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A BRIEF STATUS UPDATE ON THE NUCLEAR REACTION DATA ACTIVITIES IN BARC DURING 2021-2022

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(With inputs from nuclear data physicists of India)

Introduction

BARC is responsible for broad range of nuclear data activities in India. BARC, Mumbai, is part of DAE (Department of atomic Energy) and collaborates with IAEA-NDS, CERN, NRDC and other organisations to obtain qualified data. Several units of DAE is responsible for theoretical, experimental nuclear physics research and code development for the implementation of Indian nuclear programme. This include nuclear data generation, processing, and use of nuclear data for the reactor system design. The projects are overviewed and supported by DAE scientists as principal collaborator. Many research activities have been done in DAE and collaborative efforts with Indian universities are also taken up. A brief compilation of the different activities on Nuclear Reaction data performed over the past two years is presented here.

1.0 Activity related to EXFOR compilation

BARC has been involved successfully conducted eight DAE-BRNS Workshop cum Theme Meetings on nuclear reaction data and EXFOR compilation of Indian experimental nuclear data. These workshops have given impetus to nuclear data compilation activity and have resulted in substantial contributions to the IAEA-EXFOR database as well as encouraged Indian nuclear experimentalists to endeavour for international reckoning by making EXFOR compilation an integral part of their research, especially in DAE-BRNS supported collaborative research projects on nuclear data activities.

The said workshop and the IAEA supported AASPP (Asia-Africa Science Platform Program) could not be held during last two years due situation prevailing worldwide.

Table 1: Number of new entries compiled since the NRDC 2021 meeting

Sl. No.	Reaction Type	No. of Entries	
1.	Incident Neutron Nuclear Reaction Data	23	
2.	incident Charged Particle Nuclear Data	31	**Total=55**
3.	Incident Photon Nuclear Reaction Data	01	

2.0 A compilation of few esearch projects on experimental nuclear data and nuclear data that are coordinated by BARC

	Title of the Project	Status
1	Thermal Neutron Scattering Data for Materials of Interest in Nuclear Reactors (BeO, graphite and SiC)	Ongoing
2	Measurement Analysis, Evaluation and Compilation of Nuclear Reaction Data at Low and Medium Energy	Completed
3	Measurement of section of metastable states of a few nuclei produced through Photon	Completed
4	Nuclear Structure & Decay Data Evaluation for Nuclear Models and Dosimetric Applications	Completed

3.0 Nuclear Data Processing and Evaluation Work

3.1 Evaluation of neutron cross section data of 100Mo(n,2n)99Mo reaction using EXFOR database

In this work evaluation of neutron cross section data of 100Mo(n, 2n)99Mo reaction is performed using experimental data available in IAEA-EXFOR database library and nuclear model-based data generated using Talys 1.9 code by applying a novel method of combining Kalman filtering technique with Machine Learning (ML) regression algorithms. The neutron cross section data evaluation has been performed after a detailed study of all the EXFOR papers corresponding to 100Mo(n, 2n)99Mo reaction and nuclear model based cross section generation by executing T6 random input files using Talys 1.9 code. The evaluated curve generated is then compared with the existing evaluated curve of 100Mo (n, 2n) 99Mo reaction from nuclear data libraries such as ENDF/B-VIII.0, JEFF-3.3, JENDL-4.0, CENDL-3.1 and TENDL 2017 and found to be in good agreement with them. Chi-square and generalized Chi-square tests were employed to assess the proposed evaluation techniques and found them to be good in estimating evaluated mean values and evaluated uncertainties of cross section.

Publication: Application of Kalman filtering technique for Evaluation of neutron cross section data of ^{100}Mo(n, 2n)^{99}Mo reaction, S. Prasanna Ram, J. Nair, S. V. Suryanarayana and S. Ganesan, Nuclear Inst. and Methods in Physics Research, A 1020 (2021) 16585

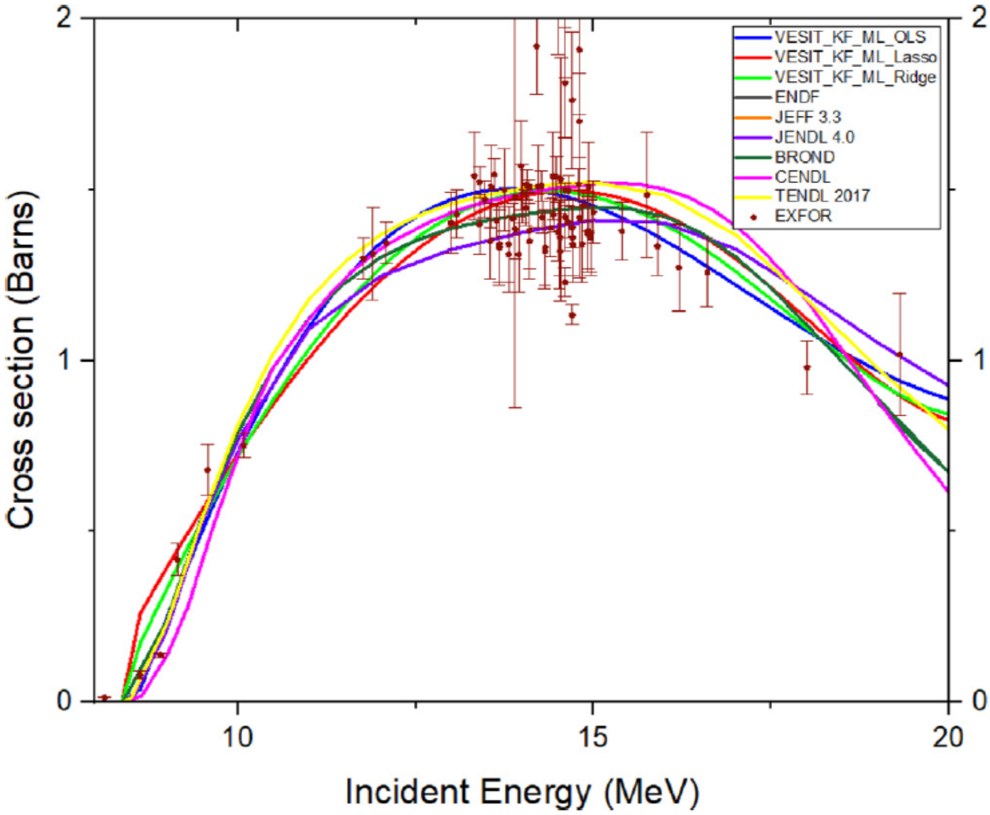

Fig. 10c. Comparison of evaluation curves. Comparison of the evaluation curves of cross-section data of ^{100}Mo (n, 2n) ^{99}Mo reaction generated using KF in combination with ML algorithms of OLS, Lasso and Ridge regression, with the standard evaluated nuclear data libraries such as ENDF/B-VIII.0 [31],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

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3.2 Generation of qualified reaction cross section data for fuel cycle analysis: The current ENDF/B-VII.I based IAEA release of WIMS formatted library contains nuclear data for the 185 nuclides including 35 actinides and 57 fission products 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

3.3 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.1and 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.

4.0 Experiments and Work related to Nuclear Reaction and Data and related Publications.

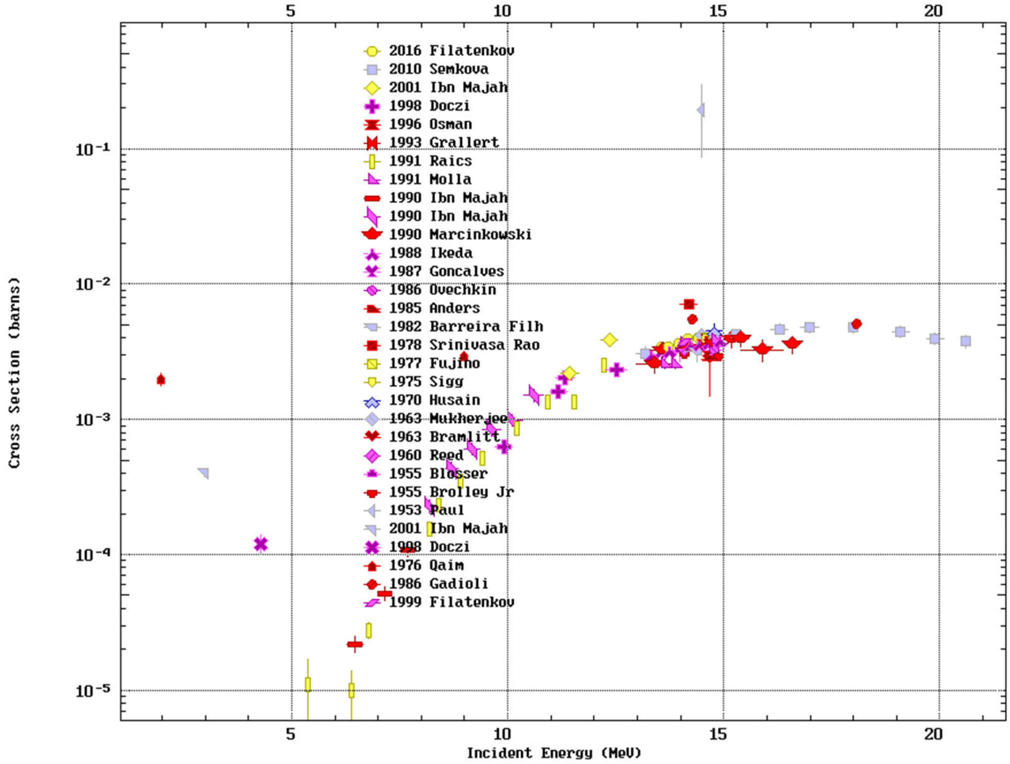
4.1 Measurements of 98-Mo(n,gamma) cross section using photoneutron source from e-LINAC

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 x10^6 n/cm^2/s for 3 kW power. The measured cross section was about was relatively highly that that obtained in thermal reactor spectrum.

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.

4.2 90Zr(n, α)87mSr and 90Zr(n, p)90mY 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.



Measured ^{90}Zr(n, α)^{87m}Sr cross-sections in EXFOR database

4.3 Other activities related to nuclear reaction data and its use for reactor analysis

A few researches on the use of reaction cross section data and its influence on reactor performance are compiled in the recent publications below.

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

10 Uncertainty and Sensitivity Analysis of Neutron Multiplication Factor in CANDU ReactorM. Mohideen Abdul Razak, P. Ravindra Babu.

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,obid

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

4.4 Collective enhancement in nuclear level density

Several experimental investigations have reported evidence of collective enhancement of the nuclear level density and its fadeout. However, a suitable method is needed for experimental determination of the enhancement factor as a function of excitation energy. In this study, neutron spectra were measured in coincidence with evaporatedα particles produced in the reactions 11 B + 181 Ta, 197 Au. The nuclear level density parameter has been extracted for the Os(A ≈ 188) and Pb(A ≈ 204) isotopes by comparing neutron spectra with statistical model prediction. Evidence for collective enhancement has been found for Os nuclei whereas no such enhancement has been seen for Pb nuclei. The energy-dependent enhancement factor has been extracted by simultaneous fitting of the neutron spectra at various excitation energies. Near a temperature of 0.8 MeV, the enhancement starts to fadeout which is lower than the theoretically predicted temperature of 1.4 MeV for 187 Os. Also, free energy surface calculation shows that the 187 Os nucleus undergoes a transition from collective prolate to noncollective oblate shape close to the temperature of 0.8 MeV, corroborating the early fadeout. No such shape transition is seen for 203 Pb.

Publication: 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)

4.5 Probing collective enhancement in nuclear level density with evaporation α particle spectra

Collective enhancement in nuclear level density (CELD) and its fadeout has been studied experimentally using neutron and high energy γ-ray spectra earlier. Attempts to probe CELD with α-particle spectra were made for compound nucleus (CN) 178 Hf in the excitation energy 54–124 MeV, but no signature of CELD was found. The possible reason behind this nonobservance has been discussed in a few subsequent reports. In our previous study, evidence of CELD was found using neutron spectra and enhancement faded away near 25 MeV of excitation energy. This implies that the effect of CELD on α particles, if any, would be found at excitation lower than 25 MeV. With the aim to observe CELD and its fadeout with α-particle spectra, two reactions 12C+116 Sn, 159 Tb, forming CN in different mass region (A ≈ 128 and A ≈ 171) were studied. Evaporation α-particle spectra were measured for the reactions in singles as well as in coincidence with neutrons.

Experimental data were compared with statistical model calculations and inverse level density parameter (k) were obtained from α-particle spectra. As a function of CN excitation energy, the k value showed peak like structure for the reaction 12C+159 Tb which indicates fadeout of CELD. No such evidence was found for the reaction 12C+116 Sn. Collective enhancement factor for daughter nuclei populated in 12C+159 Tb reaction was extracted. Critical energy of the fadeout was found to be similar to that of mass A ≈ 188 region.

Publication: Probing collective enhancement in nuclear level density with evaporation α -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).

4.6 Signature of fusion suppression in complex fragment emission

The effect of weak binding of 9 Be on complete fusion has been explored through the study of complex fragment emission in 20 Ne+ 9 Be reaction. The yields of the fragments 6,7 Li and 7,9 Be emitted from the excited compound nucleus 29 Si ∗ have been compared with the respective statistical model predictions. Emission of same fragments from another close-by compound nucleus 28 Si ∗ at similar excitation energy, formed by the fusion of two strongly bound nuclei, 16 O+ 12 C, has been studied for comparison. It has been observed that for the system 16 O+12 C, the yields of 6,7 Li and 7,9 Be fragments are close to the predictions of the statistical model. However, for the 20 Ne+ 9 Be system, although the experimental yield pattern follows the statistical model prediction, there is substantial reduction in yield for all detected fragments. These observations have been attributed to the suppression of complete fusion in 20 Ne+ 9 Be system due to the weak binding of 9 Be, a dynamical effect which is not incorporated in the conventional statistical models. It is the first time that a clear signature of the suppression of complete fusion in light systems involving weakly bound nucleus has been observed in complex fragment emission from fully equilibrated composite produced in fusion well above the barrier.

Publication: Signature of fusion suppression in complex fragment emission: S. Manna et al., Phys. Rev. C 105, L021603 (2022).

4.7 Evidence for competing bi-faceted compound nucleus fission modes in 232 Th(α, f) reaction

Relative isotopic yield distributions have been extracted for nine correlated fission fragment pairs following a detailed analysis of prompt $\gamma - \gamma$ coincidence events from 232 Th(α ,f) reaction at E lab = 30 MeV. Simultaneously, the charge and mass yield distributions of the even-even fission fragments have been obtained from the measured relative isotopic yields. The onset of a triple-hump structure is seen in the extracted charge as well as mass yield distributions of the fragments. The results are consistent with the two-mode fission hypothesis of compound nucleus and in good agreement with the theoretical predictions, based on relevant fission models. The detailed results provide experimental evidence for the presence of two distinct compound nucleus fission modes, where the asymmetric and symmetric fission components are 83% and 17%, respectively. An average neutron multiplicity value of 4.60 ± 0.09 has been obtained, and the extracted neutron multiplicity distribution pattern corroborates the observed features of the multifaceted fission modes. Comparing the measured yield distributions following the 232 Th(α ,f) surrogate reaction, which produces 236 U ∗ at an excitation energy of 21.5 MeV, with that of the direct reaction of 14 MeV neutron induced fission of 235 U, an increase of about 11% in the yield of the symmetric component has been observed.

Publication: Evidence for competing bi-faceted compound nucleus fission modes in 232Th(a, f) reaction, Aniruddha Dey et. al., Phys. Lett. B 825, 136848 (2022).

4.8 Search for the Hoyle analogue state in 16 O

The Hoyle analogue state in 16 O was explored by inelastic scattering of 45 MeV αs on a Mylar target. The break up 4αs of 16 O have been detected in coincidence with the inelastically scattered α beam particle to probe the Hoyle analogue state of 16 O in complete kinematics, for the first time. The data have been analysed for all possible configurations and the excitation function of 16 O has been reconstructed directly from 4α as well as for specific decay channels like 12 C(0 + 2) + α, 12 C(3 − 1) + α and 8 Be + 8 Be. Several previously known states have been observed above the 4α break-up threshold (14.44 MeV) in the above mentioned decay channels. However, the signature of the 15.1 MeV state, most preferable to be the Hoyle analogue state according to the theoretical prediction, remains inconclusive.

Publication: Search for the Hoyle analogue state in 16O, S. Manna et al.,.Eur. Phys. J A57, 286 (2021).

4.9 Measurement of light output response in scintillator based neutron detectors using quasi-monoenergetic neutrons

Conventional liquid scintillator (BC501A) and pulse shape discrimination capable plastic scintillator (EJ-299-33A) based detector of dimension; 5 inch diameter and 5 inch long, have been used to study pulse height response for quasi-monoenergetic neutrons of energy in the range 3 to 15 MeV generated using 7 Li(p,n) 7 Be reaction. Scintillation light output of plastic scintillator having pulse shape discrimination property is found to be 75% of the liquid scintillator at neutron energy (maximum recoil proton energy) of 3MeV which improves with the increase in energy. Functional dependence of the scintillation light output in terms of recoil protons energy has been determined for the liquid and the plastic scintillator detectors for neutron energy in the range 3 to 15MeV. This functional dependences were used in the Geant4 simulation to calculate the pulse height responses at several neutron energies.

Publication: Measurement of light output response in scintillator based neutron detectors using quasi-monoenergetic neutrons: A. S. Roy et al., JINST 16 P07045 (2021).

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