Design of Detection Probe for Weak Radioactive Substance

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Abstract. In order to improve the detection efficiency and sensitivity of the detector for weak radioactive substances, a detector probe has been designed which with double photomultiplier & NaI (TI), by using of multi pulse coincidence measurement and energy spectrum recognition algorithm to realize the fast detection of weak radioactive substances. Through the amplification factor, data calibration and detection threshold experimental research and data comparison found that, the detection efficiency and sensitivity of the detector for weak radioactive substances are improved, this also proves the effectiveness of the design of detection probe.

Keywords: Weak radioactive substance; Detection probe; Double photomultiplier; Energy spectrum recognition algorithm.

1. Introduction

With the rapid development of nuclear energy and the wide application of nuclear technology, nuclear security has become the focus of the international community. As an important means of nuclear security detection, radioactive material detection is widely used. However, the popularity and application of nuclear security checking instruments are not so high[1], and they are only deployed in some cases with high security level, and the checking technology for weak radioactive substances is not mature enough[2], that is mainly due to various environmental factors such as temperature, humidity, air pressure and so on, and those also influence performance of the nuclear detector[3,4]; in addition, radiation shielding will also reduce radioactivity The external radiation dose of the substance can deceive the security inspection instrument to pass the test; at the same time, the radioactive substance close to the natural backgr ound is more difficult to detect. Therefore, it is very necessary to design the detector for low level radioactive materials near the natural background.

In this paper, a kind of detector for weak radioactive substances has been designed, the detector is suitable for the field of nuclear anti-terrorism security. The detector is designed as two-way photomultiplier tube & NaI (TL), multiple pulse coincidence measurement and energy spectrum recognition algorithm. At the same time, the detection efficiency and sensitivity of the detector for weak radioactive substances are improved through the experimental study of magnification, data calibration and detection threshold value.
2. Probe Structure and Working Principle Design

2.1. Structure Design of Double Photomultiplier & NaI
If the distance between the photon generated by the incident particle and the collection point is far, the attenuation of the optical signal will occur, which will reduce the efficiency of photon collection. In order to improve the detection efficiency of the detector, a photomultiplier tube is added at both ends of NaI (TL), and its structure is shown in Figure 1.

![Double photomultiplier NaI(Tl) structure.](image)

The design of the structure reduces the travel and detection loss of photons, and the photomultiplier at both ends realizes the bidirectional collection of photons, which is equivalent to increasing the area of photon detection and improving the detection efficiency.

2.2. Multiple Pulse Coincidence Measurement Method
After determining the structure design of the detector's core detection components, the back-end signal amplification and processing mainly adopts the multi-channel pulse coincidence measurement method. The implementation principle of this method is shown in Figure 2:

![Double photomultiplier NaI(Tl) structure.](image)

Firstly, the photomultiplier at both ends of NaI (TL) is powered by an independent voltage divider, and the voltage signal generated is amplified by the amplifier; then the amplified signal is transmitted to a single channel analyser for integration; next, the two-way scaler will complete the sum calculation of the pulse signal; finally, the pulse signal is transmitted to the data processing unit for energy spectrum amplitude analysis and counting rate conversion.

2.3. Design of Energy Spectrum Recognition Algorithm
Through the establishment of different nuclide regions of interest (main characteristic regions), the low-energy part pulse count and high-energy characteristic pulse count of the characteristic region are judged and compared by the detection energy spectrum under the background and detection conditions.

\[
N = \frac{C_L}{C_H} - \frac{D_L}{D_H}
\]  
(1)
In the formula above, $C_L$ is the low energy pulse count in the detection energy spectrum characteristic area, $C_H$ is the high energy pulse count in the detection energy spectrum characteristic area, $D_L$ is the low energy pulse count in the detection energy spectrum characteristic area, and $D_H$ is the high energy pulse count in the detection energy spectrum characteristic area. In normal state, $N$ is very close to 0. When the radioactive substance is detected, the $N$ obtained by energy spectrum recognition and pulse counting won't become 0.

3. Experiment and Parameter Setting

3.1. Signal Amplification Test

After many experiments, it is found that when the amplifier multiple is reduced to $k=10$, the noise interference signal is obviously eliminated, and the useful signal is clearly visible without being covered by the interference signal.

Using 241Am low-energy $\gamma$ source for 6-day counting rate measurement experiment (Table 1 is the experimental record data), when the probe high pressure is adjusted to 800 V, its output signal is about 110 MV, the background count is about 800 CPS, it can be seen that its fluctuation range is acceptable, all within the statistical fluctuation range.

| Time | CPS Rang | HV/V |
|------|----------|------|
| Day 1| 806-881  | 800  |
| Day 2| 728-838  | 794  |
| Day 3| 726-789  | 791  |
| Day 4| 658-682  | 791  |
| Day 5| 690-790  | 790  |
| Day 6| 707-825  | 792  |

3.2. Dose Calibration

By using $^{137}$Cs and standard dose instrument for comparison measurement, we can get array $\{n_i, \hat{H}_i\}$ from the counting rate $n$ of the detector and the equivalent dose rate $\hat{H}$ of the standard dose instrument. According to the linear relationship of formula 2, the calibration constants $a$ and $b$ can be obtained by linear relation $[4-7]$.

$$\hat{H} = an + b$$

(2)

In order to reduce the occurrence of negative value and other abnormal conditions in the low energy region, the segmented method is used to calibrate the data. Suppose the dividing value of counting rate at the segment is $n_0$, when the counting rate $n < n_0$, the calibration constant $a_1$ and $b_1$ of the first segment is used for operation and display; when the counting rate $n \geq n_0$, the calibration constant of the second segment is used for operation and display.

Table 2 above reveals that 9 detectors with different id are calibrated, and take the average value, the parameters of the two average points are $(795,0.15)$ and $(37037,5)$. The calibration constant can be taken as the average value, and is suitable for most instruments.
Table 2. Calibration statistics.

| Id | 0.15μSv/h | 5μSv/h | b   | a      |
|----|-----------|--------|-----|--------|
| 1  | 832       | 38865  | 0.044 | 1.27E-04 |
| 2  | 761       | 37642  | 0.05  | 1.32E-04 |
| 3  | 786       | 36948  | 0.046 | 1.34E-04 |
| 4  | 713       | 32623  | 0.042 | 1.52E-04 |
| 5  | 881       | 38589  | 0.037 | 1.29E-04 |
| 6  | 799       | 36846  | 0.042 | 1.35E-04 |
| 7  | 813       | 38685  | 0.046 | 1.28E-04 |
| 8  | 783       | 36066  | 0.042 | 1.37E-04 |
| 9  | 781       | 37068  | 0.045 | 1.35E-04 |

3.3. Dose Calibration

The value of alarm threshold always depends on the natural background and its statistical fluctuation. The counting rate $n_i$ and the alarm thresholds $H_i$ can be selected according to the following numerical relationships:

(1) When $\dot{H}_i = 2\dot{H}_b$, the probability of false alarm is very low.

(2) When $n_i = (n_b + 3\sqrt{n_b}) + 3(n_b + 3\sqrt{n_b})^{1/2}$, the misreport rate will become low and sensitive enough. As is necessary, it can be converted to the standard calibration formula $\dot{H}_i$.

(3) Assume that $n_i = K \cdot n_b$ ($K = 2.3 \sim 10$), when $K = 2.3$, it is sensitive but with high probability of false report rate, while $K = 3$, the rate of misreport and false report is equal. At that time, it is the critical value. The probability of false alarm is equivalent to that of false report. But when $K = 10$ the false report and misreport rate is nearly very small. As necessary, it can be converted into according to the calibration formula $\dot{H}_i$.

4. Conclusion

The detector designed in this paper has a unique structure design of double photomultiplier tube & NaI (Tl). The detection efficiency of weak radioactive substance is improved effectively by multi-channel pulse coincidence measurement and energy spectrum identification algorithm. It is found that when the high voltage is set at 800V, the best counting effect can be obtained, and all fluctuations are within the acceptable range; in addition, the better calibration parameters are obtained through the calculation of linear regression equation. In practical application, the detection probe has high detection sensitivity and no missing detection. As the main detection component of the security inspection instrument, the weak radioactive material detector can be widely used in the practical nuclear security applications in the densely populated areas such as border ports, airports, subways and venues in the future, to improve the detection technology of nuclear security.

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