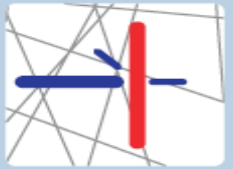
Nuclear Physics Institute of the ASCR
public research institution

Center of Accelerators
and Nuclear Analytical Methods
(CANAM)

Neutron production from the $^{7}Li(p,n)^{7}Be$ reaction

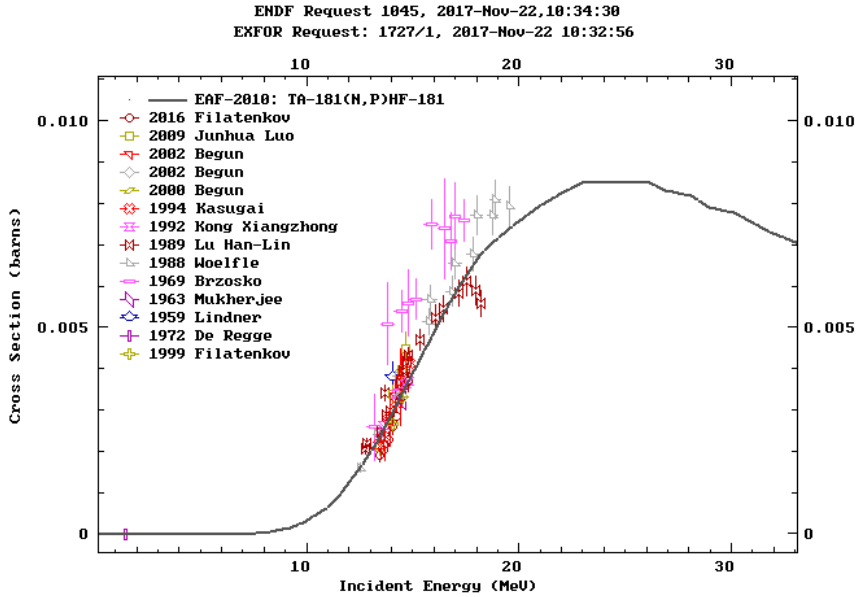
Mitja Majerle

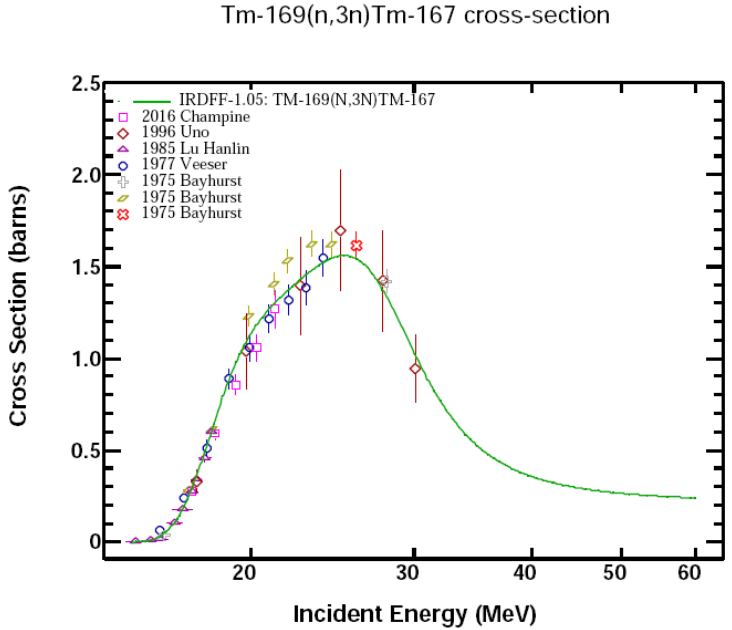
Neutron sources



- Main region of interest is/was below 20 MeV
  - Nuclear reactor spectrum decreasing exp with energy, max. ~2 MeV
  - Several sources of monoenergetic and continuous neutron spectra
- No monoenergetic neutrons above 20 MeV
  - Eg. accelerator driven systems
  - Continuous neutron spectra (spallation, p/d+thick targets)
  - Quasi-monoenergetic spectra (p+Li, p+Be, thin targets) – how well do we know them really?

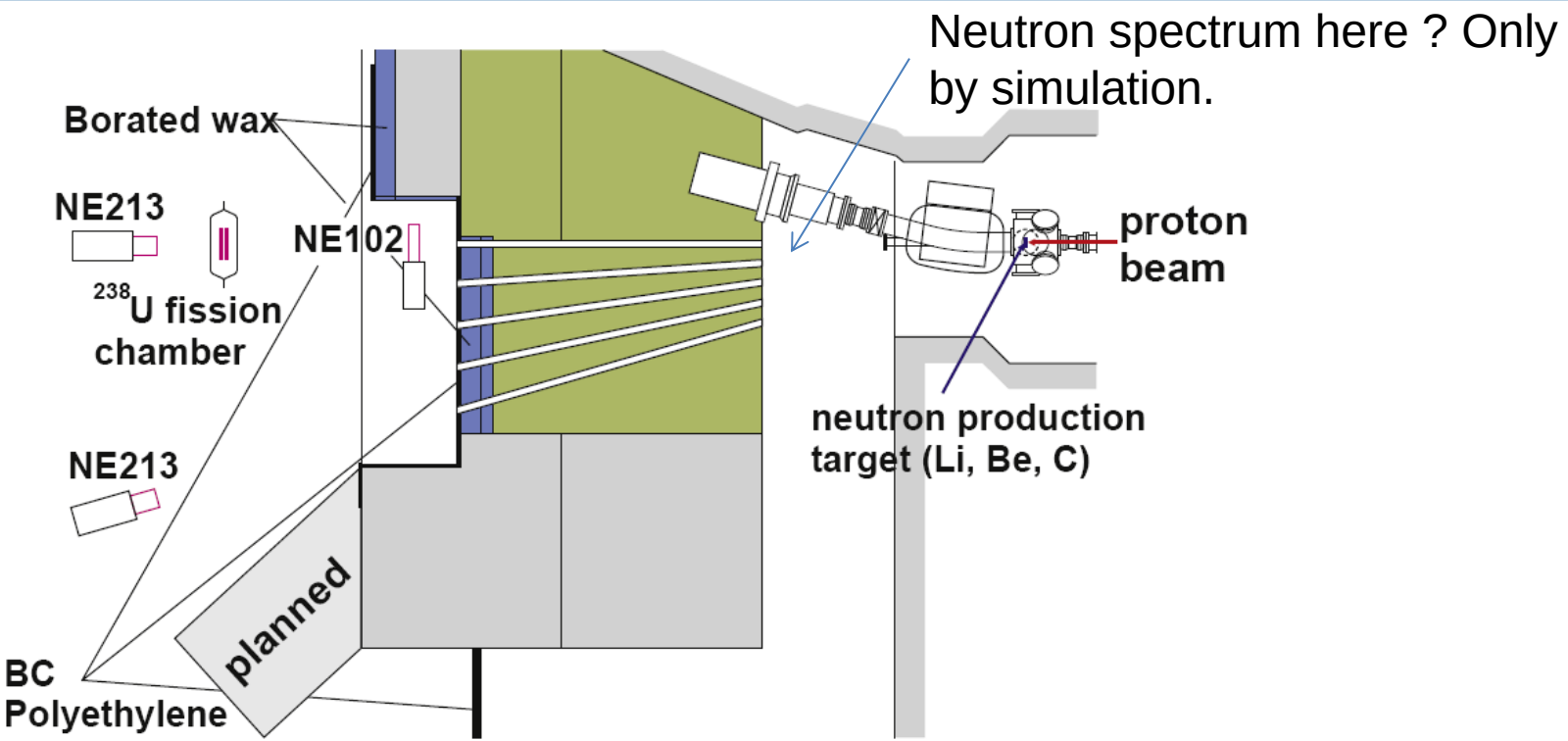
Experimental neutron CS





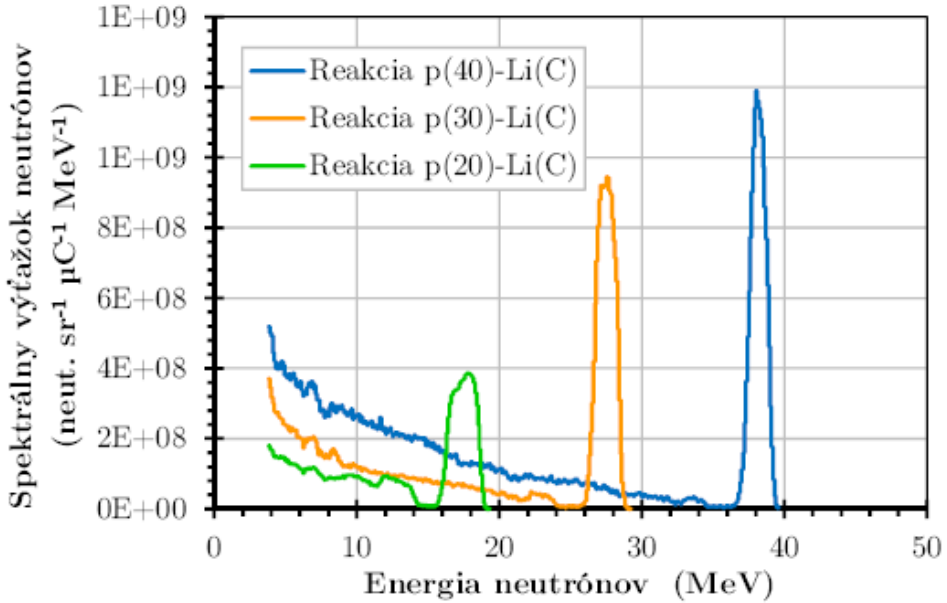
Region above 20 MeV is experimentally not well covered.

iThemba neutron station



Quasi-monoenergetic neutrons

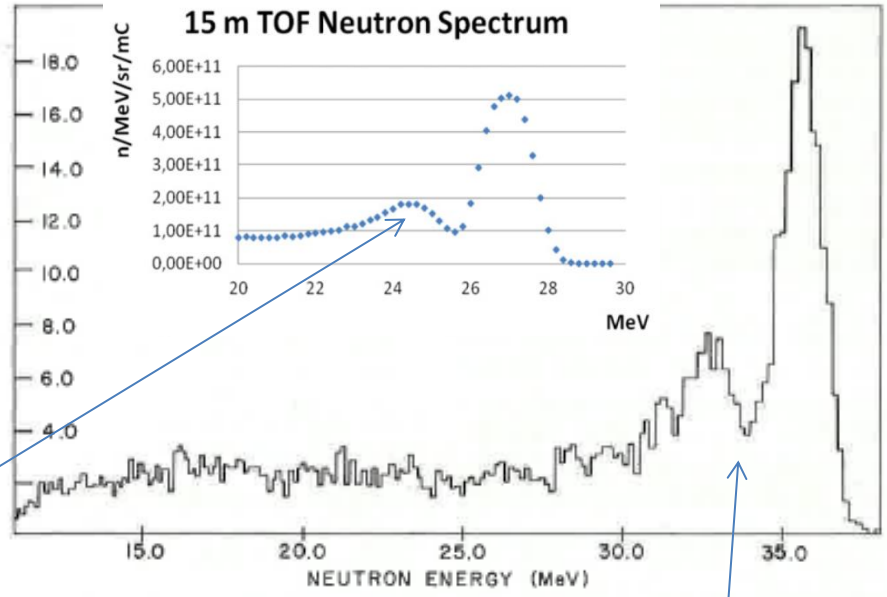
- p+Li, p+Be
- Monoenergetic neutron peaks from direct reaction + continuum
- Reactions p+Li:
  - $^{7}Li(p,n)^{7}Be$ (+excited states: 0.429, 4.57, 6.73..)
  - $^{7}Li(p,2n)$, $^{7}Li(p,n\alpha)$, $^{7}Li(p,p'n)$…



MCNPX+LA150H simulation

How well do we know QM spectra?

- **p+Be**
  - 7 publications: Kamada, Uwamino, Watson, Jungerman, Sisterson, Kim, Novak
  - Forward directed neutrons by TOF
  - Energy range 20-70 MeV
  - Kamada measured at 7 angles (up to 110°)

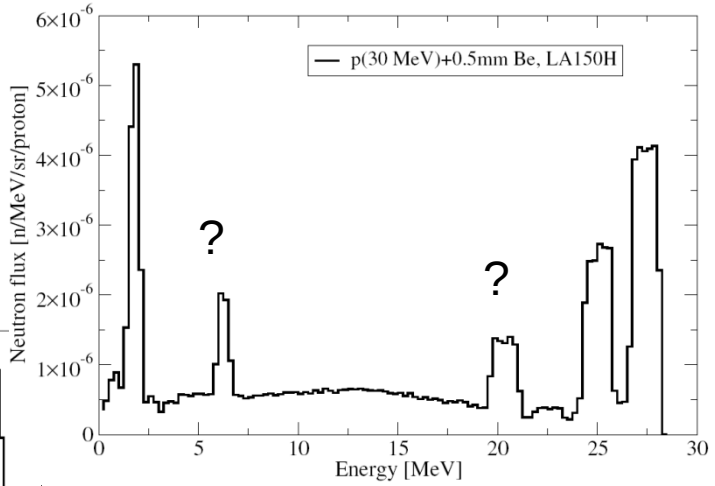


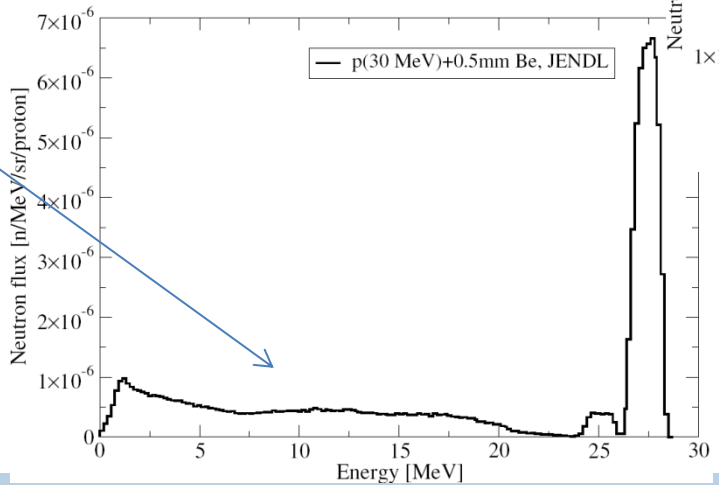
Novak, p+Be (0.5mm), 35 MeV, TOF at 0°

Jungerman, p+Be (thin), 39.2 MeV, TOF at 0°

Library implementation

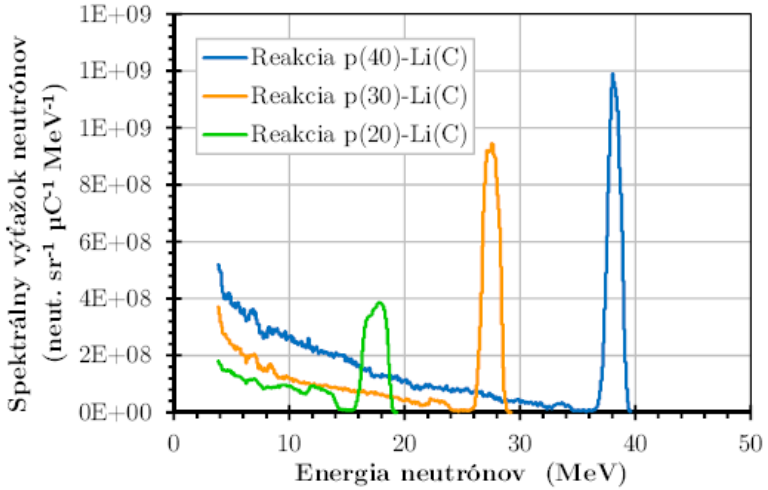
- p+Be library:
  - LA150H (simulated neutron spectrum in forward direction looks very different from experiment!)
  - JENDL4.0/HE





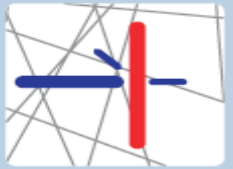
How well do we know QM spectra?

- **p+Li** - good systematics
  - 20+ publications
  - Energy range: 20-800 MeV
  - Angular distributions: 20-50 MeV, >80 MeV
- But when we want to measure the cross-sections:
  - Peak neutrons (can be determined experimentally? ^{7}Be activity+Uwamino angular integration formula ?)
  - Continuum (can we use statistical model for A=7? Optical potential)
- Experimental example (cross-sections)



MCNPX+LA150H

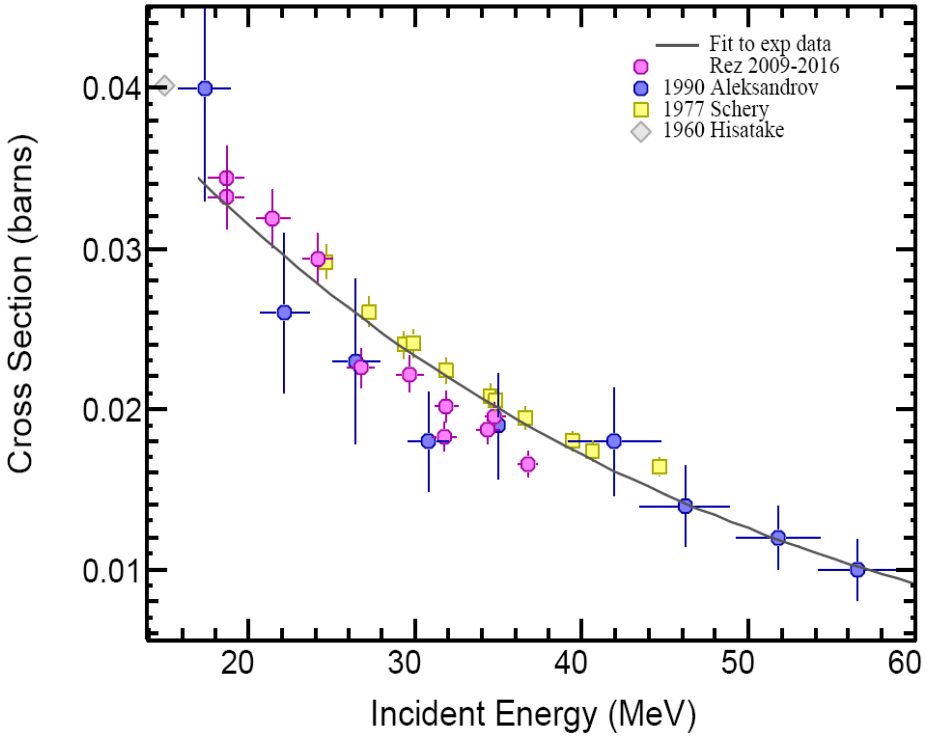
Peak neutrons



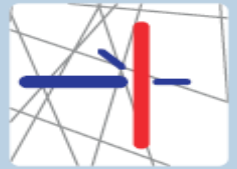
- $^{7}Li(p,n)^{7}Be(g.s.+0.429MeV)$ = peak neutrons in 4π, other reactions contribute to continuum - $^{7}Li(p,2n)^{6}Be$, $^{7}Li(p,p'n)^{6}Li$, $^{7}Li(p,n\alpha)^{3}He$…
- ^{7}Be can be measured by gamma spectroscopy, absolute accuracy ±2% - Schery 70'
- Peak neutrons in 4π vs. forward directed peak neutrons – Uwamino angular integration 90'

^{7}Be activity data from ^{7}Li(p,n)

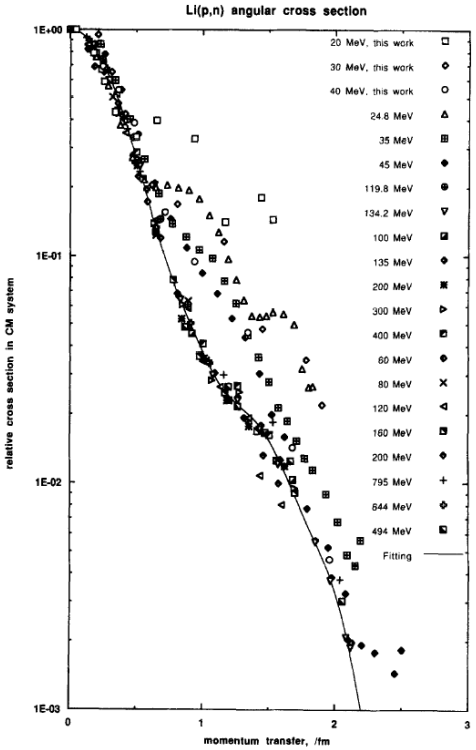
- Reliable data
- Slight disagreement Rez/Schery ~ 8%
- New measurements planned (p+^{7}Li CS)
- Problems with ^{7}Li providers (available again http://www.nccp.ru/en/products/lithium-7!!)



Forward directed neutrons formula

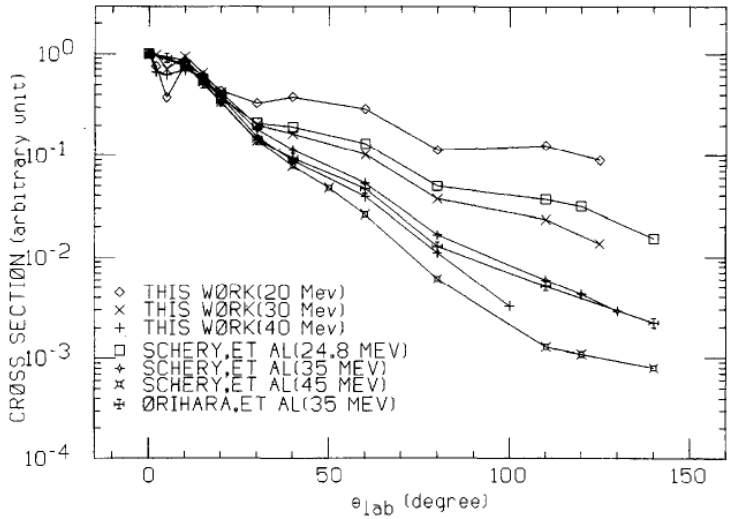


Y. Uwamino et al. / Nucl. Instr. and Meth. in Phys. Res. A 389 (1997) 463–473

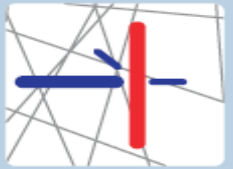


All angular distributions above the proton beam energy of 80 MeV, can be described with one curve. Below this energy Uwamino used these data:

Y. Uwamino et al. / Nucl. Instr. and Meth. in Phys. Res. A 389 (1997) 463–473



Forward directed neutrons formula



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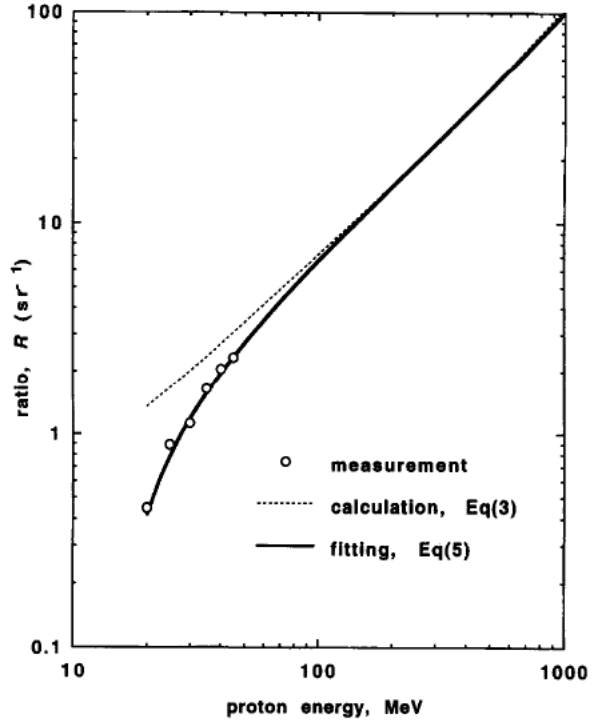
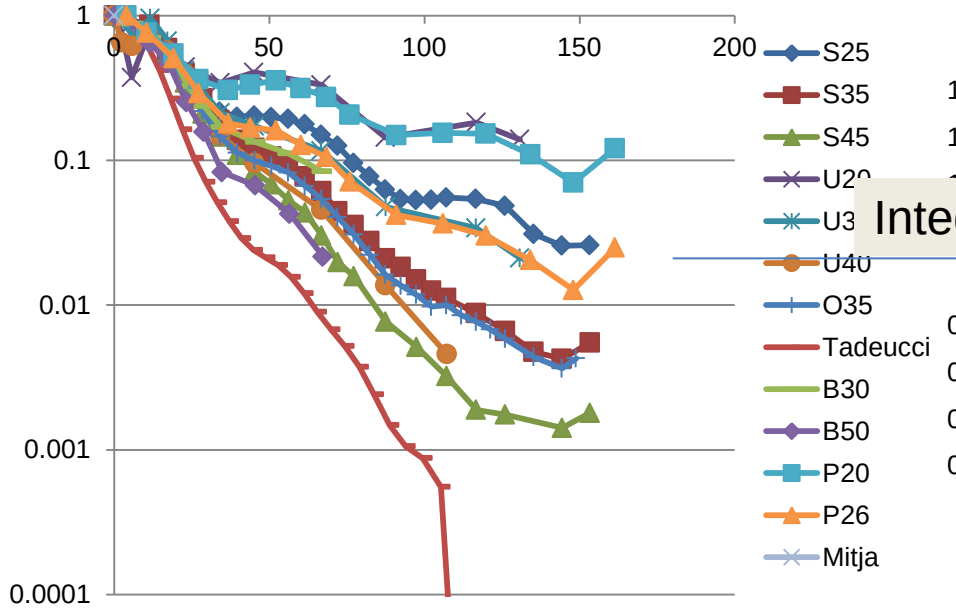


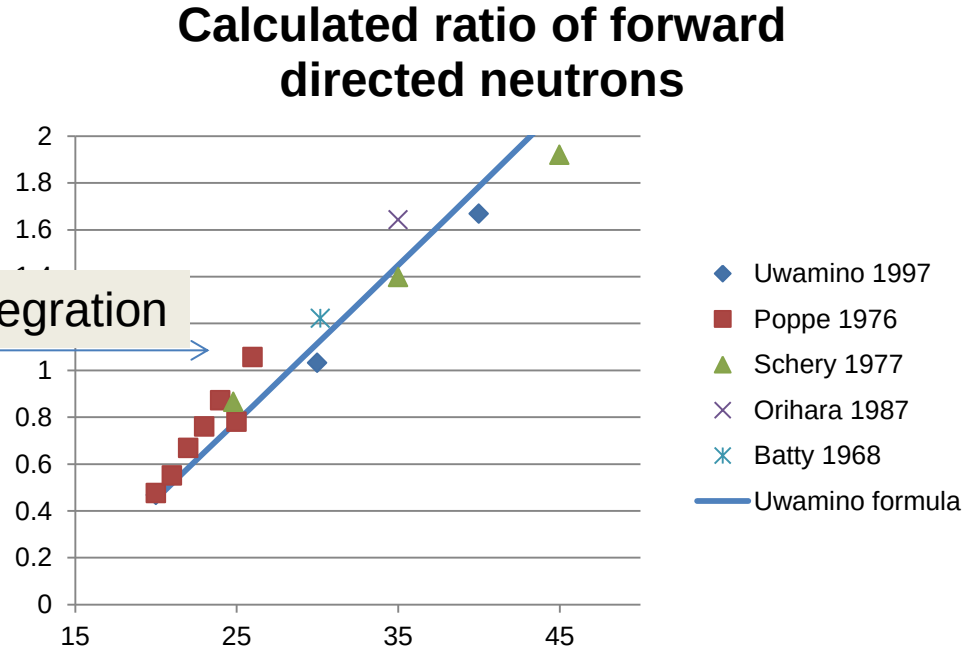
With the integration of the angular distributions Uwamino obtained the ratio of forward directed neutrons and fitted it.
Range: 20-40 MeV
Accuracy: ±6%

Forward directed neutrons formula

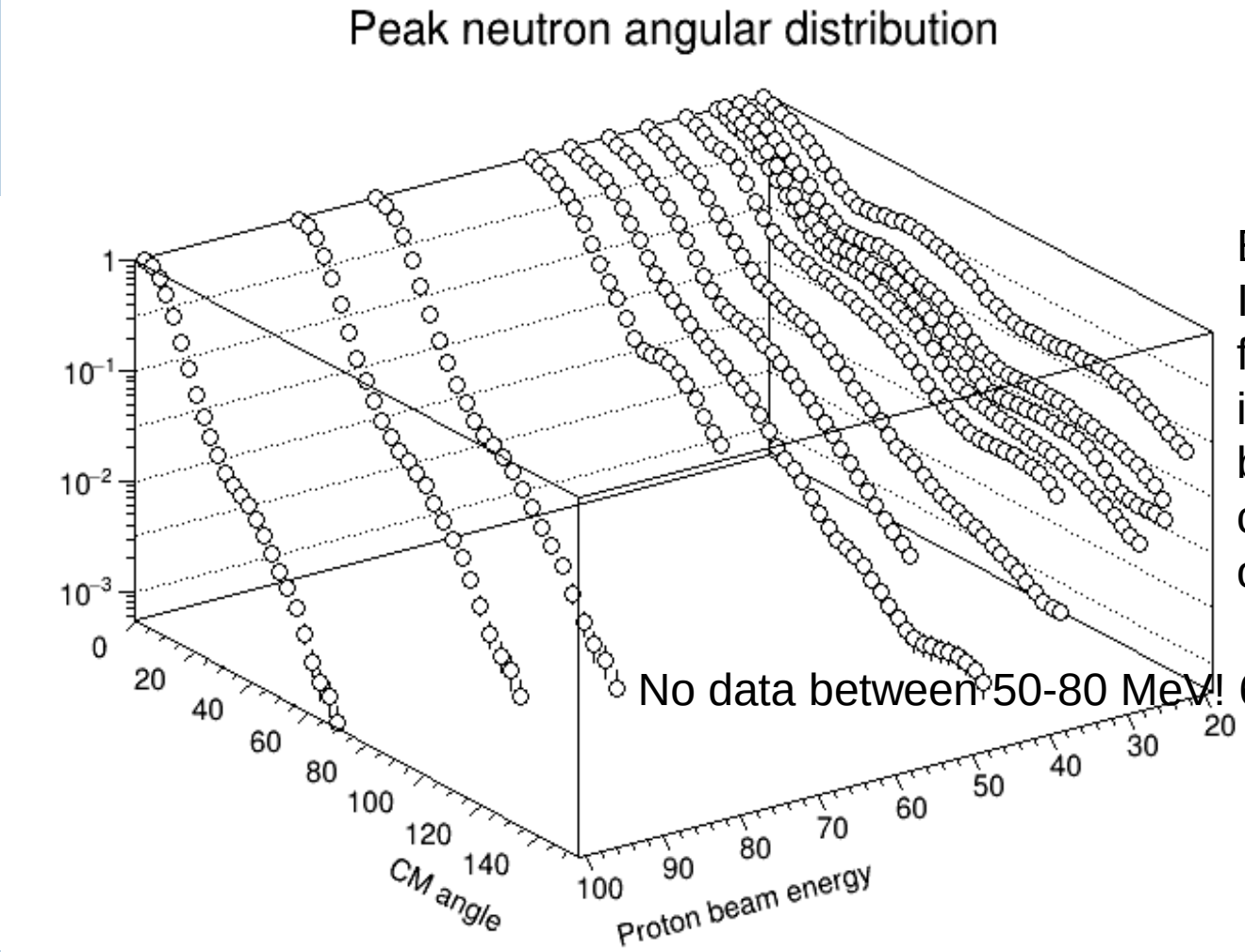
EXFOR now has more angular data:

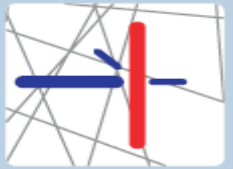


Integration



Good agreement with Uwamino formula.



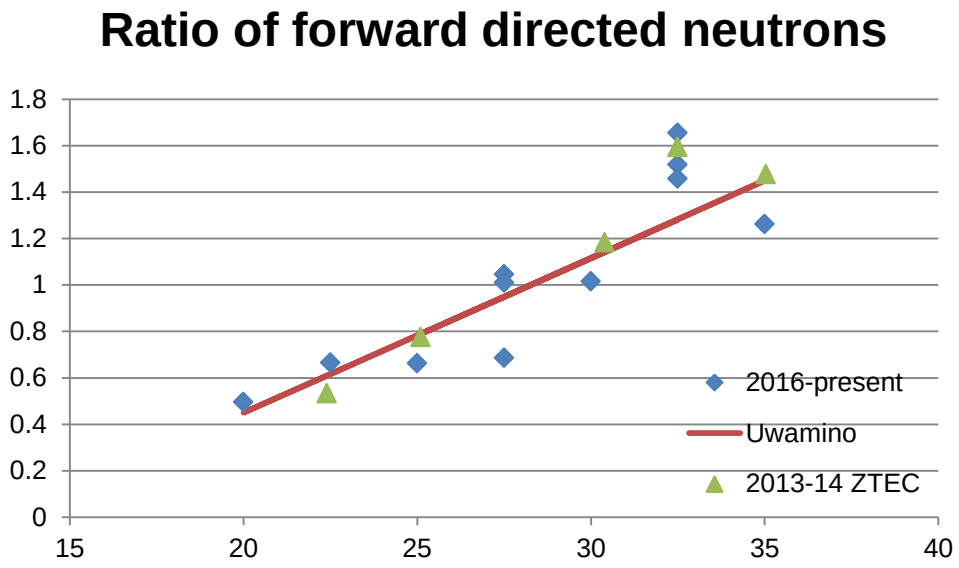


Existing experimental data. I could not make a good 2D fit to these data. In libraries it is implemented and ratios between Legendres coefficients are given – but obviously it is wrong.

No data between 50-80 MeV! 66 MeV data from iThemba?

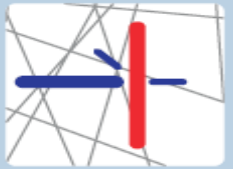
Forward directed neutrons formula

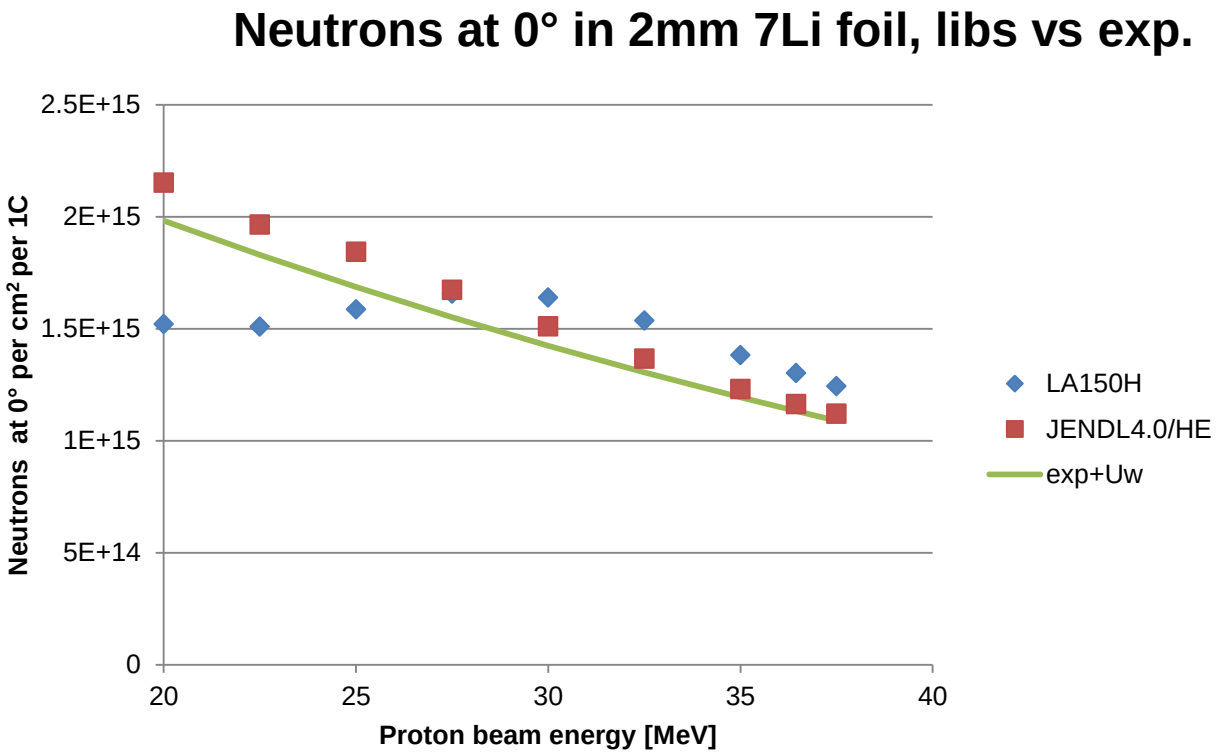
- NPI irradiations 2013-present (with Li target)
- We measured:
  - ^{7}Be activity in the lithium target
  - Number of forward directed neutrons measured with NE213 in the TOF mode (~4m)
  - Ratios compared with formula



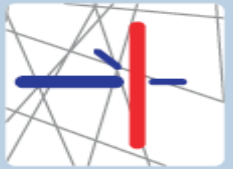
Good agreement with Uwamino. 32.5 MeV ?

Library implementation





Forward directed peak neutrons

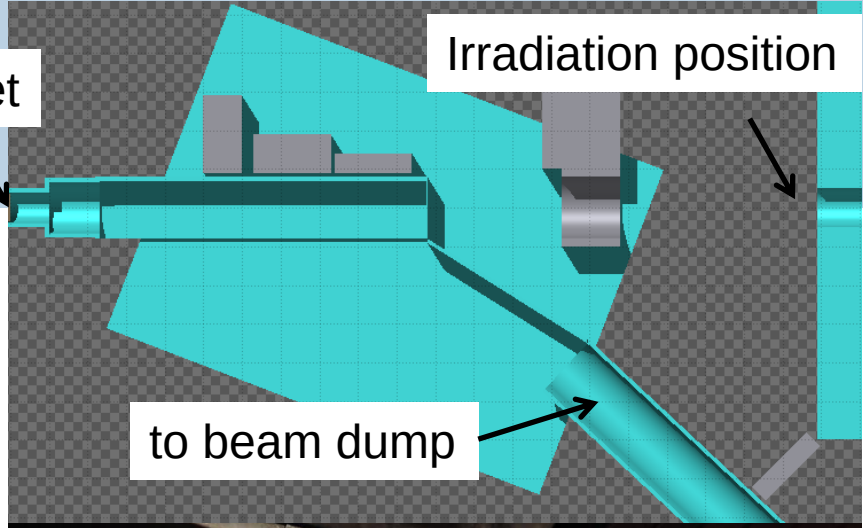


- Summary:
  - In range 20-40 MeV, ^{7}Be activity, Uwamino formula, ±5% accuracy of absolute number of peak neutrons
  - No data between 50-80 MeV, but Uwamino formula should work
  - Above 80 MeV, angular data, Watson/Tadeucci systematics
  - Reliable cross-sections if ^{7}Be measurement is impossible
  - Do not rely on libraries, always normalize!
- Possible traps:
  - Carbon beam stopper (below 40 MeV) - absorption of neutrons (1cm – 10-15%)
  - Scattering of neutrons in narrow places (TSL Uppsala)

TSL Uppsala

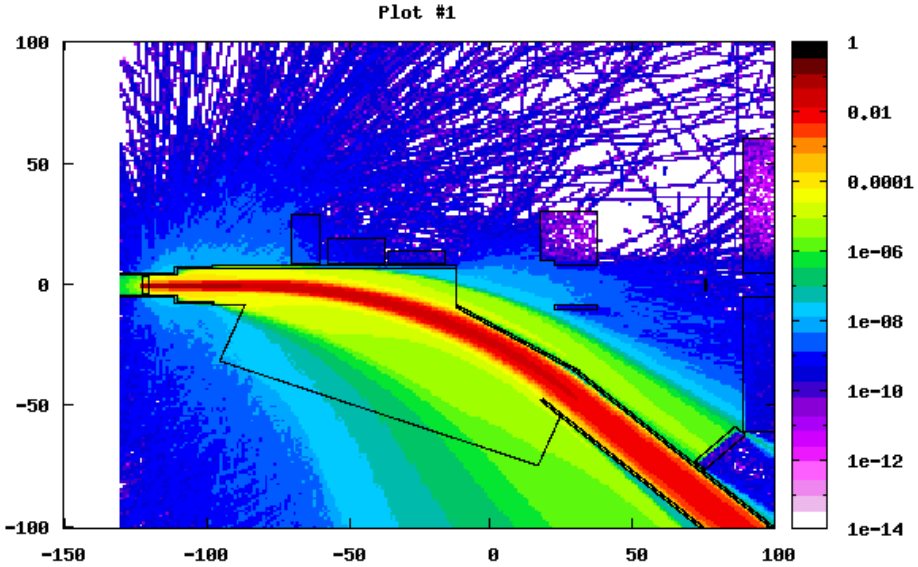
- Protons 38-100 MeV
- ^{7}Li target (4mm, 25 mm)
- Magnetic deflection of the proton beam
- Similar to iThemba

- FLUKA simulations (^{7}Li(p,n) reaction in source.f code)

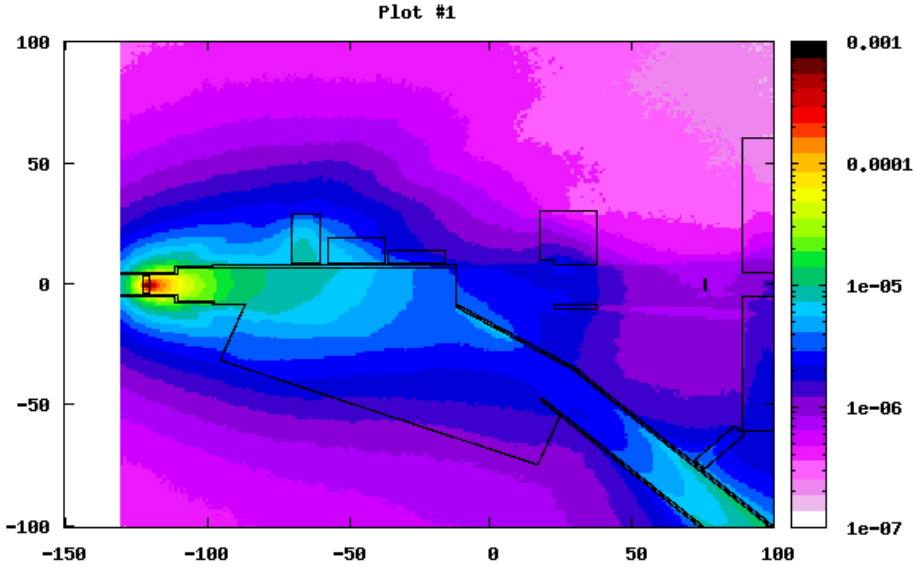


TSL Uppsala

Protons go to the beam dump

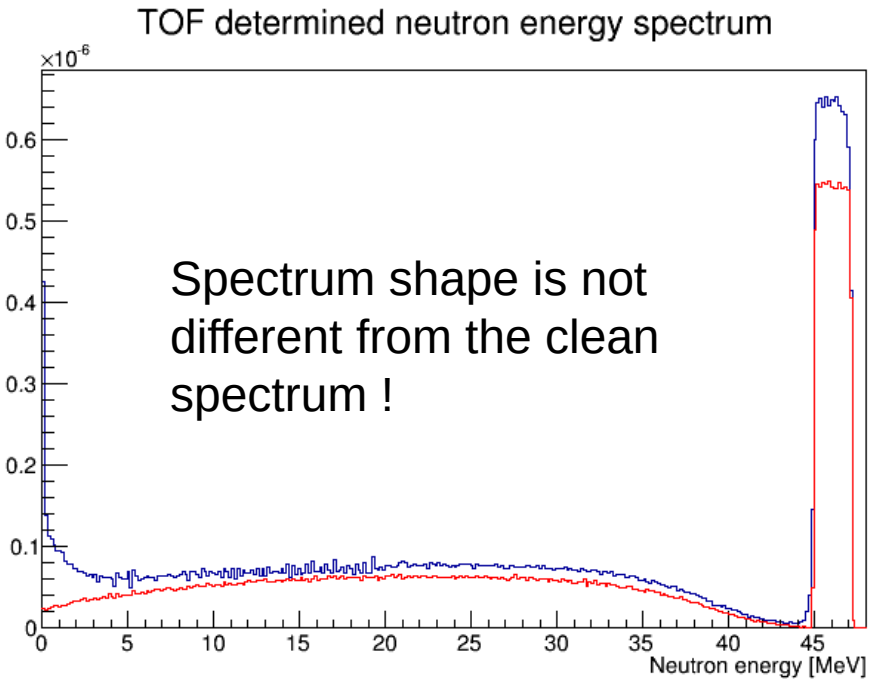


Neutrons are scattered by Fe to the sample position



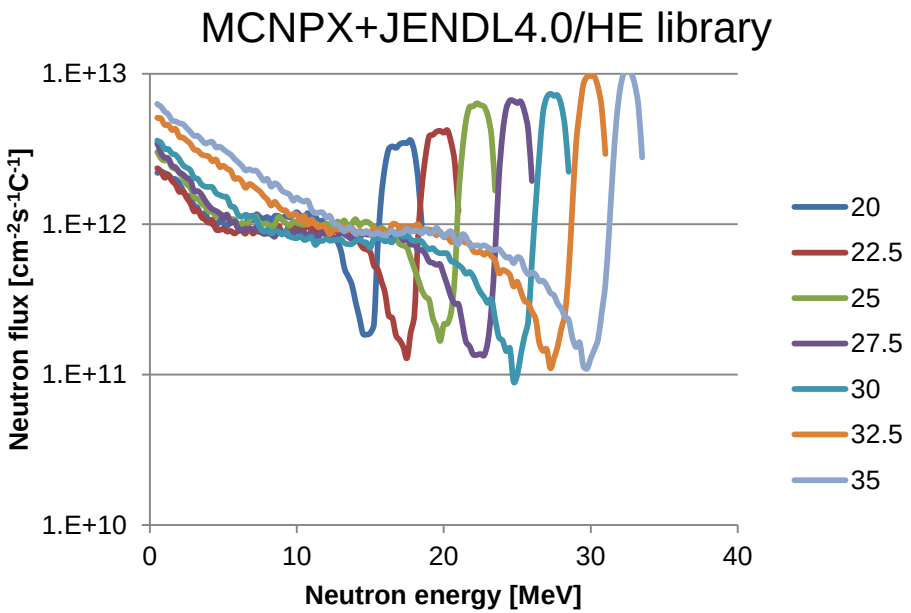
TSL Uppsala

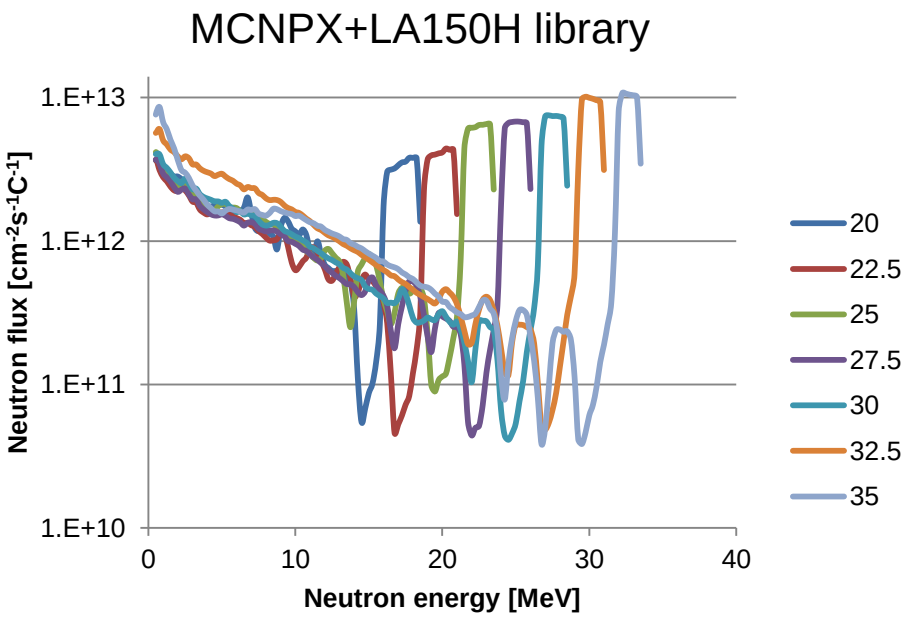
- BLUE - simulation with the magnet yoke, lead collimators
- RED - simulation without anything
- Considerable contribution of scattered peak neutrons: 19-23% (depends on the energy used)
- Contribution also to the continuum…



Continuum - simulated neutron spectra

Simulated neutron spectra for NPI irradiations. Proton energies 20-35 MeV are used.

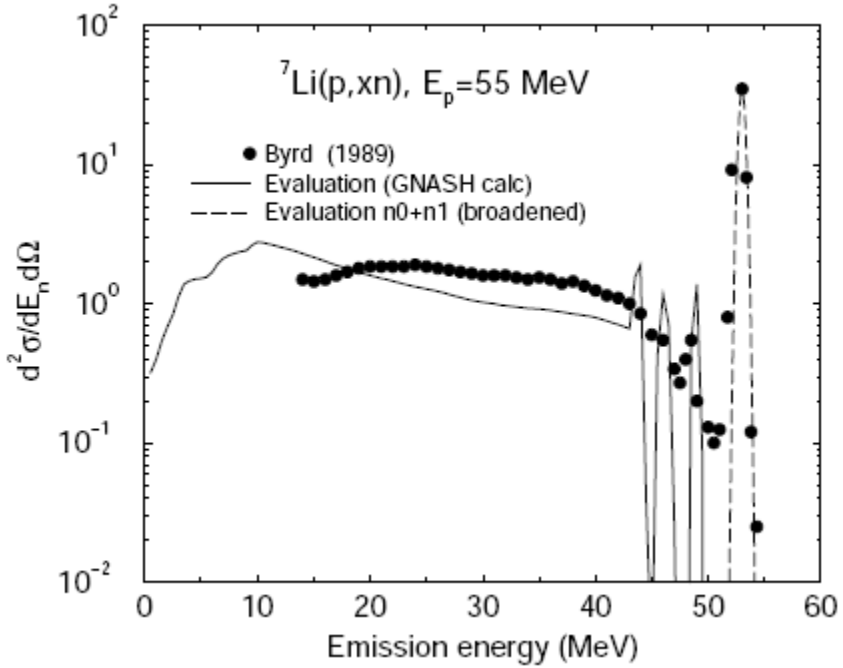




Peak neutrons normalized to the same number=experimental data from ^{7}Be+Uwamino.

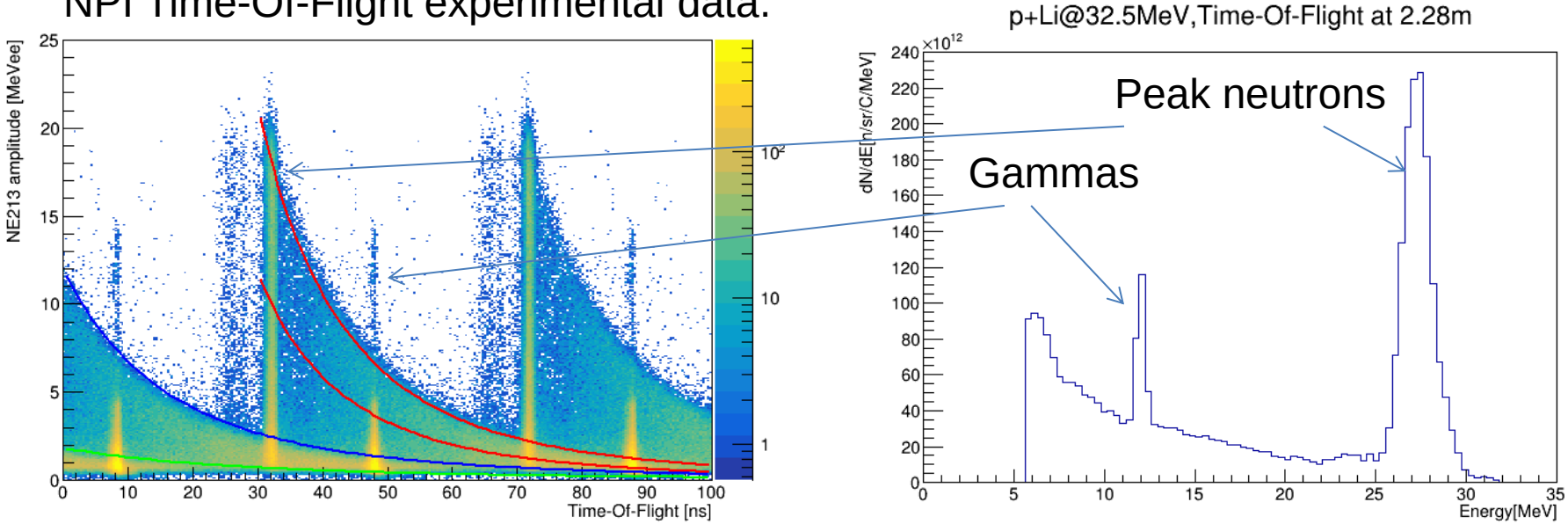
Continuum

- LA150H, Mashnik:
  - GNASH – preeq, HF, optical model from ^{6}Li
- JENDL4.0/HE, Kunieda:
  - No separate publication, personal contact.



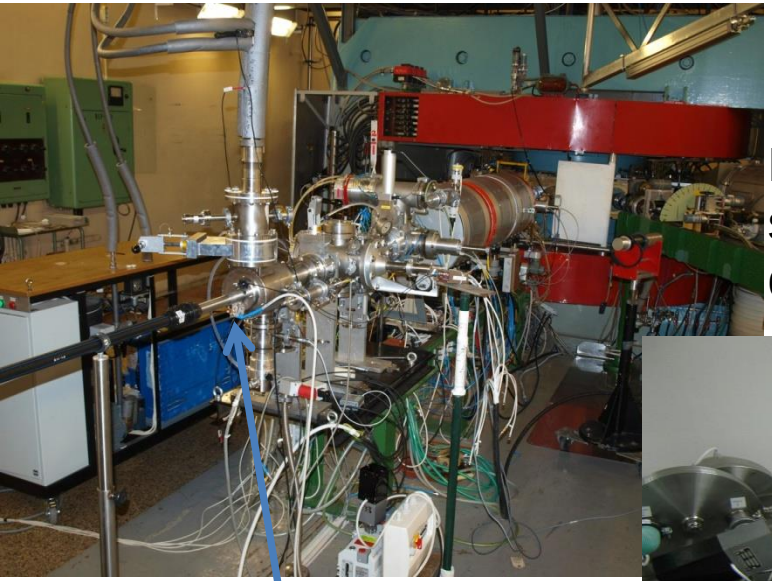
Continuum – TOF frame overlap

NPI Time-Of-Flight experimental data.



Frame overlap: Fastest neutrons from the next bunch catch up with the slowest ones.
Special cyclotron (iThemba) is necessary to measure below 5 MeV !

Irradiation (20-35 MeV), measurement

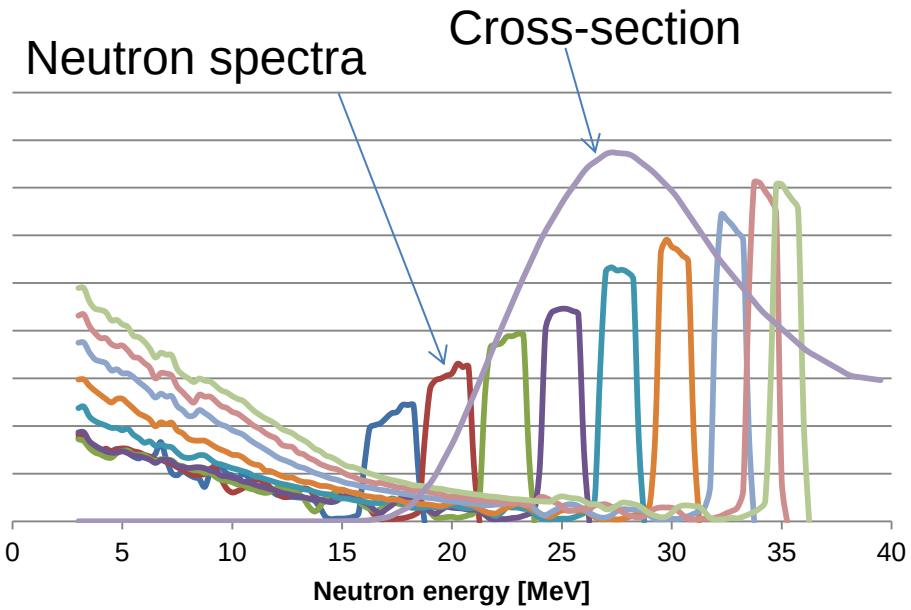


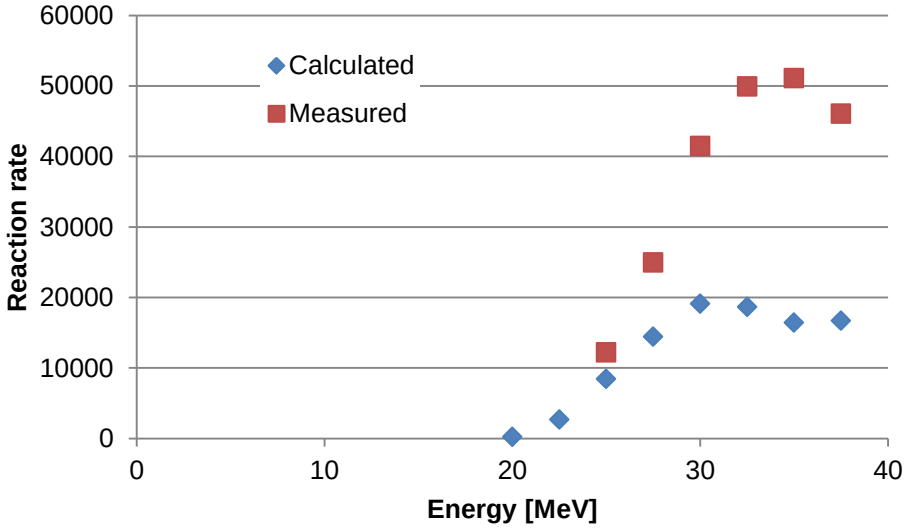
Sample location, repeated irradiation for 5 min

Pneumatic transport system ends at HPGe detectors, 6-7 sec

Samples are measured after ca 20 sec. with HPGe

Cross-section unfolding – C/E

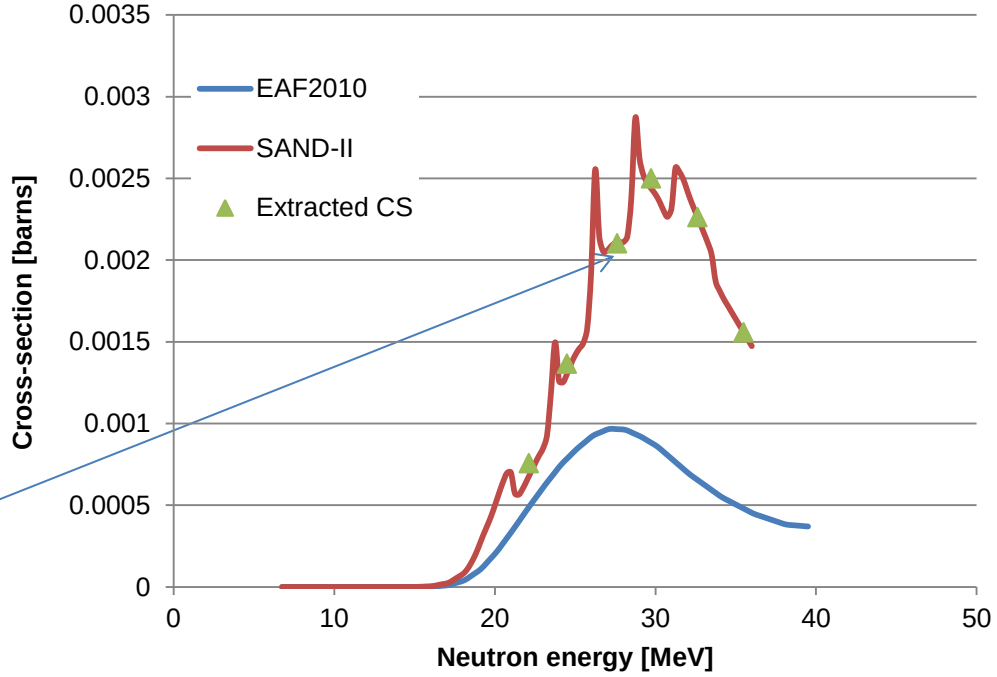




Reaction rates are cross-sections folded/multiplied with neutron spectra.

Cross-section unfolding – SAND-II

- Iterative procedure:
- CS is modified until measured reaction rates correspond to CS folded with neutron spectra
- Spikes between monoenergetic reagions – small contribution
- Monoenergetic regions are averaged to obtain extracted experimental cross-section



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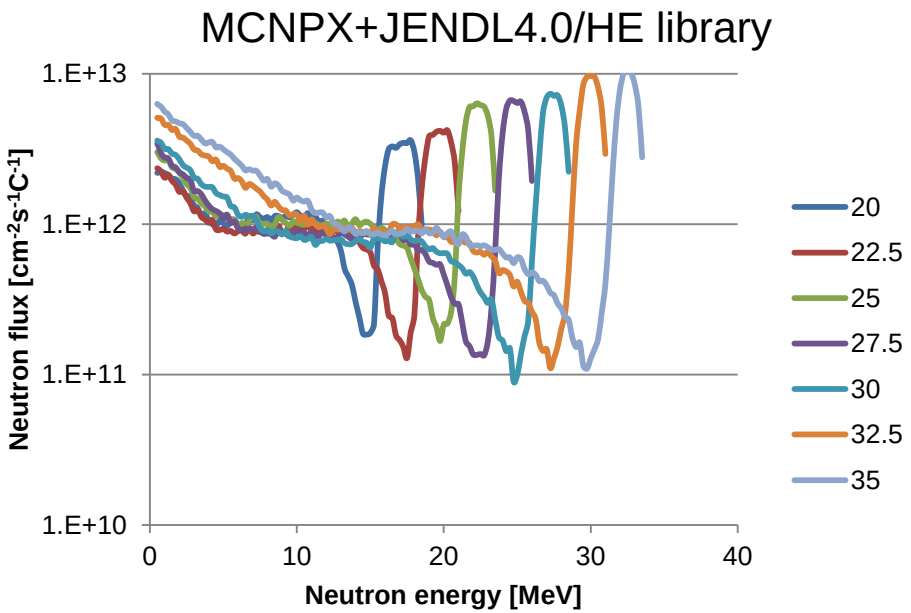
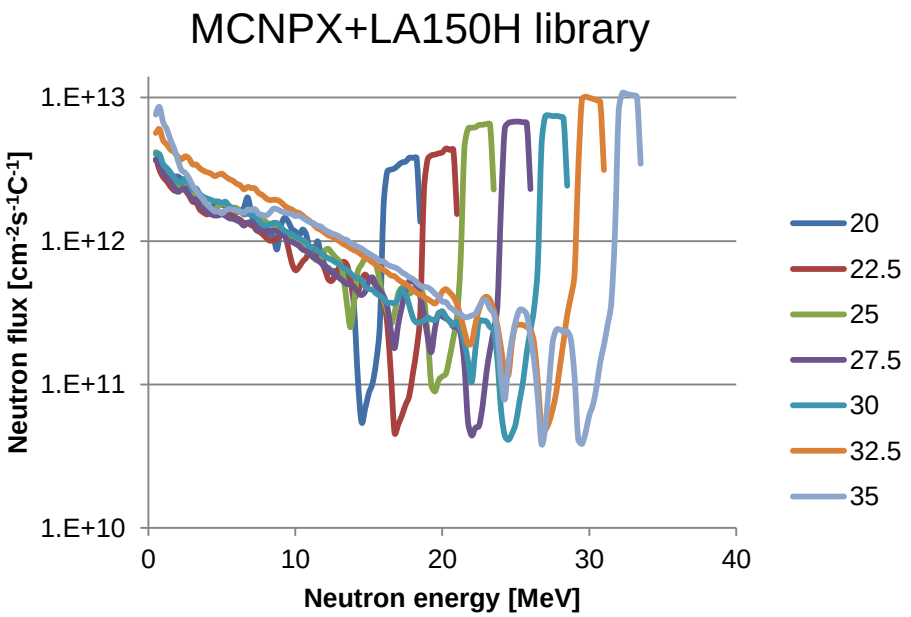
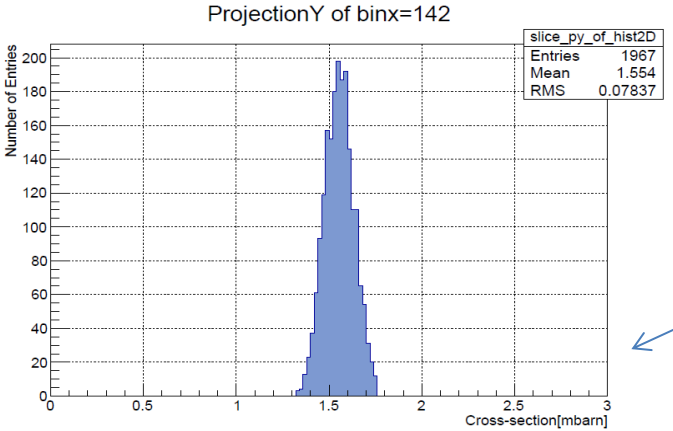


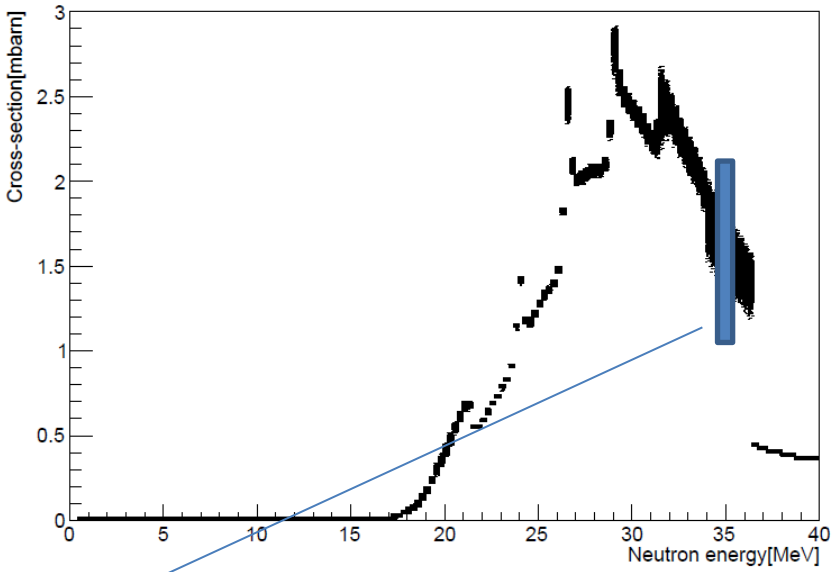


Peak neutrons normalized to the same number=experimental data from ^{7}Be+Uwamino.

Cross-section unfolding – uncertainty

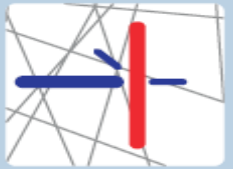
- Sensitivity analysis:
  - Input is sampled according to its uncertainty
  - Iterative procedure is performed with each set of input parameters
  - Sigma of the output is taken





Sensitivity analysis for uncertainty caused by continuum gives σ~10%.

Summary



- We know QM spectra from p+Li relatively well
  - ^{7}Be activity + Uwamino formula can be used
  - More experimental data on ^{7}Be cross-section and angular data in the range 40-80 MeV would be nice (ratio forward/4π also useful)
- LA150H and JENDL4.0/HE libraries
  - Normalize peak areas! Angular distributions of peak neutrons in both libs are not well described and you will get wrong numbers even if correct ^{7}Be cross-sections were used
- Uncertainty of extracted cross-sections (5% peak neutrons, sensitivity analysis for continuum – 10%, not negligible!)
- p+Be spectra are not so well studied, a lot of work can be done

Thank you !