Measuring the energy spectrum of neutrons from a ^{252}Cf source using the Time-of-flight technique and a liquid scintillator with pulse shape discrimination property.

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Introduction:

Neutron Spectroscopy is the primary source of experimental data in all the developments of neutron physics as well as contemporary research in nuclear physics by neutron methods. Since the neutron does not have any electric charge so no coulomb barrier opposes its penetration or coming out of nucleus, the measurement of neutron spectra is important in many nuclear reaction studies. Study of shell effects on the nuclear level density in the doubly closed shell nuclei is an example of interest as is the study of the statistical decay of compound nuclei populated in low energy fusion reactions. Also a large area neutron detector array would be of immense help in coincidence measurements using neutrons, e.g. study of fission dynamics and neutron decay following the transfer reaction.

In this project we have studied the different characteristics of a liquid (NE-213 equivalent) and plastic scintillator (equivalent to Bicron BC-408) and have extracted the neutron energy spectra through Time Of Flight (TOF) technique. Each bar of detector has a dimension of (6cm x 6cm x 100cm) and is coupled to two 5cm diameter XP2020 PMT's, one each at either end. The fast response and relatively low cost of plastic scintillators makes them a suitable candidate for large neutron measurement detector system using the TOF technique. The liquid scintillator on other hand is particularly useful for the neutron spectroscopy because of the good pulse shape discrimination (liquid nature helps the delayed fluorescence) and low average value of Z. It is mainly useful in studying spectrum of high energy neutrons(5~10 MeV) induced in heavy ion reactions. Some of characteristics of the two detectors are compared in Table-1.

Scintillator Type	*Light Output (compared to anthracene)*	*Decay Time (ns)*	*Optical Index*
Plastic	65%	~ 4	1.58
Liquid	78%	~ 3.16/32.3/270	1.50

Table-1: *Comparison of detector characteristics.*

The different aspects investigated in this project are the energy response, time response and energy for both the detectors and the pulse shape discrimination for n-γ separation in liquid scintillator.

Time of Flight Technique :

The energy of neutrons is directly related to its velocity. Since we are interested in constructing the energy spectrum of neutrons with non-relativistic speed, the time of flight (T) of a neutron on a well known distance(D) will relate to the kinetic energy in a trivial way i.e. $\frac{1}{2}mv^2 = \frac{1}{2}m\,(\frac{D}{T})^2$. Also since the neutron release in fission of ^{252}Cf is accompanied by simultaneous gamma ray emission we can demand coincidence between gamma in another scintillator detector kept close to source and the plastic (liquid) scintillator to identify the true events. To measure the time of flight of neutrons accurately the distance between the source and the detector should be large enough so that the difference between the flight time is quite large for the neutrons compared to gammas. The schematics of the method is shown in Fig-1.

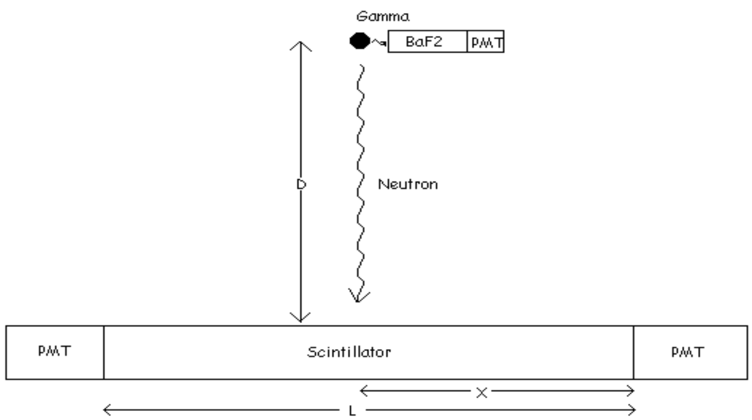

Fig-1: *Basic Schematic of the set up*

The time recorded at any one end of the detector which is at a distance x from the point of interaction will be given by $T = (D/v) + (x/c) + \delta$, neglecting the time of flight of gamma from source to BaF_2 detector. Now we can define two pseudo parameters

$$T_l - T_r = \left(-\frac{2x}{c}\right) + \left(f * \frac{L}{c}\right) + \delta - \delta'$$

And,

$$T_l + T_r = \left(\frac{2D}{v}\right) + \left(f * \frac{L}{c}\right) + \delta + \delta'$$

Where, δ and δ' are the electronic processing time and f is the mean number of reflections in the detector. From the above equations its clear that if we get rid of last three constant terms we will get the position and energy of the neutrons respectively. We can make use of a standard gamma ray source of known energy to do the position calibration. For this a collimated gamma source is kept close to the detector and $T_l - T_r$ is recorded for source at different positions of the detector bar.

Now $(T_l + T_r)/2$ is defined as the mean time of flight for an event. For the Cf-232 source then can be several coincidence events:

- gamma-gamma
- gamma-neutron
- neutron-gamma
- neutron-neutron

However in time of flight spectra the neutron-gamma and neutron-neutron events are completely or partially submerged under the gamma-gamma coincidence peak. From the $(T_l + T_r)/2$ recorded spectrum we can extract the mean time of flight of gamma (T_γ) and mean time of flight of neutron (T_n).

Then,

$$T_\gamma = \left(\frac{D}{c}\right) + (f * \frac{L}{c} + \delta + \delta')/2$$

$$T_n = \left(\frac{D}{v}\right) + (f * \frac{L}{c} + \delta + \delta')/2$$

From the above equation we can evaluate v and arrive at the energy equation for the neutrons as by getting rid of the constant terms.

$$E = \frac{1}{2}mv^2 = \frac{1}{2} * 939.5 * \left(\frac{D}{T * c}\right) \quad MeV$$

Where $T = D/v$ and m is the mass of the neutron. To convert the TOF spectra to energy spectra we have to multiply the number of events in TOF spectra with appropriate Jacobian factor $\frac{dT}{dE}$ also.

^{252}Cf source [1]:

Cf-252 decays by alpha particle emission (97%) and spontaneous fission (3%), yielding an average of 3.75 fast neutrons per fission. The half life for alpha particle decay is 2.73 years. The half life of fission process is 85.5 years which allows produce high specific activity of neutron source. The effective half life of the source is then 2.65 years. The source produces 2.3 x10^9 neutron/sec per mg, and has a specific activity of about 20Gbq/m. The neutron yield is thus 0.116 neutron/sec per Bq. The energy spectrum of ^{252}Cf source, being a fission spectrum, is well characterized and can be described by Maxwellian distribution as

$$N(E) = \sqrt{E} exp\left[-\frac{E}{T}\right]$$

where $N(E)$ is the number of neutrons emitted at energy E, per unit energy interval, and T is a calibration constant estimated to be between 1.3 MeV and 1.424 MeV, giving an average energy between 2.316 and 2.348 MeV. The difference in these values is likely due to the method of measuring the neutron spectrum and of fitting of data.

Pulse Shape Discrimination :

In the liquid scintillator most of the light is emitted with a time constant of a few ns, the remained more slowly. This phenomena is called “delayed fluorescence”**[2]** and the division between fast light and slow light depends upon the ionization density of the exciting particles. More of the fast fluorescence is produced by lightly ionizing particles like electrons from Compton scattered gamma rays or relativistic cosmic ray muons compared to the highly ionizing protons scattered by neutrons or the alpha particles in the liquid scintillator. Hence, the shape of the pulse is different for the two categories of radiation and pulse shape discrimination of the related photomultiplier signal is used to identify the neutrons. The PSD used in this project is MPD-4 (four channel pulse shape discriminator module: Mesytec made).**[3]**

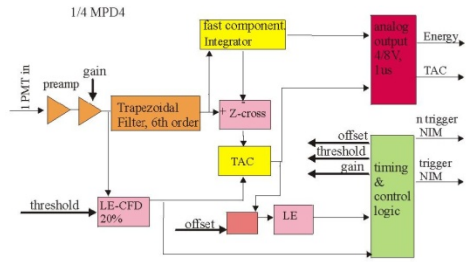

Fig-2: *Mesytec MPD-4 schematics(figure taken from MPD-4 manual)*

It provides energy independent resolution, wide dynamic range and also fast neutron-gamma discrimination performance. The detector signal is first passed through a pre-amplifier and gain stage before being split into two branches. One goes to high order trapezoidal filter to reduce noise. The filter preserves the rise and decay time of the signal. The other is connected into a constant fraction discriminator (CFD), which triggers on the leading edge of the signal and provides the "Start" signal to the Time to Amplitude (TAC) convertor of PSD. The fast component of the signal is integrated and subtracted from the shaped signal. The zero crossing point of the resulting signal is used to provide the "Stop". This method results in a pulse height independent timing of the "Stop" signals. As the TAC output is proportional to the length of the trailing edge of the detector signal, it's a measure for the particle type.

Experimental Setup :

a) For Plastic Scintillator:

The scheme of the experimental setup for the plastic scintillator is shown below with all the units used.

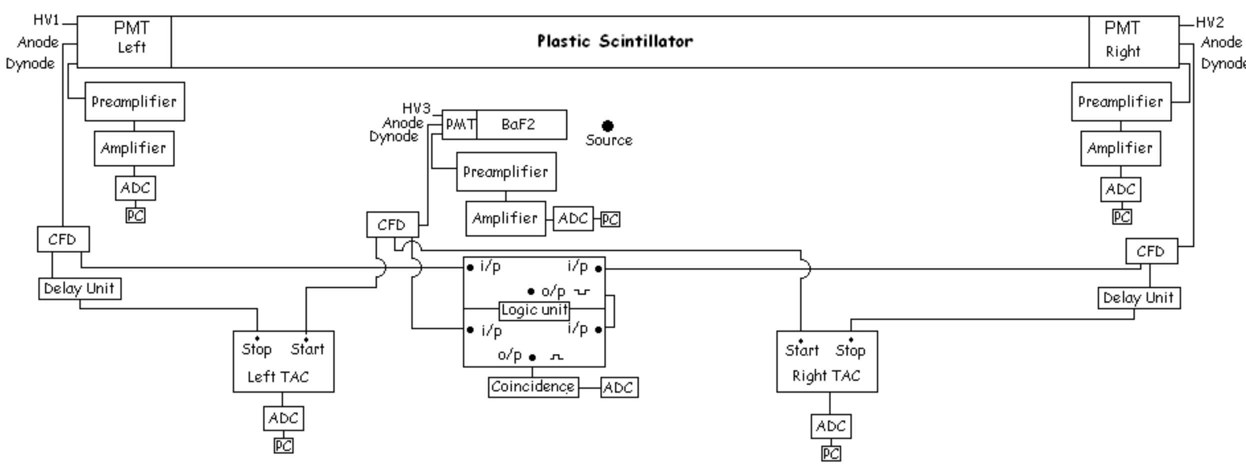

Fig-3: *Scheme of circuit for Plastic Scintillator.*

The CAMAC based acquisition system was used to record and the analyze the events.

The parameter settings for the set up are :

High Voltage**:** The left and right voltages were so chosen such that the pulse height for a source is equal for equal distances from the detector ends.

PMT Base	***High Voltage Value (Volts)***
BaF_2	2000
Left	1804
Right	1902

Amplifier Settings**:** Amplifier gains were set corresponding to full scale of 10 MeV.

	BaF_2	Left	Right
Coarse Gain	100	1000	1000
Fine Gain	10	5	5
Shaping time (μsec)	3	1	1

Constant Fraction Discriminator**:** Threshold were set just above the noise level.

Parameters	***BaF_2***	***Left***	***Right***
Threshold	-0.694V	-0.076V	-0.054V
Zero crossover	-2.8mV	-5.7mV	-2.3mV

TAC : Time range 200 ns for each of them. The TAC's are calibrated using a high precision calibrator.

The parameters recorded on LAMPS are:

i. Time of flight measured by the both PMT's ($T_l and\ T_r$).
ii. Energy seen by left and right PMT's ($E_l and\ E_r$) and Energy seen by BaF_2 detector.

The user defined pseudo parameters derived on LAMPS were:

i. Mean time of flight $(T_l + T_r)/2$.
ii. $T_l - T_r$ (position).
iii. Geometric mean of left and right energy.

Experimental Procedure :

1. The energy response of the detector for well known gamma rays is measured. Since the energy calibration is needed over a long range of energy the detectors are calibrated using ^{137}Cs (661 keV), ^{60}Co (1173keV and 1332 keV) and 4.4 MeV gamma peak from Am/Be source. The geometry was set as below to measure the Compton scattered gamma ray peak at both the ends for energy calibration.

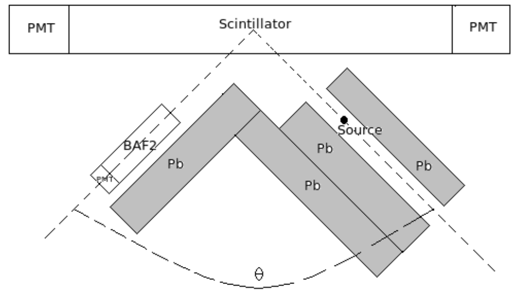

Fig-4: *Compton Backscattering Set up.*

Due to large light attenuation factor in the detector the energy falls off exponentially as a function of position. To make energy deposited in the detector roughly independent of the light attenuation factor it is calculated from the geometric mean of E_l and E_r.

$$E_{GM} = \sqrt{E_l} \times \sqrt{E_r}$$

The plot below for resolution vs. position for ^{137}Cs shows the approximate energy linearity of the geometric mean energy as a function of position.

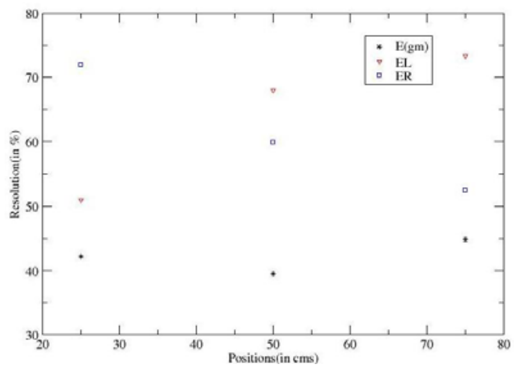

Fig-4: *Resolution as function of position for ^{137}Cs*

2. The calibration of $T_l - T_r$ as a function of position (x) using a ^{60}Co source. This is needed to define a position cut for the detector to gate the TOF spectra.

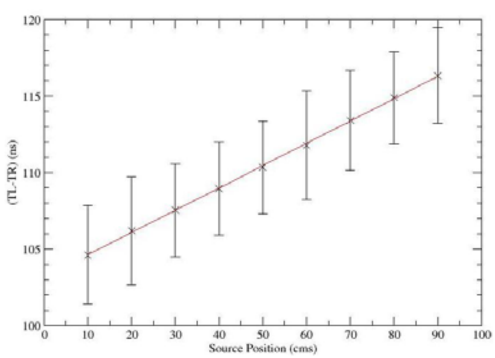

Fig-4: (T_l-T_r) *as a function of position.*

3. The ^{252}Cf source is kept at a distance of 100±2.5 cm from the centre of the scintillator bar and data is taken for 132 hrs. The TOF spectra in coincidence with BaF_2 and gated for the centre 20cms of the bar is shown below.

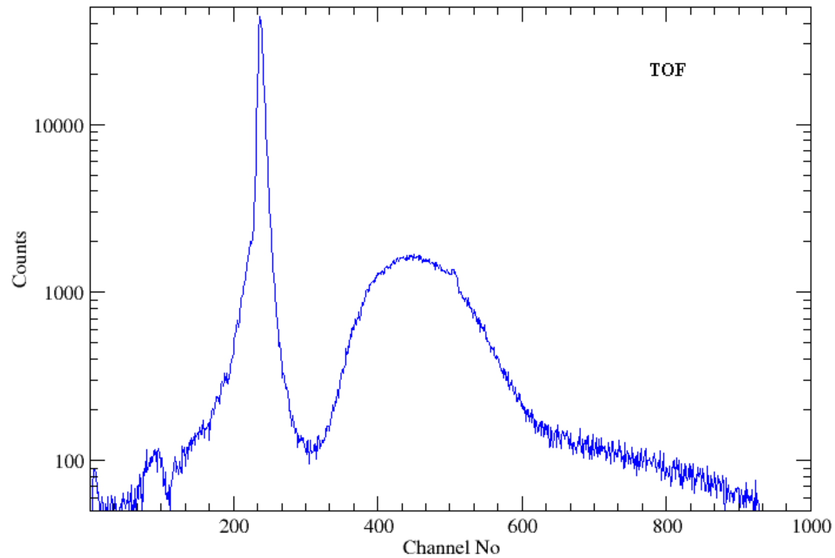

Fig-5: TOF Spectra

The above spectra is converted into energy spectra as described in TOF technique earlier and is rebinned with 0.5MeV/channel. The data points are efficiency corrected using monte carlo simulations [c.f 4]. The final spectra with fitted parameter is shown below. The T parameter obtained by fitting is T = 1.030±0.022 .

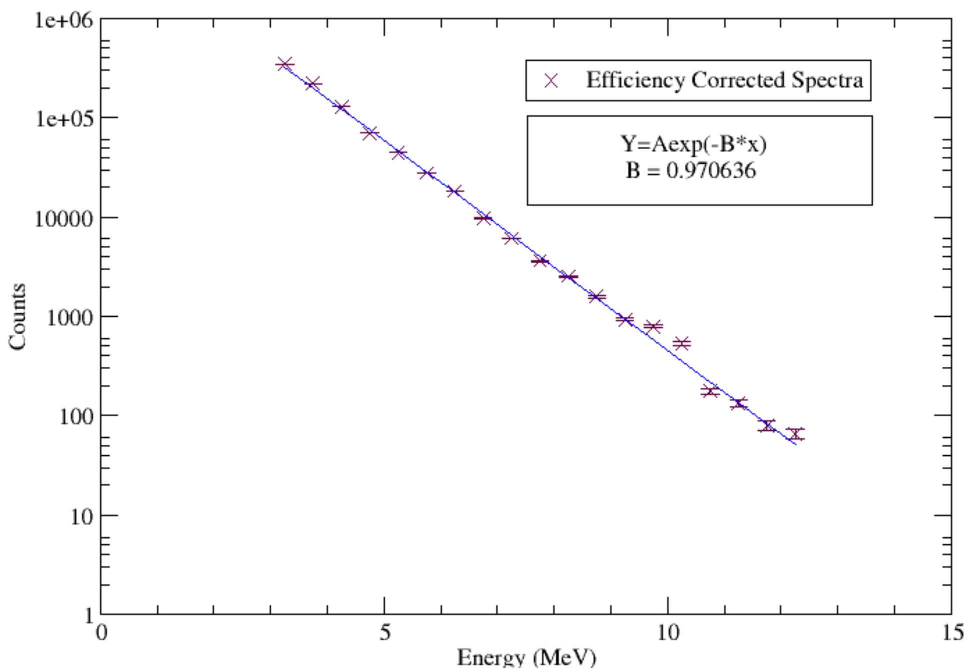

Fig-6: Efficiency corrected Neutron Spectra for Plastic Scintillator.

b) ***For Liquid Scintillator***

The schematics for the liquid scintillator using PSD is shown in **Fig-7.**

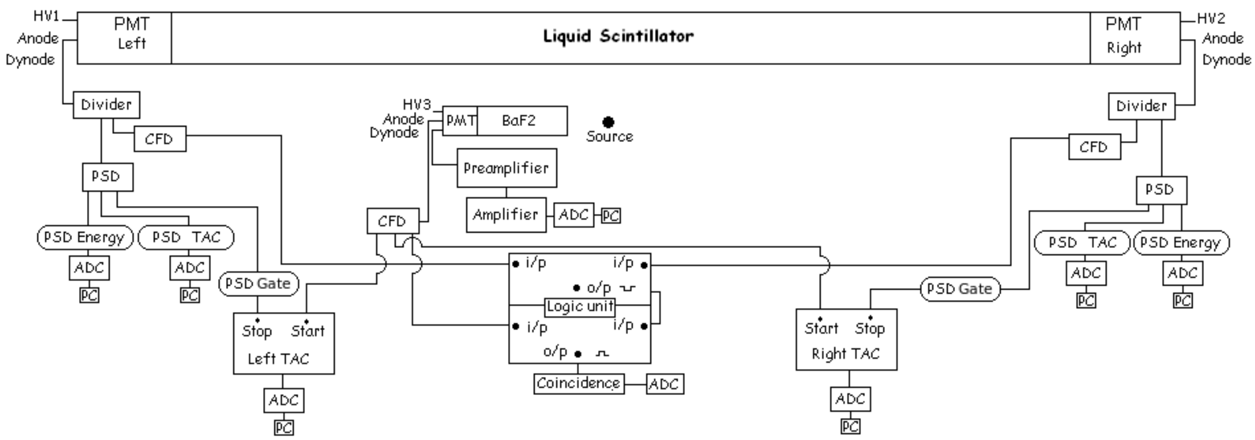

Fig-7: *Scheme of circuit for Liquid Scintillator.*

The working of PSD has already been described.

The parameter settings for liquid set up are :

High Voltage**:** The left and right voltages were so chosen such that the pulse height for a source is equal for equal distances from the detector ends.

PMT Base	***High Voltage Value (Volts)***
BaF_2	2000
Left	1450
Right	1351

Amplifier Settings**:** Amplifier gains were set corresponding to full scale of 10 MeV.

	BaF_2	Left	Right
Coarse Gain	20	200	200
Fine Gain	9	3	3
Shaping time (µsec)	1	1	1

Constant Fraction Discriminator**:** Threshold were set just above the noise level.

Parameters	***BaF_2***	***Left***	***Right***
Threshold	-0.865V	-0.959V	-0.57V
Zero crossover	-2.7mV	-5.6mV	-2.3mV

TAC : Time range 500 ns set for each of them. The TAC's are calibrated using a high precision calibrator.

PSD Settings**:** Threshold were set just above the noise level.

	Left	**Right**
Threshold(mV)	30	30
nDis (V)	1.672	1.554
Gain (V)	0.893	1.021

The ^{252}Cf source is kept at a distance of 100±2.5 cm from the centre of the scintillator bar and data is taken for 84 hrs .

A typical PSD TAC vs PSD Energy 2D plot for ^{252}Cf is shown.

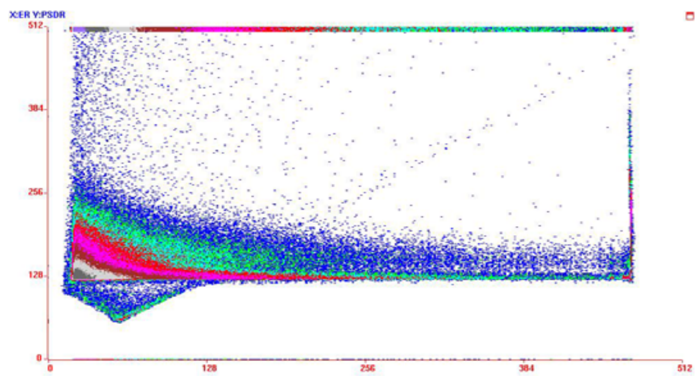

Fig-8: *PSD TAC vs PSD Energy*

Though in the 2D diagram the neutron and gamma are not very clearly separated because of drift in PSD, by taking TAC projections from the above plot at different energies it is seen that the PSD resolve between the neutron and gamma as the energy increases.

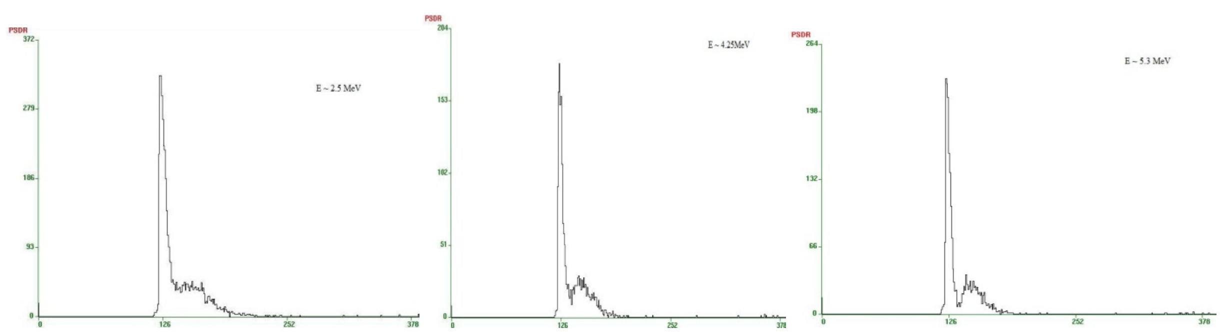

Fig-9: *PSD TAC projection at a) E~2.5 MeV b) E~4.25 MeV c) E~5.3 MeV*

The neutron spectra obtained from the PSD is shown in Fig-9. The T parameter obtained in this case is T=1.027±0.031.

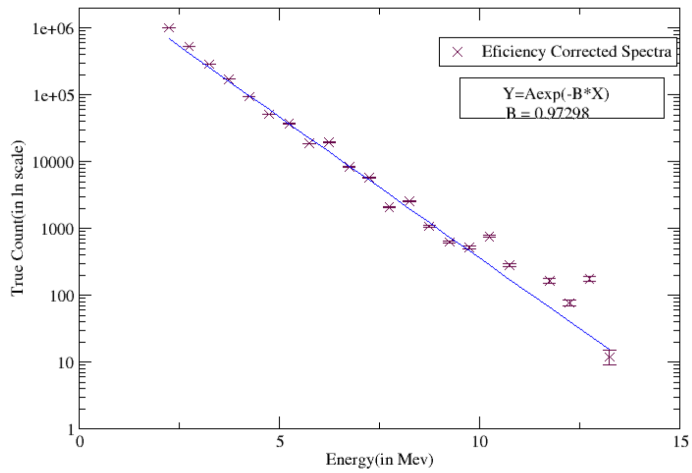

Fig-6: Efficiency corrected Neutron Spectra for liquid scintillator.

References:

[1]Handbook on radiation Probing, Gauging Imaging and Analysis by Hussein.

[2]David Denneteire , Report Submitted to Dept. Of Nuclear Sciences.

[3] A New Four Channel Pulse Shape Discriminator ,Andreas Ruben et al, 2007 IEEE Nuclear Science Symposium Conference Record.

[4] Prakash et al, A large area plastic Scintillator detector array for fast neutron measurements, Submitted to BUcl. Instr. and Meth. In Phys. Res. A.