Investigation of fast neutron spectra in the uranium assembly of the experimental set-up "Energy plus transmutation" in the JINR NUCLOTRON proton beam at an energy of 1.5 GeV

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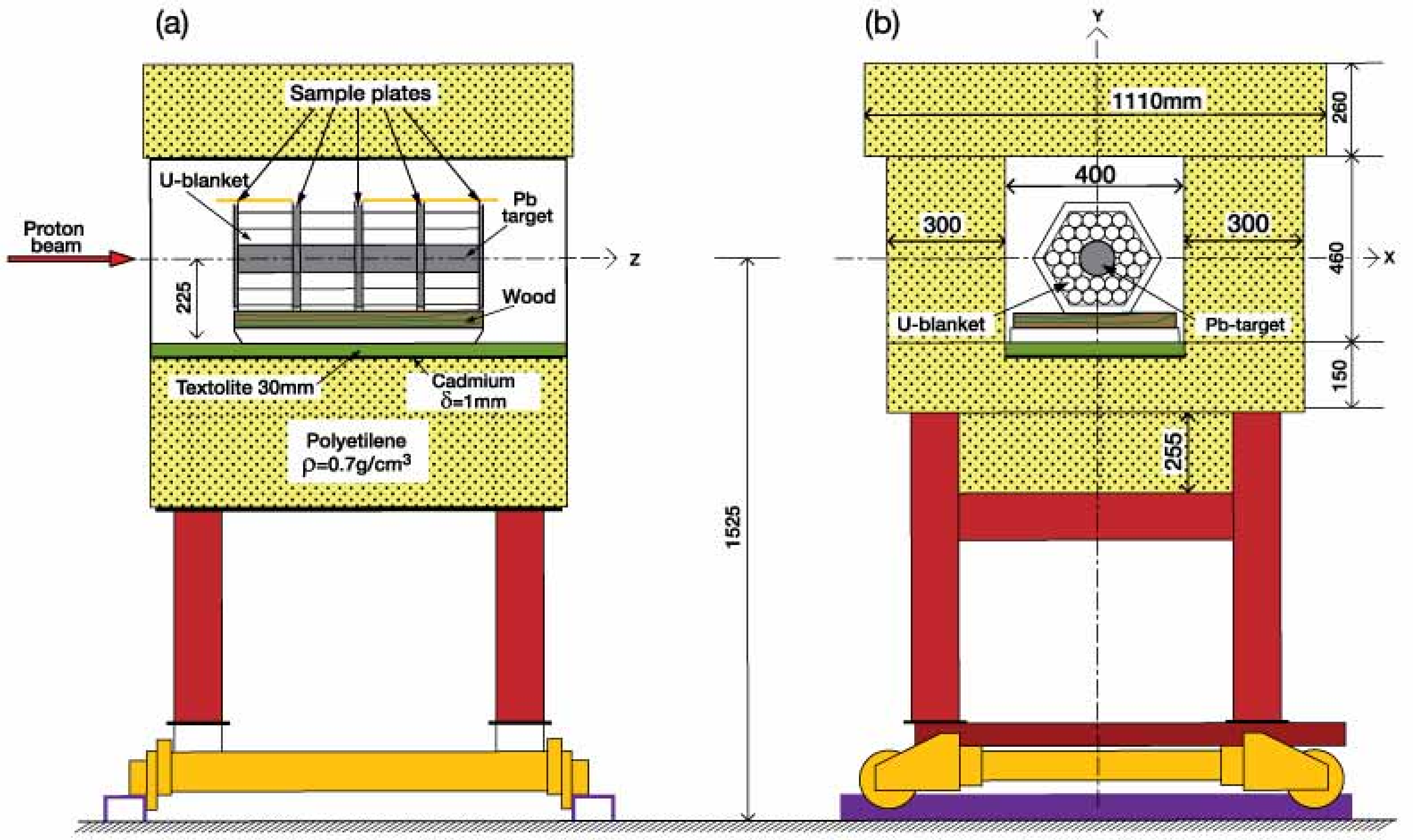
Experimental setup

Energy plus Transmutation (EPT) assembly



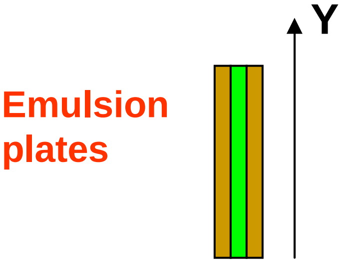
Nuclear Emulsion Chambers and Irradiation

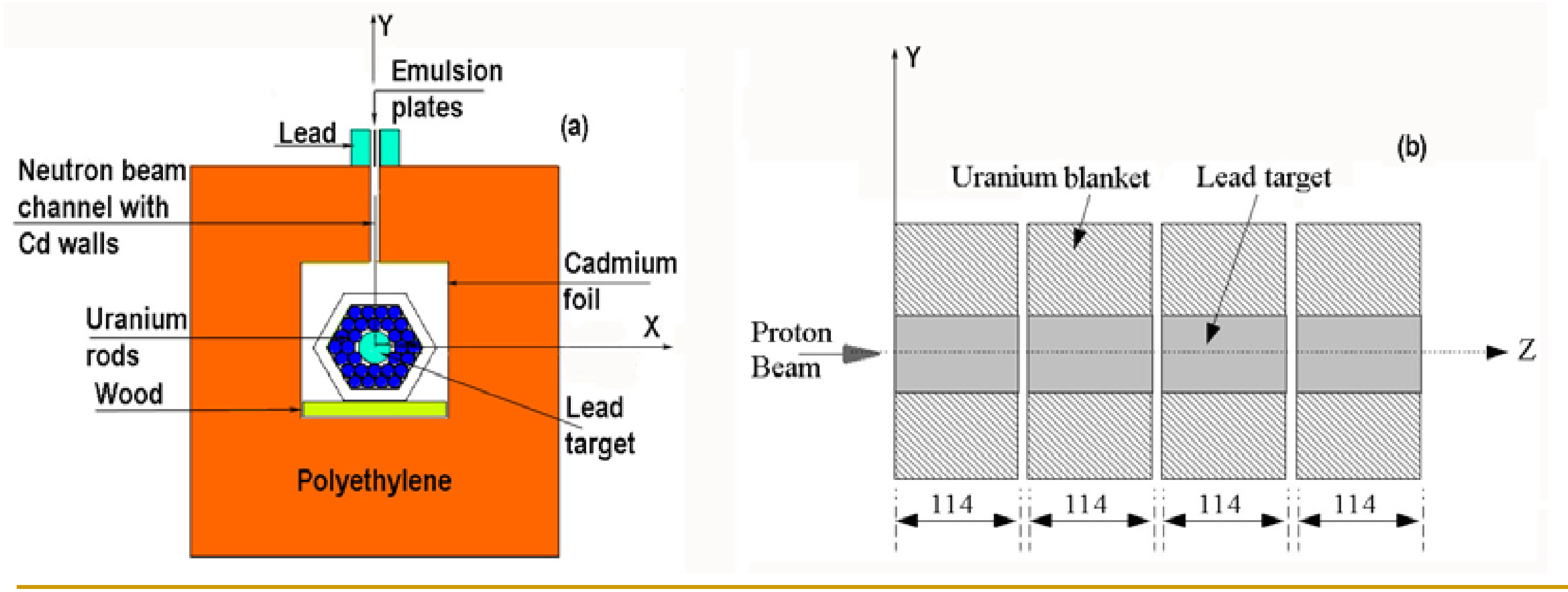
The setup was irradiated with protons of energy 1.5 GeV from the Nuclotron Accelerator.

Emulsion chambers were exposed to neutrons from the setup for a period of 0.9 s.

Total number of protons on the target was 1.5×10^{10}.

The Emulsion chambers were composed of 3 plates of 0.6 x 25 x 100 mm in contact with each other



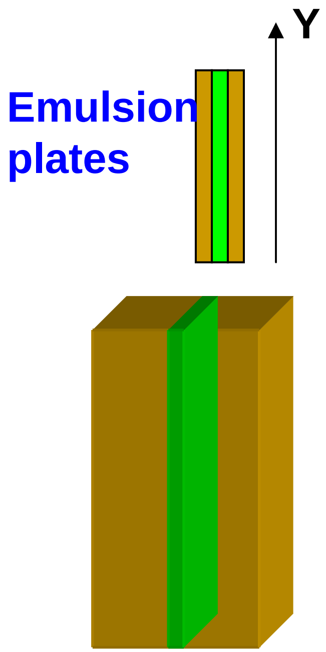


After exposure emulsions were developed and fixed in usual manner.

For more than 5000 recoil proton tracks the track length and angle with respect to Y-axis were measured.

Only tracks in the middle emulsion plate and within a volume restricted to the emulsion thickness and within a width of 1 mm at its center along its length were measured.

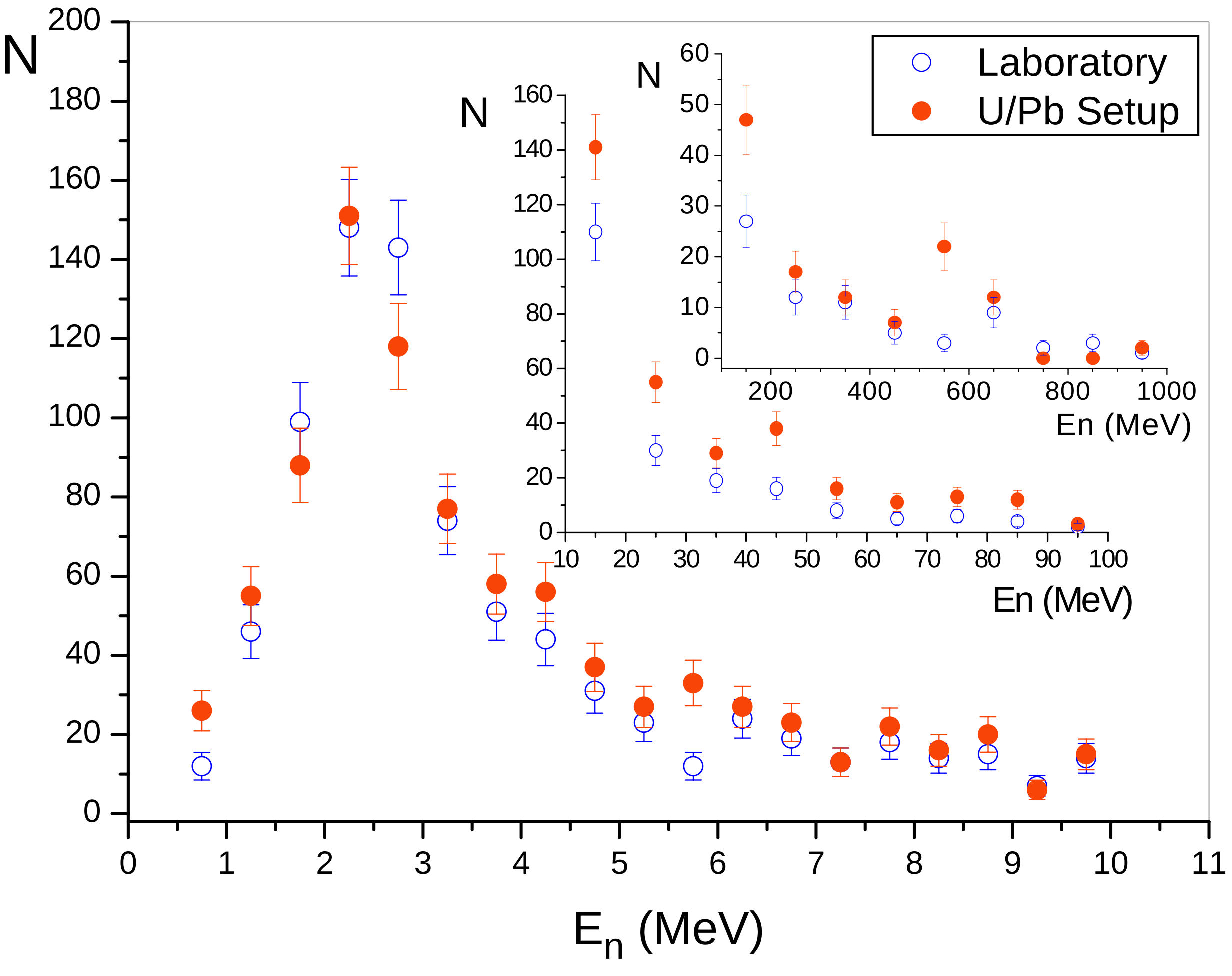
This method filters large number of the neutrons that their direction is not parallel to Y-axis.



From the track lengths the recoil proton energies were calculated.

Background neutron measurements

Two emulsion chambers were exposed to the back ground neutrons of irradiation hall and the EPT setup. Both in absence of the proton beam for a period of 150 times the when beam was on.



Red points outside the assembly

Blue points inside the assembly

Monte Carlo Simulations (a brief description)

- Main Monte Carlo simulations were performed using the MCNPX code.

- The EPT setup and the emulsion chambers were built in the code and the setup was “irradiated” with 1.5 GeV protons along the target axis. In this series of calculations the following steps were taken-

  - We used the PTRAC card in the MCNPX input file to obtain the neutron collisions with the nuclei within the emulsion. For the composition of the emulsion we used that of the Ilford G-5, with a density of 3.907 g.cm-3.

  - SSW card was used to record the neutrons that enter the emulsion volume from its different surfaces.

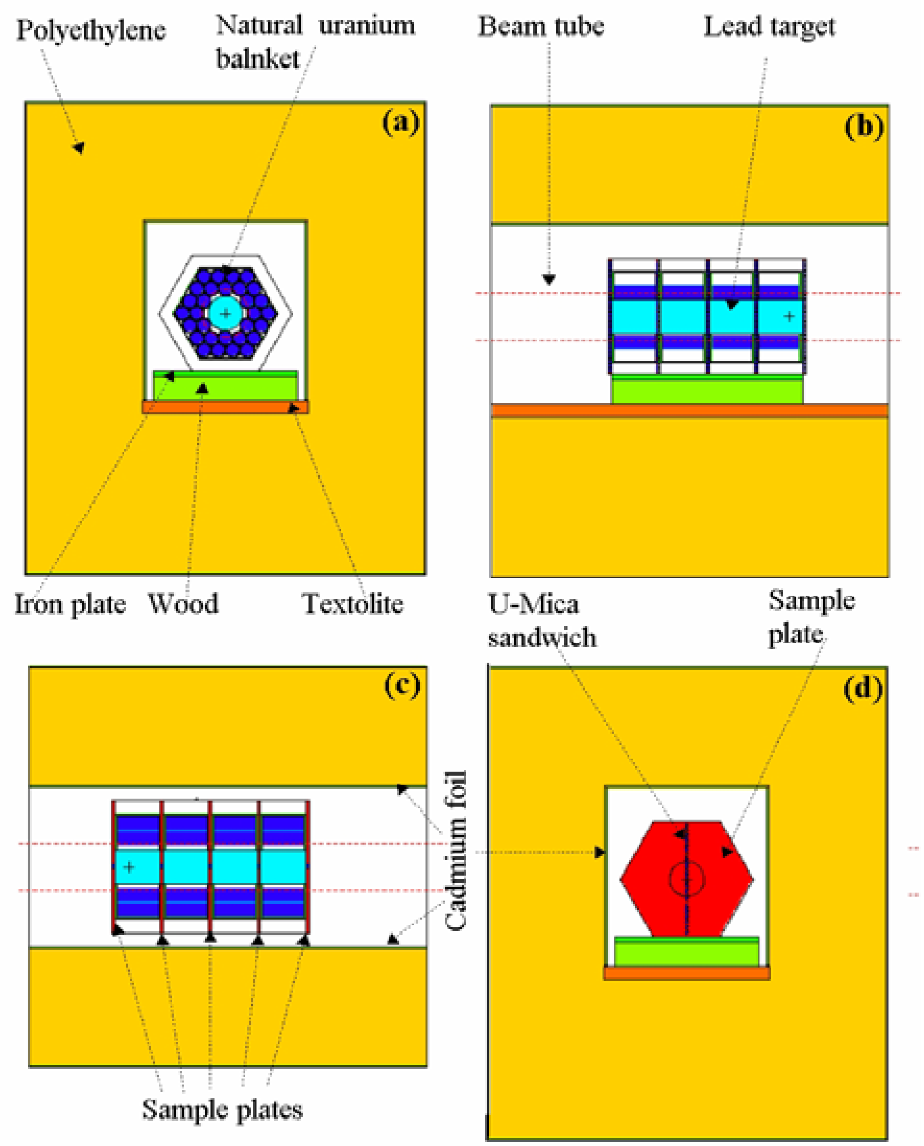
- Extra codes were written to analyze the PTRAC and WSSA output files.

- A code was written which uses the PTRAC as an input and produces the recoil events and transports recoil nuclei in the emulsion.

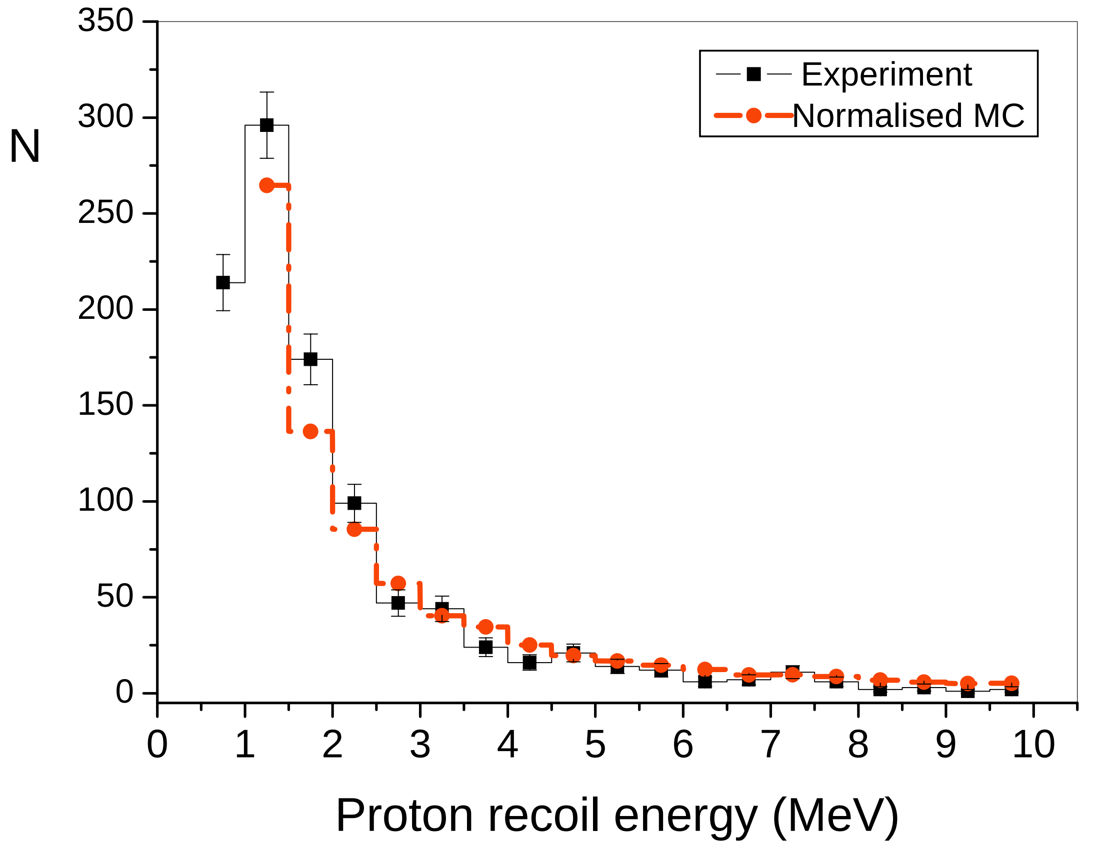
  - In this program it was assumed that the neutron scattering in the centre of mass coordinate system is isotropic.

  - The scattering angles, direction cosines and the recoil nuclei energies were calculated in the laboratory system.

EPT setup as seen by MC- code

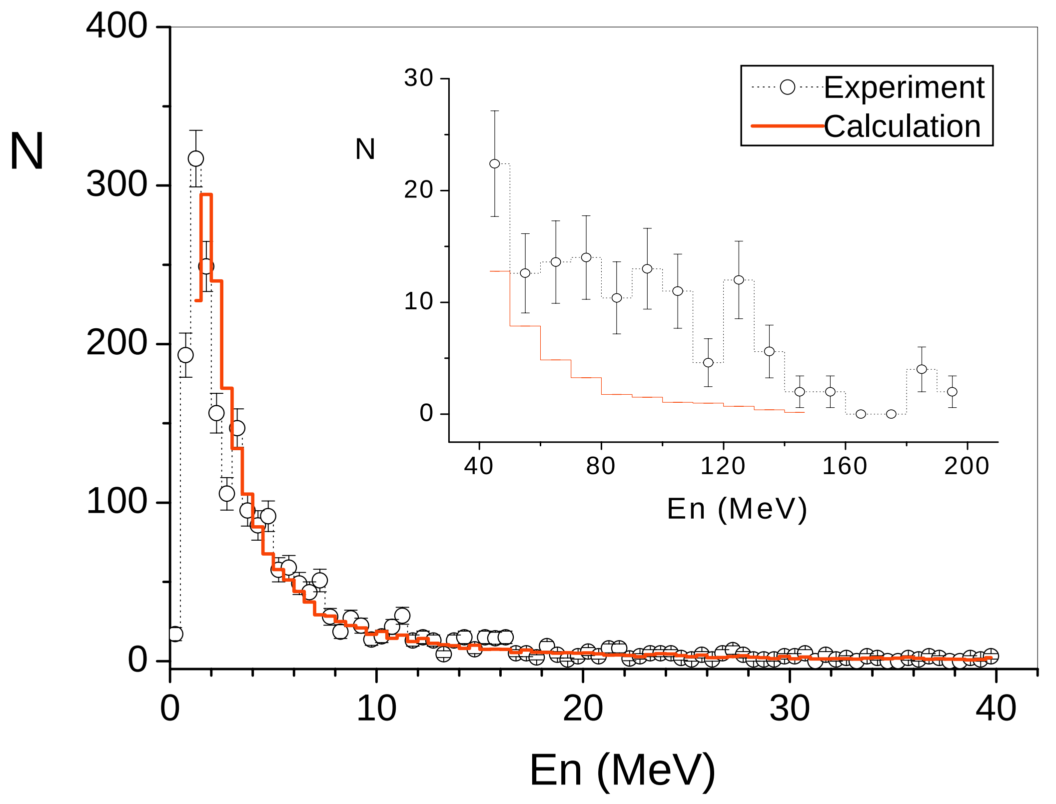


Proton recoil spectrum



MC results agree with the experiment within 1-2 σ.

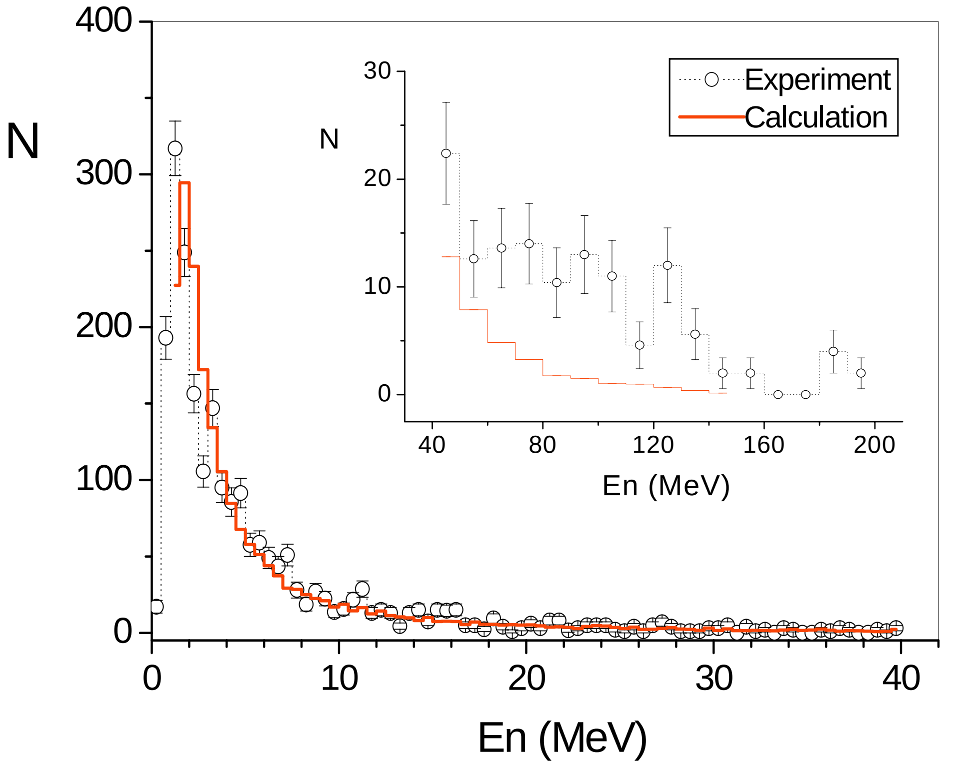
Neutron spectrum



In the calculations only neutrons that their direction is parallel to Y-axis are taken into account.

Experimental and calculated spectra of the neutrons that have resulted in proton recoils in the emulsion. The width of the energy bins at neutron energies of $E_n \leq 40$ MeV and $40 < E_n \leq 200$ MeV are $\Delta E_n = 0.5$ MeV and $\Delta E_n = 10$ MeV respectively.

Neutron spectrum (continued)



From the figure it is evident that

1) At neutron energies of $E_n \leq$ 40 MeV the experimental and calculated spectra of the colliding neutrons are in agreement within one standard deviation for E_n > 3 MeV.

2) However at neutron energies of E_n < 3 MeV the experimental and the calculated spectra are not in agreement.

3) At E_n > 40 MeV large discrepancies exist between the calculated and experimental spectra.

In spite of the observed discrepancies, the weighted mean neutron energies from the measured and calculated spectra are in agreement.

Weighted mean energy of the neutron spectra for different energy intervals

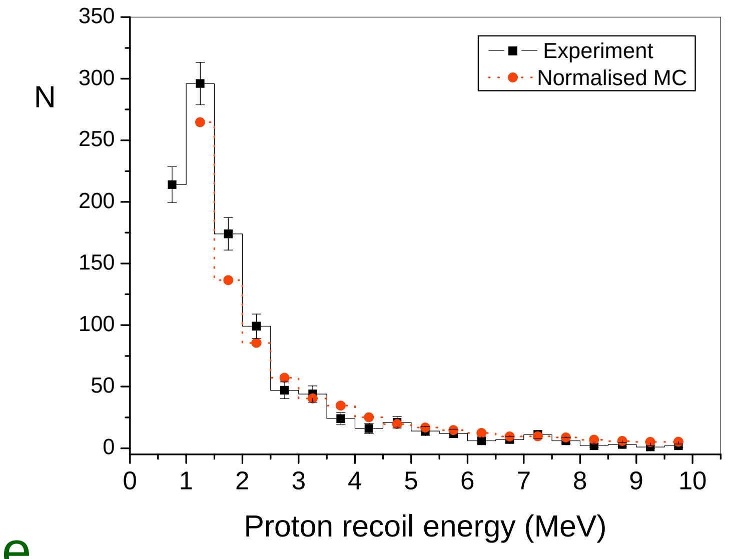
Neutron energy interval	Weighted mean energy (MeV)	
	Experiment	Calculation
1 – 20 MeV	4.7 ± 0.5	4.5 MeV
1 – 40 MeV	6.0 ± 0.5	5.7

Origins of the observed discrepancies

The observed agreement between the experiment and calculation in the case of the recoil proton spectrum as shown in the following figure, indicate that

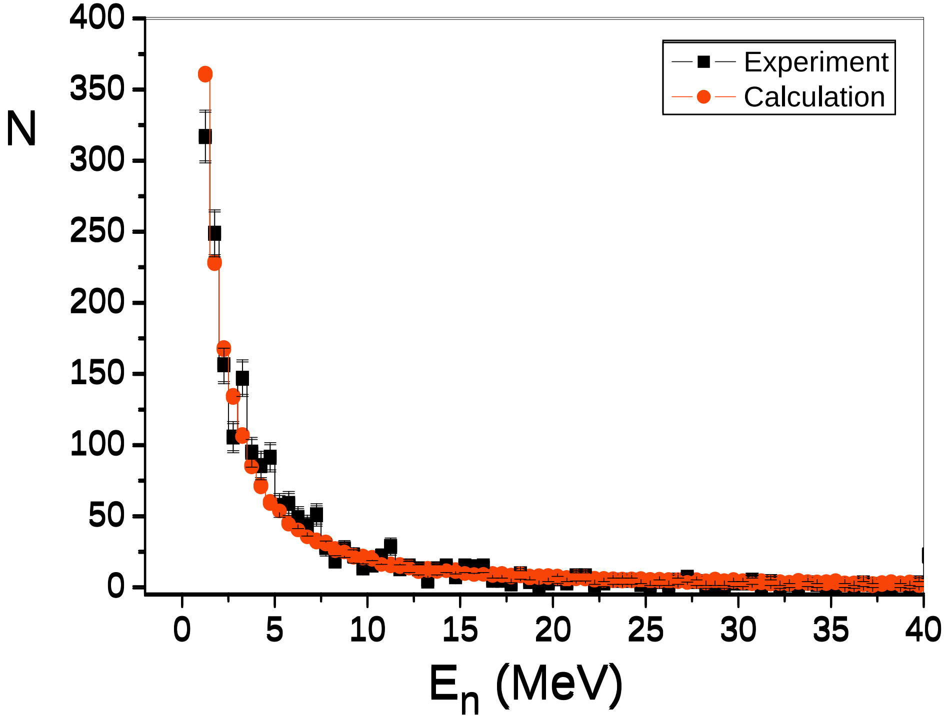
The error must have been due to the measurement related to the recoil angle θ.

$$E_p = E_n \cos^2 \theta$$



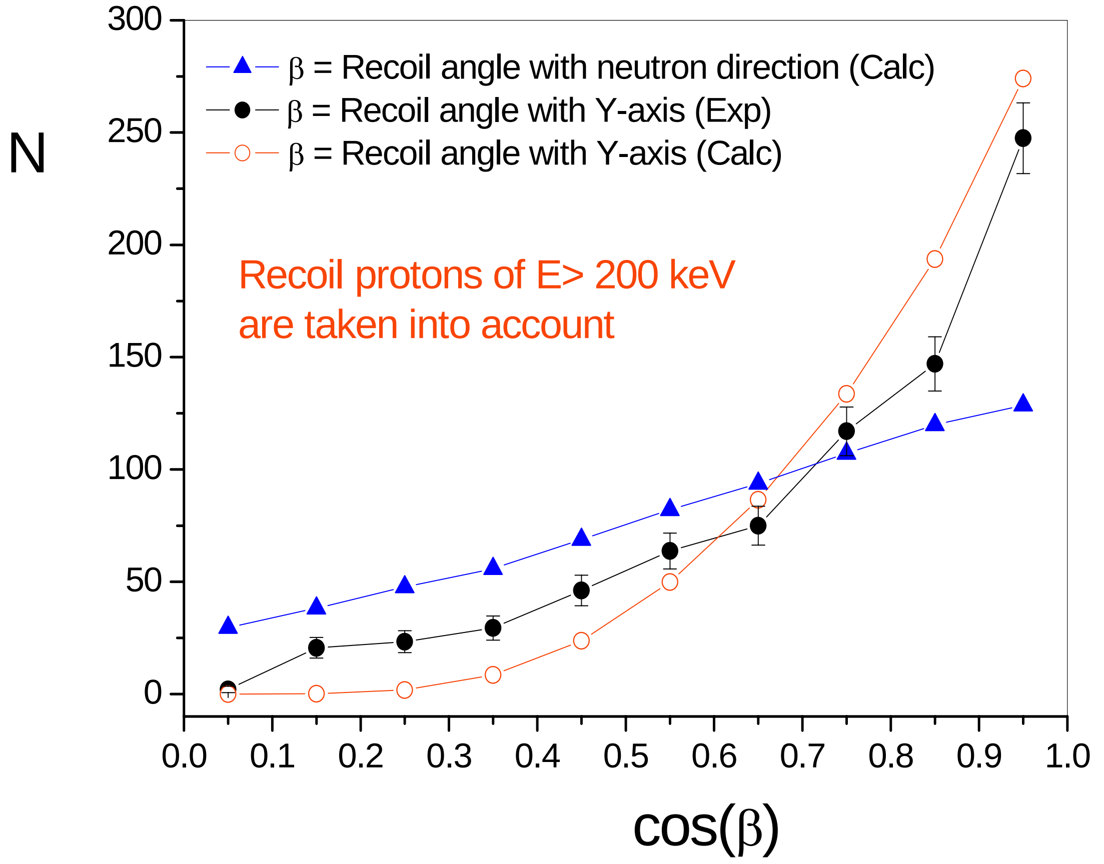
In other words some of the measured angles (with respect to Y-axis) were not the true recoil angles of the recoil protons with respect to the neutron direction.

To examine this following calculations were carried out.



The experimental and calculated energy spectra, obtained with the assumption that all neutrons involved in the proton recoil production have a direction parallel to the Y-axis (i.e. same as the experiment measurements)

A perfect agreement (within one standard deviation) between the calculated and experimental data is obtained for neutrons of energy E_n > 1 MeV.



The calculated and experimental distributions of the recoil protons space angles with respect to Y-axis and the calculated distribution of the recoil protons space angle with respect to the direction of the incident neutrons.

Conclusions

The complete agreement between the calculations and experiment the when the exact conditions of the experiment was used in MC-calculation, implies that

If properly collimated neutron beam is used or much better stray neutron filters is employed a perfect agreement between the experimental and calculated high-energy neutron spectra is expected.