Influence of Particle Incidence Angle on the Detection Efficiency of Plastic Scintillator Detector

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Abstract. When the scintillation detector is used to identify particles and position the location of radioactive source or other particle emitters, the detection efficiency has an important influence on the experimental results, and the incident angle of the particle entering the scintillation detector will affect the detection efficiency of the detector, furthermore affect the precision of positioning. In order to analysis the effect of detection efficiency due to the difference of incidence angles, this paper analysis the influence of the incidence angle for EJ299-33A plastic scintillator with size 6 (mm) × 6 (mm) × 130 (mm), under the simulation, 2 MeV source radioactive particles entering the detector at different incident angles. By the simulation, it is finding that when the incident angle of particles increases gradually from 0° to 90° in the same plane, the detection efficiency increases rapidly at 0°~30° and decreases gradually at 30°~90°. Furthermore, through the analysis of different detection efficiency in different planes, it is founded that the maximum detection efficiency lies on the plane where the azimuth angle is 0° or 90°. And through the experiment test, the detection efficiency obtained from simulation is agreed to the experimental test in the X-Z plane. Finally, we can conclude that when the incidence angle of the particle between 20°~30° and the azimuth angle is 0° or 90°, the detection efficiency reaches the highest. This conclusion can be applied to experiments such as particle identification and positioning of undiscovered radioactive source.

1. Introduction
Plastic scintillators have very important applications in radiation measurement of high-intensity pulses due to their high transparency, good light transmission performance, corresponding fast time, radiation resistance, easy processing and so on [1]. For a finished plastic scintillator detector, when testing particle identification is in an experimental test, it should improve its detection efficiency as much as possible, thereby enhancing its ability to identify particles, in addition to optimizing the hardware design, reducing noise, and improving software in addition to the screening ability of the true events[2], the angle at which the particle is incident on the scintillator also has a significant effect on the detection efficiency.

In the simulation, the scintillator selected is EJ299-33A plastic scintillator produced by EJ Company of USA. From Table 1, it can be concluded that EJ299-33A is mainly composed of C and H, which is a kind of plastic scintillator with both optical output, luminous efficiency and scintillation attenuation time technical index. The radioactive source is point source of 2 MeV, which is isotropic. With the increase
of the distance between the detector and the radioactive source, the detection efficiency will decrease gradually. In order to eliminate the influence of the distance on the detection efficiency, the relative distance between the radioactive source and the detector should be kept constant in the experiment.

Table 1. Physical properties of EJ299-33A plastic scintillator [3]

| Property                        | Value                                      |
|---------------------------------|--------------------------------------------|
| Light output                    | Equivalent to 56% of anthracene            |
| Luminescent efficiency          | 8600 photons/1 MeV e⁻                      |
| Maximum emission wavelength     | 420nm                                      |
| Number of hydrogen atoms per cubic meter | 5.13×10^{22}                              |
| Number of carbon atoms per cubic meter | 4.86×10^{22}                              |
| Number of electrons per cubic meter | 3.55×10^{22}                              |
| Density                         | 1.08g/cm³                                  |

Monte Carlo method, also known as random sampling technique or statistical experiment, is a computational method based on the theory of probability and statistics. It can describe the characteristics and physical process of the experimental model in a realistic way. It has been widely used in particle transport process[4]. MCNP is a Monte Carlo simulation tool for describing the geometric characteristics of detectors and particle tracking. It can define the geometric structure and material composition of detectors, and can accurately simulate the interaction between particles emitted from radioactive sources and EJ299-33A plastic scintillators. The number of particles interacting with the detector, particle energy deposition and other information can be obtained [5,6].

2. Simulation calculation

2.1. Analysis of detector’s detection efficiency

Among the particles emitted from point source, some particles enter the scintillator and interact with the elements in the scintillator to perform energy deposition, some particles enter into the scintillation body and fail to interact with the elements in the scintillator, passing directly through the scintillator, without energy deposition. Figure 1 is schematic diagram of MCNP simulated particle traversing and untraversing plastic scintillator detectors. The ratio of the number of particles entering the detector to the total number of particles emitted by the radioactive source N is the geometric efficiency ε₁ of the detector. The ratio of the number of particles interacting with the detector to the number of particles entering the detector λ₁ is the intrinsic efficiency ε₂ of the detector. The absolute efficiency ε of detector is the product of geometric efficiency ε₁ and intrinsic efficiency ε₂. It can also be understood that the ratio of the number of particles interacting with the detector to the total number of particles N emitted by the radioactive source is the absolute efficiency ε of the detector. [7,8,9,10,11] See formula (1)-(3), the total number of particles entering the detector and the total number of particles passing through the detector (without energy deposition) can be obtained by f1.1~f1.6 statistics of the MCNP data card. In the six planes of the detector, The data card f1.1~f1.6 counts the total number of incident particles λ₁ and the total number of particles not deposited by energy λ₂ (the number of particles passing through the opposite side of the source). The difference between the two totals is the number of particles deposited in the detector in the total particles emitted by the radioactive source.

\[
\varepsilon_1 = \frac{\lambda_1}{N} \tag{1}
\]

\[
\varepsilon_2 = \frac{\lambda_1 - \lambda_2}{\lambda_1} \tag{2}
\]

The absolute efficiency formula \( \varepsilon = \varepsilon_1 \times \varepsilon_2 \) can be obtained:
In the formula, $\varepsilon_1$ is the geometric efficiency of the detector, $\varepsilon_2$ is the intrinsic efficiency of the detector, $\varepsilon$ is the absolute efficiency of the detector, $\lambda_1$ is the number of particles in the incident detector, and $\lambda_2$ is the number of particles without energy deposition in the incident detector.

$$\varepsilon = \frac{\lambda_1 - \lambda_2}{N}$$  \hspace{1cm} (3)

3. Analysis of simulation results of different incident angles

3.1. Analysis of absolute efficiency in X-Z plane

In the X-Z plane, the radiation source is centered on the origin of the coordinates. The radius of the circle of 200 mm is increased by 10° from the positive direction of the X axis and rotated counterclockwise to the positive direction of the Z axis. The angle between the ligature of the connection point of the radiation source and the coordinate center O and the positive direction of the X axis is the particle incident angle $\alpha$, as shown in figure 2. The number of particles detected by each position detector is analyzed and the absolute efficiency of the corresponding position is calculated. With the increasing incidence angle $\alpha$, absolute efficiency is constantly changing, as shown in figure 3. By observing the change of absolute efficiency, it can be concluded that the absolute efficiency is the lowest when the incident angle $\alpha$ is 0° between X axis positive direction and Z axis positive direction on X-Z plane while the distance between radioactive source and detector is invariable. When the incident angle $\alpha$ is 20°~30°, the absolute efficiency of the detector reaches the highest. Thereafter, the absolute efficiency decreases gradually with the increase of the angle.
Fig 2. In the X-Z plane, the position relation of the radiation source’s counterclockwise rotation and the detector (α is incident angle, γ is open angle)

Fig 3. Variation of absolute efficiency of detector at different incident angles in X-Z plane

In the X-Z plane, when the incidence angle is 0°, the intrinsic efficiency is highest while the geometric efficiency is the lowest. In the process of increasing the incident angle from 0° to 30°, the angle γ is increasing rapidly, which leads to the rapid increase of the relative section area of the detector and the radiation source, thus the geometric efficiency of the detector increases rapidly, and the intrinsic efficiency decreases slightly, and the absolute efficiency of the detector increases rapidly; When the incident angle is increased from 30° to 90°, the angle of γ tends to be stable. At this time, the relative sectional area of the detector and the radiation source is change very small, and the detector's geometric efficiency slows down slowly, while the intrinsic efficiency is gradually decreasing, and the absolute efficiency of the detector is gradually decreasing.

3.2. Analysis of the absolute detection efficiency in Y-Z plane
On the Y-Z plane, the radioactive source is placed on the 200mm circle from the origin of the coordinate, increasing 10° each time from the positive direction of the Y axis, rotating counterclockwise to the positive direction of the Z axis, and the incident angle of the particle is β, as shown in figure 4. When the detector is located in Y-Z plane, the sectional area of the detector is relatively small, and the change
of incident angle $\beta$ has little effect on the absolute efficiency of the detector under the condition of equidistance. It can be seen from figure 5 that the absolute efficiency fluctuates in a narrow range with the change of incidence angle $\beta$, and the maximum value is lower than the value of X-Z plane, and the difference between the maximum and minimum absolute detection efficiency is very small. It can be concluded that different incident angles of particles have little effect on the absolute efficiency in this plane, so we should focus on the plane which has a great influence on the absolute detection efficiency.

![Diagram](image1)

**Fig 4.** In the Y-Z plane, the position relation between counterclockwise rotation of radioactive source and detector ($\beta$ is incident angle, $\delta$ is open angle)

![Graph](image2)

**Fig 5.** Change of absolute efficiency of detector at different incident angles in the Y-Z plane

### 4. Experimental test

It can be seen from the analysis of the simulation of the change of the absolute efficiency of the detector with the change of particle incident angles in different planes, for EJ299-33A plastic scintillators measuring 6 (mm) × 6 (mm) × 130 (mm), when the radioactive source is placed in the plane where the long axis of the detector is located and the plane is perpendicular to the detector, the overall detection efficiency is rather high. Then the absolute efficiency of the plane at different incident angles is analyzed by experimental test.

After the scintillator detector is finished, the experimental test platform is built. The test platform is composed of EJ299-33A plastic scintillator detector, power module, AD8014 operational amplifier,
Digitizer(4/8 Ch. 10 bit 2/1 GS/s Digitizer: 3.6/1.8MS/ch, EP3C16, SE) and a data processing unit
(programmed using root [11]), as shown in figure 6. The number of particles emitted per unit time of
the radioactive source is $9 \times 10^5$ Bq. The power supply module provides the detector with a voltage of
27V or 28V. The operational amplifier amplifies and processes the signal detected by the detector, and
the amplified analog signal is digitalized by Digitizer. The experimental data are obtained by data
processing unit and count the number of particles that interact with the detector for energy deposition.

![Fig 6. Schematic diagram of experimental test platform](image)

A plane with higher absolute efficiency, namely X-Z plane, was selected. According to the X-Z plane
simulation method, the experimental tests were carried out under different incident angles of particles,
and the experimental data were collected. The absolute efficiency of the detector is calculated by
analyzing the number of particles interacting with the detector by the data processing unit based on the
root programming, and the experimental results are compared with the simulation results, as shown in
figure 7.

From the comparison, we can see that the absolute efficiency of the detector in the experiment test
is lower than the absolute efficiency in the simulation, which is caused by the different degree of noise
produced by the hardware parts of the whole detection system, but the overall trend is roughly the same.
The absolute efficiency is the highest in the range of incidence angle of 20°~ 30°, then the absolute
efficiency decreases gradually with the increase of the incidence angle. The simulation results and the
experimental results are verified by each other.
Fig 7. The comparison between the simulation results and the experimental results

5. Conclusion
By simulation, the absolute efficiency of the detector made by EJ299-33A plastic scintillator at different incidence angles is calculated. Due to the different incident angle and the different location of the radioactive source, the open angle between the radioactive source and the detector is changed, which affects the detection efficiency and draws the following conclusions:
(1) The different incident angle of particles in the same plane influence the absolute efficiency of the detector, the absolute efficiency reaches the highest when the incidence angle between 20°~ 30°.
(2) The azimuth affects the absolute detection efficiency of the detector. The absolute efficiency reaches the highest when the incident angle of the particle is the same and the azimuth is 0°or 90°.

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