The ProSPECTus project
Translating nuclear physics techniques to medical physics

Dr Laura Harkness-Brennan
Department of Physics

@LauraHBPhysics
Outline

• Gamma-ray spectroscopy & tracking
• Opportunities in SPECT
• Compton imaging
• System design
• Experimental data
• Future outlook
Nuclear physics questions

• What is the nature of nuclear matter?
• How are stars born & how do they evolve?
• What are the fundamental constituents and fabric of the universe & how do they interact?
• How do the laws of physics work when driven to the extremes?
Gamma ray spectroscopy
Gamma ray tracking

1. Highly segmented HPGe detectors

2. Digital electronics to record and process segment signals

3. Identified interaction $(x, y, z, E, t)_i$

4. Reconstruction of tracks e.g. by evaluation of permutations of interaction points

Pulse Shape Analysis to decompose recorded waves

reconstructed $\gamma$-rays
ProSPECTus project

- STFC Particle and Nuclear Physics Applied Systems Call (£1.1m)
- Challenge-led approach to maximise KE which identifies novel use of existing funded skills and technologies
- Key nuclear physics input from internationally leading detector/instrumentation R&D
SPECT: problems and opportunities

- Compromise between sensitivity and efficiency
- Collimator heavy and bulky
- Maximum energy limit
- Dual-isotope imaging difficult due to poor energy resolution of conventional scintillator detectors
- Existing detector readout technology incompatible with magnetic fields
ProSPECTus: what is new?

- Radical change -> No mechanical collimator
- Semiconductor sensors
- Segmented technology
- Digital electronics
- Sensitivity factor ~100 larger
- Simultaneous SPECT/MRI
Compton imaging

- Gamma rays interact in two detectors
- The path of each gamma ray is reconstructed as a cone
- Source of radiation located at max cone overlap

\[
\cos \vartheta = 1 - m_e c^2 \left( \frac{1}{E_1} - \frac{1}{E_0} \right)
\]
Design criteria

- Prototype system for use with current medical radionuclides

\(^{99m}\text{Tc} 141\text{keV}\)

- Excellent energy resolution for dual isotope imaging

- High sensitivity (reduced dose or increased patient throughput)

- Excellent image quality for clinical diagnosis

- MRI compatibility for dual-modality imaging
Design: Geant4 simulations

- GEANT4 toolkit used to model proposed system
- Validated against existing experimental data
- Gamma-ray interaction energy and position used to generate images and examine efficiency
Design: Geant4 simulations

Optimised for imaging 141keV gamma rays from $^{99m}$Tc
Design: Geant4 simulations

- Total Coincident ~3.49%
- SPECT ~ 0.035% (1x10^-4 collimator)
- Factor of ~100

<table>
<thead>
<tr>
<th>Event Type</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single / Single</td>
<td>2.23</td>
</tr>
<tr>
<td>Single / Multiple</td>
<td>0.33</td>
</tr>
<tr>
<td>Multiple / Single</td>
<td>0.61</td>
</tr>
<tr>
<td>Multiple / Multiple</td>
<td>0.04</td>
</tr>
<tr>
<td>Not absorbed</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Design: Geant4 simulations

- Single Cryostat
- Separate Cryostats

% Single/single vs Detector Separation [cm]
ProSPECTus detectors

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

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

Mounting both detectors inside single cryostat

MRI compatible, custom-built cryostat (STFC Daresbury)
ProSPECTus cryostat

Challenges to be addressed:

Mounting both detectors inside single cryostat

MRI compatible, custom-built cryostat (STFC Daresbury)
Prototype system

**Scatter**
- Front: 71mm
- Back: 8mm
- Active area: 3500 mm²
- 169 Voxels (5 x 5 x 8) mm³
- Lithium drifted silicon

**Absorber**
- Front face: 60mm
- Back face: 60mm
- Height: 20mm
- Active area: (60 x 60 x 20) mm³
- 256 Voxels (5 x 5 x 20) mm³

**High purity germanium**
Experimental data

Data Sets

(a) Dual isotope imaging: $^{57}$Co (122keV) and $^{139}$Ce (165keV), $t_{1/2} > 1$ month
(b) Point-like sources and distributed sources (10mm diameter rods)

Analysis

(a) Select single-single events
(b) Calculate the total energy deposited by each incident gamma-ray
(c) Select energy range of interest - “Energy Gates”
(d) Output to a text file for image reconstruction
Experimental data

$^{139}\text{Ce}$ and $^{57}\text{Co}$
Experimental data

139Ce  165 keV

6 cm

57Co  122 keV
Experimental data

Two 10mm diameter rods filled with $^{139}$Ce

Si(Li) detector
Experimental data: 165 keV

Field-of-View corrections need to be applied

A Patel
Experimental data: 511 keV & 662 keV

- Two $^{137}$Cs sources sep 2.8cm and one $^{22}$Na line source 8 cm from scatterer
- Two 10 keV gates set around 511 keV & 662 keV
- ~ 440k cones
Experimental data: 511 keV & 662 keV

- 511 keV and 662 keV
  - ~ 440k cones
- 662 keV
  - ~ 160k cones
- 511 keV
  - ~ 280k cones

5 cm long source
Contributions to Compton camera image quality include:

- Doppler Broadening
- Energy Resolution
- Position Resolution
- Geometrical configuration

Energy resolution is characteristic of the detectors (< 2keV)

Doppler broadening is a property of the detector material

Position resolution can be improved beyond electrode segmentation

Further development of image reconstruction algorithms
PSA techniques developed through characterisation measurements
Calibration of variation in detector pulse shape response with position

Parameterisation of these pulse shapes provides increased position sensitivity
Position resolution

Image charge asymmetry varies as a function of lateral interaction position

- Calibration of asymmetry response

\[
\text{Asymmetry} = \frac{\text{Area}_{\text{left}} - \text{Area}_{\text{right}}}{\text{Area}_{\text{left}} + \text{Area}_{\text{right}}}
\]
Position resolution

DC signals

AC signals

Normalized signal height

Time (ns)

Normalized signal height

Time (ns)

DC signals

AC signals
Phantom

- Source: $^{139}\text{Ce}$ (165 keV)
- Rod diameter: 16, 12.4, 11, 10 mm

Medical Imaging quantitative assessments:
1. Resolution
2. Noise
3. Sensitivity
4. Contrast

2 sjc@ns.ph.liv.ac.uk - SPECT data acquisition, phantom holder design
Phantom

Characteristic Position resolution

1mm$^3$ Position resolution in absorber

A Patel
Conclusions and future work

• ProSPECTus is a high-sensitivity alternative to SPECT
• ProSPECTus will facilitate dual-isotope imaging
• The system is designed to be compatible with MRI
• Image reconstruction algorithms have been developed and tested on experimental data

• Evaluation of 2-cryostat system ongoing
• Construction of single cryostat system ongoing
• Application of PSA to existing data
• Compton imaging with MRI system – 2016
Translating to clinical practice
ProSPECTus collaboration

Department of Physics, The University of Liverpool, UK
AJ Boston, HC Boston, JR Cresswell, LJ Harkness-Brennan, DS Judson, PJ Nolan, A Patel, JA Sampson

STFC Daresbury Laboratory, UK
I Burrows, N Clague, J Groves, J Headspith, A Hill, IH Lazarus, J Simpson

MARIARC, The University of Liverpool, UK
W Bimson, G Kemp

Royal Liverpool University Hospital, UK
D Gould
Nuclear Physics

Welcome

Welcome to the Nuclear Physics home page. Nuclear Physics at Liverpool encompasses many areas of research that range from enhancing our fundamental understanding of the laws of physics by driving it to the extremes, to creating a positive impact on present issues such as medical treatment and preservation of the environment.

To explore further details regarding the work here at Liverpool, or would be interested in participating in some of our opportunities, please feel free to navigate through the following pages. If you have any questions, please don't hesitate to contact the relevant personnel in our group.

http://www.liv.ac.uk/physics/research/nuclear-physics

ljh@liverpool.ac.uk