# SORMA WEST 2008

## 2008 Symposium on Radiation Measurements and Applications

June 2-5, 2008 Berkeley, California, USA

# Oral Program as of May 27, 2008

We invite you to Berkeley for the first West Coast meeting of the Symposium on Radiation Measurements and Applications.

SORMA West 2008 is hosted jointly by the University of California, Berkeley and the Lawrence Berkeley and Lawrence Livermore National Laboratories. It is made possible by the generosity of our agency sponsors and private-sector supporters.

We gratefully acknowledge the cooperation and advice of the original SORMA, now SORMA East, hosted by the University of Michigan and next scheduled for 2010.

Note: the Monday opening plenaries (in International House) and Thursday summary or rapporteur plenaries are described in a different document.

Monday's plenaries will be held at International House, which is also the location of the poster session and reception. The parallel oral sessions Tuesday through Thursday, and the closing plenary, will be in Stanley Hall (rooms 105 and 106) and Bechtel Engineering Center (Sibley Auditorium).

# Table of Contents

# <u>**Wednesday, June 4**</u>
## Plan of the Day

Contributed orals in parallel sessions will be given in both the morning and the afternoon.

All start and finish times in Wednesday's technical program are 30 minutes later than usual due to the Chabot dinner event. Session AM I begins at 9:30 rather than 9, and so on throughout the day.

Lunch (on your own) is 12:30-2:30. Those holding a Wednesday ticket for an LBNL tour will be guided to the shuttle-bus stop.

At 5:40 (ten minutes after the end of Session PM II) everyone signed up for the dinner event at Chabot Space and Science Center should prepare to board buses. Afterward (leaving Chabot at approximately 10 PM) the buses will return to the Doubletree, not to the campus venue. Maps will be available at the information desk for those traveling to Chabot independently.

Those who did not sign up for the Chabot dinner event may wish to ask conference staff for restaurant guides, maps, etc.

# Neutron Detection with Scintillators

## *Wednesday AM I: Stanley 105*

*Chair: Marek Moszynski, Soltan Institute for Nuclear Studies*

*Wednesday AM I: Stanley 105-1*

**Improved Capture-Gated Neutron Spectrometers**

*J. Bart Czirr, MSI Photogenics*

We have continued to improve the efficiency and extend the energy range of a heterogeneous dual-signal neutron spectrometer that was first introduced in 1989. The latest manifestation utilizes small crystals of lithium gadolinium borate scintillators to provide a confirmation signal when a neutron is captured at low energy. Incident neutron energy is obtained from the sum of several proton-recoil pulses arising in a plastic scintillators matrix containing the inorganic crystals. Incident MeV neutrons that remain within the detector body lose almost all of their kinetic energy within 50 ns and are perceived as a single light pulse from the plastic scintillators. After slowing down, the neutrons diffuse for several microseconds before capturing in Li, Gd, or B in the borate crystals. The scintillator decay time of the inorganic crystals is approximately 200 ns and is easily distinguished from the narrow recoil-proton sum pulse. In the past, we have utilized only 6Li or 10B capture pulses and have achieved a capture efficiency of 12% for fission spectrum neutrons. This capture efficiency has been improved to 15% by including Gd capture pulses. The prompt-gamma energy released upon low-energy neutron capture in Gd is approximately 8-MeV, with an average gamma energy of 1 MeV. Several gamma rays (from a single neutron capture) Compton scatter in the detector body and provide a detectable signal indicating that the neutron deposited its kinetic energy in the hydrocarbon scintillators. To extend the detector energy range beyond 10 MeV, we have performed MCNP-X Monte Carlo calculations up to 150 MeV neutron energy. The calculations indicate a dual-signal efficiency of 0.3% at 150 MeV. Experimental confirmation will be obtained at LANL later this month. It is hoped that the spectrometer will be useful for neutron dose measurements in manned space flights, and may provide measurements of neutron spectra that are presently unavailable.

*Wednesday AM I: Stanley 105-2*

**Development of New Composite Scintillation Materials Based On Organic Crystalline Grains**

*Nikolai Z. Galunov, Institute for Scintillation Materials (ISM)*
*Eugenia V. Martynenko, Nikolai Z. Galunov, Boris V. Grinyov, Natalya L. Karavaeva (Institute for Scintillation Materials of the National Academy of Science of Ukraine); Jong Kyung Kim, Kyun Kim (Innovative Technology Center for Radiation Safety, Hanyang University), Oleg A. Tarasenko (ISM)*

To have a sensitive and convenient detection technique for fast neutron spectrometry it is necessary to obtain a large area non-hygroscopic detector, which has a high efficiency of fast neutrons detection and allows discriminating neutron scintillations from background gamma radiation. Molecular organic scintillators are the most effective for detecting short-range ionizing radiation, as well as for spectrometry of fast neutrons. The main problem of such applications can be the very low flux of radiation under detection. This means that such a detector can be thin, but must have a large diameter to increase the solid angle of detection. Recently, we have proved the idea of design of new type of organic composite materials as the detectors of large area. The single crystal with perfect structure is grinded and organic single crystal grains of different sizes is obtained. A set of sieves allows selecting the fraction of these grains of necessary sizes, which has to be comparable with the range of the ionizing particle. If the chosen fractions of the grains are introduced inside a transparent polymer ma-trix, then we obtain a composite scintillator. In this work we present both the main aspects of the proposed technology, and the results of investigation of composite scintillators up 200 mm in diameter based on stilbene (or p-terphenyl) grains as detectors of short-range and fast neutron radiation.

*Wednesday AM I:  Stanley 105*-3
**New Copolymer Architectures for Next Generation Plastic Neutron Scintillators**
*Banu Kesanli, Chemical Sciences Division, Oak Ridge National Laboratory (ORNL)*
*John S. Neal, presenter*
*Banu Kesanli, Fengjun Hua, Kunlun Hong,  Sheng Dai (Chemical Sciences Div.,, ORNL)*

A new class of plastic neutron scintillators was developed based on lithium-doped polystyrene and polyethylene oxide (PS-b-PEO) amphiphilic block copolymers. In general it is challenging to synthesize lithiated plastic scintillators as hydrophilic lithium is chemically incompatible with the hydrophobic plastic host material and the organic scintillator (e.g. PPO). Our custom-designed polymer architectures allow incorporation of both hydrophobic and hydrophilic components in nano domains via controlled microphase separation, yielding novel transparent neutron scintillators. These unique plastic neutron scintillators are relatively inexpensive and potentially could be doped with sufficient concentrations of lithium without destroying the scintillator's light yield and optical transparency. Another advantage of our amphiphilic block copolymers is their compatibility with high quantum yield organic fluorophors. Novel PS-b-PEO copolymers with varying PS weight % were synthesized and doped with Li-6 and an organic fluorophor to study the effect of PS content on the light output of the plastic neutron scintillators. In addition, different forms of Li-6, namely LiOH, LiCl and Li3PO4 nanoparticles were explored to achieve high dispersion of large quantities of Li-6 into the polymer scintillators. Lithium phosphate nanoparticles showed enhanced solubility in the polymer matrices due to their small particle sizes compared to the conventional bulk solids. Samples containing about 10 weight % Li-6 were prepared without significant loss of transparency. Am-Li thermal neutron source was used to evaluate the light yields of copolymer samples. The best light yields have been achieved when Li-6 has been incorporated in the form of lithium phosphate nanoparticles rather than LiCl and LiOH. Studies are in progress to prepare new copolymer architectures having conjugated aromatic groups such as naphthalene and diphenyloxazole (PPO) for improved light yield. Funding for this work is through the support of the Department of Energy/NNSA NA-22, Office of Nonproliferation research and Engineering program. The Oak Ridge National Laboratory is managed for the Department of Energy under contract No. DE-AC05- 00OR22725 by UT-Battelle, LLC.

*Wednesday AM I: Stanley 105-4*

**New Organic Crystals for Pulse Shape Discrimination**

*Giulia Hull. Lawrence Livermore National Laboratory (LLNL)*
*Natalia Petrovna Zaitseva, Nerine J. Cherepy, Jae-hyun Park, Wolfgang Stoeffl, Stephen A. Payne (LLNL)*

Efficient, readily-available, low-cost, high-energy neutron detectors can play a central role in detecting illicit nuclear weapons since neutrons are a strong indication for the presence of fissile material such as Plutonium and Highly-Enriched Uranium. The main challenge in detecting fast neutron consists in the discrimination of the signal from the background represented by gamma radiation. At present, the choice for scintillator organic crystals for fast neutron detection, in a n/gamma mixed field, is limited to stilbene. While offering a good pulse shape discrimination (PSD), stilbene is grown from melt, and thus the availability of large-size crystals is limited and they are expensive. In this work we will report on the development of new organic crystals that are not toxic and are easy to grow, for fast neutron detection as an alternative to stilbene. In particular, we identified several compounds that offer effective PSD, good optical quality, light yield comparable to or higher than stilbene. All the developed crystals are good candidates for the rapid solution growth, which is generally the lowest cost option for producing large-size optical crystals, and thus they represent promising organic scintillators for a widespread deployment for high energy neutron detection.
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

*Wednesday AM I: Stanley 105-5*

**Use of a Lithium-6-Glass/Plastic-Scintillation Detector for Nuclear Nonproliferation Applications**

*Marek Flaska, University of Michigan*
*Sara A. Pozzi (Department of Nuclear Engineering and Radiological Sciences, University of Michigan), J. Bart Czirr (MSI/Photogenics), W. H. (Bill) Ulbricht (ULTRONICS Instrument Co.)*

Capture-gated organic/inorganic scintillation detectors have recently attracted the attention of researchers for their potential use in the fields of nuclear nonproliferation and nuclear safeguards. These detectors are based on standard organic scintillators that are coupled with materials with a high absorption cross section for thermal neutrons (boron-10, lithium-6, etc.). Therefore, these detectors are sensitive to fast neutrons and gamma rays, but also to thermal neutrons. Fast neutron detection occurs as follows. First, the neutron interacts with the hydrogen and carbon nuclei present in the scintillator, generating a scintillation pulse. Then, the neutrons that have lost most of their energy in the scintillator are captured in the neutron-absorbing medium - usually boron, lithium, or gadolinium compounds. This technique is referred to as capture-gated neutron spectroscopy, because the acceptance of the pulse from the scintillator is gated by the subsequent neutron capture. The capture pulse occurs most probably after the neutron has lost most of its energy in the prompt pulse. In this case, the prompt pulse amplitude is strongly correlated with the incident neutron energy, and this fact can be used to estimate the incident neutron spectrum. The elapsed time between the scintillator pulse and the subsequent neutron capture is of the order of a few microseconds. In this work we present measurements and Monte Carlo simulation results obtained with a lithium-6 (Li-6) glass capturing material. We will discuss the use of the Li-6-glass/plastic-scintillation detector for the detection of special nuclear material and radioactive sources. Although these materials simultaneously emit a well known number of neutrons and gamma rays, some gamma rays and/or neutrons can be shielded by surrounding material. In addition, the presence of naturally occurring radioactive materials can also play an important role. Therefore, the accuracy of material detection can be increased by detecting neutrons and gamma rays at the same time. In addition, the detection system based on both neutrons and gamma rays is less vulnerable to false alarms, especially in the presence of shielding. We describe a Monte Carlo approach to detector characterization, and its validation through measurements in the laboratory. The signals are recorded and analyzed by a waveform digitizer. In the full paper, the simulation results will be compared to the measurements for several typical neutron and gamma-ray sources, and in various source-shielding configurations.

## Ge Detectors and Imagers

### *Wednesday AM I: Bechtel*

*Chair: Mark Amman, LBNL*

*Wednesday AM I: Bechtel-1*

**Gamma-ray Imaging with the High-Resolution Si+Ge Compact Compton Imager**

*K. Vetter, Lawrence Livermore National Laboratory*
*L. Mihailescu, presenting*

A Compton scatter camera, the Compact Compton Imager (CCI) is being developed by our group. The imager is based on position sensitive segmented planar Ge and Si detectors. All detectors are implemented in double-sided strip configuration which - along with digital signal processing - provides the necessary three-dimensional position information to perform Compton imaging. We have recently assembled our second-generation instrument, CCI-2, that consists of 2 large-volume Si(Li) and two large-volume HPGe detectors. We report on measurements we have performed with this instrument, including the determination of basic performance parameters, such as detection, imaging efficiencies, and image resolution. We have also performed experiments to demonstrate the capability of unmasking threat sources in the presence of a complex environmental background. With imaging efficiencies of 1.5% to almost 18% that have been deduced for energies between 200 keV and 2614 keV, CCI-2 is one of the most efficient Compton instrument existing today. Imaging angular resolution values of 2 degrees have been deduced. Such a gamma-ray imaging capability can be an important tool to support homeland security, international safeguards and nuclear non-proliferation efforts.

The work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

*Wednesday AM I: Bechtel-2*

**Pulse Shape Analysis of a p-Type Point Contact Germanium Detector for Dark Matter and Neutrinoless Double-beta Decay Searches**

*John L. Orrell, Pacific Northwest National Laboratory (PNNL)*
*Craig E. Aalseth, Martin E. Keillor, Jeremy D. Kephart, Harry S. Miley (PNNL); Juan I. Collar (University of Chicago)*

Recent development of a bore-hole free, 0.5 kg high purity germanium gamma-ray spectrometer advances the capability of pulse shape analysis techniques for background rejection in searches for dark matter and neutrinoless double-beta (0nuBB) decay of Ge-76. This p-type point contact (PPC) germanium crystal has a cylindrical geometry, but substitutes a small point contact in place of the typical coaxial bore hole, resulting in a greatly reduced detector capacitance. This physical configuration of electrodes results in a low energy threshold and increased time separation of pulses from the charge-cloud collection of individual interactions within the crystal. The low energy threshold (~0.3 keV) makes the detector a candidate for future dark matter searches. At the low energies investigated for dark matter, pulse shape analysis may assist in distinguishing true energy deposition pulses from microphonic or other electronics noise sources. Furthermore, a "radial" parameter determined from pulse shape analysis may permit a fiducialization of the germanium crystal volume, separating events in the bulk of the crystal (dark matter candidates) from those on the crystal's outer edge (low energy photon backgrounds). The greater differentiation of charge-cloud collections will assist neutrinoless double-beta decay searches by distinguishing single-site energy deposition events at 2039 keV (0nuBB decay candidates) from multi-site energy deposition events (high energy photon backgrounds). The pulse shape characteristics of this new detector design are presented and analyzed for their advantages in performing background rejection in searches for dark matter and neutrinoless double-beta decay of Ge-76.

*Wednesday AM I: Bechtel-3*

**The Use of High Purity Germanium (HPGe) detectors for Single Photon Emission Computed Tomography**

*Helen Boston, University of Liverpool*
*AJ Boston, RJ Cooper, JR Cresswell, A Grint, LJ Harkness, PJ Nolan, DC Oxley, DP Scraggs (Department of Physics, University of Liverpool); I Lazarus (STFC Daresbury Laboratory)*

In the last decade Germanium has evolved to a point where it is now possible to implement this material for use in medical imaging and security scanning. A dual head scanner (SmartPET) system has been built at the University of Liverpool, UK demonstrating that Germanium is a viable material for use in Positron Emission Tomography[1]. SmartPET utilises two orthogonal strip High Purity Germanium (HPGe) detectors, which were manufactured by Ortec. Each detector has an active volume of 60x60x20mm which is electronically segmented into 12 x 12 strips, each with a strip pitch of 5mm. Using digital Pulse Shape Analysis (PSA), it has been shown that the detector spatial resolution that can be obtained from this system is 1x1x2mm.

*Wednesday AM I: Bechtel-4*

**Inter-strip position interpolation in a high-purity germanium double-sided strip detector**

*Jason P Hayward, The University of Tennessee*
*David K Wehe (University of Michigan)*

One fundamental design issue in the HPGe double-sided strip detector is the gap between strips, which makes up 1/6 of the 3 mm strip pitch in the UM detector. When an interaction occurs in the gap between strips, charge-carriers from the resulting charge cloud may be split between adjacent strips. Additionally, up to 6% of the carriers may be lost. Furthermore, use of the signals obtained for interactions that occur in gaps is complicated by: 1) their sensitivity to the change in charge cloud geometries and 2) the difficulty of distinguishing single interactions from multiple close interactions. In this work, a Bayesian method for inter-strip interpolation is described for interactions which fall in detector gaps. This method exploits charge-splitting and charge loss, yielding interaction position with lateral resolution of ~160 micron FWHM at 356 keV and ~310 micron FWHM at 662 keV. According to simulation, lateral resolution in the 500 micron gap is fundamentally limited to these values due to charge cloud size, and lateral resolution < 100 micron FWHM may be achieved at 200 keV. When a second interaction falls beneath an adjacent strip, lateral resolution for the gap interaction is still finer than the width of the gap, and simulation shows potential for further improvement. For interactions that occur in the gap between strips, the position resolution and the ability to discriminate single interactions from multiple close interactions are limited by the depth resolution of the detection system.

*Wednesday AM I: Bechtel-5*

**Acquisition of Contrast Images using a Segmented Planar Germanium Detector**

*David Oxley, University of Liverpool*
*A.J. Boston, H.C. Boston, R.J. Cooper, J.R. Cresswell , P.J. Nolan, D.P. Scraggs, G. Turk, R.A. Ruddlesden (University of Liverpool); I.H. Lazarus (STFC Daresbury); M.R. Dimmock, A.N. Grint (University of Liverpool)*

The application of semiconductor detectors in medical imaging is an area which currently attracts interest from a wide range of fields. An investigation into whether a planar germanium detector could be utilized in absorption imaging has been conducted. The detector [1] has a germanium crystal with an active volume which is electronically segmented into two sets of twelve orthogonally aligned channels. This creates a raw voxel segmentation of 5x5x20mm. In the experiment three objects were placed upon the detector surface while a 241Am source was suspended 25cm above. The height ensures the radiation is incident both uniformly and perpendicularly to the whole detector surface. The contrast in detected radiation intensity created by attenuation within the object was constructed into an image. This process is analogous to a diagnostic X-ray scan. By implementation of digital pulse shape analysis (PSA) [2] techniques the spatial resolution in the detector and the resolution of the image were enhanced, allowing the fine structure detail of the objects to be resolved. Furthermore the experiment was designed to establish a limitation of the applied technique. This was found at the sub-millimetre level where finer detector pixilation failed to increase image quality. Analysis of a collimated characterization scan confirmed a non-linear relationship between position and the PSA parameter utilized. The results show how, despite limitations, employment of simple PSA techniques can enhance spatial resolution down to a sub-millimetre level and confirm the potential for planar germanium detectors to be employed in absorption imaging. The images of the chosen objects will be presented along with the quantification of the discovered limitation to the pulse shape analysis technique and its implications for position resolution.

[1] H.C.Boston et al., Nucl. Instr. and Meth.A (2007), doi:10.1016/j.nima.2007.04.017
[2] K.Vetter et al. Three-dimensional position sensitivity in two-dimensionally segmented HP-Ge detectors, Nucl. Instr. And Meth.A 452 (2000) 223

## Simulation and Analysis of Radiation Interactions

### *Wednesday AM I: 106 Stanley*

*Chair: Todd Palmer, Oregon State Univ.*

*Wednesday AM I: 106 Stanley-1*

**A First Application of the FRAM Isotopic Analysis Code to High-Resolution Microcalorimetry Gamma-Ray Spectra**

*P. J. Karpius, Los Alamos National Laboratory (LANL)*
*D.T. Vo, M.K. Bacrania, D. Dry, E.P. Hastings, S.P. Lamont, J.H. Rim, M.W. Rabin (LANL); L.R. Vale (NIST); A.S. Hoover, C.R. Rudy (LANL); J.A. Beall, W.B. Doriese, G.C. Hilton, R.D. Horansky, K.D. Irwin, J.N. Ullom (NIST); C.A. Kilbourne, J. King, F.S. Porter (NASA).*

Gamma-ray spectrometry systems based on High-Purity Germanium (HPGe) have been the long-standing leader in terms of resolution since their introduction many years ago. The application of this technology to the spectroscopic assay of special nuclear material led to the development of several isotopic analysis tools, including the advanced software package FRAM, which was, and continues to be, developed at Los Alamos National Laboratory. Although FRAM can be applied over a wide range of energies, the significantly higher intensity of the X-ray region in the neighborhood of 100 keV makes analysis of this area of the spectrum advantageous, especially in the case of plutonium. However, even with HPGe, the multitude of gamma-ray, and x-ray peaks that exist in the 100 keV region are sufficiently convoluted so as to preclude determination of plutonium isotopic composition without the introduction of some systematic error. The novel technology of microcalorimetry, shown to have an order of magnitude better spectral resolution than HPGe, has recently opened new doors with respect to these difficulties. Now, for the first time, the powerful capabilities of FRAM have been paired with the unparalleled resolution of microcalorimetry in the analysis of plutonium spectra. Preliminary results of these analyses, as well as an outlook for future measurements, heretofore unobtainable with HPGe, will be presented.

*Wednesday AM I: 106 Stanley*-2

**Cosmic-Ray Background Generator (CRY) for Monte Carlo Transport Codes**

*Douglas Wright, Lawrence Livermore National Laboratory*
*Chris Hagmann , David Lange (LLNL)*

In many basic science and homeland security applications the natural cosmic-ray background is the limiting factor for the sensitivity of a particular detector system. In order to study this background in the development of new detection techniques we have produced and distributed a free, open-source fast simulation of cosmic-ray particle showers. Our simulation is based on precomputed input tables derived from full MCNPX simulations of primary cosmic rays on the atmosphere and benchmarked against published cosmic-ray measurements. Our simulation provides all particle production (muons, neutrons, protons, electrons, photons, and pions) with the proper flux within a user-specified area and altitude. The code generates individual showers of secondary particles sampling the energy, time of arrival, zenith angle, and multiplicity with basic correlations, and has user controls for latitude (geomagnetic cutoff) and solar cycle effects. We provide a function library, callable from C, C++, and Fortran, and interfaces to popular Monte Carlo transport codes: MCNP, MCNPX, Geant4, and COG. The CRY software package is open source and can be downloaded from http://nuclear.llnl.gov/simulation.

*Wednesday AM I: 106 Stanley-3*

**Monte Carlo Assessment of Active Photon Interrogation Systems for the Detection of Fissionable Material**

*Shaun D. Clarke, University of Michigan*
*Sara A. Pozzi (University of Michigan); Scott J. Thompson, Alan W. Hunt (Idaho State University)*

Active interrogation techniques are well established for identifying concealed nuclear material using delayed neutron detection because the presence of delayed neutrons uniquely signifies the presence of fissionable material. Sufficient quantities of uranium or plutonium, for example, will generate a signal after interrogation has ceased (due to delayed neutron emission and subsequent fission reactions) whereas non-fissionable materials will not. This effect has been previously illustrated at the Idaho Accelerator Center (IAC) by Kinlaw and Hunt using bremsstrahlung photons up to 22 MeV with uranium targets. However, delayed neutron emission is rare compared to prompt neutron emission and the delayed neutrons have a lower average energy (500 keV compared to 2 MeV). The detection of the more abundant, higher-energy, prompt neutrons would be easier in complex shielding environments. However, prompt neutron emission during active interrogation is not unique to fissionable material, because photoneutron reactions (gamma, xn) also may occur in common benign materials. Consequently, accurately simulating the production and detection of these prompt photoneutrons is paramount in designing an effective interrogation system. The unique capabilities of the MCNP-PoliMi code system are ideal for simulating such behavior. MCNP-PoliMi accurately models the correlations between individual interactions and the corresponding particle production. These capabilities preserve the exact particle interaction on an event-by-event basis leading to a very accurate prediction of the detector response. This code, however, has only recently been applied to problems involving photon interrogation. The full paper will present the most current simulation results related to active photon interrogation systems. These results will be analyzed to assess the feasibility and limitations of currently proposed active interrogation systems. Consideration will also be given to the efficacy of the method in terms of real-world measurement times and projected false-alarm rates.

*Wednesday AM I: 106 Stanley-4*

**Intrinsic Properties of CsI and CdZnTe: Monte Carlo Simulations**

*Fei Gao, Pacific Northwest National Laboratory (PNNL)*
*Y. Xie, L. W. Campbell, A. J. Peurrung, W. J. Weber (PNNL)*

Different radiation sources, such as X-rays, gamma-rays, energetic electrons and ions, initially ionize detector materials by creating fast electrons. These fast electrons lose their energy though indirect (bremsstrahlung) and direct energy transfer (phonons, plasmons, interband excitations, excitons, and electron-electron scattering). These quantum-mechanical processes controlling the energy partitioning of fast electrons need to be scientifically understood in the condensed state. We have developed a Monte Carlo (MC) method to study electron cascades, and to evaluate intrinsic properties of semiconductors and scintillators, including the mean energy required to create an electron-hole pair, W, the intrinsic variance (or Fano factor, F) and the spatial distribution of electron-hole pairs In the present work, the MC code has been employed to simulate the interaction of photons with CsI and CdZnTe (CZT) over the energy range from 50 eV to 2 MeV, and the subsequent electron cascades. CsI has been experimentally investigated from the viewpoint of possible applications as a scintillator with fast timing characteristics, while CZT semiconductor detectors are of great interest because they can provide high resolution X-ray and Gamma-Ray spectra at room temperatures. One of the objectives of this work is to investigate the differences in the intrinsic properties of these two representative materials that could explain the factors contributing to fundamental performance limits and nonlinearity. In general, W decreases with increasing photon energy from 18.46 to 13.8 and from 5.7 to 4.7 for CsI and CZT, respectively, whereas F increases with increasing photon energy to the values of 0.28 and 0.22 at high-energy regions for CsI and CZT, respectively. However, these intrinsic properties show greater non-linear behavior in CsI than in CZT, which suggests that the non-proportionality of CsI response may be partially associated with intrinsic properties of the crystal. Furthermore, one of the striking results is that the spatial distribution of electron-hole pairs exhibit very different behavior in CZT and CsI. In CZT, the density of electron-hole pairs created by plasmon decay along the main electron track is very high, and the electron-hole pairs produced by interband transitions are distributed at the periphery of the cascade volume, which leads to a dispersed distribution. In CsI, the density of electron-hole pairs is relatively low, and they are mainly distributed along the fast electron track. It is found that a significant proportion of the electron-hole pairs are produced by ionization and corresponding relaxation processes in CsI, but not in CZT. The spatial distribution and density of thermalized information carriers in along the primary and secondary tracks are important for large scale simulations of electron-hole pair transport, electron-hole annihilation, trapping in activator centers and defects, and recombination of excited carriers. Although the code has been benchmarked for CsI and CZT, it can be easily applied to other scintillator and semiconductor materials.

The research was supported by the Radiation Detection Materials Discovery initiative under the Laboratory Directed Research and Development Program at the Pacific Northwest National Laboratory.

*Wednesday AM I: 106 Stanley-5*

**Monte Carlo Simulation on Early Breast Cancer Detection Using Wire Mesh Collimator Gamma Camera**

*M Iqbal Saripan, Universiti Putra Malaysia*
*Wira Hidayat Mohd Saat, Suhairul Hashim (Faculty of Science, Universiti Teknologi Malaysia); Rozi Mahmud, Abdul Jalil Nordin (Faculty of Medicine and Health Sciences, Universiti Putra Malaysia); Mohd Adzir Mahdi (Faculty of Engineering, Universiti Putra Malaysia)*

In this project, we concentrate on a functional imaging technique in nuclear medicine using a gamma camera. Primarily, nuclear imaging has been developed to show the physiological process of an organ and the body system using tracers. One of the applications of nuclear imaging is in tumor or cancer detection. This paper investigates the performance of the new Low Energy High Resolution (LEHR) wire-mesh collimator used with a gamma camera to improve the latter ability in detecting breast cancer, using Technetium-99m agent at 140keV. The limitation of the LEHR conventional multihole collimator is the lacked of sensitivity as a trade-off for obtaining better resolution. By opting to get a better resolution, only photons within a narrow stereo angle will be allowed to pass the collimator, and eventually, less photons are registered by the sequential event. This inherent property of the conventional system reduced the possibility of maximum tumour recognition thus reducing the rate of low metabolic breast tumour detection. The wire-mesh collimator is a new concept of semi-collimator and semi-coded aperture. With such a flexible structure, one may choose to have a good resolution or a good sensitivity or any configuration in between. In this paper, we investigated the performance of the wire-mesh collimator to detect a lesion inside a human breast. The model of photons propagation and detection, as well as the human cells activity are simulated using the Monte Carlo N-Particle (MCNP) code. An abnormal cell inside a simulated breast with different tumour to background ratio (TBR) is investigated and the results from the conventional collimator and wire-mesh collimator are compared. Based on the results, we show that the wire-mesh collimator is able to detect more photons at a lower TBR in comparison to the conventional collimator. The findings in this study indicate that delineation of breast lesions are better. However, the images produced are degraded by artifacts, making the classification of the breast tumour is difficult. To suppress the false hot spots, we imposed a Wiener filtering technique to the images, and the results show that the contrast of the tumour is getting better. It can be concluded that the wire-mesh collimator can provide an alternative solution for early breast cancer detection. More work will be carried out in the future to improve the performance of the image restoration and enhancement algorithm, in order to enhance imaging findings of breast cancer.

# Non-Proportionality and Characterization of Scintillators

## *Wednesday AM II: Stanley 105*

*Chair: Edgar van Loef, Radiation Monitoring Devices, Inc.*

*Wednesday AM II: Stanley 105 -1*

### Light Yield Non-Proportionality and Energy Resolution of Praseodymium Doped LuAG Scintillator

*Lukasz Swiderski. Soltan Institute for Nuclear Studies*
*Marek Moszynski, Antoni Nassalski, Agnieszka Syntfeld-Kazuch, Tomasz Szczesniak (Soltan Institute for Nuclear Studies, , Poland); Kei Kamada, Kousuke Tsutsumi, Yoshiyuki Usuki (Materials Research Laboratory, Furukawa Co., Ltd., Japan); Takeyuki Yanagida, Akira Yoshikawa (IMRAM, Tohoku University, Japan)*

Scintillation properties of Praseodymium doped LuAG have been investigated. The crystal is a dense (6.7 g/cm3) scintillator with a short decay time (23 ns) and wavelength emission spectrum peaked at 310 nm. Both tested samples were 10 mm x 10 mm x 5 mm pieces, polished on all surfaces. The dopant concentration amounts to 0.23 mol%. A light yield of (15000 +/- 1500) ph/MeV was measured for both samples using a high sensitivity (13.7 uA/lmF) Photonis photomultiplier (PMT) XP5500B. High quantum efficiency of this PMT (35 %) allowed us to register (5200 +/- 200) phe/MeV using 12 us shaping time in the spectroscopy amplifier. The measured energy resolution was 5.0 % and 5.6 % for two samples respectively. Response of LuAG(Pr) to gamma rays was found to be proportional over wide energy range. Deviation from proportionality does not exceed 3 % at 22 keV for the best sample. This results in good intrinsic energy resolution of LuAG(Pr) amounting to 2.7 % measured with 662 keV gamma rays from 137-Cs. This work was performed in cooperation with Materials Research Laboratory, Furukawa Co., Ltd., which supplied us with two samples of LuAG(Pr).

***Wednesday AM II: Stanley 105 -2***

### Comparing Fast Scintillators with TOF PET Potentiality

*Maurizio Conti,Siemens Molecular Imaging*
*L. Eriksson (Siemens Molecular Imaging), C. Melcher (University of Tenessee), H. Rothfuss (Siemens Molecular Imaging)*

The renewed interest in Time-Of-Flight (TOF) Positron Emission Tomography (PET) has been accompanied by new research in the development of fast scintillators, mainly Halides and/or Lutetium based compounds doped with Ce or Pr. A good candidate for TOF PET must offer high density and Z, fast rise and decay time, high light output. Moreover, manufacturing complexity, cost and long term reliability (due, for example, to hygroscopicity) are additional factors that can influence the choice of scintillator. In this work we concentrate on higher density materials (Lu-based) and we focus on some intrinsic properties of the materials, such as decay time and light output, which have a direct effect on time resolution, the key performance parameter for a TOF-grade detector. This work presents measurements performed on a set of materials with TOF potentialities, namely LSO(Ce), LuYAP(Ce), LuAG(Pr), LaBr3(Ce) and LaCl3(Ce). The Lu-based materials have high density, from 6.7 to 7.4 g/cm3, which is associated with

high detection efficiency for the 511 keV used in PET. The La-based materials have lower density, from 3.8 to 5.3 g/cm3, but higher luminosity. All materials are Ce-doped (or Pr-doped) materials with a fast decay time, due to the 5d-4f transition of the Ce3+ (or Pr3+ ) ions, which ranges from 20 to 40 ns. Several samples of different size were tested: cubic crystals with 5mm or 10 mm side, and long crystals suitable to be assembled in arrays, 5x5x20mm3 and 5x5x30mm3. Polished surfaces with and without reflectant were used. The three scintillators were characterized in terms of absolute light yield, decay time, energy resolution, emission and excitation spectra. Time resolution of single crystals associated with fast NIM electronics was also measured.

Wednesday AM II: Stanley 105 -3

**Progress in Studying Scintillator Non-Proportionality: Phenomenological Model and Experiments**

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We propose an approach to describe the origin of non-proportional dependence of scintillator light yield on the energy of an ionizing particle. The non-proportionality is discussed in terms of energy relaxation channels and their linear and non linear dependences on the deposited energy. In this approach, the scintillation efficiency (dL/dx) is described as a function of the energy deposition (which depends on the linear energy loss dE/dx) and the kinetics rates of each relaxation channel. This mathematical framework permits both a qualitative interpretation and a quantitative fitting representation of scintillation non-proportionality response as function of kinetic rates. This method was successfully applied to different sets of experimental data: gamma-ray response of pure CsI recorded at low temperatures [1], Tl doped CsI response excited by various particles at room temperature [2], and room temperature electron response of cerium doped lanthanum halides measured with SLYNCI [3], a new facility using the Compton coincidence technique [4]. Finally, attention is given to the physical meaning of the dominant relaxation channels, and the potential causes responsible for the scintillation non-proportionality. We find that one class of materials (e.g. the oxides) behaves as if the non-proportionality is due to competition between radiative exciton decay and non-radiative exciton-exciton annihilation. Another class (e.g. the doped alkali halides) behaves as if non-proportionality is due to competition between radiative recombination and non radiative Auger process of an electron and a hole captured at a doping ion.

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*Wednesday AM II: Stanley 105 -4*

**Ion Technique for Screening Gamma Detector Candidate Materials**

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Recent demands in nuclear nonproliferation and global security for new radiation detector materials have prompted research efforts on accelerated material discovery. New detectors with better energy resolution for gamma ray detection at room temperature are highly desirable. At current stage, a slow Edisonian process, such as combinatorial synthesis, is the main approach to new material discovery due to a general lack on fundamental understanding of scintillation mechanisms. For gamma-ray detection, a relatively large high-quality crystal is necessary for complete absorption of gamma-ray energies of interests and for reliable evaluation of the candidate properties. New material discovery has been restricted due to the difficulties inherent to large crystal growth of new materials; whereas high-quality thin films of candidate materials can be readily produced by various modern growth techniques. In this work, an ion-beam approach, applicable to thin films or small crystals, is demonstrated to quickly evaluate various materials and identify scintillation properties relevant to detector performance. The experimental setup of the ion technique consists of a Time of Flight (TOF) telescope coupled with a photo-multiplier tube (PMT). Instead of gammas, energetic charged particles, such as proton or helium ions, are used to deposit all their energy in the materials within a few tens of micrometer depth. Using a forward scatter method, energetic proton or helium ions are produced over a continuous range of energies from a few tens of keV to a few MeV of the primary ion beam. The TOF detectors record the energy of each ion, and a scintillation response in a candidate material is registered by the PMT in coincidence with the TOF measurement. Excellent energy resolution and fast response of the TOF telescope allow quantitatively and efficiently evaluate candidate materials. This ion approach is demonstrated using benchmark materials of bismuth germanate (BGO) and europium-doped calcium fluoride (CaF2:Eu) crystals. The primary assumption under this ion approach is that thin-film materials whose energy resolution for ions is poor are unlikely candidates for gamma detectors, while materials that demonstrate good detector response are candidate materials that may warrant single

crystal growth for further investigation. When considering the energy resolution attainable by a scintillator, intrinsic light yield nonlinearity along with absolute light yield are typically the most significant characteristics. Light output, nonlinearity and energy resolution obtained from the ion technique are, therefore, compared with the gamma results in BGO and CaF2 measured using the same experimental apparatus, as well as the literature data. Good agreements between the ion and gamma measurements are observed. This ion technique is practically efficient in determining the optimized stoichiometry in combinatorial syntheses, since the relative light yield and energy resolution from the candidate materials with various compositions can be compared with each other, or with a known scintillator. Good correlations between the ion and gamma measurements provide a physical basis for using the ion technique to predict scale-up material performance in scintillation-based gamma-ray detectors, and provide a pathway to assist new scintillator discovery.

Wednesday AM II: Stanley 105 -5

**Scintillation Non-Proportionality of Lutetium and Yttrium Silicates and Aluminates**

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Non-proportionality in scintillators is defined as the non-uniform conversion of gamma ray energy to the number of scintillation photons. It has been suggested in recent years that non-proportionality plays a major role in most scintillators exhibiting poor energy resolution with respect to values predicted from counting statistics. This study examines the non-proportionality of scintillators excited by gamma rays and x-rays from radioisotopic sources between 22 keV and 1.3 MeV. The samples investigated measure 10x10x10mm and are composed of single-phase Lu- and Y-based silicates and aluminates with various concentrations of tri-valent Ce or Pr activator ions. In some cases, the material was co-doped with the di-valent calcium ion as it has been shown to enhance conversion efficiency in LSO. This work utilizes Gaussian fitting parameters to determine peak positions from gamma ray spectra obtained via a Hamamatsu photomultiplier tube and standard NIM electronics. Previous work on the non-proportional response of LSO:Ce shows a steady decline in the scintillation light yield as photon energy drops below 300 keV. Initial measurements of LuAG:Pr show a similar trend, although significantly smaller in magnitude. The samples from this study will be subsequently characterized with the Compton Coincidence System (SLYNCI) at Lawrence Livermore National Laboratory.

## Other Semiconductor Detector Materials and Techniques

### *Wednesday AM II: Bechtel*

*Chair: Uri El-Hanany, Imarad Imaging Systems*

*Wednesday AM II: Bechtel-1*

**Developing Larger TlBr Detectors - Detector Performance**

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*Leonard Cirignano, Alexei Churilov, Guido Ciampi, William Higgins (RMD), Fred Olschner (Cremat Inc.), Kanai Shah (RMD)*

Thallium bromide (TlBr) is a high atomic number (81, 35), dense (7.56 g/cc) wide band gap (2.68 eV) semiconductor. In addition, TlBr has a cubic crystal structure and melts congruently at a relatively low temperature (~ 460 C). Recently, mobility-lifetime product of electrons in TlBr has been reported to be greater than 0.001 cm2/V. These properties make TlBr a promising material for room temperature gamma radiation detection. Employing device designs such as small pixel arrays that depend primarily on the motion of a single carrier type allows fabrication of thicker devices with better energy resolution than planar devices of the same thickness. We report on our recent progress in developing larger TlBr detectors. Over the past several months we have increased the electron mobility-lifetime product of our TlBr by more than one order of magnitude. Electron mobility-lifetime values as high as 3.0 x 10-3 cm2/V have been measured. Devices with small pixel design have been built with 3 and 5-mm thickness and pixel pitch of 1-mm and 1.5-mm respectively. Pulse height spectra have been recorded over a range of energies from 60 keV to 662 keV. Energy resolution (FWHM) as high as approximately 5% at 122-keV and 1.7% at 662-keV has been obtained without any 3-D corrections. Such arrays are well suited for 3-D correction techniques similar to those applied to CZT devices, indicating that further improvement in energy resolution should be achievable. These latest results demonstrate promise for TlBr as a room temperature semiconductor gamma ray detector.

*Wednesday AM II: Bechtel-2*

**Anisotropic III-VI Chalcogenide Semiconductors for Radiation Detectors**

*Krishna C. Mandal, EIC Laboratories, Inc.*
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High-quality and large chalcogenide semiconductors GaSe, GaTe, and GaSe(x)Te(1-x ) (0.1 <= x <= 0.9) with resistivities up to 4.2 x 10^9 ohms.cm were grown by a controlled vertical Bridgman technique using high purity Ga (7N) and in-house zone refined (ZR) precursor materials (Se and Te). Integrated numerical models for single crystal growth have been developed combining global heat transfer and elastic thermal stress sub-models for the Bridgman growth system. The global heat transfer sub-models account for heat transfer in the multiphase system, convection in the melt, and interface dynamics. The elastic thermal stress sub-model is used to predict the thermal stresses in the growing

crystals caused by non-uniform temperature distribution as well as interaction between the crystal and the ampoule. X-ray diffraction (XRD), scanning electron microscopy (SEM), Raman spectroscopy, low-temperature photoluminescence (PL), x-ray photoelectron spectroscopy (XPS), optical absorption/transmission and electrical charge transport property measurements have been used to characterize the grown crystals. It is observed that indium and silver doping enhances the hardness of the grown GaSe and GaSe(0.9)Te(0.1) crystals, which is very useful for processing and fabrication of large area devices. On the other hand, germanium and tin doping significantly enhances the resistivity of the grown GaTe and GaSe(0.5)Te(0.5) crystals. The crystals harvested from ingots of 8-10 cm length and => 2.5 cm diameter have been used to fabricate single element planar devices up to 1 cm^2 in area and have been characterized by current-voltage (I-V) measurement and pulse height spectra using Am-241 (60 keV) and Cm-243,244 (5.8 MeV) sources. Details of the optimum crystal conditions, various surface processing treatments, different steps involved in nuclear radiation detector fabrication and testing of these devices will be presented.
The authors acknowledge partial financial support provided by the DNDO/DHS under contract number HSHQDC-07-C-00034.

*Wednesday AM II: Bechtel-3*

**Development of 15-mm Thick HgI2 Gamma-Ray Spectrometers**

*Zhong He, The University of Michigan*

HgI2 has been studied for gamma-ray spectrometers since 1970 because of its high stopping power due to high atomic number and high density. Reasonably good gamma-ray spectroscopy has been demonstrated only on thin detectors, typically 1 - 2 mm thick, when conventional planar configurations are employed. Thicker detectors are needed to achieve higher detection efficiency for gamma rays with energy above 400 - 500 keV. In 2007, our group demonstrated about 2% FWHM energy resolution at 662 keV on an array of eighteen 10-mm thick HgI2 detectors using the 3-dimensional position sensitive single polarity charge sensing technique developed by our group. This work describes our latest progress on the development of 15-mm thick HgI2 detectors. An energy resolution of 2.02% FWHM at 662 keV was observed on the first fully working HgI2 detector, having an area of 18mm x 18mm and a thickness of 16 mm. The trapping of electrons in the central region of the detector was estimated using the depth sensing method. Our measurements show that less than a few percent of electrons become trapped through the entire thickness of 16 mm, demonstrating the potential of HgI2 to be a viable candidate for a high-resolution and high-efficiency gamma-ray spectrometer.

*Wednesday AM II: Bechtel-4*

**Novel Quaternary Semiconductor Materials: Growth and Characterization**

*N. B. Singh, Northrop Grumman Corporation ES*
*Andre Berghmans, David Knuteson, David Kahler, Brian Wagner, Sean McLaughlin, Steve Gottesman (Northrop Grumman Corporation ES)*

A great deal of researches have been performed on both semiconductor and scintillation materials. Cadmium zinc telluride and mercury halides are the most prominent materials. The wide range of application has not been materialized due to the cost and quality of crystals. There is a strong need of new material or process to improve the quality and reduce the cost of crystals by an order of magnitude. Over the past few years we have developed several materials including thallium arsenic selenide Tl3AsSe3, thallium arsenic sulfide Tl3AsS4, thallium phosphorous selenide Tl3PSe3, silver gallium sulfide AgGaS2 and silver gallium selenide AgGaSe2. For achieving the maximum performance, these materials must have a unique combination of semiconducting, radiation absorbing, low loss and mechanical characteristics. None of the available materials have all the characteristics needed for high average-power operation. We will describe the details of growth and fabrication of these materials. In addition, we will present a novel class of crystals, their synthesis, crystal growth and some of the relevant properties for its applications into detectors. These are quaternary materials with a large flexibility to design transparency, damage threshold and effective performance. In this presentation we will describe Ag-Ga- Ge-Se class of materials and challenges related to these materials. The two very important materials of this class are AgGa3Se8 and AgGaGe5Se12 stoichiometry. A comprehensive solution to produce its derivatives and experimental results will be presented. These will be compared with In-GaSe class of materials which we developed for many years. We have developed process for purification, synthesis of large batch of materials and crystal growth by vertical Bridgman method. These crystals are grown by using both capillary seeding and oriented and fabricated seeds. The details of growth process, X-ray orientation, cutting polishing, fabrication and electrode bonding and stability for large size crystal will be presented.

*Wednesday AM II: Bechtel-5*

**Proximity Charge Sensing with Semiconductor Detectors**

*Paul Luke, Lawrence Berkeley National Laboratory*
*Craig Tindall, Mark Amman (LBNL)*

Semiconductor radiation detectors are commonly used for the detection, imaging and spectroscopy of gamma-ray, x-ray and charged particles. In basic form, a detector comprises of a semiconductor crystal with two or more electrodes formed on its surfaces. The electrodes serve as a means to apply a bias voltage to the detector so that an electric field is established within the semiconductor to collect the radiation-generated carriers (electrons and holes). Besides allowing for the application of bias voltage, one or more of the electrodes on a detector also serve as readout electrode. Charge carriers drifting across the detector induce a charge signal at the electrode, which can then be measured by a charge-sensitive amplifier connected to the electrode. Although in general the readout electrodes of a detector are formed on the detector itself, this is not a prerequisite for charge induction. Charge can be induced on any electrode, even if the electrode is not physically in contact with the semiconductor. Such proximity charge sensing effects can be utilized to achieve a variety of advantages in applications involving semiconductor detectors. In this paper we report on the experimental verification of signal readout using proximity electrodes and demonstrate several possible applications of this technique, including the position-sensitive readout of detectors and the sensing of incomplete charge collection in detectors as a means to reduce spectral background.

## Imaging/Directional Algorithms

### *Wednesday AM II: 106 Stanley*

*Chair: Cornelia Wunderer, Univ. of California-Berkeley*

*Wednesday AM II: 106 Stanley-1*

**The Image Reconstruction Approach for the Nuclear Compton Telescope NCT**

*Andreas Zoglauer, University of California at Berkeley*
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The Nuclear Compton Telescope NCT is a balloon-borne gamma-ray telescope operating in the energy range from 200 keV up to several MeV. It consists of 12 double-sided Germanium strip-detectors (7.6x7.6x1.5 cm3). For September 2008, a 36 hour turn-around balloon flight is foreseen from Fort Sumner, NM. The main science goal of this flight is to observe the polarization of the Crab nebula. Reconstructing images for this telescope is a challenge task, since the origin of the measured gamma rays can only be restricted to Compton cones. The shapes of those cones are a complex function of total energy, scatter angle, incidence angle, and interaction positions. Moreover, Doppler broadening and incompletely absorbed events influence the wings of the distribution. In addition, it is modulated by the geometry of the detector, especially its BGO shields, and passive materials. Since an analytical description of the shape is difficult to achieve, we present a 4D binned response matrix for the general shape of these cones. It describes the shape of the cones as a function of measured energy, scatter angle, and distance between the interactions. A slightly modified List-Mode Maximum-Likelihood Expectation-Maximization algorithm is then applied to obtain reconstructed images from the measured events in conjunction with this response

*Wednesday AM II: 106 Stanley-2*

**Directionality in the GammaTracker Handheld Radioisotope Identifier**

*Carolyn E. Seifert, Pacific Northwest National Laboratory*

We present the performance of several computationally simple methods for determining the direction to one or more point sources using Compton images generated by the GammaTracker handheld radioisotope identifier. Source direction is defined by two quantities: heading and inclination; these quantities are sufficient for indicating to an operator where to look for an unknown source. Two of the presented methods involve collapsing the two-dimensional 4-pi angular image into one-dimensional arrays whose maxima then define the direction. A third method finds statistically significant regions of elevated counts above the image background. The final method uses the deconvolution of the point source response to find source position. The performance of each method against simulated gamma-ray images will be presented.

*Wednesday AM II: 106 Stanley-3*

**Iterative Image Reconstruction Algorithms for Post-processing of Synthetic Aperture Gamma Source Images**

*Ralph T Hoctor. GE Global Research*
*Scott Zelakiewicz, Evren Asma (GE Global Research)*

This paper deals with imaging of Gamma sources in high background using an imager mounted on a moving platform for standoff applications. We refer to the path of the platform as the imaging baseline, and we investigate methods for forming an image of one or more sources in front of the baseline. The sources are to be localized in both range and cross-range. Prior work [1] in this area of uses "image addition" of multiple far-field images with respect to the imager to produce a near-field image with respect to the baseline. Image addition is a well-known approach to aperture synthesis, and the addition of extended far-field responses as components of such a synthesis is called backprojection. In the present work, we propose backprojection without pre-processing of the imager response as a basic image formation method. Additionally, various kinds of pre-processing can be employed instead of correlation to modify the response prior to backprojection. When no pre-processing is used, the resulting back-projected image is similar to the first iteration of a class of iterative image reconstruction algorithms widely used in emission tomography [2,3]. We investigate the use of multiple iterations of these approaches as a post-processing step in reducing background artifacts and enhancing resolvability of closely spaced sources in the synthetic aperture imaging scenario of [1].

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*Wednesday AM II: 106 Stanley-4*

**Reconstruction of UCL Germanium Compton Camera Data using ITEM**

*Nicolas Dedek, University College London*
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Images of various Cs-137 source distributions were taken with the UCL Germanium Compton camera and were reconstructed in 3 dimensions. A reduced camera setup was used consisting of 16 pixels of 4 x 4 x 4 mm3 size each in the front detector and 4 pixels of 4 x 4 x 10 mm3 size each in the back detector. Both detector layers were 10 cm apart. The preamplifier signal was digitised by GRT4 VME readout cards. The deposited energy was extracted online using the moving window deconvolution technique implemented in the FPGAs of the GRT4 cards. Simpler extraction techniques leading to worse energy resolutions were applied offline for comparative studies. For the image reconstruction ITEM (Imaginary Time Expectation Maximisation) was used, an iterative algorithm based on quantum mechanics energy minimisation. ITEM is very flexible and can easily be applied to every possible Compton camera geometry. A Hamiltonian needs to be defined. The Hamiltonian proposed for Compton cameras in the original paper is shown not to work for complex source distributions and realistic energy and position resolution of the detector. It has been successfully replaced by a new Hamiltonian based on the backprojected image. The modified version of ITEM is shown to work very fast. An image with 10000 pixels can be reconstructed from 40000 events in 20 s using one 3 GHz Pentium CPU. The reconstruction time scales linearly with the number of pixels and the number of events. Images of a point source were taken in different positions on a plane located at 2 cm distance of the front detector. Through analysis of the point spread function obtained with simple backprojection the angular resolution of the camera was determined to be on average 10 degree. The point source was mounted on a translational stage to simulate linear source distributions. The lines of 2 cm and 4 cm length were oriented in all possible directions in 3 dimensions. Also circular distributions were simulated using a rotational stage. An incomplete circle (270 degree) of 3 cm diameter was used as a model of a heart after a heart attack, the missing part of the circle representing the damaged tissue. A correction for the changing camera sensitivity in the image space is required. A sensitivity map was theoretically calculated based upon differential cross sections and solid angle approximations. A correction was accordingly applied to the Hamiltonian. The source distributions were reconstructed at the expected positions with the right shapes (point, line, part-circle). However those parts of the source distributions which were where there was a rapid drop in sensitivity were not reconstructed. A precise measurement of the sensitivity map could solve this problem. All data sets were analysed with 3 different energy resolutions of the Germanium detector based on the different energy extraction techniques mentioned above (4.0%, 1.7% and 1.2% relative resolution at 356 keV). No dependence of the angular resolution of the camera or the image quality on the energy resolution of the detector could be observed.

*Wednesday AM II: 106 Stanley-5*

**Cross Section and Angular Dependence of a Bonner Sphere Extension**

*Eric Burgett, Georgia Institute of Technology*
*Rebecca Howell (M.D. Anderson), Nolan Hertel (Georgia Tech)*

Since above 20 MeV, the energy resolution for the standard polyethylene Bonner Sphere Spectrometer (BSS) is not unique, a Bonner Sphere Extension (BSE) has been created. The cost effective system expands upon the existing commercially available BSS system using either LiI(Eu) active scintillator or gold foil. The system is comprised of concentric shells of copper, tungsten, and lead which are used in various combinations with the existing spheres. Each of the sphere combinations has a similar design: An inner core sphere (3 or 5 inch) is surrounded by a concentric aluminum shell filled with approximately 1 inch of a high atomic number neutron multiplying material (Cu, W, or

Pb). The system was modeled in detail in the computer code MCNPX (Monte Carlo N-Particle eXtended). The beta test version of the code v2.6e was used. At high energies, the multiplication reactions are not well k known. The scatter and particle production reactions in copper, aluminum, lead tungsten and carbon have not been thoroughly tested. In addition, the target nucleus cross sections for gold, and lithium have not been investigated at these high energies. The LA150 cross sections have been created for many isotopes up to 150 MeV. Above this, physics models have to be utilized for radiation transport. The dependence on cross section selection for ENDF-VI, ENDF-VII, and LA150 cross sections as well as physics model options will be presented. The system was tested at the Los Alamos Neutron Science Center (LANSCE) on the Weapons Neutron Research (WNR) beam line. The target 4, 15 degrees right flight path at 90 meters was selected for the experimental validation to allow for as large a beam diameter as possible. Here an approximately ten inch square beam spot was obtained. Measured data were unfolded using the MXD-FC33 code and the calculated BSE response matrices. The unfolded spectra using the responses of the individual detectors will be presented. A secondary concern is that the design of the active and passive detectors, the system is not symmetric on all axes. The location for the detector to be inserted cannot be overcome when utilizing the existing BSS system. To compensate for this, the angular dependence of the BSE system was investigated. Measurements parallel to the axis of the detector, at 45 degrees and at a right angle to the detector were made. MCNPX was used to calculate the angular response of the BSE. These measured results are compared to experimental results obtained at the LANSCE facility. In conclusion, there were several aspects of the BSE system that drove the measured uncertainties. Two of the primary contributors to the calculated response of the BSE system were investigated. Correction factors are now known for the BSE to correct for the cross section library and the angular dependence of the BSE system.

# National and Homeland Security: Active Technologies

## *Wednesday PM I: Stanley 105*

*Chair: Alan Janos, Domestic Nuclear Detection Office*

*Wednesday PM I: Stanley 105-1*

**Muon Radiography for the Detection of Special Nuclear Materials in Containers**

*Enrico Conti, INFN Padova*

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Penetrating cosmic-ray muons are a natural radiation background on the Earth. When they traverse a body, such particles undergo coulombian multiple scattering processes, which depend on the material atomic number Z and density. The measurement of the multiple scattering angle can be used to detect and image bodies of high Z without the use of artificial radiation and in a no-destructive way. This method could be relevant for inspection of large volumes (e.g., containers) for nuclear or radioactive substances, composed or contained by high Z materials. To this end the use of large area detectors with excellent tracking capability is mandatory. The Muon Barrel chambers, built for the CMS experiment at CERN, satisfy such requirements. They have an active area of 7 m2 and 12 measurement points with a point resolution of around 200 microns, resulting in an angular resolution of the order of 1 mrad in one direction and of 10 mrad in the other. In Padova (INFN National Labs in Legnaro) we have an apparatus is composed by two such chambers. In the gap between the chambers a container and the target material can be placed. The two chambers gives the entrance and exit direction of the cosmic rays. Other two drift tube chambers, each with 4 measurement points, interleaved by a thick plane of Fe, give a rough determination of the cosmic muon momentum. We present results on the detection capability and performance of the system.

*Wednesday PM I: Stanley 105-2*

**Photofission Signatures in the Prompt Regime for Special Nuclear Material Identification**

*Sara Pozzi, University of Michigan*

Recently, active interrogation techniques based on the use of high-energy photons to induce photonuclear reactions are gaining the attention of researchers interested in homeland security and nuclear material characterization. Past efforts have shown that the delayed emissions of neutrons and gamma rays from photofission can be used to successfully detect and characterize fissile material in a variety of scenarios, for example in the analysis of nuclear waste. More recently, efforts have focused on the detection of prompt neutrons and gamma rays from photofission. The prompt emissions are up to two orders of magnitude greater than the delayed emissions, leading to potentially faster and more robust measurement systems. In this paper, we describe signatures from neutrons produced immediately following photon interrogation that can be used to detect, identify, and characterize the special nuclear material. These signatures are based on the physics of photonuclear interrogation and observable differences in the signals produced by appropriate radiation detectors. In particular, we will discuss a new methodology based on the detection and characterization of prompt neutrons emitted from fissile and nonfissile targets. The method is based on the fact that prompt neutrons emitted by photofission events have a different energy spectrum than prompt neutrons emitted by other photonuclear reactions. One approach for the measurement of the neutron energy spectra is based on time of flight (TOF), and was demonstrated at Idaho Accelerator Center by A. W. Hunt and his group. The approach proposed in this paper is based on the analysis of neutron pulse height distributions measured with liquid organic scintillators, and does not rely on detecting complete TOF information, which is highly dependent on knowledge of the target position. This important characteristic makes the method promising for applications in nuclear nonproliferation and homeland security.

*Wednesday PM I: Stanley 105-3*

**Material Response of Depleted Uranium at Various Standoff Distances from a Hardened 25 MeV Bremmstrahlung Photon Source**

*David Gerts, Idaho National Laboratory*

Material responses to high energy bremmstrahlung photons generated by linear accelerators have become a key technology in finding nuclear material at significant standoff distances in support of national and homeland security missions. For standoff detection, the Idaho National Laboratory (INL) has developed a 25 MeV LINAC in a deployable system. Because of the difficulty in performing experiments with significant quantities of highly-enriched uranium (HEU), the INL frequently uses depleted uranium as a surrogate target material. This system is expected to operate in outdoor conditions over large distances. These significant distances result in significantly hardened photon spectra at the depleted uranium target. Delayed neutron and gamma ray measurements were made at various distances of the target relative to the photon source as well as various distances between the neutron and gamma ray detectors relative to the target, with up to 100 meter separations.

*Wednesday PM I:  Stanley 105-4*

**Active Detection of Shielded SNM with 60-keV Neutrons**

*Christian Hagmann, Lawrence Livermore National Laboratory (LLNL)*
*Jim Hall, Phil Kerr, Mark Rowland, Dan Dietrich, Les Nakae, Jason Newby, Neal Snyderman, Wolfgang Stoeffl (LLNL)*

LLNL-ABS-401525 : We present recent progress in the development of a cargo interrogation system based on the detection of fast neutrons emitted by fissile material. The cargo is illuminated by 60-keV neutrons from a pulsed, directional source employing the Li-7(p,n) reaction. These low-energy neutrons can induce fissions in SNM (e.g. Pu-239 or U-235), but not in other materials. The escaping fast neutrons are detected in a bank of liquid scintillators. Pulse shape information is used to discriminate proton recoils from events caused by gammas created by neutron capture or generated in the source itself. A suitable energy threshold ensures that interrogating neutrons are not counted. Background events in the scintillator due to cosmic neutrons are suppressed by requiring coincidence with the source. The detectability of a given amount of SNM concealed in cargo depends on the shielding material, its thickness, and morphology. Neutron-moderating (low-Z) shields are the hardest to penetrate, since incoming neutrons tend to be captured and outgoing neutrons are moderated. We have constructed a prototype system comprising a neutron source with a rate of ~1e6/s, and a large-area detector array. Using this experimental setup, we were able to cleanly detect kg-quantities of HEU embedded in ton-quantities of either plywood or steel with measurement times of order a few minutes.

Acknowledgement: This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344.

*Wednesday PM I:  Stanley 105-5*

**Using CsI and NaI detectors for Beta-Delayed Delayed Gamma-Ray SNM Detection Study**

*Willem G.J. Langeveld, Rapiscan Laboratories, Inc.*
*Dan A. Strellis, presenter*
*Timothy J. Shaw,  Tsahi Gozani (Rapiscan Laboratories, Inc.)*

To counter the threat of smuggled Special Nuclear Material into the United States, DNDO has recently supported research activities to develop SNM detection systems. Measuring beta-delayed gamma-rays emitted from fission fragments is one of several methods that have been studied for determining the presence of SNM. Organic (plastic) scintillator (OS) detectors offer a low-cost detection method when a proper energy threshold is determined and interfering gamma rays are minimized. More thorough gamma-ray spectroscopy methods can be applied with inorganic scintillation detectors such as CsI and NaI. In addition, lower-cost sources can be used compared to those required by the OS applications. Although more expensive per unit volume than the OS, they offer more discriminating spectral information. Using them in place of OS to detect SNM alone may not in general make practical sense. However, when the spectral features of these detectors are required to detect the presence of other threats (such as explosives or chemical weapons), using them is more plausible. Measurements were performed at

Rapiscan Laboratories by irradiating a 2-kg U3O8, (19.9% enriched) sample buried at several depths in several cargoes interrogated with a spectrum-tailored highly penetrating 14-MeV pulsed neutron source operating at 125 Hz and an average intensity of 10^8 neutrons/sec. Spectral data were collected between pulses with both a NaI and CsI detector (6-in right cylinders) to study the relative merits and shortcomings of each compared to an organic scintillator detector. Despite the activation of the detector material producing gamma-ray backgrounds from the 128I and 24Na decay and the 6.13-MeV oxygen activation gamma-ray line, a delayed gamma-ray signal was observed to be up to a factor of 3 larger than the background for significant cargo burial configurations. For deep burial positions and at the source intensity used, a net signal from beta-delayed gamma-rays was not observed. Using the results in this study and those in published literature, the assessment of sensitivity and appropriate detection means will be presented.

# Photodetectors and Scintillators

## *Wednesday PM I: Bechtel*

*Chair: Nerene Cherepy, LLNL*

*Wednesday PM I: Bechtel-1*

**A Comparative Study of Fast Photomultipliers for Timing Experiments and TOF PET**

*Tomasz Szczesniak, Soltan Institute for Nuclear Studies*
*Marek Moszynski. Lukasz Swiderski, Antoni Nassalski, Agnieszka Syntfeld-Kazuch (Soltan Institute for Nuclear Studies, Poland); Anne-Gaelle Dehaine, Maciej Kapusta (Photonis, France)*

The new 1 inch and 1.5 inch in diameter photomultipliers for timing applications from Photonis and Hamamatsu have been tested. The time resolution of XP1020, XP3060, R9800 and R9420 was measured with the 10x10x5 mm3 LSO crystal in coincidence experiments with 511 keV annihilation quanta from 22Na gamma source. Results are discussed in terms of measured photoelectron number and time jitter. Final comparison of the tested tubes and their timing properties are presented in relation to large amount of experimental data of various types of PMTs collected during last few years. Especially, observed linear dependency between time resolution normalized to the number of photoelectrons and time jitter is pointed out. Additionally the optimization of electronics needed to achieve the best time resolution in the case of each tube is presented. Analysis of factors influencing timing performance and connected with production process and construction of the PMTs like quantum efficiency, time jitter and anode pulse shape is also made. Finally, the application of the studied photomultipliers for the future TOF PET and possible level of advancement is discussed.

*Wednesday PM I: Bechtel-2*

**Polycrystalline Mercuric Iodide Photodetectors for Cesium Iodide Scintillators**

*William C. Barber, DxRay Inc.*
*Neal E. Hartsough, Jan S. Iwanczyk (DxRay, Inc.)*

We have fabricated polycrystalline thin films of mercuric iodide for use as photodetectors coupled to cesium iodide scintillators. The compound semiconductor mercuric iodide has a large band gap (2.13 eV) causing a peak in its quantum efficiency (570 nm) which is well matched to the output of Cesium Iodide (550 nm). Single crystal mercuric iodide phtodetectors coupled to cesium iodide has demonstrated a full width at half maximum (FWHM) energy resolution of 4.58% at 662 keV. Single crystals providing sufficient surface areas for coupling with scintillators are difficult to grow and are therefore cost prohibitive to use in large field of view applications. Polycrystalline films however can be fabricated quickly and cheaply on a variety of surfaces including curved ones. We have therefore developed a physical vapor transport method of growing polycrystalline mercuric iodide films onto transparent substrates coated with indium tin oxide. A

palladium thin film is thermally evaporated on top of the film and the photodetectors are operated at low voltage (up to 80 V) demonstrating the first use polycrystalline mercuric iodide as a photodetector. The polycrystalline mercuric iodide films have a high resistivity producing a very low dark current typically about 10 pA per square mm. When coupled to cesium iodide a FWHM energy resolution of 9% at 662 keV is obtained. The quantum efficiency at 570 nm is about 40% as compared to single crystal mercuric iodide which is 80%. We are currently optimizing the growth method to improve the quantum efficiency with the ultimate goal of obtaining an energy resolution close to that of single crystal performance.

*Wednesday PM I: Bechtel-3*

**A Comparative Study of Silicone Drift Detectors with Photomultipliers, Avalanche Photodiodes and PIN Photodiodes in Gamma Spectrometry with LaBr3 Crystals**

*Marek Moszynski, Soltan Institute for Nuclear Studies*
*Cristina Plettner (ICx Radiation GmbH); Agnieszka Syntfeld-Kazuch, Wieslaw Czarnacki, Antoni Nssalski, Tomasz Szczesniak, Lukasz Swiderski (Soltan Institute for Nuclear Studie); Guntram Pausch, Juergen Stein (ICx Radiation GmbH); Adrian Niculae, Heike Soltau (PNSensor GmbH)*

The performance of a silicon drift detector (SDD) with integrated FET, delivered by the company PNSensor, Munich, Germany, was studied in gamma spectrometry with 6 mm in diameter and 6 mm in height LaBr3:Ce crystal. The characteristics of SDD were compared with those measured with Photonis XP5212 photomultiplier, Large Area Avalanche Photodiode (LAAPD) of Advanced Photonix, Inc., and Hamamatsu S3590-18 Photodiode (PD). Energy resolution versus gamma ray energies and its components related to the photoelectron/electron-hole pair statistics and dark noise were measured and compared. It has been showed that at low energies, below 100 keV, photomultiplier gives the best results, while for high energies, above 300 keV, SDD allows getting superior energy resolution. Particularly, the best energy resolution of 2.7% was determined for 662 keV gamma rays from a Cs-137 source.

*Wednesday PM I: Bechtel-4*

**A High-Speed, High Dynamic-Range, Linear Optical Sensor Array**

*Stuart Kleinfelder, University of California, Irvine (UCI)*
*Kris Kwaitkowski (Los Alamos National Laboratory), Ashish Shah (UCI)*

A high-speed, high dynamic-range monolithic linear optical image sensor system has been designed and fabricated in a standard 0.35 um, 3.3V, thin-oxide digital CMOS process. It consists of a 1-D linear array of 150 integrated photodiodes, followed by fast analog buffers and on-chip, 150-deep analog frame storage. Each pixel's front-end consists of an n-diffusion / p-well photodiode, with fast complementary reset transistors, and a source-follower buffer. Each buffer drives a line of 150 sample circuits per pixel, with each sample circuit consisting of an n-channel sample switch, a 0.1 pF double-

polysilicon sample capacitor, a reset switch to definitively clear the capacitor, and a multiplexed source-follower readout buffer. Fast on-chip sample clock generation was designed using a self-timed break-before-make operation that insures the maximum time for sample settling. The electrical analog bandwidth of each channels buffer and sampling circuits was designed to exceed 1 GHz. Sampling speeds of 400 M-frames/s have been achieved using electrical input signals. Operation with optical input signals has been demonstrated at 100 MHz sample rates. Sample output multiplexing allows the readout of all 22,500 samples (150 pixels times 150 samples per pixel) in about 3 ms. The chip's output range was a maximum of 1.48 V on a 3.3V supply voltage, corresponding to a maximum 2.55 V swing at the photodiode. Time-varying output noise was measured to be 0.51 mV, rms, at 100 MHz, for a dynamic range of ~11.5 bits, rms. Circuit design details are presented, along with the results of electrical measurements and optical experiments with fast pulsed laser light sources at several wavelengths. Applications of this device include very high density optical fiber readout and digital schlieren photography.

*Wednesday PM I: Bechtel-5*

**Luminescence of Heavily Cerium Doped Alkaline-Earth Fluorides**

*Alexandr Gektin, Institute for Scintillation Materials, Ukraine (ISM)*
*N. Shiran, V. Nesterkina (ISM); G. Stryganyuk (HASYLab at DESY, Germany), K. Shimamura, E. Villora, F. Jing (National Institute for Materials Science, Japan)*

The maximum light yield of activated scintillators is known to be achievable at the optimum concentration of the activator. Using solid solutions instead that contain rare-earth (RE) ions employed as the lattice-forming components, is realizable as an important tool to be used for clarification on the rare-earth activator concentration role relative to the energy losses at the energy transfer stage. This work devoted to study of Ce-containing M1-xCexF2+x (M=Ca, Sr, Ba, 0.22 < x < 0.5) crystals for which we assumed originally a higher luminescence yield. In particular, it was shown that the absorption and luminescent characteristics of these mixed compounds are similar, although shifted to UV region depending on the forbidden gap (Eg=10.6, 11.2 and 12.1 eV for BaF2, SrF2 and CaF2, respectively). Luminescence spectra typical for d f transitions in Ce3+ are similar for all compounds studied. The excitation spectra consist of a series of overlapping bands in the range 225-325 nm, the most intensive out of which emerging at 306, 312 and 326 nm in Ca1-xCexF2+x, Sr1-xCexF2+x and Ba1-xCexF2+x, accordingly. The complex excitation spectrum can be viewed as a variety or superposition of several possible types of clusters according to [1]. That is to say that the Stokes shift is small and decreases with cerium concentration increasing. The luminescence decay (~25 ns) is typical for d f transitions in Ce3+ ions. However, alongside there is a fast component (tau, approximately equal to 4 ns), the contribution of which varies within the limits 12 to 25%. The emergence of the short component and the similarity of the decay components relationship are found for various concentrations and types of crystals. On the whole, the Stokes shift proved very small in all cases, resulting in the overlap of excitation and

luminescent bands. This tends to cause the re-absorption and irreversible losses in the luminescence yield regardless of the losses at the energy transfer stage.

[1] B.P. Sobolev, A.M. Golubev, and P. Herrero, Crystallography Reports, 48(1) (2003) 141-169

# National and Homeland Security: Passive Technologies

## *Wednesday PM II: Stanley 105*

*Chair: Robert Mayo, DOE NA-22*

*Wednesday PM II: Stanley 105*-1

**A High-Efficiency Fieldable Germanium Detector Array**

*Dr. James Fast, Pacific Northwest National Lab*

Historically, large germanium arrays for field applications have consisted of multiple detectors each housed in their own cryostat. Ruggedized detector mounts for field use have had additional support material introduced that significantly impacted cryogenic performance. This paper presents the development of a new HPGe detector array and cryostat design that achieves outstanding cryogenic performance (~5 W) while providing the high detection efficiency (~500% relative efficiency) required for stand-off measurements and the ruggedization required for use in a variety of field applications.

*Wednesday PM II: Stanley 105-2*

**Directional Detection of Special Nuclear Materials Using a Neutron Time Projection Chamber**

*Igor Jovanovic, Purdue University*

*M. Heffner(Lawrence Livermore National Laboratory (LLNL)); L. Rosenberg (University of Washington); N. Bowden (LLNL); M. Howe, M. Hotz, A. Myers (University of Washington); D. Carter, C. Winant, A. Bernstein (LLNL)*

High-energy neutrons represent a highly penetrating and reliable signature of the presence of special nuclear material (SNM), and occur both in passive and active interrogation scenarios. Detection of high-energy neutrons shows significant promise as a SNM search method complementary to detection of gamma-rays, since the neutron and gamma signatures of SNM require very different types of materials for effective shielding. Directionally sensitive detection offers additional attractive features: improvement in detection speed compared to proximity searching, powerful suppression of backgrounds, and the ability to map multiple or distributed sources. We report our progress in the development and commissioning of a directional neutron detection system based on a time projection chamber (TPC) detector. The TPC has been used in particle and nuclear physics research for approximately 3 decades. TPC utilizes a convenient, scalable electronic readout system capable of measuring charged particle trajectory over a full solid angle, specific ionization, and energy, which aids particle identification. Over the past year we have designed, constructed, and tested a neutron TPC (nTPC) detector adapted for directional detection of MeV-energy neutrons. Our detector consists of a ~40 cm-diameter, ~50-cm long pressure vessel, which contains the detector gas, drift field cage, amplification region, and the readout 2D plane consisting of crossed 128 anode wires and 64 cathode strips. Low event multiplicity allows the use of a cost-effective readout system employing independent readouts for cathode and anode planes, resulting in a total of 192 channels. 192 preamplified waveforms are digitized in a data acquisition system based on nine 22-channel digitizer cards (FZ Karlsruhe) and ORCA software (University of Washington). Real-time event reconstruction software has been developed and interfaced with the data acquisition system. In our preliminary experiments we activated ~1/4 of the available nTPC volume. The nTPC was filled with hydrogen gas under ~1 atm pressure. Hydrogen provides favorable recoil kinematics and scattering cross-section, but its pointing ability is stochastic due to the uncertainty in the incident neutron direction, which requires time integration. Future use of the 3He(n,p)T reaction will result in full kinematic reconstruction from a single incident high-energy neutron. We used an internally mounted alpha-emitter and an external Cf-252 source with SNM fission-like neutron spectrum for detector commissioning and testing. Neutron tracks were measured in the nTPC detector, and crude pointing ability in the horizontal plane has been demonstrated. We are proceeding to activate the remaining detector volume and refine the reconstruction to arrive with the measurement of nTPC angular resolution and event rejection based on specific ionization. Scaling of the nTPC to compact, fieldable sizes is of particular interest and will be considered in future work.

*Wednesday PM II: Stanley 105-3*

**Demonstration of a Dual-Range Photon Detector with SDD and LaBr3(Ce3+) Scintillator**

*Guntram Pausch, ICx Radiation GmbH*

*Cristina Plettner (presenting), Claus-Michael Herbach, Juergen Stein (ICx Radiation GmbH, Koelner Str. 99, D-42651 Solingen, Germany); Marek Moszynski, Antoni Nassalski , Lukasz Swiderski, Tomasz Szczesniak (Soltan Institute for Nuclear Studies, PL 05-400 Swierk-Otwock, Poland); Adrian Niculae, Heike Soltau (PNSensor GmbH, Romerstr. 28, D-80803 Munchen, Germany)*

A new concept for a compact detector improving gamma ray spectroscopy in homeland security applications is demonstrated. The dual-range photon detector consists of a LaBr3(Ce3+) scintillator with a silicon drift detector (SDD) on top. The SDD works as low-energy photon detector on its own. Higher-energetic gamma rays interact with the scintillator. Here, the striking energy resolution of LaBr3(Ce3+) with SDD readout is available. Pulse shape discrimination (PSD) allows separating the detection mechanisms. Since LaBr3(Ce3+) is distinguished by a short light decay time, PSD benefits only from pulse shape differences due to the irradiation geometry and specifics of the charge collection process in SDD. Two detection systems consisting of 30sqmm SDD modules and encapsulated D=6mm, H=6mm BrilLanCe 380 crystals were built up and have been tested. Energy resulutions of 2.7% and 2.9% at 662keV were measured in scintillation mode at room temperature, while the scintillators exhibited a resolution of only ~3.5% if coupled with common photomultipliers. Measurements with standard sources have evidenced the direct SDD mode uncovers line structures which could never be resolved with a scintillation or CZT detector: In addition to the improved scintillator spectrum due to SDD readout, complementary high-resolution information is gathered in a wide energy range below 100keV. Such detection modules are well suited for application in RID and SORDS.

*Wednesday PM II: Stanley 105-4*

**Development of Flat Panel Amorphous Silicon Imaging Detectors for Cargo Imaging**

*Clifford Bueno, GE Global Research*
*Forrest Hopkins, William Ross, Jeffrey Shaw, Daniel McDevitt, William Leue, Robert Kaucic, Donald Castleberry, Douglas Albagli, Bernhard Claus (GE Global Research); Joseph Bendahan (GE Homeland Protection); Edward Nieters, John McLeod (GE Global Research)*

Flat panel detectors offer potential advantages for cargo radiography scanning for detection of special nuclear material (SNM). Flat panel detectors based on amorphous silicon read structures mated with optimized scintillators can be employed in a variety of detector configurations to produce enhanced image quality with respect to existing linear detector array (LDA) technology. Flat panel detectors were configured for 9 MV imaging, where multiple panels were coupled to produce larger arrays with minimal gaps between panels. Using this approach, in either continuous or "step and shoot" scanning modes, the flat panel approach offers improvements in spatial resolution, image contrast, and area coverage.

*Wednesday PM II: Stanley 105-5*

**Three-Dimensional Imaging of Hidden Objects Using Positron Emission Backscatter**

*Laura C. Stonehill, Los Alamos National Laboratory (LANL)*
*Mark Galassi, Mark Wallace, Ed Fenimore, Wendy Vogan McNeil, Quinn Looker (LANL)*

Positron Emission Backscatter Imaging (PEBI) is a technique for three-dimensional gamma-ray imaging of objects when only one side is accessible, such as for objects behind a wall or for buried objects. This technique utilizes a positron source to produce back-to-back 511-keV gammas, one of which provides timing and directionality tagging, while the other backscatters off the object to be imaged. The scattering location can be reconstructed using the relative timing of the two gamma-ray signals and the positions at which they are detected. Excellent timing resolution is required, since the time-of-flight information is essential for reconstruction. Three-dimensional imaging requires two arrays of detectors, one for the 511-keV tagging gamma and one for the backscattered gamma. We are studying the feasibility of a PEBI system using a pixellated LaBr detector coupled to a multi-anode PMT for detection of the 511-keV gamma, and an array of a dozen or more 1-inch LaBr crystals coupled to 1-inch PMTs for detection of the backscattered gamma. This paper will provide an overview of the PEBI concept's capabilities and preliminary results from a laboratory system. We will present one-dimensional position reconstruction measurements demonstrating that the required timing resolution has been achieved. In addition, initial characterization of the pixellated LaBr detectors and multi-anode PMTs will be presented, showing the position resolution measured in the detector plane. Simulation results showing the expected three-dimensional position reconstruction will also be presented.

## Silicon Photomultipliers

### *Wednesday PM II: Bechtel*

*Chair: James Christian, Radiation Monitoring Devices, Inc.*

*Wednesday PM II: Bechtel-1*

**Energy Resolution from an LYSO Scintillator Coupled to CMOS SSPM Detectors**

*Erik Johnson, Radiation Monitoring Devices, Inc. (RMD)*
*Christopher J. Stapels (RMD, Paul Barton (Nuclear Engineering and Radiological Sciences, College of Engineering, The University of Michigan), Radia Sia (RMD), David K. Wehe (Nuclear Engineering and Radiological Sciences, College of Engineering, The University of Michigan), James F. Christian (RMD)*

SSPMs consisting of arrays of 30- and 50-micron square pixels in 1.5 mm x 1.5 mm total area with high and low fill factors (packing density) were used to measure the photon intensity resolution for a pulsed laser light source. Different sources of noise (i.e. crosstalk, dark counts, and electronic) have a deleterious effect on the energy resolution, and this work looks at the relative sizes of these contributions. The SSPM's performance is investigated by comparing input from light sources and a calibrated input pulse from a tail pulse generator. Using a constant, low-intensity light source on each of the four SSPM designs, the best photon intensity resolution of 7% was obtained for the array of large pixels with a low packing density at an operating bias of 13.4 volts excess bias. This photon intensity resolution is primarily shot-noise limited for approximately 200 detected photons, with fluctuations in the dark counts contributing the majority of the rest of the noise. The apparent optical photon detection efficiency obtained for each of the quadrants at the ideal operating bias was 5.6%, 10.1%, 6.7% and 11.2% for the 29%, 43%, 49% and 61% fill-factor arrays, respectively. The contributions from each noise source are explored. In addition, the energy resolution obtained for an LYSO scintillation crystal is measured and compared to the pulsed laser results to examine all contributions to the energy resolution. To provide insight into the critical detector parameters for device optimization, a detailed analysis of the energy resolution for 662-keV gammas incident on 1.5 mm x 1.5 mm x 3 mm of LYSO will be provided.

*Wednesday PM II: Bechtel-2*

**Features of Silicon Photo Multipliers: Precision Measurements of Noise, Cross-Talk, Afterpulsing, Detection Efficiency**

*Paolo Finocchiaro, INFN-LNS*
*Sergio Billotta (INAF Osservatorio Astronomico di Catania, 95125, Italy), Alfio Pappalardo (INFN Laboratori Nazionali del Sud, Via S.Sofia 62, Catania, Italy); Massimiliano Bellus, Giovanni Bonanno (INAF Osservatorio Astronomico di Catania); Luigi Cosentino (INFN-LNS); Salvatore Di Mauro (INAF Osservatorio Astronomico di Catania)*

Solid state single photon detectors are nowadays an emerging issue, with applications in the wide field of sensors and transducers. A new kind of planar semiconductor device has slowly but steadily come out, namely the Silicon Photomultiplier (SiPM), with outstanding features that in some respect could even replace traditional photomultiplier

tubes. Based on a Geiger-mode avalanche photodiode elementary cell, it consists of an array of n independent identical microcells whose outputs are connected together. The final output is thus the analog superposition of n ideally binary signals. This scheme, along with the sensitivity of each individual cell to single photons, would allow in principle to have the perfect photosensor capable of detecting and counting the single photons in a light pulse. Unfortunately this is not the case, as this kind of device has several drawbacks, all of them mainly deriving from its noise features: due to its intrinsic properties, in no way can the dark counts be reduced below a given rate. Cooling the device works to a certain extent, but then afterpulsing sets in, due to charge carriers trapped within the semiconductor during the avalanche signal and later exponentially released. The lowest operating temperature becomes a trade-off between random thermal counts and long-lasting afterpulse counts. Even though not capable of totally replacing the traditional photomultiplier tubes, the SiPM already promises to fulfill a wide set of requirements coming from numerous applications. In this paper we illustrate a complete method for the evaluation of dark noise, afterpulsing, cross-talk and detection efficiency of SiPM detectors. In this respect we will then show the performance of our newly developed SiPM (produced by ST Microelectronics), comparing it to another sensor present on the market (produced by Hamamatsu), proving that the device performance is indeed already outstanding.

*Wednesday PM II: Bechtel-3*

**High Performance Solid-State Photodetector for Nuclear Detection and Imaging**

*Purushottam Dokhale, Radiation Monitoring Devices, Inc. (RMD)*
*Kanai Shah (presenting), Rob Robertson, Christopher Stapels, James Christian (RMD, Inc., 44 Hunt Street, Watertown, MA 02472. USA)*

Current and next generation systems employed in nuclear and particle detection require photodetectors with fast response, high gain and high signal to noise ratio. Photomultiplier tube (PMT) has been playing an important role as a photodetector for last several decades. PMTs, however, have several limitations. They cannot operate under pressures exceeding a few atmospheres and under high magnetic fields, their sensitivity is limited over a small wavelength band, their optical quantum efficiency is relatively low, and they are bulky. To overcome many of the limitations of PMTs in scintillation spectroscopy, we have designed and developed a complementary metal-oxide-semiconductor (CMOS) solid-state photomultiplier (SSPM). Here we present different designs of SSPM and their performance evaluation for scintillation spectroscopy, time-of-flight studies and gamma-ray imaging. The measured FWHM energy resolution for 511 keV gamma rays was 11% for a detector consisting 1.5mm x1.5 mm SSPM coupled to 1.5mm x 1.5mm x 10 mm LYSO. The timing resolution measured was 480ps in coincidence with a detector consisting LaBr3 coupled to PMT. The timing resolution was also measured for four 1.5mm x 1.5 mm SSPMs arranged in a 2x2 array having different designs and density of micro pixels. The measured coincidence timing resolution ranged from 480ps to 560ps, confirming that upon sufficient optimization, these devices would be suitable for fast timing studies. The position sensitive SSPM (PS-SSPM) was also designed, build and evaluated. A flood image was recorded with a 6x6 LYSO array (each LYSO element measuring 1mm x 1mm x 10mm) coupled to a PS-SSPM with 6mm x 6 mm active area. All 36 LYSO elements were clearly visible and well separated from each other in the flood image.

*Wednesday PM II: Bechtel-4*

**Mass Sample Test of HPK MPPCs for the T2K Neutrino Experiment**

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The Multi-Pixel Photon Counter (MPPC) produced by Hamamatsu Photonics which is new semiconductor photon sensor is developed for an application in T2K neutrino oscillation experiment starts from April 2009. MPPC has the advantage in the photon-counting capability, stability to the magnetic field, small size, and high photon detection efficiency. About 60,000 channels of detectors are planed to be used in off-axis detector or and in on-axis neutrino monitor, INGRID, in the J-PARC site. About 15,000 MPPCs are produced by Hamamatsu Photonics up to May 2008. For the quarantee of quality to all MPPCs, MPPC checking system at Kyoto University was developed using the custom MPPC reading electronics with Trip-t ASIC chip which can measure 64 MPPCs at the same time. This system can measure gain, breakdown voltage, noise rate, photo detection efficiency, and cross-talk/after-pulse rate in condition of the controlled temparature and bias voltage. We check the device-by-device variation of all MPPCs about these parameters. Our measurement is the first evaluation of a large scale of MPPCs.The information will contribute grately to users who study or consider MPPC or similar device I report the study of the basic performance and the result of mass sample test for more than 10,000 MPPCs compared with the requirement from T2K experiment.

*Wednesday PM II: Bechtel-5*

**Silicon Photomultipliers As Readout for the CEDAR counter of the K+ -> pi+ nu Nubar Experiment P326/NA62 at CERN**

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The K+ -> pi+ nu nubar rare decay experiment P326/NA62 at CERN will employ an unseparated beam of positive hadrons (75 GeV/c in momentum) derived from the primary protons at the CERN SPS. The K+ component in the beam can be tagged positively by using an improved version of the existing CEDAR-type differential Cherenkov counters. The CEDAR volume (5 metres long) will be filled with hydrogen at a pressure below 3 bars. The optical system, consisting of a Mangin mirror and a chromatic corrector reflects and focuses the light on to a narrow and adjustable ring diaphragm, behind which 8 condensor lenses and the readout photodetectors are located (on a circle). The expected K+ rate is 50 MHz and the full beam almost 1 GHz. Approximately 10 Cherenkov photons per K+ will illuminate each of the 8 light spots which are 12 x 12 mm^2 wide. We are investigating the use of matrices of silicon photomultipliers (SiPM) to detect Cherenkov photons at the mentioned rates, with a single photon time resolution below 50ps and with very high effciency (above 50%), which cannot be accomplished with conventional (UV sensitive) photomultipliers. The individual detection of the more than 30 photo-electrons will result in a extremely clean kaon tagging and in a resolution on the single kaon timing at a level better than 10 ps rms. Silicon photo-multipliers (SiPM) are semiconductor devices consisting in matrices of tiny avalanche photo-diode pixels (10^3 / mm^2) grown on a common Si substrate and connected in parallel via integrated resistors. The diodes are operated in Geiger mode (i.e., biased at few volts above breakdown) so that any single carrier, generated either by photons or thermally in the depletion region, might trigger a self-sustaining avalanche which is quenched by the integrated resistors. Because all SiPM pixels work together on a common load, the output signal is a sum of the signals from all fired pixels. So, while each pixel is an independent binary photon counter the SiPM works as an analogue detector able to stand very high rates (several tens MHz) with almost no dead-time. High gain (10^6) and high efficiency (up to 80%) in detecting low optical photon fluxes with unprecedented charge resolution, extreme single photon timing resolution, low voltage operation and insensitivity to magnetic fields and EM pickup make SiPM suitable for many applications, as an alternative to vacuum photo-multiplier tubes, and in particular an excellent detector for Cherenkov counters. There are two issues for the use of SIPM's in our (P326) CEDAR application: (1) the radiation hardness, as the SIPM devices will be illuminated by the halo of an intense hadron beam. (2) the reduction of the dark count rate, which is easily accomplished by moderate cooling. To this purpose it has to be noted that the coincidence of the signals of more than 30 photo-electrons produced by the 80 cherenkov photons per Kaon will allow a very good signal to background ratio. In the talk we'll discuss the first results of the tests finalized to the CEDAR/Cherenkov application made on Hamamatsu and FBK-IRST (Trento, Italy) SiPM devices concerning response to UV light, cooling, ageing, radiation hardness, efficiency and timing properties of the detectors. First results on matrices of SiPM recently produced (only) at FBK-IRST and covering an area of 4 x 4 mm^2 (16 channels) will be also discussed. Finally the fast, low-noise front-end electronics and the high performance 1 GHz sampling FADC system for the signal readout will be discussed. More information about the SiPM's and the CEDAR project can be fund at the web page: http://collazug.home.cern.ch/collazug/seminario_sipm.pdf

# Author Index

# Session Index