Vol 17 No 12, December 2008
1674-1056/2008/17(12)/4466-06

Chinese Physics B

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A new method for detecting pulse gamma ray with scattered electrons

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(Received 19 January 2008; revised manuscript received 22 April 2008)

This paper describes a newly designed gamma pulse detector of current mode that uses the scattered electron method. Tungsten is used as the scattering target, an organic thin film scintillator ST401 is used to collect the scattered electrons. The spatial distribution of the electronic energy-flux density is studied by using the MCNP code. The optimization of the target and the thickness of the scintillator are also discussed. The results indicate that the energy response is relatively flat in the range of 0.4 to 5 MeV.

Keywords: scattering, electron, gamma, response
PACC: 0785, 2940M

1. Introduction

With the development of various pulse power devices, such as the nuclear weapon, pulse power accelerator, pulse power reactor, and pulse x-ray sources, the development of pulse radiation detectors becomes increasingly important[1−3]. The durations of the pulse are typically sub-microsecond or even short, and the number of gamma particles can be $10^{10}-10^{20}$ or more per pulse, so the intensity of the gamma or x-ray pulse can be more than $10^{20}\gamma$/s, even more than $10^{30}\gamma$/s. Under this condition, many traditional gamma detectors, such as ionization chamber and proportional counter, cannot work. Because the gamma ray cannot be detected separately, the detectors should work in current mode instead of counting mode.[4,5] Accordingly, the sensitivity is defined as the ratio of the output current to the particle fluence rate, the convenient unit is $\mathrm{A}/(\gamma\cdot\mathrm{s}^{-1}\cdot\mathrm{cm}^{-2})$. While in the counting mode, the sensitivity is often defined as the particle detecting efficiency. Another character for pulse detecting is that, during the pulse time, the energy of the gamma ray is not definite but dispersed, the energy spectrum and the average energy are changing and can not be clearly known. If we need to measure the absolute fluence rate in different time, the sensitivity of the detector should be independent of energy. When the sensitivities are the same for gamma ray with different energy, we say that the detector has a flat energy response. For this reason, the absolute measurement of fluence is challenging.[6] However, the generally used gamma ray detectors of current mode, such as scintillation detectors,[7] Compton diodes,[8] semiconductors[9,10] and so on can not meet this requirement. The sensitivity variations of such detectors differ by several times or even an order of magnitude with the concerned energy range of 0.2 to 5 MeV. It is difficult to measure the absolute gamma fluence with existing detectors, much effort is applied to improve the energy response.

2. New structure design

Based on the characters of the interaction between gamma rays and materials, a new method with relatively flat energy response in the range of 0.4MeV to 5MeV is designed. The structure of the new designed detector is shown in Fig.1.

The detector is composed of scattering targets, incident and exit windows, sweeping magnets, thin film scintillators, and photoelectric devices such as photomultiplier tubes (PMT). The windows are made of an aluminium foil of 20–50 μm. The intensity of the sweeping magnetic field is about 2000 Gs. The target is hung to the target frame with fine wire, whose effect

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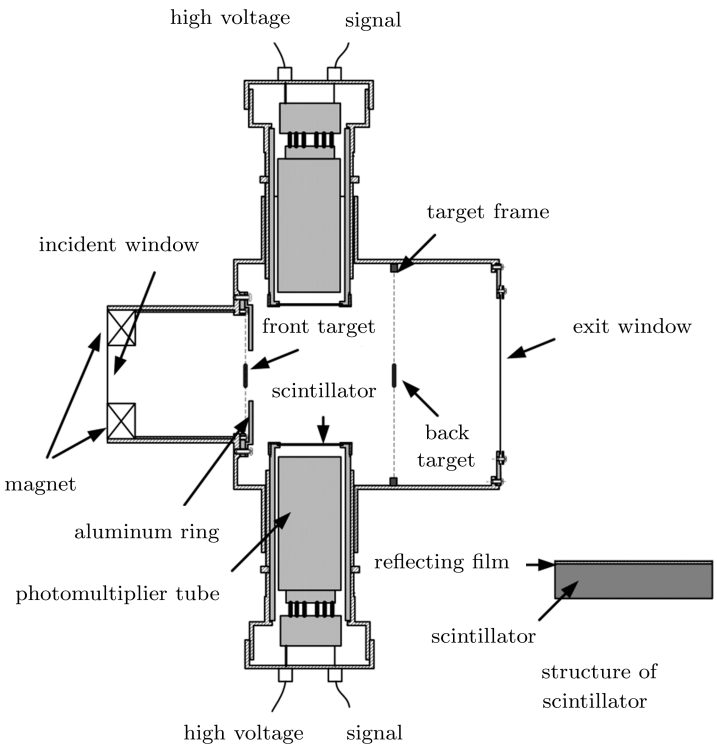


Fig.1. Schematic diagram of the scattering electron detector.

is negligible and from which the targets can release the accumulated charge. An aluminium panel as a whole in the centre is used as an electron diaphragm so as to reduce the effects of air. A reflecting plastic film is used to increase the collecting efficiency of scintillation photons.

When a collimated parallel beam of gamma rays passes through the detector, the electrons produced by the Compton and photoelectric effects in the incident window are swept out by the magnets. Abundant electrons, including photoelectrons, Compton electrons, and Auger electrons, are ejected from the targets when the gamma rays interact with them. Their directions are diversified by multiple Coulomb scattering. Some of the scattered electrons reach the scintillator and transfer part of their energy to the thin film scintillator, and the resulting scintillation is transformed into an electric signal by a PMT. Scattered gamma rays can also be collected and can also deposit energy in the scintillator, though their contribution is about one to two orders of magnitude lower than that of the electron. As the effect of gamma-electron transformation is relatively low, typically 10^{-4} to 10^{-3} for most thin target, the sensitivity of the detector is low. It is therefore suitable for intense pulse gamma ray detection.

A simplified mathematical model is established based on the structure of the detector. The optimal target and scintillation materials were calculated using the MCNP 4C code[11].

The detector uses a ST401 organic scintillator. The light yield of the organic scintillator is proportional to the energy deposited by the electrons when the electron energy is higher than 0.1 MeV according to Birks' formula[12]. Therefore, the curve of energy deposition will be the same as that of the energy response.

3. Spatial distribution of electron energy flux density

When gamma rays pass through the detector, electrons are also generated by the interaction between gamma rays and the air. These electrons are not needed, therefore the effect of the air should be considered. The distributions of electrons that are generated from air and from the target are different. We can arrange the scintillator and the target in a suitable position to reduce the effect of the air.

Suppose that a beam of parallel gamma ray with evaporation spectrum injects, we have calculated the electron energy flux density within the whole volume.

The distribution isograms are shown in Figs.2 and 3. From the isograms, we can compare the differences of target and air. In order to evaluate the effect of the air, the density ratios of target to the air are calculated which are shown in Fig.4.

According to the charts, we can select the appropriate position. Here, the distance between the scintillator surface and the gamma beam is 6 cm, the distance from the axis of the scintillator to the target is 5 cm. In this position, the density ratios are more than 50, then the effect of the air is less than 3 percent.

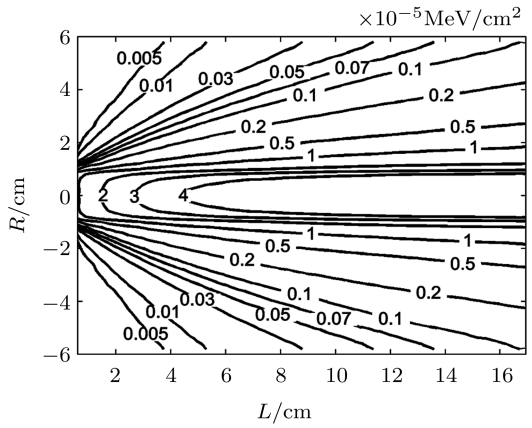
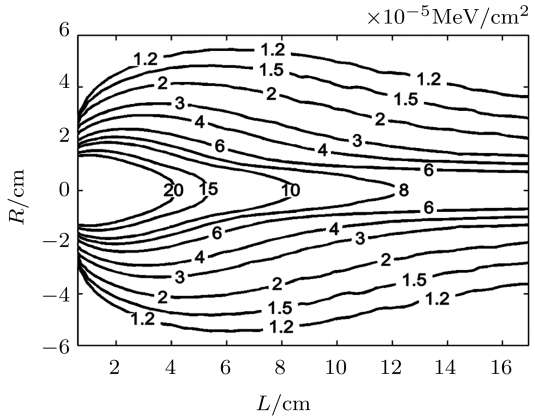
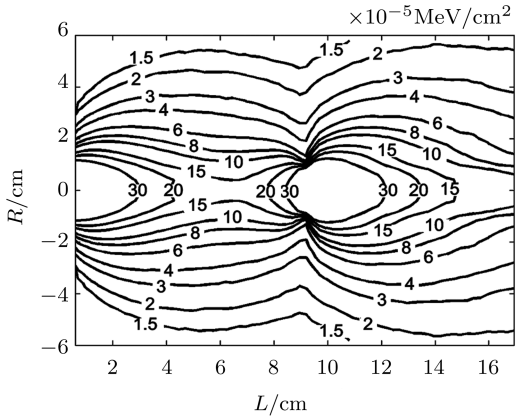


Fig.2. Distribution of electron energy flux density induced by the air.

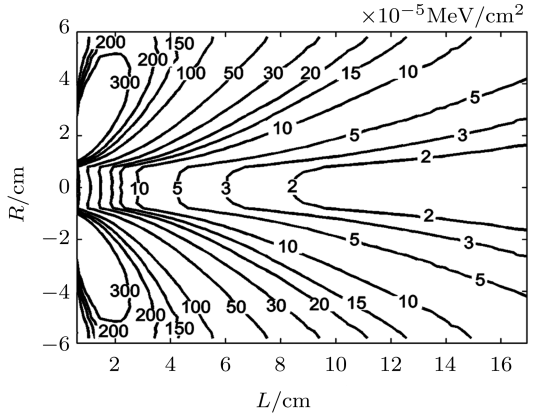


(a) Single target

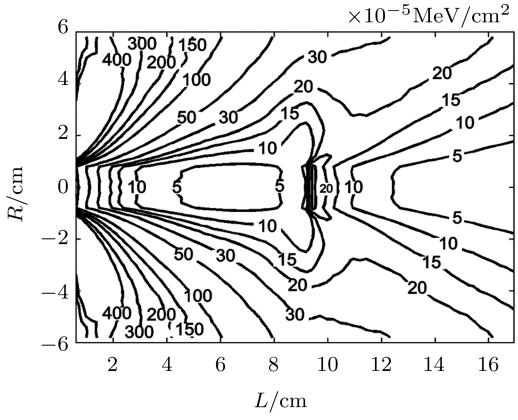


(b) Double targets

Fig.3. Distribution of electron energy flux density induced by the tungsten target.



(a) Single target/air



(b) Double targets/air

Fig.4. Electron energy flux density ratios of target to air.

4. The spectrum of the scattered electrons

When gamma rays with different energy inject, the spectra of scattered electrons are different. The scattered electrons with emergent angle range of 30 to 60 degree are calculated with two typical materials, graphite and tungsten. The results are shown in Fig.5.

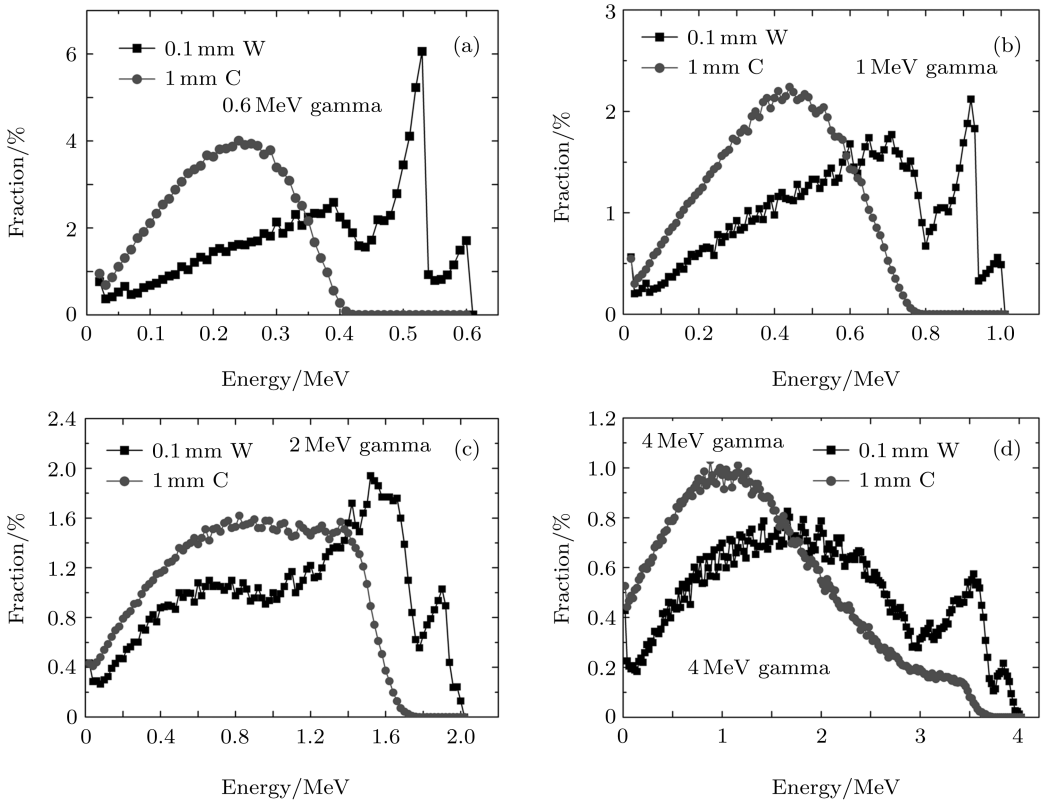


Fig.5. The spectrum of scattered electrons (emergent angle: 30–60 degree).

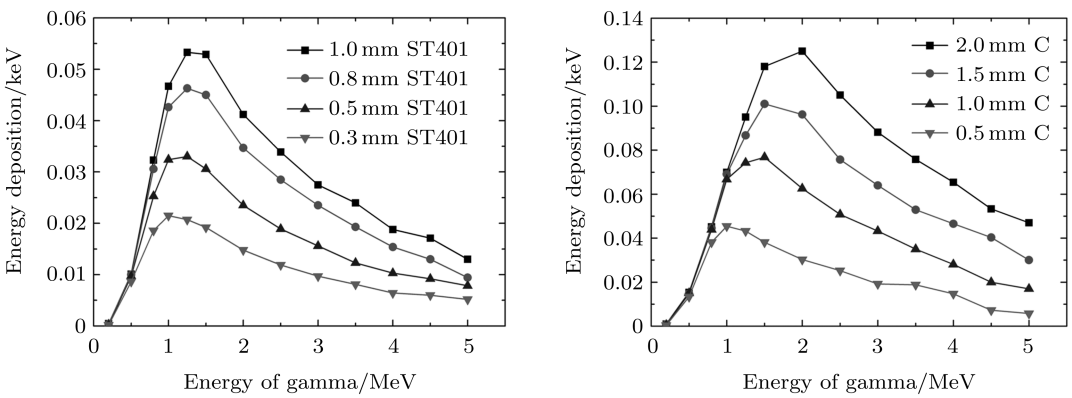
5. Optimization of the target

In order to make the energy response flat, we calculated the energy deposition curves with different kinds of targets, such as graphite, tungsten, aluminium, ferrum, nickel, and so on. For each target, the energy responses of different thickness are compared.

The energy responses of graphite are shown in Figs.6(a) and 6(b). The energy responses with nickel, aluminium and ferrum target are shown in Fig.7.

The energy responses with tungsten target are shown in Figs.8(a) and 8(b).

Typically normalized energy responses of four targets are drawn together in Fig.9.



(a) 1 mm fixed graphite target (b) 1 mm fixed ST401

Fig.6. Energy responses with graphite target.

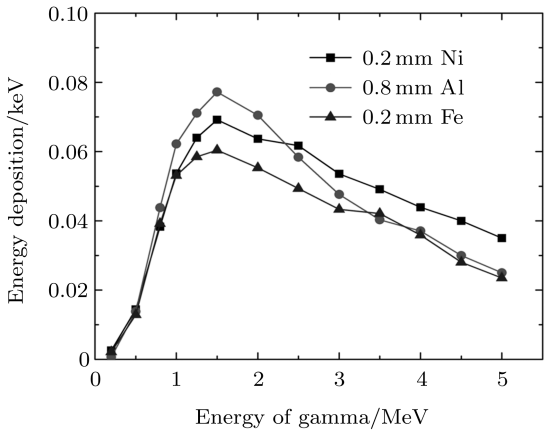
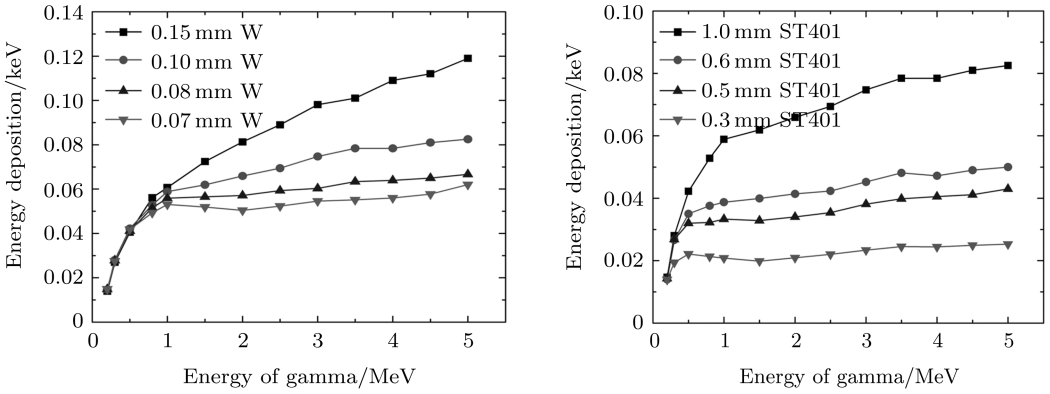


Fig.7. Energy response for Ni/Al/Fe target (scintillator thickness 1 mm).

We can conclude that, in the energy range of 0.2 to 5MeV, the energy response with high Z material targets is much flatter than that with low and middle Z material targets. For high Z material, the main effect is photoelectric effect when the gamma ray energy is below 0.4MeV, and the main effect will be photoelectric and Compton effect when the energy is 0.4 to 1 MeV; when the energy is 1 to 4 MeV, the Compton and pairs effect will be the most important.

In order to collect more electrons and to flatten the response, two tungsten targets are placed parallel with a distance of 10 cm. The optimized energy responses for single and double targets are obtained. the results are shown in Fig.10.

The optimized response with double targets is flatter than that with single target. In the energy range of 0.4 to 5 MeV, the sensitivity variation is less than 10%.



(a) 0.1 mm fixed tungsten target (b) 1 mm fixed ST401

Fig.8. Energy responses with tungsten target.

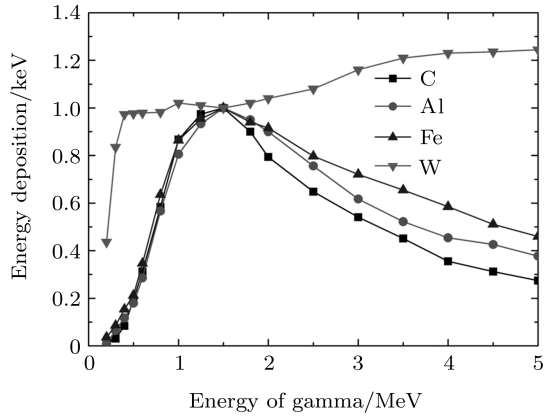


Fig.9. Normalized responses of four targets (scintillator thickness 1 mm).

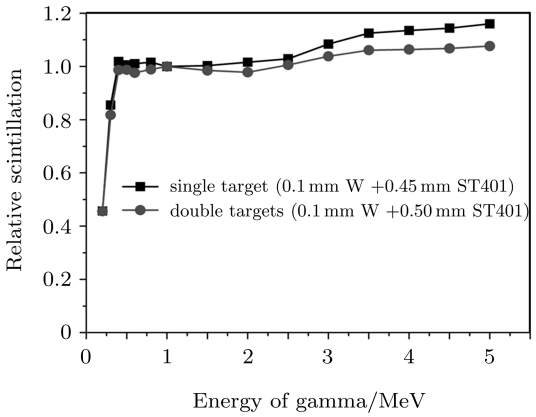


Fig.10. Optimized responses with single and double tungsten targets.

6. Comparison with traditional scintillation method

For traditional scintillation method of current mode, the scintillators are placed directly in the gamma beam.[13] The energy response is mainly determined by the energy deposition in the scintillator. The response curves are different with varied thickness. The same ST401 organic scintillator is used as the example. The features of other scintillators are similar. The energy response curves with different thickness are compared and the results are shown in Fig.11.

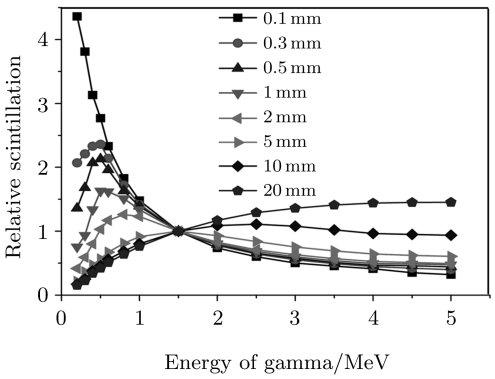


Fig.11. Energy response with traditional method (ST401).

Using traditional scintillation method, we are difficult to flatten the response in the concerned energy range whether with the thin or thick scintillators.

7. Conclusions

Due to the structure design, the optimization of target material and the thickness of the scintillator, our proposed detector is able to obtain a flat energy response in the range of 0.4 to 5 MeV. Using double targets structure, we find that the response is much flatter than with single target. Because the particle transformation efficiency of the target is low, the sensitivity is 2 to 3 orders of magnitude lower than traditional scintillation detectors. The detector is suitable for detecting intense pulse gamma rays, the shielding and collimation is crucial. In order to improve the performances of the detector, more works are needed. Other properties, such as the time response and the gamma-neutron discrimination, need to be investigated theoretically and experimentally.

Acknowledgments

We are grateful to Song Zhaohui, Zhang Zhongbing and Han Hetong for their valuable advice and thank the gamma team of the Northwest Institute of Nuclear Technology for sincere help.

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