R_3
T3	DD	^{60}Co	4 MeV X-ray	R_1, R_4
T4	DD	^{60}Co	9 MeV X-ray	R_1, R_5
T5	DD	^{137}Cs	^{88}Y	R_2, R_3
T6	DD	^{137}Cs	4 MeV X-ray	R_2, R_4
T7	DD	^{137}Cs	9 MeV X-ray	R_2, R_5
T8	DD	^{88}Y	4 MeV X-ray	R_3, R_4
T9	DD	^{88}Y	9 MeV X-ray	R_3, R_5
T10	DD	4 MeV X-ray	9 MeV X-ray	R_4, R_5
T11	DT	^{60}Co	^{137}Cs	R_6, R_7
T12	DT	^{60}Co	^{88}Y	R_6, R_8
T13	DT	^{60}Co	4 MeV X-ray	R_6, R_9
T14	DT	^{60}Co	9 MeV X-ray	R_6, R_{10}
T15	DT	^{137}Cs	^{88}Y	R_7, R_8
T16	DT	^{137}Cs	4 MeV X-ray	R_7, R_9
T17	DT	^{137}Cs	9 MeV X-ray	R_7, R_{10}
T18	DT	^{88}Y	4 MeV X-ray	R_8, R_9
T19	DT	^{88}Y	9 MeV X-ray	R_8, R_{10}
T20	DT	4 MeV X-ray	9 MeV X-ray	R_9, R_{10}
T21	DD	DT	^{60}Co	R_1, R_6
T22	DD	DT	^{137}Cs	R_2, R_7
T23	DD	DT	^{88}Y	R_3, R_8
T24	DD	DT	4 MeV X-ray	R_4, R_9
T25	DD	DT	9 MeV X-ray	R_5, R_{10}

Table 3 The 10 FNGR fourfold beam systems which studied in the present work

Combination	Sources				*R* values
Q1	DD	^{60}Co	DT	^{137}Cs	R_1, R_2, R_6, R_7
Q2	DD	^{60}Co	DT	^{88}Y	R_1, R_3, R_6, R_8
Q3	DD	^{60}Co	DT	4 MeV X-ray	R_1, R_4, R_6, R_9
Q4	DD	^{60}Co	DT	9 MeV X-ray	R_1, R_5, R_6, R_{10}
Q5	DD	^{137}Cs	DT	^{88}Y	R_2, R_3, R_7, R_8
Q6	DD	^{137}Cs	DT	4 MeV X-ray	R_2, R_4, R_7, R_9
Q7	DD	^{137}Cs	DT	9 MeV X-ray	R_2, R_5, R_7, R_{10}
Q8	DD	^{88}Y	DT	4 MeV X-ray	R_3, R_4, R_8, R_9
Q9	DD	^{88}Y	DT	9 MeV X-ray	R_3, R_5, R_8, R_{10}
Q10	DD	4 MeV X-ray	DT	9 MeV X-ray	R_4, R_5, R_9, R_{10}

considered, either as a single value or combined in pairs or in four. In this way, the efficiency of multiple source systems in separating similar materials is sought. Overlapping *R* values would lead to false identification of a material.

The percentage and number of materials with overlapped *R* values are given in Tables 4, 5 and 6, for the dual, triple and quadruple source cases, respectively. This information, in ascending order, is given for overlaps: (1) between all the materials considered, and (2) between the illicit and not-illicit materials. The number of materials with overlapped *R* values decreases with increasing number of sources in the system. The best dual beam system is based on the combination of a DD neutron generator and an X-rays source with 4 MeV end point energy with Bremsstrahlung spectra (D_4 combination). In this system, there are 258 pairs of materials with overlapped *R* values when the total number of possible overlaps is 13,530. The decrease, by a factor of at least two, is particularly prominent when a third source is added to the system. Hence, the 258 pairs of materials with overlapped *R* values in the case of the dual source system are reduced to 117 in a triple beam system incorporating the neutron generators DD, DT and the gamma source ^{88}Y (T23 combination).

The inclusion of a fourth beam, further reduces these overlapped materials to 108 (Q6 combination based on the neutron generators DD, DT the gamma-rays from ^{137}Cs and the 4 MeV X-rays). It should be noted that even the worst fourfold beam system (Q4 combination with the neutrons from DD, DT, gamma-rays from ^{60}Co and 9 MeV Bremsstrahlung X-rays) has just 127 overlapped pairs of materials out of the 13,530 possible combinations of all the materials considered in this study. The trend of the results is the same in case the *R* values are compared for the 6,000

Table 4 The percentage and the number of the pairs with overlapped *R* values (dual beam systems)

R values with variable amplitude deviation		
Dual beam system	Percentage and number of pairs with overlapped *R* values	Percentage and number of pairs with overlapped *R* values between illicit–not illicit materials
D4	1.91 % (258)	0.98 % (59)
D3	1.93 % (261)	0.97 % (58)
D2	1.95 % (264)	1.07 % (64)
D1	2.03 % (275)	1.03 % (62)
D5	2.05 % (278)	1.15 % (69)
D7	7.36 % (996)	4.29 % (257)
D9	7.44 % (1006)	4.45 % (267)
D6	7.49 % (1013)	4.42 % (265)
D10	7.49 % (1014)	4.40 % (264)
D8	7.49 % (1014)	4.60 % (276)

Table 5 The percentage and the numbers of the pairs with overlapped *R* values (triple beam systems)

Triple beam system	Percentage and number of pairs with overlapped *R* values	Percentage and number of pairs with overlapped *R* values between illicit–non illicit materials
T23	0.86 % (117)	0.37 % (22)
T24	0.89 % (120)	0.37 % (22)
T22	0.92 % (124)	0.35 % (21)
T21	0.92 % (124)	0.43 % (26)
T25	0.92 % (125)	0.37 % (22)
T7	0.97 % (131)	0.47 % (28)
T4	0.99 % (134)	0.45 % (27)
T6	1.04 % (141)	0.42 % (25)
T3	1.05 % (142)	0.43 % (26)
T9	1.10 % (149)	0.53 % (32)
T5	1.17 % (158)	0.57 % (34)
T10	1.19 % (161)	0.60 % (36)
T8	1.24 % (168)	0.63 % (38)
T2	1.26 % (170)	0.62 % (37)
T1	1.44 % (195)	0.83 % (50)
T16	3.27 % (443)	1.79 % (107)
T17	3.30 % (447)	1.80 % (108)
T14	3.33 % (450)	1.87 % (112)
T13	3.35 % (453)	1.87 % (112)
T15	3.49 % (472)	2.14 % (128)
T12	3.61 % (489)	2.24 % (134)
T18	3.76 % (509)	2.37 % (142)
T19	3.78 % (511)	2.30 % (138)
T20	3.96 % (536)	2.55 % (153)
T11	4.00 % (541)	2.57 % (154)

Table 6 The percentage and the numbers of the pairs with overlapped *R* values (systems with four beams)

R values with variable amplitude deviation		
System with four beams	Percentage and number of pairs with overlapped *R* values	Percentage and number of pairs with overlapped *R* values between illicit–non illicit materials
Q6	0.80 % (108)	0.33 % (20)
Q7	0.84 % (113)	0.35 % (21)
Q8	0.85 % (115)	0.32 % (19)
Q9	0.86 % (117)	0.32 % (19)
Q5	0.86 % (117)	0.35 % (21)
Q2	0.88 % (119)	0.37 % (22)
Q10	0.89 % (120)	0.37 % (22)
Q1	0.89 % (121)	0.35 % (21)
Q3	0.92 % (124)	0.37 % (22)
Q4	0.94 % (127)	0.37 % (22)

combinations between illicit and non-illicit materials from the 165 considered in the study. This is an important consideration bearing in mind the costs involved in creating a system. The sources yielding the fewer overlapped materials are DD, Y, 4 and 9 MeV X-rays.

Conclusions

Neutron and photon sources have been combined in a Dual-, Triple- and Quadruple-source mode, in order to evaluate their performance to the material characterisation of a suspicious bulky object. The evaluation has been carried out on the basis of the *R* values and the number of materials with similar *R* values was used as indicators of the effectiveness of each source mode. The use of three sources, instead of two, significantly improves the capability of neutron/photon combination to separate similar in composition materials. Hence, the inclusion of a third source reduces the overlapped materials by a factor of nearly two, from 1.91 to 0.86 % of the 13,530 combinations of all the materials considered in this study. The use of a fourth source further reduces the overlapped materials to 0.80 %. In all cases, the use of the DD, ^{88}Y, 4 and 9 MeV X-ray sources offered advantages in material discrimination.

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