Investigation of Characteristics of Low-energy X-ray Radiated from the Crookes Tube Used in Radiological Education

Do Duy KHIEM, Hirokazu ANDO, Hirotu MATSUURA, Masafumi AKIYOSHI

Graduate School of Engineering, Osaka Prefecture University, Japan
1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan

Received Feb. 1, 2019; accepted May. 23, 2019

Crookes tubes have been used as fundamental equipment for science education in junior-high schools in Japan. However, radiation protection and safety guidelines have not been evaluated sufficiently to date. Estimations of the X-rays radiated from the Crookes tubes under various systematic conditions are required to establish these guidelines. Energy spectrum of the X-rays was obtained by CZT detector with very fine collimator to avoid pile-up effect. The peak energy of the X-rays was about 20 keV, and the most frequent voltage of pulses applied from an induction coil was matched with this peak energy. The correlation between the distribution of the applied voltage and X-ray spectra was obtained in this study. The energy of the X-rays was also estimated by a linear attenuation coefficient of Al plates. The effective X-ray energy estimated by this conventional method showed good agreement with the result obtained by CZT detector.

Key Words: Crookes tube, CZT detector, radiation education, radiation protection, X-ray energy spectrum

1. Introduction

A Crookes tube is the oldest fundamental X-ray device, used by Roentgen in early studies on radiation. It is a type of discharge tube, usually used with an induction coil as a power supply. By applying a voltage of several tens of kV between the cathode and the anode in the tube, the cations in the evacuated tube are accelerated and impact the cathode, which displace secondary electrons. These electrons emitted by the cold cathode are accelerated to collide with a glass tube to create a bremsstrahlung X-ray.

In Japan, Crookes tubes have been used in junior-high science classes, and the primary purpose is to teach the characteristics of electrons and current. In addition, a following course of study was published in 2017 by MEXT, which requires understanding the nature of radiation related to cathode-rays\(^1\). Supplementary reading materials for radiological education have been added to school curricula by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan since 2008\(^2\)-\(^4\), but there is no mention of the Crookes tube.

During demonstrations and experiments using a Crookes tube, teachers and participating students may be exposed to X-ray radiation. The use of radiation in teaching environments should strictly adhere to the guidelines of laboratory procedures to prevent undesirable exposure and to not exceed the safety limits regarding effective dose for teachers or students. Regarding this issue, some studies on radiation safety involving the teaching of natural sciences using the Crookes tubes have been performed in Japan\(^5\)-\(^9\). An assessment conducted on some Crookes tubes showed that X-rays emitted by Crookes tubes produce very low energy (approximately 20 keV). However, the 1 cm dose equivalent was remarkably high (up to 143 mSv/h at 5 cm)\(^5\). This caused a maximum dose (Hp(10)) of 0.15 mSv per experiment for students, which is higher than the recommended value of 0.05 mSv per experiment in ICRP publication 36\(^10\). Another study indicated that there was a
distribution of leakage dose caused by scattered photons in all directions from the Crookes tube, but the investigation of X-ray energy was not performed\(^7\).

The measurement of the X-ray energy spectrum from the Crookes tube and the dose estimate is considered difficult to perform because the X-ray energy is very low. In addition, various models of Crookes tubes with different specifications under different operating conditions have been used in scientific laboratories and junior-high schools. In practice, it is necessary to provide the radiation protection and safety guidelines that have not yet been sufficiently evaluated in Japan.

In this study, we conduct an initial evaluation of the characteristics and properties of X-rays emitted by a Crookes tube. Such X-ray energy, dose, electrical parameters, and the relevance of operational factors were investigated and are discussed. This work develops a practical system that can actually be used for measurements of low energy X-rays.

2. Materials and Methods

A. Materials

The experiments were conducted with a Crookes tube (model: 3C-B, Kenis Ltd., Japan), and high voltage was supplied from an induction coil (new power induction coil ID-10, Kenis Ltd., Japan). The voltage applied to the Crookes tube was regulated through a spark gap, as well as by an output power (PW) dial on the induction coil. The output voltage from the induction coil is adjusted by the voltage applied to the primary coil. In turn, the applied voltage to the primary coil is adjusted by the power dial. The range of the spark gap is 10–100 mm and the discharge can be adjusted by changing the distance of a plate and needle pair. The electrical components of the induction coil, such as the high voltage supplied to the Crookes tube, were measured using a digital oscilloscope (PC USB oscilloscope 6000BD, Hantek Ltd.).

All X-ray spectra were acquired with a high-performance X-ray and gamma-ray CZT detector (XR-100T-CZT, Amptek Inc., USA). The CZT detector consisting of a CZT crystal, a Be window, and a Peltier cooler can detect energies from a few to several hundred keV\(^{11}\). The spectrometer system consists of the CZT detector connected to a power supply and an amplifier (PX2T-CZT, Amptek Inc., USA), and a multichannel amplifier (MCA8000D, Amptek Inc., USA). Amptek DPPMCA software was used for data acquisition, spectral analysis, and control of the signal processors.

B. Experimental setup

Establishing an energy calibration curve. The standard calibration spectrum was established using a \(^{241}\)Am standard source with three main energies of 13.95 keV, 26.34 keV, and 59.54 keV to determine the low energy of the X-ray tube emission. The standard source measurement was performed without a collimator. The count was 120,000 for data acquisition, and the MCA was set to 2048 channels.

Measurement of the X-ray energy spectrum. Figure 1 shows the experimental setup and equipment used to measure the spectrum of low energy X-rays from the Crookes tube. In this experiment, the plate-needle distance (spark gap) of the induction coil (Figure 1-b) was set to 40 mm, and the variable applied voltages were controlled by changing the output power controller from 0 to 20. High voltage was output from the induction coil in an unformed pulse. Therefore, the applied high voltage was monitored with an oscilloscope. The high

![Image 1](image1.jpg)
pulse voltage can damage the oscilloscope voltage probes, so a voltage divider circuit was used to reduce the voltage value during measurements. The circuit consists of two resistors in series: a 500 MΩ glass resistor and a 100 kΩ resistor. Two electrodes of the induction coil are connected to the two channels of the oscilloscope through resistive dividers. Thereby, a floating oscilloscope measurement technique was used to determine the voltage bias between the two electrodes.

It is well known that a high X-ray flux during spectrum measurement causes a pile-up effect. In addition, in the case of X-ray measurements using the Crookes tube, this pile-up effect is significant even at very low count rates (several tens of cps) and dead time (< 1%). It arises owing to the pulse-shaped high voltage profile from an induction coil. The pulse width is approximately 20 µs and pulses are formed every 1 ms, and after approximately 10 pulses, the interval time is approximately 20 ms. This rather inhomogeneous high-voltage profile produces an inhomogeneous pulsed X-ray field. During the measurement, X-rays are emitted less than 1% of the live time, and we had to consider the count rate, which is 100 times higher than the value obtained. Thus, cylindrical and plate collimators were used to limit the count rate to a low level in order to reduce the pile-up effect. Cylindrical Pb collimators with a 3 mm pinhole were used at low photon rates, and, furthermore, at high photon rates, a collimator with a 1.5 mm thick pinhole of 0.5 mm diameter was attached to the surface of the cylindrical collimator (Figure 1-c). Then this collimator was arrayed with two other collimators in a brass tube to act as a coaxial collimator (Figure 1-d). Using these collimators, the count rate of each measurement was adjusted to a low value (less than 20 cps).

The CZT detector was placed in the brass tube adjacent to the arrayed collimators to shield it from background and scattering X-rays. The detector-collimator assembly was aligned coaxially with the incoming X-ray beam using a laser pointer. A distance of 90 cm from the Crookes tube to the detector is suitable for obtaining the spectrum.

**Measurement of the X-ray transmissions.** The transmission of X-rays was estimated by the ambient dose equivalent H*(0.07) using an ionization chamber (ICS-1323, Hitachi Ltd., Japan). The dose was measured at various thicknesses of aluminum (Al) layers placed in front of the ionization chamber. Al thickness was in the range of 0.5–6 mm, and measurements were taken at a distance of 30 cm from the X-ray source. The output voltage was controlled by adjusting the output power (PW) dial from 0 to 14 in steps of 2, which changed the voltage applied to the primary coil.

**3. Results and Discussion**

**A. X-ray energy spectrum and applied voltage measurement**

In this study, a CZT detector was used owing to its expanding applications in the medical, industrial, and physical fields in recent decades.

The full width at half maximum (FWHM) of the standard 241Am spectrum was measured as 590 eV at 59.54 keV and 410 eV at 13.95 keV. These results are similar to the reference values from the manufacturer’s manual. This confirmed that the spectrometer has good energy resolution and is accurate, so it is well-suited to low-energy X-ray measurements. With the exception of the three main peaks from the standard source, the spectrum exhibited other peaks deriving from the detector material and X-rays from the 241Am source. Escape peaks are an important effect that is well known in the CZT detector. In the CZT detector, Cd and Te produce both Kα and Kβ peaks, and the characteristic energies are 23.2 keV (Kα) and 26.1 keV (Kα) for Cd, and 27.5 keV (Kα) and 31.0 keV (Kβ) for Te. Hence, a photo peak of 59.54 keV from the 241Am source produced four escape peaks, shown in Fig. 2.

The distinct spectra of X-rays modified by applied voltages and acquired using the CZT detector, are shown in Fig. 3. Then the spectra are fitted using a Gaussian function and the best-fit

---

![Fig. 2. Gamma energies of the calibration spectrum produced by 241Am. The escape peaks produced by the interaction of 59.54 keV photopeak from 241Am source with CZT detector material also appeared in this spectrum.](image-url)
values are obtained for single peak fitting. The fitting result determines the X-ray energy corresponding to various output voltages: PW0, PW2, and PW4 as 15.8 keV, 17.0 keV, and 18.1 keV, respectively. In addition, a high voltage measurement was carried out simultaneously with the acquisition of X-ray spectra to obtain the correlation between the distribution of the applied high voltage and the X-ray energy spectrum.

The output voltage pulses observed with an oscilloscope provided the distribution of the applied voltage (Figs. 4 and 5). In the case of our induction coil, the maximum voltage was estimated as 24 kV, 28 kV, and 33 kV for PW0, PW2, and PW4, respectively. According to the Gaussian fit, the peak voltage was 16 kV, 17 kV, and 18 kV for PW0, PW2, and PW4, respectively. This indicated a good correlation in the distribution behavior between the X-ray energy spectrum and the applied voltage.

Because the nominal dielectric breakdown voltage in air is approximately 1 kV per 1 mm\(^1\),\(^2\), the desired output voltage can be obtained by regulating the distance between the discharge electrodes. Below the discharge voltage, the voltage can be continuously controlled by changing the output power. If the output power keeps adjusting even though the discharge voltage occurs, the discharge will become unnecessarily severe. Therefore, to obtain the target output voltage, it is necessary to control the output power to a level at which the spark has just occurred.

Figure 6 shows the correlation between the distribution of the X-ray energy and the applied voltage. The maximum voltage was increasingly distributed between 24–39 kV along with an increase in output power and reached its highest value at PW12 (42 kV). In this experiment, a spark appeared at PW9, and then the output voltage remained relatively stable from PW9 to PW20. The actual maximum operating voltage was approximately 40 kV, which shows good agreement with the nominal discharge voltage at a distance of 40 mm from the plate to the needle.

The voltage applied to the Crookes tube corresponds to the energy of the displaced electrons in the tube. The energy spectrum of bremsstrahlung X-rays from these electrons is described by Kramers’ law or by Birch and Marshall’s law\(^3\). These laws describe an almost linear correlation between intensity and
energy, which is higher at low energy and equal to 0 at the incidence energy of the electrons. After the emission of X-rays, these X-rays are filtered through a glass wall that forms the Crookes tube itself. At approximately 20 keV, the transmission factor changes drastically with a small change in energy, which makes the energy spectra exhibit the characteristics shown in Figure 3. There was good agreement between the peak energy of the X-ray and the peak voltage. The spectral distribution changed between 15.8 and 20.2 keV, which corresponds to a change in the peak voltage from 16 to 20 kV (Fig. 6). When the applied voltage was stable, the X-ray energy also exhibited saturation at PW9, with an average energy of approximately 19.5 keV.

B. Estimation of the X-ray transmission

In junior-high schools, spectrometer equipment such as a CZT detector may be too expensive to own. In addition, it takes time to perform configuration/collimator adjustments in the experimental setup and requires the appointed teacher to have detailed knowledge of spectral analysis. Therefore, a transmission measurement is often used as an alternative approach to estimate X-ray properties. The linear attenuation coefficient or the mass attenuation coefficient is determined from the attenuation of the initial intensity of the X-rays based on the thickness of the material, specified by its shielding parameter. On this basis, the effective energy of X-rays can be interpolated. It is also approved as a method for converting from a half-value layer to effective energy\(^{21-23}\).

The transmission factor should decrease proportionally to the filter thickness in the determined photon energy range; therefore, it is necessary to eliminate any filtering material that creates a transition of both K and L-edges that would lie in the expected X-ray energy spectrum. According to the CZT detector measurements conducted in this study, the Crookes tube emitted X-rays with soft energy of approximately 19.5 keV. Aluminum meets these criteria, so it was used as an attenuator in this experiment.

Figure 7 shows the transmission of X-rays at different applied voltages generated by the Crookes tube through Al using an ICS-1323 ionization chamber at a distance of 30 cm.

The energy of kilo-volt X-rays is called the effective energy because it is a heterogeneous energy. The effective energy of a heterogeneous beam is defined as the energy of a mono-energetic beam having the same attenuation rate\(^{20}\). Owing to its dependence on energy, each given material is characterized by a linear attenuation coefficient (\(\mu\)). Thus, the energy of a mono-energetic beam is determined by a given energy in the literature,
Investigation of Characteristics of Low-energy X-ray Radiated from the Crookes Tube Used in Radiological Education

which has the same $\mu$. Consequently, the effective energy of X-rays was determined from the linear attenuation coefficient of Al using data from the National Institute of Standards and Technology (NIST, USA) and from the XCOM program\(^2\)

The first half-value layer (HVL) calculated for the lowest and highest energy was 17.1 keV and 21.4 keV for an Al thickness of 0.48 mm and 0.90 mm, respectively.

The interpolated effective energy from the Al attenuator and X-ray energy from the CZT detector are shown in Fig. 8. The energy was proportional to the output power and reached saturation at PW6 using either method. The effective energy from the transmission measurement was in relatively good agreement with the spectra from the CZT detector. The average difference in energy between the two measurements was 7.5\%, and the average energy was approximately 19.5 keV for the CZT detector and 20 keV for attenuation measurement (Table 1). This difference is caused by the effect of the filtration of the X-rays in the Al attenuation measurement. The filtration caused hardening of X-rays because it absorbed photons with lower energy. As a result, this caused a shift in the effective energy of the X-rays. This means that the filtration increases the average energy, but does not change the maximum energy in the spectrum\(^2\)

The ambient dose equivalent $H^*(0.07)$ without shielding at a distance of 30 cm from the Crookes tube rapidly rose and reached a slight rise, beginning at PW10 (Table 1). At a distance of 30 cm from the tube, the maximum $H^*(0.07)$ dose rate was 5.84 mSv/h (20.8 keV) at PW14, and the minimum dose rate was 0.22 mSv/h (17.1 keV) at PW0. Ohmori\(^5\) conducted a study on Crookes tubes that resulted in a maximum $H_p(10)$ dose rate of 143 mSv/h at 5 cm with an effective energy of approximately 19 keV. This caused a maximum dose ($H_p(10)$) of 0.15 mSv per experiment (for 3 min, at 50 cm from a Crookes tube) that exceeded the dose limit recommended by ICRP publication 36\(^1\) (0.05 mSv per each teaching exercise). However, the type of Crookes tube, working voltage, and operating conditions were different, so it is difficult to compare Ohmori’s study to ours.

4. Conclusion

The low-energy X-rays radiated from the Crookes tube at variable voltages was estimated, which is considered difficult to perform. The peak energy was approximately 20 keV at a discharge distance of 40 mm.

Correlation between the applied voltage and the radiated X-ray energy was estimated. The applied voltage from an induction coil was in pulse shape and the distribution of the pulse height was obtained by integration of many pulses to a histogram manually. This experiment confirmed that the energy was shifted to a higher region of the spectrum as the applied voltage increased, and the peak voltage represents the peak energy of the X-rays.

A linear attenuation coefficient measurement was

| Output power | $H^*(0.07)$ (mSv/h) | $\mu$ (cm$^{-1}$) | Energy (keV) |
|--------------|--------------------|------------------|-------------|
| PW0          | 0.22               | 14.58            | 17.1        | 15.8        |
| PW2          | 0.56               | 11.70            | 18.5        | 17.0        |
| PW4          | 2.06               | 9.12             | 20.1        | 18.1        |
| PW6          | 4.09               | 8.94             | 20.3        | 19.0        |
| PW8          | 4.18               | 8.62             | 20.5        | 19.3        |
| PW10         | 5.07               | 7.66             | 21.4        | 19.9        |
| PW12         | 5.24               | 8.22             | 20.9        | 19.7        |
| PW14         | 5.84               | 8.32             | 20.8        | 19.7        |
performed to obtain an effective energy of X-rays. This method should be considered as an alternative conventional approach to a CZT detector for estimating low energy X-rays in the education field. These results will contribute to establish recommendations and guidelines on radiation protection rules to prevent any harmful effects of radiation.

5. Acknowledgment

This study was supported by the Crookes tube project in Japan and the JSPS KAKENHI Grant number JP18K02961.

References

1) Ministry of Education, Culture, Sports, Science and Technology (MEXT): Junior-high school course of study (2017 Notification) commentary for Science, pp. 155 (2017). Available at: http://www.mext.go.jp/component/a_menu/education/micro_detail/_icsFiles/afieldfile/2019/03/18/1387018_005.pdf (in Japanese).
2) Tsubokura, M., Kitamura, Y. & Yoshida, M.: Post-Fukushima radiation education for Japanese high school students in affected areas and its positive effects on their radiation literacy, Journal of Radiation Research, Vol. 59(S2), pp. i65–ii74 (2018).
3) Murai, K.: The current state of radiation education in schools and results of the opinion survey on radiation, INSS Journal, Vol. 20, pp. 28–37 (2013) (in Japanese).
4) Ministry of Education, Culture, Sports, Science and Technology (MEXT): Supplemental reading on radiation. Available at: http://www.mext.go.jp/b_menu/shuppan/sonota/detail/1311072.htm. (Accessed: Sept. 20, 2018) (in Japanese).
5) Ohmori, G.: X-ray exposure in the teaching of science at junior and senior high schools, Man-made Radiation Source-A, NIRS-M—105, Japan, pp. 107–112 (1995) (in Japanese).
6) Ohmori Giroh: Leakage of X-rays from a Crookes Tube and Protection from It, Journal of the Physics Education Society of Japan, Vol. 43(1), pp. 29–32 (1995) (in Japanese).
7) Fujibuchi, T. et al.: Measurement of leakage dose distribution from Crookes tube using imaging plate, Nippon Hoshasen Anzen Kanri Gakkai-Shi, Vol. 10(3), pp. 40–45 (2011) (in Japanese).
8) Tabara Takashi, Niimi Katsuhiko, Kusama Tomoko & Yoshizawa Yasuo: Radiation protection for pupils and teachers in the use of discharge tubes at school, Journal of the Physics Education Society of Japan, Vol. 35(3), pp. 150–153 (1987) (in Japanese).
9) Shigenori UTOH: Cold-cathode tube containing the problem of leakage x-ray in a physics class of education at schools, Bulletin of University of Teacher Education Fukuoka. Part III, Mathematics, natural sciences and technology, Vol. 66(1), pp. 1–11 (2017) (in Japanese).
10) ICRP Publication 36: Protection against Ionizing Radiation in the Teaching of Science, Annals of the ICRP, Vol. 10(1) (1983).
11) Redus, B. & Xr, A.: Efficiency of Amptek XR-100T-CdTe and -CZT Detectors Application Note ANCDTE1 Rev 2. 8.
12) Miyajima, S., Imagawa, K. & Matsumoto, M.: CdZnTe detector in diagnostic x-ray spectroscopy, Medical Physics, Vol. 29(7), pp. 1421–1429 (2002).
13) Redus, R. H., Pantazis, J. A., Pantazis, T. J., Huber, A. C. & Cross, B. J.: Characterization of CdTe Detectors for Quantitative X-ray Spectroscopy, IEEE Transactions on Nuclear Science, Vol. 56(4), pp. 2524–2532 (2009).
14) Matsumoto, M., Yamamoto, A., Honda, I., Taniguchi, A. & Kanamori, H.: Direct measurement of mammographic x-ray spectra using a CdZnTe detector, Medical Physics, Vol. 27(7), pp. 1490–1502 (2000).
15) Krmar, M., Bucalović, N., Baucal, M. & Jovančević, N.: Possible use of CdTe detectors in kVp monitoring of diagnostic x-ray tubes, Nuclear Instruments Methods Physics Research A, Vol. 622(1), pp. 256–260 (2010).
16) XR-100CdTe X-Ray & Gamma Ray Detector—Amptek—X-Ray Detectors and Electronics. Available at: http://amptek.com/products/xr-100cdte-x-ray-and-gamma-ray-detector/#7. (Accessed: Sept. 23, 2018).
17) Redus, R.: CdTe Measurement of X-Ray Tube Spectra: Escape Events Application Note ANCDTE1 Rev A. 3 (2008).
18) Kang, Y. et al.: Breakdown Characteristics and Mechanisms of Short Needle–Plate Air Gap in High-Speed Airflow, IEEE Transactions on Plasma Science, Vol. 45(9), pp. 2406–2415 (2017). 
19) Sankar, P. B.: Measurement of air breakdown voltage and electric field using standard sphere gap method. Master thesis, National Institute of Technology, India (2011). Available at: http://ethesis.nitk.ac.in/2875/.
20) Kramers, H. A.: XCIII. On the theory of X-ray absorption and of the continuous X-ray spectrum, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, Vol. 46(275), pp. 836–871 (1923).
21) Behnke, B. & Hupe, O.: Can half value layer measurements be used together with the effective energy to obtain conversion coefficients for X-ray spectra?, Radiation Protection Dosimetry, Vol. 173(4), pp. 277–285 (2017).
22) Kato, H. et al.: Problems of the effective energy used as a quality expression of diagnostic X-ray, Nihon Hoshasen Gijutsu Gakkai Zasshi, Vol. 67(10), pp. 1320–1326 (2011) (in Japanese).
23) Gotanda, T. et al.: Half-Value Layer Measurement for Effective Energy, Using Radiographic Film and Step-Shaped Aluminum Filter, World Congress on Medical Physics and Biomedical Engineering, September 7–12, 2009, Munich, Germany (eds. Dössel, O. & Schlegel, W. C.), Springer Berlin Heidelberg, pp. 58–61 (2009).
24) Khan, F. M. & Gibbons, J. P.: Chapter 7. Quality of X-ray beams, Khan’s the physics of radiation therapy, Edition 5th, Lippincott Williams & Wilkins/Wolters Kluwer, pp. 89–96 (2014).
25) Supplee, C.: XCOM: Photon Cross Sections Database. NIST (2009). Available at: https://www.nist.gov/pml/xcom-photon-cross-sections-database. (Accessed: Sept. 25, 2018).
26) Sprawls, P.: Chapter 11. Radiation Penetration, Physical principles of medical imaging, Edition 2nd, Medical Physics Publishing, Madison, Wisconsin, pp. 159–170 (1995).