Applications of gamma-ray detectors

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Outline

• Gamma-ray detectors

• Compton imaging
  – Example data
  – Liverpool projects

• Positron Emission Tomography (PET)
Gamma-ray detectors

Provide a response from transfer of energy from incident gamma rays to electrons in the detector via Photoelectric absorption, Compton scattering and pair production.
Gamma-ray detectors

- Semiconductor detectors, e.g. HPGe, Si, CZT
  - Excellent energy resolution – HPGe ideal for spectroscopy
  - Good efficiency
  -Insensitive to magnetic fields
- Scintillation detectors, e.g. CsI, BGO, LaBr$_3$
  - Very efficient (good for Compton suppression)
  - Relatively poor energy resolution
  - Cheap and robust – good for applications
  - PMTs sensitive to magnetic fields
Compton imaging

• Used to detect sources of gamma radiation
• Can locate radiation via imaging methods
• Can identify what the source of radiation is via gamma-ray spectroscopy
• The system has a wide range of view so is possible to locate radiation at different scales – in a lorry, in a room, in a body
• Can be used to image radiation for vehicles in transit
Compton imaging – some history

- Compton imaging not a new concept
- Astrophysicists have been using this method since the 1970’s
- Low energy, near field applications have some challenging limitations:
  - Detectors with very low noise properties
  - Read-out electronics with very high readout capabilities
  - Advanced image reconstruction algorithms, including computing power
- Developments here have led to a resurgence in research activity
How does it work?

- Gamma rays interact in both detectors (scatterer and absorber)
- The path for each gamma ray is reconstructed as a cone
- Source located at max cone overlap

\[ \cos \theta = 1 - m_e c^2 \left( \frac{1}{E_1} - \frac{1}{E_0} \right) \]
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What makes a good system?

- Sensitivity of a Compton camera is a factor of:
  - Detector materials: Compton scattering cross-section in scatterer and Photoelectric absorption cross-section in absorber\(^1\)
  - Detector thicknesses
  - Configuration geometry
  - Low energy noise thresholds

- Quality of the reconstructed image is a factor of:
  - Detector energy and position resolution
  - Doppler broadening

Example data

- Two HPGe SmartPET detectors in Compton imaging mode
- 2.5cm separation between cans
- Multi-isotope imaging:
  - $^{137}$Cs point sources 662keV
  - $^{22}$Na line source 511keV and 1274keV
- Measurements at multiple angles, (varying 5° to 15° increments across a 20° to 110° range)
Example data sets

(a) Two $^{137}$Cs point sources, separated by 2.8 cm
(b) One $^{22}$Na line source, separated by 1 cm from two $^{137}$Cs point sources separated 2.8 cm from each other
Results: Two $^{137}$Cs point sources separated by 2.8 cm

- Two sources 5 cm from scatterer
- Fold $[1,1,1,1]$ addback spectrum generated
- 10 keV gate set around the 662 keV addback photopeak
Results: One $^{22}$Na line source and two $^{137}$Cs point sources

- Two $^{137}$Cs sources sep 2.8cm and one $^{22}$Na line source 8 cm from scatterer
- Fold [1,1,1,1] addback spectrum generated
- Two 10 keV gates set around the 511 keV and 662 keV addback photopeaks
Multi-isotope imaging

- $^{22}\text{Na} - 511\text{keV}$
- $^{137}\text{Cs} - 662\text{keV}$
- $^{22}\text{Na} - 1274\text{keV}$
Let's break it down...

**Line Source and Point Source**
- Line Source: ~440k events

**Point Source**
- ~160k events

**Line Source**
- ~280k events
Can image quality be improved?

• Contributions to Compton camera image quality include\(^1\):
  - Doppler Broadening
  - Energy Resolution
  - Position Resolution
  - Geometrical configuration

• Doppler broadening is a property of the detector material
• Energy resolution is characteristic of the detectors
• Position resolution can be improved beyond electrode segmentation
• Development of image reconstruction algorithms

Compton imaging projects at Liverpool

- **AWE project**: imaging across a wide energy range – threat reduction
- **PorGamRays**: a portable device (room temperature detectors)
- **NNL Collaboration**: coupled with an optical image
- **GammaKeV**: a robust portable camera
- **Distinguish**: imaging of goods in transit
- **ProSPECTus**: nuclear medicine
Nuclear decommissioning and security

- **PorGamRays** – room temperature, small area, semiconductor detectors portable for “in the field” measurements

- **NNL project** – real time gamma ray imaging coupled with optical images from a camera

- **GammaKeV** – imaging of gamma rays from the reactor of a nuclear submarine
Security applications

- Monitoring luggage at airports, and cargo at shipping docks is important.
- The luggage is passed through **x-ray scanners**.
- The radiation is used to image what is inside containers without opening them.
- Can identify objects through their **shape** and **density**.
Security applications

• Useful to identify specific materials, e.g. drugs and explosives

• Research at UoL Physics Dept: Detection of gamma-rays from neutron activated materials

• Can both form an image and produce a gamma-ray spectrum

• The peaks in the gamma-ray spectrum contain elemental information: what is inside?

• Explosives and drugs contain combinations of light elements e.g. Oxygen (6.1 MeV), carbon, (4.4 MeV) nitrogen (1.64, 2.31, 5.11 MeV)
Security – new research

Neutron detector

14MeV pulsed neutrons.

Neutron generator

Inelastic scattering.

Characteristic gamma rays emitted

Detection & imaging (Compton Camera)
AWE project

- Development of an imaging device in the detection of illicit nuclear materials
- Energy range 59.4 keV to 2 MeV
- 3 detectors:
  - 5mm HPGe scatter detector (medium to high energy)
  - 8 mm Si(Li) scatter detector (low energy)
  - 20 mm SmartPET HPGe absorber detector (all energies)
AWE project Si(Li) detector

- Canberra Si(Li) DSSD detector 13 strips on each face
- 8 mm thick, 66 mm diameter
- Cryogenically cooled using a CryoPulse CP5 cooler
- Energy resolution of all strips measured to be (1.4 to 1.6) keV at 59.4 keV using $^{241}\text{Am}$ (excluding channel 14)
$^{241}\text{Am}$ surface scan of Si(Li)

- 1 mm collimated $^{241}\text{Am}$ source scanned in 1 mm steps with a duration $\sim 40$ s across the AC face, DC face and detector side
- Data recorded using GRETINA cards
AC face intensity plots

8 keV energy gate on 59.5 keV

a) Energy Gated Counts reduced by ~8%

b) Energy Gated Single Pixels

Reduced Counts between DC12 & DC13
Multiple pixel intensity plots

8 keV energy gate on 59.5 keV

a) DC surface scan

b) AC surface scan

L J Harkness et. Al, JINST (accepted)
Side scan intensity plots

a) Single pixel energy gated intensity map

b) Single pixel energy gated t30 map, AC contacts

c) Single pixel energy gated t30 map, DC contacts
AWE project

- Characterisation of Si(Li) detector underway to determine PSA parameters
- Investigation of charge collection properties of Si(Li) detector ongoing
- Compton camera data currently being taken with the Si(Li) detector and SmartPET HPGe absorber detector (A. Sweeney)

- Characterisation of 5mm HPGe detector to determine PSA parameters
- Compton camera data will be taken with the 5mm HPGe detector and SmartPET HPGe absorber detector
Conventional medical imaging

**Anatomical Imaging**
- **X-rays**
- **CT** – Computed Tomography
- **MRI** – Magnetic Resonance Imaging

**Functional Imaging**
- **SPECT** – Single Photon Emission Computed Tomography
- **PET** – Positron Emission Tomography
Nuclear medical Imaging: SPECT

• Nuclear imaging used to study biological functions: SPECT

• Inject a radioactive biological compound to patient, $^{99m}\text{Tc}$

• Compound travels to organ of interest (e.g. tumour)

• Single gamma rays emitted from compound, detected by a gamma camera which has a mechanical collimator and gamma-ray detectors
SPECT research

ProSPECTus

• £1.1 million project
• Prototype system
• High-sensitivity alternative to SPECT
• A Compton camera used instead of a gamma camera
• Semiconductor detectors
Why ProSPECTus?

Conventional SPECT is limited by:

- Compromise between sensitivity and image resolution
- Maximum gamma ray energy limit
- Collimator bulky and heavy
- Existing detector readout technology incompatible with magnetic fields
- Dual-isotope imaging difficult due to poor energy resolution of scintillator detectors

Small animal SPECT collimator
http://www.nuclearfields.com
ProSPECTus

- Planar Si(Li) detector
  - (60 x 60 x 9) mm crystal
  - 15 strips on each detector face, 4mm pitch

Photo Courtesy of Semikon

- Planar HPGe detector
  - (60 x 60 x 20) mm crystal
  - 12 strips on each detector face, 5mm pitch

Photo Courtesy of ORTEC

- Custom-built cryostat
  - MRI compatible
MRI investigation

- TESSA coaxial HPGe detector
- 1.5 T Siemens Symphony MRI Scanner
- Data acquired for 2 B field orientations: longitudinal and transverse
- Pulser and Sources: (80keV->1332keV)
MRI images

- Phantom – cylinder of distilled water
- TESSA detector doesn’t degrade MRI image quality
- MRI imaging doesn’t further degrade TESSA energy spectra

L J Harkness et. al, NIM A (2011) 638, 67-73
ProSPECTus – an improvement?

- Sensitivity maximised for 141 keV gamma rays – 1 in every 30 used instead of 1 in every 3000 used in LEHR collimated SPECT
- Lower dose to patient or shorter data acquisition times
- Multi-isotope imaging in single acquisition
- Wide energy range with one system
- Compatible with MRI systems
Nuclear medical imaging: PET

• Nuclear imaging used to study biological functions: PET

• Inject a radioactive biological compound to patient, $^{18}\text{F} – \text{FDG}$

• Compound travels to organ of interest (e.g. tumour)

• Positron emitted, annihilates in body

• Two gamma rays emitted from annihilation, back-to-back

• Gamma rays detected outside body – Line of Response LOR

• Overlapping LOR’s shows location of the radiation
Conventional PET

- Scintillation detectors typically employed, e.g. NaI
  - ✓ high stopping power
  - ❌ poor energy resolution
  - ❌ limited position resolution
  - ❌ PMTs sensitive to MRI fields

- Detectors with better energy resolution would improve discrimination of scattered coincident events
## SmartPET motivation

<table>
<thead>
<tr>
<th>Current Standards</th>
<th>SmartPET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillation detectors</td>
<td>2 HPGe planar detectors</td>
</tr>
<tr>
<td>Poor energy resolution</td>
<td>Excellent energy resolution</td>
</tr>
<tr>
<td>Limited position resolution</td>
<td>Enhanced position resolution through PSA</td>
</tr>
<tr>
<td>PMTs unable to function in B field</td>
<td>Complimentary with MRI</td>
</tr>
</tbody>
</table>
SmartPET

- Two double sided HPGe strip detectors
- (60 x 60 x 20) mm active area
- 12 x 12 orthogonal strips
  - 5mm x 5mm x 20mm voxels
- Fast charge-sensitive preamplifiers
- Energy resolution < 1.5keV FWHM at 122keV
- Intrinsic photopeak efficiency – 19% at 511keV
Detector Response

- PSA techniques developed through characterisation measurements
- Calibration of variation in detector pulse shape response with position
We can calibrate the variation in real charge timing characteristics with interaction position.

*Risetime analysis*

Analyse the variation in image charge area/magnitude.

**Image charge asymmetry**

\[
\text{Asymmetry} = \frac{\text{Area}_{\text{left}} - \text{Area}_{\text{right}}}{\text{Area}_{\text{left}} + \text{Area}_{\text{right}}}
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Imaging with SmartPET

PET data recorded with $^{22}\text{Na}$ point and line sources

0.0014MBq
0.0307MBq
0.0037MBq

~0.9MBq
Imaging results with SmartPET

Point source
FWHM ~1.4 mm

Line source FWHM ~2.9 mm
(line source has ~ 2.5 mm internal diameter)
Is it any better?

Dr RJ Cooper
Conclusions

• Gamma-ray detectors such as those used in nuclear structure physics experiments can be used in a number of applied fields

• Existing imaging modalities such as PET can be improved using detectors and techniques developed in blue-skies physics research

• Novel approaches are being developed which are targeted to the growing nuclear imaging industries for homeland security and nuclear decommissioning.

A large number of people have input to this work from the University of Liverpool nuclear instrumentation group and STFC Daresbury Laboratory
If you are interested, we have information about our research projects on the web!