Simulation and measurement of spectra of reference filtered X radiation

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Abstract: The energy spectrum is one of the most effective methods to characterise the quality of reference filtered X radiations. To obtain the energy resolution, the authors choose seven sealed standard radioactive sources to carry out energy calibration for high-purity germanium detector whose energy resolution is within 5%. Then they use this spectrometer to measure the reference filtered X radiations with its energy from 55 to 125 keV of low air-kerma rate series, meanwhile the BEAMnrc is used to simulate the spectra of the same four radiation qualities. By analysing the data of spectral distribution, they can determine mean energy and spectral resolution of these reference radiation qualities. By comparing simulation results with actual measurements, the result shows the spectra stimulated by the BEAMnrc are consistent with the spectra measured by high-purity germanium detector and the deviation of the mean energy is within 4.0%. The spectral resolution of the reference filtered X radiation is 22.8, 22.4, 22.5 and 22.8%, respectively.

1 Introduction

Since Roentgen discovered X radiation in 1895, X radiations have widely utilised in various fields such as disease treatment, medical diagnosis, radiation protection, and environmental protection and so on. X-ray is a double-edged sword. If X-rays are used excessively, it will cause radiation damage to the human, so we need to control the total of X-rays while using its advantages to benefit to human. In order to unify the methods of calibrating dosimeters and dose rate meters that are used to measure radiation precisely in different countries, International Organization for Standardization revised ISO4037 and published four technical specifications, including ISO4037-1, ISO4037-2, ISO4037-3, ISO4037-4 [1–4]. According to ISO4037-1 which is used to describe the radiation characteristics and production methods, we have established four reference filtered X radiations of the ISO 4037 low air-kerma rate series in the range from 55 to 125 kV. Generally, the quality of a filtered X radiation is characterised by the following parameters:

(a) mean energy of a beam expressed in kiloelectronvolts;
(b) resolution expressed in percentage;
(c) half-value layer expressed in millimetres of Al or Cu.

Actually, the quality of the radiation obtained depends primarily on the following parameters:

(d) the high-voltage of the X-ray tube;
(e) the thickness and quality of the total filtration;
(f) the quality of the target.

By experiment, we obtain the half-value layer of four reference radiations, then use the Monte Carlo to simulate spectrum, and calculate mean energy and spectral resolution [5–7]. Moreover, the high-purity germanium detector is used to measure these reference radiations to identify simulation results.

2 Experimental principle

When high electron charges are fired at a metal target, charges will be decelerated to lose energy which is transformed into bremsstrahlung. Because the loss energy is randomised, the bremsstrahlung is characterised by a continuous distribution of X radiation. Characteristic X-rays are emitted from heavy elements when their electrons make transitions between the lower atomic energy levels such as K, L. The X-ray unit used in the experiment is a bipolar industrial X-ray unit with various advantages, such as adjustable X-ray tube voltage, small temperature drift, continuous exposure, long-term use, stable performance and so on. The model of the X-ray tube is COMET MXR-320/26. The energy of X-rays generated by the X-ray unit not only continuous but single.

The experimental device of reference filtered X radiation shown in Fig. 1 is mainly composed of X-ray shielding box, X-ray unit, primary diaphragm, filtration system, secondary diaphragm, removable rails, calibration platform, controlling software and other components. The shielding box has three shielding structures, aluminium, lead and aluminium, respectively. The 5 mm thick lead as the main shielding material can effectively reduce the leakage and part of scattered radiation. Primary diaphragm and secondary diaphragm are made of 20 mm thick tungalloy, which can effectively reduce the impact of scattered radiation on the experimental results. Filtration system consists of additional filters, filter discs, controlling software and other components. The purity of additional filtrations, including tin, copper and aluminium, are >99.99%. By using additional filtration, the desired reference radiations shown in Table 1 are obtained. The deviations of the first half-value layer are all within 5%, which are complying with the certain conditions given in ISO4037-1.

3 Energy calibration of gamma spectrometer

Nuclear radiation detectors are known as nuclear radiation that use nuclear radiation to cause ionising effects, luminescence, physical or chemical changes in gas, liquid or solids to detect nuclear radiation. Common ionising radiation detectors can be divided into gas detectors, scintillation detectors, semiconductor detectors.

Gas detectors measure nuclear radiation by collecting the ionised charge generated by the radiation in the gas [8]. The main types are ionisation chamber, proportional counter and Geiger–Müller counter. Their structure is similar, they are generally cylindrical containers with two electrodes, filled with some kind of gas, the voltage between the electrodes. And they all have their own characteristics and applicable fields. The difference of them is the operating voltage range is different.

The scintillation detector is driven by a charged particle on a scintillator to ionise and excite atoms or molecules, emit light in a desensitisation process, and measure the nucleus by using an
optoelectronic device to convert an optical signal into a measurable electrical signal [9] radiation. The scintillation counter has a short resolution time and high efficiency, and it can also determine the energy of the particles based on the size of the electrical signal.

Semiconductor detectors are radiation detectors using semiconductor materials as the detection medium [10]. The most common semiconductor materials are germanium and silicon. The basic principle of the semiconductor detector is that charged particles generate electron–hole pairs in the sensitive volume of the semiconductor detector. The electron–hole pairs drift under the effect of the external electric field and output electrical signals, and the radiation is measured by the electrical signals. Common semiconductor detectors include P–N junction semiconductor detectors, lithium drift semiconductor detectors, and high-purity germanium semiconductor detectors. High-purity germanium detectors have the advantages of high energy resolution, short manufacturing cycle, and storage at room temperature. The use of ultrapure germanium materials also facilitates the fabrication of X and gamma-ray detectors, which can be made of very sensitive volumes with very thin dead layers that can be used to detect both X and gamma rays.

In order to use high-purity germanium detector to detect X-rays precisely, it is most important to carry out energy calibration. In fact, we get every channel and its total counts when we use gamma spectrometer to detect X-rays, and the channel is a function of energy. First of all, we select six sealed standard radioactive sources for energy calibration, which are $^{57}$Co, $^{133}$Ba, $^{241}$Am, $^{137}$Cs, $^{109}$Cd, $^{139}$Ce, respectively. Secondly, as shown in Fig. 2, we use gamma spectrometer to detect the energy of rays emitted by the six radioactive sources to carry out energy calibration for the relationship between energy and channel [11]. In the measurement process, it should be noted that the central of these radioactive sources and the probe are in a line. And the distance between them is 5 cm. The functional relationship between energy and channel generally can be expressed as a linear function shown as following equation:

$$E_{\gamma} = a + b \times \text{channel}$$  \hspace{1cm} (1)

where the intercept $a$ in the formula is the corresponding energy when the channel is zero, and the slope $b$ represents the energy of one channel. If some non-linear factors in the spectrometer and electronic system are considered, a non-linear quadratic term can be added to the equation, expressed as a quadratic function

$$E_{\gamma} = a + b \times \text{channel} + c \times \text{channel}^2$$  \hspace{1cm} (2)

where $c$ is the coefficient of the quadratic term. Because the linear relationship between energy and channel of the gamma spectrometer is good enough to detect the energy of rays, we choose the first to carry out energy calibration. The measurement results of these sources are shown in Table 2. Then we use a gamma spectrometer to detect the X-rays emitted by $^{55}$Fe whose energy of the characteristic X-rays is 5.9 keV. The amount of characteristic rays all exceeds 10,000 to decrease the error of statistical fluctuations. In the end, by data processing, we can get the relationship between energy and channel that is shown in Fig. 3. The linear correlation coefficient $R^2$ is equal to 1, and the deviation of the energy emitted by $^{55}$Fe is within 0.79%, which proves that the linear fit is good enough to get the correct energy of these reference radiations.

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**Table 1.** Results of half-value layer

| Radiation quality | Spectral resolution | Measurement | Deviation, % |
|-------------------|---------------------|-------------|--------------|
| L-55              | 0.25Cu              | 0.262Cu     | 4.0          |
| L-70              | 0.49Cu              | 0.504Cu     | 2.86         |
| L-100             | 1.24Cu              | 1.271Cu     | 2.50         |
| L-125             | 2.04Cu              | 2.09Cu      | 2.45         |

**Table 2.** Measurement results of the sources

| Radioactive nuclide | Energy, keV | Channel |
|---------------------|-------------|---------|
| $^{55}$Fe           | 5.9         | 69      |
| $^{109}$Cd          | 22.2        | 258     |
| $^{241}$Am          | 59.5        | 693     |
| $^{133}$Ba          | 81          | 943     |
| $^{57}$Co           | 122         | 1421    |
| $^{139}$Ce          | 165.7       | 1930    |
| $^{137}$Cs          | 661.6       | 7706    |

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**Fig. 1** Experimental device

**Fig. 2** Energy calibration of the detector by radioactive sources

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Simulation and measurement of spectra

According to the experimental device shown in Fig. 1, we had established four radiation qualities of the ISO 4037 low air-kerma rate series in the range from 55 to 125 kV which are in conformance with the given specifications. In addition, the spectra can be obtained by simulation and measurement. The EGS (Electron-Gamma-Showe) system of computer codes is a general purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies above a few keV up to several hundreds of GeV. In this experiment, we use the enhanced version called EGSnrc where the radiation transport of electrons or photons can be simulated in any element, compound, or mixture [12]. BEAMnrc is built on the EGSnrc Code System for modelling radiotherapy sources with various independent modular components [13, 14]. The X-ray tube as a prototype is simulated by BEAMnrc in which the target material is tungsten, and the target inclination is set to 20°C. The energy of incident electron is adjusted by tube potential. The number of histories is set to $1.0 \times 10^9$. In the coupled transport of particles, all information is stored in the phase-space file. BEAMDP can be used to analyse the phase-space file and to derive the data of spectral distribution [15]. Moreover, the high-purity germanium detector was used to measure the actual spectra of these radiation qualities. The simulated spectra by EGSnrc and measured spectra by high-purity germanium detector are shown in Figs. 4–7. By comparison, we can find that the simulated spectra are in well conformance with the measured spectra. By analysing the data of spectral distribution, the mean energy of the corresponding radiation is obtained. As shown in Table 3, we can see the results of the mean energy whose deviations are all within 4.0%. And the spectral resolution of the reference filtered X radiation shown in Table 4 is 22.8, 22.4, 22.5 and 22.8%, respectively, whose deviations are all within 8.6% of the values given in ISO4037-1.

5 Conclusion

The spectrum is one of the most effective ways to characterise the reference filtered X radiation. In this experiment, we have obtained the spectra by simulation and actual measurement, which are all consistent. And the deviation of the mean energy and the spectral resolution is within 4.0, 8.6%, respectively, which are all conforming to the requirements of the standard specifications. These all approve the established reference filtered X radiations by experiment are conforming to the requirements of the standard specifications. It lays the foundation for the follow-up study on the methods of traceability and transmission of X-ray at the low dose rate.

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