NUCLEAR DATA MEASUREMENTS WITH COLLIMATED FAST NEUTRON BEAMS GENERATED ON U-120M CYCLOTRON

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Cross-sections for Reactions Induced by Fast Neutrons

- Fast neutrons – at NPI it means energy region 1-33 MeV
- In long-term materials are activated and damaged by fast neutron irradiation
- Energy region above 20 MeV – Few experimental data
- Testing and validation of construction materials for usage in future projects (fusion -ITER, DEMO, IFMIF; ADS; spallation neutron sources)
- Physics of nuclear reactions induced by fast neutrons – Double-Differential CS for (n, cp) reactions

Double-differential cross sections and kerma coefficients for light-charged particles produced by 96 MeV neutrons on carbon

U. Tippe, A. A., R. S., S. Pome, J. Bion, A. S., G. Gustavsson, J. K. K., P. Nade, T.,
Watanabe, H.
Laboratory of fast neutron generators

- Isochronous cyclotron U-120M - p, d, He, alpha ~ 1-35 AMeV
- Production of fast neutrons in reactions p+\(^7\)Li, p+\(^9\)Be
- Quasi-Monoenergetic or white energy neutron spectra are produced
- Maximum kinetic energies range 18 - 33 MeV
- Collimated neutron beams coupled with semiconductor detectors for on-beam measurements
New thin-Be FNG driven by U-120M cyclotron

2.5 mm Be foil backed with Graphite beam stoper, cooled with demineralized water.

Neutron Energy Spectrum at 2.5m distance on collimated beam

$p + 2.5 \text{ mm} \ ^9\text{Be}

E_{\text{proton}} = 33 \text{ SMev}
Detection Systems for Collimated Beams of Fast Neutrons at NPI

- ToF Technique for energy spectra determination with organic scintillators
- Array of four HPGe detectors for on-beam gamma spectroscopy – \((n, \gamma)\) (see talk of Mr Koliadko):
  - prompt gammas
  - Delayed gammas - isotopes with decay times down to ms
- Vacuum chamber for light ion detection - \((n,cp)\)
- Transmission experiments with total neutron cross-section extraction - \((n, tot)\)
NPI Chamber for Light Ion Detection – „CLIDevice“

- Detection of light ion particles (p, d, t, $^3$He, α) produced in nuclear reactions induced by fast neutrons
- Measurements of double-differential cross sections for reactions (n, cp) with Time-of-Flight method
- Equipped with dE-E Si-detector telescopes for distinguishing between cp types
- Digitalized data acquisition
- Since October 2019 operated in test mode
- High degree of automation
First tests with CLIDevice

- Beam of collimated neutrons (collimator diam. 3 cm) from p(34 MeV)+Be (2.5 mm) reaction
- Two Silicon detectors mounted on the remote-controlled table in vacuum chamber
- The PE target foil (thickness of 180 um, diam 3 cm) was mounted into the central position - $^1$H(n,p), $^{12}$C(n,p/d/t/α)
- Irradiation time 5h 50min

Telescope n. 2 (Si dets 150um + 5mm, Angle 36.4°):
Time resolution of Si dE-E telescopes

- Tested with alpha source
- Estimation of Upper limit for time resolution
- Measurement of trigger-time difference between two detectors in one telescope (time diff between dE_det(25um) and E_det(50um))

\[ FWHM_{max} = \text{Std} \div \sqrt{2} \times 2.355 \approx 4.0 \text{ ns} \]

- Possible resolution enhancement with offline analysis of the sampled signal
Complex Geant4 model

- Based on CAD drawings of chamber
- Precise representation of the real-world chamber structure
- Model is prepared for simulations of whole experiments with neutron induced reactions
- Modular C++ environment of the Geant4 framework preserves ability to implement whatever new is needed in the future
- Geant4 has well implemented neutronics (transport) up to 20 MeV – evaluated CS for neutrons
- In region above 20 MeV the general models for nucleon interactions are used
Simulation vs. Experiment comparison

Qualitative comparison shows good ability to predict experimental data

Investigation and estimation of various effects in data acquisition

Future possibility for tuning parameters of nuclear reaction models to get better agreements with specific experimental data
Transmission measurements with liquid oxygen

- Repeated experiment with improved approach
- White neutron spectrum produced on thick beryllium target
- Two measurements with continuous neutron spectra with energies up to 21 MeV and 33 MeV
- Sample with liquid oxygen was placed in polystyrene box and remotely manipulated during irradiation – In and Out
- TOF neutron energy spectrum with/without box filled with liquid O$_2$ is measured
- Decrease in neutron energy spectrum is calculated as transmission coefficient
- $(n,\text{tot})$ reaction cross-section is calculated based on the transmission $T_{\text{lo2}}$, known density $\rho_{\text{lo2}}$ and sample thickness $l$:

\[
\sigma_{\text{tot}} = -\frac{1}{nl} \ln T_{\text{lo2}}
\]

\[
n = \frac{N_A}{M} \rho_{\text{lo2}}
\]
Experimental set-up

- Liquid oxygen with natural abundance of its isotopes
- Polystyrene box (inner dimensions: 16 × 21 cm; 3 cm thick walls) with liquid oxygen
- Scintillator NE-213 with standard 2” × 2” cylindrical active volume
- Collimated beam of fast neutrons with continuous
- Flight path over 9 meters
Preliminary Results

Cross-section data for (n,tot) reaction on $^{\text{nat}}\text{O}$

- Řež 2019
- ENDF/B-VIII.b4
- R.W. Finlay+, 1993
- Řež 2020 - Be 22.5 MeV
- Řež 2020 - Be 35 MeV

Cross section (b)

Incident neutron kinetic energy (MeV)
Corrections and Uncertainties

- Two main effects of fast neutron interacting in matter:
  - Neutron is excluded from the collimated beam by an interaction in matter
  - Neutron scatters on sample nuclei but still reaches by the detector without sufficient kinetic energy loss (so-called „In-Detector-Scattered effect“)

- In-Detector-Scattered effect - underestimating the CS results, corrections ranges from 0.2 to 1 % (depending on kinetic energy and box orientation)

- Corrections on Pile-Up and Dead-Time (saturated digitizer) during ToF measurements

- Transmission experiments are based on comparison of relative values which is advantage for uncertainty analysis

- Main sources of uncertainties are
  - Time-resolution of accelerated proton bunches, bunch duration up to few nanoseconds, standard deviation up to 1.5 ns
  - Energy calibration during ToF technique
Conclusion

- Collimated beams of fast neutrons are accessible at NPI (up to 33 MeV)
- New detection systems (HPGe - (n, $\gamma x$), Si dE-E – (n, cp) ) are in final stage of development, tuning of acquisition
- (n, tot) cross-section measurements with transmission technique has been successfully used with liquid samples of oxygen - $^{nat}O(n,tot)$

We are looking for new colleagues (employees, postdocs, students...:-)

Visit http://www.ujf.cas.cz or email on ansorge@ujf.cas.cz in case of any questions
Thank you for your attention

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