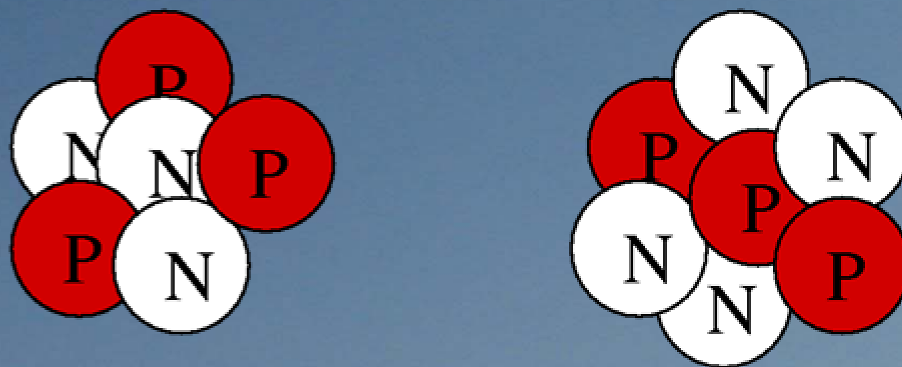
Photodisintegration of Lithium Isotopes



Department of Physics and Engineering Physics

University of Saskatchewan

Ward Andrew Wurtz

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Contents

Introduction

- I will discuss recent measurements of the photodisintegration cross sections of the lithium isotopes
- These measurements use
  - The High Intensity Gamma-Ray Source (HIGS) at Duke University in Durham, NC, USA to produce monochromatic, polarized gamma-ray photons
  - The Blowfish Neutron Detector Array to detect neutrons produced in these reactions

Introduction: Few-Body Problems

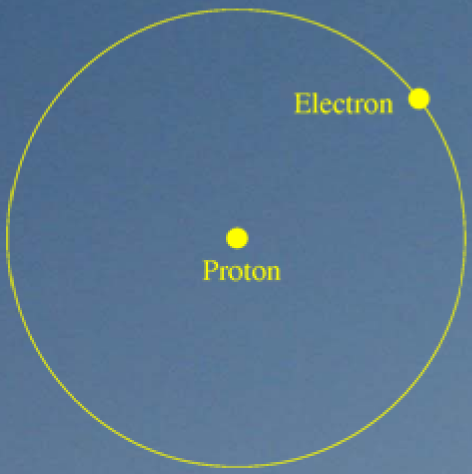
- Nuclear physics can be divided into two regimes:
  - Many body problems that must be handled statistically
  - Few body problems that can be studied by performing computations based on protons and neutrons interaction through a model of the nuclear force:
    - Hydrogen Isotopes
    - Helium Isotopes
    - Lithium Isotopes (only recently)

Introduction:
Recall Physics 381

- The Schrödinger equation can be used, with appropriate constraints, to describe non-relativistic quantum systems

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = E\psi$$

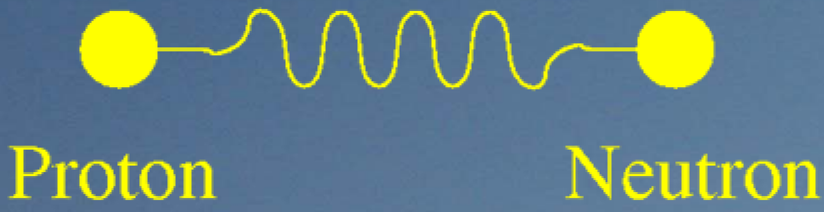
Introduction:
The Hydrogen Atom



- One proton
- One electron
- Simple potential
- Analytic solution

$$V(r) = -\frac{e^2}{r}$$

Introduction:
The Deuteron

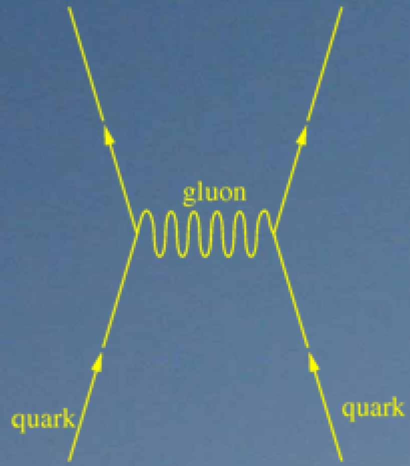


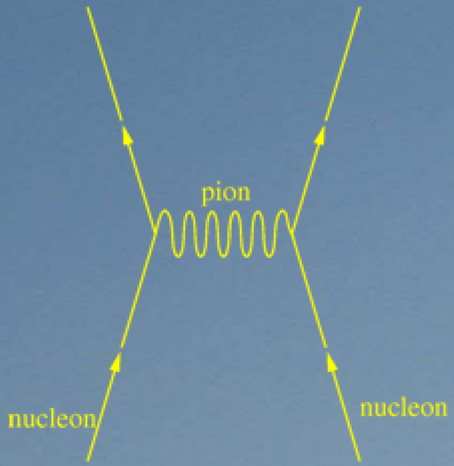
Which is the neutron and
Which is the proton?

$$V = -\frac{g^2}{r} e^{-m_\pi c r/\hbar} \times ?$$

- Nuclear analogue to the hydrogen atom
- Two nucleons:
  - One proton
  - One neutron
- Potential with many, many terms

Introduction:
The Strong Force





- Fundamental strong force results from quarks interacting by exchanging gluons
- Residual strong force results from nucleons interacting by exchanging mesons (such as the pions)
- Mesons are quark-antiquark particles
- Nucleons are three-quark particles

Introduction:
The Nuclear Potential

- Physicists have not been able to construct a model of the nuclear potential from quark-gluon interactions (Quantum Chromodynamics, QCD)
- Instead, we model the nuclear potential with semi-empirical techniques
- For example, the Argonne V18 (AV18) potential uses 40 adjustable parameters found by fitting to experimental data

Introduction:
Semi-Realistic Potentials

- The AV18 is very detailed but too complex to use in many calculations
- Instead we use semi-realistic potentials such as the AV4’ and Malfliet-Tjon (MT I-III) (below)
- Note that the parameters in the MT I-III depend on whether the nucleons are in a spin singlet or spin triplet state

$$V(r) = -\lambda_A \frac{e^{-\mu_A r}}{r} + \lambda_R \frac{e^{-\mu_R r}}{r}$$

Introduction: Cross Section

- Theoretical physicists predict it and experimental physicists measure it
- The probability of an interaction with the geometric aspects removed
- The number of outgoing particles (neutrons in our case) is equal to the number of incoming photons (flux), times the atomic density of the target, times the length of the target, times the cross section
- The cross section contains the physics

$$N_{out} = \Phi N \ell \sigma$$

Introduction: Photodisintegration

- Photons with sufficient energy can break apart nuclei
- Experimental physicists measure the cross section
- Theoretical physicists attempt to compute the cross section based on the nuclear potentials we have discussed

Introduction: Computing the Cross Section

- Direct computations involve a bound initial state being transformed to a continuous final state
- The Lorentz Integral Transform (LIT) transforms the unbounded problem into a bounded one

$$\sigma(E_\gamma) = 4\pi^2 \alpha E_\gamma R(E_\gamma)$$

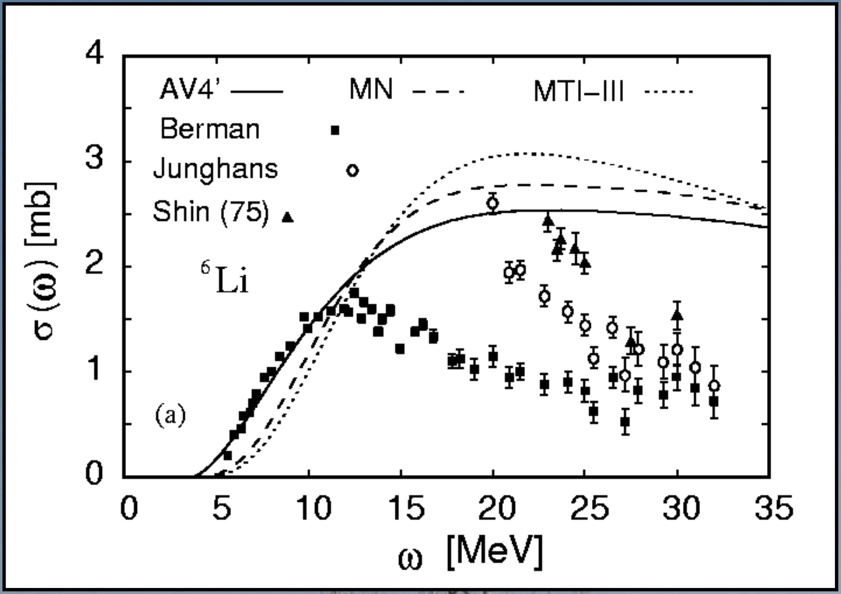
$$\left\langle \tilde{\Psi} \middle| \tilde{\Psi} \right\rangle = \int_{E_{th}}^{\infty} dE_\gamma \frac{R(E_\gamma)}{(E_\gamma - s_R)^2 + s_I^2}$$

Introduction:
The LIT and Lithium

- There are two lithium isotopes: ^{6}Li and ^{7}Li
- Traditionally they have been studied theoretically using cluster models: is ^{6}Li more like $^{2}H+^{4}He$ or $^{3}H+^{3}He$?
- The LIT allows us to avoid cluster models and perform calculations based on nucleons interaction through a nuclear potential

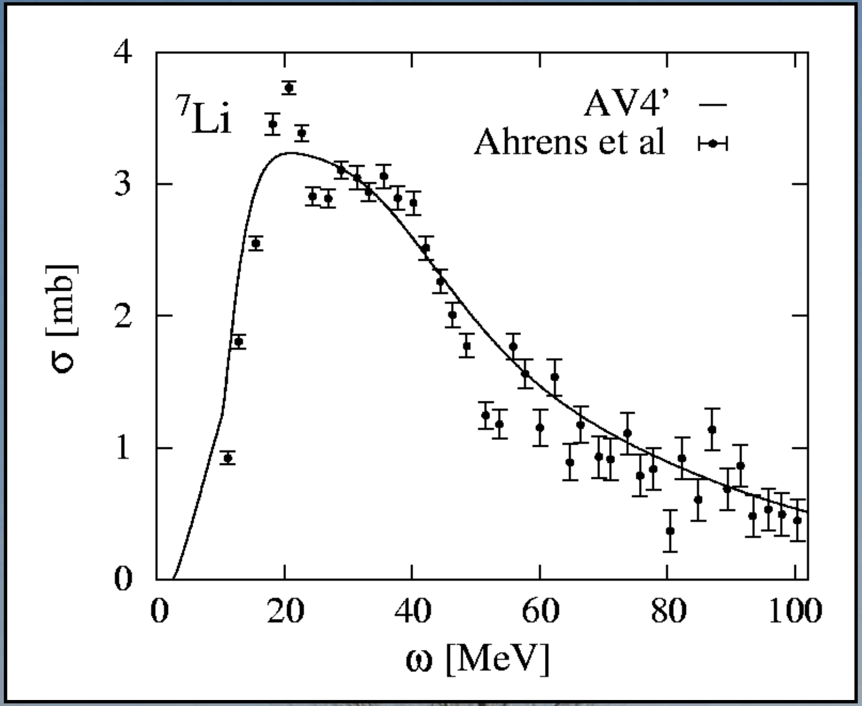
Introduction:
The LIT and ^{6}Li

- Bacca, *et al*., Phys. Rev. C **69**, 057001
- Prediction of the total photodisintegration cross section using semi-realistic potentials
- Agreement with experiment is very poor
- New experimental data needed



Introduction:
The LIT and ^{7}Li

- Bacca, *et al*., Phys. Lett. B **603**, 159 (2004).
- Better agreement
- We cannot construct the total cross section using only neutrons
- We can construct cross sections for some reaction channels
- Very useful for motivating future predictions



Introduction:
The Photodisintegration of Lithium

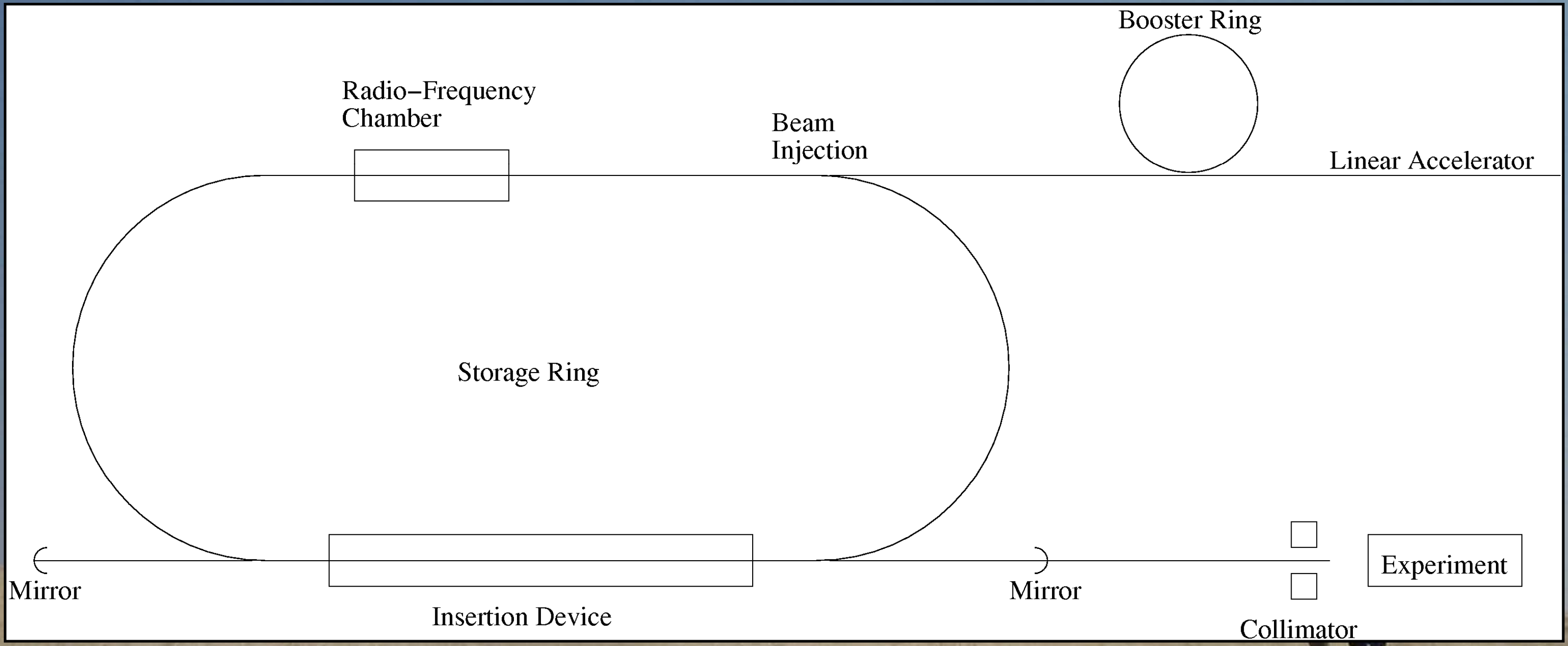
- The photodisintegration of lithium isotopes have been studied by many researchers for over 50 years
- It is only recently that we have been able to expand few-body nuclear physics to include the lithium isotopes
- New, precision measurements are required in order to further our understanding

Instruments and Instrumentation

- We need three things to perform a measurement of the photodisintegration cross section of the lithium isotopes:
  - A source of gamma-ray photons
  - Quantities of ^{6}Li and ^{7}Li (the targets)
  - A method of detecting reaction products (neutrons in our case)

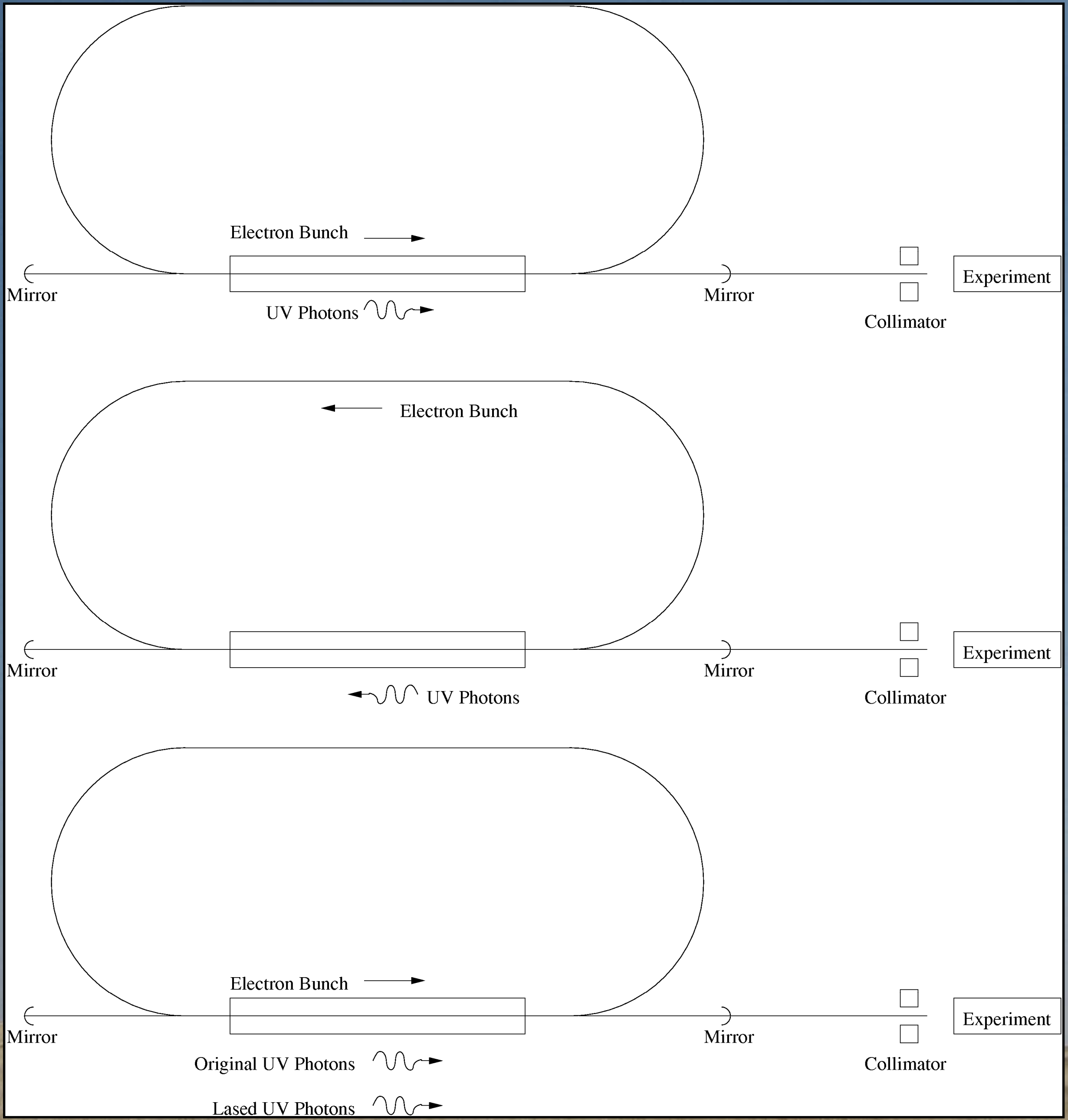
Instrumentation:
The High Intensity Gamma-Ray Source

- The High Intensity Gamma-Ray Source (HIGS) uses Compton backscattering of photons inside a Free Electron Laser to produce monochromatic, polarized gamma rays



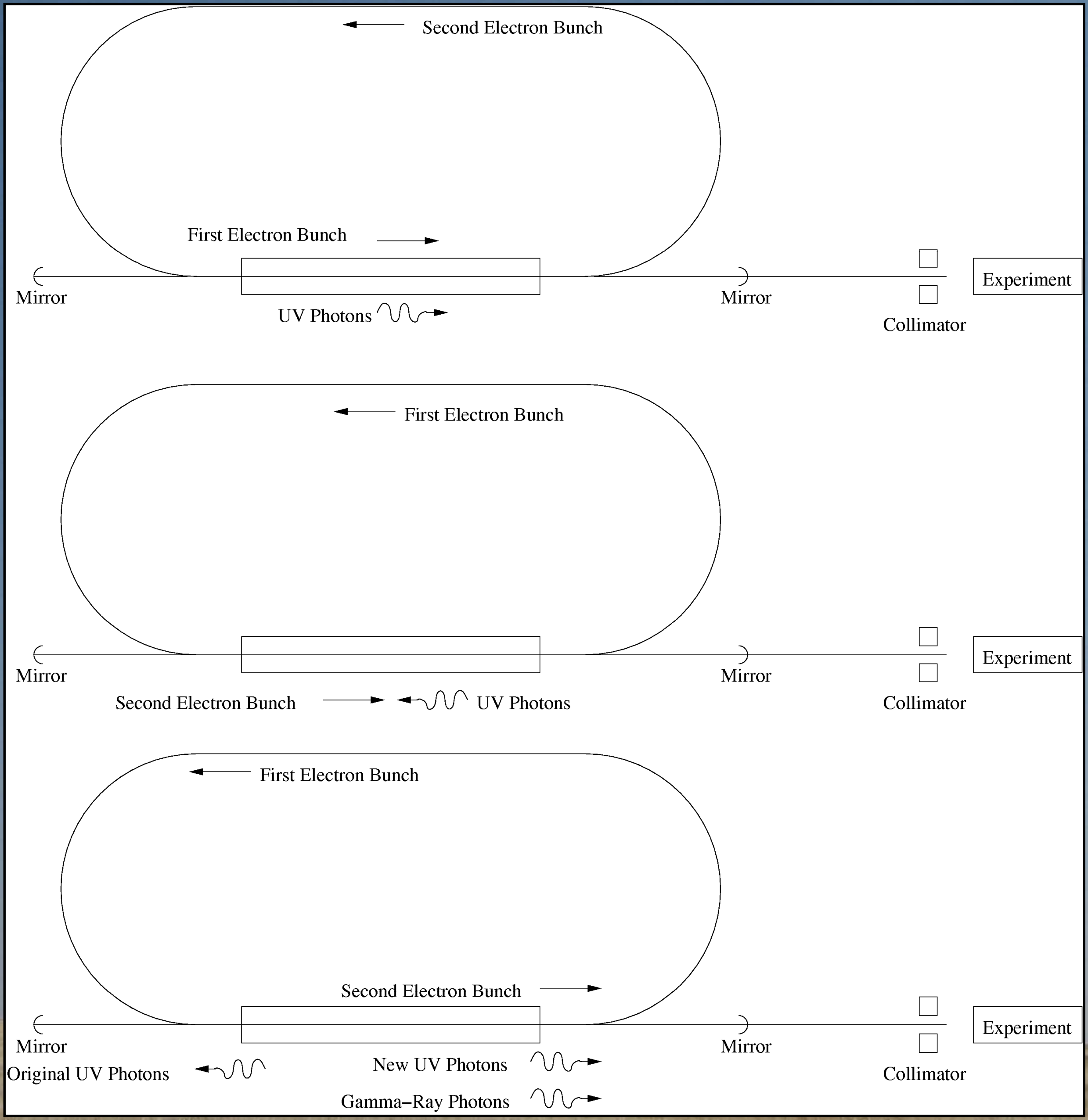
The Free Electron Laser

- Electrons travel around the storage ring
- They emit photons as they pass through the ID
- Existing photons generate micro bunches
- Increased photon production power



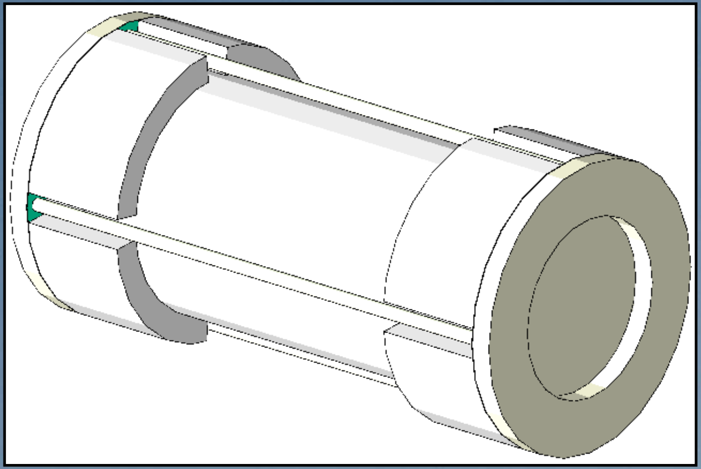
Gamma-Ray Production

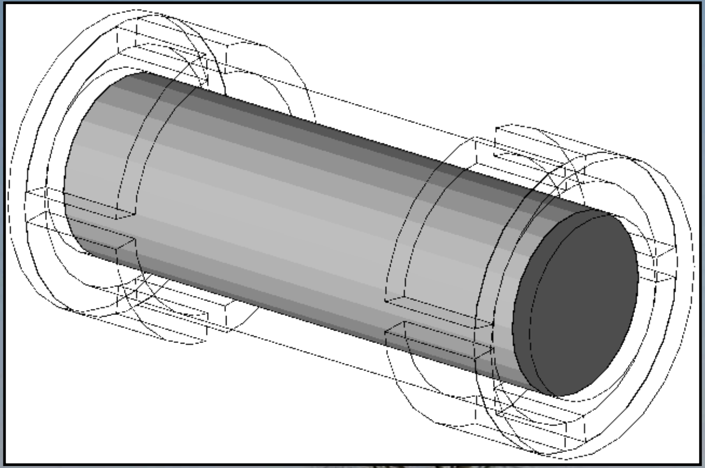
- Add a second electron bunch
- The UV photons will Compton scatter of these electrons
- Gamma-rays retain polarization with energy resolution dependent on collimator size



Instrumentation: The Lithium Targets

- Three targets: ^{6}Li, ^{7}Li and empty
- Solid lithium inside a Teflon container
- Ends capped with PVC film and aluminium foil (thin)
- 12.7 cm long, 4.1 cm in diameter
- Containers built by the Physics Machine Shop





Instrumentation:
The Lithium Targets

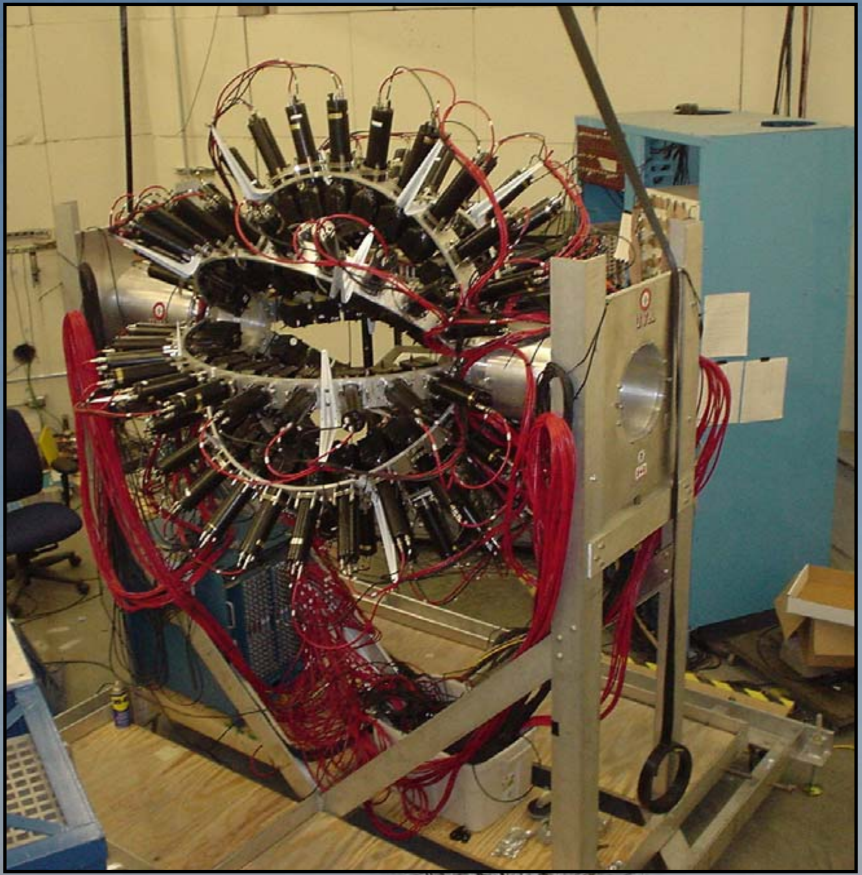
- Enriched ^{6}Li was obtained from an old target used for a previous experiment
- ^{7}Li target was made from natural lithium wire, which is 92.4% ^{7}Li and two orders of magnitude less expensive than enriched ^{7}Li
- Lithium reacts violently with air so caution is required when handling and storing it

Instrumentation: Casting the Lithium Targets

- The lithium had to be melted, poured and cast into the new target containers
- Used a glove box filled with Argon gas
- A special thanks to Johannes Vogt and the CLS staff for their help and the use of their glove box

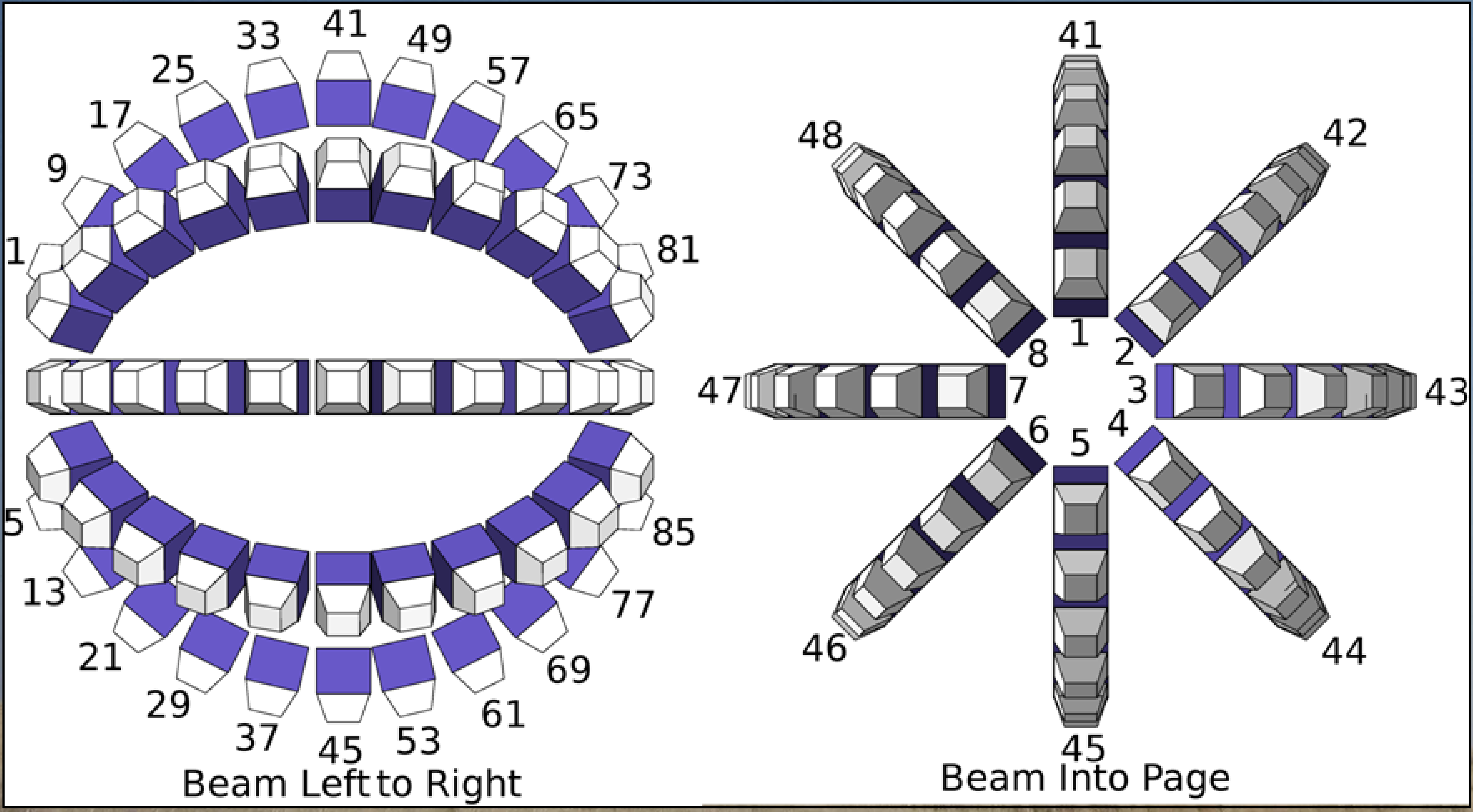
Instrumentation: The Blowfish Neutron Detector Array

- 88 neutron detectors arranged in a spherical shell
- Photon beam passes through the array
- Target is placed in centre of array
- Built by Brad Sawatzky using the detectors from the Fly's Eye Array



Instrumentation:
Detector Arrangement

- Detectors are arranged in 8 arms and 11 rings

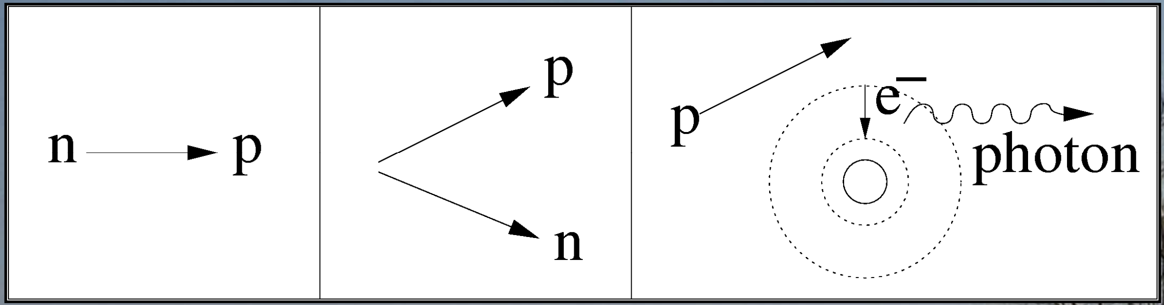


Instrumentation: Detecting Neutrons

- Neutrons have essentially no electromagnetic interaction
- Four forces of nature:
  - Electromagnetic (no electric charge)
  - Weak (too weak)
  - Gravity (much too weak)
  - Strong (by process of elimination)
- The processes of neutron-proton scattering and neutron capture can be used to detect neutrons

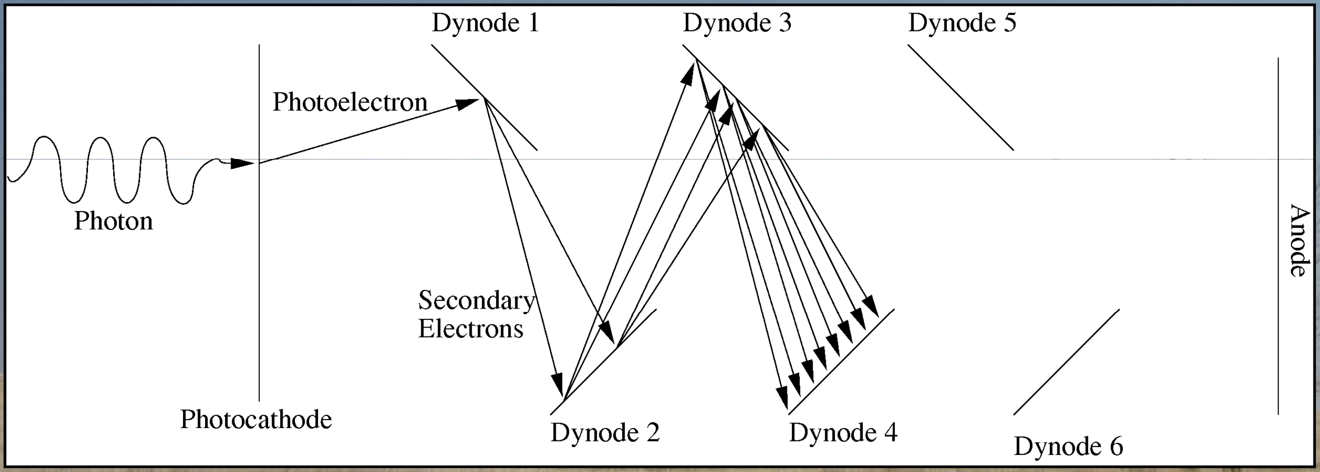
Instrumentation: Scintillation Detectors

- Elastic neutron-proton scattering transfers kinetic energy from the chargeless neutron to a charged proton
- The charged proton excites and ionizes atoms
- The atoms decay and produce blue/UV light



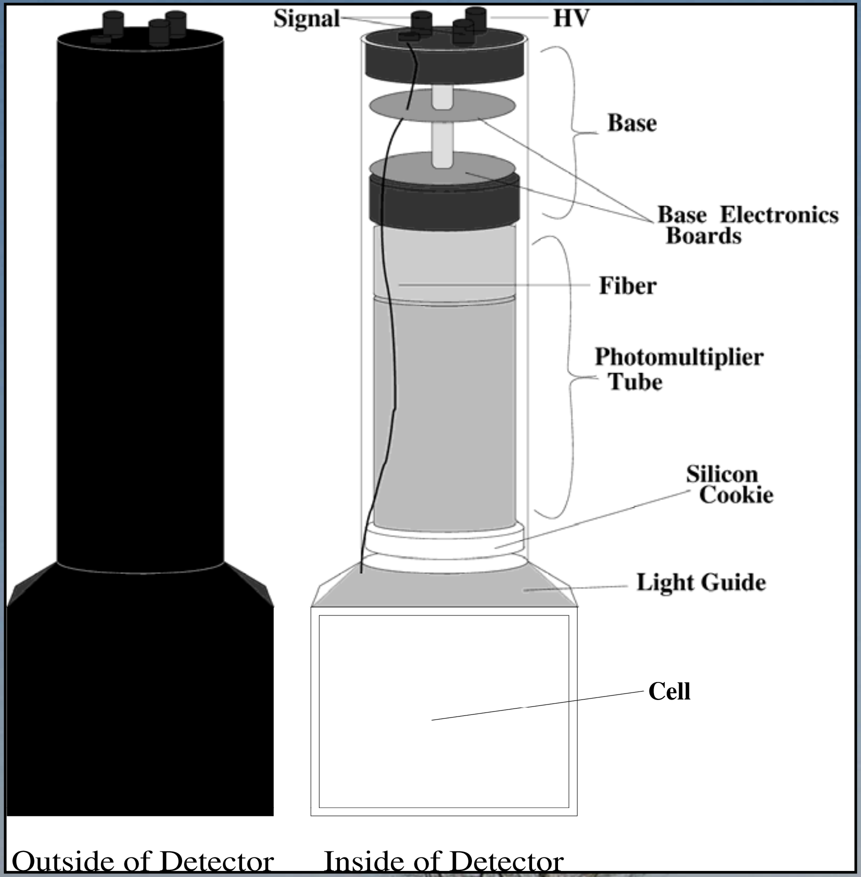
Instrumentation: Photomultiplier Tubes

- Photons strike the photocathode and produce photoelectrons
- Photoelectrons are accelerated into the first dynode plate by an electric field
- More electrons are produced and the process continues
- A useable electric signal is produced at the anode



Instrumentation: Detector

- Scintillation occurs in the cell
- The light is transmitted to the photomultiplier by the light guide and silicon cookie
- A usable electric signal is output from the photomultiplier
- Optical fibre allows for monitoring of the detector gain
- Diagram courtesy of Jennifer Robb

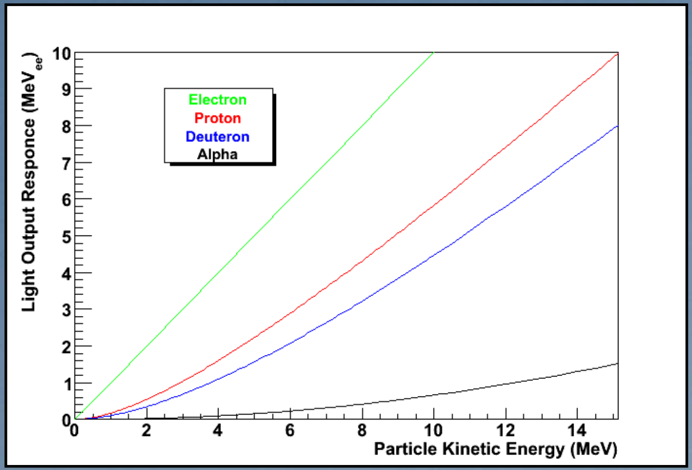


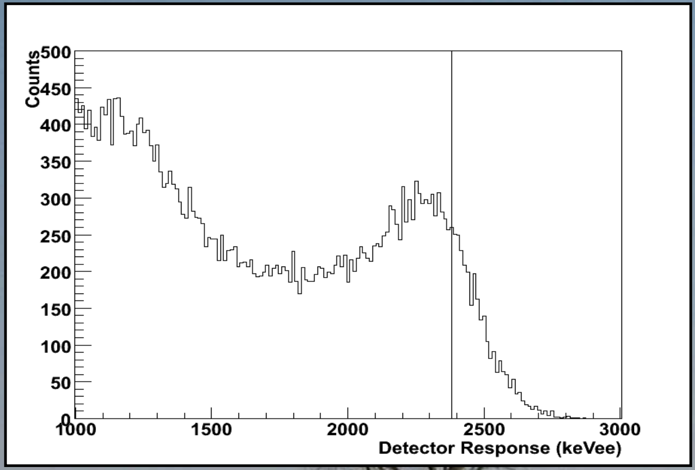
Instrumentation: Measured Quantities

- We obtain three pieces of information from our detectors:
  - Light output of the scintillator
  - Time-of-flight of the particle
  - The detected particle's type (pulse shape discrimination)
- We also obtain information from scalers to measure the photon flux and perform diagnostics on the equipment

Instrumentation: Light Output

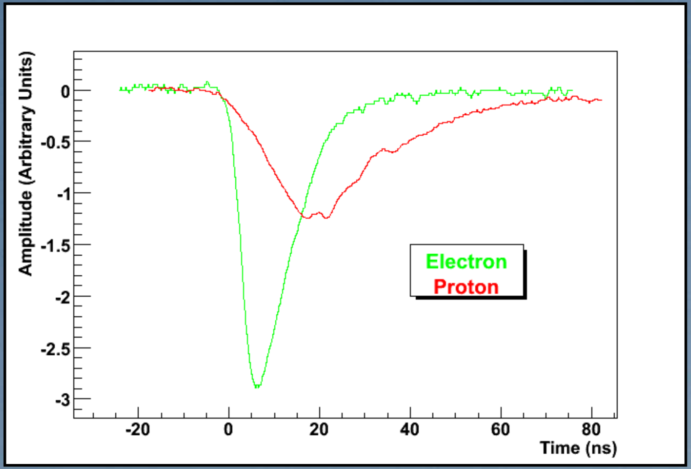
- The light output of the scintillator is related to the energy deposited and particle type
- It is measured by an integrating analog-to-digital converter called a charge-to-digital converter (QDC)

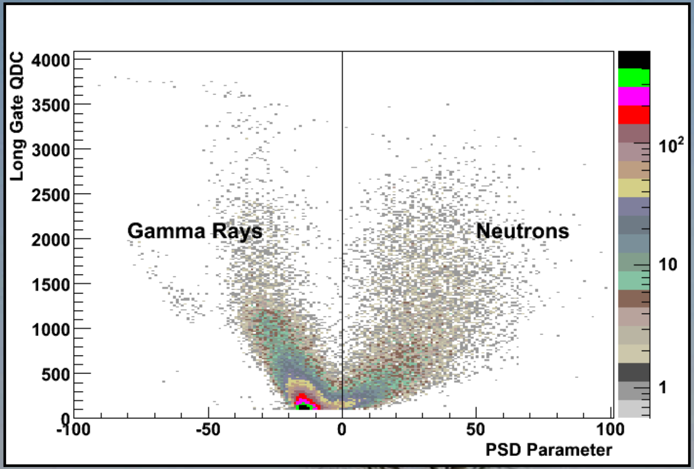




Instrumentation: Pulse Shape Discrimination

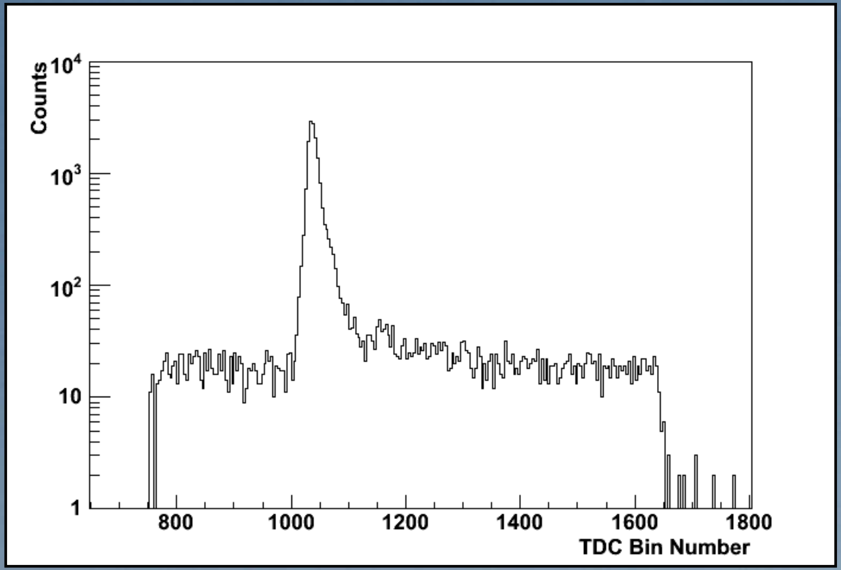
- Electrons (due to scattered gamma-rays) and Protons (due to scattered neutrons) have different pulse shapes
- By looking at the difference between a QDC integrating over the entire pulse and one integrating over a short time, we can distinguish incident gamma-rays from neutrons





Instrumentation: Time of Flight

- We use time-to-digital converters (TDC) to measure the time-of-flight of reaction products using the accelerator signal as the ‘start’ and the neutron detectors as the ‘stop’
- We can determine the kinetic energy of the detected neutrons since they travel a fixed distance



$$K_n = \frac{m_n d^2}{2t^2}$$

Analysis and Results:

- We take the ~50 GBytes of data produced by the experiments and extract a few parameters
- We use a simulation to separate the data into individual reaction channels
- We then compute cross sections from the neutron yields

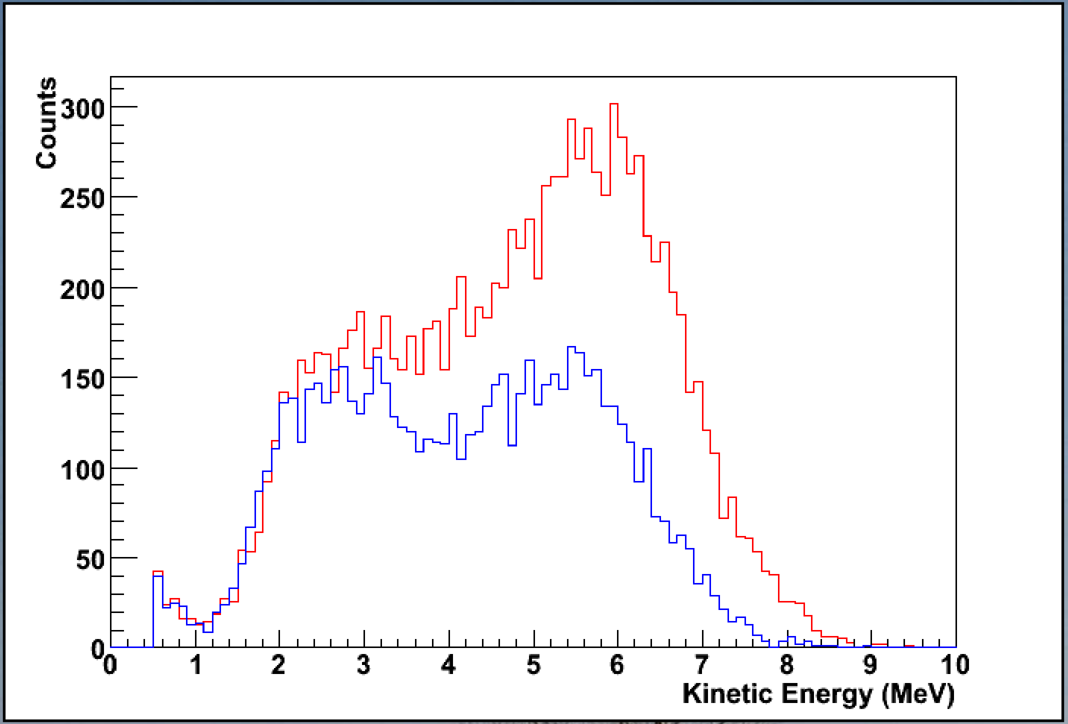
Analysis and Results: Data Acquisition

- Four days of beam time: 30 June to 3 July 2008
- Obtained ^{6}Li data at 8, 9, 10, 11, 12, 13, 15 and 15.6 MeV
- Obtained ^{7}Li data at 10, 11, 12, 13 and 15 MeV
- Used a planar wiggler (OK-4) to generate linearly polarized photons

- Three days of beam time: 1 Oct to 3 Oct 2008
- Obtained ^{6}Li and ^{7}Li data at 20, 25, 30 and 35 MeV
- Used a helical wiggler (OK-5) to generate circularly polarized photons

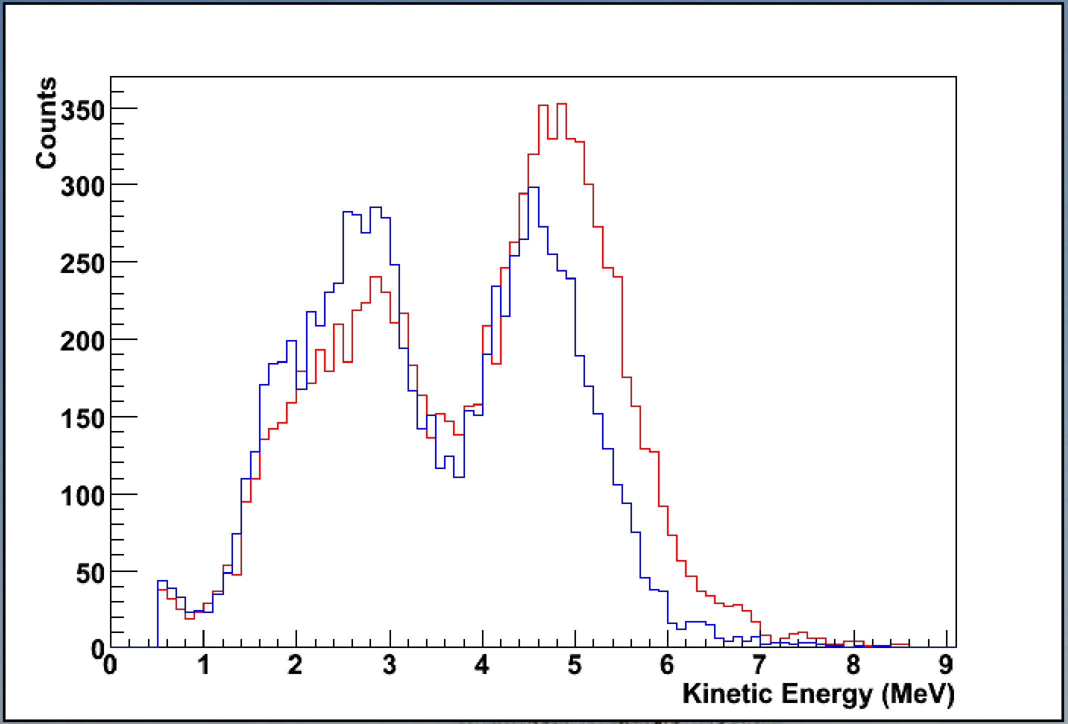
Analysis and Results: ^{6}Li Neutron Kinetic Energy Spectra

- Neutron kinetic energy spectra for detectors at 90^{O} to the beam axis and a photon energy of 13 MeV
- Red: Along polarization vector
- Blue: Right angle to polarisation vector



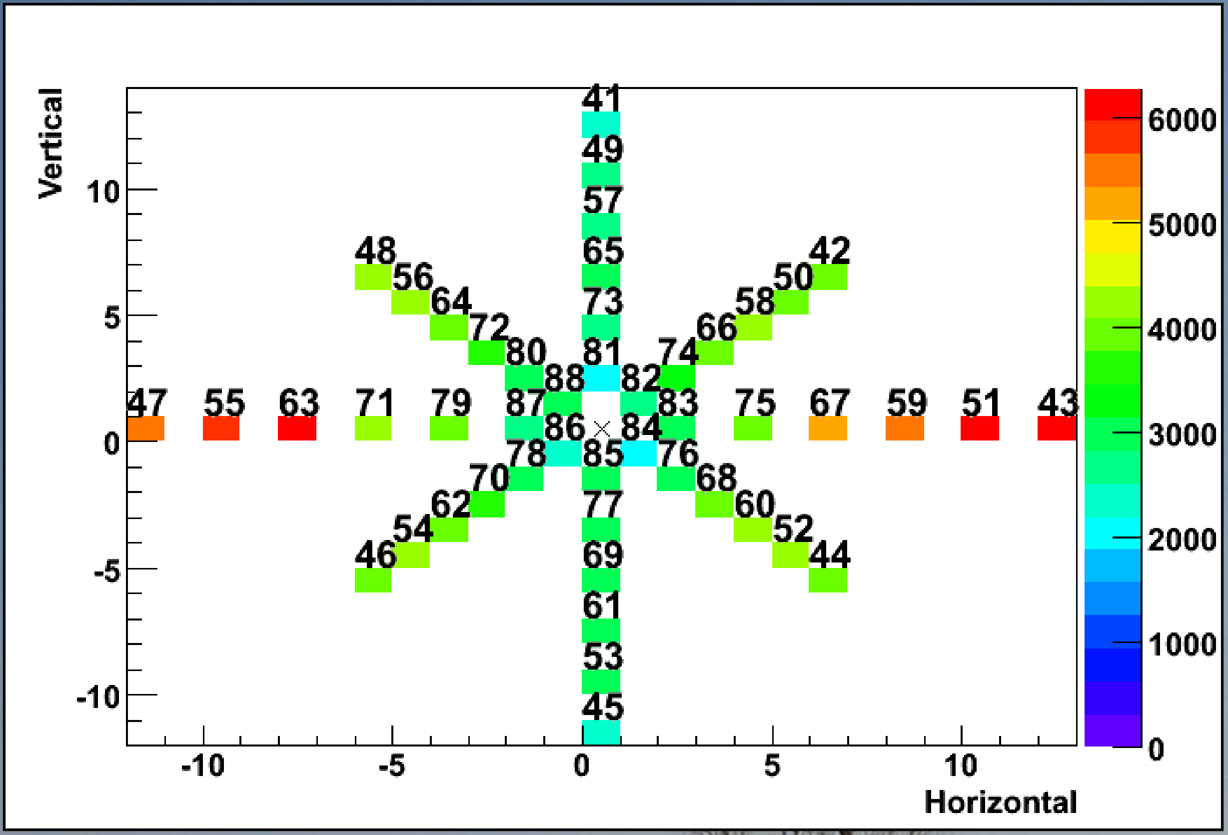
Analysis and Results: ^{7}Li Neutron Kinetic Energy Spectra

- Neutron kinetic energy spectra for detectors at 90^{O} to the beam axis and a photon energy of 13 MeV
- Red: Along polarization vector
- Blue: Right angle to polarisation vector



Analysis and Results: ^{6}Li Relative Neutron Yields

- Number of neutrons detected by each detector for the high energy portion of the spectrum
- Each detector is represented by a coloured box
- Beam is into the screen



Analysis and Results: ^{7}Li Relative Neutron Yields

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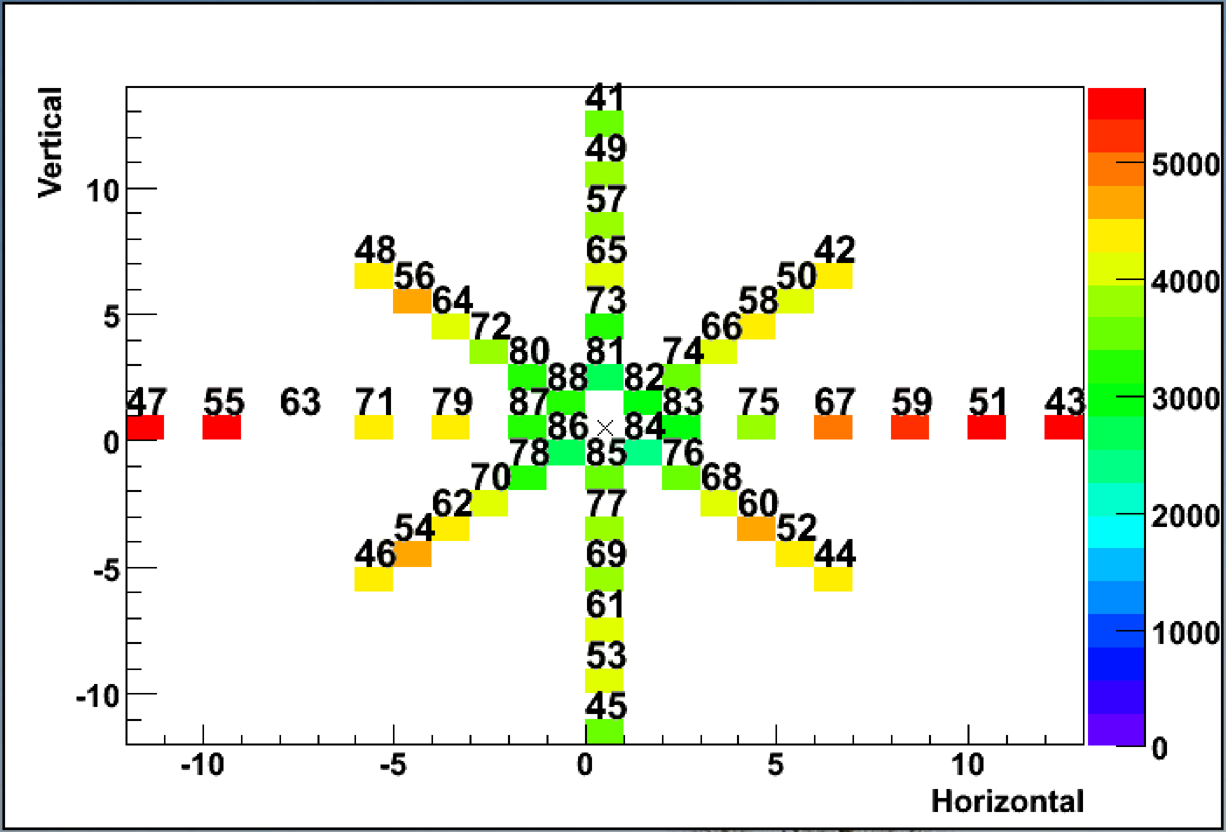


Analysis and Results: ^{6}Li Reaction Channels

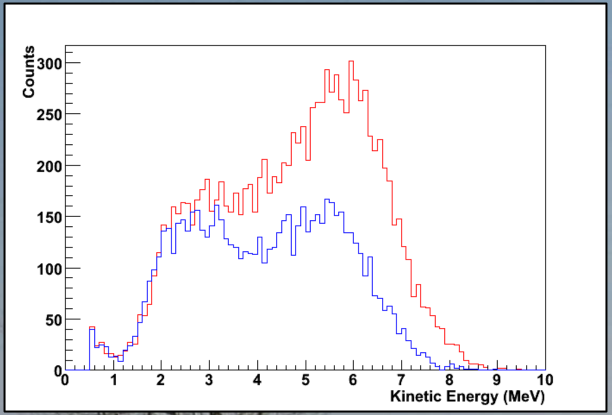
- We model the photodisintegration of ^{6}Li below 15.8 MeV as occurring through the following four reaction channels
- The three body decay is energetically allowed but does not appear to contribution substantially

$$^{6}\mathrm{Li}+\gamma \rightarrow n+{}^{5}\mathrm{Li(g.s)} \rightarrow n+p+{}^{4}\mathrm{He}$$

$$^{6}\mathrm{Li}+\gamma \rightarrow n+{}^{5}\mathrm{Li(1.49)} \rightarrow n+p+{}^{4}\mathrm{He}$$

$$^{6}\mathrm{Li}+\gamma \rightarrow p+{}^{5}\mathrm{He(g.s)} \rightarrow n+p+{}^{4}\mathrm{He}$$

$$^{6}\mathrm{Li}+\gamma \rightarrow p+{}^{5}\mathrm{He(1.27)} \rightarrow n+p+{}^{4}\mathrm{He}$$



Analysis and Results: ^{7}Li Reaction Channels

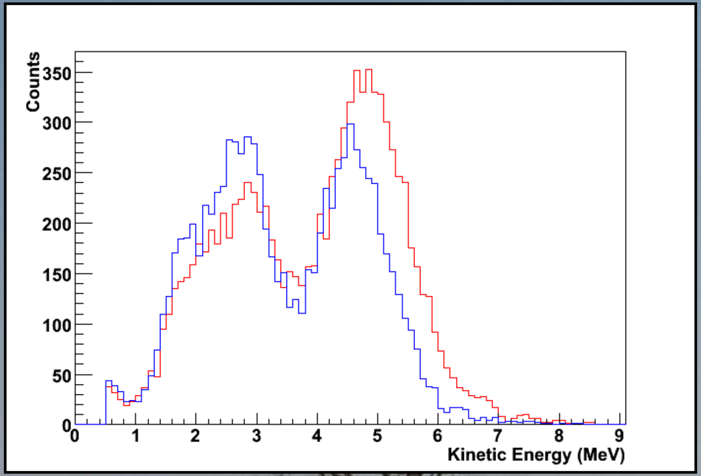
- The highest energy neutrons are all due to the single neutron knockout reaction to the ground state of ^{6}Li
- Not all reaction channels produce neutrons
- Many reaction channels to contend with

$$^{7}\mathrm{Li}+\gamma\rightarrow{}^{3}\mathrm{H}+{}^{4}\mathrm{He}$$

$$^{7}\mathrm{Li}+\gamma\rightarrow n+{}^{6}\mathrm{Li}$$

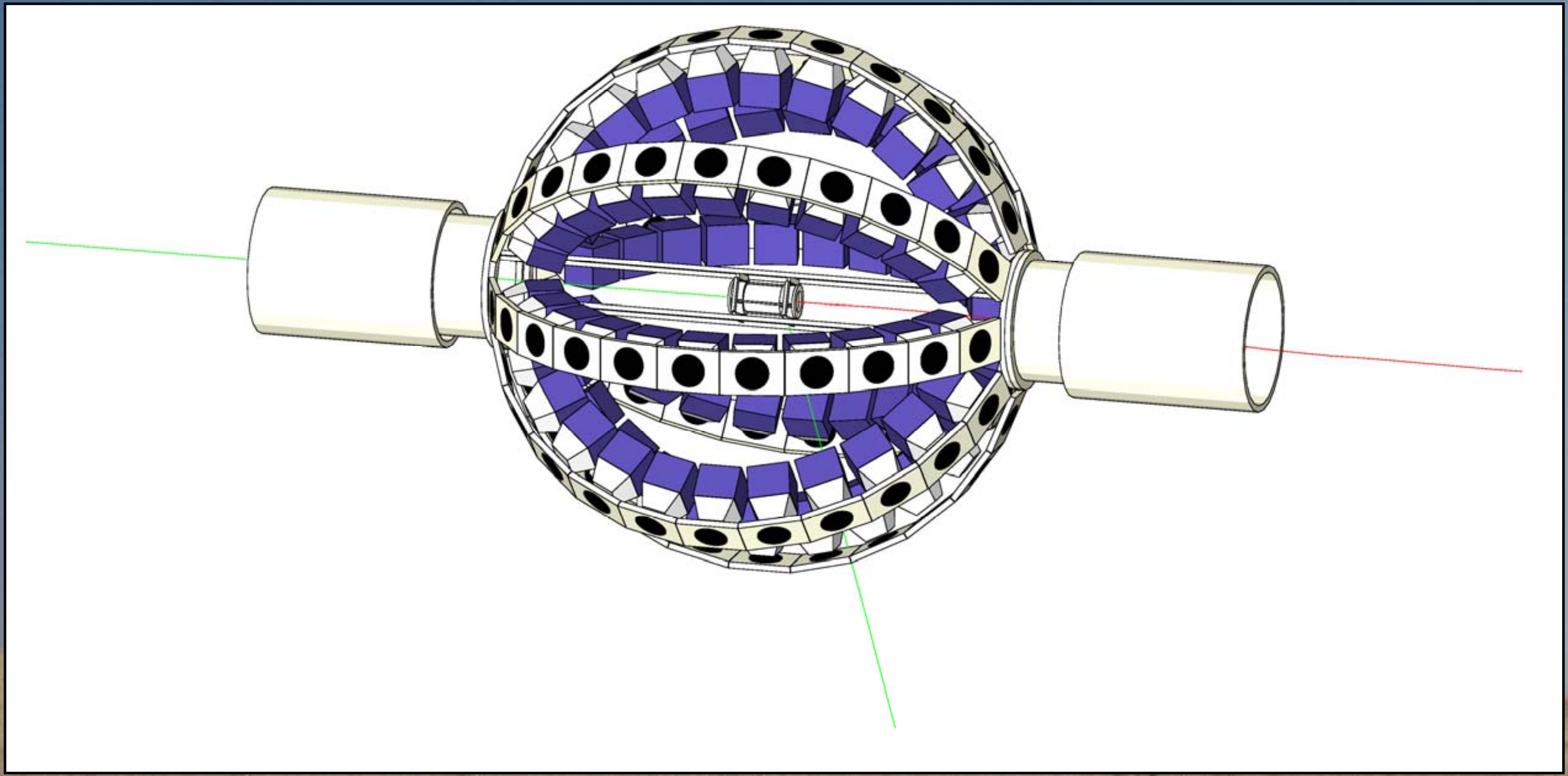
$$^{7}\mathrm{Li}+\gamma\rightarrow d+{}^{5}\mathrm{He}\rightarrow n+d+{}^{4}\mathrm{He}$$

$$^{7}\mathrm{Li}+\gamma\rightarrow p+{}^{6}\mathrm{He}$$



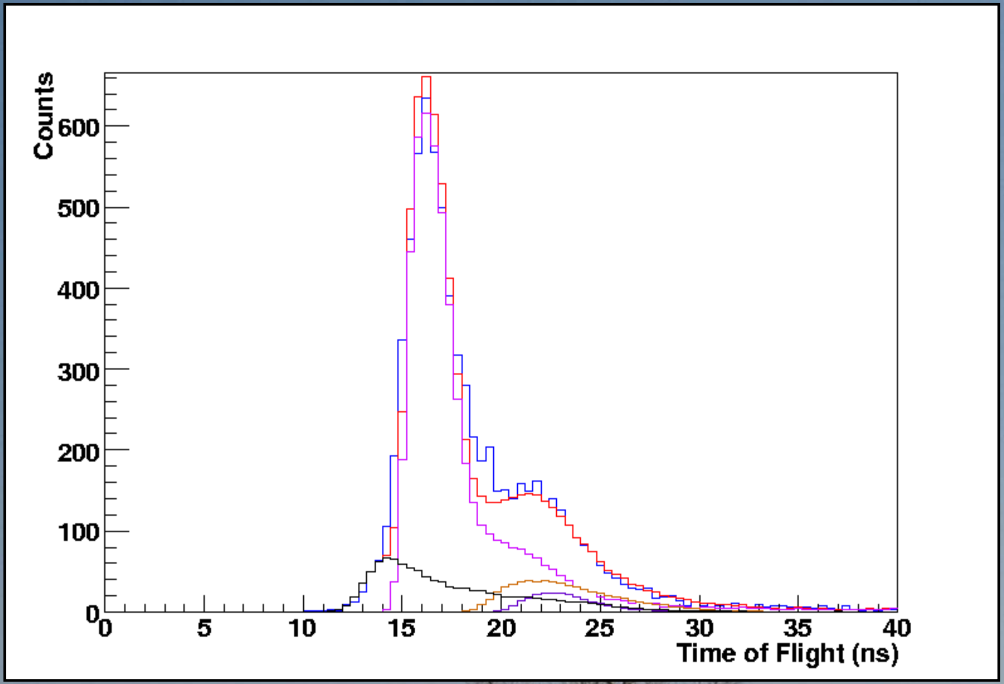
Analysis and Results: Simulating the Reaction Channels

- We use a Geant4 simulation
- Input neutron kinetic energy and angular distributions
- Output neutron detector responses

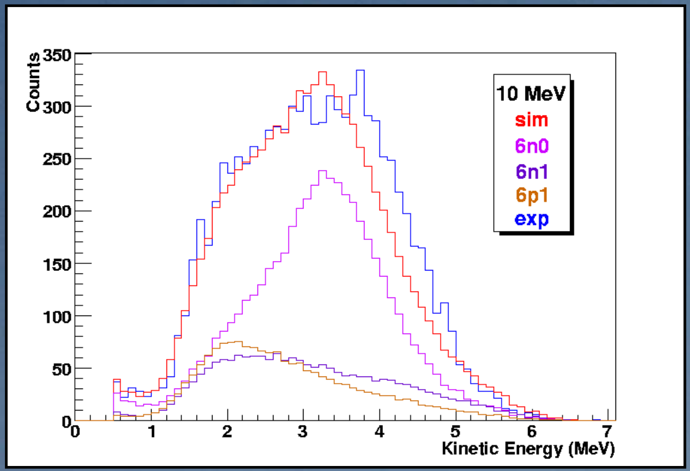


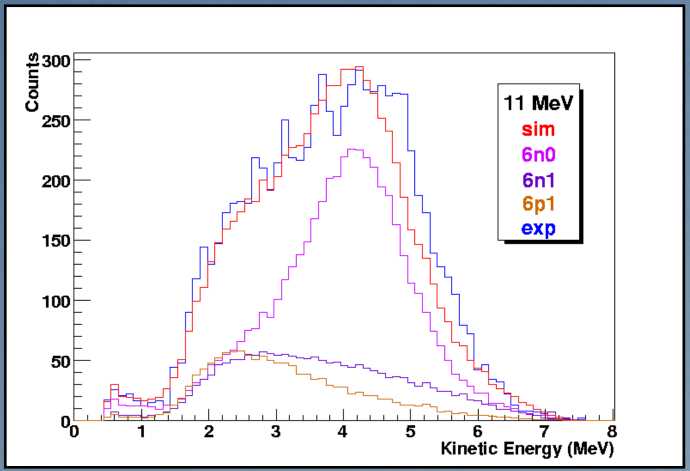
Analysis and Results: Data Comparison

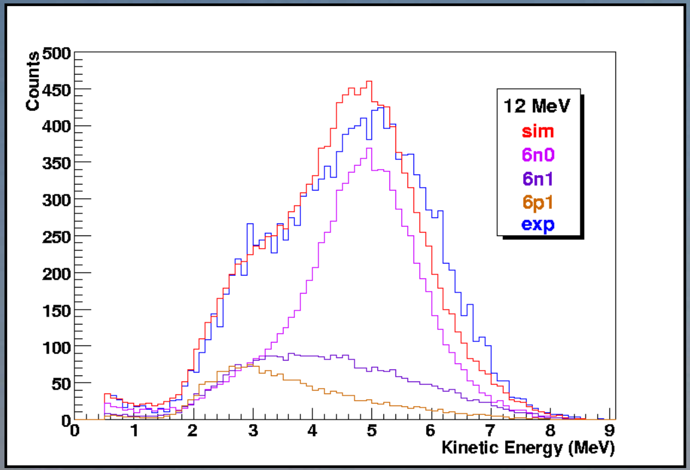
- We use the simulated data to separate the different reaction channels by fitting to the time-of-flight spectra:
  - Blue: ^{7}Li measurement
  - Black: ^{6}Li contribution
  - Red: Total simulation
  - Purple: Single neutron knockout (simulation)
  - Orange: Single deuteron knockout (simulation)

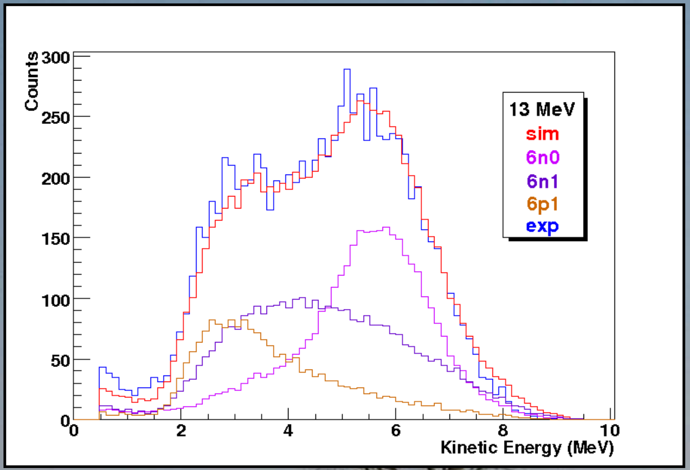


Analysis and Results:
^{6}Li Data Separation

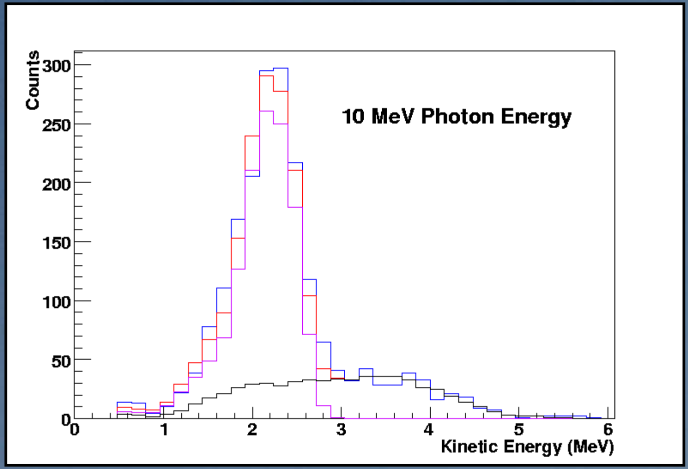


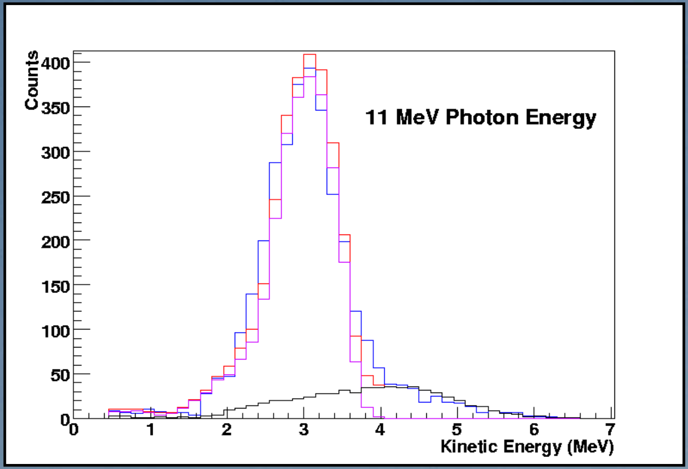


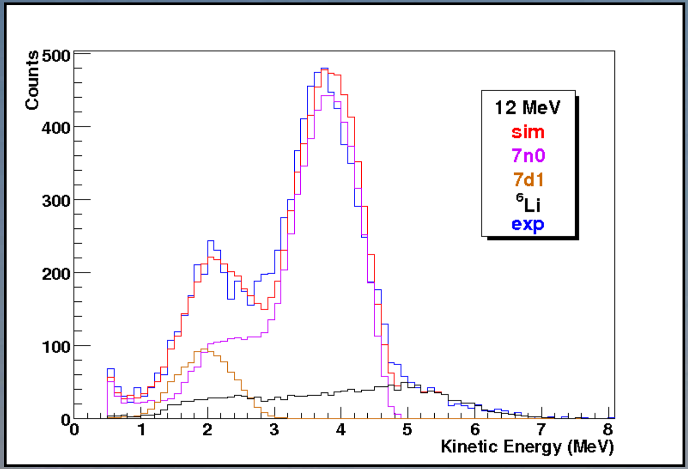


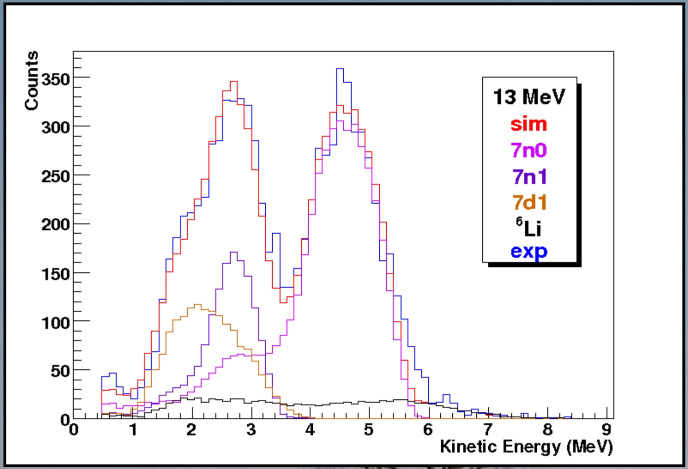


Analysis and Results: ^{7}Li Data Separation









Analysis and Results: Continuing Analysis

- Finish separating measured data into reaction channels (good progress made)
- Extract angular dependence of cross sections (in progress)
- Attempt to extract total cross sections
  - Need angular distributions first
- Will have software infrastructure finished before March

Concluding Remarks: Discussion

- We have made unique measurements to obtain the cross sections of specific reaction channels for the photodisintegration of the lithium isotopes
- Agreement between the simulation and the measured data is excellent
- Analysis is proceeding well

Concluding Remarks: Graduate Student Opportunities

- Today, nuclear and particle physics involve large collaborations with students being involved with only a very small portion of an experiment
- Photonuclear physics is different and a student can take a project from start to completion, participating in all aspects and having the opportunity to be a leader, not just a worker
- Photonuclear physics is an excellent opportunity for a student to be exposed to subatomic physics

Graduate Student Opportunity: The Photodisintegration of ^{9}Be

- The inverse reaction has astrophysical relevance as it allows for the production of heavier elements
- The two v.s. three body nature of the reaction is not adequately understood
- This experiment could be done using the same techniques as the photodisintegration of lithium (analysis techniques and software infrastructure already in place)

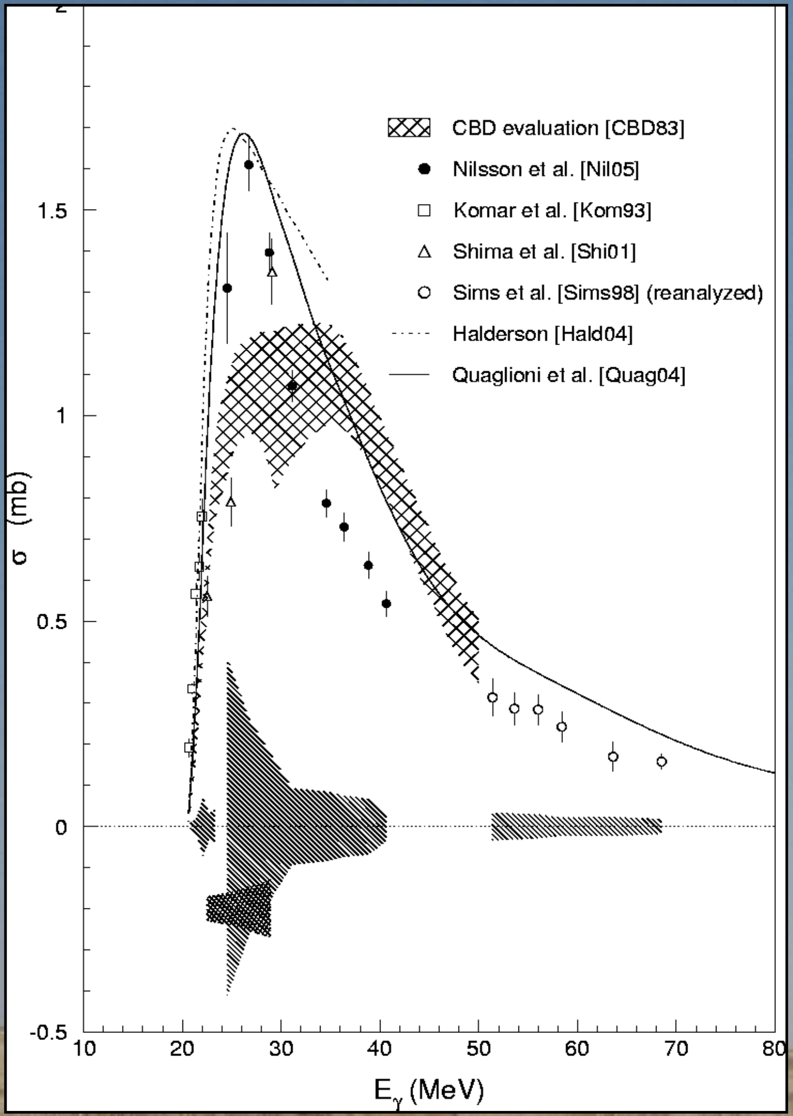
$$^{9}\mathrm{Be} \rightarrow n + 2\alpha$$

$$^{9}\mathrm{Be} \rightarrow n + {}^{8}\mathrm{Be} \rightarrow n + 2\alpha$$

$$^{9}\mathrm{Be} \rightarrow \alpha + {}^{5}\mathrm{He} \rightarrow n + 2\alpha$$

Graduate Student Opportunity: The Photodisintegration of ^{4}He

- Cross section is very controversial
- Theoretical LIT calculation does not agree with former consensus value
- Measurements do not agree with each other



Questions