FINAL REPORT

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Project Title: Electro-optic Laser-Sampled Neutron Detector

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Proposal Objectives: A new method of detecting radiation which can allow for long distance measurements is being investigated. The device is primarily for neutrons detection although it could, in principle, be used for gamma ray detection. The neutron detection medium is a solid, transparent, electro-optical material, such as lithium niobate, lithium tantalite, or barium borate. Crystals of these materials act as optical gates to laser light, allowing light to pass through only when a neutron interaction occurs in the crystal. Typical light detection devices, such as CCD cameras or photomultiplier tubes, can be used to signal when light passes through the crystal. The overall goal of the project is to investigate the feasibility of such devices for the detection of neutron radiation and to quantify their capabilities and limitations.

The goal of this project is to develop an electro-optic radiation detection device using a cadmium zinc telluride (CdZnTe) or lithium niobate (LiNbO₃) Pockel's cell. Although the results have been inconclusive thus far whether CdZnTe or LiNbO₃ Pockel's cells can be effectively used in detecting neutrons, the concept has not been disproved.

Review: Literature research for the electronic, physical and optical properties of lithium niobate, in the past year, raised a few questions about it being the optimal choice for obtaining detection of individual events. Further study was done on electro-optic materials containing neutron absorbing elements. The study found most crystals, which have the necessary electro optic effect and neutron absorbing elements, are of a lithium X-ate class (e.g. lithium tantalate). These crystals would have similar properties as the lithium niobate and thus would not prove any better. The study disclosed barium borate, cadmium telluride and a few other exotic crystals. The properties of cadmium telluride as an electro-optic device along with the electronic properties were promising.

Rigorous calculations have since shown why any generated signal went unnoticed. Three non-optimal experimental conditions existed in the original experimental apparatus. First, the laser light sources were much too unstable. Manufacturer rated values for power noise were 0.5% RMS for the lasers used. Signals are expected to be approximately 0.1% of the steady state light level, much too low to be seen using the present laser systems. Second, the laser source was focused at a single spot in the crystal center. A single charge cloud is expected to be 200-

300 μm in diameter. As a result, the effect was confined to a small volume, and signals were integrated spatially over an area much larger than necessary. Finally, necessary precautions against photodiode noise were not taken, including properly shielding them against stray light and capacitively coupling them to the detection system.

In order to reduce the noise in the results and to obtain more significant data, the previous setup was changed. A light-tight Faraday cage was designed and built for the experiment to shield the sensitive devices from electromagnetic and light interference. The laser has been replaced with a low-noise fiber optic laser of 1064 nm wavelength with noise rated at less than 0.1% RMS (Orbits Eternal ETH-26 Laser). A beam expander was placed between the laser and the first polarizing lens to produce nearly parallel light through the entire crystal sample. A second cross polarizing lens was placed after the crystal, followed by a focusing lens pointed directed onto a highly sensitive InGaAs PIN photodiode (Newport 818-BB-30). The current output from the photodiode was measured with a Keithley 617 electrometer.

The polarizers used to observe the change in polarization have been replaced with far better polarizers (Thorlabs). Extinction ratios of the polarizers have been improved from 10^2 to 10^6 to reduce the amount of light “leaking” past the polarizer and analyzer. In summary, the modified experimental apparatus is expected to be at least 50 times more sensitive than previous arrangements thus providing a far better ability to detect the small signals developed during radiation interactions. The new experimental arrangement can be shown is depicted in Fig. 1 and shown in Fig. 2.

Status: The CdZnTe crystals proved to show the electro-optic effect. The detector consists of a 2x19x19 mm CdZnTe crystal with electrodes coated the 10x10 mm surfaces. Since the crystal is thinner than previous arrangements, less voltage is necessary to rotate the polarized light. The collimated beam directed through the CdZnTe crystal was between 0.5 – 1.0 mm in diameter. The light passes through the crystal and into the photodiode, as shown in Fig. 1. The current produced by the photodiode was measured with the electrometer.

Background: The Pockels effect has been utilized as a new method for detecting radiation and may hold some unique advantages for certain applications. The technique involves shining laser light through a crystal sandwiched between cross polarizers and onto a single photodiode. The amount of rotation of the polarized light caused by the Pockels cell depends on the electric field established within the crystal. Radiation interactions causing extensive ionization within the cell can change the electric field slightly. This disturbance changes the rotation which changes transmission through the second polarizer and the output of the photodiode.

One unique characteristic of this detection system is the ability to measure sensor response with no physical connection to the sensor. All sensing equipment can be located at some distance away from the crystal sensor. The system operates in a “current mode” so pulse processing electronics were also not necessary and an instrument with nanoAmpere range sensitivity can be used to measure response.

CdZnTe and LiNbO₃ are both birefringent crystal materials and are commonly used as Pockels cells. They were considered for neutron detection because each contains a natural abundance of a highly absorbing neutron reactive constituent: ¹¹³Cd in CdZnTe and ⁶Li in LiNbO₃.

Theoretical Considerations

In a Pockels cell, the intensity of light reaching the light detector and electric field applied to the crystal are related by the following:

$$I = I_o \sin^2 \left(\frac{\pi n_o^3 r d}{\lambda} E \right) \quad (1)$$

where I_o is the maximum light intensity transmitted through crossed polarizers, n_o is the zero bias refractive index, r is the Pockels electro-optic coefficient for the crystal, d is the path length of light transmitted through the crystal, λ is the wavelength of incident light, and E is the electric field perpendicular to the optical path and I is the transmitted light [1]. Note, the sine-squared curve (Pockels curve) in light intensity as a function of electric field establishes a maximum sensitivity at mid-wave. Here, at maximum slope, the change in response is maximized for slight changes in electric field and marks an optimal operational environment.

^{113}Cd and ^6Li have neutron absorption cross sections of 20,000b and 940b with natural abundances of 12% and 7.5% [2-4]. The reactions are as follows [5-7]:

The neutron reaction products are then responsible for causing ionization in the crystal. When enough ionization takes place the free carrier concentration is assumed to build up excessively. The space charge associated with the high concentration of free carriers changes the electric field distribution in the device.

Experimental Procedure

A 2x10x10 mm CdZnTe crystal was mounted to have the 10x10 mm gold coated faces perpendicular to the 3 inch diameter neutron beam. A 1064nm Orbits Eternal ETH-26 laser was used to direct a beam through a collimating lens approximately 30 cm from the crystal, the first polarizer oriented 45 degrees to the laser, and through the crystal (Fig.1 - Fig.4). The laser beam diameter was approximately 0.5-1 mm as it entered the crystal. The light exiting the crystal was focused onto a Newport 818-BB-30 InGaAs PIN photodiode after passing through the second polarizer oriented 90° to the first polarizer. The photodiode was placed approximately 10 cm from the crystal. The entire assembly was laid out on a large optical table with a light-tight enclosure to keep out ambient light and background noise. The current produced at the photodiode was measured directly by a Keithley 617 electrometer with current range of 2pA-20mA.

Figure 1: A Pockels cell setup in a neutron beam.

Figure 2. The new optical configuration, showing the dark box and the optical configuration.

Figure 3. Test box with the CdZnTe Pockels cell.

Figure 4. Experimental Arrangement.

A Pockels curve for CdZnTe was obtained by recording the **current** on the electrometer in 50V increments from 0 to 1550V. This verified the correct behavior of the materials and setup and identified the voltage at mid-wave. The CdZnTe crystal was then exposed to neutrons in a radial beam port at the Kansas State University TRIGA Mark II nuclear reactor at powers of 100, 200, 300, 400, and 500kW. At each power the difference in photodiode current with the shutter open and closed was recorded. A slab of borated HDPE and lead provided an effective shutter for the neutron beam. Current measurements were recorded at 5-10 seconds after opening and closing the shutter to ensure a steady state reading of the current. The experimental setup and procedure was reproduced using a 2x4x25mm LiNbO₃ cell.

Experimental Results

From the Pockels curves generated in Figs. 5 and 6, the mid-wave voltages for CdZnTe were determined to be 610V and 1500V. Similarly for LiNbO₃ the first mid-wave voltage was 550V, while the second was not considered for experimentation.

Figure 5: The Pockels Curve obtained from CdZnTe.

Figure 6: The Pockels Curve obtained from LiNbO₃.

The change in photodiode current using CdZnTe at different reactor powers for both applied biases is shown in Figure 7. With the applied bias at the mid-wave voltage the base photodiode current was approximately 700nA with the neutron beam shutter closed. The deviation from the base current observed with the shutter open was recorded. The current from the photodiode increased steadily with neutron flux at the first mid-wave voltage of 610V. Meanwhile, at the second mid-wave operating voltage of 1500V on the other side of the Pockels curve, the current decreased from the base photodiode current of 700nA with increasing flux.

Figure 7: The change in photodiode current with increasing reactor power at 610V and 1500V of applied bias.

To ensure that the response was due to neutron interactions and not the gamma-ray component associated with reactor beams, a thin sheet of Cd was placed in the beam with the shutter open. The system responded as in the case for a closed beam, indicating that stimulus for response was indeed neutron dependent. Another reality check was performing the experiment with the laser off, to ensure that the InGaAs photodiode was not responding to some other stimulus during the experiment.

Identical setup and procedures were executed with LiNbO₃. No change in photodiode current was observed with incident radiation, even with an increased reactor power of 640kW.

Discussion

An increase in current in the positive slope of the Pockels curve at 610V as well as a decrease in current at the negative slope of the curve at 1500V ensures that the Pockels effect is responsible for the change in light intensity, concurrent with an increase in the electric field within the device for both cases. Other mechanisms outside of the Pockels effect that may be in question, such as light scattering from free electrons, would be expected to behave similarly in both cases. Thus, rotation of the polarization angle of the light is indeed deviating with response to radiation.

The major difference between the CdZnTe cell and the LiNbO₃ cell is the carrier mobilities and lifetimes. From gold foil activation analysis, the flux at the exit plane of the radial beam port at 500kW of power was $8 \times 10^6 \text{ n cm}^{-2} \text{ s}^{-1}$. The lifetime in LiNbO₃, is considered on the order of 0.1ns [8], whereas for CdZnTe a lifetime of 0.2μs is commonly achievable. As a result, with the

lifetime 5 orders of magnitude shorter than the interaction rate of neutrons, one would expect charges to be readily recombined hindering the excessive build-up of free carriers.

Conclusion

The Pockels effect has been successfully implemented to detect neutrons. CdZnTe, a birefringent semiconductor crystal with relatively long carrier lifetimes demonstrated a change in electric field due to extensive ionization within the crystal that is observable through the Pockels effect. This is the first recorded attempt to utilize the Pockels effect in a neutron detection system. On the other hand, LiNbO₃ did not produce such a response even though its composition is much better suited to capture neutrons and their reaction products. This is considered to be attributed to the very short carrier lifetimes associated with the material.

The optical form of signal formation in such systems demonstrates unique characteristics in a detection system including non-contact read-out and no need for pulse processing equipment. Besides the connection of a bias supply to the crystal, signal was extracted from the device with a laser and photodiode, both many centimeters away from the sensor crystal and well clear of the irradiation beam during the experiment.

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