Establishment of Experimental System for Radiation Safety Management in Teaching of Science Using Crookes Tubes

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Abstract

In Japan, Crookes tube has been used in the teaching of science for junior-high school students where the first purpose is to learn characters of electron and current. During experiments, the X-rays radiated from a Crookes tube caused a high dose ($H_p(0.07)$ up to 250 mSv/h at 5 cm) that may expose to the participants. However, a low energy X-ray is hard to measure using conventional survey meters. From March 2017, a project named "Establishment of radiation safety management system for low energy X-rays at education sites" was started in Japan. Its scope aims to establish a guideline on radiation safety management at the educational sites. In this study, as the partials of the project, we investigated characteristics of X-rays emitted by Crookes tubes, the relevance of operational factors and the effects of electrical setting on leakage dose from Crookes tube.

A variable applied voltage (HV) from a power supply (an induction coil) to a Crookes tube created inhomogeneous energy of X-rays radiated from a Crookes tube. In a conventional Crookes tube, the maximum applied voltage was approximately 25 – 40 kV, and the tube emits X-rays at the low energy of approximately 16 – 20 keV. By increasing the applied voltage, the X-ray energy peak was shifted to a higher region in the X-ray energy spectrum. As a result, the X-ray energy spectrum and applied voltage were changed by HV equipment setting that gives a large change in leakage dose. The results also indicated that the dose depended on a change of current in the Crookes tube, and changed with a distance as a square of the distance. Recently, we initially applied cloud chamber to simulate the X-ray energy spectrum from the Crookes tube. It showed a correlation between X-ray track length and X-ray energy. With a low energy X-ray of 19.5 keV, the length was observed at 3~4 mm by the cloud chamber.

Keywords: *Crookes tube, radiological education, radiation protection, X-ray energy spectrum*

1. INTRODUCTION

Crookes tube is the oldest fundamental X-ray device that was used by Roentgen to start the study of 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 to hit the cathode, which knocks out secondary electrons. These electrons emitted by the cold cathode are accelerated to collide with the glass tube to create a bremsstrahlung X-ray.

In Japan, Crookes tube has been used for the teaching of science in junior-high schools, and its first purpose is to learn the character of electron and current. In addition, the next course of study was published in 2017 and that required understanding the nature of radiation related to the cathode rays [1]. In other countries, Crookes tube has been used in the teaching of physics and chemistry, especially in the teaching of X-ray radiation, and the basics of radiation interaction with material for high school student [2, 3]. However, there is not a practice of Crookes tube in the teaching of science in Vietnam although radiological education has been added to school curricula at high school for several tens of year.

During demonstrations and experiments on Crookes tube, teachers and participating students may be exposed to X-ray radiation. Regarding this problem, some studies on radiation safety in the teaching of the natural sciences using the Crookes tubes have been performed in Japan [4-6]. An assessment conducted on some Crookes tubes showed that X-rays emitted by Crookes tubes had very low energy (approximately 20 keV). However, the 1 cm dose equivalent was remarkably high (up to 143 mSv/h at 5 cm) [4]. It caused a maximum dose ($H_p(10)$) of 0.15 mSv per experiment for students, which is higher than the recommended value in ICRP publication 36 [7]. Another study indicated that there was a distribution of leakage dose caused by scattered photons in any direction enclosing the Crookes tube, but the investigation of X-ray energy information was not performed [5].

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 low. In practice, it is necessary to accomplish the radiation protection and safety guideline that has 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, leakage dose, electrical parameters, and the relevance of operational factors were investigated and discussed. In addition, a cloud chamber is initially used in stimulating an X-ray spectrum as an onsite method for junior-high school students to practice [8]. This work provides a development of the system that can actually be used in measurements of low energy X-rays.

2. MATERIALS AND METHOD

The experiments were conducted with a conventional 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 using 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 a power dial in several products. The range of the spark gap is 10 – 100 mm and the discharge can be adjusted by changing the distance of the electrodes. 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.).

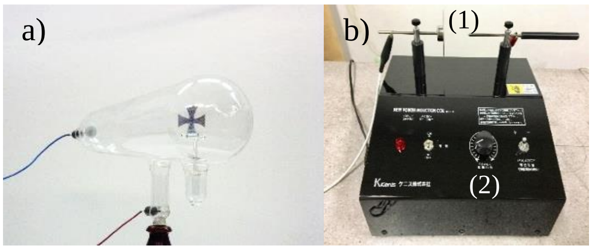


Figure 1. a) Crookes tube equipment uses an induction coil as a power supply; b) An induction coil that a desired output voltage can be obtained by regulating the distance of the electrodes (1) and/or output power with a scale from 0 to 20 (2).

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 with a CZT crystal, a Be window, and a Peltier cooler can detect energies from a few to several hundred keV [9]. 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 is used for data acquisition, spectral analysis, and control of signal processors.

3. RESULTS AND DISCUSSION

A. Measurement of X-ray energy spectrum and applied voltage

In this experiment, the distance of the electrodes (spark gap) of the induction coil was set to 40 mm, and the variable applied voltages were controlled by changing the output power controller from 0 to 20.

To determine the low energy of the X-ray tube emission, 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. The distinct spectra of X-rays modified by applied voltages and acquired using the CZT detector, are shown in Fig. 2. Then the spectra are fitted using a Gaussian function and the best-fit values are obtained for single peak fitting. The fitting result determines the effective energy of X-rays corresponding to various output voltages: PW0, PW2, and PW4 as 15.8 keV, 17.0 keV, and 18.1 keV, respectively.

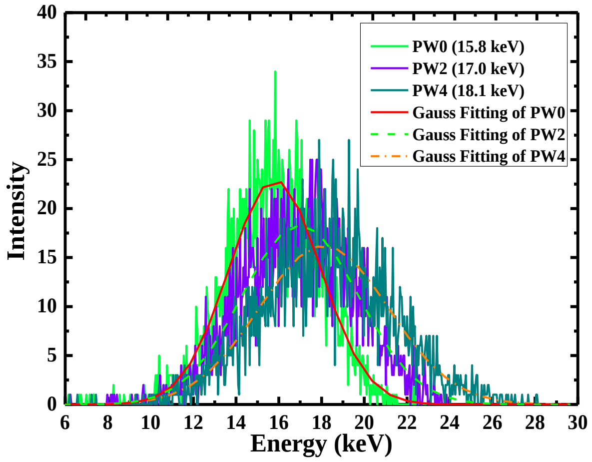


Figure 2. X-ray spectra radiated by the Crookes tube acquired by the CZT detector. Each X-ray spectrum corresponds to an output power of PW0, PW2, and PW4.

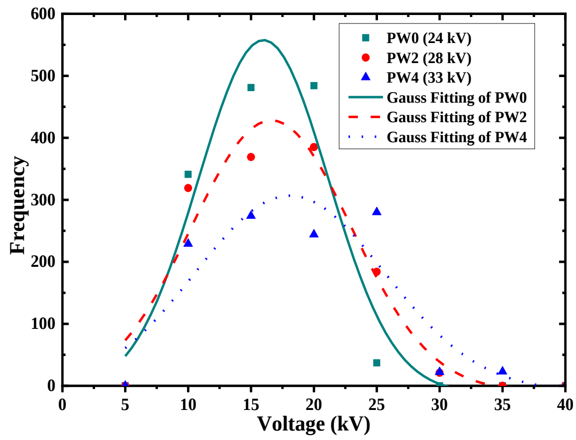


Figure 3. The distribution of the applied voltage shows an increase in the output voltage of PW0, PW2, and PW4.

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 (Fig. 3). 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 confirmed that the effective energy was shifted to a higher region of the spectrum as the applied voltage increased.

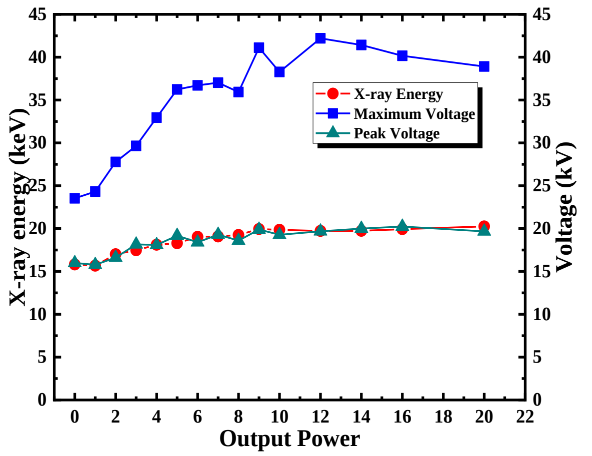


Figure 4. The relevant graph of the applied voltage and the spectral distribution corresponding to the output voltage distribution from PW0 to PW20.

The voltage applied to the Crookes tube corresponds to the energy of the electrons flying 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 [10]. 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 2. 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. 4). When the applied voltage was stable, the effective energy also exhibited saturation at PW9, with an average energy of approximately 19.5 keV.

B. Effects of electrical setting on a leakage dose

A change of setting on the power supply leads to a change of the output electrical components (applied voltage, current) and it affects X-ray properties (energy, leakage dose).

Effect of current on dose rate. The output power was changed from PW0 to PW8 at the electrode distance of 20 mm, 25 mm, and 30 mm. An ionization chamber (Hitachi ICS-1323) and an analog ammeter were used to estimate the ambient equivalent dose rate ($H^*(0.07)$) and the average current, respectively. Figure 5 shows the correlation between the average current and the dose rate at a distance of 30 cm from the Crookes tube. At the electrode distance of 20 mm, the air discharge becomes intense at PW4 then it keeps stability. These results show that the electrode distance does not affect the current or dose rate if a discharge does not occur. In addition, the current and dose rate increase with the discharge output. The correlation between the average current and dose rate was determined using an exponential function (Fig. 5). However, even though a quadratic function is used, a fitting can be determined with similar accuracy. Thus, it is an uncertain assumption whether the transmissivity of glass (forming the Crookes tube itself) changes exponentially due to a slight voltage increase, whether the dose is determined by the squared current.

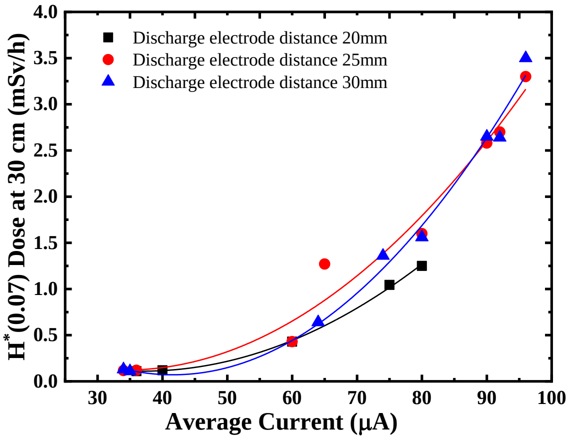


Figure 5. The dose rate was changed with the change of the current.

However, the relevance between electrical components and leakage dose is different from each tube. Some new Crookes tubes releasing a large current at a low voltage expose very low leakage dose or complete elimination.

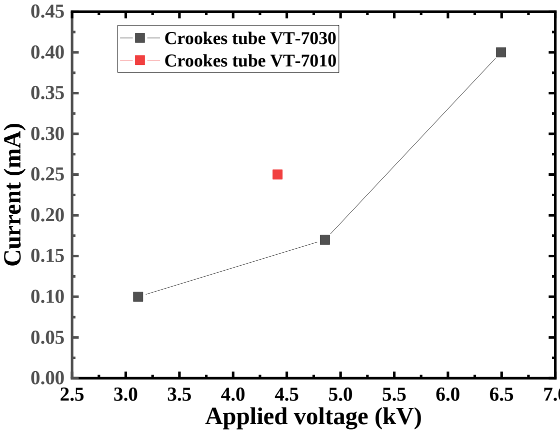


Figure 6. The conductance of new types of Crookes tube.

The experiment was conducted on new types of Crookes tube manufactured by Horizon Co., Japan as VT-7030 tube and VT-7010 tube. Figure 6 shows the conductance of new types of Crookes tube whose current is from 0.1 to 0.45 mA and the applied voltage releases from 3.1 to 6.5 kV. The VT-7030 tube using the Cockcroft Walton high voltage unit (type-MY, Kenis Ltd., Japan) was regulated with three scales of output voltage released the maximum voltage approximately 6.5 kV. While VT-7010 tube using the VTS-40 power supply (Horizon Co., Japan) released an output voltage of approximately 4.4 kV. In the teaching of science, an X-ray apparatus is extremely safe if the applied voltage does not exceed 5 kV [3]. The leakage dose is measured of equal background, so it sufficiently assures radiation protection during a demonstration.

Effect of measurement distance on a leakage dose. The output voltage from the induction coil was sequentially regulated by changing the electrode distance at 15 mm, 20 mm, and 30 mm, and the output power was set at scales of PW0, PW2, and PW4, respectively. The glass badge dosimeters (type-FX, Chiyoda Technol) were put in the front direction of the Crookes tube at a distance from 15 cm to 50 cm, and a changing step is 5 cm. A measurement performed in 10 min, then the $H_p(0.07)$ equivalent dose was converted to dose rate per hour. The dose rate is fitted as a linear function which inversely proportional to the square of the distance

(Fig.5 a). Although the Crookes tube is not a point source, it can be seen that the dose rate decreases with the inverse square of the distance as a point source. It means that the exposure can be reduced as the ALARA principle in the case of the Crookes tube.

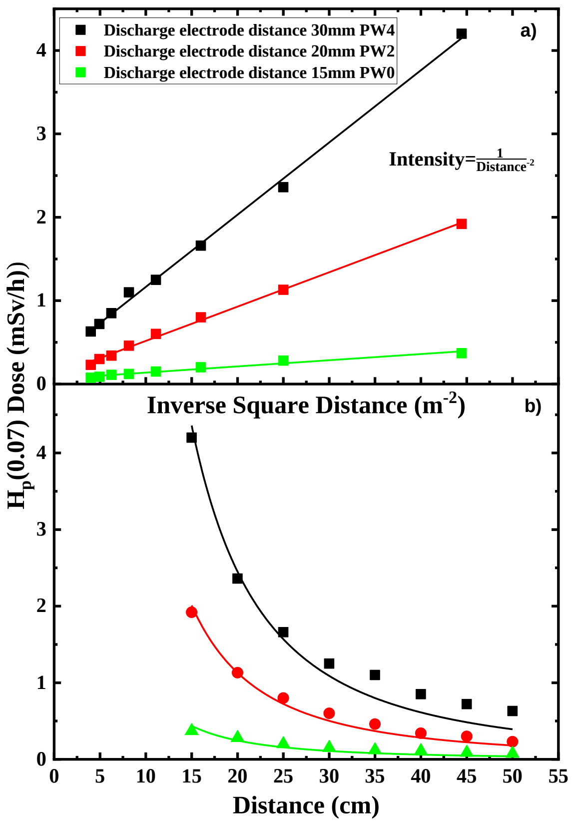
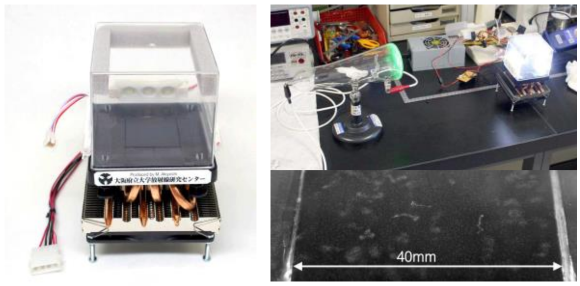


Figure 7. The dose rate was changed with measurement distance.

Moreover, the dose rate can be reduced significantly by narrowing the distance of the electrodes. However, at an electrode distance of 15 mm, a spark occurred intensely depending on the weather conditions, so this distance should be limited in the setting.

C. Simulation X-ray energy spectrum using a cloud chamber.

Alpha particles and electrons are too small to be seen, and the velocity of a high energy particle (in MeV) cannot be caught up by a super high-speed camera. However, the trace which radiation remained in ambient is visible with eyes. Cloud chamber is a high-performance “fog box” developed to visualize a length of radiation track. It used a Peltier-cooler to drop the temperature inside the box to down below -20^{0}C, and ethanol was used as an ionization ambient. When the temperature is dropped, the saturated vapor pressure is dropped that causes the evaporated gaseous ethanol tries to return to liquid. White particles that look like mist are small particles of liquid ethanol (Fig. 8). However, even though the temperature has dropped, there is also a supersaturated gas that does not turn into liquid particles. By giving a stimulus, the supersaturated vapor will turn into liquid particles one after another.



When radiation travels through the air, it repels many electrons to form positive and negative ion pairs (ionization). Then these ions are formed in supersaturated ethanol vapor, and it becomes a core of small liquid particles. Many of the particles of this liquid are formed after the radiation passed, so the radiation trace is observed as a white line. As a result, the cloud chamber can observe not only alpha particles but also beta particles, and X-rays irradiated from a Crookes tube. Basing on the correlation between X-ray track length and X-ray energy, the cloud chamber was applied to simulate the X-ray energy spectrum from the Crookes tube.

The Crookes tube emits X-ray with soft energy of approximately 19.5 keV directly exposing to a cloud chamber at a distance of 30 cm (Fig. 8). A camera attached outside the cloud chamber recorded radiation interaction inside the box. It is possible to obtain an energy spectrum by using image analysis of the length of radiation track. Figure 9 shows the correlation between the X-ray spectrum and simulating spectrum basing on the distribution of length of radiation tracks for X-ray energy of 19.5 keV. A low energy electron of 20 keV travels a mean free path approximately 8.1 mm in the air (density of air at 20^{0}C) [11]. In the cloud chamber with the gaseous ethanol ambient, the mean free path of X-ray energy of 20 keV is approximately

3.6 mm is shorter than the nominal value. This can be explained that the cloud chamber contains ethanol vapor and droplets to increase the density, and its temperature is at a very low minus degree (approximately -20^{0}C).

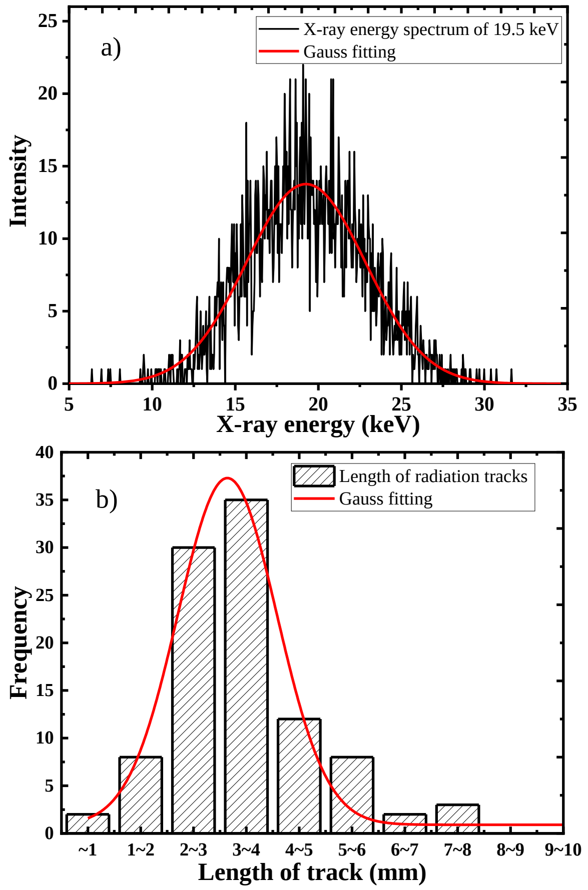


Figure 9. Distribution of the length of radiation tracks for X-ray energy approximately 19.5 keV.

4. CONCLUSION

We established an experimental system to estimate characteristics of X-ray radiated from the Crookes tube.

- The conventional Crookes tube emitted low energy X-ray approximately 19.5 keV, and the X-ray energy peak was shifted to a higher region of the spectrum with the increase of applied voltage.
- The changes of the electrical setting affected the leakage dose by an assumption of an exponential function or a quadratic function. However, the new types of Crookes tube released a high current with low voltage, and the leakage dose was of equal background. In addition, the leakage dose rate depended on distance as a function of the inverse square of the distance.
- The cloud chamber device has been developed to support radiological education. The visualized length of radiation track helps students to understand radiation energy. Our initial results confirmed that it is possible to evaluate the X-ray energy spectrum on education sites as a low-cost device. In addition, by replenishing ethanol, it is possible to operate for a long time, so it is also suitable for exhibitions at science museums and events.

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Thiết lập hệ thống thực nghiệm trong việc quản lý an toàn bức xạ khi sử dụng ống Crookes trong giảng dạy khoa học tại Nhật Bản

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