Experimental Evidence of Triboluminescence Induced by Hypervelocity Impact

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The emission of light due to crystal fracture, or triboluminescence (TL), is a phenomenon that has been known for centuries. One of the most common examples of TL is the flash created from chewing wintergreen Lifesavers®. For the last couple of years, the authors have been measuring fluorescence properties of phosphors like zinc sulfide doped with manganese (ZnS:Mn). Preliminary results indicate that impact energies greater than 16 mJ produced measurable TL from ZnS:Mn. Light was generated from the interaction of a dropped mass and a small number of luminescence centers in the ZnS:Mn powder. To extend this research, a two-stage hypervelocity light gas gun located at NASA's Marshall Space Flight Center (MSFC) was used to evaluate equipment and settings that show promise for hypervelocity TL detection. In these experiments, a projectile was accelerated to approximately 5-6 km/s before striking a ZnS:Mn phosphor-coated aluminum plate. This paper will provide an overview into the first experimental evidence of TL emission from ZnS:Mn due to hypervelocity impact. It is hoped these results will generate interest in future hypervelocity research.

I. INTRODUCTION

Background

Phosphors are materials doped with impurities that give off cold light when excited. This fluorescence is caused by ions in the lattice structure emitting a photon to de-excite, versus non-luminescent phonon processes. Light emitted from a phosphor is not caused by thermal effects, and as such, is considered "cold". Fluorescent light bulbs and traditional cathode ray tube (television) pixels are examples of phosphor applications. There exist many different excitation sources, such as photons (photoluminescence), electrons (cathodoluminescence), and ionizing radiation (radioluminescence). Excitation of phosphors by crystal stress or fracture, known as triboluminescence (TL), has been observed in such crystals as sucrose for many centuries. One of the most common examples of TL is the flash created from chewing wintergreen Lifesavers® [ref. 1-3].

Prior Research and Applications

Beginning in 2003, research was conducted to induce TL from a low energy (low velocity) impact. A typical TL response from the ZnS:Mn powder is shown in Figure 1 for a drop height of 39 inches (1 m) [ref. 3]. A series of drops would start with one from the maximum height (42 inches or 1.07 m). Subsequent shots were done from progressively decreasing heights until no light was observed. Notice in Figure 1 that TL decay appears to follow the standard exponential decay curve of luminescence [ref. 3-5]. The color inset shown in Figure 1 is a picture of actual TL light produced when a 130 g steel ball bearing was dropped on a small quantity of ZnS:Mn powder. When excited, the ZnS:Mn phosphor emits bright yellow light with a broad emission peak centered at 585 nm and a full width at half maximum (FWHM) of about 125 nm.

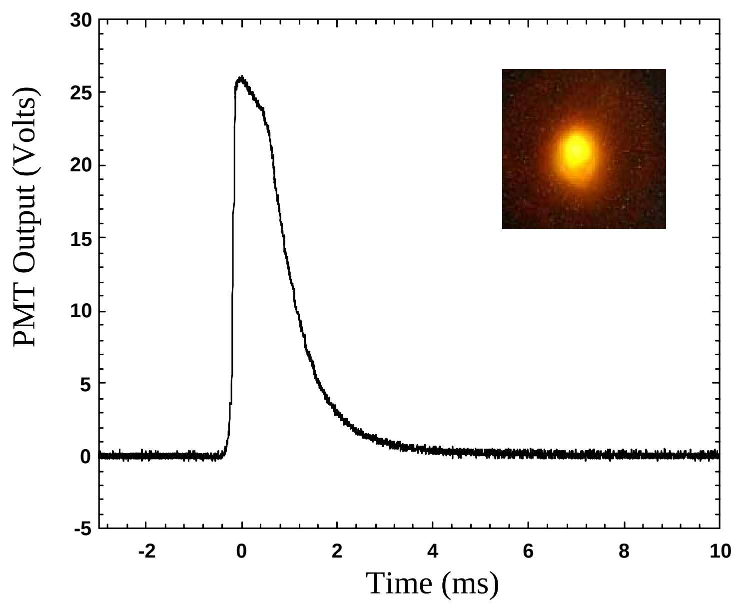

Figure 1. Typical photomultiplier detector response for ZnS:Mn.

Figure 2 shows the variation in TL emission characterized by the output voltage from a photomultiplier detector as a function of the drop kinetic energy [ref. 3]. The measurement uncertainty is approximately ± 5%, as shown by the error bars in Figure 2. The intensity of the TL response appears to be a function of impact energy with two regions of interest as shown in Figure 2. The first region is in the energy range below 0.26 J. Here the production of TL light appears to have a threshold of approximately 16 mJ. Above this threshold, the projectile has sufficient energy (or velocity) to break ZnS:Mn crystals, producing light. The intensity increases rapidly until about 0.26 J. The second region begins at 0.26 J and appears to be more like a saturation state: here the slope is shallow which indicates that the sample is less sensitive to impact energy. This is almost certainly due to the ball breaking as many crystals as it can in the area of impact. Increasing the energy above this threshold cannot generate more light because there are no more crystals in the impact area. So, a more appropriate measure may be intensity as of function of the impact energy normalized by impact area.

From these results, the authors desired to expand the base of knowledge and application of TL induced impacts with the specific goal of demonstrating the potential of phosphor based impact sensors. Such events as the loss of the Columbia orbiter demonstrate the need for sensors to detect hypervelocity impact. Given the author's previous research experience, it was felt that the state of phosphor-based impact detection had matured to the point of detection of hypervelocity impact.

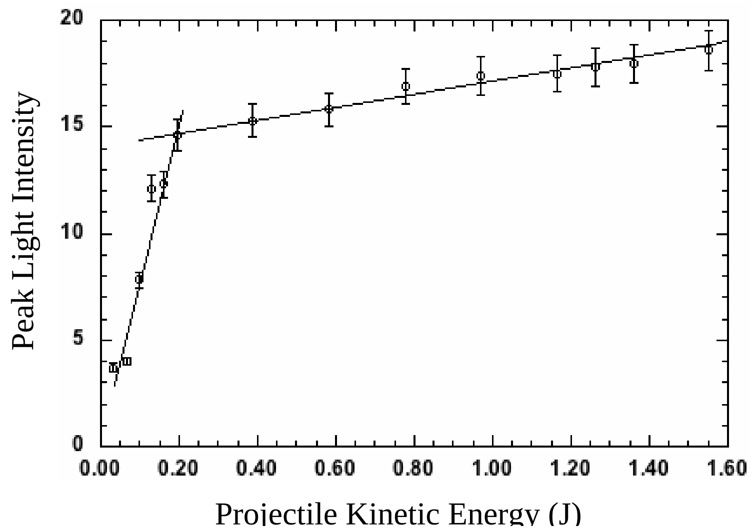

Figure 2. Plot of the peak TL intensity as a function of impact kinetic energy for the ZnS:Mn powder [ref. 3].

II. RESEARCH HISTORY

A brief history of our hypervelocity research can be found in Table 1. Research in hypervelocity TL began in August 2003, when the authors were invited to conduct research with the two-stage light gas gun located at the NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama. Prior to this research, the only instrumentation in the MSFC gun consisted of two silicon light detectors used to determine projectile velocity. In addition, the backplane of the impact chamber was constructed of clear Plexiglas and lacked any feedthroughs. As such, a new backplane was required. Specifications for the backplane were: use of multiple BNC and fiber optic feedthroughs, ability to keep out ambient light, and vacuum tight to about 10 torr. The new backplane was constructed of surplus aluminum and brass at the UL Lafayette Physics Department machine shop. Figure 3 shows pictures of the original Plexiglas and revised instrumented backplanes.

Table 1. Personal history of hypervelocity research.

Experiment	Date Preformed	Accomplishments
One	3/16/04 – 3/17/04	Backplane fit and vacuum test at MSFC.
Two	4/13/04 – 4/16/04	Initial use of backplane with two silicon photodiodes to measure light emission from ZnS:Mn.
Three	6/14/04 – 6/16/04	Improved experiment design and finalized paint binder.
Four	12/14/04 – 12/15/04	Developed and tested method to shield photodetectors from muzzle flash and measured triboluminescence for ZnS:Mn on six shots.
Five	3/28/05 – 3/29/05	Measured triboluminescence for ZnS:Mn at multiple shot velocities and captured muzzle flash spectra of hydrogen and helium.

A **B**

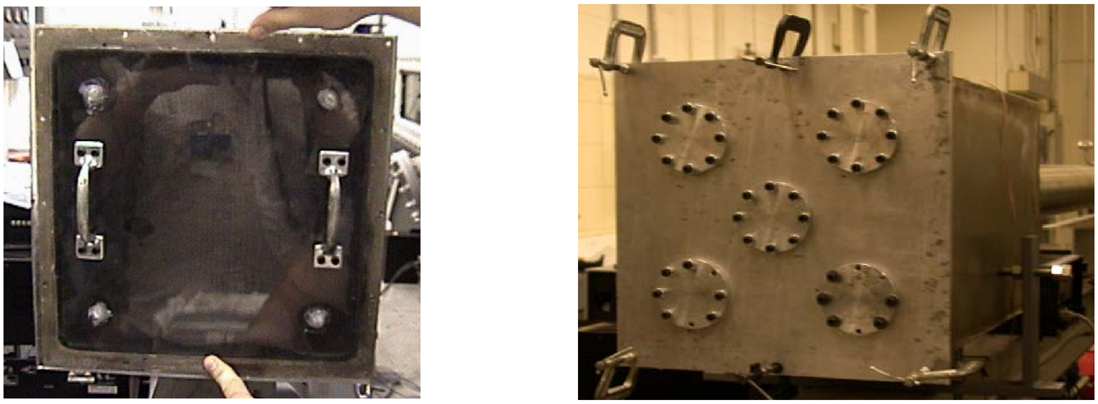

Figure 3. Pictures of the original MSFC gun backplane (A) and the new instrumented backplane (B) showing five available flange ports.

The authors visited several impact research centers, such as the United States Air Force Arnold Engineering Development Center (AEDC) in Tullahoma, Tennessee, Sandia National Laboratories in Albuquerque, New Mexico, Lawrence Livermore National Laboratory in Livermore, California, and the NASA Johnson Space Center White Sands Test Facility in Las Cruces, New Mexico to collaborate on gun operation and analysis. These visits contributed technical expertise and provided insight as to the viability of hypervelocity TL studies.

III. TARGET MATERIALS

Aluminum plate (0.1875 inch thick) was machined at UL Lafayette to create individual targets that were 11.5 inches (29 cm) long and 4 (10 cm) inches wide. A ZnS:Mn and binder paint was applied to a 4 x 4 inch (10 x 10 cm) area on one side of each plate. An example painted target plate in visible (A) and ultraviolet (B) light can be found in Figure 4. The pink ZnS:Mn paint shown in the visible light picture (A) corresponds to the bright yellow fluorescence illuminated with ultraviolet light (B). The ZnS:Mn was purchased from Phosphor Technology, Limited (Hertfordshire, U.K.) and was selected because it emits copious amounts of light when struck with a projectile.

A **B**

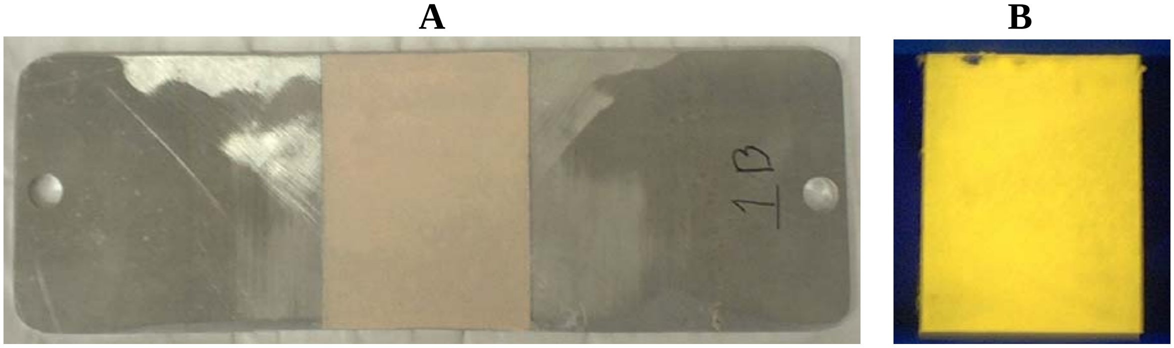

Figure 4. Picture of an example painted target plate taken in visible (A) and ultraviolet light (B).

The ZnS:Mn paint presented a unique problem. Initially, the it consisted of ZnS:Mn and Resbond Cotronics 793 in a 1:4 phosphor:binder ratio sprayed on to an aluminum plate by commercial airbrush. This binder was chosen for its high temperature survivability and ease of application. However, Cotronics 793 is a ceramic, and as such, highly brittle [ref. 6]. Initial hypervelocity impacts with this binder caused the entire phosphor/binder to shatter and completely delaminate from the aluminum plates.

Further investigations concluded that poly (phenyl methyl) siloxane (PPMS) gave the toughest and most wear resistant paint and was sufficiently resistant to hypervelocity impacts [ref. 3]. Using a 1:4 ZnS:Mn phosphor:binder ratio, the loss of coating would only occur at the site of impact for roughly twice the crater diameter as shown in Figure 5. PPMS provided the best impact performance and was used throughout the rest of the study.

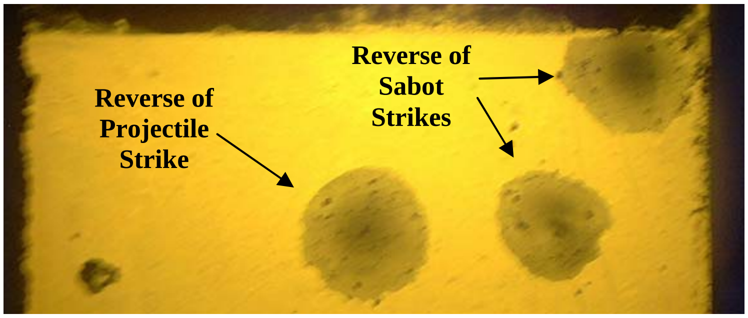

Figure 5. Picture (ultraviolet light) of the painted side (reverse from impact) of an aluminum target plate showing the effects of the projectile and sabot strikes.

IV. GUN DESCRIPTION

The light gas gun located at the NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama was used for this research [ref. 7-8]. This gun is a two-stage device constructed by Southwest Research, Incorporated. The first stage is constructed from a Sako .22-250 bolt action rifle. Instead of the typical lead copper-jacketed projectile fired by this rifle, a high-density polyethylene cylinder is the initial projectile. The cylinder travels down a section of 0.224 inch (0.57 cm) diameter barrel until it encounters a second barrel that narrows progressively. As the cylinder travels down these two barrel sections, it compresses hydrogen or helium gas in the high pressure chamber of the gun. Both hydrogen and helium have low atomic masses, allowing them to be compressed to higher pressures than is possible with gasses composed of elements with higher atomic masses. A Mylar burst disk holds the high pressure gas until it ruptures. At that point, the light gas then drives the impact projectile down the third and final barrel section. The impact projectile is form of a 1 mm aluminum sphere positioned inside a plastic sabot. The projectile then enters the flight tube of the gun. If the projectile has a sabot, it will separate and the projectile will travel downrange to the impact chamber. The MSFC gun has no sabot catcher in the flight tube, and instead, has a scatter shield as part of the target holder system. This scatter shield will occasionally catch the sabots, but more frequently the sabots impact the target with the aluminum sphere.

V. EXPERIMENTAL DESIGN

The target holder system consists of an aluminum plate that has two 1/4-20 threaded rods spaced 11.0 inches (28 cm) apart. Stop plates, targets, and the scatter shield are attached to the holder through the threaded rods. During the initial shots, there was a tendency for both the sabots and the projectile to impact the scatter shield. To prevent this occurrence, the scatter shield was removed until several of the gun components could be re-machined, preventing unwanted impact of the projectile on the scatter shield.

To capture a TL event, silicon detectors were placed in the impact chamber, with their output running into amplifiers before the signal was displayed on an oscilloscope. This presented several challenges to the acquisition of a signal that could be positively identified as a TL event. For the first test series, two detectors were placed 1 inch (2.5 cm) behind the target plate, with one detector directly behind the coated section, and the second facing bare aluminum. The lower detector functioned as a trigger for the detector facing the coating, and served to record a background signal. When the data from this test series was analyzed, it was found that there was no measurable difference in signal between the lower detector and the one facing the coating. Upon conferring with AEDC, it was discovered that light gas guns produced significant blackbody radiation out of their muzzles when fired.

A solution to properly shield the silicon detectors from muzzle flash was found in a local hardware store. The silicon detectors were placed into 2 in (5.1 cm) diameter holders. It was found that soft PVC pipe adapters would fit around the detectors to shield them from muzzle flash. An example of a single shielded detector mounted to a holder assembly is shown in Figure 6. The second unshielded detector was used-to trigger the oscilloscope. Figure 7 shows an example of a typical impact and how the detectors are mounted to the holder [ref. 7-8].

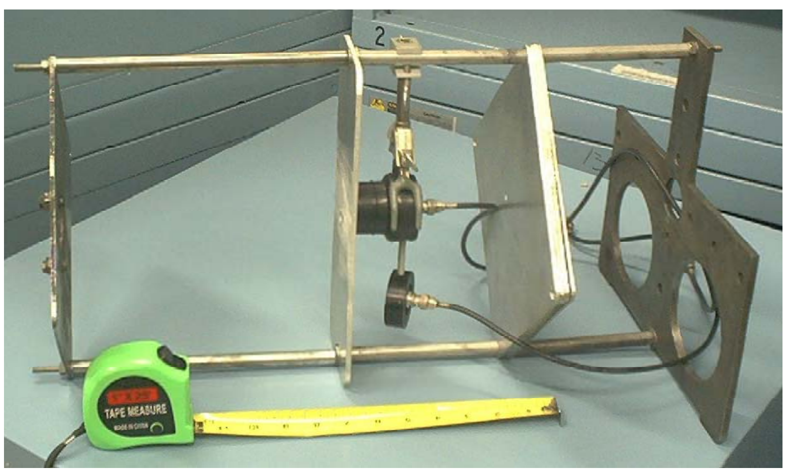

Figure 6. Single shielded detector mounted to a holder assembly for the MSFC gun [ref. 7-8].

Once the proper target, target holder, and detector design was established, it was then necessary to determine proper settings for the amplifiers and oscilloscope. This was conducted through trial and error until captures of the TL event were recorded that did not exceed the detection range of input or output devices. While work commenced in April 2004, it was not until December 2004 when the final experimental setup was determined.

To properly characterize the "muzzle flash" of the MSFC gun, a fiber optic feed through was placed on the backplane of the impact chamber in March 2005. The fiber was routed into an Ocean Optics S2000 spectrometer and the spectrum of the muzzle flash was taken. Results of that experiment showed that the muzzle flash had a significant contribution of light at 585 nm, which is same emission wavelength as ZnS:Mn. Considering that muzzle flash and other luminescence from the gun was occurring at the similar wavelengths, a proper shielding system became a necessity as shown in Figure 7.

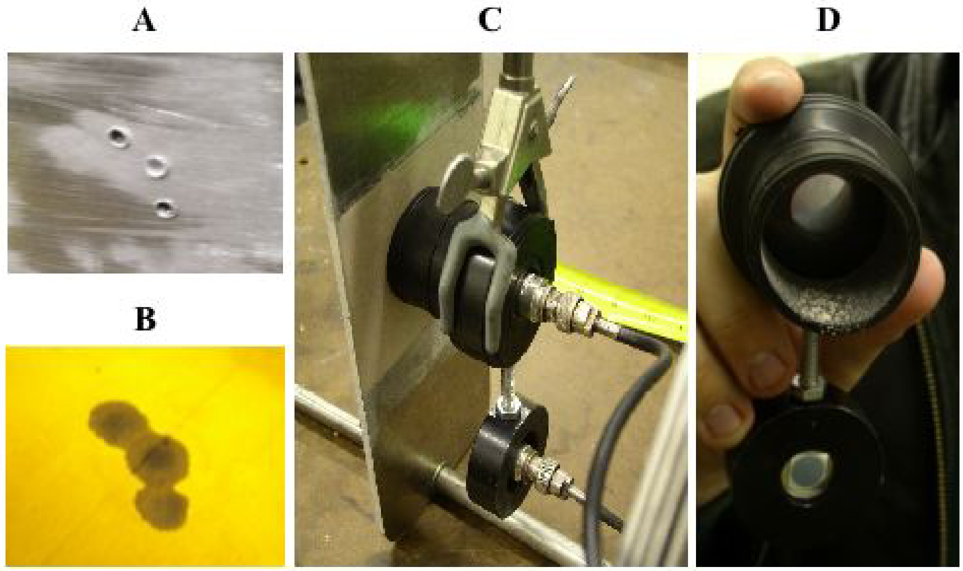

Figure 7. Pictures of an example impact showing the front unpainted side of plate with center projectile and two surrounding sabot hits in visible light (A), back painted side of plate showing center projectile and two surrounding sabot hits in ultraviolet light (B), back side of plate showing two silicon detectors looking at the paint behind the impact with rubber shield (C), and inside of the silicon detectors and black rubber shield showing residue paint powder after the hypervelocity impact (D).

VI. RESULTS

In December 2004, a series of preliminary measurements was completed to determine if TL light could be detected as a result of a hypervelocity impact. A ZnS:Mn and PPMS painted plate with two light detectors (one shielded and one unshielded) were positioned in the impact chamber of the MSFC gun as shown in Figure 7. Results from shot one of this test series is shown in Figure 8. The projectile velocity for shot one was approximately 5-6 km/s. The light intensity from both the unshielded and shielded photodetectors saturates the identical amplifiers. However, the light intensity from the unshielded detector starts earlier and takes more time to saturate when compared to the shielded detector. Light from the unshielded detector is an indicator of the muzzle flash of the MSFC gun. Conversely, light from the shielded detector is TL from the ZnS:Mn and PPMS paint. Only TL generated inside the shield can be detected. The impact of the 1 mm projectile generated TL light, which was detected by the photodetector on the painted side of the aluminum plate. The rapid increase in light intensity from the shielded detector shows the TL rise time for ZnS:Mn.

Additional evidence can be found in Figure 9 for shot five of the December 2004 test series. A 1 mm projectile with a velocity of 5.6 ± 0.5 km/s impacts with an aluminum target plate and detector assembly as described in Figure 7. The time dependent light intensities for the shielded and unshielded photodetectors for shot 5 are shown in Figure 9. Like before, the shielded photodetector measured only TL from ZnS:Mn produced by the hypervelocity impact. For shot five, the corresponding TL decay time for ZnS:Mn was estimated to be about 300 μs, which is totally consistent to what was previously measured using ultraviolet excitation.

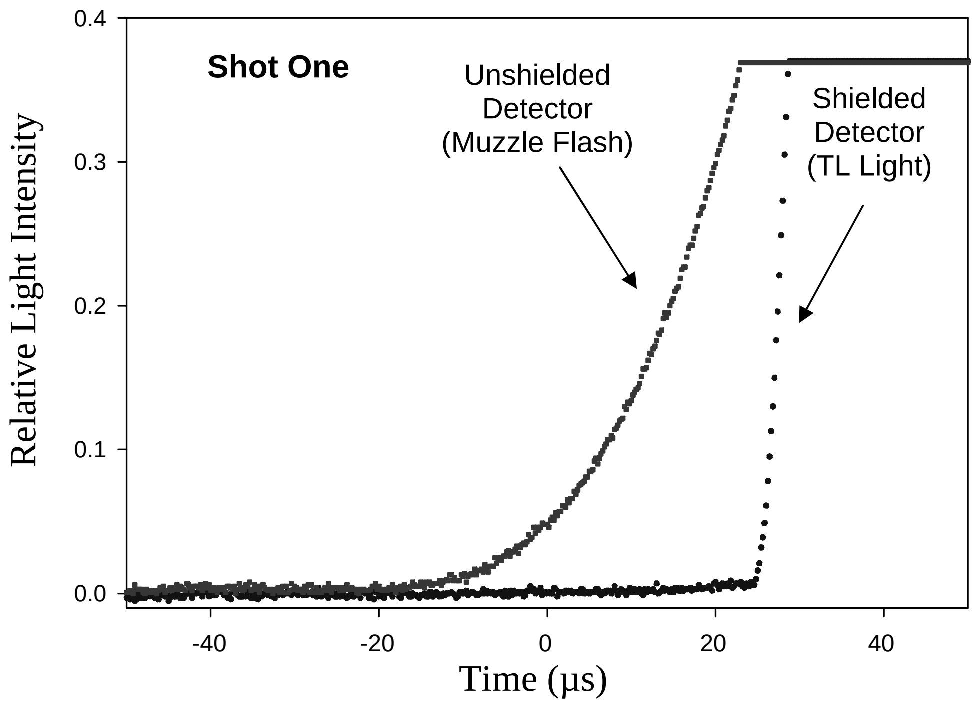

Figure 8. Light intensity comparison from unshielded and shielded detectors as a result of a hypervelocity impact on a ZnS:Mn coated plate for Shot One during the December 2004 test series at MSFC.

VII. CONCLUSIONS

The emission of light due to TL is a phenomenon that has been known for centuries. For the last couple of years, the authors have been measuring fluorescence properties of phosphors like ZnS:Mn. Preliminary results indicate that impact energies greater than 16 mJ produced measurable TL from ZnS:Mn. Light was generated from the interaction of a dropped mass and a small number of luminescence centers in the ZnS:Mn powder. To extend this research, a two-stage hypervelocity light gas gun located at MSFC was used to evaluate equipment and settings that show promise for hypervelocity TL detection. Results from these measurements indicate that TL from ZnS:Mn was detected from the impact of a 5.6 ± 0.5 km/s aluminum projectile with a painted aluminum target. The corresponding TL decay time for ZnS:Mn was estimated to be about 300 µs, which is totally consistent to what was previously measured using ultraviolet excitation. Additional research will be completed to further quantify these results.

More TL research needs to be completed to further phosphor-based impact detection. The production of TL light needs to be investigated in the hypervelocity regime in order to make predictions for impact characteristics. Such velocity or energy predictions make a potential sensor more useful than a simple binary (impact or no impact) system. The measurement of the TL spectra is also very useful for the development of an impact sensor. The authors plan to measure the TL spectrum for ZnS:Mn produced by a hypervelocity impact in a future series of experiments. Given the large number of TL phosphors, future investigations should include phosphors other than ZnS:Mn. By careful consideration of the environment where impact detection is desired, other phosphors may offer TL at more useful wavelengths and be more radiation resistant [ref. 9]. Also, other ways to apply a phosphor coating have been used in sensing, and these are also worth investigating.

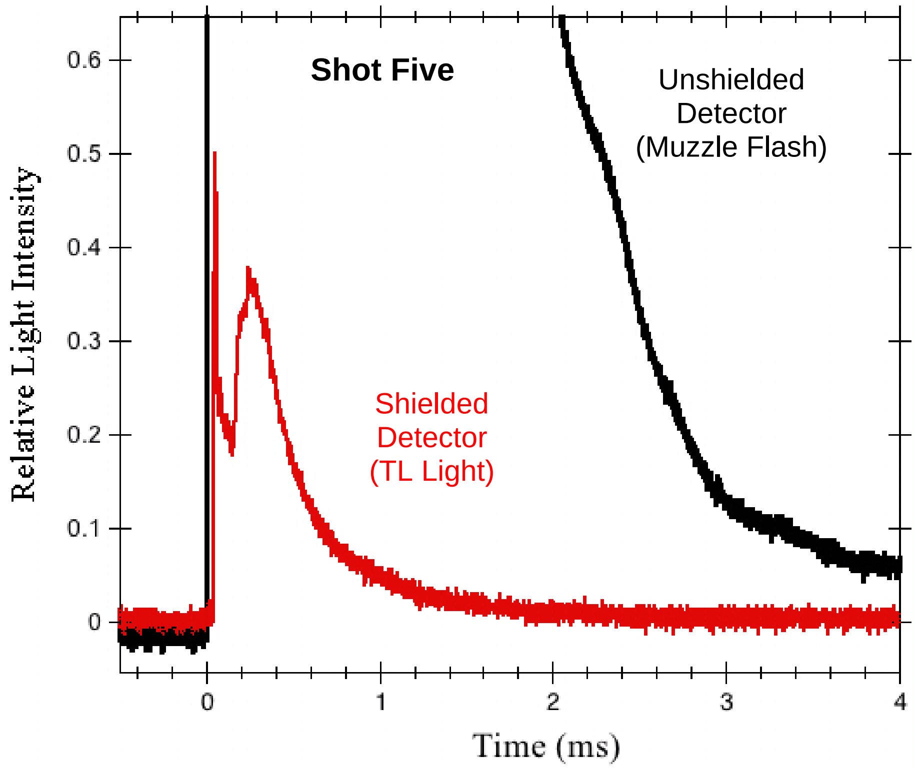

Figure 9. Light yield comparison from unshielded and shielded detectors as a result of a hypervelocity impact on a ZnS:Mn coated plate for shot five during the December 2004 test series at MSFC.

VIII. ACKNOWLEDGEMENTS

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