Using Video Photometry to Measure the 3 MeV Proton Half Brightness Fluence for Tetrakis (Dibenzoylmethide) Europium (III) Triethylammonium

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Tetrakis (Dibenzoylmethide) Europium (III) Triethylammonium (EuD₄TEA), commonly known as europium tetrakis, is one of the brightest known luminescent materials and is a potential candidate to detect space radiation. The half brightness fluence ($N_{1/2}$) is a material figure of merit and is defined as the fluence required to reduce the luminescent light intensity to half of its original value. In 2016, the $N_{1/2}$ for EuD₄TEA irradiated with 3 MeV protons was measured to be about $2.8 \times 10^{10} \text{ mm}^{-2}$, which is similar to what a spacecraft close to the Earth will receive from a large solar event. An old 30 Hz video taken from this research with an iPhone 6s was recently re-analyzed using photometric techniques. The resulting photometric $N_{1/2}$ for EuD₄TEA was found to be $3.3 \times 10^{10} \text{ mm}^{-2}$, which is statistically the same as was measured using the traditional method.

Introduction

A phosphor is a solid material that emits luminescence that is not caused by incandescence. The word phosphor comes from Greek meaning *light bearer* (1). Phosphors are able to emit light due to the excitation of electrons that are caused by the absorption of energy from an external source such as another electron, photon, or electric field (1). The basic physics of phosphors is well established, and researchers have demonstrated applications in illumination, glow-in-the-dark products, radiation detectors/indicators, electroluminescent devices, light emitting diodes (LEDs), and thermometry (2). Two informative review articles on phosphors have been written by Dramićanin and Allison (3-4).

Phosphors provide most of the illumination produced by fluorescent lamps and are also used to improve the quality of light produced by metal halide lamps (2). Various neon signs use phosphors to produce different colors of light (2). Electroluminescent displays in aircraft use phosphors to produce glare-free illumination as numeric and graphic display devices (2). White LED lamps consist of a blue or ultraviolet emitter with a phosphor coating that emits at longer wavelengths such as red, thereby providing a more complete spectrum of visible light (2).

Theoretical Considerations

Ionizing radiation hazards provide a significant challenge and threat to human and robotic exploration missions to the Moon, Mars, and beyond. Ionizing radiation has sufficient energy per particle to remove electrons from the orbits of target atoms creating charged particles. It is this type of radiation that is evaluated for purposes protecting personnel and property. Ionizing radiation is different from ion formation in ordinary

chemical reactions, such as the generation of table salt from sodium and chlorine. In such reactions, only the outermost electron is removed to form a positively charged ion. If the incoming energy is sufficient, electrons other than those in the outermost shells can be released by ionizing radiation. This process renders the atom very unstable, and these ions are quite chemically reactive. In space, ionizing radiation includes charged particle cosmic rays, neutrons, and high energy gamma rays.

Types of Ionizing Radiation

Charged Particles. TABLE 1 shows the particle types and energies for common charged particle sources in space (5). These radiation hazards include galactic cosmic rays (GCRs) and solar energetic particles (SEPs). GCRs are present throughout the solar system and are comprised of roughly 85% protons, 14% helium, and about 1% high-energy and highly charged ions called HZE particles (6-8). An HZE is a heavy ion having an atomic number greater than that of helium and having high kinetic energy (8). Examples of HZE particles include carbon, iron, or nickel nuclei (heavy ions). Though the HZE particles are less abundant, they possess significantly higher ionizing power, greater penetration power, and a greater potential for radiation-induced damage. GCRs are extremely damaging to materials and living systems (8). In general, we are largely shielded from GCRs on Earth because of our atmosphere and magnetic field. The Moon is not shielded from GCRs because it lacks a global magnetic field and atmosphere (8).

TABLE 1. Particle types, energies, and surface doses for space radiation sources.

Source of Space Radiation	Type of Radiation	Energy (MeV)
Sun	Protons	20 to 10^3
	Electrons	0.05
Galaxy	Protons	100 to 10^3
Internal Radiation Belt (Earth)	Protons	10^{-3} to 70
	Electrons	0.02 to 1.0
External Radiation Belt (Earth)	Protons	≤ 60
	Electrons	0.02 to 5.0

Sudden intense bursts or SEP events can last several days with an intensity that increases and decreases with time (6-8). On Earth, these particles affect radio transmissions, the upper atmosphere composition, and ozone layer (6). The damage caused by radiation affects electronics and photocells, which power and provides space imagery (6). However, the most significant risk is to the health and lives of the astronauts. As we consider long duration missions to the Moon and Mars or even the International Space Station (ISS), the risk from radiation exposure increases. Protons with energies of about 30 MeV can penetrate spacesuits and spacecraft walls. High energy radiation, e.g., greater than 100 MeV, produces secondary penetrating particles such as neutrons and nuclear fragments inside the shielding material (6-8). Some shielding can actually increase the radiation hazard (6-8). As a result, the hazard must be characterized to determine if long missions outside of low Earth orbit can be accomplished with acceptable risk (6-8).

Practical space-based sensors based on luminescence will depend heavily upon research investigating the resistance of these materials to ionizing radiation and the ability to anneal or self-heal from damage caused by such radiation. In 1951, Birks showed experimentally that the fluorescence efficiency of anthracene bombarded by alphas varies with total fluence (N) as

$$\frac{I}{I_0} = \frac{1}{1 + \frac{N}{N_{1/2}}}, \quad [1]$$

where I is the luminescence yield, I_0 is the initial luminescence yield, and $N_{1/2}$ is the half brightness fluence, which is a useful figure of merit for the material and incident irradiation energy (9-10).

The $N_{1/2}$ can be calculated from a set of collected data by plotting the inverse of the luminescence yield versus particle fluence. This expression can be written in slope-intercept form by taking the reciprocal of both sides of Equation [1]:

$$\frac{1}{I} = \frac{1}{I_0} + \frac{1}{I_0} \frac{N}{N_{1/2}}. \quad [2]$$

Equation [2] is written so the y-intercept of the linear fit (b) is equal to:

$$b = \frac{1}{I_0}. \quad [3]$$

Equation [2] can also be written so the slope of the linear fit (m) is equal to:

$$m = \frac{1}{I_0 N_{1/2}} = \frac{b}{N_{1/2}}. \quad [4]$$

Based on Equations [2] and [3], the inverse luminescence yield ($1/I$) can be re-written including these definitions in slope-intercept form:

$$\frac{1}{I} = b + mN. \quad [5]$$

The $N_{1/2}$ for the material can be calculated from re-arranging Equation [4]:

$$N_{1/2} = \frac{b}{m}. \quad [6]$$

Equation [5] shows that the $N_{1/2}$ can be found by calculating the ratio of the y-intercept to the slope for a linear fit.

Broser and Kallmann developed a similar relationship to the Birks equation for inorganic phosphors irradiated using alpha particles (11). Since 1990, the authors have found that the Birks relation describes the reduction in emission yield due to proton irradiation for every tested luminescent material except lead phosphate glass (12-16). These results indicate that radiation produced quenching centers compete with emission centers for absorbed energy.

Neutrons. Neutrons in space are produced when the primary charged particles or cosmic rays interact with surrounding matter. Neutrons hold nuclei together, have no net electric charge, and have a mass slightly greater than that of a proton. Free neutrons are unstable and have a half-life of about eleven minutes by beta minus decay (17). For all practical purposes, there are no neutrons in the primary GCR environment. By the time GCRs enter our solar system, any neutron created at the source has decayed away. There are some neutrons emitted from the Sun that do live long enough to reach the vicinity of Earth. Solar neutrons are few in number compared to the other emitted radiations (18).

When free neutrons come into contact with matter, they do not interact with the electrons as they do charged particles, but instead only interact with nuclei (17-19). When this happens, several results are possible depending on the energy of the neutron and the mass of the nucleus; however, all interactions are governed by the laws of conservation of momentum and energy. Since neutrons interact primarily with the small nuclei rather than the atomic electrons, they can penetrate very deeply into matter. These particles traditionally react by elastic collisions, inelastic collisions, and neutron capture.

Gamma Rays. Gamma rays are photons with the smallest wavelengths and the most energy of any wave in the electromagnetic spectrum (19). They are produced by the hottest and most energetic objects in the universe, such as neutron stars and pulsars, supernova explosions, and regions surrounding black holes. On Earth, gamma rays are generated by lightning and through nuclear reactions of natural and human-made radioactive elements.

Radiation Exposure Limits and Levels

The specific career exposure limits for ionizing radiation in humans are determined by age and gender. A typical average whole-body dose equivalent for a human is about 3.6 mSv/yr (17-19). However, international standards allow exposure to as much as 50 mSv/yr for persons who are occupationally connected to radioactive materials (17-19). Conversely, the general public has an exposure limit to ionizing radiation of 1 mSv/year (17-19). For spaceflight, the limit is higher. The NASA limit for radiation exposure in low-Earth orbit is 500 mSv/yr (17-19). Career exposure limits are set lower for younger astronauts. It is presumed that exposure to larger amounts of radiation early in a career could present greater health risks during old age.

The career equivalent dose limit is based upon a maximum 3% lifetime excess risk of cancer mortality (17-19). The total equivalent dose yielding this risk depends on gender and age at the start of radiation exposure. Assume that a younger person should be exposed to less radiation because they have more life to live, and therefore a longer chance to develop subsequent health problems.

TABLE 2 shows a comparison between a selection of historical and proposed future space missions with the corresponding dose equivalent for the astronauts (8). Crews aboard the Space Station receive an average of 80 mSv for a six-month stay at solar maximum (the time period with the maximum number of sunspots and a maximum solar magnetic field to deflect the particles) and an average of 160 mSv for a six month stay at solar minimum (the period with the minimum number of sunspots and a minimum solar magnetic field). Although the type of radiation is different, 1 mSv of space radiation is approximately equivalent to receiving three chest x-rays (8). On Earth, we receive an average of 2 mSv every year from background radiation alone (8).

TABLE 2. Direct comparison between historical and proposed space missions with corresponding astronaut dose equivalents (8).

Space Mission	Mission Duration and Orbit Type	Astronaut Dose Equivalent (mSv)
Space Shuttle Mission 41-C	8 days orbiting the Earth at 400 km	5.59
Apollo 14	9 days mission to and from the Moon	11.4
Skylab 4	87 days orbiting the Earth at 473 km	178
ISS mission	6 month (maximum) orbiting the Earth at 353 km	160
Estimated Mars Mission	6 month transit time to and from Mars with 2 years on surface for a total of 3 years	1,200

The Moon and Mars are extremely vulnerable to the effects of space radiation because they do not have global magnetic fields like those of Earth (8). As a result, their surfaces are not shielded from SPE that erupt from the surface of the Sun. In addition, the GCR that permeates interstellar space can freely bombard the surface of the Moon and Mars (8). Finally, the Moon and Mars do not have dense atmospheres. Although Mars has an extremely thin atmosphere composed primarily of carbon dioxide, it is not thick enough to shield it from most cosmic radiation (8). The Moon essentially lacks an atmosphere altogether. Astronauts on a mission to the Moon or Mars will be exposed to higher levels of ionizing radiation from the time they leave Earth until they return.

Data in TABLE 2 shows that astronauts on a three-year Mars mission would receive a whole-body dose equivalent radiation exposure of about 1,200 mSv or 1.2 Sv. The lethal dose equivalent of ionizing radiation for 50% of the population is about 4.5 Sv (20). This indicates that an average astronaut would receive about a quarter of a lethal dose of ionizing radiation during one complete trip to Mars. ALARA measures can be completed on the astronauts to mitigate some of this exposure. However, this estimate clearly shows that exposure to space radiation is the long pole in the tent in the process of sending astronauts to Mars and beyond (8, 20).

Since neutrons are not charged, they have a high potential to induce biological damage. Early data has shown that about 30-40% of the astronaut dose equivalent aboard the ISS was caused by neutrons (21). However, predicted neutron fields underestimate the measured flux spectra on the ISS by 30-50% (21-22). The Bonner Ball Neutron Detector (BBND) experiment was conducted in the U.S. laboratory module of the ISS over an eight-month period of 2001 (22). During this experiment, the neutron dose equivalent rates were measured to be 69 and 88 μ Sv/day for two locations inside the U.S. laboratory module, representing a 30% increase due to the difference in the localized shielding environment inside the same pressured volume (22). The influence of ISS altitude variation was estimated for the neutron dose equivalent rate to increase by a factor of two between 300 to 500 km. The increase in the cumulative neutron dose equivalent due to the most significant solar event during the BBND experiment was found to be 0.15 mSv, which contributes less than 1% to the annual neutron dose equivalent estimated from the BBND experiment (22). Additional research needs to be done to understand neutron production processes in spacecraft from cosmic rays.

Photometry

Photometry is the science of measuring light in terms of its perceived brightness to the human eye. Photometric measurements are weighted by the spectral response of human

vision involving the wavelengths between 360 to 830 nm, or in practical terms from 400 to 700 nm (23-24). One of the main quantities in photometry is luminance (23-24). The International Commission on Illumination (CIE) has defined luminance as an objective quantity that is related to brightness (23-24). Luminance describes the amount of light that passes through or is emitted from a particular area and falls within a given solid angle. The standard SI unit for luminance is candela per square meter (cd/m^2).

In image production, such as applications involving photography, video, or cinema, the absolute luminance of the original scene is rarely reproduced. Instead, a relative luminance that is only approximately proportional to the original scene value is used. Relative luminance follows the photometric definition of luminance, with the values normalized to a reference. The use of relative values is useful in systems where absolute reproduction is impractical. For example, in standard published media, the absolute luminance of light reflecting off the print depends on the illumination and therefore absolute reproduction cannot be assured.

The luminance of a scene can be computed as the weighted sum of suitably selected red, green, and blue values. If suitable spectral weighting functions are used, any color can be described by just three components, called tristimulus reproduction (23-24). These coefficients are vision functions of the white reference and of the particular red, green, and blue (RGB) spectral weightings (23-24). These three RGB colors are an additive model in which red, green, and blue light is combined to reproduce a broad array of colors. RGB is a device-dependent color model.

The main purpose of the RGB color model is for the sensing, representation, and display of images in electronic systems and conventional photography. Before the electronic age, the RGB color model already had a solid theory behind it, based on the human perception of colors (23-24). The relative luminance (Y) can be calculated from the RGB color model from:

$$Y = 0.2126R + 0.7152G + 0.0722B, \quad [7]$$

where R , G , and B are the linear red, green, and blue components respectively (23-24). The constant coefficients associated with the R , G , and B terms adjust the luminance for the perception of color by humans. Human eyesight is most sensitive to green light. For this reason, nearly 72% of luminance comes from the green part of the spectrum. Likewise, 21% and 7% of the luminance comes from the red and blue parts respectively. A “zero” intensity for each component gives the darkest color, which is no light and is considered “black”. Conversely, full intensity of any component gives “white” (23-24).

Experimental Methods

Tested Sample Material

Europium Tetrakis. One of the brightest organic phosphors, europium tetrakis (EuD_4TEA), was first synthesized by Hurt *et al.* in 1966 (25). The original Hurt *et al.* synthesis used EuCl_3 as a precursor reagent that required washing with ethanol to remove excess chlorine (25). A picture of some synthesized EuD_4TEA crystal powder is shown in Figure 1. EuD_4TEA exhibits strong red luminescence around 611 nm when excited and can be observed in daylight (26-28). Detailed information on the methods used to synthesize EuD_4TEA can be found in References 26-28. The authors have developed an innovative

EuD₄TEA-based radiation sensor is scheduled to fly into low Earth orbit on a small satellite sometime in the near future.

Figure 1. Close-up photograph showing synthesized yellow EuD₄TEA powder.

Previous research has shown that EuD₄TEA crystals appear to be monoclinic in shape (13-14). In 2011 Fontenot *et al.* modified the Hurt *et al.* synthesis to use europium nitrate which required no washing (26). Fontenot *et al.* also improved the synthesis yield and built a custom drop tower to measure the relative triboluminescent emission and decay times for a host of phosphors (27). This synthesis improved emission yield and proved to be robust (26-27). To date, Fontenot *et al.* has synthesized over five hundred separate batches of tetrakis materials, with a measured variance of properties on the order of 7% (26-28). According to the International Union of Pure and Applied Chemistry, the proper name for EuD₄TEA is tetrakis (dibenzoylmethide) europium (III) triethylammonium (29).

Polymer Binder. For this original research, a poly (phenyl methyl) siloxane (PPMS) polymer binder was utilized. Individual sample paints were made by mixing a 1:1 ratio (by mass) of EuD₄TEA powder with PPMS binder. The thick PPMS paint was spread on an aluminum card using a technique that is analogous to applying butter to sliced bread owing to the paint being too thick to be applied using a standard airbrush. The EuD₄TEA samples were cured at 40 °C for 40 minutes.

Experimental Apparatus. In 2016, the EuD₄TEA sample was exposed to protons using the 5SDH-2 tandem Pelletron accelerator located on the campus of the University of Louisiana at Lafayette (30). A beam of 3 MeV protons were used for these measurements. The EuD₄TEA sample being was mounted to an electrically isolated, one-dimensional translational holder as shown in Figure 2. This sample holder is located on the bottom of the former student beam line at the accelerator center. This apparatus was used to measure the $N_{1/2}$ for EuD₄TEA as reported in Reference 30.

A cylindrical aluminum Faraday cup surrounds the sample holder to collect stray secondary electrons for a full current measurement. A hole cut into the front of the Faraday cup allows the incident beam to irradiate the sample. A similar hole also allows the emitted radioluminescence to be recorded by the camera. The Faraday cup is electrically connected to the sample holder for precise current measurements. Measured beam current is passed from the scattering chamber using a 2.75 inch Conflat[®] flange electrical feedthrough.

Figure 2. Diagram of the $N_{1/2}$ measurement apparatus that was used in 2016 (30).

While the $N_{1/2}$ was being measured for EuD₄TEA, it was decided to position an iPhone 6s on a simple tripod next to the front Conflat window on the student chamber to see if we could collect a video of the irradiation sequence. The position of the camera was kept constant when the movie was being made. The Conflat window was positioned at an angle of about 45° with respect to the incident beam direction. The iPhone 6s has a standard 12 million pixel (4032 x 3024 pixels) rear-facing camera. The video was recorded with the standard Apple® camera application which has a 30 Hz frame rate.

Results and Conclusions

Summary of Original Half Brightness Fluence Measurements

A detailed discussion for the original 2016 $N_{1/2}$ measurements completed can be found in Reference 30. The 3 MeV proton beam current was kept small each of the seven useful data runs to minimize sample charging and heating. The resulting average $N_{1/2}$ for the EuD₄TEA and PPMS paint sample irradiated with 3 MeV protons was measured to be $(2.83 \pm 0.50) \times 10^{10} \text{ mm}^{-2}$ (30). In fact, the measured $N_{1/2}$ for 3 MeV proton irradiation is almost a thousand times smaller than was found for other measured materials, which is reasonable since EuD₄TEA is an organic compound (30). Organics are often fragile and thus more susceptible to radiation damage (30).

Re-Analysis of iPhone Camera Video

The iPhone 6s camera was used to collect a 7.6 second video. The EuD₄TEA sample was exposed to an average 3 MeV proton beam current of $44.1 \pm 2.4 \text{ nA}$. From 2016 to early 2020, this video was used as part of many presentations to illustrate the effects of proton irradiation on emission yield. Recently, it was decided to re-analyze this video using photometric methods to see if the 3 MeV proton $N_{1/2}$ for EuD₄TEA could be determined.

The *iMovie* software application from Apple® was used to analyze the collected video. An iPhone 6s was mounted upright in a soft jaw clamp on a tripod next to a clear Conflat window on the sample chamber. To mark the start of the light, still images were made from this video every 30 frames (1 second) so the brightness of the images being irradiated could

be determined. Figures 3(a) through 3(h) shows color still images extracted at frames 22, 30, 60, 90, 120, 150, 180 and 210 respectively in the video. Frames 22, 30, 60, 90, 120, 150, 180, and 210 correspond to elapsed video times of 0.73 s, 1.00 s, 2.00 s, 3.00 s, 4.00 s, 5.00 s, 6.00 s, and 7.00 s respectively. Note the radioluminescence from EuD₄TEA is bright red in color as observed in earlier research (30).

Figure 3. Still images marked (a) to (h) listed by frame number and elapsed time showing a general reduction in luminescence yield when a 3 MeV proton beam irradiates a EuD₄TEA and PPMS paint sample. These still images were taken from a 7.6 second video collected with an old iPhone 6s.

The raw frames from the video were large and showed reflections and large areas of black around the irradiation spot. Each still frame shown in Figure 3 was rotated 90° to the left and cropped in size to just show the primary irradiation spot. The *GraphicConverter II*® software package from LemkeSoft was used to edit the size of each frame. The irradiation spot can easily be seen in each image as the round hole in the Faraday cup inside the sample chamber as shown in the frames of Figure 3. Each image was

cropped in size to just include light from the round hole in each image. These smaller images files were then used for additional analysis which will be described below. Luminescence was first observed in Frame 22 (0.73 s) after the start of the video.

The frames in Figure 3 also show the irradiation spots are elliptical in shape. The irradiation spot on the EuD₄TEA sample from the 3 MeV protons was circular with an area of 2 mm². Since the iPhone 6s was positioned at approximately 45° with respect to the incident beam direction, the light spot should be stretched into an ellipse. Careful inspection of Figure 3 show that the semi-major and semi-minor axes for the light spot ellipse is about 2:1 for all images. For this reason, radioluminescence was emitted over an area of about 4 mm².

The key to completing this analysis is to find a method to determine the radioluminescent yield emitted as a function of incident proton fluence. Normally, the $N_{1/2}$ is measured using a dedicated light detector or spectrometry system. For this new effort, still images captured from an iPhone 6s video were used. Photometry is the key to this analysis. Each captured still image will be analyzed to find its average RGB value. Equation [7] will be used to calculate the average relative luminance of radioluminescence in that image. The inverse of the average relative luminance will be plotted versus the incident proton fluence as outlined in Equations [1] through [6].

The proton fluence n (mm⁻²) at any time can be calculated using:

$$n = \frac{t I_{avg}}{e A}, \quad [8]$$

where t is the time (s), I_{avg} is the average beam current (44.1 nA), e is the electronic charge (1.6021×10^{-19} C), and A was the area (4 mm²). Finally, the $N_{1/2}$ for EuD₄TEA will be calculated using Equation [5] from the y-intercept (b) and slope (m) of the best-fit linear fit line. Results from these calculations are shown in TABLE 3.

TABLE 3. Summary of data used in this analysis to determine the inverse average relative luminance for each still frame image.

Frame Number	Elapsed Time (s)	Proton Fluence ($n \times 10^{10}$ mm ⁻²)	Average Frame Color Model Numbers			Average Relative Luminance (Y)	Inverse Average Relative Luminance ($1/Y \times 10^{-2}$)
			R	G	B		
30	1.00	6.8816	202	75	46	99.9064	1.0009
60	2.00	13.3632	129	31	20	51.0406	1.9592
90	3.00	20.6448	87	18	12	32.2362	3.1021
120	4.00	27.5264	77	14	10	27.1050	3.6894
150	5.00	34.4080	65	11	8	22.2638	4.4916
180	6.00	41.2896	58	10	7	19.9882	5.0030
210	7.00	48.1712	49	8	6	16.5722	6.0342

The average frame color (RGB) numbers were found using Reference 31. This website allows users to upload an image to a website and return the average RGB values to the screen. For this work, the frame still images were in portable network graphics (PNG) format. The website uses open source Javascript with a hidden proprietary code to calculate the average RGB values for each image (31). It should be noted that using average RGB

values over the whole frame to calculate relative luminance should work for this analysis because the pixels away from the beam spot are uniformly black. If this was not the case, then a more extensive analysis of individual pixels in the irradiation would be necessary. Figure 4 shows a plot of the inverse average relative luminance (I/Y) versus 3 MeV proton beam fluence (n) for EuD₄TEA. The line shown through the data is a linear least-squares fit that was calculated using the stock routine available in *KaleidaGraph* version 4.5.4 from Synergy Software. The error bars shown in Figure 4 are based on 5% of the standard error calculated in *KaleidaGraph*. The calculated y-intercept (b), slope (m), and R^2 error values for the least-squares fit for the plot shown in Figure 4 are shown in TABLE 4.

Figure 4. Plot of the inverse average relative luminance versus 3 MeV proton beam fluence for EuD₄TEA.

TABLE 4. Summary of the *KaleidaGraph* fit used for the EuD₄TEA analysis.

Fit Type	Y-Intercept (b)	Slope (m) (mm^2)	R^2
Linear Least-Squares	0.0038621	1.1717×10^{-13}	0.990

Equation [6] can be used to calculate the $N_{1/2}$ for EuD₄TEA:

$$N_{1/2} = \frac{b}{m} = \frac{0.0038621}{1.1717 \times 10^{-13} \text{ mm}^2} = 3.3 \times 10^{10} \text{ mm}^{-2}. \quad [9]$$

Using the video method, the $N_{1/2}$ for EuD₄TEA was measured to be about $(3.3 \pm 1.0) \times 10^{10} \text{ mm}^{-2}$ for 3 MeV protons. Surprisingly, the $N_{1/2}$ measured in the traditional way was found to be $(2.83 \pm 0.50) \times 10^{10} \text{ mm}^{-2}$ for 3 MeV protons (30). The value measured here

using a new photometric method is statistically identical to what was found in Reference 30. This result opens the exciting possibility that a phosphor like EuD₄TEA can be used with a simple cell phone camera to measure radiation exposure in adverse environments. It should be noted that the uncertainty in this measurement is about 30% based on the possible maximum and minimum slopes that will fit this small set of data. It is very satisfying to know that the combination of simple and inexpensive camera with commercial software products can be used to successfully measure radiation fluence. Additional research is needed to better understand this analysis method.

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