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Abstract- Bremsstrahlung sources have been utilized for various non-intrusive inspection or interrogation applications for over 100 years - with the primary focus being radiographic imaging. In the last several decades, it has become evident that photons of energy greater than 6 MeV can also provide useful photonuclear information that can extend the capabilities and information available from active inspections. These energetic inspection photons can be produced as a continuum of energies (i.e., bremsstrahlung distribution) or as a set of one or more discrete photon energies (i.e., monoenergetic distribution). This paper will discuss the photonuclear process and its energetic photon energy dependence, will discuss the photonuclear role in nuclear material detection, will present applicable photon sources along with their field deployment status, and highlight some advantages and disadvantages of bremsstrahlung and monoenergetic photons sources.

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I. Introduction

For over a century[1] photons have enabled many unique radiographic, medical, and industrial applications, and their interactions in the environment and shielding materials are well understood and accepted. Photons are readily available using radioisotopic sources or produced by accelerators. Since higher energy photons can provide significant penetration into inspected objects, as well as inducing material identifiable signatures, energetic (> 6-MeV) photon inspection systems continue to be of interest for numerous homeland security and nonproliferation applications, especially for the detection of concealed nuclear materials. These energetic photons can be produced having a broad-energy, continuum spectra (i.e., bremsstrahlung) or be generated having discrete or monoenergetic emissions.

This paper will present applicable photon sources along with their field deployment status, identify the photon dose rates as a function of source-to-inspected object distance (i.e., standoff distance), present the higher energy photon component that can contribute to nuclear material detection, and highlight some of the advantages and disadvantages of bremsstrahlung and nuclear reaction-driven, monoenergetic photons sources.

II. Photon Sources and Fieldability

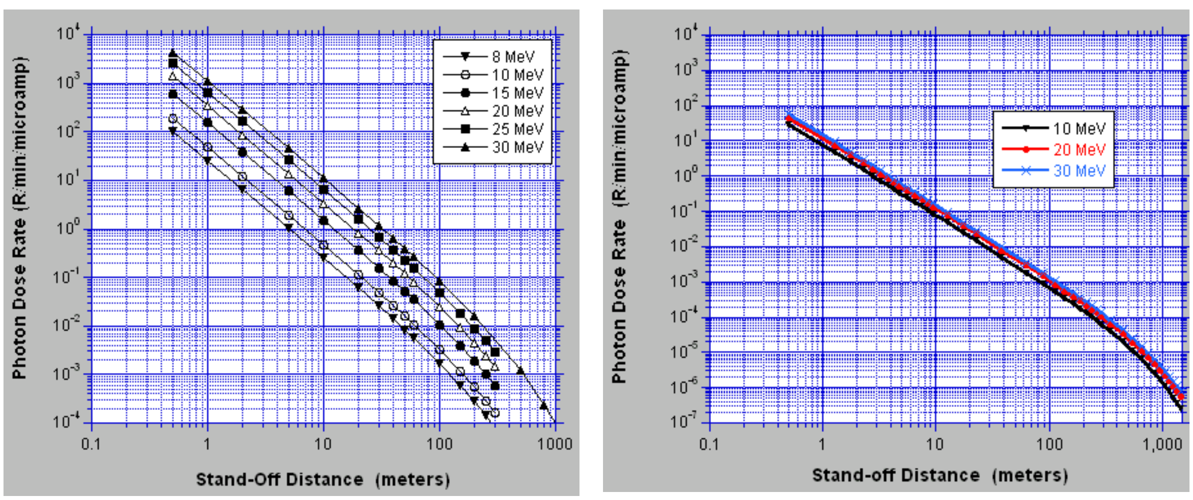
The most common and well-understood monoenergetic photon sources are the radioisotopic sources such as Co-60 (1170 and 1330 keV) and Cs-137 (667 keV). These types of gamma-ray sources, while being monoenergetic and field deployable, do not produce energetic photons capable of penetrating significant shielding, supporting enhanced source-to-inspection object standoff distances, or inducing photofission reactions (i.e., > 6 MeV). Other radioactive sources are available, such as Th-232 (with 2600 keV gamma-rays), but these sources provide additional decay channels resulting in mixed radiation field. To achieve more energetic and tunable photons, accelerator and/or nuclear-driven reactions continue to be investigated.

An electron accelerator, such as a pulsed linear accelerator, will easily produce energetic photons having a continuous energy spectrum extending up to the maximum electron energy (i.e., bremsstrahlung). These photons are copiously generated when an accelerated electron traverses through an array of positive charges, such as material nuclei. The denser the charge array of the electron/photon converter, the more bremsstrahlung photons produced. This photon yield process increases with the square of the atomic number (Z) of the material and nonlinearly with the electron energy. While various converter materials and thickness can be selected, this paper uses a 0.25-cm thick tungsten converter (19.3 g/cm^3 density) for generating optimal bremsstrahlung radiation for this study. Bremsstrahlung photon sources are commercially available and some are available in transportable configurations. Customized, transportable systems are already being incorporated into active interrogation systems[2] for inducing time-correlated, fission signatures and, potentially, other nuclear signatures such as Nuclear Resonance Fluorescence (NRF).[3]

Monoenergetic sources are of particular interest because of the desire to increase the sensitivity of a detection system while potentially lowering the overall radiation dose to the object and environment. Monoenergetic photons can be produced with nuclear reaction-based, particle-driven sources[4] and Laser Compton Scattering (LCS) sources.[5] While various reactions are possible, this paper will consider one of nature's lowest energy nuclear reaction, $^{11}B(p,\gamma)^{12}C$, that produces three gamma-rays at 4.4-MeV, 11.7-MeV, and 16.1 MeV. The latter two gamma-rays are energetic enough to induce photofission. Based on recent work by Sandia National Laboratory and Lawrence Berkeley National Laboratory, these particle-driven sources are becoming more feasible and fieldable. The LCS source is another monoenergetic source that utilizes the scattering interaction of a high intensity laser with an intense pulse of high energy electrons. The scattering interaction produces well defined, monoenergetic photons. Wide energy-range tuning of the scattered photon is ultimately desirable. There has been considerable LCS source development and laboratory advances are continuing; but, eventual field deployment of LCS systems will depend on advancements in electron beam optics, electron-laser interactions and, like many accelerator-driven sources, development of rugged, compact, relocatable/transportable accelerators.

III. Bremsstrahlung and Monoenergetic Photon Doses vs Stand0off Distance

Figure 1 shows the bremsstrahlung photon and an ideal nuclear reaction-driven, monoenergetic photon dose rates in units of rads per minute per microampere of electron/particle beam currents and for source particle energies ranging from 8-30 MeV. In order to compare the dose rates, the monoenergetic photon source is assumed to be isotropic and have a particle-to-photon conversion efficiency of unity, which means every incident particle produces one monoenergetic photon. Note that for any specific nuclear reaction selected, the conversion efficiency will be <u>much less than one</u> and, like the bremsstrahlung source electrons, will be dependent on the incident particle energy. The bremsstrahlung converter or photon source point is assumed to be in air (@ STP) at 1 meter above a 122-cm thick concrete ground plane. The dose rates clearly increases with increasing source energy and will penetrate to greater standoff distances. All monoenergetic sources show similar responses due to similar air attenuation effects and are lower than for the comparable bremsstrahlung cases. The ground plane was determined to have no affect in these results.



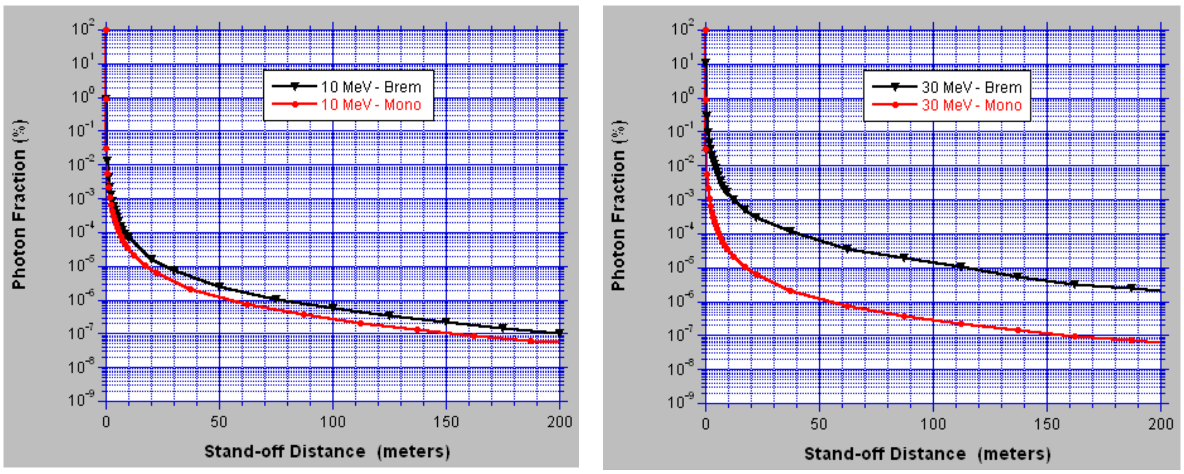
(A) (B)

Figure 1. Bremsstrahlung photon dose rate for maximum electron beam energies, A, and monoenergetic photon dose rate for selected source photon energies, B, versus standoff distance down the beamline axis.

IV. Higher Energy Spectral Photon Component

The higher energy photon component of the bremsstrahlung and the nuclear-reaction-driven, monoenergetic photon sources can better penetrate shield materials and can induce photonuclear, especially photofission (for >6 MeV photons), signatures in nuclear materials. Hence, it is of interest to know what fraction of the source photons have energies greater than 6 MeV as a function of the standoff distance.

Figure 2 compares the percentage of photons, along the beamline axis, having energy greater than 6 MeV relative to the total number of photons produced at the source location. Comparisons are made for bremsstrahlung maximum electron energies of 10 and 30 MeV (with no ground plan) and corresponding monoenergetic photons from an ideal isotropic source.



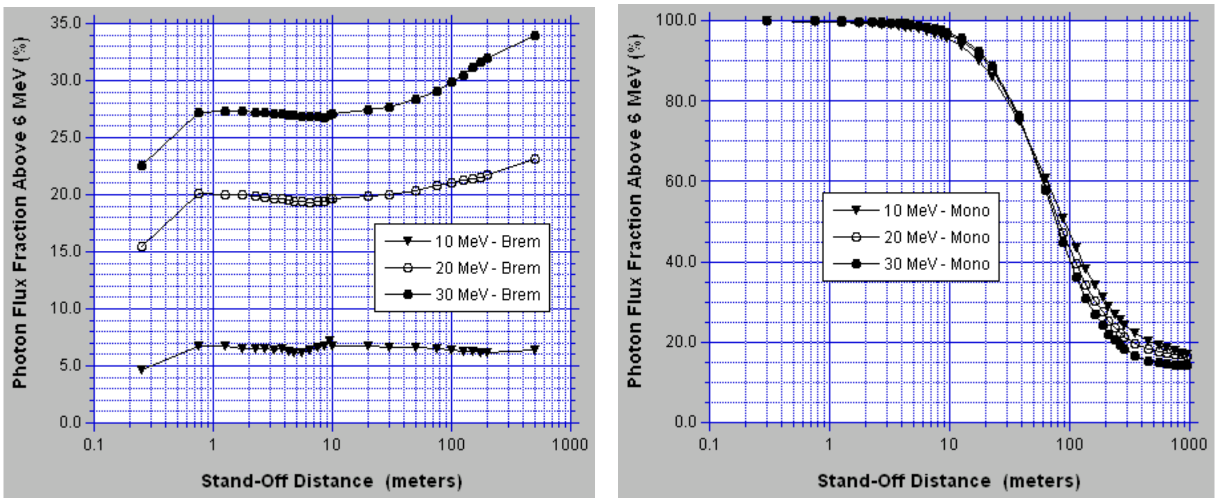
(A) (B)

Figure 2. Fraction of photons with energies greater than 6 MeV relative to the total source photons for 10 and 30 MeV bremsstrahlung maximum electron energy, A, and the corresponding monoenergetic photons, B, as a function of standoff distance.

The percentage of bremsstrahlung photons of energy greater than 6 MeV produced near the source relative to the total number of initial source photons is approximately 5% for the 10-MeV case (100% for the 10-MeV monoenergetic photons), but increases to about 23% for the 30-MeV case. As the source energy is increased to 30 MeV, the higher energy bremsstrahlung fraction increases with standoff distance relative to the monoenergetic fraction. This response can be attributed to the bremsstrahlung distribution and the enhanced forward peaking of the bremsstrahlung peak along the beamline axis with increasing electron energy.

Also the 10-30 MeV monoenergetic photon fraction with energy greater than 6 MeV appears to be nearly identical over the 0-200 m stand-off distance. This is largely due to the similar air attenuation coefficient in this energy range and the dominate loss due to $1/r^2$-geometric dispersion.

At a given standoff distance along the beam axis, Figure 3 presents the local spectral content of the bremsstrahlung photon flux and the monoenergetic photon flux. This figure gives the fraction (percent) of the photons with energies greater than 6 MeV at a standoff distance for source energies of 10, 20, and 30 MeV. Note that the local bremsstrahlung spectrum hardens noticeably for the 20 and 30 MeV cases at standoff distances greater than 30 meters. Also, at the higher energies, the bremsstrahlung fraction above 6 MeV is larger than the monoenergetic fraction for the larger stand-off distances (>150 meters for the 30-MeV case and >200 meters for the 20-MeV case).



(A) (B)

Figure 3. Local Bremsstrahlung, A, and Monoenergetic, B, spectral content along the beamline for 10, 20, and 30 MeV maximum source energies.

V. Summary

Advanced, energetic photon sources continue to be investigated for their ability to address challenging inspection problems, especially those involving increased inspection distances and concealed nuclear material. These photon sources can be bremsstrahlung sources or monoenergetic sources (nuclear reaction, particle-driven or LCS sources). Fieldable bremsstrahlung sources are currently available, nuclear reaction, particle-driven sources are being developed for field applications, and LCS sources are still in a laboratory-development phase with significant advances anticipated that may be able to optimize the advantages of both monoenergetic and bremsstrahlung sources. For photonuclear inspection assessments, the photon fraction (percent) and the bremsstrahlung photon dose data provided can be used directly, but the monoenergetic photon dose rates must be reduced for actual nuclear reaction, particle-driven production efficiencies. (For example, $\sim 10^{-9}$ for the $^{11}B\ (p,\gamma)^{12}C$ reaction at $E_p = 163$ keV with higher yields possible with increased proton energies and/or different nuclear reaction types.)

Monoenergetic photon sources provide overall photon doses that are much lower than comparable energy bremsstrahlung sources for at least up to 1 km inspections and 30-MeV interrogations. However, bremsstrahlung sources do show greater high energy photon fractions, or photonuclear stimulation capability, at standoff distances greater the ~150 m with electron beam energies above 20 MeV.

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