Development of a Compton camera for the imaging of prompt gammas during proton therapy

Cyclotron Institute REU Career Day 2014

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July 25, 2014

My Background

Graduate work at TAMU-CI

Postdoc at TAMU-CI/LLNL

Current work in medical physics at University of Maryland

So you want to be a medical physicist?

Background: Education

- Attended high school at the Texas Academy of Mathematics and Science at the University of North Texas
  - Started working part time in the accelerator lab at UNT
  - Graduated May 2003
- Undergraduate at Texas A&M
  - Student worker at the cyclotron
  - BS in physics, minor in mathematics, May 2006
- Graduate school at Texas A&M
  - Research Assistant at the cyclotron
  - PhD in physics December 2011

Background: Research experience prior to grad school

- Student worker at UNT accelerator lab
  - Maintained lab equipment (kept detectors cool, did plumbing, did accelerator maintenance, made targets etc.)
  - Did materials characterization work for semiconductor industry (RBS, (PI)XRF, NRA)
- Undergraduate worker at TAMU-CI
  - Prof. at UNT introduced me to Prof. Tribble
  - Worked in Prof. Tribble's group, mostly on MARS cryogenic target
- REU at UNT summer 2005
  - Accelerator based Materials analysis

Thesis work

- Thesis title: ^{14}C(n,γ)^{15}C as a Test Case in the Evaluation of a New Method to Determine Spectroscopic Factors Using Asymptotic Normalization Coefficients.
- Motivation: Would like to determine neutron direct capture rates on unstable nuclei… How?
  - Make radioactive beam of unstable nuclei and react with target
    - No neutron target exists
  - Make target out of unstable nuclei of interest and use neutron beam
    - Nuclei of interest often short lived
    - Neutron beam present their own problems
- Answer: need an indirect method
  - Stable/long lived targets
  - charged particle beams of normal laboratory energies

Indirect method: Spectroscopic factor

- We want to determine A(n,γ)B rates when A is unstable with rather short t$_{1/2}$
- Spectroscopic factor is the measure of of the probability of n $+$ A $\leftrightarrow$ B
- Sometimes given as the normalization of the DWBA cross section: $\frac{d\sigma}{d\Omega} = SF\dot{\sigma}_{DWBA}$
    - Using this definition is the "traditional" way of extracting SF's via transfer reactions such as (d,p)
    - Strongly model dependent (need to know details of DWBA calculation in order for SF to be useful, for instance)
    - Since SF depends strongly on what is going on in the interior of the nucleus and transfer reactions are dominated by external contributions... we have a problem
- Can also be defined in terms of the nuclear overlap function: $SF = \langle I^B_{An} | I^B_{An} \rangle$

New approach to determine SF's

- recall: transfer reactions often have very strong peripheral component
- The peripheral component can be described by the ANC (Asymptotic Normalization Coefficient)
- Idea:
    - Determine ANC by measuring non-peripheral reaction
    - Measure non-peripheral reaction and use ANC to fix external portion, increasing sensitivity to the internal portion
    - Result: SF with less uncertainty

$^{14}C(n,\gamma)^{15}C$ test case

- Astrophysical importance:
  - Inhomogeneous BBN
  - Depletion of CNO isotopes in the He-burning region of AGB stars
  - influence on production of seed nuclei for possible r-process in core-collapse supernovae
- Long life of ^{14}C means that it can be directly measured to check indirect methods
- Due to experimental error in the early direct measurement, significant disagreement between direct measurements, indirect measurements and calculations has persisted until recently → a new, independent determination is desireable
- Because of spin and parity selection rules, $^{14}C(n,\gamma)^{15}C$ is dominated by p-wave neutron capture, which is a peripheral process whose rate is determined by the tail of the overlap function, and thus by the ANC

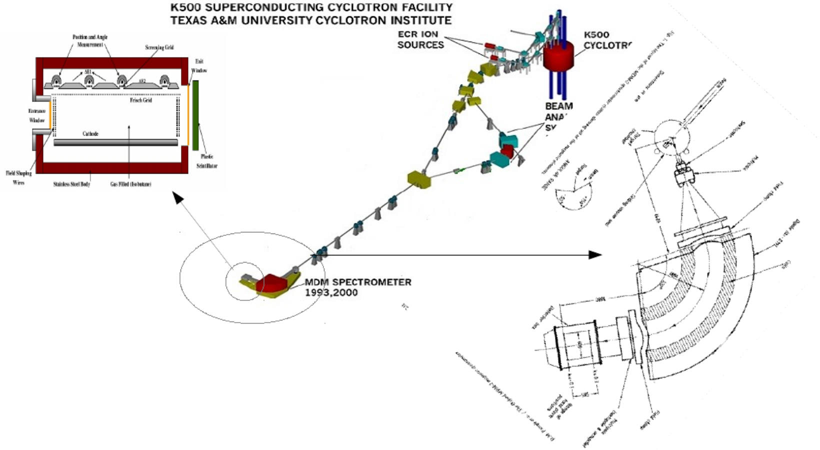
Reactions

- ^{13}C(^{14}C,^{15}C)^{12}C transfer (peripheral - ANC)
  - Neutron transfer reaction with 12A MeV ^{14}C accelerated by the K500 cyclotron at TAMU
- ^{14}C(d,p)^{15}C (low and high E - ANC/SF)
  - 'High' energy experiment performed at TAMU with $E_d = 60$ MeV from K500: SF
  - Low energy forward kinematics measurement from Czech Republic: ANC
  - Low energy inverse kinematics measurement with TECSA at TAMU: ANC

Heavy ion reaction $^{13}\mathrm{C}(^{14}\mathrm{C},^{15}\mathrm{C})^{12}\mathrm{C}$

peripheral: ANC

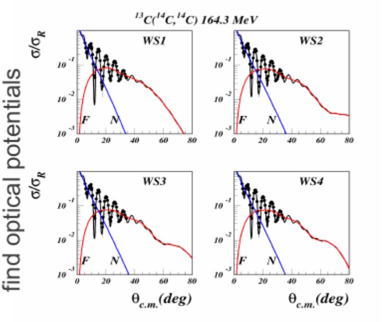
MDM:



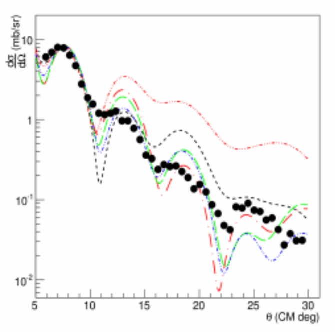
Heavy ion reaction $^{13}C(^{14}C,^{15}C)^{12}C$

peripheral: ANC

Elastic scattering- used to find optical potentials

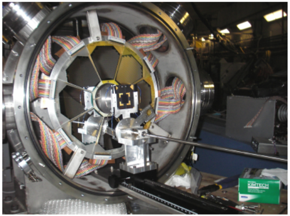


Transfer- used to find ANC



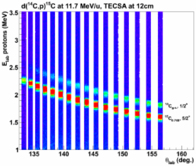
Inverse kinematics *d*(^{14}C,^{15}C)*p*

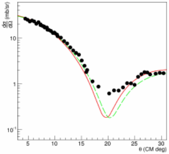
12 MeV/u ^{14}C on deuterated polyethylene target, measured with TECSA (**T**exas A&M **E**dinburg **C**atania **S**ilicon **A**rray)



This detector array to be used in conjunction with MDM in with future T-REX RI beams

T-REX





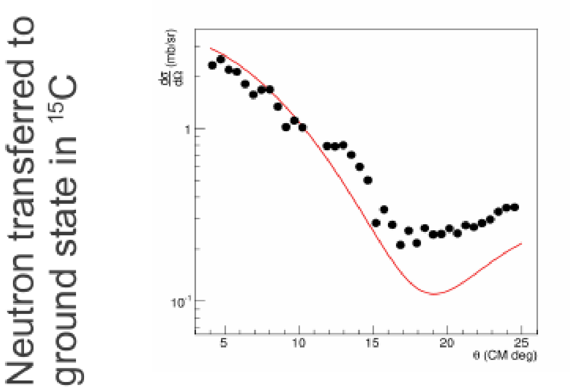
ADWA calculation

Red line: CH89 potentials

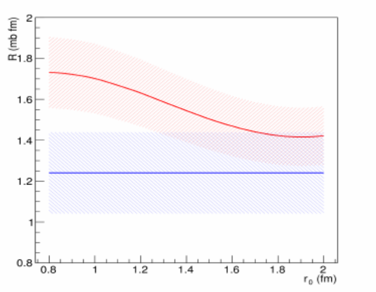
Green line: KD03 potentials

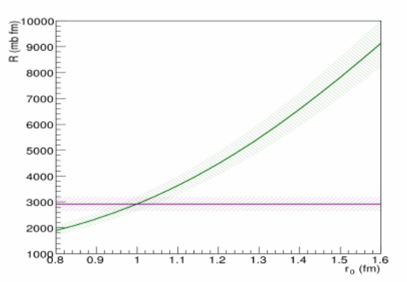
High energy forward kinematic ^{14}C(d,p)

60 MeV deuterons on ^{14}C target, measured with MDM



Evaluating new method



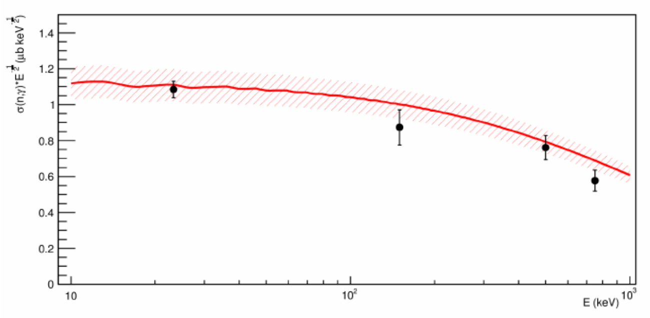


Compare Rexp to RDW. Conclusions:

- Even at 60 MeV deuteron energy this (d,p) reaction is mostly surface
- GS: Interior contribution too small to adequately constrain binding potential geometry, gives SF upper limit of 0.93
- In case of excited state, overlap of RvR gives too large SF

emphNeed more sophisticated microscopic calculation of the interior

Astrophysical cross section



Due to selection rules, this capture is dominated by p-wave not s-wave... rate dominated by tail of overlap which is normalized by the ANC

Black dots are the most recent direct measurement by Reifarth et al. We have good agreement.

Postdoc at TAMU: STARLiTeR

Silicon **T**elescope **A**rray **Li**vermore, **Te**xas A&M, U. **R**ichmond

STARLiTeR: silicon telescope array for reaction studies, used to measure surrogate reactions

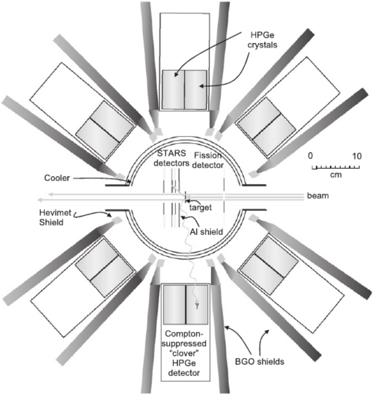
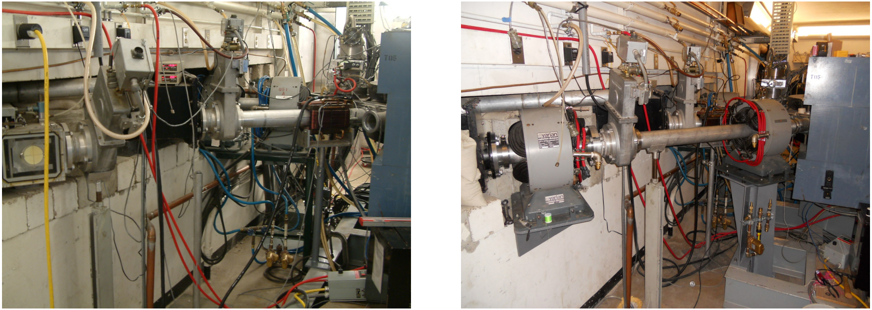


Figure : Lesher et al, NIMA 2010

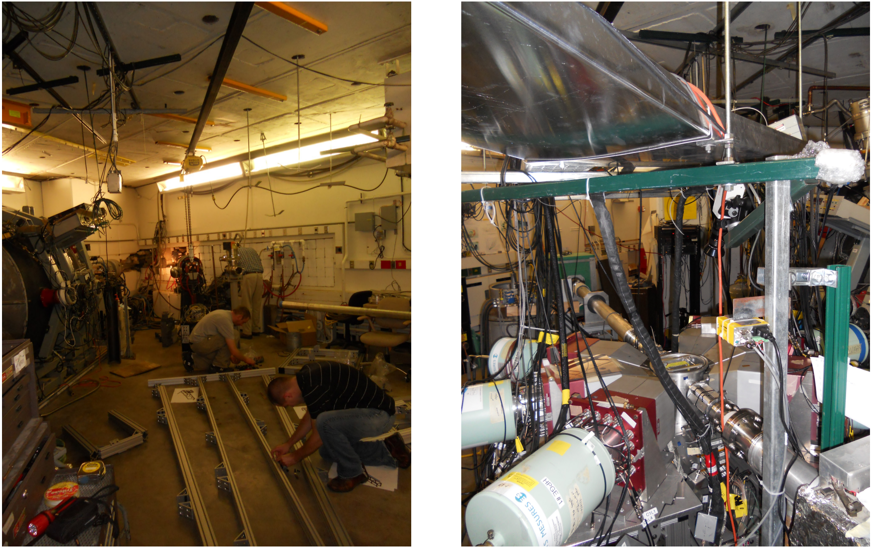
My job as postdoc for STARLiTeR

- Installed STARS at TAMU (previously at LBNL)
- made modifications to beamline to implement optics improvment proposed by George Kim
- designed automated LN2 fill system
- provided support to visiting researchers (first year alone saw 9 experiments, over 1100 hours of beam time)

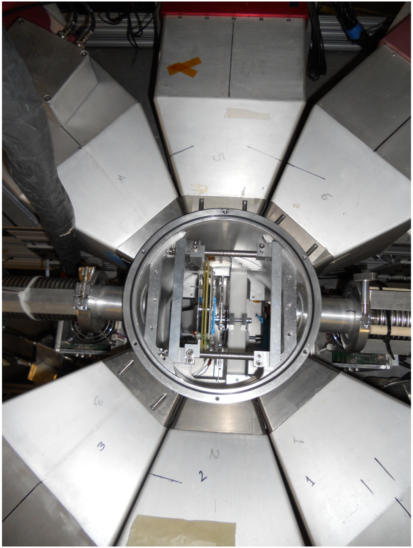
upstream optics before/after



beamline before/after



STARLiTeR chamber with Si and Ge detectors



Current work in medical physics at University of Maryland

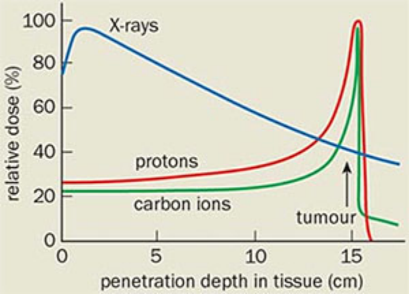
Presently a postdoc at the University of Maryland, School of Medicine, Department of Radiation Oncology

- Made contact with my current boss while I was grad student at TAMU, he was at MD Anderson
- Helped him make prompt gamma measurements at TAMU using proton beams
- He had an interesting project and needed a postdoc...

Current work in medical physics at University of Maryland

Proton therapy is a rapidly growing treatment option because:

- dose is deposited in relatively narrow distance along path of proton (Bragg peak)
- minimal dose outside of Bragg peak
  - can be used to treat tumors near vital organs/sensitive structures
- easy to control depth via beam energy
- can control shape of field with pencil beam scanning or molds



D. McCormick, spectrum.ieee.org

image source: iuhealth.org

Monitoring dose delivery profile

There is currently no way to montior online where the dose is going

- uncertainties in dose delivery depth means saftey margins around critical structures are necessary
  - may lead to under treatment of some tumor area
- being able verify dose delivery depth could allow less conservative and more effective treatment planning

How to monitor dose delivery?

Several methods have been proposed, including

- positron emission tomogrophy (PET)
- slit compton camera
- time of flight (TOF)
- open compton camera

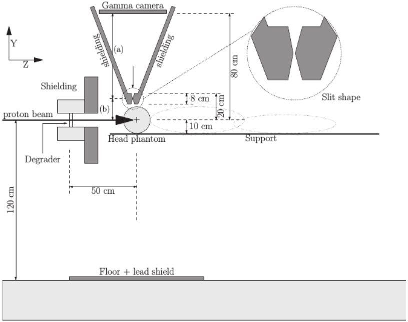


Figure : Bom et al, Phys Med Biol 2012

Prompt Gammas

Measured spectrum of prompt gammas measured at TAMU

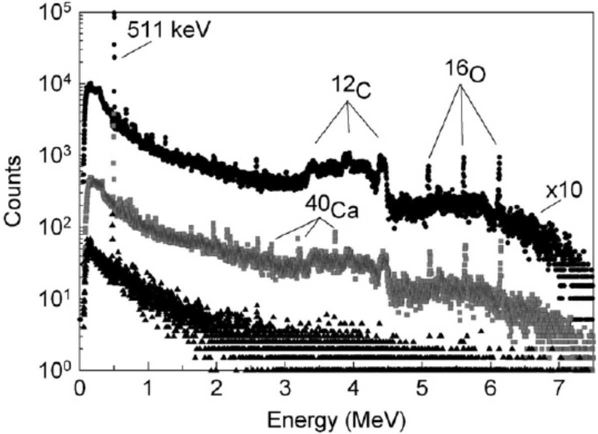
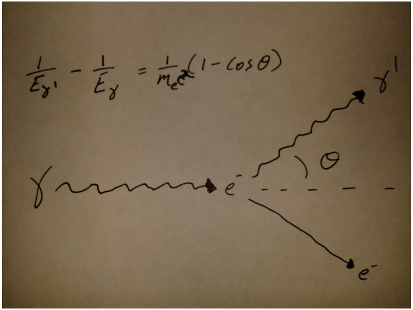


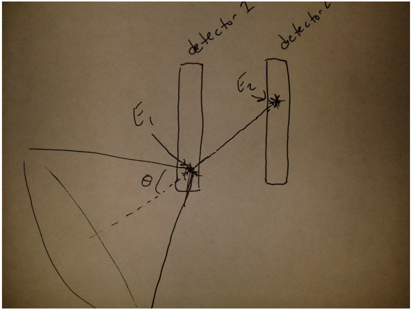
Figure : Polf et al, Phys Med Biol 2009

Aside: Compton Scattering

Compton scattering is the process of a gamma ray (photon) scattering on an electron

- $\frac{1}{E_{\gamma'}} - \frac{1}{E_{\gamma_0}} = \frac{1}{m_e c^2}(1 - \cos(\theta))$





How to monitor dose delivery?

part II

Several methods have been proposed, including

- slit compton camera
  - small solid angle, low efficency, poor statistics
- positron emission tomogrophy (PET)
  - measured after treatment, biological washout limits resolution
- time of flight (TOF)
  - requries *very* good time resolution, needs high statistics to get good position resolution
- open compton camera
  - efficency better than slit camera, but still low, background may be a problem

How to make a compton camera

Answer: CdZnTe

Our prototype compton camera is composed of four stages of position sensitive CdZnTe from H3D.

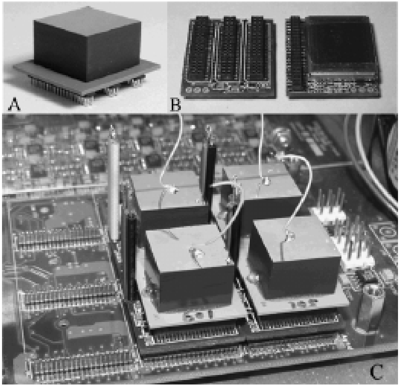
the good:

- Operates at room temperature, no need for cryogenics
- Resoultion approaches that of Ge
- Position resolution <2mm
- current rates up to a few kHz

the not so good:

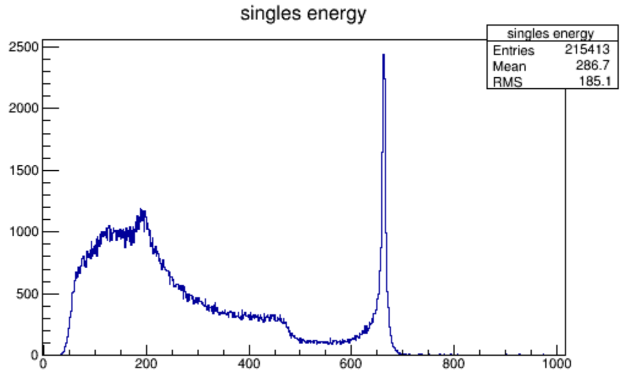
- high photoabsorption (great for second stage, not so good for scattering stage)
- need to handle higher rates for clinical use (maybe 100's of kHz)
- Energy range limited by CSA saturation to 3 MeV, want to see prompt gammas up to 6.2 MeV

CdZnTe Compton camera



F. Zhang and Z. He IEEE Trans. Nuc. Sci 2007

Source Spectrum



about 6 keV FWHM for ^{137}Cs 662 peak (2-3x worse than HPGe)

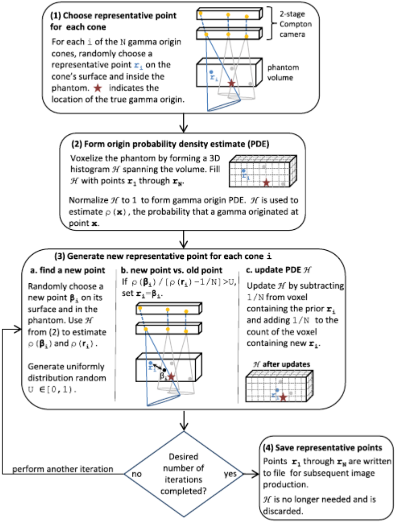
Image reconstruction

remember the cone? there are a lot of cones...

Need to go figure out where on the cone the gamma originated in order to know where the interaction between the target and the proton beam took place. Two ways we are working on to do that:

- Stochastic Origin Ensemble (SOE)
  - Voxelize target area
  - randomly pick a point on each cone that falls in the target area
  - move point to new point on cone and check if overall density increases
- Point of Closest Approach (PCA)
  - Find the point on the cone closest to known beam vector
  - if two intersects within target area, pick one randomly

SOE algorithm



(1) Choose representative point for each cone

For each i of the N gamma origin cones, randomly choose a representative point $\mathbf{r}_i$ on the cone's surface and inside the phantom. ★ indicates the location of the true gamma origin.

(2) Form origin probability density estimate (PDE)

Voxelize the phantom by forming a 3D histogram $\mathcal{H}$ spanning the volume. Fill $\mathcal{H}$ with points $\mathbf{r}_1$ through $\mathbf{r}_N$.

Normalize $\mathcal{H}$ to 1 to form gamma origin PDE. $\mathcal{H}$ is used to estimate $\rho(\mathbf{x})$, the probability that a gamma originated at point $\mathbf{x}$.

(3) Generate new representative point for each cone i

a. find a new point

Randomly choose a new point $\boldsymbol{\beta}_i$ on its surface and in the phantom. Use $\mathcal{H}$ from (2) to estimate $\rho(\boldsymbol{\beta}_i)$ and $\rho(\mathbf{r}_i)$.

Generate uniformly distribution random $U \in [0,1)$.

b. new point vs. old point

If $\rho(\boldsymbol{\beta}_i)/[\rho(\mathbf{r}_i)-1/N]>U$, set $\mathbf{r}_i=\boldsymbol{\beta}_i$.

c. update PDE $\mathcal{H}$

Update $\mathcal{H}$ by subtracting $1/N$ from voxel containing the prior $\mathbf{r}_i$ and adding $1/N$ to the count of the voxel containing new $\mathbf{r}_i$.

$\mathcal{H}$ after updates

Desired number of iterations completed?

(4) Save representative points

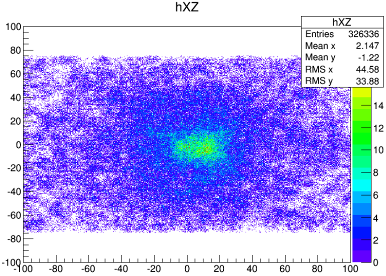
Points $\mathbf{r}_1$ through $\mathbf{r}_N$ are written to file for subsequent image production.

$\mathcal{H}$ is no longer needed and is discarded.

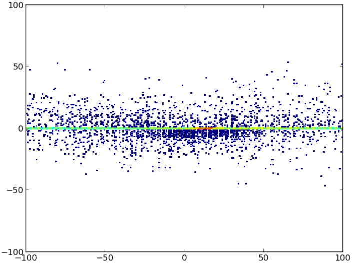
D. Mackin et al, Phys Med Biol 2012

Reconstruction of a ^{60}Co point source

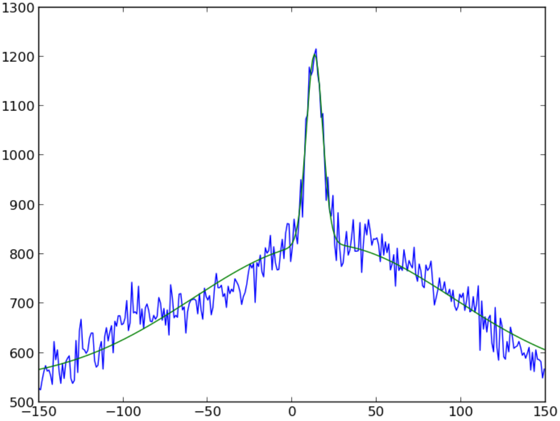
SOE



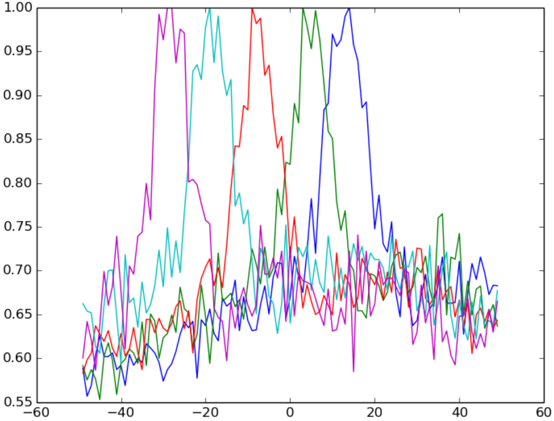
PCA



PCA 1D with fit

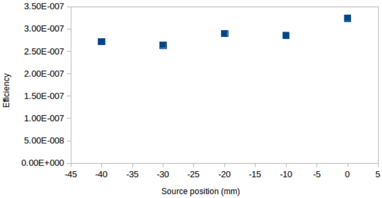


^{60}Co position scan



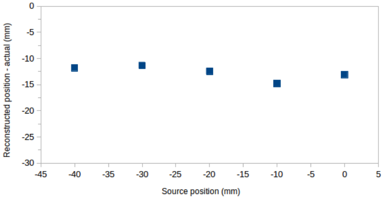
^{60}Co position scan

Absolute efficiency as a funciton of position:



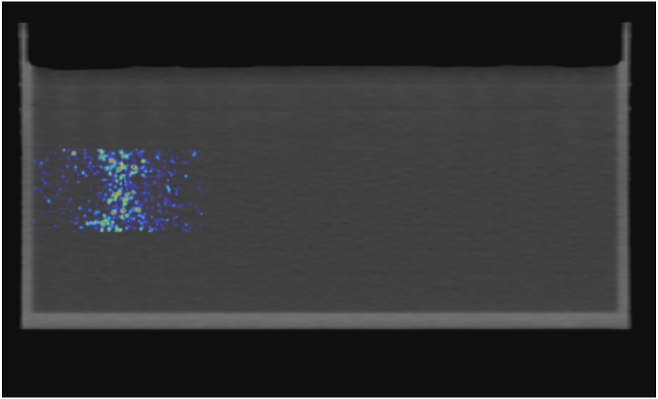
about 16% reduction in efficiency from center to 4 cm

Reconstructed position - actual source position:



standard deviation 1.36 mm

Very preliminary results from UPenn



SOE reconstruction of proton beam on water tank phantom overlayed on CT image of phantom

Si as a scattering stage

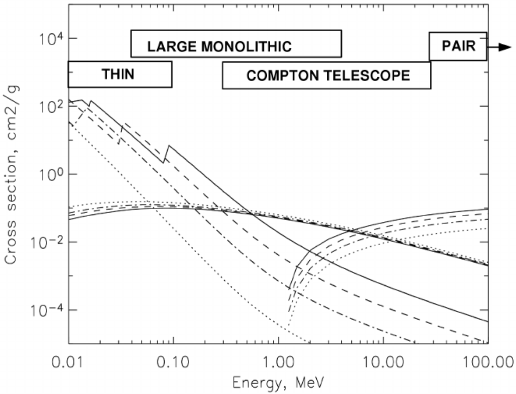


Figure : Smith ISSI Scientific Report 2010

Geant4 simulation gives 25% reduction in doubles efficiency if replacing CZT first stage with Si, but gives factor of 22 decrease in photo absorption events in that first stage.

Future work on Compton camera

- need to reduce rate (to decrease dead time) while maintaining reasonable geometry
- with rate reduced, measure Bragg peak shifts in phantom
- increase energy range of detectors
- increase rate the detector can handle
- explore Si as a first stage material

So you want to be a medical physicist?

(the right way)

- Clinical or Research focus?
  - Clinical: MS in medical physics + residency
  - Research: PhD in medical physics + residency
- Residencies typically have >50 applicants per spot
- Caution: not all residencies or degree programs are CAMPEP accredited!

So you want to be a medical physicist?

(part II: the *other* way)

It is possible,

- With a PhD in physics or a related field
- Six courses in medical physics
  - Radiological Physics and Dosimetry
  - Radiation Protection and Safety
  - Fundamentals of Medical Imaging
  - Radiobiology
  - Anatomy and Physiology
  - Radiation Therapy Physics
- these courses should be from an accredited program
- up to two courses may be taken while in a residency (but most residency programs will want them done before)
- With degree + courses apply for a residency

check out http://www.campep.org/ProspectiveApplicants.asp

Thanks for having me!

Questions?