Neutron emission after muon capture: work plan for 2013 run and a possible PSI-2015 run

Aji Daniel

University of Houston

AlCap Collaboration meeting, March 25, 2014, FNAL

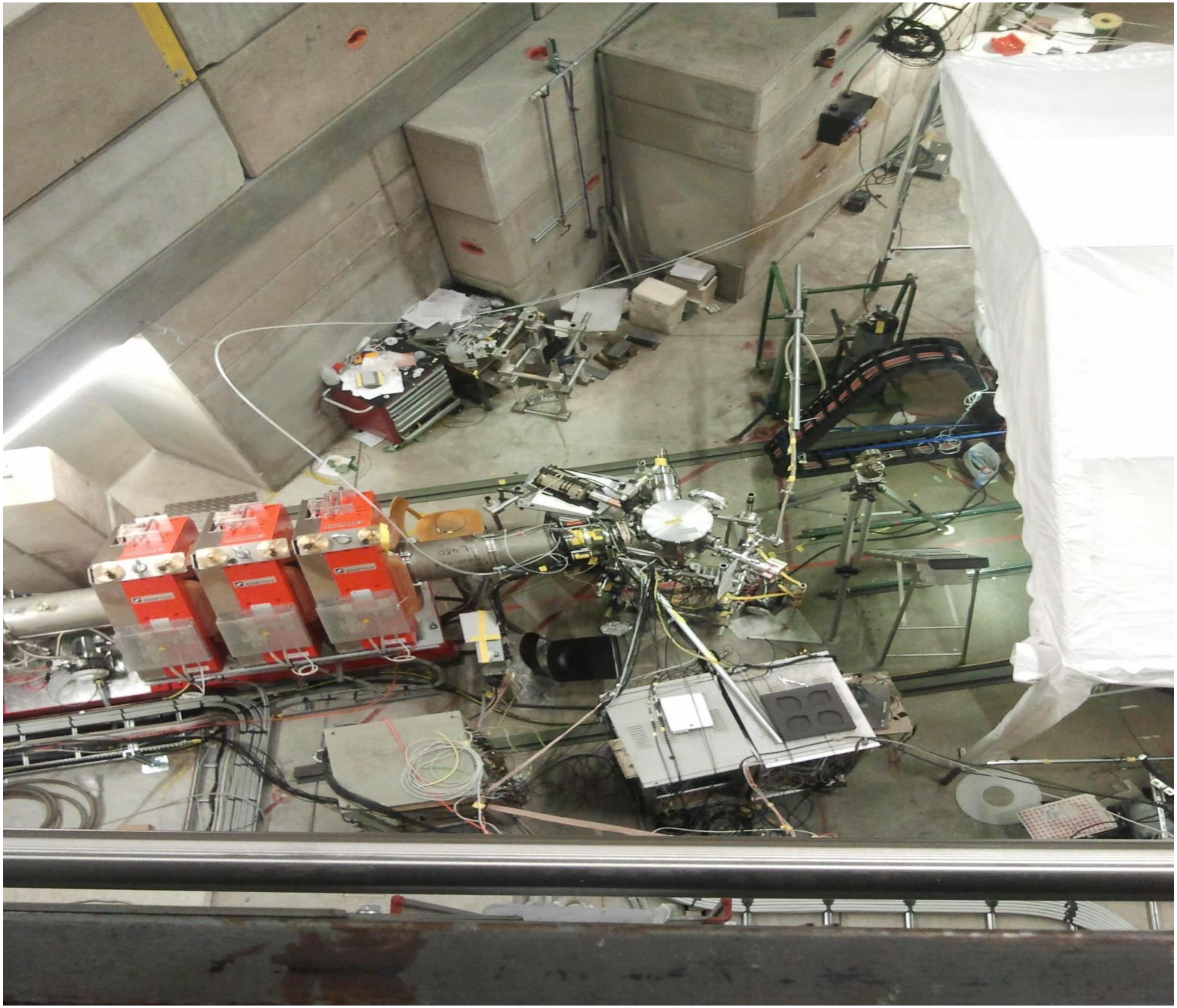
Motivation for neutron measurements

- Apart from the physics interest of its own,
- Back grounds for calorimeter and the scintillators of the cosmic veto of the muon to electron conversion experiments;
- Fast neutrons can cause damage to front end electronics.

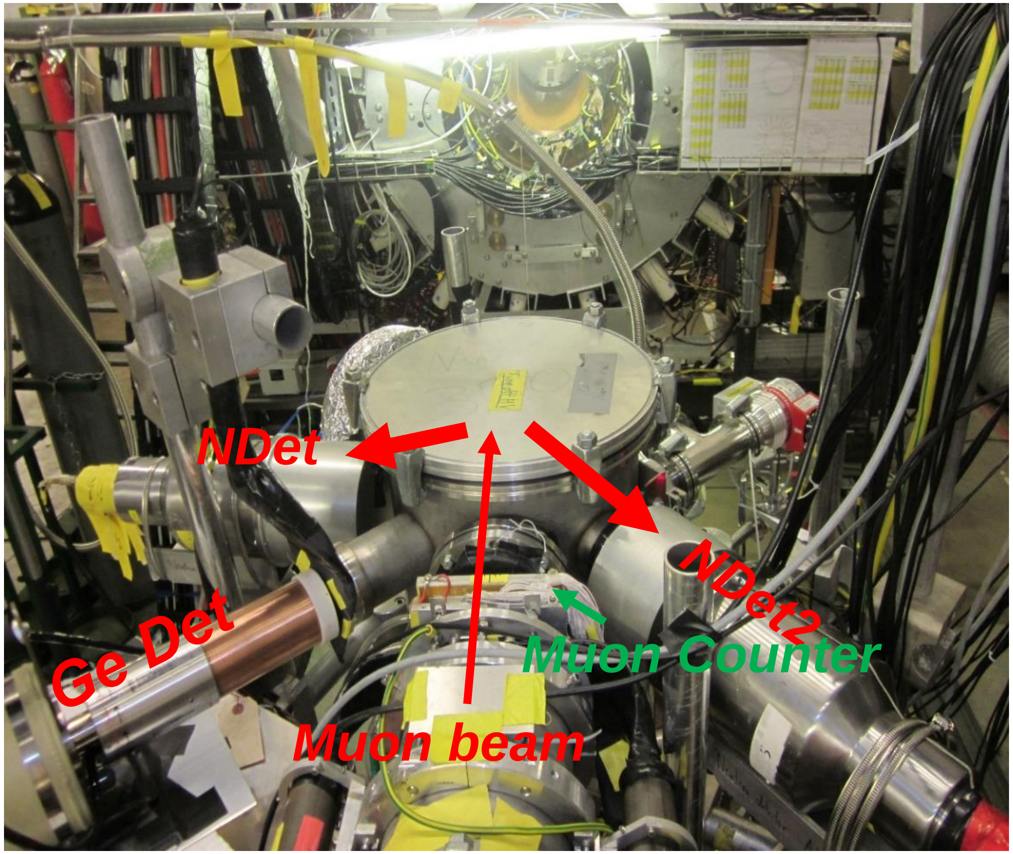
- Important to understand the rate and spectrum of neutrons after muon capture

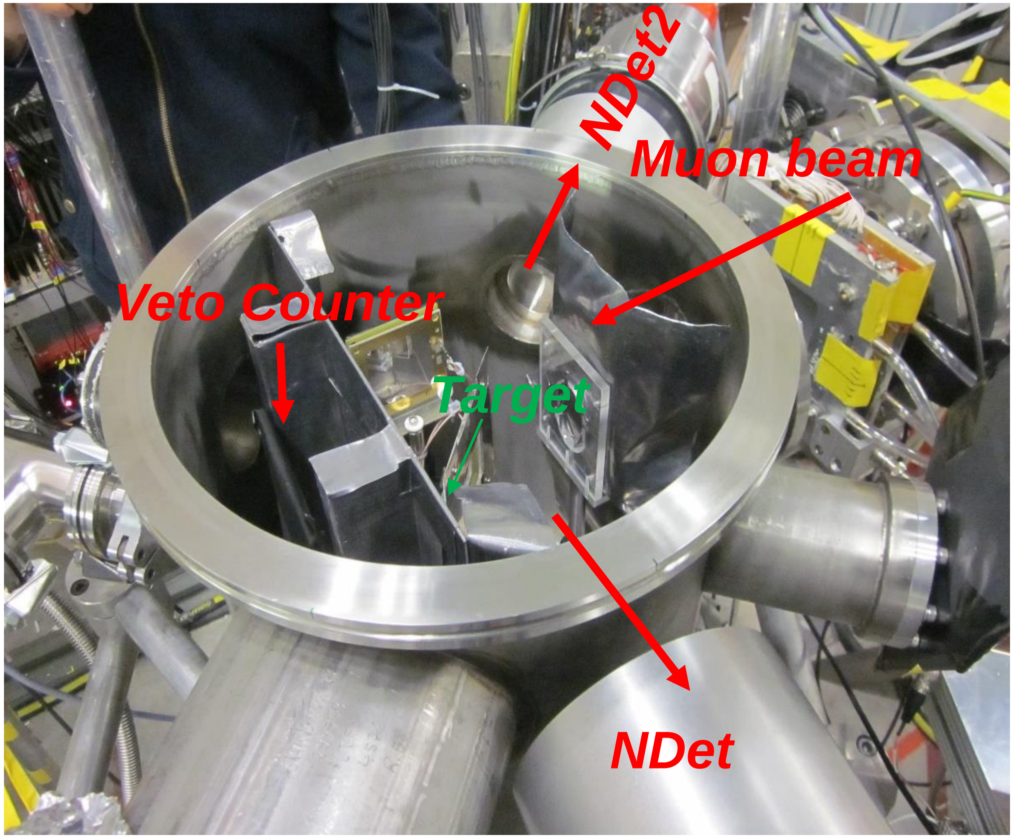
(See previous talk by Dr. Hungerford's talk in this session)

Aerial view of the setup during R13



R13 setup


NDet
NDet2
Ge Det
Muon Counter
Muon beam


NDet2
Muon beam
Veto Counter
Target
NDet

Neutron detector set-up during 2013 run

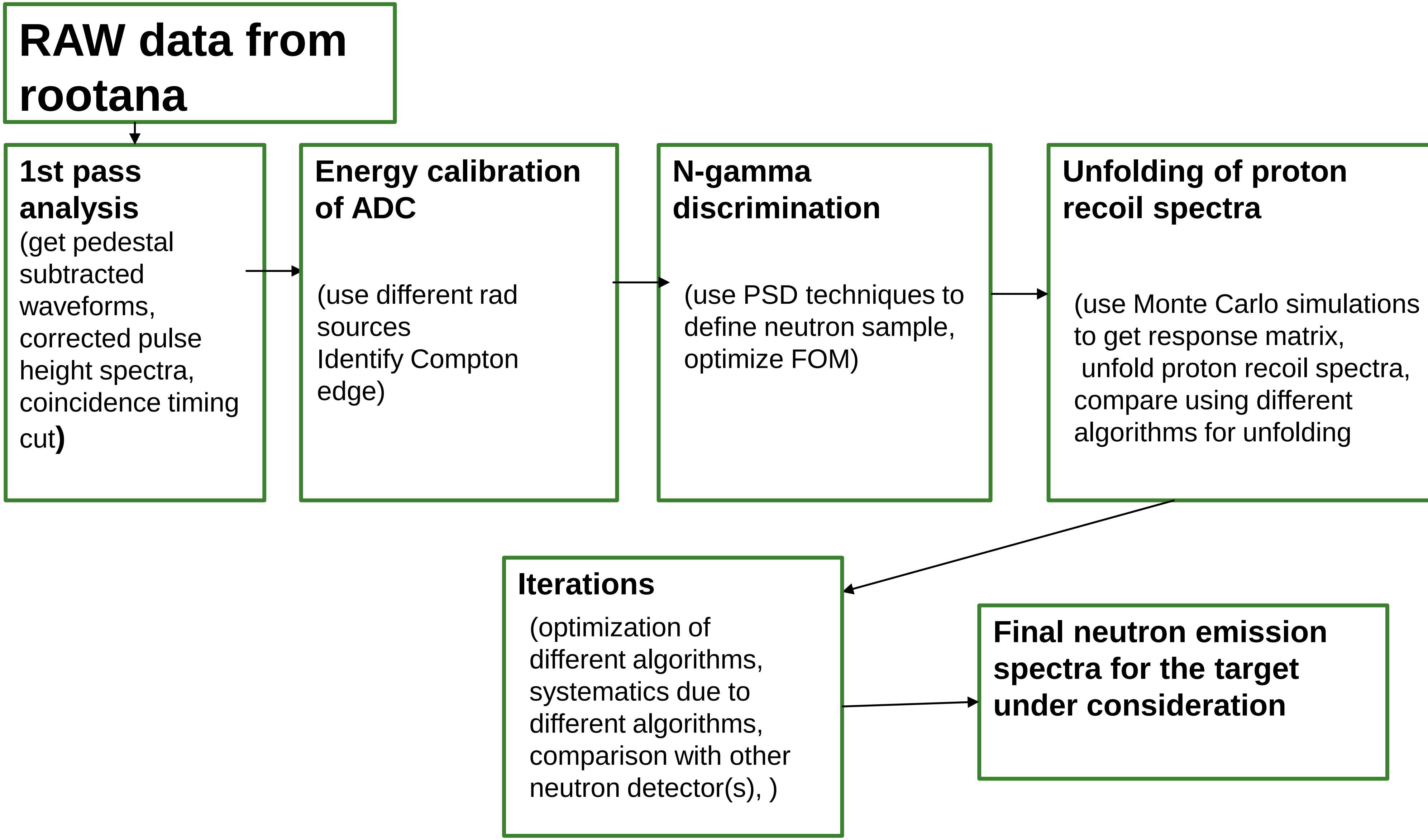
- BC501A detectors borrowed from MuSun (NDet ->ND03; NDet2->NU03)
- NDet2 was on only last few days (from Dec 20 onwards)
- NDet was hooked to BU digitizer during earlier part of the run
- Later (Dec18), this was hooked up to an FADC , NDet2 was also hooked up to an FADC (Data collected with FADC may be the most promising one)
- BC501A's are cylindrical cells of 5'' dia and 5'' depth
- These were connected to a PMT (Philips VD105K)
- NDet (NDet2) is placed to beam left (right)
- Front of NDet to target chamber is ~3.7 cm (~6.8 cm for NDet2)
- Both N detectors, roughly 21 cm from the target center.

Neutron detector set-up during 2013 run

- Earlier we took some opportunistic photon source runs with (Cs137, Co60, AmBe, ..) but these were on BU CAEN digitizer
- On FADCs, data on targets Al100, Al50, Si16, Si
- Calibration runs on FADCs were done with Co60 (an AmBe run on NDet2 as well, Christmas -> had to return other sources)
- Calibration runs were taken by sticking the source on to the front face of each detector (may not be a good idea)
- Also, took some pulser data on the FADC channels on last day

(For more information see Damien's talk)

Work plan for the analysis



Calibration of ADC pulse height spectra

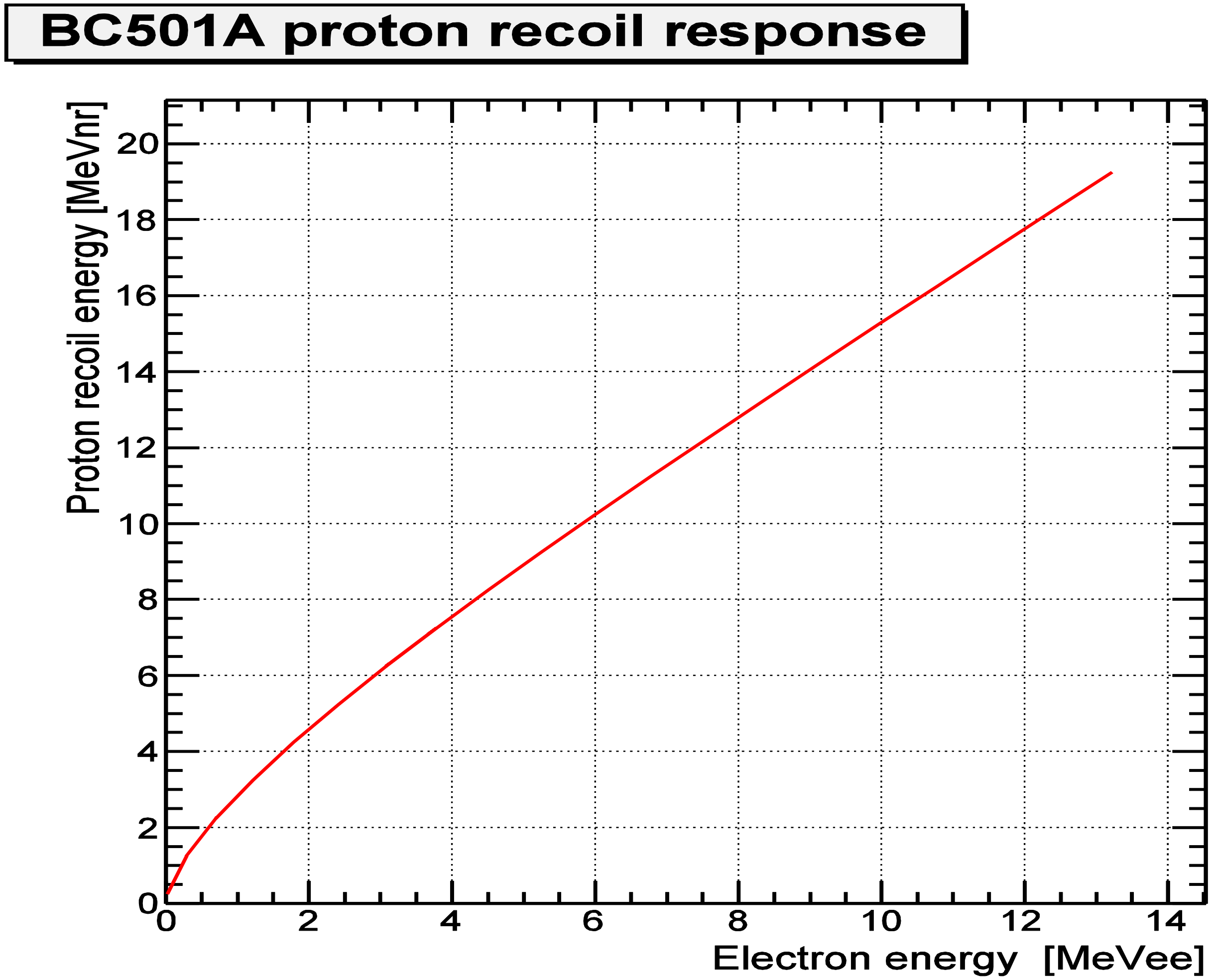
- **Scintillator response to electrons are fairly linear, so gamma ray source is used to calibrate the energy scale. Calibration yields PH spectra in units of MeVee.**
- **Low Z values of organic scintillators results in very low photo electric cross sections, virtually all gamma interactions are Compton scattering**
- **Since there is no photo peak, the next best option is finding the characteristic Compton edge**
- **Different ways to find CE in literature [see for example Yan Jie et al, CPC 34, 993 (2010)] for the energy value of Compton edge (0.5 to 0.90 of maximum peak height), conventionally half height of the maximum peak is used and is a good approximation to start the initial analysis.**
- **But eventually we should use Monte Carlo method with realistic energy resolution of the neutron detector used for DAQ (which strongly depends on the composition, scintillator volume, type of PMT used …)**

Few possible photon sources for calibrations

Source	Compton peak (MeV)	Calculated Compton Edge
^{22}Na	0.511	0.341
^{137}Cs	0.662	0.477
^{60}Co	1.173	0.956
^{22}Na	1.275	1.061
^{60}Co	1.333	1.118
^{40}K	1.461	1.243
^{232}Th	2.614	2.381
AmBe (n/gamma)	4.43	4.19

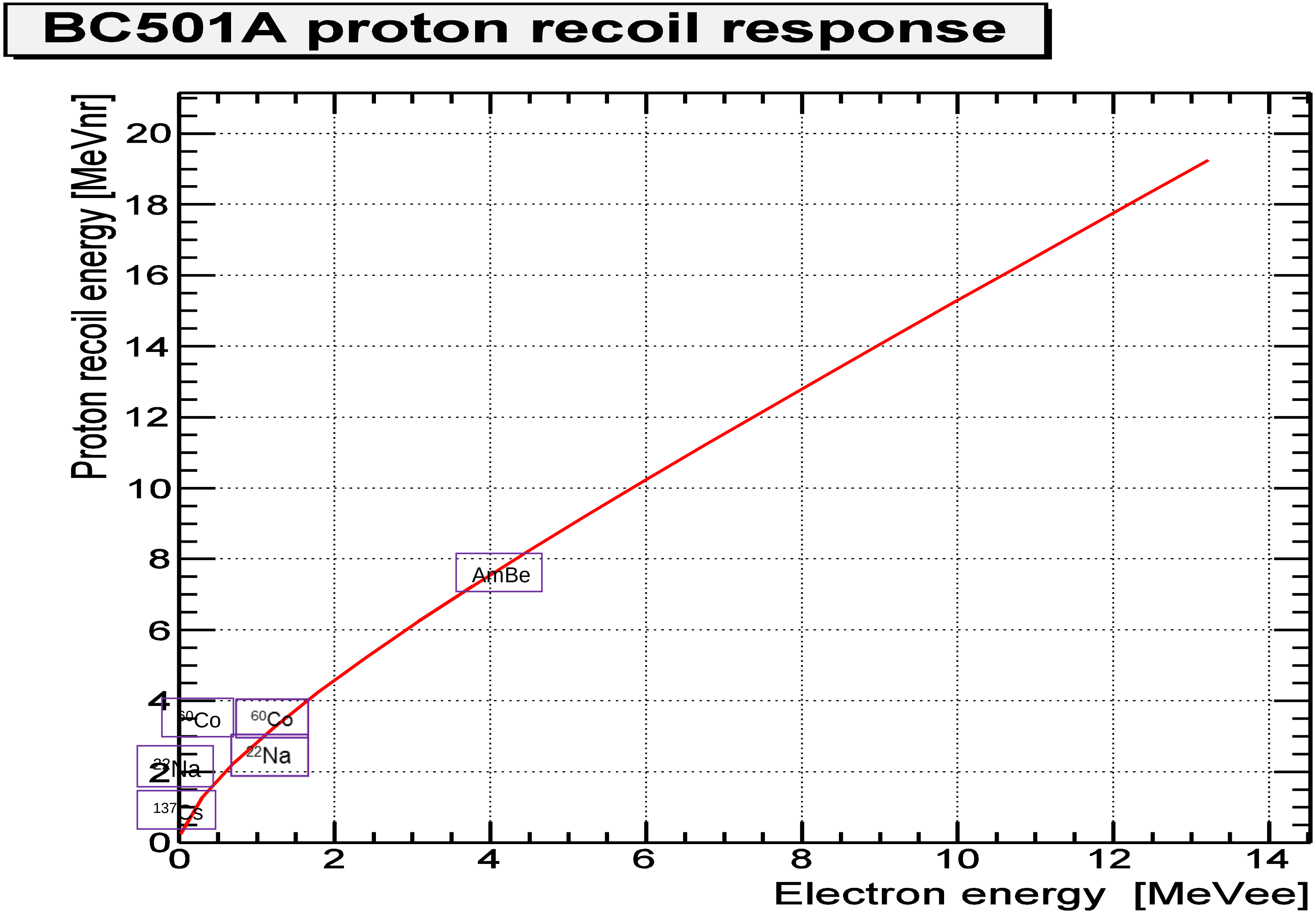
AmBe, after good neutron/gamma discrimination very useful for energy calibrations and checking unfolding procedures

BC501 response



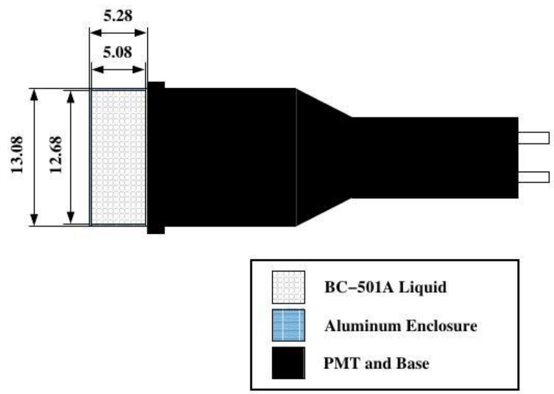
- From BC501A data sheet (Cecil 1978)
- With BC501A what we measure is electron recoil (due to gamma) and proton recoil (due to neutrons)
- Desired range 0.25 MeVee ~8 MeVee (which gives approximately 1-13 MeV neutrons

Calibration points along BC501 response curve



Some characterstics of BC501A

$$p(n,n)p$$
$$^{12}C(n,n)^{12}C$$
$$^{12}C(n,n+3\alpha)$$
$$^{12}C(n,\alpha)^{9}Be$$

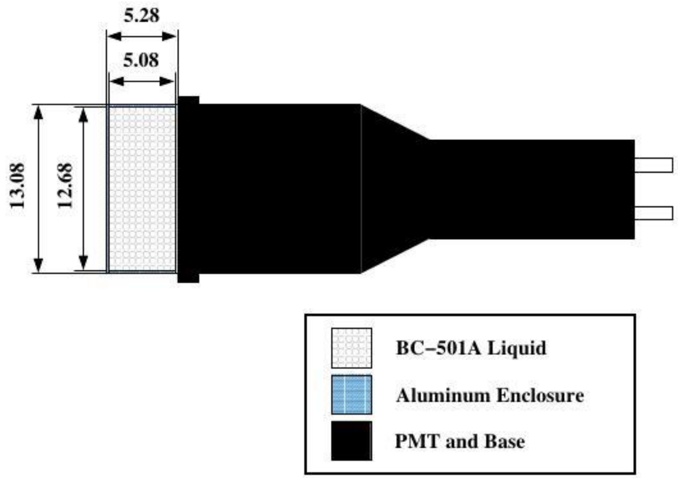


Value	Property
Density	0.874 g/cc
Refractive index	1.505
Light o/p (% Anthracene)	78
H atoms per cc ($x10^{22}$)	4.82
C atoms per cc ($x10^{22}$)	3.98
Mean decay time of first three components	3.16, 32.3 & 270 ns

From Bicron data sheet

- **Xylene (C_8H_{10}) and Naphthalene ($C_{10}H_8$)**
- **High hydrogen content**
- **High light o/p**
- **Low self-absorption**
- **Fast timing response**
- **Good n/gamma pulse shape discrimination**

TUNL BC501A neutron detector characteristics



- 5" X 2" Al cells filled with BC-501A scintillating liquid
- Cells are Al cylinders with Al plate at one end and glass window at other end
- Glass surface of each surface directly connected to Hamamatsu Photonics model R1250 PMT with optical grease

Brent Perdue, TUNL Ph. D Thesis

Calibration of ADC pulse height spectra: using Monte Carlo

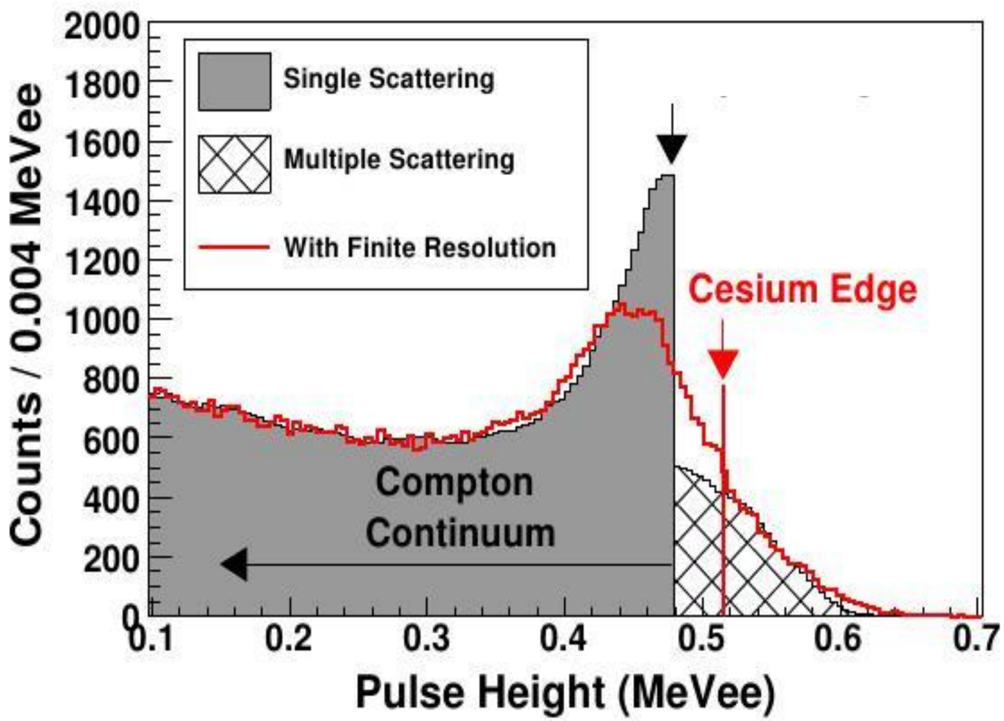
- GEANT4 simulation with a point source at target center (~75cm from detector, Egamma=0.662MeV, ^{137}Cs gamma line)

- Besides single scattering, incident gamma can scatter from two or more electrons (hatched area).

- Red curve after folding with detector resolution by matching the experimental resolution of neutron detectors

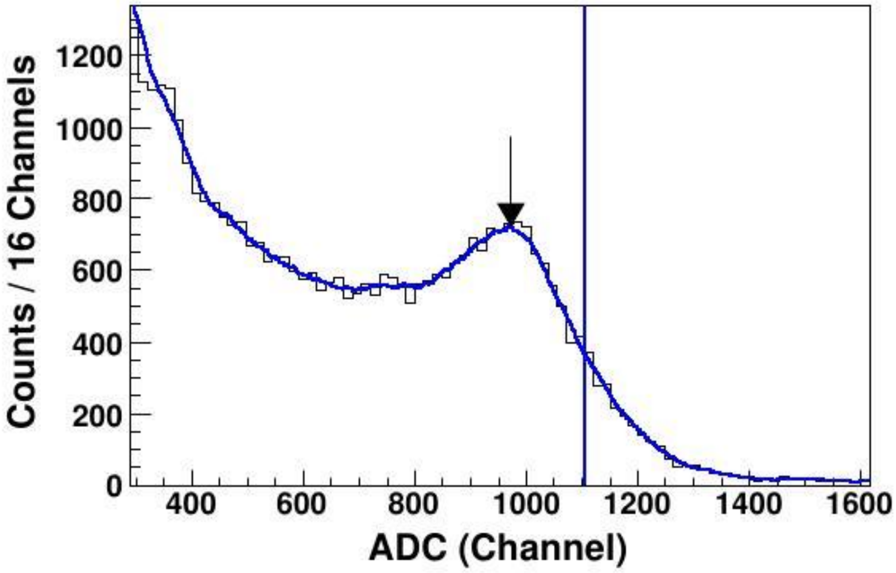
- Compton peak is at 0.478 MeVee and the Compton_edge_sim is found by the half_maximum of red curve which is 0.517 MeVee (~92% of theorectical Compton peak)

- Note that the resolution effects pushes the Compton peak to lower MeVee value) from the theoretical values



Brent Perdue, TUNL Ph. D Thesis

Calibration of ADC pulse height spectra: using Monte Carlo



- Experimental ADC spectra for the ^{137}Cs run (blue curve is a smoothed version of histogram)
- On the smoothed curve, Compton peak is indicated by arrow and the ADC_compton_edge is denoted by vertical line (half maximum of experimental Compton peak)

- Then the calibration is

$$PH = PH^{CE}_{Sim} \quad (ADC_{exp} - ADC_{ped}) / (ADC^{CE} - ADC_{ped})$$

Brent Perdue, TUNL Ph. D Thesis

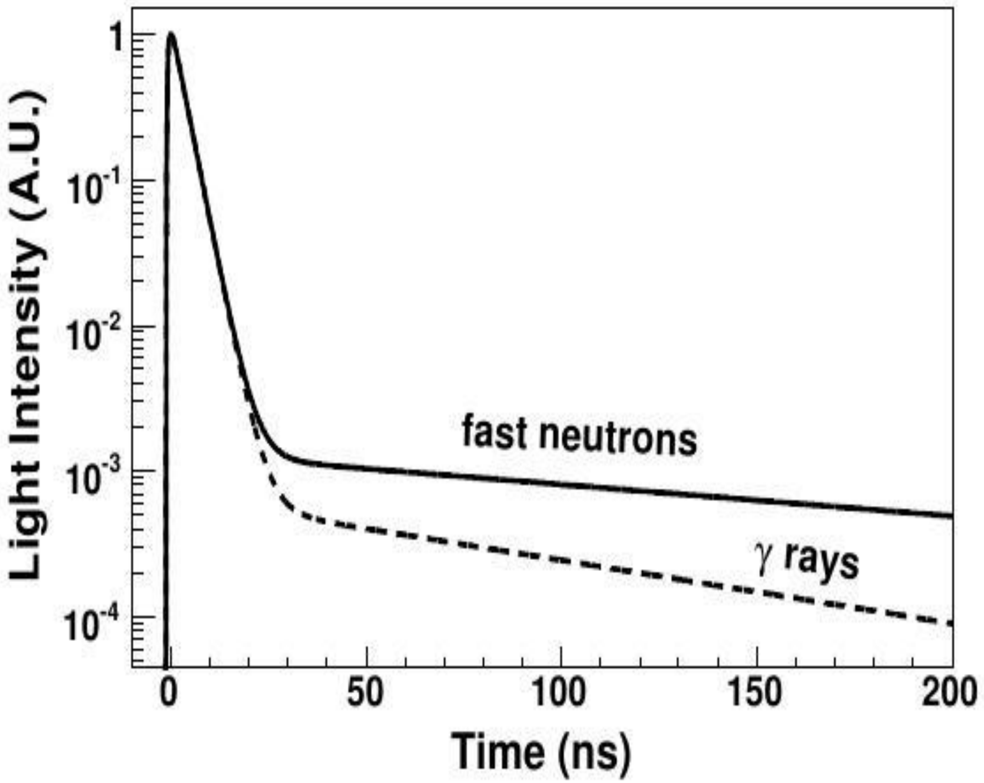
BC501A: Pulse Shape Discrimination (PSD)

- Most of the emitted scintillation light results from prompt fluorescence (t~3.2 ns), but some from delayed fluorescence (t~ several hundreds of nano second)

- Fraction of the delayed component depends on the type of exciting particle and the rate of energy loss

- Neutrons, producing recoiling protons with larger dE/dx will have a larger delayed component than gammas

- Make use of this property to discriminate between neutrons and gammas



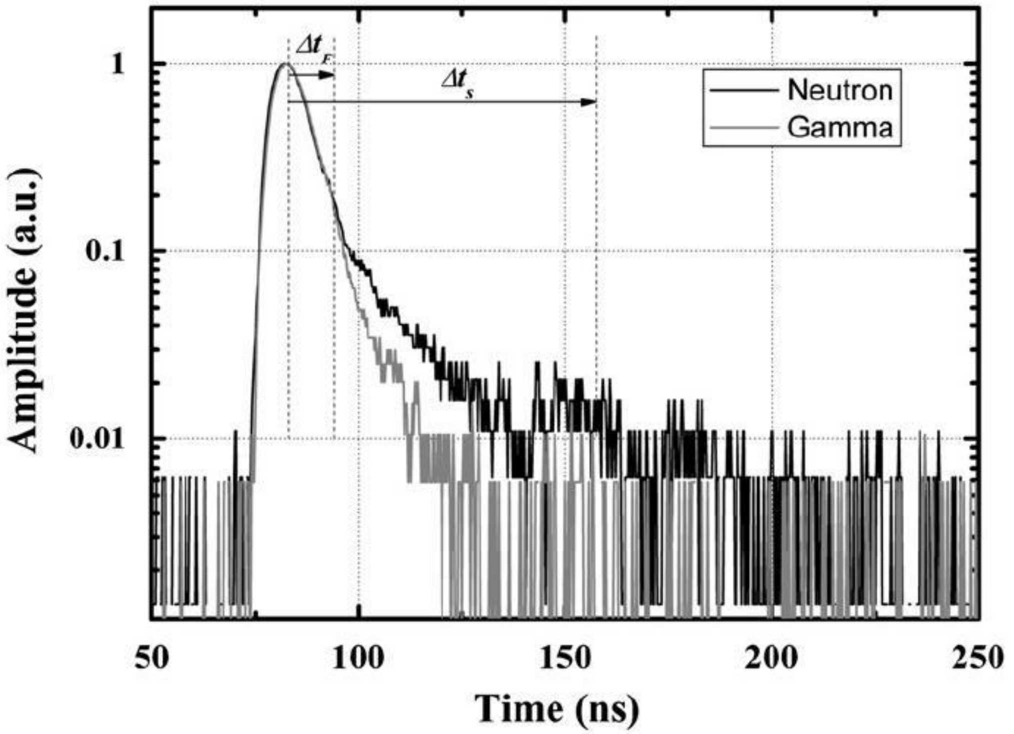
BC501A: Pulse Shape Discrimination (PSD)

- Most of the emitted scintillation light results from prompt fluorescence (t~3.2 ns), but some from delayed fluorescence (t~ several hundreds of nano second)

- Fraction of the delayed component depends on the type of exciting particle and the rate of energy loss

- Neutrons, producing recoiling protons with larger dE/dx will have a larger delayed component than gammas

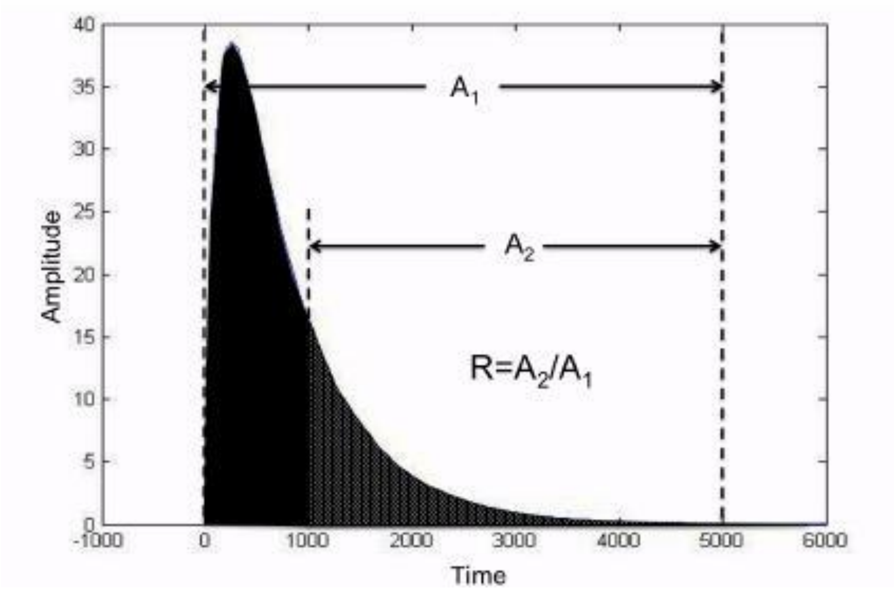
- Make use of this property to discriminate between neutrons and gammas

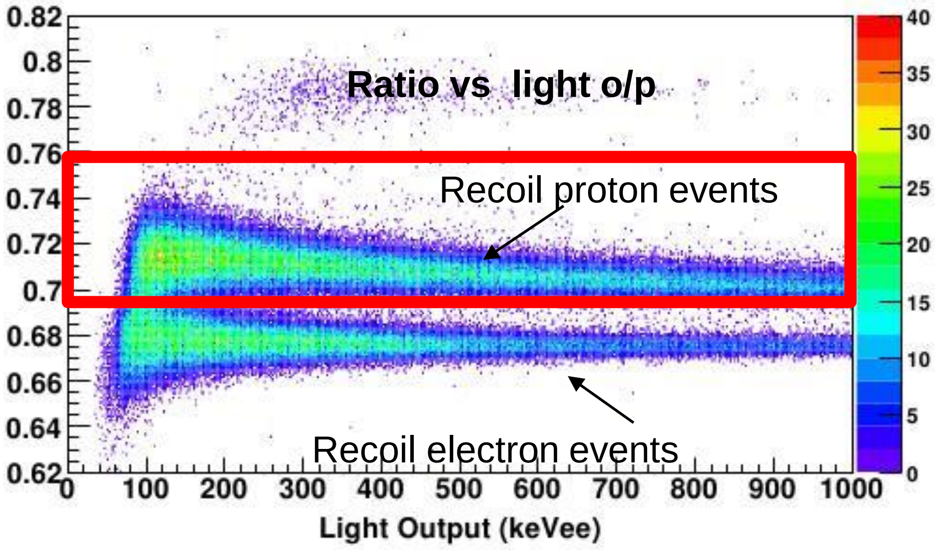


In reality, a sample might look more or less like this

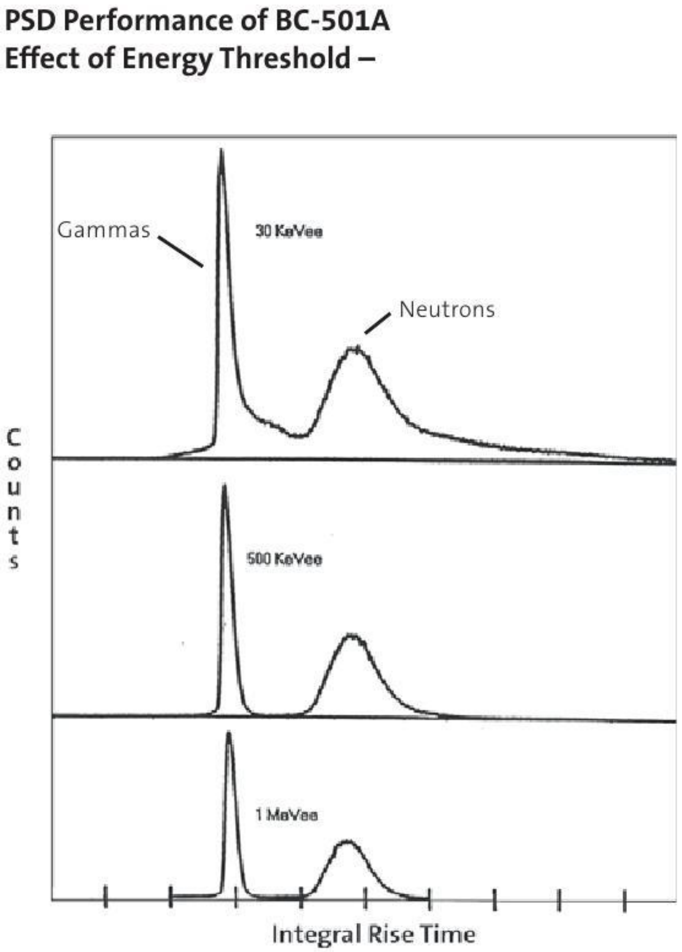
Pulse shape discrimination by charge integration

- Each waveform is integrated with two gates
- Total integral -> from beginning of the pulse to the end
- Tail integral-> a certain starting point after the maximum of the waveform to the end
- Plot the ratio of tail to total versus total integral (or any observable of interest), this ratio is energy dependent qty
- Figure of Merit= separation_between_peaks/(FWHM_n+FWHM_gamma)





BC501 response: effect of energy threshold



From BC501A data sheet

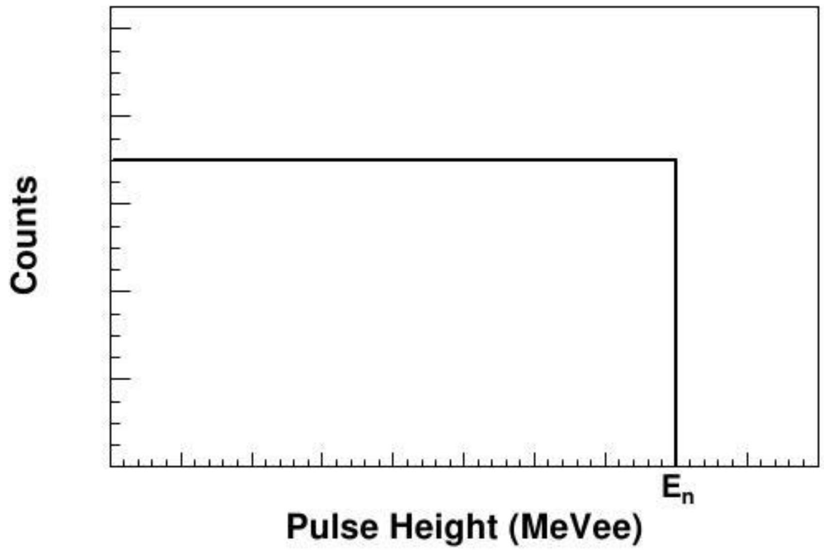
- From 0.5 MeVee (ie 2 MeVnr) and above good separation
- Lowest energy neutrons (1 to 2 MeVnr) may need some extra attention (correct by fitting the number of electron recoil events leaked in to the proton recoil area and vice versa)
- Formulate electron recoil energy dependent n/gamma separation cuts

BC501A: Light output resonse

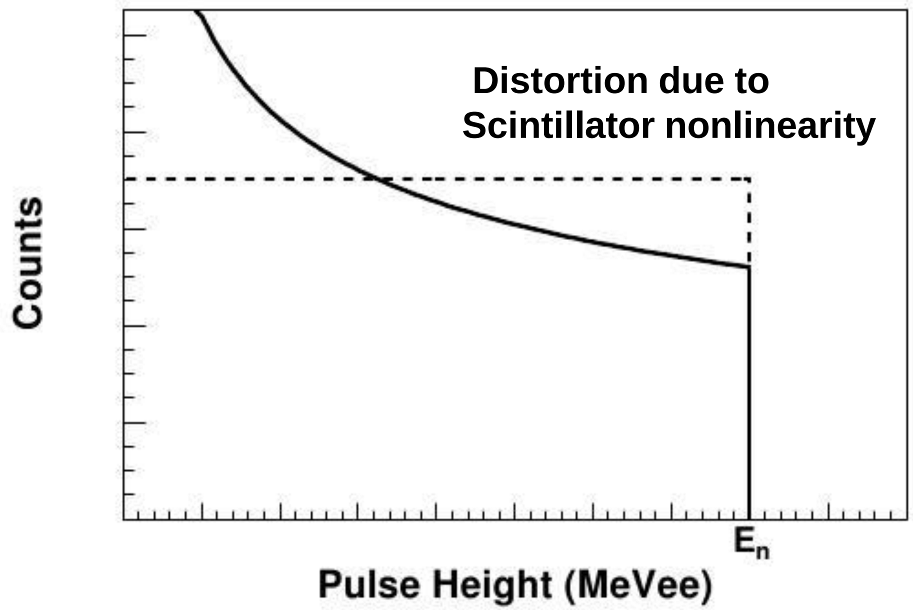
- Response of the organic scintillator can be described by a modified form of Birk's law

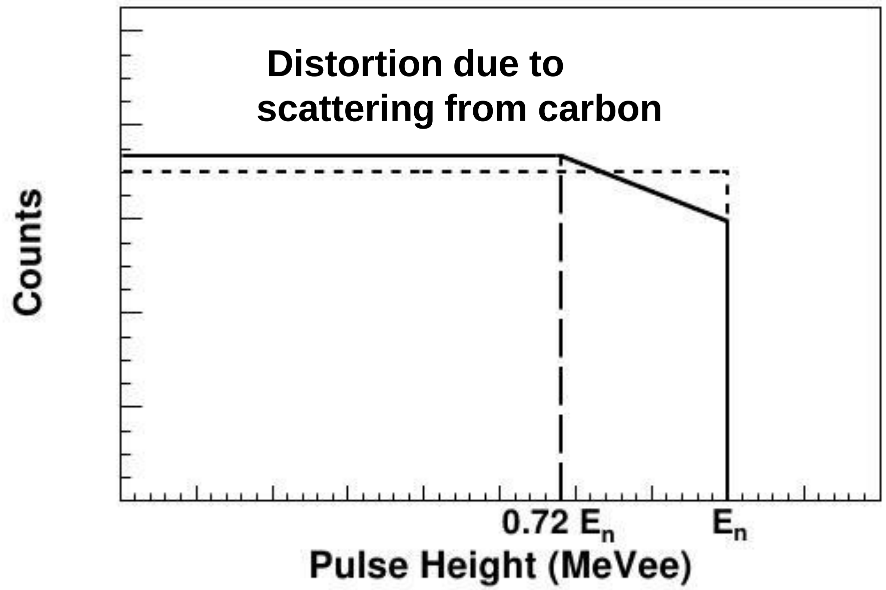
$$\frac{\mathrm{d}L}{\mathrm{d}x} = \mathrm{S}\,\frac{\mathrm{d}E}{\mathrm{d}x}\left[1 + \mathrm{kB}\,\frac{\mathrm{d}E}{\mathrm{d}x} + \mathrm{C}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^2\right]^{-1}$$

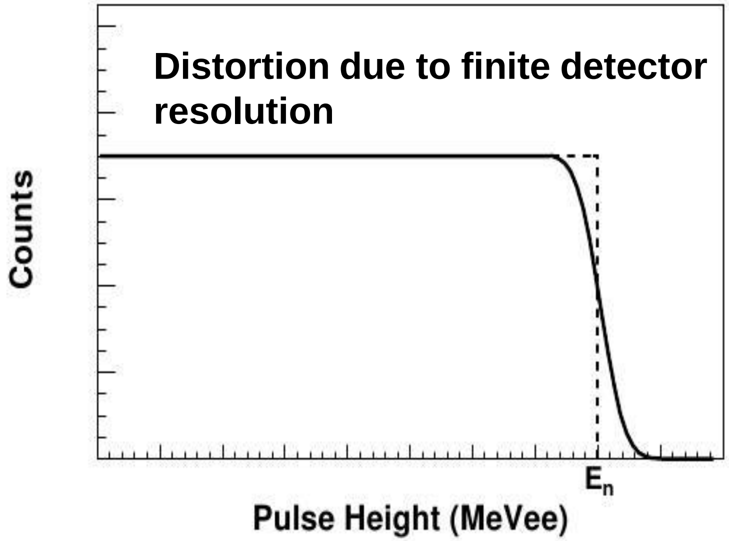
- If the light o/p increases with linearly with deposited energy, then the PH distribution from single neutron-proton scattering would be a rectangle for isotropic scattering



BC501A: Light output resonse

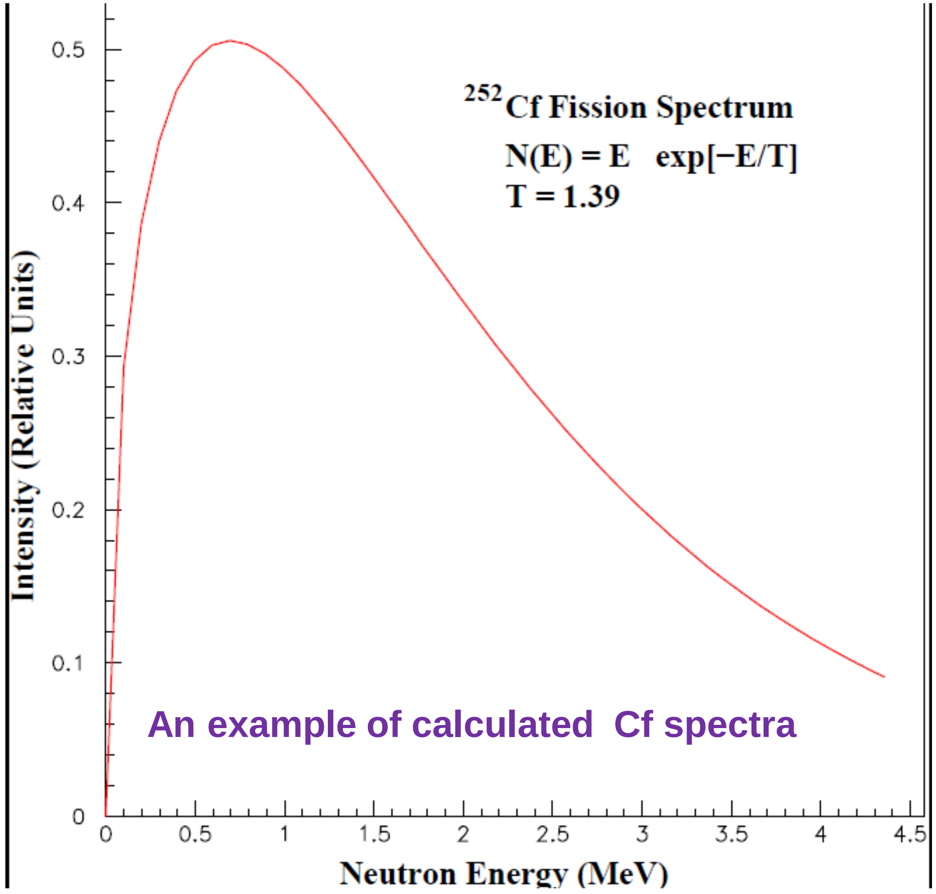






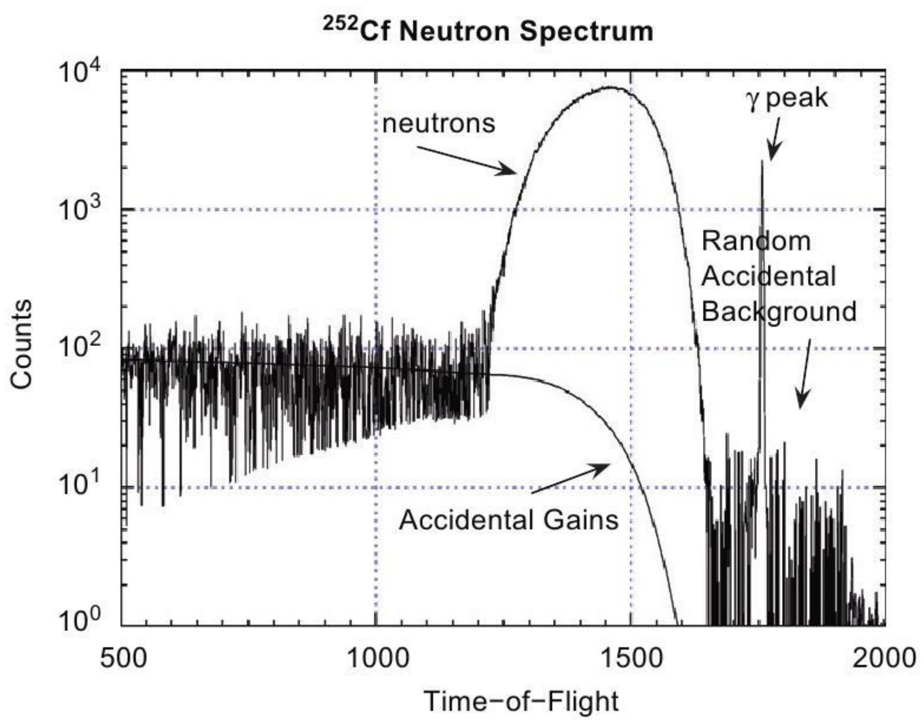
TUNL : BC501A Light output response studies

- ^{252}Cf deposited on a circular disk
- Placed inside a low-mass parallel-plate ionization chamber which is used to detect fission fragments
- Neutrons resulting from the spontaneous fission of 252Cf were detected via TOF method using BC501A
- 3m flight path
- Start signals from produced neutrons, fission fragments provided the TDC stop (after suitable delay)
- A scatter plot of the PH spectra vs TOF spectra (with suitable small time gate) will provide PH spectra for 'mono' energetic neutrons.
- Hence, the detector response for 'mono' energetic neutrons can be mapped out.

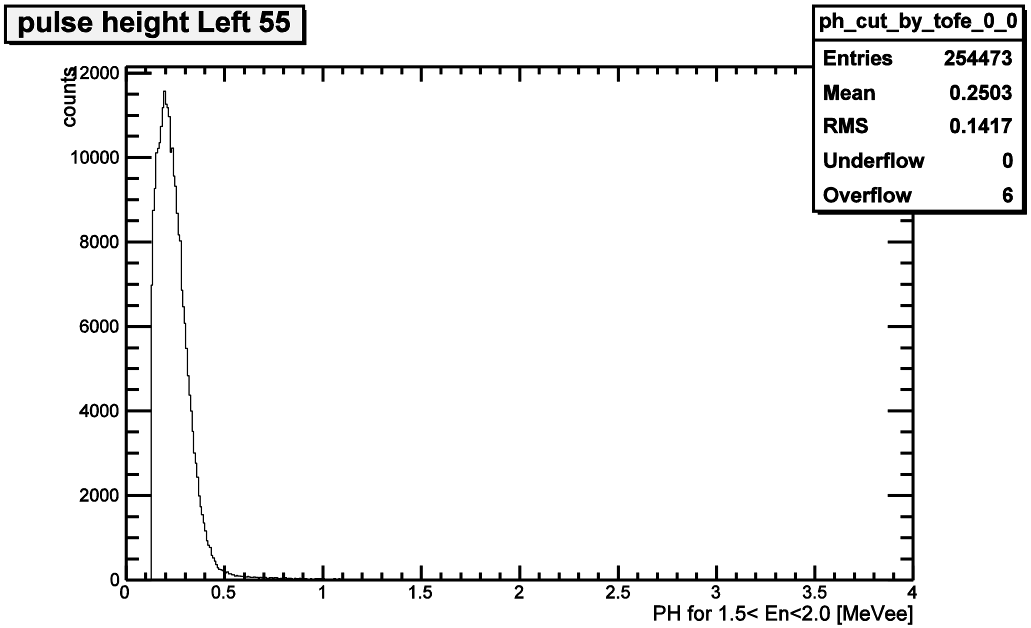


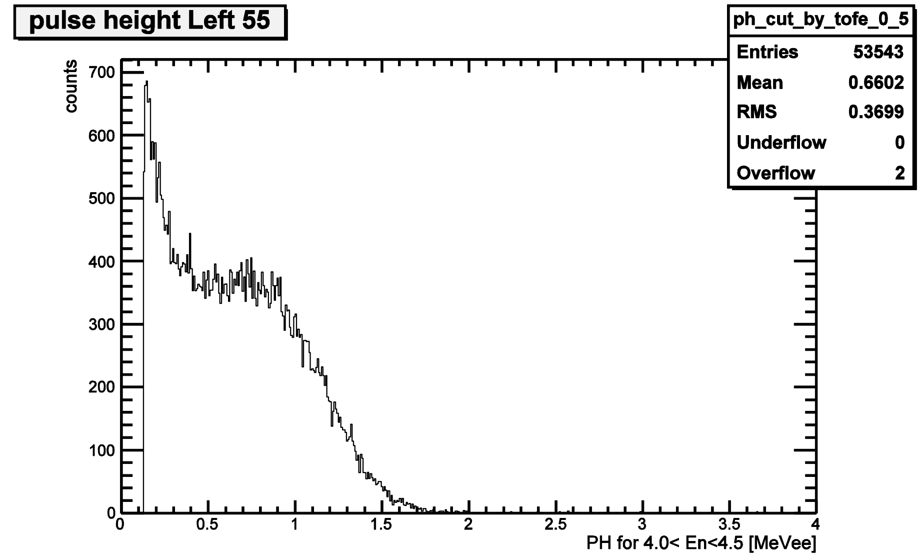
TUNL : BC501A Light output response studies

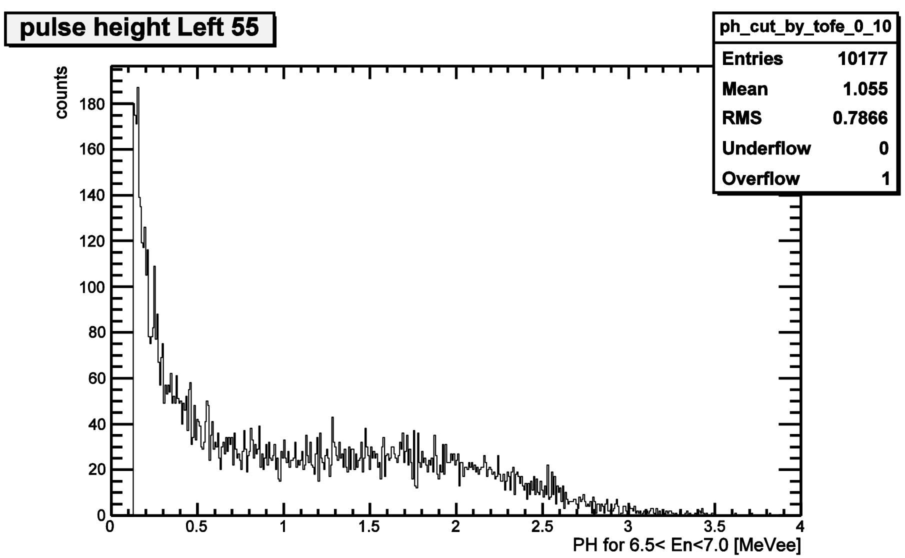
- 252Cf deposited on a circular disk
- Placed inside a low-mass parallel-plate ionization chamber which is used to detect fission fragments
- Neutrons resulting from the spontaneous fission of 252Cf were detected via TOF method using BC501A
- 3m flight path
- Start signals from produced neutrons, fission fragments provided the TDC stop (after suitable delay)
- A scatter plot of the PH spectra vs TOF spectra (with suitable small time gate) will provide PH spectra for ‘mono’ energetic neutrons.
- Hence, the detector response for ‘mono’ energetic neutrons can be mapped out.

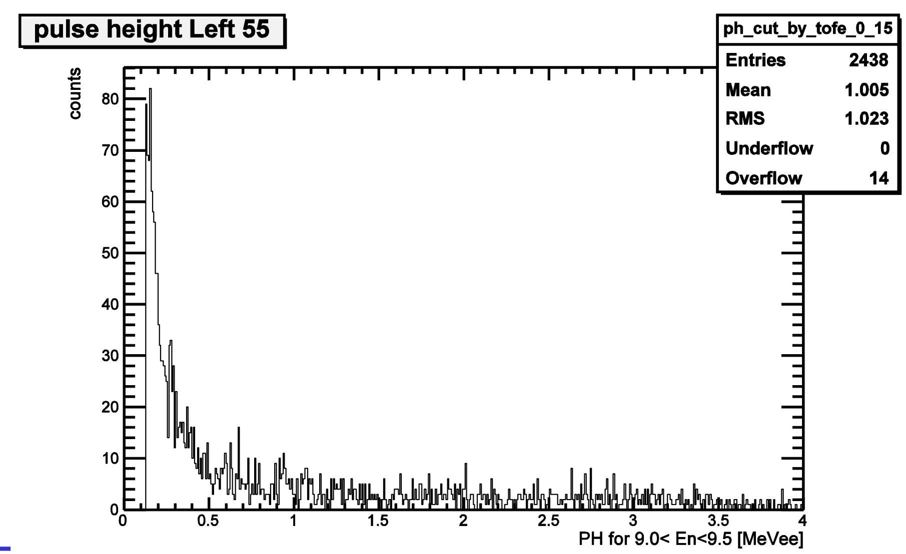


BC501A: Light output response studies at TUNL









Detector response matrix and unfolding

- Detector response, count rates and neutron spectrum are related through Fredholm integral equation

$$N(E) = \int R(E_n, E)\Phi(E_n)dE_n$$

- E is the measured value and E_n is the true neutron energy

- This can be reduced to a discrete matrix form $N_j = \Sigma_i R_{ij} \Phi_j$

- Response matrix-> probability that a neutron with energy E_n will scatter once with a nuclei (hydrogen) and create a recoil proton of energy E_p , which in turn produce a pulse height (corresponding to energy E) in the detection system.

- Each row correspond to a given neutron energy and each column correspond to a given pulse height

- True value extracted depends on the response matrix, so a high degree of accuracy is desired.

Detector response matrix and unfolding

$$N(E) = \int R(E_n, E)\Phi(E_n)dE_n$$

$$N_j = \Sigma_i R_{ij} \Phi_j$$

- **Obtaining the true spectra from measured pulse height distribution is not trivial; because of experimental error, $[R^{-1}][N]$ may have negative values which is nonphysical since Phi represents the number of neutron counts in a given energy range.**

- **Experimental and statistical error in the measurement, error in calculation of response matrix itself, error in PSD process, … is of concern.**

- **These errors produce large oscillations about the true spectrum in the solution vector, and can cause significant deviation of de-convoluted value from the true value of the spectra**

Detector response matrix and unfolding

- Response matrix can be simulated using a Monte Carlo (such as MCNP-PoliMi, SCINFUL, NRESP7, O5S …), extracted from TOF measurements, or a combination of both MC and experiment.

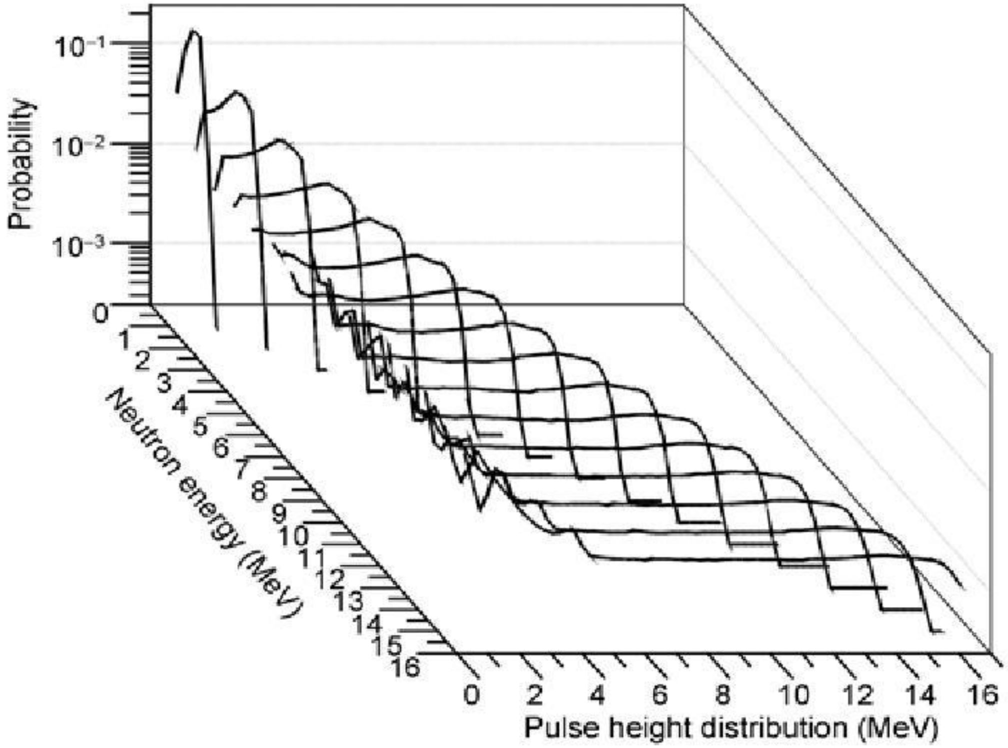


Figure 2 Response functions for the Φ2″×2″ BC501A scintillation detector in energy range of 0.25–16 MeV, generated by O5S.

Yan J et al , Sci China Phys Mech Astron 54, 3 (2011)

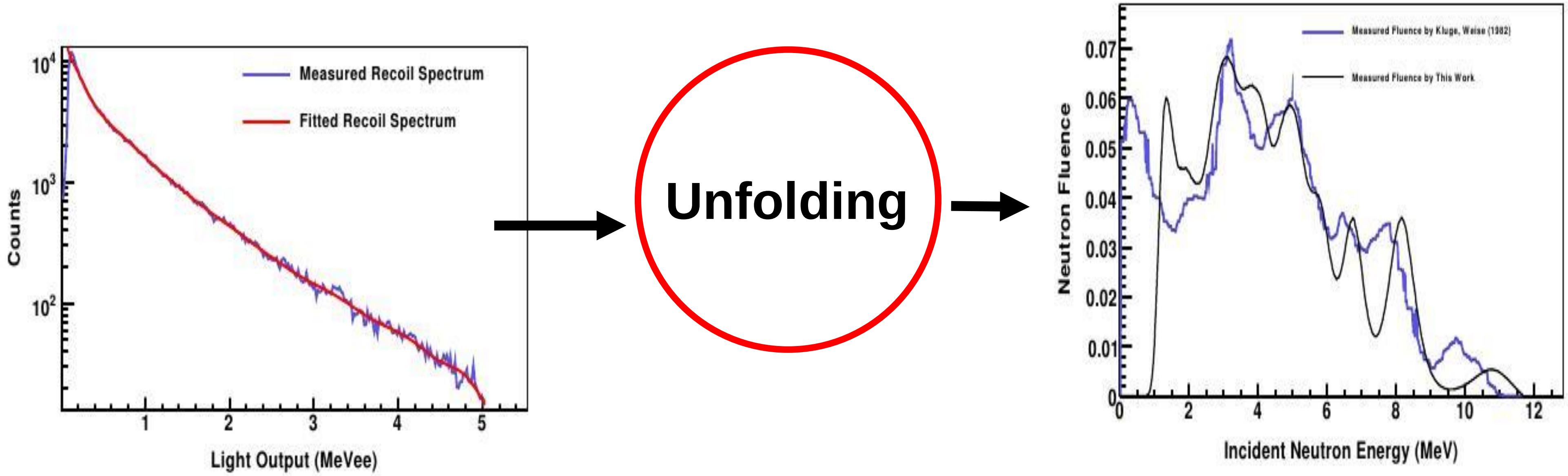
Detector response matrix and unfolding

Koohi-Fayegh, R NIMA 460, 391 (2001)

- **Several unfolding methods/codes are available**
- **Least square method (FORIST, FERDOR, ..)**
- **Bayes theorem/Maximum entropy (HEPROW package, MAXED, ..)**
- **Artificial Neural Network**
- **….**

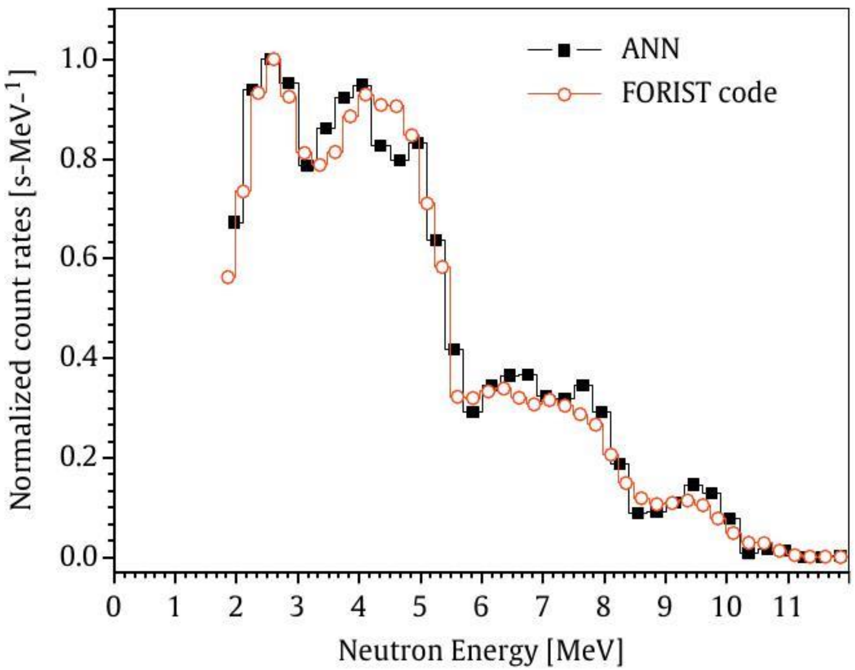
Deconvolution: example AmBe spectra

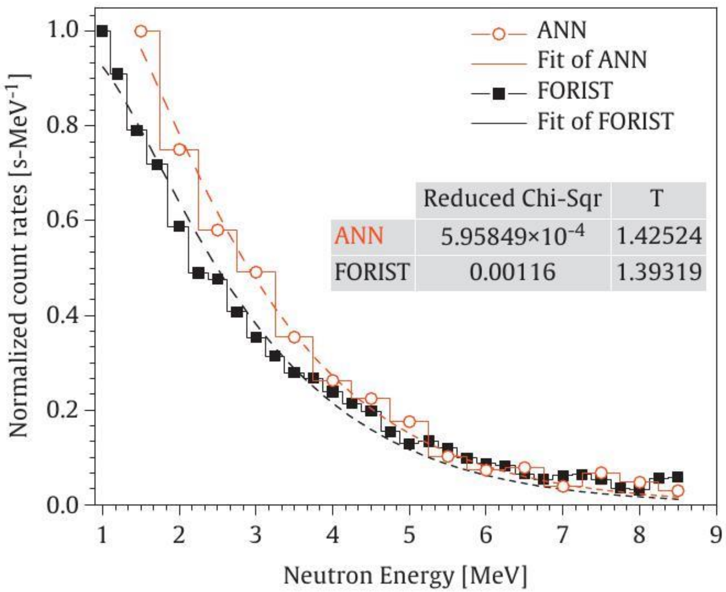
Yildirim, I.O; Thesis, Middle East Technical university



- **May not be the best example, but as the author points out this highlights to the importance of getting the ingredients right.**
- **Energy Calibrations, resolutions**
- **Uncertainties in the data collection.**
- **Here, source and detector at close proximity; results in multiple scattering**
- **Uncertainties in the detector response matrix**

Deconvolution: example AmBe and Cf spectra





	Reduced Chi-Sqr	T
ANN	5.95849×10^{-4}	1.42524
FORIST	0.00116	1.39319

Ido et al.O; Applied radiation and Isotopes, 67, 1912 (2009)

❑ **Reasonable agreement between the two methods, still some differences**
❑**Not clear which code is suitable for our purpose, most of them now distributed through RSICC (costs $$$, restricted for a single user)**

❑**Any reliable in-house unfolding code available???**

Next run: guidance from existing data/simulations

- Develop analysis tools based on existing data from run 2013.

- Pulse shape discrimination using different algorithms

  More data with AmBe source for a better understanding PSD at lower energies?

- Simulations of neutron detector response using GEANT4 (for energy calibrations and detector response functions).

- Develop unfolding procedures, and its systematic studies

- Simulation of neutron emission with existing AlCap simulation code with current geometry (and possible variations of it)
  a) *Determine how many neutrons are coming out of the target per stopped muon from simulations*
  b) *Rates, time estimates for required statistical precision*

Next run: Plans, hardware

- **Borrow BC501A detector (at least two) from TUNL**
- **Map out response of these detectors at TUNL using TOF; they already have this data except for the higher (>10 MeV) energies**

  Use longer runs with Cf source,

  or request for dedicated neutron beam time for detector characterization
- **Borrow a Mesytec MPD-4 from TUNL (pulse shape discriminator) for online monitoring (and perhaps for offline analysis) ?**
- **Need Germanium detector to detect muonic x-rays for normalization.**

Next run: Plans, hardware

- During the run, careful gamma calibration runs at PSI
- More BG runs with detector positioned in the expt area.
- In terms of DAQ, basically repeat what was done during 2013 run; Data acquisition on CAEN digitizers (existing FADCs) by capturing the waveforms

Module	Number of bits	Frequency	Dynamic range	Number of channels
V1724	14	100MHz	2.25Vpp	8
DT5720	12	250MHz	2Vpp	4
FADC	12	170MHz	1Vpp??	8

- If neutron DAQ on FADC, perhaps split into two regions with some overlap region (1 to 5 MeV, 4MeV to 13 MeV?)

Next run: Plans, hardware

- *Do we need scintillators in front of Ndet to veto high energy electrons?*
- *Is it possible to run without target chamber for neutron runs?*
- *Can we run with a thick target, so essentially all the muons are stopped in the target?*

- **Need a big NaI detector if we want to investigate high energy gamma's (3 - 6MeV ??) in coincidence with neutrons if we want to examine GDR excitations**

- **Germanium detector can't be used for above purpose (detects < 1MeV gammas?)**

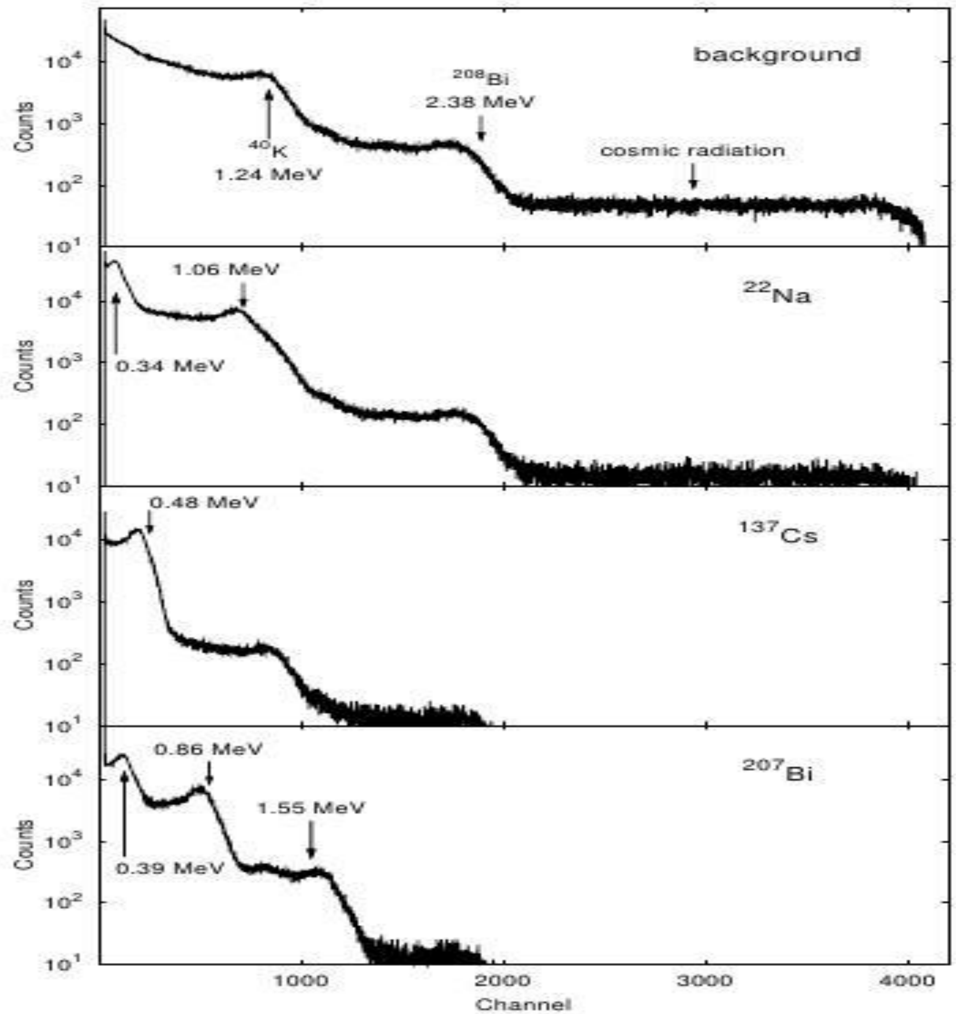
- **UH has a 2"X2" NaI detector, but may not be useful because of the smaller solid angle**

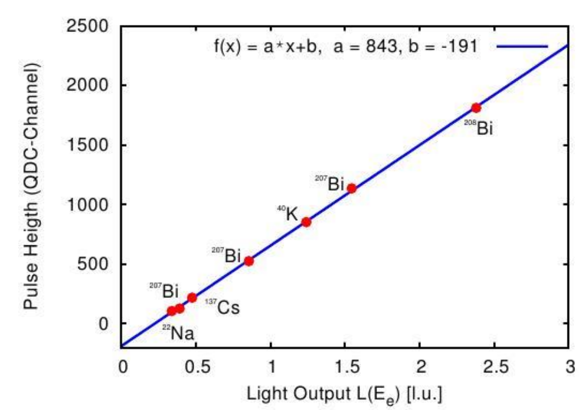
(fractional solid angle for a 2" detector at 50 cm is 0.65mSr and 10" is 16mSr)

Spare

- 5”X2” BC501A detector
- Source at 28.5cm from detector
- ^{137}Cs and ^{207}Bi for only 2 hours
- ^{22}Na for 21 hours, cosmic BG tail visible here

Isotope	$T_{1/2}$ [y]	E_γ [MeV]	Branch [%]	E_C [MeV]
^{40}K	$1.28 \cdot 10^9$	1.460	11.0	1.243
^{208}Bi	$3.68 \cdot 10^5$	2.614	100.0	2.382
^{22}Na	2.60	0.511	179.9	0.341
		1.275	99.9	1.062
^{137}Cs	30.07	0.661	84.6	0.477
^{207}Bi	31.55	0.570	97.7	0.393
		1.064	74.5	0.858
		1.770	6.9	1.547





Heilmann, Thesis, Universitat Darmstadt