Radioluminescence by synchrotron radiation with lower energy than the Cherenkov light threshold in water

Yoshiyuki Hirano1,4, Masataka Komori4, Daichi Onoda2, Takayuki Nagae3 and Seiichi Yamamoto1

1 Radiological and Medical Laboratory Sciences, Nagoya University Graduate School of Medicine, Japan
2 School of Health Sciences, Nagoya University, Japan
3 Synchrotron Radiation Research Center, Nagoya University, Japan
4 Author to whom any correspondence should be addressed.

E-mail: hirano@met.nagoya-u.ac.jp

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Abstract
Radioluminescence by protons and carbon ions of energy lower than the Cherenkov threshold (∼260 keV) in water has been observed. However, the origin of the luminescence has not been investigated well. In the present work, we imaged radioluminescence in water using synchrotron radiation that was of sufficiently lower energy (11 keV) than the Cherenkov threshold and we measured its spectrum using a high-sensitivity cooled CCD camera and optical longpass filters having 5 different thresholds. In addition, to determine effects of impurities in water, the water target was changed from ultrapure water to tap water. Monte Carlo simulation (Geant4) was also performed to compare its results with the experimentally obtained radioluminescence distribution. In the simulation, photons were generated in proportion to the energy deposition in water. As a result, the beam trajectory was clearly imaged by the radioluminescence in water. The spectrum was proportional to \( \lambda^{-3.4 \pm 0.4} \) under an assumption of no peaks. In the spectrum and distribution, no differences were observed between ultrapure water and tap water. TOC (total organic carbon) contents of ultrapure water and tap water as an impurity were measured and these were 0.26 mg l\(^{-1}\) and 2.3 mg l\(^{-1}\), respectively. The radioluminescence seemed to be attributable to water molecules not impurities. The radioluminescence distribution of the simulation was consistent with the experimental distribution and this suggested that radioluminescence was proportional to dose, which is expected to allow use for dose measurement.

1. Introduction
Radiation induced emission of visible light in water or tissue has many applications in medical physics (see the review [1] and references therein). Radiotherapy quality assurance and radiotherapy dosimetry are two important clinical applications [2–5]. These photons originate from Cherenkov radiation; and Cherenkov luminescence imaging (CLI) has been applied to imaging of radionuclides and radiotherapy beams. Several reviews of medical applications for Cherenkov radiation have been published [6–8]. Cherenkov radiation is induced by successive polarization and depolarization of the medium along the charged particle trajectory, which gives rise to constructive interferences. For electrons in water, the Cherenkov radiation threshold is ∼260 keV. However, Yamamoto et al [9, 10] imaged radioluminescence by secondary electrons with lower energy than the threshold during proton and carbon ion irradiation to water. They also imaged radioluminescence by photons produced by a diagnostic x-ray tube [11], and showed the radioluminescence had a potential for imaging a dose distribution. Prior to these three imaging studies by Yamamoto et al, Tarasov et al [12] had observed radioluminescence in water irradiated by accelerated electrons with energy lower than 230 keV, and found that the measured efficiency was approximately 60 times lower than the efficiency of radioluminescence in air. However the mechanism of the radioluminescence has not been investigated well.
In the present study, we imaged radioluminescence in water irradiated by x-rays using synchrotron radiation. We need an x-ray source with lower energy than the Cherenkov threshold and with high intensity because yield of radioluminescence in water is very low as shown by Tarasov et al [12] and another study by Yabe et al [13] in which the yield was estimated to be 0.2 photons/MeV. Synchrotron radiation source fulfills the requirements. Because radioluminescence may be due to impurities in water, we used ultrapure water and tap water as targets. Spectra were measured using 5 optical longpass filters as described previously [14]. The radioluminescence distributions and spectra were compared between ultrapure water and tap water. To check the impurities of water, total organic carbon (TOC) was measured. In addition, we performed a Monte Carlo simulation to confirm whether the radioluminescence is attributable to energy deposition. The simulated distribution in which photon yield was proportional to energy deposition was compared to the experimental distribution. The simulation results were also used for some corrections to obtain a more accurate spectrum. These basic data will be useful for understanding the mechanism and for using the radioluminescence as a new probe to measure radiation.

2. Materials and methods

2.1. Synchrotron radiation
As the synchrotron radiation source, we used the Nagoya University beam line BL2S1 in the Aichi Synchrotron Radiation Center in Aichi Prefecture, Japan. The beam line is mainly intended for use in x-ray diffraction measurements of single crystals of macromolecules such as proteins and nucleic acids. The available wavelength range is 0.7–1.8 Å and the beam size is 200 × 200 μm (FWHM). The x-rays of 11.1 keV (1.12 Å) were used in this study and the flux was 1.1 × 10¹⁰ photons/s. The details of the beam line have been given elsewhere [15].

2.2. Experimental set-up
The experimental set-up is shown in figure 1. A water target was positioned on the beam line. Because a container holding water also will produce luminescence [11], we prepared a water flow circulating system which enabled us to irradiate the water directly without a container. The diameter of the water path was about 7 mm. A high-sensitivity cooled CCD camera (BU-50LN, BEITRAN, Japan) with a F-1.4 lens (M1214-MP2, CBC computar, Japan) (detector system 1) was used for the imaging of the radioluminescence at 80 mm from the target. To confirm the reproducibility of the experimental results, another camera system (detector system 2) was used that consisted of a UV sensitive CCD camera (BU-56DUV, BEITRAN, Japan) and a F-2.8 UV transparent lens (UV0928CM2, Universe Optical Industries Co., Japan). To obtain spectra, we separately used 5 optical longpass filters in front of the camera; all were manufactured by Asahi Spectra Co., Ltd (Japan) and had specifications of wavelength longer than 350 nm (LU0350), 450 nm (LV0450), 550 nm (LV0550), 650 nm (LV0650), and 750 nm (LI0750).

2.3. Spectrum measurement
The spectra of the radioluminescence in water irradiated by synchrotron radiation were measured with 5 longpass filters. First, we determined a region of interest (ROI) including a hot spot in the image obtained with

![Figure 1. Experimental set-up of the spectrum measurements: top view (a) and side view (b). Water flowed using the circulation system. The diameter of the water path was about 7 mm. The CCD camera was located 80 mm from the water target.](image-url)
At 680 °C, the TOC which is often monitored in water purification systems was measured by the TOC-L, Shimadzu Scientific Instruments, Japan. The minimum limit of determination was 0.05 mg l⁻¹. TOC contents of ultrapure water and tap water were measured by the MST (Foundation for Promotion of Material Science and Technology of Japan). If the radioluminescence in water is attributed to organic carbon, the yield and spectrum of the radioluminescence will be affected by the level of the TOC contents.

2.4. TOC measurement

As an index of impurities in water, TOC which is often monitored in water purifier systems was measured by the 680 °C combustion catalytic oxidation method with a TOC analyzer (TOC-L, Shimadzu Scientific Instruments, Japan). The minimum limit of determination was 0.05 mg l⁻¹. TOC contents of ultrapure water and tap water were measured by the MST (Foundation for Promotion of Material Science and Technology of Japan). If the radioluminescence in water is attributed to organic carbon, the yield and spectrum of the radioluminescence will be affected by the level of the TOC contents.

2.5. Monte Carlo simulation

To understand the radioluminescence distribution, we did Monte Carlo simulation with Geant4 [16, 17]. Another purpose of the Monte Carlo simulation was to estimate correction factors described in section 2.6. Geant4 is widely utilized in radiation research and it enables simulation of interactions between radiation and materials by a Monte Carlo method. In addition, Geant4 includes optical photon processes such as scintillation, Cherenkov and boundary processes, and it calculates tracking of the photons. We constructed the experimental set-up consisting of a cylindrical column of water as the target, a lens of the CCD camera and a light shielding box (figure 1). The x-rays with energy of 11 keV were irradiated to the water. Proportional to the energy deposition in water, optical photons were produced and emitted isotropically. At the boundary between water and air, the direction of the photons was changed by Fresnel refraction, Fresnel refraction or total internal reflection. We tracked photons from the production position to the lens surface. Detection of the photons was determined by the transmittance of the lens and quantum efficiency of the CCD camera. We recorded the last interaction position and made a histogram of the position on the beam axis. For instance, a photon was produced at a position inside the water and was reflected at a boundary, before reaching the lens and being detected. In this case, the refraction position was recorded. In the simulation, we took into account optical material properties: refractive index of water as a function of wavelength (figure 2(a)), 1.0 refractive index of air, 0.2 photons/MeV (200–800 nm) photon yield in water estimated in our previous study [13], 19 ± 3 photons/MeV (200–650 nm) photon yield in air [18], emission spectrum of water [14], and spectrum of air [19]. At the same time, to obtain dose distribution, we recorded a position where energy was deposited and made a histogram of the position weighted by the energy deposition. We compared the distribution of the last

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Figure 2. Quantum efficiencies of CCD cameras and transmittances of lenses (a). We used two combinations of a CCD camera and a lens: BU-50LU and F-1.4 lens (detector system 1), and BU–56DUV and F-2.8 (detector system 2). The latter system was sensitive to UV light. Transmittance of 5 optical longpass filters (b).

no filter. The ROI was a square shape with the width at half maximum of the image intensity. Then, bin content in a spectrum was got using two images obtained with different filters. For instance, to obtain bin content of 350–450 nm, ROI values in the image obtained with the 450 nm filter were subtracted from ROI values in the image obtained with the 350 nm filter. The bin content was corrected for the transmittances of the lenses and filters, and quantum efficiencies of the CCD cameras. The quantum efficiency curves and transmittances of the filters were available from the specification sheets of the manufacturer, and we measured the transmittances of the lenses. These are shown in figure 2. The spectrum measurements were repeated 3 times: 2 times with detector system 1 and 1 time with detector system 2. The exposure time was 3 min for each filter. For each filter, a background image without the beam was measured and subtracted from the image with the beam. For each image, no processing such as noise removal process and median filter were applied. After the measurements with ultrapure water as a target, the target was replaced with tap water. Each spectrum was fit with a simple function, \( a \times \lambda^n \), where \( \lambda \) is wavelength, and \( a, n \) are fit parameters.
interaction positions with the radioluminescence distribution obtained in the experiment. The bin size of both the radioluminescence and dose distributions was 0.08 mm same as pixel size of images. To estimate a correction factor for the spectrum described in the following section, fraction of radioluminescence by air in the ROI was calculated.

2.6. Corrections of the spectra
To obtain accurate spectra, we applied 5 corrections as follows. (1) Transmittance of lenses and quantum efficiency of CCD cameras were corrected. The bin width of a spectrum was large (100 nm width). Then, the area under the curve of each wavelength region of the transmittance and efficiency curves was used as the correction factor. (2) Transmittance of the longpass filter was corrected. For longpass wavelength regions, transmittances are not equivalent among filters. The filter transmittance factor was needed for subtracting two ROI values: (ROI value 1 - factor × (ROI value 2). (3) Fraction of radioluminescence attributed to air in ROIs was estimated by the simulation. (4) Due to the wide bin width, the systematic error of \( n \) (index of \( \lambda \)) by fitting was not negligible. Thus, we estimated the error under a simple assumption that a spectrum was proportional to \( \lambda^n \). To do that, we generated fine spectra (1 nm bin width) by changing \( n \) from –1.0 to –5.0 (true \( n \)). Then, for each spectrum, we reshaped the spectrum with coarse sampling (100 nm width) considering transmittance of the lens and quantum efficiency. Finally, correction (1) was applied again to the reshaped spectrum, and fitting was applied. By comparing fitting results of \( n \) and true \( n \), we estimated systematic error of the fit parameter \( n \).

3. Results

3.1. Images of radioluminescence in water
Figure 3(a) shows an image of luminescence in a water target when irradiated by 11 keV x-rays. The trajectory of the beam was clearly imaged. Figure 3(b) is a superimposed image of the radioluminescence on an image of the water target without the beam. Figures 3(a), (b) are crop of the original CCD image. The hot spot was clearly attributed to the water target. In addition to the water, radioluminescence in air was also observed upstream from the water target.

3.2. Spectrum of radioluminescence in water
Images obtained using the longpass filters are shown in figures 4(a)–(e). The ROIs are also drawn on the images. Bin contents of spectra were obtained using two ROI values as described in section 2.3. The spectra of ultrapure water and tap water are shown in figure 4(f), and they were almost identical. A summary of the corrections is listed in table 1. Correction factors of quantum efficiency and transparency of the lens normalized to 450–550 nm are listed in the first row. Due to the low efficiency and transmittance, a large factor of 3.40 was needed for bin content of 350–450 nm in detector system 1. In the ROI of 350–450 nm, fraction of radioluminescence in air within the ROI was 5% and that of other wavelength regions was negligibly small. The main component of radioluminescence in air was due to excitation and de-excitation of N2 molecules as has been reported in the literature [20]. The emission wavelength was shorter than 450 nm.
The errors of bin contents were estimated using three measurements. The relationship between fit parameter $n$ and systematic error is shown in figure 5. For detector systems 1 and 2, 5% overestimation and 3% underestimation were obtained, respectively. The corrected fit parameter $n$ was $-3.4 \pm 0.4$.

### 3.3. TOC of water

TOC contents of ultrapure water and tap water after the experiments are listed in table 2. They were 0.26 mg l$^{-1}$ and 2.3 mg l$^{-1}$, respectively. TOC of the target ultrapure water that had passed through the circulation system was higher compared to TOC contents of commonly used ultrapure water ($\sim$0.03 mg l$^{-1}$).

![Figure 4. CCD camera images obtained using longpass filters. The filter thresholds were 350 nm (a), 450 nm (b), 550 nm (c), 650 nm (d), and 750 nm (e). Observed spectra of ultrapure water and tap water (f). The fit curve for the spectrum of ultrapure water is also shown.](image)

![Figure 5. Relationship between fit parameter $n$ (fit function: $a \times \lambda^n$) and the systematic error for the two detector systems. The vertical axis shows the ratio of fit result $n$ to true $n$.](image)

| Correction term | 350–450 nm | 450–550 nm | 550–650 nm | 650–750 nm |
|-----------------|------------|------------|------------|------------|
| QE × trans factor (detector system 1) | 3.40 | 1.00 | 1.12 | 1.90 |
| QE × trans factor (detector system 2) | 1.23 | 1.00 | 1.27 | 1.97 |
| Filter transmittance factor | 0.97 | 1.02 | 1.01 | 0.99 |
| Air fraction | 5% | ~0 | ~0 | ~0 |
3.4. Distribution of radioluminescence

Distributions of radioluminescence on the beam axis of ROI images obtained using ultrapure water and tap water are shown in figure 6. The distribution of tap water was almost identical to that of ultrapure water. Due to reflection, intensities at edges of both water targets were raised. The same as shown in figure 3, radioluminescence in air was confirmed in the distribution. A comparison between radioluminescence distributions of the experiment and simulation is shown in figure 7(a), and the dose distribution by the simulation is shown in figure 7(b). The radioluminescence distribution of the simulation reasonably reproduced the experimental results when normalized by the area under the curve of the water region. The fit results obtained with an exponential function are also drawn. The slopes of the experiment and the simulation curves were 0.19 ± 0.004 and 0.21 ± 0.007, respectively. These slopes were consistent with each other. On the other hand, the slope of the dose distribution was 0.37 ± 0.001 and that was almost the same numerical value as the attenuation coefficient of the 11 keV photon in water, 0.3823 mm⁻¹[21]. We did not measure dose distribution in the experiment.

As for yield of water and air, the ratios (water/air) were 0.01 and 0.007 in the simulation and the experiment, respectively. The yield ratio in the simulation was derived from simulation parameters: 0.2 photons/MeV for water and 19 photons/MeV for air. The experimental distribution in the air region was about 1.6 times higher than that of simulation, resulting in 0.007 of the yield ratio.

4. Discussion

Imaging of radiation-induced luminescence is one promising method to measure dose distribution in medical physics. The origin of photons is believed to be Cherenkov light. Yamamoto et al observed luminescence in water with lower energy than the Cherenkov threshold in carbon ion and proton irradiations. However, in these particle irradiations, beta emitters or positron emitters generated as a result of nuclear interactions were included and they might be a source of Cherenkov light. In the present study, the energy of secondary electrons (with a maximum energy of 11 keV) was sufficiently lower than the threshold and no other radiation except for

| Table 2. Total organic carbon (TOC) contents of ultrapure water and tap water measured after the experiments. |
|-----------------|-----------------|
| TOC contents (mg/l) |
| Ultrapure water 0.26 |
| Tap water 2.3 |

Figure 6. A CCD camera image obtained without using filters and marked for the ROI (rectangular box) (a). Distributions on the beam axis of the ROI images obtained for ultrapure water and tap water targets (b).
x-rays was present, which ensured the existence of radioluminescence by radiation with lower energy than the Cherenkov threshold. Moreover, our results showed the radioluminescence did not have a lower threshold until at least 11 keV.

Regarding the spectra, our spectra showed a similar tendency to previous work with carbon ion irradiation \([14]\). The spectra had the largest component of short wavelength and that was gradually decreased. However, index value of \(\lambda\) was somewhat high compared to \(\lambda\) of 2 observed in the carbon ion irradiation. This may be due to the correction accuracy. The \(\lambda\) is critically sensitive to the bin content in the 350–450 nm region. But transmittance of the lens and efficiency of the CCD camera were very low in this wavelength region, leading to low accuracy of the correction. Nevertheless, the mechanism of the radioluminescence is not largely understood, and spectra in this work do not necessarily have to be the same as previously obtained spectra. Possibly, the spectra may depend on the energy distribution of secondary electrons. When estimating \(\lambda\), we assumed a smooth spectrum curve. If some large spike peaks are on the curve, the accuracy of the index will be degraded. However, for the spectrum of alpha radiation-induced radioluminescence in HNO\(_3\) solution, no peaks were observed \([22]\). We need a detector system with high wavelength resolution to observe peaks. At first, we used a detector system that consisted of a monochrometer and photomultiplier tube (PMT) guided by an optical fiber similar to the set-up used in \([22]\). However, due to the low intensity of radioluminescence and the low photon correction efficiency, a large signal to noise ratio made it difficult to observe fine spectra. We need a higher intensity for the x-ray source or a PMT with low dark counts. To obtain the spectra, we applied some corrections. Except for the correction of the quantum efficiency and the transmittance of the lens used, effects of corrections on the spectra were small, within 5%. On the other hand, deviation among repeated measurements was large. This is perhaps due to the set-up error, including the position of the camera and lean of the longpass filters.

One of our findings was that the TOC, representing impurities in the water, did not contribute to the radioluminescence. Though the TOC of ultrapure water (0.26 mg l\(^{-1}\)) was significantly lower than that of tap water (2.3 mg l\(^{-1}\)), no differences in their spectra and distributions were observed. Other impurities such as salts and minerals were not likely to affect the radioluminescence. These impurities in ultrapure water were expected to be lower than the tap water. The origin of the radioluminescence seems to be water molecules. This will be an important advantage for measurement of radioluminescence in water if we do not need to use ultrapure water in experiments. It is difficult to keep purity of the ultrapure water because some impurities are immediately dissolved.

For the radioluminescence distribution, we got reasonable accuracy for the simulation. This supported the idea that the amount of the produced photons was proportional to the energy deposition, i.e. dose, because in the simulation, we generated photons to be proportional to the dose as the radioluminescence. However, due to total internal reflections or refraction, radioluminescence distributions were distorted, resulting in different from the dose distribution. On the other hand, the dose distribution in the simulation showed theoretical attenuation for mono-energy x-ray in water. Although we did not obtain experimental dose distribution because it was difficult to measure it due to the thin water stream, it would be a distribution such the obtained by simulation. These results suggest radioluminescence is attributed to energy deposition (dose).
Regarding the photon yield, yield ratio (water/air) of the simulation was overestimated by 30%. For yield in water, no observed value was found except for 0.2 photons/MeV and the error was not estimated [13]. The yield value may be overestimated. Additional experiments are desirable for determination of yield in water.

5. Conclusions

We observed radioluminescence in water generated by synchrotron radiation of 11 keV x-rays. The beam trajectory was clearly imaged by the luminescence. We measured the spectrum and it was proportional to $\lambda^{-3.4\pm0.4}$ under assumption of no peaks on the spectrum. We also observed no differences between the spectra and distributions of ultrapure water and tap water targets, suggesting impurities in water did not contribute to the radioluminescence. TOC as representative of impurities was irrelevant to the radioluminescence. In addition, we performed the Monte Carlo simulation and it reproduced the experimental distribution of the radioluminescence. This suggested that the amount of radioluminescence in water was proportional to the energy deposition (dose), which is expected to allow use for dose measurement.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID iDs

Yoshiyuki Hirano @ https://orcid.org/0000-0002-9053-0595
Masataka Komori @ https://orcid.org/0000-0002-4545-4917
Seiichi Yamamoto @ https://orcid.org/0000-0002-1280-0043

References

[1] Klein J S, Sun C and Prats G 2019 Feb 6 Radioluminescence in biomedicine: physics, applications, and models Phys. Med. Biol. 64 04TR01
[2] Glaser A K, Zhang R, Gladstone D J and Pogue B W 2014, Jul 21 Optical dosimetry of radiotherapy beams using Cherenkov radiation: the relationship between light emission and dose Phys. Med. Biol. 59 3789–411
[3] Helo Y, Rosenberg I, D’Souza D, MacDonald L, Speller R, Royle G and Gibson A 2014 Imaging Cherenkov emission as a quality assurance tool in electron radiotherapy Phys. Med. Biol. 59 1963
[4] Jarvis L A, Zhang R, Gladstone D J, Jiang S, Hitchcock W, Friedman O D, Glaser A K, Jermyn M and Pogue B W 2014 Cherenkov video imaging allows for the first visualization of therapy in real time Int. J. Radiat. Oncol. 89 615–22
[5] Komori M, Sekihara E, Yabe T, Horita R, Toshito T and Yamamoto S 2018 Luminescence imaging of water during uniform-field irradiation by spot scanning proton beams Phys. Med. Biol. May 29 63 11NT01
[6] Grimm J 2015 Cherenkov Luminescence Imaging and Visualization in the Modern Operating Room. ed Y Fongtgal (New York: Springer) p 107–20 https://doi.org/10.1007/978-1-4939-2326-7
[7] Tanaka K, Pashazadeh A M and Pogue B W 2015 Review of biomedical Čerenkov luminescence imaging applications Biomed. Opt. Express 6 3053–65
[8] Ciarciocechi E and Belcari N 2017 Čerenkov luminescence imaging: physics principles and potential applications in biomedical sciences EJNMMI Phys. 4 14
[9] Yamamoto S, Toshito T, Okumura S and Komori M 2015 Luminescence imaging of water during proton-beam irradiation for range estimation Med. Phys. 42 6498–506
[10] Yamamoto S et al 2016 Luminescence imaging of water during carbon-ion irradiation for range estimation Med. Phys. 43 2455–63
[11] Yamamoto S, Koyama S, Komori M and Toshito T 2016 Luminescence imaging of water during irradiation of x-ray photons lower energy than Čerenkov light threshold Nuclear Inst. and Methods in Physics Research–A 832 264–70
[12] Tarasov M D et al 2007 Efficiency of radioluminescence of water under the action of accelerated electrons Instrum. Exp. Tech. 50 761–3
[13] Yabe T, Komori M, Toshito T, Yamaguchi M, Kawachi N and Yamamoto S 2018 Estimation and correction of produced light from prompt gamma photons on luminescence imaging of water for proton therapy dosimetry Phys. Med. Biol. 12 63 04NT02
[14] Yamamoto S, Alagio T, Yamashita T, Toivonen J, Yamaguchi M, Komori M and Kawachi N 2018 Source of luminescence of water lower energy than the Čerenkov-light threshold during irradiation of carbon-ion J. Phys. Commun. 2 065010
[15] Watanabe N, Nagae T, Yamada Y, Tomita A, Matsugaki N and Tabuchi M 2017 Protein crystallography beamline BL2S1 at the Aichi synchrotron J. Synchrotron Radiat. 24 338–43
[16] Agostinelli S et al 2003 Geant4—a simulation toolkit Nucl. Instrum. Methods Phys. Res. A 506 250–303
[17] Allison J et al 2006 Geant4 developments and applications IEEE Trans. Nucl. Sci. 53 270–8
[18] Sand J, Ihanola S, Peräjärvi K, Toivonen H and Toivonen J 2014 Radioluminescence yield of alpha particles in air New J. Phys. 16 053022
[19] Kerst T and Toivonen J 2018 Intense radioluminescence of NO/N2-mixture in solar blind spectral region Opt. Express Dec 24 26 33764–71
[20] Ave M et al 2007 Measurement of the pressure dependence of air fluorescence emission induced by electrons Astropart. Phys. 28 41–57
[21] Berger M J, Hubbell J H, Seltzer S M, Chang J, Coursey J S, Sukumar R, Zucker D S and Olsen K 2010 NIST Standard Reference Database 8 (XGAM) Last Update to Data Content: November 2010 NBSIR 87-3597 accessed 2020-06-27 https://www.nist.gov/pml/xcom-photon-cross-sections-database https://doi.org/10.18434/T48G6X
[22] Kerst T, Malmbech R, Lal Banik N and Toivonen J 2019 Alpha radiation-induced luminescence by Am-241 in aqueous nitric acid solution Sensors (Basel) Apr 2 19 E1602