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Realization and Research of Single Energy X-ray Based on X-ray Machine in Low Energy Region

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ABSTRACT. *In order to achieve single-energy X-rays in low-energy regions, a single-energy X-ray radiation device based on an X-ray machine was developed. Performance test of the device using HPGe detector, 3keV-30keV single-energy X-rays achieved by the crystal Bragg diffraction principle. The energy spectrum measurement results show that FWHM shows an upward trend with increasing energy. The energy resolution is generally 3%, and the monochromaticity is good. The monochromatic luminous flux is linear with the tube current, the tube current can be adjusted to control the photon flux. Meet the calibration requirements of the detector.*

KEYWORDS: *Single energy X-ray, Bragg diffraction, Energy resolution, Monochromatic luminous flux*

1. Introduction

Nuclear technology is widely used in medical diagnosis, radiation therapy, industrial non-destructive testing, nuclear power generation, radiation processing, materials analysis and scientific research. With the development of nuclear radiation detection technology, the measurement accuracy requirements of detectors have gradually increased. Due to the different types of detectors, the photon response detected in each energy band will also be different, which requires the development of stable reference radiation sources with different energy intervals to calibrate the detector.

Currently, there are four main ways to generate single-energy X-rays: radionuclides, synchrotron radiation X-ray crystal diffraction, K fluorescence, and X-ray machine crystal diffraction. Commonly used radioactive sources, such as ^{60}Co, ^{137}Cs, ^{241}Am, etc.They can obtain single energy photons of different energy levels through these radioactive sources, but there are very few types of radioactive

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sources with X (γ) ray energy branches below 100keV, and the energy is not adjustable. The synchrotron radiation source is currently a relatively advanced single-energy X-ray device in the world. The synchrotron radiation device currently achieves a single-energy X-ray energy range of (0-8GeV), but the synchrotron radiation device has a large volume and high operating cost. The energy of the photon generated by the K fluorescence radiation source depends on the material of the radiator. Single-energy X-rays of different energy levels can be obtained by replacing the radiator. However, high-energy X-rays cannot be obtained due to the limitation of the radiator material. Tune. The single-energy X-ray fluence generated by X-ray machine crystal diffraction is large, the energy point is continuously adjustable, and the cost is relatively low. It is currently widely used in the calibration of astronomical satellite payloads. Based on the advantages of X-ray machine crystal diffraction, many countries in the world have established corresponding single-energy radiation devices. SOLEX installations in France [1-4], XACT installations in Italy [5], XRCF installations in the United States [6], and PANTER installations in Germany [7], etc.

2. Implementation principle of single energy X-ray

X-ray machine is mainly composed of cooling system, anode target material, high voltage power supply and filament power supply, vacuum glass tube and cathode filament. When high voltage is applied to the two poles of the X-ray machine, the electrons emitted from the cathode accelerate the bombardment of the anode metal target under the action of the electric field. The electrons interact with the metal target to generate characteristic X-rays and bremsstrahlung. The X-ray spectrum generated by the characteristic X-ray is the identification spectrum, and the X-ray spectrum generated by the bremsstrahlung is a continuous spectrum. The energy of the identification spectrum is related to the target material and has nothing to do with the voltage. Together. The principle of the X-ray machine is shown in Figure 1.

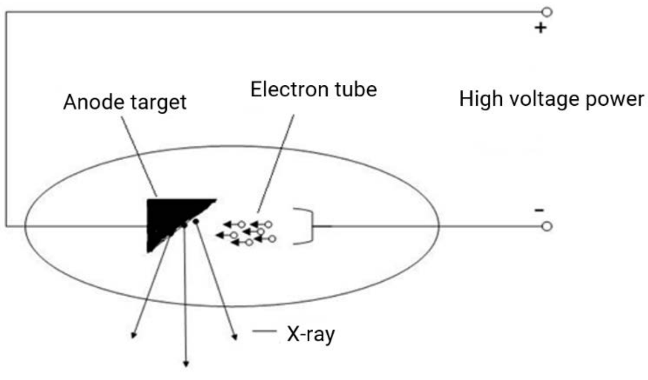

Figure 1. X-ray machine principle

The crystal lines produced by some solid-state crystals after reflecting X-rays are different from other physical states. The photon radiation reflected by such crystals at a specific wavelength and incident angle will form a single concentrated peak, which is the Bragg diffraction phenomenon [8-9].

Bragg diffraction occurs when X-rays are irradiated on the crystal, according to the Bragg formula:

$$n\lambda = 2d \sin \theta$$

Combined with the photon energy formula:

$$E = h c / \lambda$$

The single-energy X-photon energy formula can be obtained:

$$E = (nhc)/(2d \sin \theta)$$

Where *h* is Planck constant, *c* is the speed of light, *θ* is the lattice spacing, and is the Bragg angle related to the direction of X-ray incidence. In the experiment, the energy of the single-energy X-ray generated by the first-order diffraction is generally taken as 1. Therefore, by changing the crystal material and the Bragg diffraction angle of the crystal monochromator, the corresponding single-energy X-ray energy can be obtained, which is basic principles of monochromators [10].

3. The built up of the experimental device

Single-energy X-ray radiation device based on X-ray machine is mainly composed of four parts: X-ray machine, single crystal monochromator, collimator and standard detector; X-ray tube uses Oxford light tube. The anode target is a copper target with a maximum tube voltage of 50kV and a maximum tube current of 1.0mA. The single crystal monochromator consists of a LiF (200) crystal [11], a crystal fixed structure and a rotating turntable; the collimator consists of a laser collimator, a front collimator tube and a rear collimator tube. The standard detector uses a low-energy HPGe detector produced by Canberra. The HPGe crystal is a cylinder with an effective area of 100 mm^2 and a crystal length of 10 mm, thickness of beryllium window is 0.08 mm, and the total number of electronic multi-channel sites is 8192. The detector has been calibrated with standard radioactive sources ^{133}Ba, ^{109}Cd, ^{55}Fe, ^{241}Am, ^{152}Eu and ^{57}Co for energy linearity, energy resolution and detection efficiency, energy detection range is 5keV-300keV. The experimental setup is shown in Figure 2.

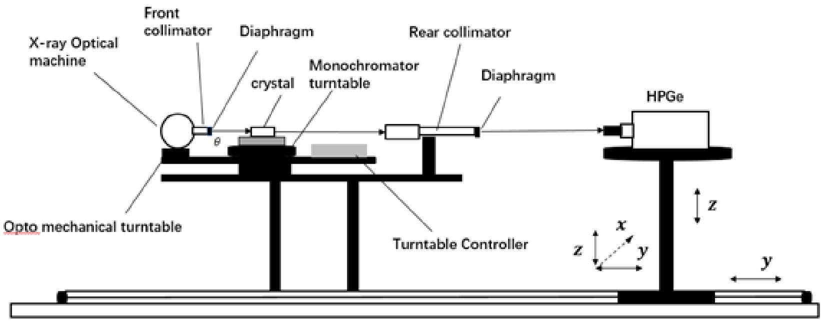

Figure 2. Single energy X-ray radiation device

A small-aperture collimator is installed at the X-ray machine ray exit to achieve the function of limiting the X-ray beam current and prevent the beam from hitting the crystal completely, which will affect the local environment. The monochromator turntable is used to control the incident angle of X-rays, and the corresponding single-energy X-rays can be obtained based on the Bragg diffraction principle. The single-energy X-rays are used to restrict the single-energy X-rays through a rear collimator and a small aperture stop. To improve the monochromaticity of single-energy X-rays. Figure 3 shows field experimental device diagram.

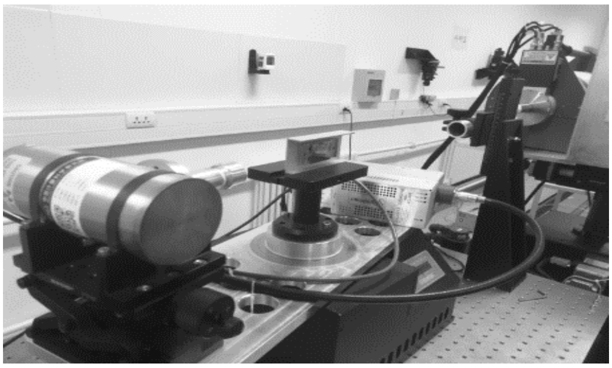

Figure 3. Field experimental device diagram

4. Test results and analysis

4.1 Rejection of harmonics

According to the Bragg diffraction theorem, higher order diffraction occurs under appropriate circumstances. To obtain single-energy X-rays, unwanted harmonics need to be eliminated. As shown in Figure 4, this is an energy spectrum with higher-order diffraction.

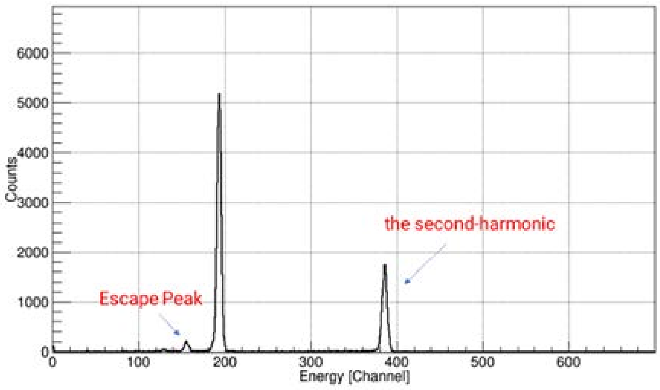

Figure 4. Higher order energy spectrum of Bragg diffraction

The first harmonic generated in the picture is the harmonic formed by the Ge element being excited to generate X-rays with characteristic Kα and Kβ escape. The second harmonic is the target energy point 8keV we want to get, the third harmonic is the second-order harmonic due to Bragg diffraction, and the energy obtained is twice the energy of the second harmonic 16keV. The peaks formed by higher-order diffraction will disappear. It can be obtained through experiments that when the energy (E) and voltage (U) satisfy the following relationship, the second harmonic can be eliminated:

$$E < U < 2E$$

In the following experiments, this method is used to eliminate the second harmonic.

4.2 Energy range and spectrum

In this experiment, single-crystal monochromators were used to adjust different X-ray incident angles and X-ray tube currents and voltages, and single-energy X-rays were obtained from Bragg diffraction. Use HPGe detector for measurement and HPGe detector GENIE 2000 energy spectrum acquisition and analysis software to record the spectrum data collected from multi-channel analyzers, and use the ROOT program to perform Gaussian fitting on the energy spectrum to obtain single energy X-ray energy, and single energy peak area counts. The measurement time of each energy point in this experiment is 100s, and the energy area covers 8keV-30keV. After deducting the background fitting, the energy spectrum is shown in Figure 5.

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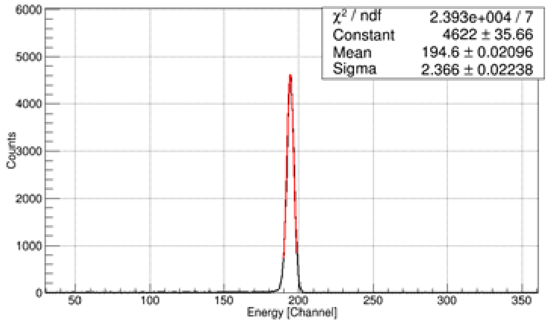
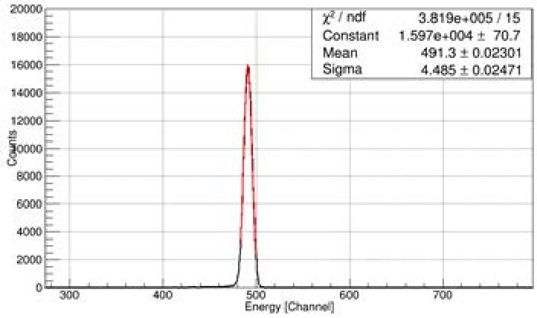
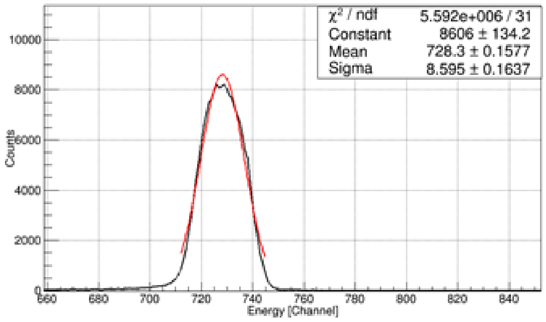


(a) 8keV spectrum



(b) 20.3keV spectrum



(c) 30keV spectrum

Figure 5. Single energy X-ray energy spectrum

As shown in Figure. 4, the energy spectrums of single-energy X-rays 8 keV, 20.3 keV, and 30 keV are obtained, where black lines represent data and red lines are curves after Gaussian fitting. After fitting, we can get three important parameters: constant, mean and sigma, which respectively represent the corresponding counting of peak location, peak location channel and standard deviation. Generally, the energy resolution can be described by the full-width at half height (FWHM) of the full-energy peak after Gaussian fitting. The relationship of sigma, FWHM, and energy resolution (η) is:

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$$FWHM = 2\sqrt{2\ln 2}\sigma \approx 2.355\sigma$$

$$\eta = \frac{FWHM}{E} \times 100\%$$

E is the energy of the all-energy peak position. As shown in Figure 4, we can notice that as the value of sigma increases, the resulting energy spectrum becomes wider. The relationship between Sigma, FWHM, energy, and energy resolution in the data obtained from the measurements is shown in Table 1 energy spectrum measurement results.

Table 1 Energy spectrum measurement results

Energy/keV	Sigma	FWHM	Energy resolution (η)
8	2.366	5.572	2.863%
12	2.789	6.568	2.264%
16	3.401	8.009	2.070%
20.3	4.485	10.562	2.150%
23	5.443	12.818	2.298%
28	7.479	17.613	2.591%
30	8.595	20.241	2.780%

In the low energy region of 8keV-30keV, the energy resolution is less than 3%, which shows good monochromaticity. As the energy increases, the broadening of the single-energy X-ray becomes more severe, and the monochromaticity decreases. The relationship between FWHM and energy is shown in Figure 6.

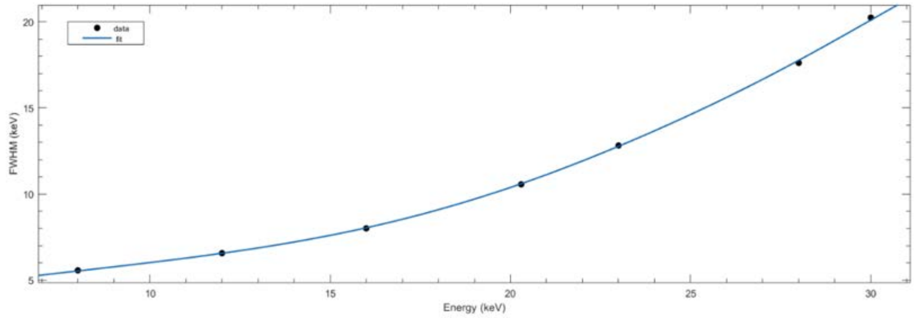

Figure 6. FWHM vs energy

4.3 Photon flux

During the experiment, the angle of the rotating turntable was adjusted, the tube voltage was set to 20 kV, the tube current was 0.05 mA, and X-rays were subjected

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to Bragg diffraction to obtain 13 keV single-energy X-rays. The relationship between the photon flux and the tube current is obtained with a step size of 0.02 mA, as shown in Figure 7.

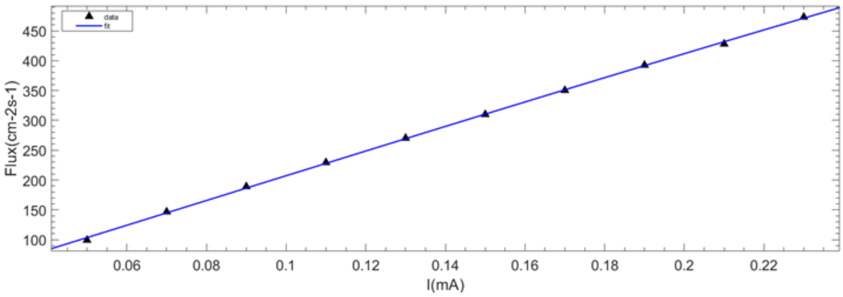

Figure 7. Flux vs I

As can be seen from Figure 7, the tube current and flux have a good linear relationship. We can control the corresponding current to obtain the photon flux required to meet the calibration of the detector. Generally, the single-energy X-ray photon flux can reach $500cm^{-2}.s^{-1}$, which can meet the photon flux of most detectors for calibration the amount.

5. Conclusion

This experiment mainly carried out 8keV-30keV energy spectrum test, energy resolution test and photon flux test on X-ray machine based single energy X-ray device.

The test results show that the single-energy X-ray device based on the X-ray machine can achieve a single-energy X-ray range of 8keV-30keV, the energy resolution is better than 3%, the monochromaticity is good, and the monochromatic luminous flux has a good linear relationship with the tube current. At present, most detectors use standard radioactive sources for calibration. The realization of single-energy X-rays in the low energy region can make up for the problem that the radioactive source has less energy branches below 100keV. At the same time, it can provide spaceborne detectors and highly sensitive detectors. Calibration of low energy areas.

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