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Imaging of alpha emitters in a field environment

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ABSTRACT

Cameras sensitive to ultraviolet light can be applied to detection of surface contamination induced by alpha particle emitters. When absorbed in air, alpha particles excite nitrogen molecules and the radiative relaxation creates a faint light emission. This radioluminescence can be used for detection purposes, provided that background lighting levels are low. In this work, three low-light sensitive camera technologies (CCD, EMCCD and ICCD) were utilized in a nuclear facility, and their performance in detecting alpha emitters was investigated. The results show that low readout noise is essential for the detection of radioluminescence, as it allows short exposure times to be used. The ICCD camera was found to perform slightly better than the EMCCD camera in the field, while both enable the detection of MBq level alpha activities in 100 s in the test configuration (camera-target distance 0.5 m). Overall, the cameras and techniques used in this study are shown to be effective in detecting alpha emitters in a standard glovebox. This technology can be applied to nuclear security, safety and safeguards, when stand-off detection of alpha emitters is required.

1. Introduction

Detection of alpha-particle-emitting sources via radioluminescence of air has recently gained increasing interest [1–8]. The technique suits the optical measurement of all ionizing radiations but is especially useful for the detection of alpha particles. This is due to their short range and high ionization capability, which cause the air in the proximity of an emitter to luminesce. Hence, an image taken in total darkness will reveal point emitters as small scintillating hemispheres, whereas widespread surface activity emits light more evenly. The technique is attractive for safety and security purposes, since it enables convenient and remote detection of alpha-particle-emitting materials that are highly hazardous but tedious to detect with conventional means.

The radioluminescence imaging is based on observing optical photons which are induced during the passage of charged particles through air. The most intense light emission occurs in the near ultraviolet (UV) region, between 300 nm and 400 nm, due to the radiative relaxation of nitrogen molecules [9]. The conversion efficiency of alpha particle kinetic energy into optical radiation is of the order of 20 photons per MeV released in dry air at normal pressure [10]. For this reason, the light emission of alpha emitters is always rather weak, but still strong enough for detection purposes, provided that the level of background UV lighting is sufficiently low. Because the signal is at single photon levels, the intrinsic noise level of the camera sensor has to be low to allow long exposures times. Additionally, high-end readout electronics are required for detection. For these reasons, scientific grade cameras need to be utilized to achieve the desired noise performance and high UV sensitivity.

An emerging method to investigate an area for alpha contamination is to acquire two images, one conventional image under normal lighting and another UV image in complete darkness. Then, the images are processed and superimposed so that the alpha emitters, revealed in the UV image, are seen as bright spots on top of the conventional daylight photograph [3]. The conventional image provides coordinates for the contamination and the UV image contains quantitative information on the activity of the alpha emitter, since the intensity of radioluminescence is proportional to the total energy loss in air of the alpha particles emitted [10]. However, accurate quantitative measurements require exact knowledge of the background lighting level, and therefore, they are best suited for applications where complete darkness is ensured. Also, the self-absorption of the emitter affects the

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radioluminescence yield and has to be accounted for when quantitative measurements are conducted [11].

The alpha imaging concept was originally proposed and demonstrated by using conventional film photography techniques [1,2]. Yet the pioneering in-field measurements were published by Lamadie et al., using charge-coupled device (CCD) camera for the purpose [3]. Lamadie et al. applied the method at nuclear facilities at various phases of the nuclear fuel cycle, and also, the characterization of gloveboxes was demonstrated by Mahé from the same group [12]. The imaging detector technology itself has been rigorously developed by Cousins, Ingrig, and others with the focus on security applications [4,6]. Additionally, Chichester et al. have addressed the topic for nuclear safeguards [13] while Feener and Carlton have studied the potential of radioluminescence imaging in nuclear warhead verification [8]. It is evident that the camera-based detection methods have potential users throughout the whole nuclear field, and the decommissioning of old facilities will further emphasize the need for efficient alpha-screening practices in the future. Still, more research and development are needed to facilitate the adoption of optical techniques into widespread use since the method is limited to dim environments.

This work presents the first side-by-side comparison of the most promising camera technologies for imaging alpha-particle-emitting materials. The camera technologies selected are an electron-multiplying (EM) and an intensified (I) CCD, both known to perform well in low-light imaging. Additionally, the conventional CCD readout option is compared with the EM amplifier of the EMCCD camera. To test the true in-field capability of the techniques, the experiments were conducted at a nuclear facility where complete darkness could not be guaranteed. The radioactive samples illustrating the method include mixed-oxide (MOX) nuclear fuel pellets and plutonium nitrate, whereas the quantitative investigations were conducted with well-characterized alpha emitters.

2. Experimental methods

2.1. Camera technology

The electron-multiplying camera selected for this work was iXon3 897 and the intensified camera was iStar 320T, both from Andor Corporation. The cameras utilize a CCD for the imaging sensor but they use a different approach to amplify the initial charge induced by a photon. The EMCCD technology relies on signal amplification on the silicon chip, while the ICCD is based on a traditional image intensifier.

The EMCCD camera has two different output amplifiers. The conventional readout enables the device to be used as a traditional scientific CCD camera when long exposure times can be applied. The EM readout is suited for the measurement of minute amounts of light very rapidly. The detection of weak signals is based on impact ionization during charge transfer in the EM amplifier and it is voltage controlled. The optimum multiplication factor is just high enough to make the number of noise electrons of analogue-to-digital (AD) conversion process negligible compared to the number of signal electrons. For this reason, the most significant noise contributions in this camera type are dark current of the sensor head and electron emission during charge transfer process. The latter can be optimized by selecting high transfer speed to obtain less spurious electrons at the cost of reduced charge transfer efficiency. The camera uses multi-stage thermoelectric cooling to counter dark current and the sensor temperature varied between $-85\,^{\circ}$C and $-95\,^{\circ}$C during the experiments. Only air cooling was used and the ambient temperature in the laboratory was between 22 °C and 28 °C.

The ICCD technology is based on the photoelectric effect. In this camera type, a photoelectron emitted from the photocathode is multiplied in the micro-channel plate (MCP) and the resulting electron cloud produces light in the adjacent phosphor. The image is then acquired with a CCD that is optically connected to the phosphor. The gain of the intensifier is controlled with the voltage applied to the MCP. This camera also utilizes cooling of the sensor to reduce dark current, but the temperature requirements are not as stringent as with the EMCCD, since the signal is already amplified before the CCD. Instead, the most significant noise contribution is the thermal emission of electrons from the photocathode and therefore, the best noise reduction would be achieved by cooling the photocathode. During the experiments, no photocathode cooling was applied but the sensor was electrically cooled to $-35\,^{\circ}$C.

The major difference between the two cameras is that the EMCCD is based on a silicon sensor (model UVB) which has higher sensitivity to UV light than the photocathode-based ICCD (photocathode model Gen 2 (W-AGT, -E3)). On the other hand, the ICCD reaches its maximum sensitivity in the UV region and cuts off already at 900 nm, whereas the EMCCD exhibits the highest response in the visible region and the tail extends up to 1100 nm. This broad response can be a hindrance, if filters need to be utilized to suppress natural light. The quantum efficiency (QE) curves of the cameras are presented in Fig. 1a together with highlighted near UV region (300–400 nm), where the most intense nitrogen emission takes place. The spectral lines of nitrogen, based on the relative intensity measurements of Ave et al. [9], are shown in more detail in Fig. 1b. According to the data, the average QE for the total radioluminescence signal of nitrogen is 38% and 20% for the EMCCD and ICCD, respectively. Both cameras have high sensitivity to visible light, which is not desirable for UV selectivity, but can be well used to produce conventional photographs to locate radioactive sources.

The imaging lens systems used in this work are a commercially available UV objective and a variety of lens combinations specifically designed for the task. The simple objectives were constructed of plano-convex and aspheric fused silica lenses (e.g. 49-695, Edmund Optics) and used in the demonstrative imaging. These single and two lens configurations provide a good light throughput with a limited field-of-view (FOV). A camera objective (UV1228CM, Kogaku) was acquired for the side-by-side comparison of the cameras. This objective has a focal length of 12 mm and good image quality, but fairly low light collection efficiency (F/2.8).

2.2. Imaging procedure and radioactive samples in-field

The images presented in this work were captured during two different measurement campaigns at the Institute for Transuranium Elements in Karlsruhe, Germany. There, the imaging

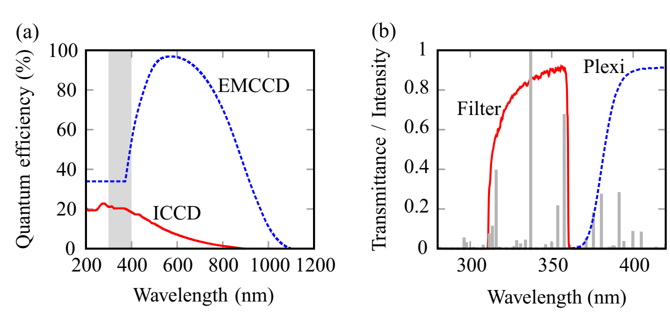

Fig. 1. (a) Quantum efficiency curves of the cameras. The most intense radioluminescence emission is observed in the gray-colored area, at 300–400 nm wavelengths. (b) Transmittance of the glovebox plexiglass and interference filter (Semrock, 334/40). The main nitrogen emission bands are illustrated with gray bars [9].