Fast neutron laboratory at NPI

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NPI cyclotron facility

Cyclotron U-120M

- U-120 (1960) upgrade
  - to isochronous regime (1975)
  - to alternative operation in +/- mode of ion acceleration

- Cyclotron U-120M upgrade to U-120M in 1990
  - high-power beams
    - protons 6-38 MeV (50-30 μA)
    - deuterons 11-20 MeV (35-20 μA)

- Experimental hall
  - well defined beams
    - protons 6-25 MeV (3 μA)
    - deuterons 12-20 MeV (3 μA)
    - he-ions 18-55 MeV (1 μA)

- (+) ion deflector

- H(-)/D(-) extractor

- Alternating target stations
  - isotope production and neutron irradiation experiments (Li(C) and D₂O targets)
Neutron generators
\[ p+Li/C, p+Be \]

QM neutron spectrum \( p+Li \)

\( ^7\text{Li}(p,xn) \)
\[ E_p = 70 \text{ MeV} \]
\[ 0\text{-deg.} \]

P+Be (thick target) neutron spectrum

Fig. 7. (Color online) The results of \(^9\text{Be}(p,xn)\) thick target spectrum at 11 MeV.

In development…
NPI quasi-monoenergetic \( p+7\text{Li}(C) \) neutron source

- Present neutron source for activation experiments is a copy of CYRIC (Tohoku Univ.):
  - QME neutrons in the energy range 18-36 MeV are produced in standard \( ^7\text{Li}(p,n) \) reaction using
  - Irradiation of static 2mm \( ^7\text{Li} \) target followed by beam stopper (8mm thick C disk)

- Only minor variation was provided:
  - Separate setting of Li foil and carbon stopper
  - Li disk and carbon stopper cooled by medium stream

- The neutron flux up to \( 6 \times 10^8 \) n/cm\(^2\)/s in QME peak is operated for 38 MeV /6 \( \mu \)A proton beam and for minimal target-to-sample distance of 48 mm
CYRIC (Tohoku) p+7Li(C) neutron spectra

- Spectra were measured by TOF technique (in point-like geometry arrangement, PLG)
- How to use the TOF data for determination of flux at sample positions
- Different arrangement of NPI and CYRIC targets may change the relative contribution of neutrons from Li foil and target set up in the spectra
MCNPX simulation of p\(^+\)\(^7\)Li(C) spectra for NPI source

Calculated neutron flux at different distances averaged over sample dimensions

Calculated neutron flux ratio \(\Phi(87)/\Phi(48)\)

The MCNPX simulation with LA150-h library well describes
the effect of different s-to-s distance for C disc and Li foil
the integration effect of \(^7\)Li(p,\(n_{O1}\)) XS over solid angle of distant samples
the effect due to emission of QME neutrons from different thickness of \(^7\)Li foil
Target Specification:
- protons accelerated to 20-38 MeV
- high proton beam power (800W for 37 MeV)
- complicated cooling, PC controlled
- target cell:
  30 mm in diameter and 16 mm of length
  equipped by 40 μm thick entrance Ta foil
  (0.5 MeV thickness for the 37 MeV protons)

p+D$_2$O type of high-power neutron source is routinely operated
- for activation XS integral benchmark experiments
- neutron hardness tests of microelectronics components
Combination of MCNPX and multi-foil activation method

- set of dosimetry foils
  - Al, Ti, Fe, Co, Ni, Y, Nb, Lu, Au
  - irradiated at 3 and 156 mm s-to-s distances
  - 29 activation reactions employed for the neutron spectra adjustment

- modified SAND-II unfolding code
  (data up to 55 MeV added from EAF-2005)

- Guess spectrum: combined
  - by MCNPX simulation below 5MeV
  - and measured by NE213 detector

- resulting C/E are displayed along energy weighted with product of neutron flux and corresponding XS

- uncertainty of resulting adjusted spectrum
  - in 7 to 25 MeV energy range 3%.
  - assessed as a mean square deviation of C/E ratios from unity
  - above 25 MeV, 20-30% reflects mean deviations of EAF-2005 cross sections from measurement

Neutron flux up to $5 \times 10^{10}$ n/cm$^2$/s and energy extending to 32 MeV provide suitable tool for validation of IFMIF-relevant activation XS
validated nuclear database and computational tools needed above 20 MeV the motivation for NPI FNF activity
F4E: CS measurements 20-37 MeV on QM neutron source

Current status of CS - example

$^{59}\text{Co(n,p)}^{59}\text{Fe}$
7 irradiations

- Protons with energies 20, 25, 27.5, 30, 32.5, 35, 37.5 MeV
- ca. 20 hours @ 5 µA
- 0.5 C on target ~ samples irradiated with ca. $10^{13}$ neutrons

Neutron spectra for different proton energies.
Some results – step 1

Several methodics to extract data – deconvolution, minimisation..
Some final results
Details of uncertainty analysis

- Statistical: HPGe spectra peak fitting (2%), gamma instensities (1%), efficiency calibration (2%), MCNPX simulations < 0.5%
- Systematical (MCNPX sensitivity analysis)
  - FWHM, profile and displacement of proton beam – negligible
  - Sample displacement 1-2%
  - Neutron shielding by samples 0.5% @ 48 mm, 2-3% @ 87 mm
  - Li thickness 5%
  - Current measurement 5%
- CS extraction in table below

Table 4: Differences in activities produced by MCNPX and extrapolated CYRIC spectra.

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<tr>
<th>Ep [MeV]</th>
<th>$^{92m}$Nb</th>
<th>$^{92}$mNb</th>
<th>$^{96}$Nb</th>
<th>$^{99m}$Y</th>
<th>$^{99}$mY</th>
<th>$^{90}$mY</th>
<th>$^{88}$Y</th>
<th>$^{57}$Co</th>
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<td>14%</td>
<td>-8%</td>
<td>-4%</td>
<td>-14%</td>
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</table>
Methodics: Proton recoil telescope

- Successfully operated at one experiment on QM target, 25 MeV neutrons
- The goal was to validate the use of MCNPX for QM spectra determination
- Good agreement with Uwamino and MCNPX (10% disagreement)
Methodics: TOF measurement

- Cyclotron
- Neutron generator
- $p^+ \rightarrow n, \gamma$
- TOF base (ca. 4 m)
- 500 MHz (=2ns) continuous acquisition

Energy spectrum

TOF spectrum

$E_n = 70$ MeV
0-deg.

$\theta = 0^\circ$
Pulse time structure (on NE213)

- Macrostructure – RF needs to be switched on and off to avoid discharges (frequency 100-150 Hz), duty-cycle 5-80% 
- Microstructure - Several bunches of protons at different cyclotron orbits, exiting with RF frequency (20-30 MHz)
Pulses timescale in detail

- Micropulse duration is ca 50 ns.
- Pulses from NE213 scintillator (50Ω) are 10-20 ns long.
- 1000-4000 pulses from scintillator per macropulse.
- The idea is to record the time of all pulses and to put it in the histogram – this should give some TOF structure.
Scintillator response to neutrons and photons

- Photons in light material – Compton edge
- Neutrons – elastic scattering – proton
- Proton/electron – different light output
- n/g discrimination possible on falling edge

MCNPX simulation

4 MeV $\gamma$
10 MeV n

Neutron and photon pulses on stilbene, photomultiplier 1 MΩ
Sorting by energy, p+Li/C

All pulses

Only pulses with high energy

Histograms showing the distribution of Time Of Flight for both All pulses and Only pulses with high energy. The histograms are accompanied by tables showing the number of entries, mean, and RMS for each category.
Diamond detector response

- ERINDA cooperation with IRMM – A. Krasa
- Continue their measurements at higher energies
- Improve the knowledge of our neutron fields
- Simple online detector of neutrons?
- PRT with DD and TOF capability?
- CS \( n(C,Be)a \) – interesting results obtained
SPIRAL2 activities:

Construction of NFS irradiation box, first day experiments – to be seen tomorrow on excursion

Design of neutronics and thermal aspect of NFS targets irradiated with protons – poster right
Future plans with fast neutrons

Continuation in F4E program
measurement of CS – completed, new tasks expected
integral CS validation – new tasks expected
gas production with activation method (pneupost) – new task

Improvements of targets and our knowledge of neutron spectrum
online neutron monitor
RADMON detector testing
Single-crystal diamond detector testing – completed, DD PRT ?
PRT with TOF capability

Possible participation in other CS measurements
program ERINDA (diamonds, CS measurements Y)
participating in design phase and first experiments on SPIRAL2

Contribution to evaluated libraries for target materials (d and Be libraries)