Effect of natural background on detection threshold of radioactive material detection system

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Abstract. In this paper, the relationship between detection limit and error probability is studied based on the statistical law of radioactivity. The conversion method between the lowest detectable radioactivity count and the activity can be obtained, which provides the basis for setting the alarm threshold reasonably.

1. Introduction

The radioactive background usually comes from cosmic rays and natural radioactivity in the earth's environment. Background radiation has statistical fluctuation, which is closely related to environmental factors, such as mechanical vibration, noise, electromagnetic radiation, which will produce interference and make background count rate fluctuate obviously[1]. When the activity of gamma radionuclide to be measured is very low, it belongs to low level radioactivity measurement. Because of the statistical fluctuation of background count, it is difficult to distinguish whether there is radioactivity or not. Therefore, it is necessary to set a threshold for the detector[2-4]. The threshold value of the detector is the lowest detectable limit for the activity of gamma radionuclide, which is an important performance index of the radioactive material detection system[5,6]. Under normal circumstances, the detection threshold can also be regarded as the alarm threshold of the monitoring system for a specific gamma radionuclide. If the threshold value is exceeded, the alarm will be given, so as to distinguish the boundary between the background radiation and the additional radiation generated by the radioactive material, that is, to determine whether there is any radioactive material.

2. Statistical error and background count

The statistical error is caused by the fluctuation of the measured physical quantity, and has nothing to do with the measurement process. The value of radioactivity meter obeys normal distribution, and its statistical error is related to the count value itself. It is expressed by confidence interval equivalent to certain confidence. For a measurement count N, the measurement result can be expressed as:

\[ N \pm \sigma = N \pm \sqrt{N} \]  (1)

\( \sigma \) is the standard error. The probability of falling into the interval of \( N \pm \sigma \) was 68.3% after repeated measurements, and probability of falling into the interval of \( N \pm 2\sigma \) and \( N \pm 3\sigma \) is 5% and 99.7% respectively. Absolute error can’t fit the accuracy of the measurement results, the relative error
can be clearly seen, the greater the \( N \), the smaller the relative error, the higher the measurement accuracy. The relative error \( \varepsilon \) can be expressed as follows:

\[
\varepsilon = \frac{\sigma}{N} = \sqrt{\frac{N}{N}} = \frac{1}{\sqrt{nt}}
\]

\( n \) is the counting rate and \( t \) is the measurement time. It can be seen that increasing the count rate and increasing the measurement time can help to reduce the measurement error, which is why the total count is always required to be large in the measurement.

In order to get a more accurate background count, it is often necessary to repeat the measurement for many times. Assuming that the background of each measurement is \( N_b \), the arithmetic mean value \( \bar{N}_b \) and the experimental standard error \( \sigma_b \) of the background can be calculated according to the following two formulas:

\[
\bar{N}_b = \frac{\sum N_{bi}}{n}
\]

\[
\sigma_b = \sqrt{\frac{\sum (N_{bi} - \bar{N}_b)^2}{n-1}}
\]

Due to the discreteness of components, the background counts of instruments with the same structure are different. For batch instruments, in some cases, their maximum background can be taken as a reference value.

The statistical fluctuation of radioactive measurement count obeys normal distribution. The experimental standard error of 3 times background count of detector indicates that the confidence probability can reach 99.7%, which means that the probability is more than 99% of the indication range of background count is within \( \bar{N}_b \pm 3\sigma_b \). Once the data exceeds \( \bar{N}_b \pm 3\sigma_b \), which means there's radioactive material.

3. Two kinds of errors in low level radioactivity measurement

In order to measure the radioactivity count of the sample, two measurements must be made, one is to measure the count \( N_s \) of the sample, the other is to measure the count \( N_b \) which the sample was removed, namely the background count, the difference between the two is the net count of radioactivity in the sample \( N_0 \). Usually the same time is taken to measure the sample and background, which is called isochronous measurement or paired measurement. The net count \( N_0 \).

\[
N_0 = N_s - N_b \quad \text{or} \quad N_s = N_0 + N_b
\]

The standard error \( \sigma_0 \) of net count is given by the standard error \( \sigma_s = \sqrt{N_s} \) and \( \sigma_b = \sqrt{N_b} \), the two independent measurements.

\[
\sigma_0 = (\sigma_s^2 + \sigma_b^2)^{1/2} = (N_0 + 2N_b)^{1/2}
\]

When the content of radioactive material is high, the net count is much higher than the background, so it is not difficult to determine the presence of radioactivity. But for low-level radioactivity measurement, the count of the measurement is almost the same as the background, or even lower, so it is difficult to distinguish whether it is the contribution of the sample or the fluctuation of the background. For any sample, the measurement results are nothing more than two cases: the sample contains radioactivity and the sample does not contain radioactivity. Due to statistical fluctuations, two types of errors may occur. The first type of error: there is no radioactivity in the sample, which is a mistaken for radioactivity, which is a false record or false alarm; the second type of error: there is actually radioactivity in the sample, which is mistaken for no radioactivity, which is omitted.
4. Detection limitation
From the statistical point of view of radioactivity counting measurement, judgement limit \((L_c)\), detection limit \((L_D)\) are introduced, which can make both qualitative analysis and quantitative analysis.

4.1. Judgement limit
For non-radioactive samples, the net count \(N_0\) has a normal distribution \(P(N_0)\) with symmetry axis of \(N_0=0\).

\[
P(N_0)dN_0 = \left(\sigma_0(0)\sqrt{2\pi}\right)^{-1}\exp[-N_0^2/2\sigma_0^2(0)]dN_0
\]

(7)

For samples containing \(L_D\) radioactivity, \(N_0\) has a normal distribution with \(N_0=L_D\) as the symmetry axis

\[
P(N_0)dN_0 = \left(\sigma_0\sqrt{2\pi}\right)^{-1}\exp[(N_D - L_D)^2/2\sigma_D^2]dN_0
\]

(8)

In which \(\sigma_0(0)\) stands for the stand error of \(N_0=0\), \(\sigma_D\) is the stand error of \(L_D\), \(N_D\) the count when there is \(L_D\). Since the statistic fluctuation, \(N_0=N_s - N_b\) varies. When \(N_0\) is very low, it is hard to determine whether there is radioactivity in the sample, therefore, a number \(L_c\) greater than zero is set as the judgment limit or critical level. \(N_0>L_c\) means the existence of radioactivity and verses means no radioactivity. The selection of \(L_c\) is always associated with the probability that the measured count is greater than or less than the judgment limit.

4.2. lower detection limit
For radioactive samples, due to statistical fluctuations, \(N_0<\L_c\) may occur, and a second type of error occurs, resulting in a radioactive record missing. The probability of a second type of error is the integral of formula 8 from \(-\infty\) to \(\L_c\) (the shaded portion of Figure 1b). The probability of occurrence of a record missing is not only related to the judgment limit \(L_c\), but also related to the actual radioactivity \(L_D\). For a certain \(L_c\), the higher the radioactivity content of the sample, the smaller the probability of

Figure 1 Schematic diagram of detection limit

The judgment limit is related to the occurrence of the first type of error, and the probability of error is the integral from \(L_c\) to infinity of formula 7 (diagonally delimited part of Figure 1a). When \(N_0>\L_c\), you can't just say there must be radioactivity, we can say there is radioactivity but the probability of error is very small. When \(N_0=\L_c\) radioactivity is considered to exist. Although the error rate is small, the relative error of the net count is large. Therefore, the judgment limit can only be used as a qualitative indicator of radioactivity and not as a quantitative indicator of intensity. For convenience, \(L_c\) may be expressed as a multiple of the standard error sigma \(\sigma_0(0)\) for the net count of non-radioactive samples.

\[
L_c = K_1\sigma_0(0) = K_1\sqrt{2N_b}
\]

(9)

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record missing. According to the requirement of the missed probability, the corresponding minimum radioactivity count $L_D$ can be determined, which can still be expressed by the multiple $K_2$ of the standard error $\sigma_D$ of the sample net count:

$$L_D = L_c + K_2 \sigma_D$$  \hspace{1cm} (10)

According to formula 6, replace $\sigma_0$ with $\sigma_D$ and replace $N_0$ with $L_D$, then $\sigma_D = (L_D + 2N_b)^{1/2}$, set $K_1 = K_2 = K$, the record missing rate of 5%, then

$$L_D = K^2 + L_c$$  \hspace{1cm} (11)

The radioactive count $L_D$ is also not isolated and must be relevant to the probability of record missing. When the net count $N_0 \geq L_D$, it is considered to be radioactive, the error of the miss is small, $N_0 \leq L_c$ is unlikely to occur; when $N_0 = L_D$, it is determined that there is radioactivity, and the error rate is also small, the relative error of the net count also reduced. The radioactive count is called the lower detection limit of the measurement and is also a quantitative concept.

5. Selection of alarm threshold

From the above analysis, it can be seen that the detection threshold is for a specific nuclide, which represents the lowest detectable activity of the nuclide, also represents the detection ability of the radioactive material detection system, and is also the basis for setting the alarm threshold. The radioactivity detection threshold can be calculated by the activity response coefficient of the detection background and the reference measurement point. For the reference measurement point, the detection threshold is related to the statistical fluctuation of the background count of the detector and the gamma radiation spectrum.

The average background counting rate is about $n_b = 900\text{cps}$, The calibration of the instrument is expressed by the equivalent dose rate, so the count rate $\dot{H}$ is displayed before calibration, and the unit is $s^{-1}$, after calibration, the equivalent dose rate is displayed , and the unit is $\mu S v/h$. After the contrast test, the average background equivalent dose rate caused by background natural radioactivity is about $\dot{H} = 0.15 \mu S v/h$, the minimum value was 0.05 and the maximum value was 0.25. Only the background equivalent dose rate caused by natural radioactivity is considered here, and other additional factors are not considered. The selection and setting of alarm threshold should be moderate. If it is too low, it will cause false alarm, else if it is too high, it will cause false alarm.

6. Conclusion

It is of great practical significance to study the characteristics and laws of the measurement of low level radioactive substances from the concept of statistical fluctuation of radioactive measurement count, which is of great practical significance to the setting of sensitivity and alarm threshold of radioactivity measurement.

References

[1] Englerblum, G., Meier, M., Frank, J., & Muller, G. A. (1993). Reduction of background problems in nonradioactive northern and southern blot analyses enables higher sensitivity than 32p-based hybridizations. Analytical Biochemistry, 210(2), 235-244.

[2] Naiming, H.. (2004). Concept and calculation of detection limit in low level radioactive sample measurement. Radiation Protection Bulletin.

[3] Sokalski T, Ceresa A, Zwickl T.(1997) Large improvement of the lower detection limit of ion-selective polymer membrane electrodes. Journal of the American Chemical Society, 119(46): 11347-11348.

[4] Zhao-Yang, L., Dian, D., Xia, D., Shuai, S. (2016). Study of impact limiter for transportation package for radioactive material. Annual Report of China Institute of Atomic Energy.

[5] Rousseau, R. M. (2001). Detection limit and estimate of uncertainty of analytical XRF results. Rigaku J, 18(2), 33-47.
[6] Shumakov, A. V. (2013). Determination of the detection threshold of a radiation monitor. Atomic Energy, 113(5), 337-344.