METHOD AND APPARATUS FOR RADIATION DETECTION AND IMAGING

Abstract: A device for measuring energy and incident angle of gamma radiation of an external source includes a radiation scattering layer and a radiation absorbing layer. The radiation scattering layer includes a first two-dimensional array of a first plurality of lanthanum tri-bromide crystal scintillator detectors. The radiation absorbing layer includes a second two-dimensional array of a second plurality of lanthanum tri-bromide crystal scintillator detectors. The second radiation absorbing layer is spaced from the radiation scattering layer.

FIG. 1 (prior art)
Published:

Upon receipt of that report (Rule 48.2(g))
DESCRIPTION

METHOD AND APPARATUS FOR RADIATION DETECTION AND IMAGING

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 61/034,755, filed March 7, 2008, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF THE INVENTION

Gamma ray imaging and detection are used in many scientific and commercial applications, including medical imaging, nuclear spectroscopy, and gamma ray astronomy (U.S. Patent No. 6,528,795). A traditional Compton imaging design includes two position sensitive detector layers, as shown in Figure 1. In the top level, the gamma ray Compton scatters off an electron in the detector material, where some energy is lost and energy is transferred to the electron off of which the scattering occurs. The energy transferred to the electron creates multiple electron-hole pairs, which combine to create light that is detected. The light can be detected by, for example, a scintillator detector. The scattered photon, scattered in the top level, then travels into the second detector layer, where it is completely absorbed. When both layers are triggered in coincidence, the instrument is read out. The energy of the gamma ray, $E_\gamma$, is determined by summing the energy deposited in both detector layers ($E_\gamma = \Delta E_1 + \Delta E_2$). Positional information from the detector layers and the amount of energy deposited in each layer allow for reconstruction of the original gamma ray direction via the Compton scattering formula:

$$\cos \theta_1 = 1 + m_e c^2 \left( \frac{1}{E_\gamma} - \frac{1}{E_1} \right)$$

where $\theta_1$ is the Compton scattering angle of the incident gamma ray, $m_e$ is the mass of an electron, $c$ is the speed of light, and $E_1$ is the energy of the scattered gamma ray. From $\theta_1$ and the position of the two interactions, a cone can be drawn that includes the direction of the incident gamma ray. As shown in Figure 1, the overlap of cones from multiple events gives the original source position (U.S. Patent No. 6,528,795).
While typical Compton imaging devices using Si as the absorber layer provide high angular resolution, it would be advantageous to have a method and apparatus for detection of energy and incident angle of gamma radiation that improves on detection efficiency and/or image resolution of current techniques.

BRIEF SUMMARY

Embodiments of the invention relate to a method and apparatus for measuring energy and incident angle of gamma radiation of an external source. Embodiments can incorporate a radiation scattering layer and a radiation absorbing layer. In a specific embodiment, the radiation scattering layer includes a one-dimensional array of a plurality of scintillator detectors or the radiation absorbing layer includes a one-dimensional array of a plurality of scintillator detectors, where the radiation absorbing layer is spaced from the radiation scattering layer. In a specific embodiment, the radiation scattering layer includes a first two-dimensional array of a first plurality of scintillator detectors and the radiation absorbing layer includes a two-dimensional array of a plurality of scintillator detectors, where the second radiation absorbing layer is spaced from the radiation scattering layer. In a specific embodiment, the spacing between the radiation absorbing layer and the radiation scattering is adjustable.

Specific embodiments incorporate lanthanum halide scintillator detectors in the radiation scattering layer and/or the radiation absorbing layer. Examples of a lanthanum halide scintillator detector that can be utilized with embodiments of the invention include a lanthanum tri-bromide (LaBr₃) crystal scintillator detector and a lanthanum tri-chloride (LaCl₃) crystal scintillator detector.

In a specific embodiment, a system using LaBr₃ as both detector and absorber can provide higher imaging efficiency than typical Compton imaging devices using Si as the absorber layer. Figure 2 shows a comparison of single Compton scattering efficiency as a function of detector thickness, for two energies. As shown, at energies near 500 keV, LaBr₃ provides a higher efficiency than Si as a scatter detector for detector material thicknesses less than 1.2cm, and this "cutoff" thickness increases with photon energy (at 2 MeV the "cut off" thickness is greater than 3cm as shown). As the scatter detector should be thinner than 1.2cm to allow a single scatter, but not the absorption of the entire energy of the photon for photon energies above 500 keV, using LaBr₃ as both scatter and absorber detector allows a higher Compton efficiency for the energy range 0.5 MeV and higher, as compared to using Si for the scatter detector. Specific embodiments of the subject detector, which are advantageous in
detection of photons under 500 keV of energy, can incorporate scattering layers less than or equal to 1.5cm. Further embodiments can utilize absorbing layers less than or equal to 6.62cm, and more particularly in the range 5.08cm to 5.62cm.

Figures 3, 4A and 4B illustrate the use of LaBr₃ in a Compton imaging array system, with parallel two-dimensional arrays for both scatter and absorber detector layers and adjustable spacing between the layers.

While Compton imaging using LaBr₃ material does provide high imaging efficiency above 500 keV, as shown in Figure 5 the efficiency drops off at energies below 500 keV as photon interactions in LaBr₃ below this energy are dominated by multiple scattering and photoelectric interactions, rather than single Compton scattering. In order to address this issue, an achieve other advantages, an embodiment of the subject invention is directed to a hybrid imaging routine involving traditional Compton imaging methods for photon energies above 500 keV, and use of a coded aperture method for energies below 500 keV.

The coded aperture method uses a shielding element and a position sensitive photon detector, such as a radiation absorbing layer. The shielding element, or coded aperture, is composed of "mask elements" that are distributed in a predetermined pattern, which is placed on a grid. In a specific embodiment, the mask elements can be of an equal size. The position sensitive detector has a spatial resolution that is sufficient to resolve the mask-pattern grid. Photons from a given direction project the mask pattern on the detector; this projection has the same coding as the mask pattern, but is shifted relative to the central position over a distance uniquely correspondent to this direction of the photons, as seen in Figure 6. The image of the incident photons is reconstructed via a decoding algorithm, using the accumulated distribution of shifts and intensities from a source.

Historically, hybrid systems using a coded aperture in front of a Compton camera have used passive coded apertures as masks, made from material with high Z and high density for high photon attenuation. However, at higher photon energies, coded aperture masks may introduce additional scattering and decrease the signal to noise ratio (SNR) of Compton scattering, degrading the Compton imaging resolution. In order to address this issue, and achieve other advantages, an embodiment of the invention uses a hybrid approach in which the coded aperture incorporates active detection elements of LaBr₃(Ce) in the scatter detector layer, as shown in Figure 7. In such an embodiment, the detector elements of the radiation scattering layer can act as the shielding element to implement the coded aperture technique. Accordingly, embodiments of the subject gamma radiation detection device can utilize a hybrid detection scheme, where for photon energies at or below 500 keV, the shift in
the mask pattern of the radiation scattering layer can be used to determine the angle of incidence and absorption in the radiation absorbing layer can be used to determine the photon energy and count (note, absorption in the radiation scattering layer can also be used to determine photon energy and count), and for photon energies above 500 keV Compton imaging using the radiation scattering layer and radiation absorbing layer can be used to determine incident angle, photon energy, and photon count.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a schematic diagram of a Compton imaging device.

Figure 2 shows a comparison of single Compton scattering efficiency as a function of detector thickness for Silicon (Si) and lanthanum tri-bromide (LaBr₃) for photon energies of 0.511 MeV and 2 MeV.

Figure 3 shows a three-dimensional view of a second lanthanum tri-bromide (LaBr₃) radiation absorbing array adjustably spaced from a first lanthanum tri-bromide (LaBr₃) radiation scattering array.

Figures 4A-4B show a three-dimensional view of a LaBr₃ array and the adjustable array angle (90°).

Figure 5 shows a plot from the National Institute for Standards and Technology (NIST) Photon Cross Section Database (XCOM) of photon interaction probabilities as a function of energy in lanthanum tri-bromide (LaBr₃).

Figure 6 shows a schematic diagram of an imaging detector system in accordance with the subject invention using a coded aperture mask.

Figure 7 shows a three-dimensional view of a second lanthanum tri-bromide (LaBr₃) radiation absorbing array adjustably spaced from a first lanthanum tri-bromide (LaBr₃) radiation scattering array, with the first lanthanum tri-bromide (LaBr₃) array also functioning as an active Coded Aperture mask element.

The figures may not be drawn to scale. Moreover, where directional terms (such as above, over, left, right, under, below, top, bottom, etc.) are used with respect to the illustrations or in the discussion, they are used for ease of comprehension only and not as limitations. The elements of the devices may be oriented otherwise, as readily appreciated by those skilled in the art.
DETAILED DISCLOSURE

Embodiments of the invention relate to a method and apparatus for measuring energy and incident angle of gamma radiation of an external source. Specific embodiments relate to a method and apparatus for gamma ray detection. Further embodiments relate to a method and device for directional imaging of gamma radiation. Embodiments of the subject invention can also be used for nuclide identification. Standard methods can be utilized, in conjunction with the detector materials and structures described herein, to accomplish isotope identification, where detector energy signals can be processed via electronics such as analog-to-digital converters and multi-channel analyzers. A gross count detector can also be implemented. Embodiments can incorporate a radiation scattering layer and a radiation absorbing layer.

In a specific embodiment, the radiation scattering layer includes a one-dimensional array of a plurality of scintillator detectors or the radiation absorbing layer includes a one-dimensional array of a plurality of scintillator detectors, where the radiation absorbing layer is spaced from the radiation scattering layer. In a specific embodiment, the radiation scattering layer includes a first two-dimensional array of a first plurality of scintillator detectors and the radiation absorbing layer includes a second two-dimensional array of a second plurality of scintillator detectors, where the radiation absorbing layer is spaced from the radiation scattering layer. In a specific embodiment, the spacing between the radiation absorbing layer and the radiation scattering is adjustable.

Specific embodiments incorporate lanthanum halide scintillator detectors in the first radiation absorbing layer and/or the second radiation absorbing layer. Examples of a lanthanum halide scintillator detector that can be utilized with embodiments of the invention include a lanthanum tri-bromide (LaBr₃) crystal scintillator detector and a lanthanum tri-chloride (LaCl₃) crystal scintillator detector. A specific embodiment, as shown in Figure 7, relates to a Compton imaging and radiation detector incorporating two lanthanum tri-bromide (LaBr₃) two-dimensional arrays. The arrays are nxn scalable substantially planar element arrays with lanthanum bromide (LaBr₃) cylindrical crystals having photomultiplier tubes. In a specific embodiment, n=8. Each detector can be monitored separately. Specific embodiments can incorporate photodiodes with the crystals. The detector crystals can have other cross-sectional shapes as well, such as square, rectangular, and hexagonal. In an exemplary embodiment, each layer of scintillator detectors is of fixed geometry and incorporates separate, relatively large-area crystals. In one embodiment, the crystal dimensions are 5.08 cm in diameter by 1.27 cm for the top or "scattering" layer, and 5.08 cm
in diameter by 5.08 cm for the bottom or "absorbing" layer. The separation between the layers is approximately 30 cm initially but is adjustable to enable fine-tuning of angular resolution and efficiency. The unit can operate with custom multi-channel signal shaping and read-out electronics.

Embodiments can be used, for example, for both Department of Homeland Security (DHS) and National Nuclear Security Administration (NNSA) nuclear emergency response radiation detection work, as well as medical imaging applications. Homeland Security related embodiments include portable, vehicle based or portal radiation monitoring, detection and identification systems. Embodiments can have the higher gamma-ray detection and nuclide identification performance than commonly used room-temperature gamma-ray detectors for DHS work. Moreover, a smaller package can be used and simultaneously provide imaging and directional capability. The higher Z of LaBr$_3$ can provide detectors with an efficiency 60% greater than detectors using NaI(Tl), a common detector material for DHS and NNSA applications. Specific embodiments can use crystals of sufficient size and thickness in both layers, and/or hybrid imaging routines, to provide gamma-ray detection, and/or imaging capability, in the energy range 0-20 MeV, which is often of interest for DHS applications and medical physics applications. Further embodiments can operate in the 0-3 MeV energy range. Specific embodiments operate in the 20 keV-5MeV range. Specific embodiments can provide imaging capability with a resolution of 0.1 radians. LaBr$_3$ can provide improved energy resolution as compared to NaI, for example, 3% at 662 keV for LaBr$_3$ compared to 6% with NaI. Thus, embodiments can provide a compact, fieldable unit with higher detection efficiency, better energy resolution, and position-sensitive imaging capability.

Embodiments of the subject device can detect radiation emanating from a source and can measure energy and angle of incident gamma radiation from the external source. Specific embodiments measure the quantity of radiation and provide spectral information. The two array layers, when operated in a summed mode, can provide high efficiency gamma-ray detection and spectral identification data by summing the individual crystals. The two layers can also be operated in coincidence mode (coincidence between layers) to provide angular and directional information.

As a specific embodiment, LaBr$_3$ can be used in a device in accordance with the subject invention for providing angular and directional information due to its excellent timing properties as compared to other high-efficiency room-temperature gamma-ray detector materials.
Medical physics embodiments include medical imaging of photons in the 0-20 MeV range. Medical imaging embodiments include 3-dimensional image reconstruction with proton therapy and other medical imaging applications. Specific embodiments using position sensitive LaBr₃ detectors can provide 3-dimensional image reconstruction of high energy photons from proton therapy as well in the energy range of 0 – 20 MeV, with a resolution of, for example, 5mm or less for 2 MeV photons.

In addition, other "4-pi" imaging techniques and/or subtraction and subtraction of interfering self-activation lines found in LaBr₃ can be accomplished using embodiments having the two-dimensional detector array geometry. The "4-pi" directional technique can be used in each detector. Other embodiments can use a solid layer for either the radiation scattering layer or the radiation absorbing layer.

A solid layer of LaBr₃ crystal, for example, a 3" x 3" crystal, can be used. Smaller individual crystals in an array layout can allow the system to be used for nuclide identification as well as gamma-ray detection and directional imaging.

LaBr₃ is superior to NaI for both gamma-ray detection (NaI has almost a factor of 2 lower detection efficiency for gamma-rays at 662 keV), LaBr₃ is superior for nuclide identification as it has a superior energy resolution (below 3% at 662 keV as compared to 6% or higher in NaI), and LaBr₃ also is superior for Compton imaging applications due to its much faster timing (18ns compared to 180 ns for NaI).

A Compton imager or "Compton camera" in accordance with embodiments of the subject invention can use a thinner radiation scattering layer detector thickness, oriented at the "top" of the system, or pointing toward the desired detection direction. The gamma-ray will scatter first in the detector of the radiation scattering layer, but not be completely absorbed or stopped in this detector as it is too thin. This allows the gamma-ray to enter the detector of the radiation absorbing layer where it scatters again, and is absorbed. The two scattering positions and partial energy loss in the first detector allow determination of its incoming angle or direction, and its absorption in the second thicker detector allows determination of its energy. A smaller spacing can increase the detection efficiency, the spacing can be adjusted in real time, depending on the situation.

Spacing of detectors and distance between the arrays, as well as the distance of the source, can affect both angular resolution and detection efficiency. Larger spacing between absorber and scatterer planes in general produce greater angular resolution. In specific embodiments, the spacing between the planes can be adjusted in real time to optimize resolution and efficiency for a specific source distance.
The Compton efficiency increases in general with radius of the detectors, but angular error can also increase with a larger error in position for larger detector (if non-position sensitive detectors are used). A larger spacing between detectors increases angular error and reduces efficiency. A larger spacing between detector planes in general reduces angular error (increases angular accuracy) but as a function of detector dimensions.

Position sensitive detectors can be used in the arrays. Such an array design can be implemented with either standard non-position sensitive detectors with photo-multiplier tubes (PMT's) and associated standard shaping and read-out electronics, or with position-sensitive detectors and a type of ASICs (Application Specific Integrated Circuit) electronics, for example having compact, multi-channel read-outs, and shaping electronics.

In "summed mode" the counts from all detectors can be read out at once, allowing the detectors to function like one large detector, for use with gamma-ray detection. For Compton imaging, a "coincidence" read-out between two or more detectors can be incorporated, where detector information is recorded if a trigger occurred within a given time window. This can allow read-out for detector hits related to a specific gamma-ray. Nuclide identification can be implemented in accordance with embodiments of the invention, using LaBr₃ as the detector material and can also utilize either single read-out of detectors or coincidence read-out.

Four-pi imaging techniques can be utilized and can use a single position-sensitive crystal for both scatter and absorber detector, to provide the gamma-ray direction and energy, thus allowing a solid angle or field-of-view of 4-pi. Imaging efficiencies may vary with incoming angle due to the dimensions of the crystal.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.
1. A device for detection of gamma radiation, comprising:
   a radiation scattering layer; and
   a radiation absorbing layer, the radiation absorbing layer being spaced from
the radiation scattering layer, wherein at least one of the radiation scattering layer and
the radiation absorbing layer comprises an array of scintillator detectors.

2. The device according to claim 1, wherein the radiation scattering layer
comprises a first two-dimensional array of a first plurality of scintillator detectors.

3. The device according to claim 2, wherein the radiation absorbing layer
comprises a second two-dimensional array of a second plurality of scintillator detectors.

4. The device according to claim 1, wherein the radiation absorbing layer
comprises a two dimensional array of a plurality of scintillator detectors.

5. The device according to claim 1, wherein the scintillator detectors are
lanthanum halide crystal scintillator detectors.

6. The device according to claim 1, wherein the scintillator detectors are
lanthanum tri-bromide crystal scintillator detectors.

7. The device according to claim 3, wherein the first plurality of scintillator
detectors and the second plurality of scintillator detectors are lanthanum halide crystal
scintillator detectors.

8. The device according to claim 3, wherein the first plurality of scintillator
detectors and the second plurality of scintillator detectors are lanthanum tri-bromide
crystal scintillator detectors.
9. The device according to claim 3, wherein a spacing between the radiation scattering layer and the radiation absorbing layer is adjustable.

10. The device according to claim 3, further comprising a photomultiplier tube associated with one or more scintillator detectors.

11. The device according to claim 3, further comprising a photodiode associated with one or more scintillator detectors.

12. The device according to claim 1, wherein the radiation scattering layer comprises a first one-dimensional array of a first plurality of scintillator detectors.

13. The device according to claim 12, wherein the radiation absorbing layer comprises a second one-dimensional array of a second plurality of scintillator detectors.

14. The device according to claim 1, wherein the radiation absorbing layer comprises a first one-dimensional array of a first plurality of scintillator detectors.

15. The device according to claim 3, wherein the device detects gamma radiation in the energy range of 0-3 MeV.

16. The device according to claim 3, wherein the device detects gamma radiation in the energy range of 0 keV - 5MeV.

17. The device according to claim 3, wherein the device detects gamma radiation in the energy range of 0-20 MeV.

18. The device according to claim 3, wherein the device detects gamma radiation in the energy range of 20 keV - 5MeV.

19. The device according to claim 3, further comprising a means for measuring energy of a gamma radiation photon and an incident angle of the gamma radiation
photon with respect to the scintillator detector of the radiation scattering layer the
gamma radiation photon is incident to.

20. The device according to claim 19, wherein the means for measuring energy
and incident angle of the gamma radiation photon incident the scintillator detector of the
radiation scattering layer comprises a means for detecting a first amount of energy lost by the
gamma radiation photon in the radiation scattering layer and a means for detecting a second
amount of energy lost by the gamma radiation photon in the radiation absorbing layer.

21. The device according to claim 20, wherein the means for measuring energy
and incident angle of the gamma radiation photon incident the scintillator detector of the
radiation scattering layer further comprises:

a means for determining the coincident gamma radiation photon's interaction
between the radiation scattering layer and the radiation absorbing layer;

a means for determining a first position of the first two-dimensional array
where the first amount of energy was absorbed; and

a means for determining a second position of the second two-dimensional
array where the second amount of energy was absorbed.

22. The device according to claim 20, wherein the means for measuring energy
and incident angle of the gamma radiation photon incident the scintillator detector of the
radiation scattering layer determines the incident angle, via the following
equation:

\[
\cos \theta_i = 1 + m_e c^2 \left( \frac{1}{E_\gamma} - \frac{1}{E_i} \right)
\]

where \( \theta_i \) is the Compton scattering angle of the incident gamma radiation photon, \( E_i \)
is the energy of the scattered gamma radiation photon after scattering from the radiation
scattering layer, \( m_e \) is the mass of an electron, \( c \) is the speed of light, and \( E_j \) is the energy of
the incident gamma radiation photon \( (E_\gamma - AE_i + \Delta E_2) \), where \( \Delta E_i \) is the first amount of
energy and \( \Delta E_2 \) is the second amount of energy.
23. The device according to claim 19, further comprising:
   a shielding element having a mask pattern, wherein the shielding element is positioned such that the gamma radiation incident on the device passes through the shielding element prior to incidenting on the radiation absorbing layer; and
   a means of determining a shift of the mask pattern relative to a central position, wherein the incident angle of the gamma radiation angle of the gamma radiation incident on the device is determined from the shift of the mask pattern relative to the central position.

24. The device according to claim 23, wherein the radiation scattering layer is the shielding element.

25. The device according to claim 1, wherein a spacing between the radiation scattering layer and the radiation absorbing layer is adjustable.

26. A method for detection of gamma radiation, comprising:
   locating a radiation scattering layer in a region of interest; and
   locating a radiation absorbing layer in the region of interest, wherein the radiation absorbing layer is spaced from the radiation scattering layer, wherein at least one of the radiation scattering layer and the radiation absorbing layer comprises an array of scintillator detectors.

27. The method according to claim 26, wherein the radiation scattering layer comprises a first two-dimensional array of a first plurality of scintillator detectors.

28. The method according to claim 27, wherein the radiation absorbing layer comprises a second two-dimensional array of a second plurality of scintillator detectors.

29. The method according to claim 26, wherein the radiation absorbing layer comprises a two dimensional array of a plurality of scintillator detectors.

30. The method according to claim 26, wherein the scintillator detectors are lanthanum halide crystal scintillator detectors.
31. The method according to claim 26, wherein the scintillator detectors are lanthanum tri-bromide crystal scintillator detectors.

32. The method according to claim 28, wherein the first plurality of scintillator detectors and the second plurality of scintillator detectors are lanthanum halide crystal scintillator detectors.

33. The method according to claim 28, wherein the first plurality of scintillator detectors and the second plurality of scintillator detectors are lanthanum tri-bromide crystal scintillator detectors.

34. The method according to claim 26, wherein a spacing between the radiation scattering layer and the radiation absorbing layer is adjustable.

35. The method according to claim 28, wherein a spacing between the radiation scattering layer and the radiation absorbing layer is adjustable.

36. The method according to claim 28, wherein further one or more scintillator detectors comprise a photomultiplier tube.

37. The method according to claim 28, wherein further one or more scintillator detectors comprise a photodiode.

38. The method according to claim 26, wherein the radiation scattering layer comprises a first one-dimensional array of a first plurality of scintillator detectors.

39. The method according to claim 38, wherein the radiation absorbing layer comprises a second one-dimensional array of a second plurality of scintillator detectors.

40. The method according to claim 26, wherein the radiation absorbing layer comprises a first one-dimensional array of a first plurality of scintillator detectors.
41. The method according to claim 28, wherein the method detects gamma radiation in the energy range of 0-3 MeV.

42. The method according to claim 28, wherein the device detects gamma radiation in the energy range of 0 keV—5MeV.

43. The device according to claim 28, wherein the device detects gamma radiation in the energy range of 0-20 MeV.

44. The method according to claim 28, wherein the device detects gamma radiation in the energy range of 20 keV - 5MeV.

45. The method according to claim 28, further comprising measuring energy of a gamma radiation photon and an incident angle of the gamma radiation photon with respect to the scintillator detector of the radiation scattering layer the gamma radiation photon is incident to.

46. The method according to claim 45, wherein measuring energy and incident angle of the gamma radiation photon incident the scintillator detector of the radiation scattering layer comprises detecting a first amount of energy lost by the gamma radiation photon in the radiation scattering layer and detecting a second amount of energy lost by the gamma radiation photon in the radiation absorbing layer.

47. The method according to claim 46, wherein measuring energy and incident angle of the gamma radiation photon incident the scintillator detector of the radiation scattering layer further comprises:
   determining the coincident gamma radiation photon's interaction between the radiation scattering layer and the radiation absorbing layer;
   determining a first position of the first two-dimensional array where the first amount of energy was absorbed; and
   determining a second position of the second two-dimensional array where the second amount of energy was absorbed.
48. The method according to claim 46, wherein measuring energy and incident angle of the gamma radiation photon incident on the scintillator detector of the radiation scattering layer determines the incident angle, via the following equation:

\[
\cos \theta_i = 1 + \frac{m_e c^2}{E} \left( \frac{1}{E_y} - \frac{1}{E_1} \right)
\]

where \( \theta_i \) is the Compton scattering angle of the incident gamma radiation photon, \( E_1 \) is the energy of the scattered gamma radiation photon after scattering from the radiation scattering layer, \( m_e \) is the mass of an electron, \( c \) is the speed of light, and \( E_y \) is the energy of the incident gamma radiation photon \( (E_y = \Delta E_1 + \Delta E_2) \), where \( \Delta E_1 \) is the first amount of energy and \( \Delta E_2 \) is the second amount of energy.

49. The method according to claim 45, further comprising:

a shielding element having a mask pattern, wherein the shielding element is positioned such that the gamma radiation incident on the device passes through the shielding element prior to incidenting on the radiation absorbing layer; and

a means of determining a shift of the mask pattern relative to a central position, wherein the incident angle of the gamma radiation angle of the gamma radiation incident on the device is determined from the shift of the mask pattern relative to the central position.

50. The method according to claim 49, wherein the radiation scattering layer is the shielding element.
FIG. 1 (prior art)
Adjustable Array Angle (3-D Rotation)

FIG. 4A
FIG. 5