BARC Progress Report
NRDC-2022

(June 14 – June 17, 2022)

Devesh Raj

BARC, India

EXFOR Compilation activity

For EXFOR compilation Russian EXFOR editor and Japanese Digitizer GSYS 2.4.9. are used.

The JCPRG: EXFOR compilation internal tool is used for the checking purpose.

The EXFOR compilation work is done by:

- Regular compilation activity.
- Organization of workshop for EXFOR compilation every two years by BARC.
- The numerical data collection is done by BARC.
- The EXFOR compilation is done by BARC and DAE project holders.

Number of new EXFOR entries compiled since the NRDC 2021 meeting:

Neutron = 23

CPND = 31

PhND = 01

Total = 55

Unusual tabulation of the monitor cross section uncertainty

1) partial uncertainty in barn instead of %, which adds redundancy to the article table and EXFOR entry, and
2) treatment of the monitor reaction cross section uncertainty which should be not the uncertainty IN the monitor cross section and should not be coded under MONIT-ERR.

```
SUBENT        33129002   20211202   20220112   20220112       3204
BIB                  4         19
REACTION   (41-NB-93(N,2N)41-NB-92-M,,SIG)
           # (41-NB-93(N,2N)41-NB-92-M,,SIG)
           # Target:NB-93 #Projectile:N #Reaction:N,2N  #Quantity:,SIG:CS:Cross section
           # Product: [41-NB-92]
DECAY-DATA (41-NB-92-M,10.15D,DG,934.4,0.9915)
           # Decay-data: [41-NB-92]
ERR-ANALYS (ERR-T) Total uncertainty propagated from
            Monitor reaction cross section
           (ERR-1) Gamma-ray peak counts, Nb
           (ERR-2) Gamma-ray peak counts, Au
           (ERR-3) Decay constant, Nb
           (ERR-4) Decay constant, Au
           (ERR-5) Weight, Nb
           (ERR-6) Weight, Au
           (ERR-7) Average atomic mass, Nb
           (ERR-8) Average atomic mass, Au
           (ERR-9) Gamma-ray abundance, Nb
           (ERR-10) Gamma-ray abundance, Au
           (ERR-11) Efficiency of detector, Nb
           (ERR-12) Efficiency of detector, Au
           (ERR-13) Gamma attenuation, Nb
           (ERR-14) Gamma attenuation, Au
HISTORY    (20211201C) VS. MONIT(-ERR) moved to 001.
ENDBIB              19
COMMON              14          1          12
            #Legend: 14 x 1 x 12 : data columns * lines * column width
            #ERR-1    1st partial uncertainty, defined under ERR-ANALYS   B  barns
            #ERR-2    2nd partial uncertainty, defined under ERR-ANALYS   B  barns
            #ERR-3    3rd partial uncertainty, defined under ERR-ANALYS   B  barns
            #ERR-4    4th partial uncertainty, defined under ERR-ANALYS   B  barns
            #ERR-5    5th partial uncertainty, defined under ERR-ANALYS   B  barns
            #ERR-6    6th partial uncertainty, defined under ERR-ANALYS   B  barns
            #ERR-7    7th partial uncertainty, defined under ERR-ANALYS   B  barns
            #ERR-8    8th partial uncertainty, defined under ERR-ANALYS   B  barns
            #ERR-9    9th partial uncertainty, defined under ERR-ANALYS   B  barns
            #ERR-10   10th partial uncertainty, defined under ERR-ANALYS  B  barns
            #ERR-11   11th partial uncertainty, defined under ERR-ANALYS  B  barns
            #ERR-12   12th partial uncertainty, defined under ERR-ANALYS  B  barns
            #ERR-13   13th partial uncertainty, defined under ERR-ANALYS  B  barns
            #ERR-14   14th partial uncertainty, defined under ERR-ANALYS  B  barns
            #/Legend
ERR-1      ERR-2      ERR-3      ERR-4      ERR-5      ERR-6      ERR-7      ERR-8      ERR-9      ERR-10     ERR-11     ERR-12     ERR-13     ERR-14
B          B          B          B          B          B          B          B          B          B          B          B          B          B
2.742e-02  2.861e-03  2.887e-05  4.436e-06  1.777e-04  8.813e-05  8.788e-09  1.554e-09  2.059e-04  1.759e-03  8.540e-03  7.463e-03  7.515e-04  8.812e-05
ENDCOMMON
DATA                 4          1          12
            #Legend: 4 x 1 x 12 : data columns * lines * column width
            #EN          Energy of incident projectile, laboratory system  MEV  MeV
            #EN-RSL-HW   Incident projectile energy resolution (Half width) MEV  MeV
            #DATA        Cross section                                     B    barns
                         #+ 41-NB-93(N,2N)41-NB-92-M,,SIG
            #ERR-T       Total uncertainty (1-Sigma)                       B    barns
            #/Legend
EN         EN-RSL-HW  DATA       ERR-T
MEV        MEV        B          B
14.78      0.19       0.5103     0.03365
ENDDATA
ENDSUBENT           37
ENDENTRY
```

Journal of Radioanalytical and Nuclear Chemistry (2019) 320:561–568 565

Table 4 Detailed of partial uncertainties and correlations from the different attributes of measured reactions relative to monitor reaction

Attributes	Nuclide ^{92m}Nb	Nuclide ^{90m}Y	Nuclide ^{92m}Nb	Correlation
Monitor reaction cross section σ_M	4.682E−03	4.768E−05	5.743E−04	Correlated
γ-ray peak counts C_S	2.742E−02	1.842E−04	9.289E−03	Uncorrelated
γ-ray peak counts C_M	2.861E−03	2.913E−05	3.509E−04	Fully correlated
Decay constant λ_S	2.887E−05[a]	4.168E−06[b]	2.287E−06[c]	a and c are fully correlated c is uncorrelated
Decay constant λ_M	4.436E−06	4.518E−08	5.441E−07	Fully correlated
Weight of sample Wt_S	1.777E−04[a]	1.809E−06[b]	1.818E−05[c]	a and b are fully correlated c is uncorrelated
Weight of monitor Wt_M	8.813E−05	8.975E−07	1.081E−05	Fully correlated
Isotopic abundance a_S	–[a]	–[b]	1.292E−04[c]	a and b found to be with no error and c with error
Average atomic mass A_{VS}	8.788E−09[a]	8.949E−11[b]	1.158E−10[c]	a and b are fully correlated c is uncorrelated
Average atomic mass A_{VM}	1.554E−09	1.583E−11	1.907E−10	Fully correlated
γ-rayabundance $I_{\gamma S}$	2.059E−04[a]	2.136E−06[b]	2.525E−05[c]	a and c are fully correlated b is uncorrelated
γ-rayabundance $I_{\gamma M}$	1.759E−03	1.792E−05	2.159E−04	Fully correlated
Efficiency of detector $\varepsilon(E_\gamma)_S$	8.540E−03[a]	8.875E−05[b]	1.047E−03[c]	a and c are fully correlated b is uncorrelated
Efficiency of detector $\varepsilon(E_\gamma)_M$	7.463E−03	7.601E−05	9.154E−04	Fully correlated
γ-attenuation coefficient $(\Gamma_{atm})_S$	7.515E−04	2.894E−05	8.959E−05	Uncorrelated
γ-attenuation coefficient $(\Gamma_{atm})_M$	8.812E−05	8.944E−07	1.081E−05	Fully correlated

Table 5 The experimentally estimated reaction cross sections relative to the ^{197}Au(n,2n)^{196}Au monitor reaction with its uncertainty and correlation matrix

Reaction	Cross section (barns)	Correlation matrix		
^{93}Nb(n,2n)^{92m}Nb	0.5103 ± 0.03365	1		
^{93}Nb(n,α)^{90m}Y	0.0052 ± 0.00027	0.28	1	
^{92}Mo(n,p)^{92m}Nb	0.0626 ± 0.00968	0.14	0.12	1

Evaluation Work

- Indian evaluation of basic nuclear data including use of nuclear physics model codes, statistical inference tools, and covariance.
- Understanding format and procedures including processing of covariance for advanced reactor applications. Indian processing of nuclear data files to produce plug-in data libraries for engineering and other application.
- Use of covariance to define error margins due to uncertainties in nuclear data and adjustment of cross-sections. Perspectives on uncertainty in quantities other than nuclear data, affecting target accuracy in advanced reactor designs.

Project on Evaluation activity:

- The DAE-BRNS project (Phase-2) has been completed in Manipal.
- The project in VESIT, Chembur, Mumbai is in the last year and will end soon.

Evaluation of neutron cross section data of 100Mo(n,2n)99Mo reaction using EXFOR database library and nuclear model-based data generated using Talys 1.9 code by combining Kalman filtering technique with Machine Learning (ML) regression algorithms.

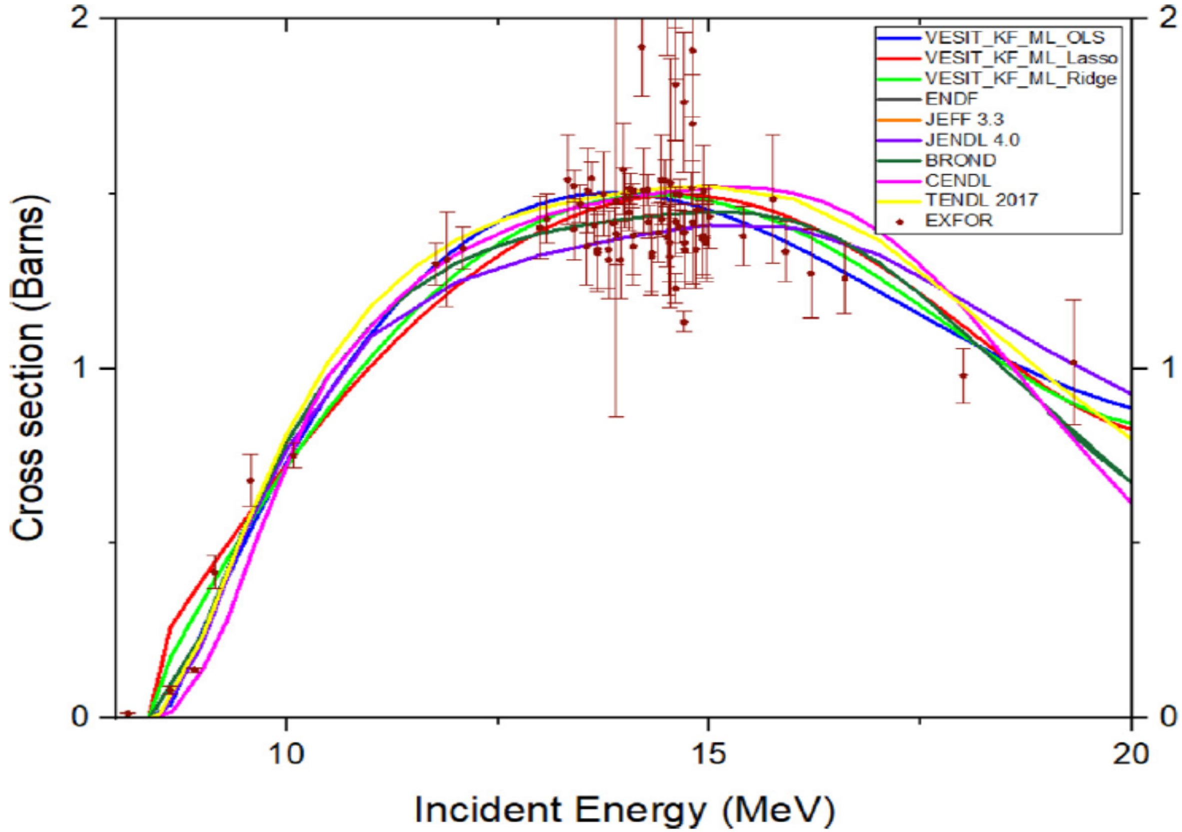

Fig. 10c. Comparison of evaluation curves. Comparison of the evaluation curves of cross-section data of ^{100}Mo (n, 2n) ^{99}Mo reaction generated using KF in combination with ML algorithms of OLS, Lasso and Ridge regression, with the standard evaluated nuclear data libraries such as ENDF/B-VIII.0 [31], JEFF-3.3 [32], JENDL-4.0 [33], BROND-3.1 [34], CENDL-3.1 [35] and TENDL 2017 [36] and EXFOR database [2].

Publications

- Sangeetha Prasanna Ram, Jayalekshmi Nair, et al., "Application of Kalman filtering technique for Evaluation of neutron cross section data of $^{100}Mo(n, 2n)^{99}Mo$ reaction", Nuclear Inst. and Methods in Physics Research, A 1020 (2021) 165850.
- Sangeetha Prasanna Ram et al., “Application of Machine Learning algorithms for experimental data processing and estimation of ^{96}Mo (n, p)^{96}Nb reaction cross section”, Abstract accepted for presentation in the ND2022, 15th International Conference on Nuclear Data for Science and Technology, July 24-29, 2022, Sacramento, California https://indico.frib.msu.edu/event/52/contributions/1121/
- Meghna Karkera et al., “Evaluation of nuclear data of 232-Th(n, 2n)231-Th reaction cross section with inclusion of a comprehensive covariance analysis”. Abstract accepted for presentation in the ND2022, 15th International Conference on Nuclear Data for Science and Technology, July 24-29, 2022, Sacramento, California https://indico.frib.msu.edu/event/52/contributions/1123/

Generation of qualified reaction cross section data for fuel cycle analysis

The spectrum averaged one group effective microscopic cross sections for each fuel region has been generated and tested from a PHWR and an Advanced heavy water Reactor (AHWR) fuel cycle. The decay data for actinides have also been obtained. The self-shielded burnup dependent cross section have been obtained from transport theory simulations. The development of AHWR reactor specific data library has facilitated estimation of fuel cycle parameters like discharge fuel composition, activity and decay heat. The activity in the reprocessed uranium due the decay of bred 232U and it decay product has also been estimated. The results show the rise in activity in reprocessed uranium. The in-situ breeding potential of 233U in AHWR has been estimated.

Publication : Devesh Raj and Umasankari Kannan, "Development of computer code ADWITA and data library for the solution of transmutation chain equations and application to the analysis of nuclear fuel cycles", Annals of Nuclear Energy 164 (2021) 108619

Use of updated delayed neutron spectrum data for reactor simulations

The delayed neutron fraction data has been processed for U-235, U-238, Pu-239, Pu-241, Pu-242, Am-241, Am-243, Cm-242 from ENDF/B-VII.1 and updated explicitly in the transport simulation of reactor lattices using WIMSD code. The delayed neutron fraction and delayed neutron spectrum has been used to estimate the burnup dependent effective delayed neutron fraction, mean generation time and mean lifetime of PHWR and IPWR fuel lattices. Delayed neutron fraction of IPWR decreases by inclusion of contribution from higher actinides while there are no major changes in natural uranium based PHWR lattice.

Publication:: Development of WIMS-Beta with inclusion of more nuclides and estimation of kinetic parameters PHWR and IPWR with same, Anindita Sarkar, Umasankari Kannan, RPDD/GEN/44/30th June2021.

Measurements of 98-Mo(n, g) cross section using photo-neutron source from e-LINAC

Recently the capture cross section of Mo-98 was measured in a Ta-Beo-HDP set-up using photo neutrons from 10 MeV e-LINAC moderated to thermal energies. The neutron flux was about 1.0×10^6 $n/cm^2/s$ for 3 kW power.

Publication : Kapil Deo, Rajeev Kumar and Umasankari Kannan, "Feasibility of producing 99Mo using electron accelerator", 2nd RCM on CRP on New ways of producing Tc-99m and Tc-99 generators (beyond fission and cyclotron methods), May 2019.

90Zr(n, α)87^{m}Sr and 90Zr(n, p)90^{m}Y reaction cross-section measurements

It is proposed to carry out the above reaction cross-section measurements using 9Be(p,n) reaction at the 6M elevation level of the BARC-TIFR Pelletron Linac accelerator facility. The measurements will be carried out using neutron activation method combined with off-line gamma-ray spectroscopy. The proton beam of nearly 5 MeV energies (~ 500nA current) will be used. Neutron fluxes incident on the sample will be monitored using 94Zr present in the sample itself. Additionally, Fe foil will also be placed to monitor the fast neutron fluxes using 54Fe(n, p) reaction. The irradiation may be required for nearly 10 hrs for sufficient activity build-up in the sample.

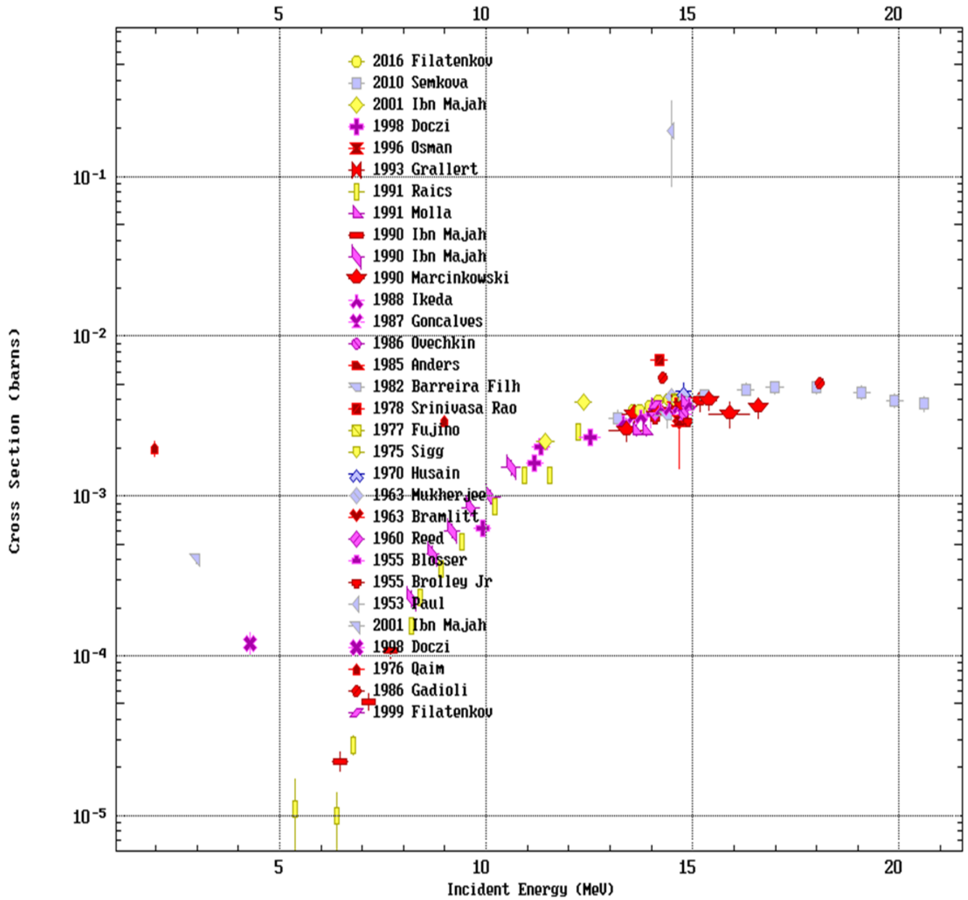

Fig: Measured 90Zr(n, α)87mSr cross-sections in EXFOR database

Activities related to nuclear reaction data and its use for reactor analysis

(Recent publications in nuclear reaction data analysis in national symposium ARP-2022)

1. Analysis of Doppler reactivity (Mosteller) benchmarks using ENDFB8GX library, V. Harikrishnan, R. Karthikeyan and Usha Pal, Proc of Advances in Reactor Physics (ARP-2022), May 19-21, 2022.
2. Stochastic Interpolation of Nuclides to Represent Doppler Broadened Data in Reactor Physics Calculation, Rashbihari Rudra, Rashmi Rai, K. P. Singh and Umasankari Kannan, *ibid.*
3. Lattice Level Sensitivity Analysis of Indian PHWR, Ishi Jain, Manish Raj, Sherly Ray and M.P.S. Fernando, *ibid.*
4. Studies on the Variation of Reactor Kinetic Parameters with Latest ENDF-6 Nuclear Data Libraries, Arun Stanley, Puspendu Hazra, T. Sathiyasheela, K. Devan, *ibid.*
5. Development of a New Neutron Multi-Group Cross Section Set in ABBN Format from the Latest ENDF-6 Files for Fast Reactors, Puspendu Hazra, A. Riyas, K. Devan, *ibid.*
6. Quantification of Nuclear Data Contribution to Uncertainty in Fuel SA Decay Power, G. Pandikumar and A. John Arul, *ibid.*
7. Estimation of Uncertainty in The Control Rod Worth in CANDU PHWR , M. Mohideen Abdul Razak, *ibid.*
8. Dynamic Uncertainty Analysis in the Power Transient of CANDU PHWR, M. Mohideen Abdul Razak, *ibid.*
9. Nuclear Data Sensitivity of VVER-1000 Pin-Cell Benchmark, V. Harikrishnan, Anek Kumar and Usha Pal, *ibid.*
10. Uncertainty and Sensitivity Analysis of Neutron Multiplication Factor in CANDU ReactorM. Mohideen Abdul Razak, P. Ravindra Babu, *ibid.*
11. Theoretical Calculation of Excitation Function of Proton Induced Reaction and Evaluation of Recommended data by TALYS – 1.95 and Empire – 3.2.2 Code , Sourav Mondal and Rebecca Lallunthluangi, *ibid.*
12. Production of Ru-105 and Rh-105 through Proton Induced Reaction on Natural Uranium, Najumunnisa T, M. M. Musthafa, C. V. Midhun, Alok Saxena, P. Surendran, J. P. Nair and Anil Shanbhag, *ibid*.
13. A Study of Alpha-Induced Pre-Equilibrium Neutron Emission in Natural Titanium, Gokul Das H, MM Musthafa, Midhun C V, Swapna B, Vafiya T, Najmunnisa T, F S Shana, Rijin N T, S Dasgupta, J Datta, S Ganesan, S V Suryanarayana, *ibid*.

Activities related to Theoretical nuclear reaction data

1. Collective enhancement in nuclear level density, G. Mohanto, A. Parihari, P. C. Rout, S. De, E. T. Mirgule, B. Srinivasan, K. Mahata, S. P. Behera, M. Kushwaha, D. Sarkar, B. K. Nayak, and A. Saxena. Physical Review C 100, 011602(R) (2019).
2. Probing collective enhancement in nuclear level density with evaporation alpha-particle spectra, G. Mohanto, P. C. Rout, K. Ramachandran, K. Mahata, E. T. Mirgule, B. Srinivasan, A. Kundu, A. Baishya, R. Gandhi, T. Santhosh, A. Pal, S .Joshi, S. Santra, D. Patel, Prashant N. Patil, S. P. Behera, P. Yashwantrao, N. K. Mishra, D. Dutta, A. Saxena, B. K. Nayak , Phys. Rev. C 105, 034607 (2022).
3. Signature of fusion suppression in complex fragment emission: S. Manna et al., Phys. Rev. C 105, L021603 (2022).
4. Search for the Hoyle analogue state in 16O, S. Manna et al.,.Eur. Phys. J A57, 286 (2021).
5. Measurement of light output response in scintillator based neutron detectors using quasi-monoenergetic neutrons: A. S. Roy et al., JINST 16 P07045 (2021).

Thank You Very Much !!

Contributors

- Umasankari Kannan, Head, RPDD, BARC, Member INDC, IAEA.
- Vidya Thakur, now at IAEA.
- Devesh Raj, RPDD, BARC.
- Kapil Deo, RPDD, BARC.
- Dipanwita Dutta, NPD, BARC.
- Gayatri Mohanto, NPD, BARC
- Gopal Mukherjee, PG, VECC