INVESTIGATION OF LOW ENERGY X-RAY RADIATED FROM CROOKES TUBE USED IN RADIOLOGICAL EDUCATION

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INTRODUCTION

BACKGROUND

- 2008: The radiological education guideline has been added to the school's curricula by MEXT.
- March, 2011: Fukushima nuclear accident occurred.
- Oct., 2011: MEXT accomplished the radiation education materials.
- 2014: The supplemental reading documents included the accidental information have been published (MEXT).

- Crookes tube has been used in the teaching of science at a junior and high school in Japan.
- X-ray radiation is possible exposure to a teacher who conducts the demonstrations and experiments as well as participated students.
- It was reported in Japan that the X-ray radiated from the Crookes tube had very low energy (about 20 keV) but the dose was very high (up to several hundred mSv/h).
- It is necessary to accomplish the radiation protection and safety guideline that have not been evaluated sufficiently yet in Japan.

OBJECTS OF THE PRESENT RESEARCH

- Conducting an initial evaluation of the characteristics and properties of X-ray beam radiated from the Crookes tube used in the junior-high school for educational science.
- Developing the system that actually can be used in measurement of low energy X-rays.
- Submitting the results as the recommendation and guideline for radiation protection rules to prevent unwanted harmful effects from radiation.

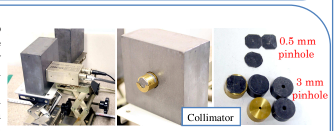
MATERIALS AND METHODS

X-ray spectrometer

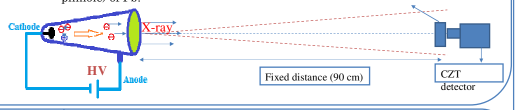
Crookes tube (3C-B, Kenis Ltd., Japan) → CZT Detector (XR-100T-CZT, Amptek Inc., USA) → Power supply and Amplifier (PX2T, Amptek Inc., USA) → Pocket Multichannel (MCA8000D, Amptek Inc., USA) → DPPMCA Software (Amptek Inc., USA)

Induction coil:
- High voltage power supply, spark gap of 10 – 100
- Nominal dielectric breakdown voltage in the air
- The desired output voltage can be obtained by [change] of the discharge electrodes or discharge output.
- In this experiment, the discharge distance was [v]ariable applied voltages were controlled by change of discharge output from 0 to 20 in scale.

Collimator:
- Reduce pile-up effect and dead time due to high X-ray flux in spectrum acquisition.
- Cylinder (3mm pinhole) and thin plate (0.5 mm pinhole) of Pb.



Crookes tube:
By applying a voltage of several tens kV between cathode and anode in the tube, cations in the evacuated tube are accelerated to hit the cathode that knockout secondary electrons. These electrons emitted from the cold cathode are accelerated to collide the glass tube to create stopping X-ray.

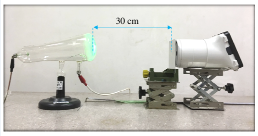


Applied voltage distribution

Purpose:
- Investigating the interrelation between the distribution of applied high voltage and the X-ray spectrum.
- Carried out simultaneously with X-ray spectra acquisition.

Voltage divider circuit:
- Reducing the magnitude of voltage during measurement against damage to oscilloscope voltage probes due to high pulse.
- The circuit consists of two resistors in series, one of 500 MΩ glass resistor, and another of 100 kΩ.

Estimation of transmission



- Transmission of X-ray with various output applied voltages generated by Crookes tube through Aluminum layers.
- The transmission of X-rays was estimated by the ambient dose equivalent H*(0.07) using an ionization chamber (ICS-1323, Hitachi Ltd., Japan).

RESULTS AND DISCUSSION

1. X-RAY SPECTRUM MEASUREMENT

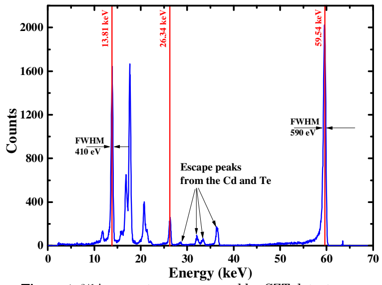


Figure 1. ^{241}Am spectrum measured by CZT detector

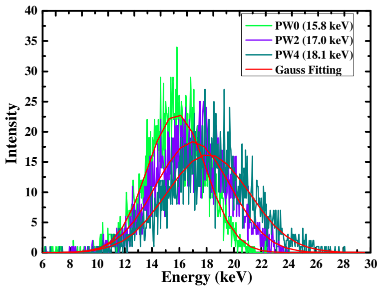


Figure 3. X-ray spectra radiated from Crookes tube acquired by CZT detector. Each spectra corresponds to output power of PW0, PW2, and PW4.

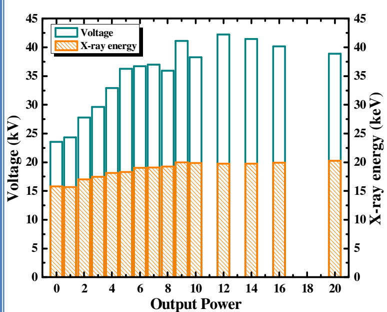


Figure 5. The relevant graphic of the applied voltage and spectral distribution corresponding to output voltage distribution from PW0 to PW20.

2. APPLIED VOLTAGE MEASUREMENT

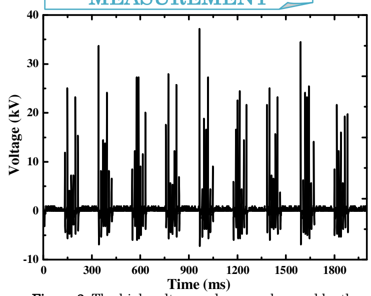


Figure 2. The high voltage pulse was observed by the oscilloscope with a buffer length of 32K, and a Time/DIV of 20 ms.

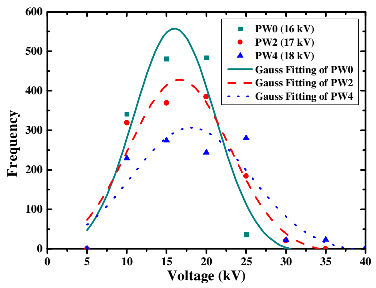


Figure 4. The distribution of applied voltage shows the increase in the output voltage of PW0, PW2, and PW4.

Correlation between applied voltage and X-ray energy:

- There was a good correlation in the distribution behavior between the X-ray spectrum and applied voltage (Fig. 3&4).
- The output voltage distributed increasingly in 23.5 ~ 38.9 kV along with increasing output power.
- A spark appeared at PW9 then the output voltage kept relatively consistent.
- The actual average operating voltage was about 40 kV that shows good agreement with the nominal discharge voltage at 40 mm of plate-needle distance.
- The spectral distribution changed in 15.8 ~ 20.3 keV corresponding to the applied voltage change.
- With the consistency of applied voltage, the X-ray energy also showed saturation at PW9 (applied voltage reaches 40kV) with an average energy of about 19.5 keV.

3. TRANSMISSION MEASURMENT

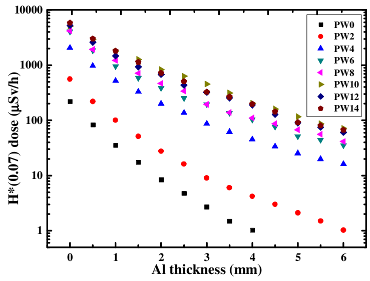


Figure 6. Transmission of X-ray with various output applied voltages generated by Crookes tube through Al using ionization chamber ICS-1323.

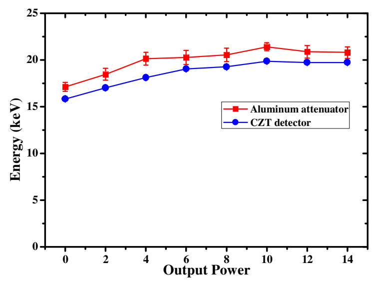


Figure 7. X-ray energies with various output powers obtaining by attenuation measurement and CZT detector.

- The transmission curve could be fitted with the linear expression of $\ln(I) = -\mu x + \ln(I_0)$.
- The slope of the graph is the Al linear attenuation coefficient (μ) with the best fitting coefficients rather than 0.98.
- The effective energy of X-ray was determined from the linear attenuation coefficient of Al using data from the National Institute of Standards and Technology (NIST, USA) and X-COM program.

Table 1. X-ray energy estimated from Al attenuator and CZT detector. The ambient dose equivalent H*(0.07) measured at a distance 30 cm from the Crookes tube.

Output power	H*(0.07) (μSv/h)	μ (cm^{-1})	Energy (keV) Al attenuator	Energy (keV) CZT detector
PW0	219	14.58	17.12	15.81
PW2	557	11.70	18.46	17.01
PW4	2064	9.12	20.13	18.11
PW6	4086	8.94	20.27	19.04
PW8	4182	8.62	20.53	19.26
PW10	5070	7.66	21.40	19.86
PW12	5244	8.22	20.87	19.73
PW14	5838	8.32	20.79	19.73

Relevance of X-ray energy between CZT detector and transmission measurement:

- The effective energy from the transmission measurement was relatively good agreement with the spectra from CZT detector (Fig. 7).
- The average percent difference between the two measurements was 7.5%, and the average energy was about 19.5 keV for CZT detector and about 20 keV for attenuation measurement (Table 1).
- This difference caused by the effect of the filtration on an X-ray beam in Al attenuation measurement. Added filtration caused hardening the X-ray beam because it absorbed the lower energy photons. As a result, it produced a shift in the effective energy of the X-ray beam.

SUMMARY

- We estimated low energy X-ray from the Crookes tube with variable voltages considered hard to perform. It was about 19.5 keV with the discharge distance of 40 mm.
- We estimated the correlation in distribution between applied voltage and X-ray energy. The X-ray energy was shifted to higher region in the spectrum when increasing the applied voltage.
- We used the attenuation measurement as an effective approach to yield information of low photon energy as well as reflected the change of energy along with the change of output power. It should be considered as an alternative approach of CZT detector in the estimation of low X-ray energy in the teaching of science at junior-high school.