Portable gamma and thermal neutron detector using ${}^6\text{LiI}(\text{Eu})$ crystals

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ABSTRACT

Simultaneous detection of gamma rays and neutrons emanating from an unknown source has been of special significance and importance to consequence management and first responders since the earliest days of the program. Bechtel Nevada scientists have worked with ${}^6\text{LiI}(\text{Eu})$ crystals and ${}^6\text{Li}$ glass to develop field-operable dual sensors that detect gamma rays and neutrons simultaneously. The prototype ${}^6\text{LiI}(\text{Eu})$ counter, which has been built and tested, is designed to collect data for periods of one second to more than eight hours. The collection time is controlled by thumbwheel switches. A four-pole, high pass filter at 90 KHz reduces microphonic noise from shock or vibration. ${}^6\text{LiI}(\text{Eu})$ crystals generate completely separable gamma-ray and thermal neutron responses. The ${}^6\text{LiI}(\text{Eu})$ rate meter consists of a single crystal 3.8 x 3.8 cm (1.5 x 1.5 in) with a 2.54-cm-(1-in-) thick, annular, high-density, polyethylene ring around the cylinder. Special features are (1) thermal and epithermal neutron detection (0.025eV to 250keV) and (2) typical gamma resolution of 8% at 661.6 keV. Monte Carlo N-Particle calculations for characteristics of gamma spectral behavior, neutron attenuation length, relative neutron and gamma detection efficiency are reported.

Keywords : ${}^6\text{LiI}(\text{Eu})$ crystal, pulse height separation, thermal neutrons, gamma detector

1. INTRODUCTION

In use today, small, hand-held, portable, low-powered, dual detectors capable of detecting gamma rays and neutrons simultaneously are very important to consequence management and first responders. The detector described in this article makes use of a ${}^6\text{LiI}(\text{Eu})$ crystal to generate completely separable gamma-ray and thermal neutron responses¹. The gaseous detectors now in use, while efficient and virtually immune to gamma rays, limit packaging options and are not suitable for dual gamma-neutron operation. Proportional counters like those built with pressurized ${}^3\text{He}$ or BF_3 have some safety and performance limitations, too.² Dual neutron and gamma detection capability would find immediate application in the U.S. Department of Energy's inventory and provide, in one instrument, simultaneous space-correlated data. Having the capability in a single detector would greatly ease packaging and power concerns.

2. ${}^6\text{LiI}(\text{EU})$ CRYSTAL

Europium-activated lithium iodide is a scintillator useful for neutron counting. The crystal contains the ${}^6\text{Li}$ component enriched to 96% and uses the high thermal neutron absorption cross section of ${}^6\text{Li}$ (941 barns). Neutrons are detected through interaction with the ${}^6\text{Li}$ component of the crystal via the reaction $n + {}^6\text{Li} \rightarrow {}^4\text{He} + {}^3\text{H} + 4.78 \text{ MeV}$. Lithium-loaded glass scintillator combinations with ${}^6\text{Li}$ and ${}^7\text{Li}$ beads have been successfully used in detecting thermal neutrons in high gamma backgrounds.³ In normal ${}^7\text{LiI}(\text{Eu})$, a thickness of 20 to 40 mm (0.8 to 1.6 in) is required for total absorption of thermal neutrons. For ${}^6\text{LiI}(\text{Eu})$, a thickness of 2 to 3 mm (0.08 to 0.12 in) totally absorbs thermal neutrons. However, a thickness of 3.8 cm (1.5 in) was chosen for the current detector in order to stop gamma rays up to 3.0 MeV. The special features of the thermal neutron and gamma dual detectors are:

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- Thermal and epithermal neutron detection (0.025eV to 250keV)
- Dimension: 3.8- x 3.8-cm (1.5- x 1.5-in) cylinder
- Annular polyethylene ring (2.5-cm [1-in] radius) moderator around the crystal
- Simple pulse height separation from gamma rays up to 3.0 MeV
- Light output of 35% relative to thallium-activated sodium iodide (NaI[Tl])
- Liquid crystal display (LCD) display of neutron and gamma counts
- Typical gamma resolution of 8% at 661.6 keV

The distinct pulse height separation of the response pulses generated by gamma rays and thermal neutrons inside a ${}^6\text{LiI}(\text{Eu})$ crystal is shown in Figure 1. The actual detector system is shown in Figure 2.

Figure 1. Gamma and thermal neutron response from a 2.54 x 2.54 cm (1 x 1 in) ${}^6\text{LiI}(\text{Eu})$ crystal.

The reaction products from thermal neutrons absorbed in ${}^6\text{Li}$ into the crystal ${}^6\text{LiI}(\text{Eu})$ generates the same quantity of light as that accompanying the complete absorption of 3 MeV of electrons. Naturally occurring background gamma rays have an upper energy bound of 2.7 MeV. A crystal of ${}^6\text{LiI}(\text{Eu})$ of the dimensions 50 mm x 6 mm (2 x 0.24 in) will register very few background gamma rays above 2.7 MeV. The experimental count rates is 0.22 cps at the natural background of 0.18 $\mu\text{R}/\text{Hr}$. Thus, a clean pulse height separation between gamma rays and neutron is possible. The number of the neutrons detected is simply defined by the number of events in the energy range 2.7 ? 3.3 MeV.

While performing gamma-ray source inspection, the characteristics of $\text{LiI}(\text{Eu})$ as a gamma-ray detector are essentially the same as those of $\text{NaI}(\text{Tl})$ because:

- The value of gamma-ray detection efficiency by both types of scintillation detectors is mainly defined by iodine concentration.
- The relative energy resolution of ${}^6\text{LiI}(\text{Eu})$ detectors is acceptable for a majority of radiation control applications such as radionuclide identification and certification of radioactive sources (8% at 661.6 keV).

Figure 2. $^6\text{LiI(Eu)}$ rate meter consists of a single 3.8-cm x 3.8-cm (1.5- x 1.5-in) crystal with an annular high-density polyethylene ring around the cylinder.

3. $^6\text{LiI(EU)}$ RATE METER ELECTRONICS

The number of gamma and neutron events per defined interval is displayed simultaneously on two 8-digit LCDs. The $^6\text{LiI(Eu)}$ rate meter electronic circuitry is composed of four major components:

- High-voltage power supply
- Preamplifier and analog conditioning circuitry
- Neutron/gamma separation circuitry
- 4 counters/display drivers

The high-voltage power supply provides up to 1000 volts to the photomultiplier tube. The unique design of this power supply uses an inductive oscillator to drive the Cockcroft-Walton bridge at a frequency of approximately 1 MHz. This frequency is far beyond the band pass of the circuitry and, therefore, does not interfere with the circuit operation. Since the supply operates at the natural frequency of the oscillator, the power consumption is smaller than that of units employing square wave drivers. Using surface-mounted components, the 44-stage multiplier is still quite small and the transformer does not need to handle high voltages; the majority of the voltage multiplication is accomplished by the Cockcroft-Walton string. The entire power supply uses only 25.8 cm^2 (2 in^2) of circuit board area.

The photomultiplier tube output is connected to a lossy integrator with a time constant of 55 microseconds. A pole-zero stage follows this section of circuitry. The output of this stage is fed into a DC-restored circuit. The output of the DC-restored circuit is connected to a two-pole, low-pass shaping filter. The input for the lower level discriminator (LLD) is taken prior to the low-pass filter.

The separator circuit consists of a voltage comparator and timing circuitry to permit events exceeding a set threshold (corresponding to neutrons) to be routed to the appropriate counter. Any event with an amplitude exceeding the LLD but less than the neutron threshold is considered to be a gamma. Figure 3 shows a block diagram of the electronics for the dual detector.

Figure 3. Diagram of the electronic components used in the $^6\text{LiI(Eu)}$ rate meter

4. RATE METER PERFORMANCE

The $^6\text{LiI(Eu)}$ rate meter outperforms mini-multichannel analyzers (MCAs) that are commercially available for dual gamma and neutron detection. The mini-MCA, model mMCA-430, manufactured by TSA Systems Ltd., is a 256-channel MCA with a 2.54- x 5.04-cm (1- x 2-in) NaI(Tl) detector. The MCA is packaged with an optional neutron rate meter made of a $^6\text{LiI(Eu)}$ crystal into a small, hand-held unit. The neutron detector has a 2.54- x 0.5-cm (1- x 0.2-in) cylindrical crystal. TSA's mMCA-430 is a 256-channel, field-grade, multi-channel analyzer and neutron counter in one compact unit. The monitor is simple to operate and can be set up and run using the internal keypad or its Windows-based communications program. Data may be exported in comma-separated variable format for use by other software programs.

The detector described in this article has gamma and neutron response superior to that of the mMCA-430 detector system. Neutron and gamma counts, as observed by the two detectors, are recorded as a function of the source distance. A small ($< 5\mu\text{Ci}$) ^{137}Cs button- source was used as a gamma source; an unmoderated ^{252}Cf sample was used as a neutron source.

Figure 4. Comparison of neutron and gamma count rates from the Bechtel Nevada $^6\text{LiI(Eu)}$ detector and the mMCA-430, a commercially available portable dual detector manufactured by TSA Systems Ltd. Neutron sensitivity is markedly higher for the Bechtel Nevada rate meter than for the mMCA-430.

The neutron detection efficiency of a $^6\text{LiI(Eu)}$ crystal depends heavily on the moderation of the neutron energy by hydrogenous materials like polyethylene. In principle, the neutron detection efficiency increases up to a certain maximum for a given thickness of a $^6\text{LiI(Eu)}$ crystal with increasing moderator thickness. The neutron detection efficiency initially increases with the thickness of the $^6\text{LiI(Eu)}$ crystal but becomes constant for a reasonably thin crystal. The simultaneous effect of crystal thickness and moderator thickness on the neutron detection efficiency of a $^6\text{LiI(Eu)}$ crystal is shown in Figure 5. The curves shown in Figure 5 are experimentally determined.

Figure 5. Thermal neutron detection efficiency by different thicknesses of $^6\text{Li(Eu)}$ crystal⁴. Layers of various thicknesses of polyethylene rings were used to optimize the neutron energy moderation.

5. LITHIUM GLASS

Lithium glass detectors are scintillation-type detectors; that is, they emit light in response to excitation energy received from ionizing radiation. The detectors are silicate-based glass into which a few weight percent of lithium have been incorporated. The detectors also contain a small percentage of an activator species (necessary to produce the fluorescence effect), which is usually cerium in the form of an oxide. These detectors, most often for neutron detection, are often enriched with the isotope ^6Li . Lithium-6 undergoes a nuclear reaction by absorbing a neutron, usually a low-energy neutron, and releasing an alpha particle and a triton (nucleus of a tritium atom).

The alpha particle and triton deposit several million electron volts of energy in the scintillation detector and produce a readily measurable light output toward the blue end of the visible spectrum. This output is usually detected with a photomultiplier tube. Pulses from the photomultiplier tube are fed to a preamplifier, amplifier, discriminator and an appropriate recording device.

Lithium glass detectors for neutron detection do not have very good inherent energy resolution characteristics; thus, they are not often used for neutron spectral measurements, although they are commonly used for indirect, "time-of-flight" energy measurements. In this process, time is measured from when a neutron is produced until it travels a known distance between the source and a lithium glass detector. The time is correlated with the energy of the neutron. Lithium glass detectors can also be depleted in the isotope ^6Li and enriched in the second natural isotope of lithium, ^7Li . Such

detectors are quite insensitive to neutrons and have been used to evaluate the gamma radiation response in the presence of neutrons. By using two detectors (one that will respond to both neutrons and gamma rays is enriched in ^6Li , and a second similar to the first but enriched in ^7Li), the net response of the first detector to neutrons can be estimated by subtracting the second detector response from that of the first.

Lithium glass detectors have an advantage over some other neutron detectors. The glass can be fabricated into any of several geometries, so detectors of unusual shapes and sizes can be fabricated for specialized applications. The lithium glass detector also offers the advantage of being a relatively fast scintillator; that is, the decay time of the fluorescent light pulse is relatively short (about 75 nanoseconds for cerium-activated glass). Therefore, the detector can handle reasonably high count rates. The glass detectors are also quite rugged, can sustain high temperatures and may have applications in environments unsuitable for some other detector types.

6. MONTE CARLO N-PARTICLE WORK WITH LITHIUM GLASS

A recently developed Monte Carlo N-Particle (MCNP) Visual Editor Graphical User Interface was used to characterize the basic scintillation properties and detection parameters of two glass scintillators, namely GS-20 (doped with enriched ^6Li) and GS-30 (doped with ^7Li). Both types of glass are manufactured by Saint-Gobain Corporation. The neutron response has been compared with that of a typical ^3He tube pressurized at 3 atmospheres. Figure 6 shows that a neutron loses a significantly larger amount of energy in glass (mostly because of its density) than it does in helium gas.

Figure 6. Neutron energy deposited in GS-20 (lithium glass, 7.6-cm-diameter x 0.3-cm-thickness [3- x 0.12-in]) and in a ^3He -tube (33- x 5-cm [13- x 2-in] cylinder under 3 atmospheres of pressure).

Neutron detection efficiency increases with the thickness of the lithium glass. However, GS-20 (with a thickness of only 3 mm [0.12 in]) was chosen for practical reasons. This GS-20 is used in conjunction with an identical piece of GS-30 (with ^7Li doping, therefore it has no neutron sensitivity) to obtain a better estimate of net neutron counts in a measurement. In Figure 7, neutron detection efficiency is shown as a function of GS-20 thickness.

Figure 7. Lithium glass (GS-20) neutron detection efficiency simulation with MCNP. Efficiency is shown as a function of scintillator thickness.

MCNP4C2 was used to simulate the gamma detection efficiency of GS-20 glass as a function of scintillator thickness. The gamma response of GS-20 follows the general pattern seen in crystals such as NaI(Tl). The efficiency increases with increasing thickness, because of the presence of more material to stop the incident gamma radiation. Figure 8 shows graphically the way in which gamma sensitivity changes with glass thickness.

Figure 8. Lithium glass efficiency for counting gamma radiation (without discrimination) is a function of glass thickness. The sensitivity corresponds to the relative efficiency of the GS-20.

Even though the energy deposited by neutrons is higher in lithium glass than in helium tubes, the total neutron efficiency (or the number of interactions of neutrons within the active volume of a detector) is much higher in the case of a pressurized helium tube. The relatively higher efficiency for ^3He tubes is primarily because the $^3\text{He}(n, p)$ reaction has a larger cross section at thermal neutron energy than the $^6\text{Li}(n, t)\alpha$, as demonstrated in Figure 9.

Figure 9. The neutron sensitivity of GS-20 compared to that of a helium-tube (33-cm active length x 5-cm diameter [13 x 2 in] under 3 atmospheres of pressure) is shown as a function of source-to-sensor separation. The source used is moderated ^{252}Cf .

Figure 10 shows the MCNP simulation results for the acceptance angle of a lithium glass crystal (GS-20, 76.2-mm diameter x 3- mm thick [3- x 0.12-in]) compared to that of a helium tube (330 mm active length and 50.8 mm diameter [13 x 2 in]). One important piece of information can be deduced from the plot. For ^6Li glass, the response is forward-peaked. Therefore, one can use a cylindrical piece of polyethylene (76.2-mm diameter x 25.4-mm thickness (3- x 1-in)) on the face of the GS-20 to achieve nearly 100% thermalization of neutrons.

Figure 10. Angular response of lithium glass and a helium tube to thermal neutrons. The response for the lithium glass sample is forward-peaked.

CONCLUSIONS

A prototype hand-held dual counter capable of measuring gamma and neutron counts in a mixed radiation field has been built using a $^6\text{LiI}(\text{Eu})$ crystal. In comparison to similar hand-held equipment that is commercially available (mMCA-430 manufactured by TSA Inc.), the new $^6\text{LiI}(\text{Eu})$ detector outperforms the commercial detector in both gamma and neutron sensitivity.

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