Scattering-absorbing method for the detection of 16.7 MeV high-energy pulse gamma

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Abstract: Based on theoretical calculation and Monte Carlo simulation, this paper proposes a new method for the diagnosing of 16.7 MeV high-energy pulse gamma, named "scattering absorption method". The ratio of the sensitivity of high-energy gamma to that of the low-energy background gamma can reach 10^6 to 10^8 by this new method. The sensitivity of 16.7 MeV high-energy gamma ranges from 10^{-21} to 10^{-16} C• cm^2. It's better than the traditional method which is based on the magnetic analyzer and Cherenkov detector on some aspects.

Key words: high-energy gamma; Cherenkov detector; scattering absorption method

1 Introduction

The 16.7 MeV high-energy pulse gamma ray generated by DT reaction is ideal for the reaction-history diagnosis. However, the low-energy background gamma ray emitted by the other reactions is extremely intense sometimes. The background gamma ray is 2 MeV on average, and their flux is expected to be several orders of magnitude larger than the peak flux of 16.7 MeV gamma[1]. In order to measure the 16.7 MeV gamma ray, the detector should be insensitive to the background gamma rays.

Traditionally, the system composed of Cherenkov detector and specific bending magnet has been used to measure the 16.7 MeV high-energy gamma[1-4], whose ratio of signal-to-noise achieves $10^5 \sim 10^6$. However, the big dimension and complex magnet-adjusting-process make it not convenient. Moreover, the ratio of signal-to-noise is un-adjustable. It means such system can't handle much more intense background. This paper proposes a new method named "scattering absorption method (SAM for short)". The SAM overcomes the traditional system's defects, and is convenient for the 16.7 MeV high-energy gamma measurement.

2 The principle of SAM

Considering about the energy is $0.5 \sim 3$ MeV, the background gamma rays interact with the materials which they pass through mainly by Compton scattering process. The gamma rays will be scattered to an angle φ relative to its original direction. The lower of the energy, the larger φ will the gamma be scatted to. Meanwhile, the cross section of Compton scattering is inverse to the energy of gamma ray. It means that much more of the high-energy gamma will penetrate the material relative to the background gamma ray.

Supposing that the gamma ray will be scattered away from the original beam direction once it interacts with the material. The penetrating probability of the high-energy gamma and low-energy background gamma is $P_H(l)$ and $P_L(l)$, where l is the thickness of the material. Define the ratio of $P_H(l)$ and $P_L(l)$ as "separating ability" of the medium. $P_{HL}(l) \equiv P_H(l)/P_L(l)$. Define the separating ability achieved by each times of attenuation of high-energy gamma as ζ.

$\zeta \equiv P_{HL}(l)/[1/P_H(l)] = P_{HL}(l)P_H(l)$, then

$$P_H(l) = \exp(-\frac{\sigma_H N_A}{A}\rho l) \tag{1}$$

$$P_L(l) = \exp(-\frac{\sigma_L N_A}{A}\rho l) \tag{2}$$

$$P_{HL}(l) = \exp(\frac{\rho N_A(\sigma_L - \sigma_H)}{A} \times l) \equiv \exp(\mu_{HL} l) \tag{3}$$

$$P_H(l) = [P_{HL}(l))^{-\frac{\sigma_H}{\sigma_L-\sigma_H}} \equiv [P_{HL}(l)]^{-\varepsilon} \tag{4}$$

$$\zeta = \exp(\frac{\rho N_A}{A}(\sigma_L - 2\sigma_H)l) = \exp(\eta_{HL} l) \tag{5}$$

Where, σ_H and σ_L are the total micro cross section of high energy gamma and low energy background gam-

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ma. The ρ and A is the density and atomic number of the medium. N_A is the Avogadro constant. Define $\mu_{HL} \equiv (\sigma_L - \sigma_H)\rho N_A / A$ as the relative penetrating factor of high-energy gamma and low-energy background gamma. Define $\varepsilon \equiv \sigma_H / (\sigma_L - \sigma_H)$ as the preserving factor of high-energy gamma. Define $\eta_{HL} \equiv (\sigma_L - 2\sigma_H)\rho N_A / A$. The larger η_{HL} of the medium, the easier to separate high-energy gamma from the background gamma. Table 1 shows the value of μ_{HL} , ε and η_{HL} for some media. These values are calculated for the 16.7 MeV high-energy gamma and 2 MeV low-energy background gamma. Obviously, the graphite has the largest value of η_{H} , and is the best scattering material.

Table 1 Value of μ_{HL} , ε and η_{HL} for some media

Media	ρ /(g· cm^{-3})	μ_{HL}	ε	η_{HL}
Liquid H_2	0.078	5.04E-3	0.369	3.20E-3
$(CH_2)_n$	0.92	1.69E-2	0.521	8.09E-3
Li	0.535	1.40E-2	0.449	7.71E-3
Be	1.848	4.89E-2	0.490	2.49E-2
C	2.267	6.38E-2	0.582	2.63E-2
Fe	7.86	8.87E-1	2.771	-1.57

Generally, the gamma ray needs to be converted to charged particle, such as electron or positron, before it can be detected. The energy of most of the secondary electron or positron generated by low-energy background gamma is much smaller than that by high-energy gamma. So the secondary electron or positron generated by low-energy gamma is much easier to be stopped (or absorbed) when traveling in the material. It means that the effect of the low-energy background gamma will be restrained if we put some appropriate absorbing material in front of the sensitive cell (scintillant for example). Beware of the scatted background gamma rays, which will penetrate the absorbing material and interact with the sensitive cell. So, the dimension and position of sensitive cell should be designed specially to reduce the interference induced by the scattered background gamma.

Fig. 1 illustrates the sketch of the detector system. The system is composed of scattering part and detecting part. The scattering-stick scatters the low-energy background gamma away from the beam direction. Gamma to electron or positron transforming process is accomplished by the converter. In order to get high transforming efficiency, choose 0.1 mm thickness tungsten as converter. According to the theoretical calculation, the scattering angle of 2 MeV gamma-ray peaks at 23°. So the detecting angle of the secondary electron or positron generated by high-energy gamma is optimized between 2° and 8° to restrain the interference by low-energy gamma. Fast plastic scintillant ST401 is chosen to detect the secondary electrons. Considering the energy and emitting angle of the secondary electrons, the ST401 is cone-shaped and 2.5 cm thick in axis direction. In order to stop the low-energy electron by ionization process as more as possible, the atomic number of absorber material should be very small. According to the MonteCarlo simulation result, 10 mm Polythene (PE) can accomplish the low-energy electron absorption.

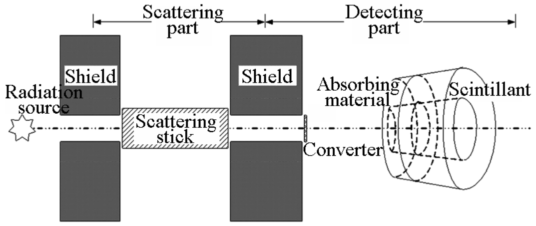

Fig. 1 Sketch of scattering absorption method

3 Theoretical simulation

To get high ratio of signal-to-noise, the detecting efficiency of the low energy gamma ray must be very low. As result, it's not easy to simulate the radiation transporting process in the whole system. This paper will simulate the scattering part and detecting part separately.

3.1 Simulation of scattering part

Because of the cumulating effect, the penetrating-probability and separating-ability calculated by Eq.(1) ~ Eq.(3) are not precise enough. According to the Monte-Carlo simulation by MCNP4C, Table 2 lists the length of the graphite to achieve different separating ability P_{HL}. For example, when the length of graphite varies from 107.0 cm to 177.9 cm, the separating ability grows from 10^3 to 10^5, and the penetrating probability of high-energy gamma (P_H) decreases from 1.88×10^{-2} to 1.30×10^{-3}.

Table 2 Parameter of detector for different P_{HL}

P_{HL}	Length of graphite/cm	P_H
10^3	107.0	1.88E-2
10^4	142.0	4.94E-3
10^5	177.9	1.30E-3
10^6	213.9	3.42E-4

3.2 Simulation of detecting part

Basing on the model sketched by Fig. 1, the detector sensitivity to gamma and neutron, and the time responding are calculated by Geant4.

3.2.1 Gamma and neutron sensitivities

Fig. 2 illustrates the average energy deposition in the scintillant by each gamma or neutron, which injects vertically on the converter. According to Fig. 2, regardless of the difference of scintillation process and the light collecting process induced by particle energy, the detector sensitivity to 16.7 MeV gamma is almost 900 times bigger than that to 2 MeV gamma. The detecting efficiency to 16.7 MeV gamma is about 3.6×10^{-3}, while it's about 3.1×10^{-5} to 2 MeV gamma.

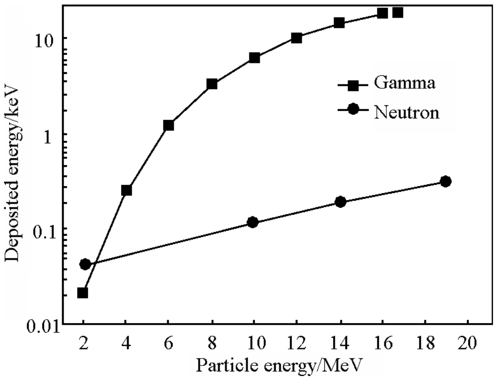

Fig. 2 Sensitivity curve of gamma and neutron

According to Fig. 2, the energy deposition by each 14.1 MeV neutron is about 100 times smaller than that by 16.7 MeV gamma ray. It means that the detector should avoid the neutron influence by the other technical method, such as TOF (time of flight)[5].

3.2.2 Time responding

Simulation code follows the time history of secondary particle generated by gamma-ray with different energy, and record the time spectrum of energy deposition (Fig. 3, where the time zero is the time when the gamma-ray arrive the converter).

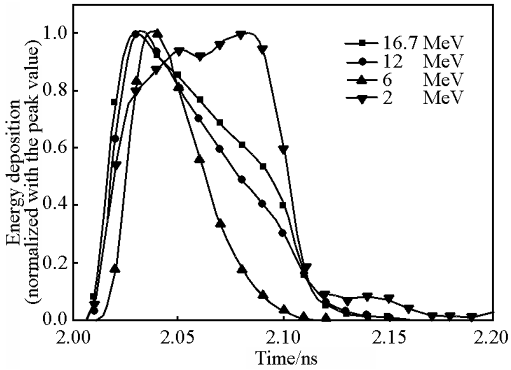

Fig. 3 Time spectrum of energy deposition (peak normalized)

According to Fig. 3, the energy deposition process accomplishes within 0.1 ns. The rising edge is very sharp and almost rises at the same time. It proves that the radiation converting process, the divergence of the flight time of the secondary particles, and the absorbing material is negligible to the responding time. By choosing fast scintillant, such as BC422, it's compatible to the fusion diagnosing[6]. Notice that the time spectrum of 2 MeV gamma is relative flat. That's because most of the energy deposition are contributed by secondary gamma, the time distribution width is almost equal to the flight time of the gamma ray in the scintillant (about 0.08 ns).

4 Conclusion

The scattering absorption method is composed of scattering part and detecting part. The graphite is chosen as scattering material to separate 16.7 MeV high energy gamma rays from 2 MeV background gamma rays. By varying the length of the graphite, this method can handle different background level. The signal-to-noise ratio provided by the detecting part achieves 900. Cooperating with 110 cm or 180 cm graphite, the total signal-to-noise ratio by this scattering absorption method achieves 10^6 or 10^8. By choosing photoelectric tube or photomultiplier tube whose enlargement factor is 10^5, the detector sensitivity to the high energy gamma is $10^{-21} \sim 10^{-16}$ C· cm^2.

The energy deposition process accomplishes with 0.1 ns theoretically, regardless of the energy of the incident gamma energy. So, by choosing fast scintillant and fast photoelectric tube, the system responding time can achieve nanosecond or subnanosecond.

5 Discussion

Based on the interaction characteristics between gamma (or electron) and material, the scattering absorption method can be used for high energy pulse gamma diagnosing within extensive low energy background. The structure of such system is simple. Moreover, it can handle different background levels. There is no doubt that the adjustable high signal-to-noise ratio and fast responding time makes it to be a competitive candidate for the high energy pulse gamma diagnosing.

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References

[1] Ye Yuyun, Chen Hande, He Xijun et al. The measurement of 16.7 MeV γ ray from d-T reaction for ns duration[J]. Atomic Energy Science and Technology, 1996, 30(2): 127-133. (in Chinese)

[2] Moran M J. The fusion diagnostic gamma experiment: a high-bandwidth fusion diagnostic of the national ignition facility[J]. Rev. Sci. Instrum., 1999, 70(1):1226-1228.

[3] Caldwell S E, Berggren R R. Observation of d-t fusion gamma rays (invited)[J]. Rev. Sci. Instrum., 2003, 74(3): 1837-1841.

[4] Brolley J E, Ladish J S, et al. A gas Cerenkov detector for measuring 16.7-MeV gamma rays from the D(T, γ)5He reaction[R]. 1983. LA-UR-83-1864.

[5] Wu Zhihua, Zhao Guoqing, Lu Fuquan, et al. Experimental Approaches of Nuclear Physics[M]. Beijing: Atomic Energy Press, 1997. (in Chinese)

[6] Lerche R A, Phillion D W, Tietbohl G L, et al. 25 ps neutron detector for measuring ICF-target burn history[J]. Rev. Sci. Instrum. 1995, 66(1): 933-935.

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