Research activities at BHU and with JINR, Dubna

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Plan of talk

1. Who we are

2. What we are doing at BHU

3. Research activities at JINR, Dubna

4. Outcome of the collaboration

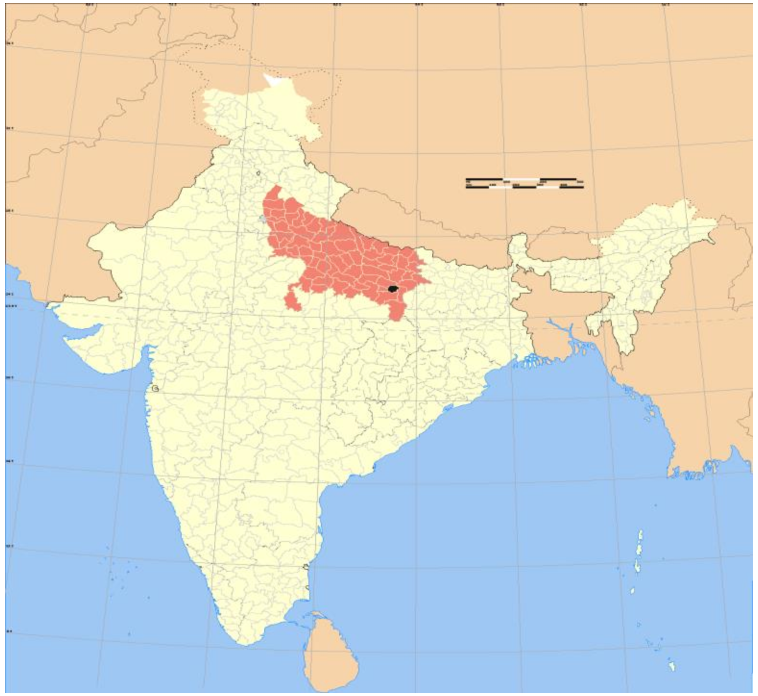
5. Future plans

Banaras Hindu University, Varanasi, India

- Varanasi is located in the middle-Ganges valley in the southeastern part of the state of Uttar Pradesh, lies on the left bank of the river. It is 692 kilometers (430 mi) to the southeast of India's capital New Delhi.

- Banaras Hindu University was founded in 1916 with area1300 acres (5.3 Km^2). It is the largest residential university of India having more than 30,000 students, 1700 faculty members and 144 departments.

- A large number of students from U.S.A, Europe, Asia, Middle East, Africa etc., come to BHU.



Department of Physics, BHU

- The Department of Physics is having 65 faculties with 6 specializations and more than 160 PhD students.

We are having a vibrant group of seven PhD students from different parts of India and working on very interesting Nuclear Physics problems and publishing their work in highly repute research journals.

1. Heavy Ion fusion–fission dynamics by using 15 UD Pelletron at IUAC, New Delhi, India.

2. Neutron scattering experiments at BARC, Mumbai, India

3. Surrogate reaction dynamics by using BARC-TIFR, Pelletron facility Mumbai

4. Alpha and Proton scattering experiments at Variable Energy Cyclotron (VECC), Kolkata

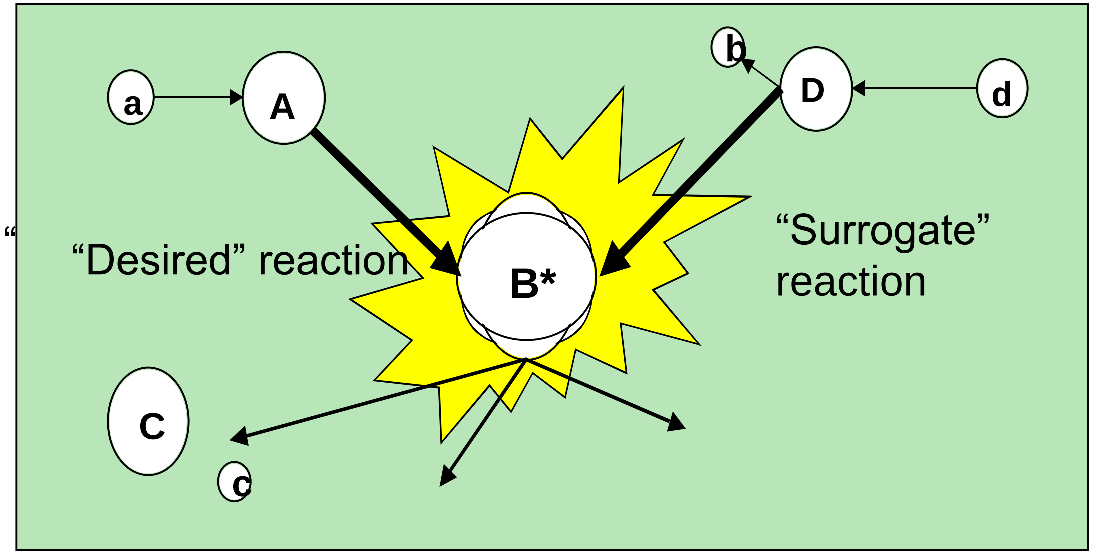
5. Neural networks and Nuclear Physics

Study of the surrogate ratio method by determination of ^{56}Fe (n,xp) cross sections

The cross section $\sigma_{\alpha\chi}$ for the “desired” two-step reaction

a + A --> B* --> c + C

can be determined indirectly with the Surrogate method.



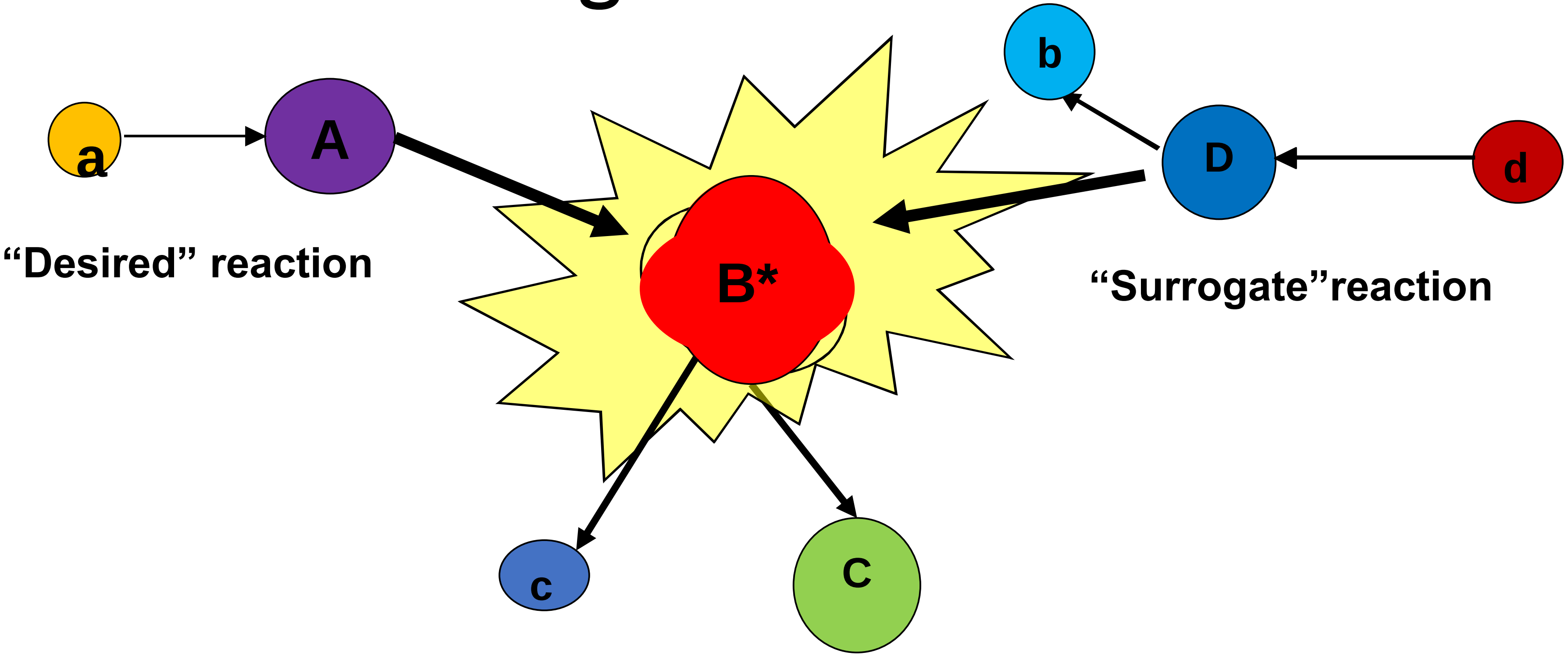
Form the compound nucleus B* via an alternative (“Surrogate”) reaction:

d + D --> b + B*

Then combine the measured decay probabilities for:

B* --> c + C + …

Absolute surrogate method

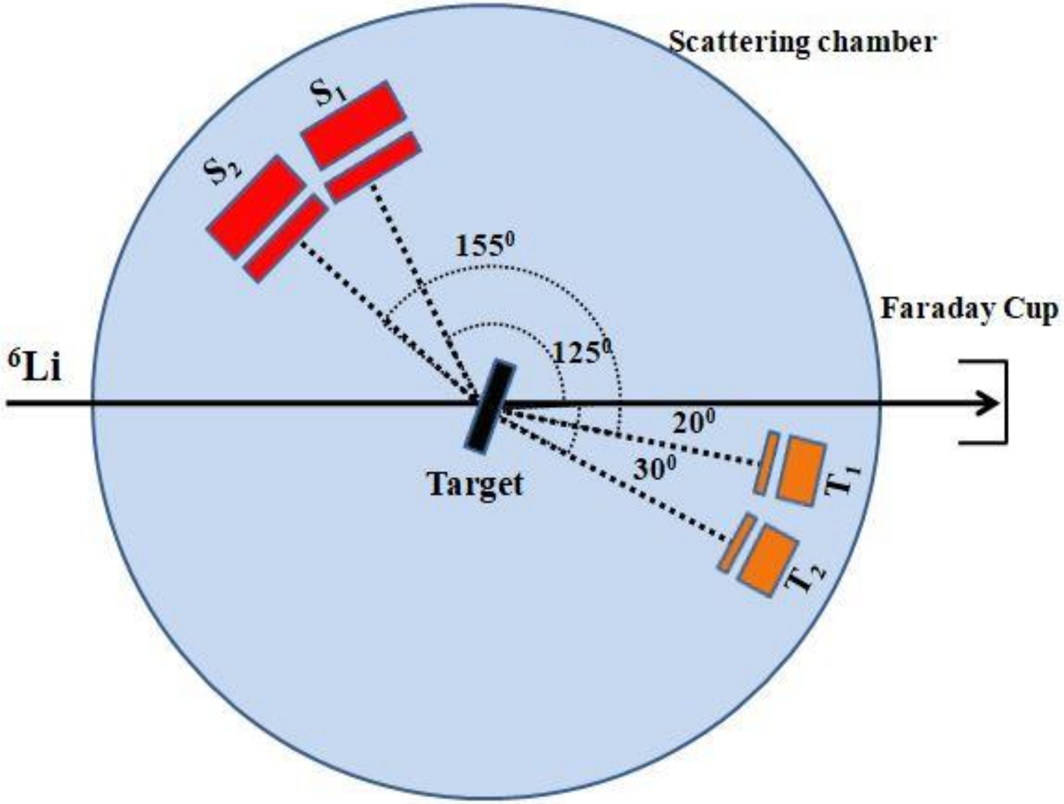


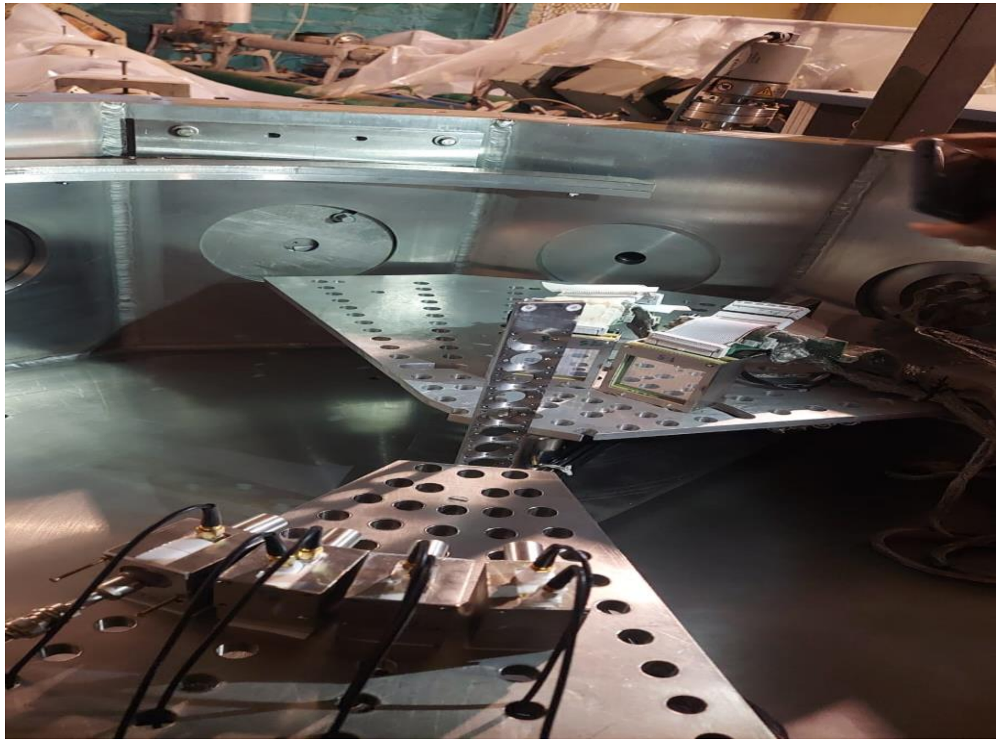
“Desired” reaction

“Surrogate”reaction

$$\sigma_{A(a,c)C} = \sigma^{CN}_{a+A}(E_x)P_c(E_x)$$

Requirements





Chiba-Iwamoto condition

1. Spin of CN is less than 10 ħ
2. Spin distribution of two reactions → similar

Methodology

Desired reaction: $^{56}Fe(n,xp)$

Surrogate reaction:
$^{6}Li + ^{55}Mn \rightarrow ^{4}He + ^{57}Fe^* \rightarrow ^{56}Fe\ (n, xp)$

$E(^{6}Li)$=25 MeV

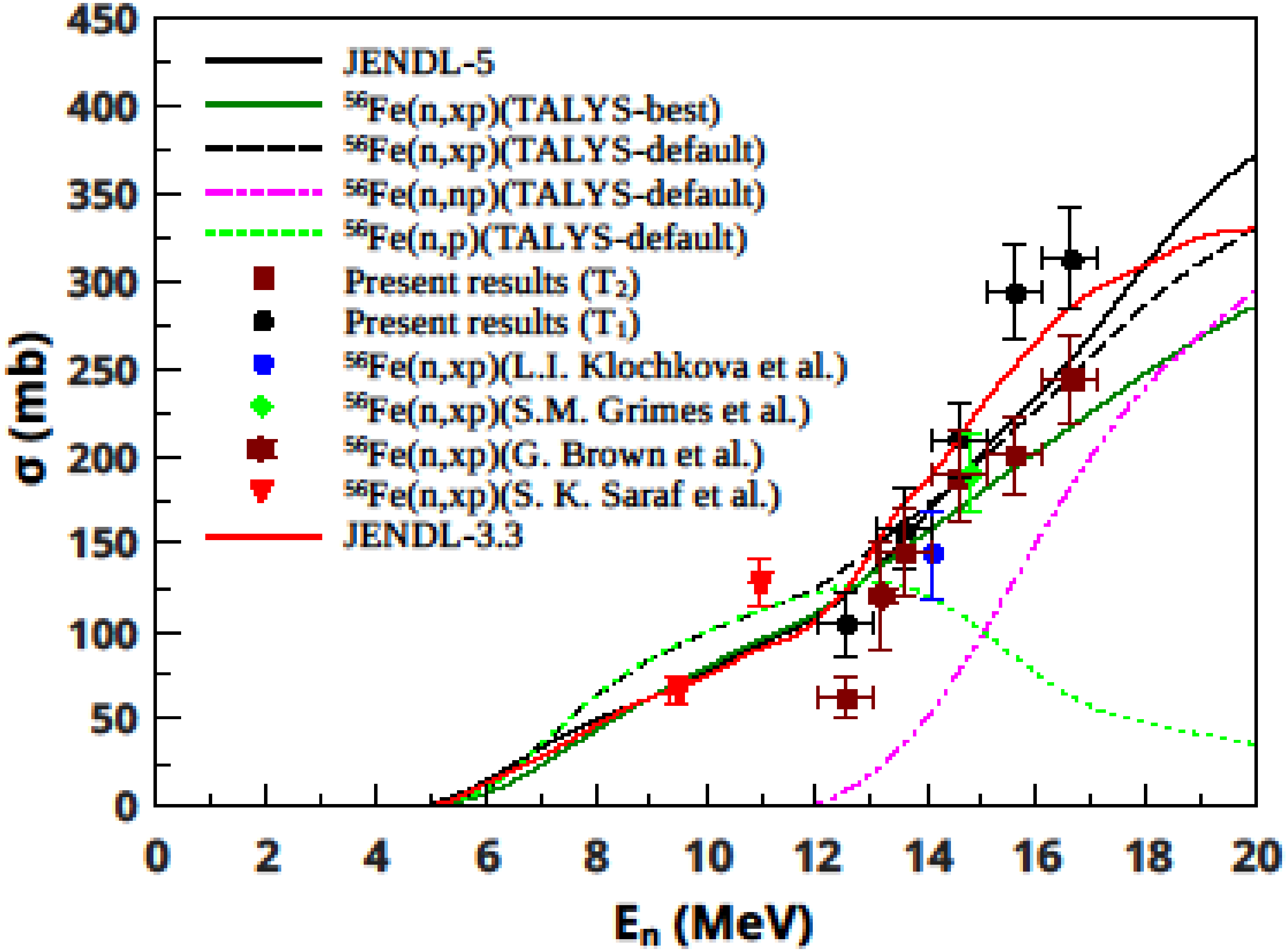
Reference reaction : $^{52}Cr(n,p)$

Surrogate reaction:
$^{6}Li + ^{51}V \rightarrow ^{4}He + ^{53}Cr^* \rightarrow ^{52}Cr(n,xp)$

$E(^{6}Li)$=25 MeV

$$\frac{\sigma^{^{56}Fe(n,xp)}(E^*)}{\sigma^{^{52}Cr(n,xp)}(E^*)} = \frac{\sigma_{CN}^{n+56Fe}(E^*)P_{xp}^{^{57}Fe}(E^*)}{\sigma_{CN}^{n+52Cr}(E^*)P_{xp}^{^{53}Cr}(E^*)}$$

$$P_{xp}^{CN}(E^*) = \frac{N^{\alpha-p}(E^*)}{N^{\alpha}(E^*)}$$

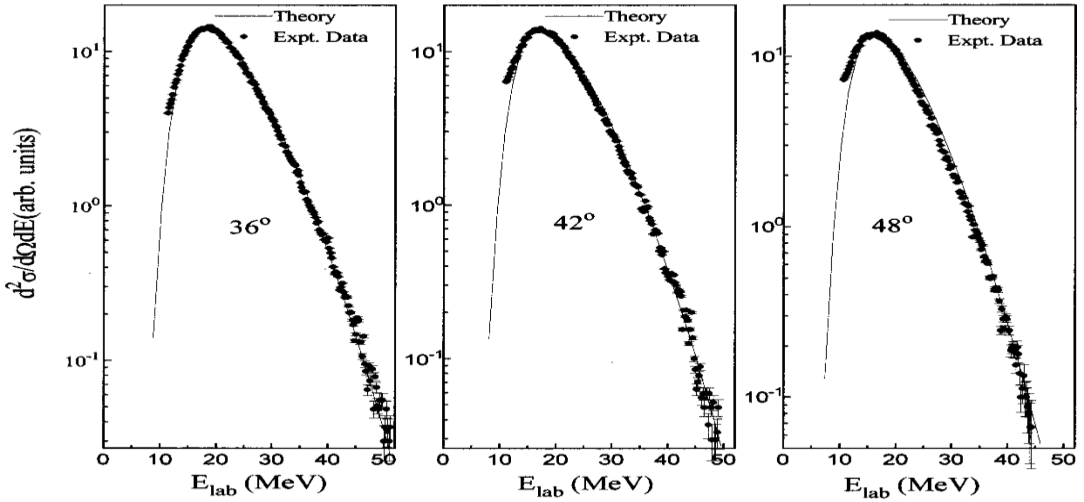


Revised manuscript under consideration in Phys Lett B

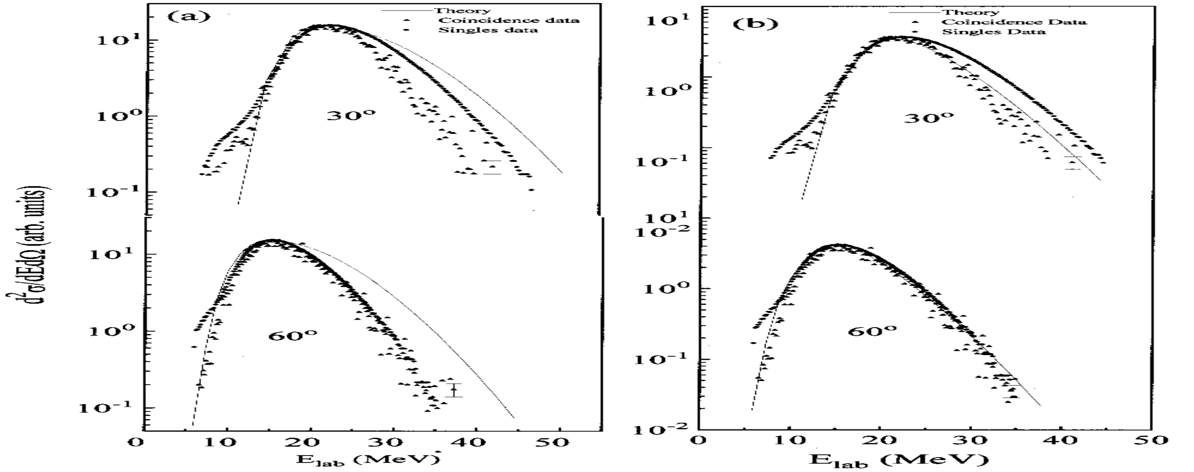
Investigation of Weisskopf-Ewing approximation for the determination of (n,p) cross sections using the surrogate reaction technique, Aman Sharma, Ajay Kumar, Phys. Rev. C, 105, 014624, (2022).

The Weisskopf-Ewing approximation is not valid for the (n,xp) reactions because decay probabilities are highly spin dependent.

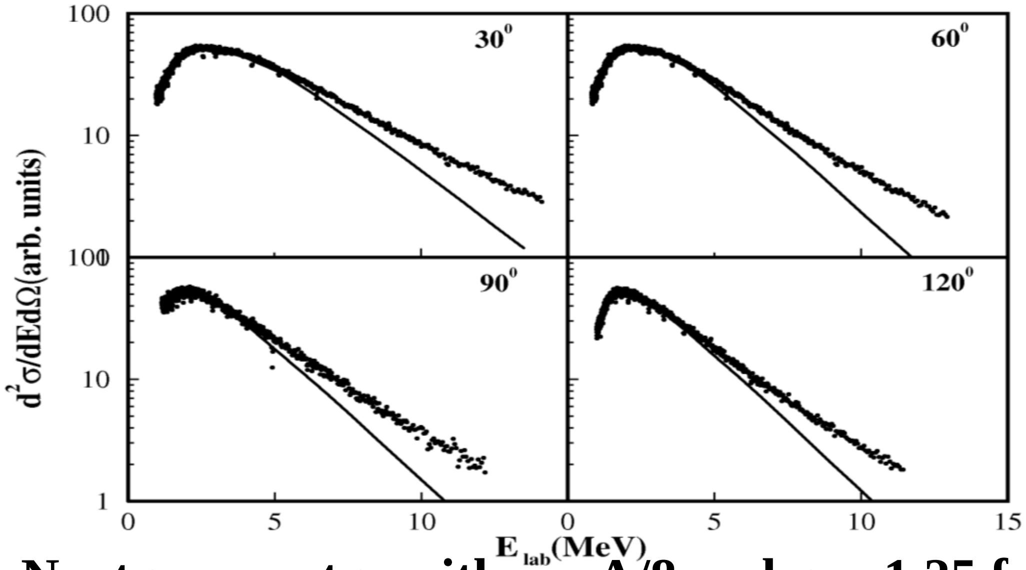
Study of heavy ion fusion dynamics



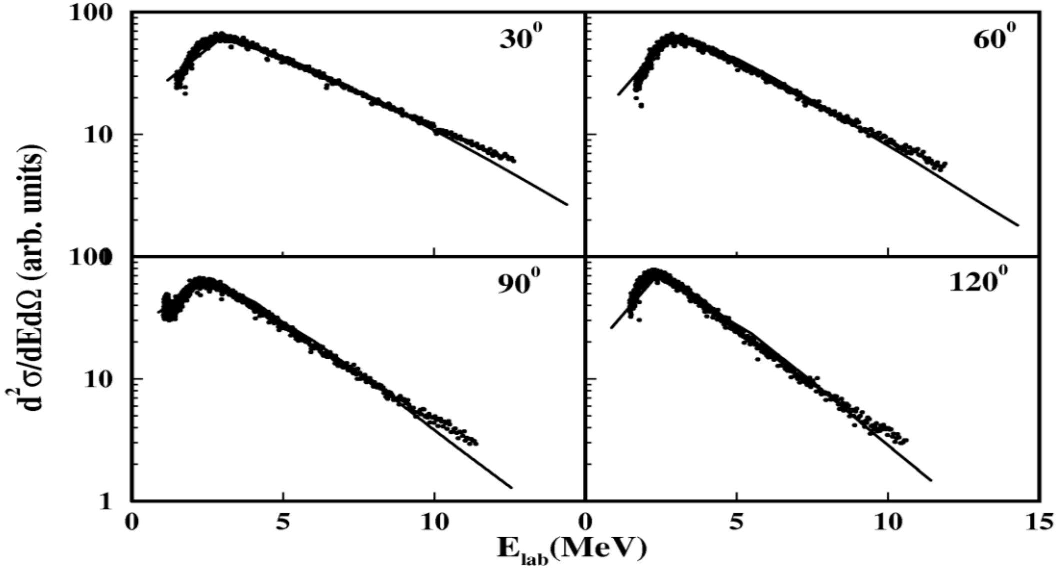
α-spectra with ℓ_{max}=48ħ for ^{16}O+ ^{54}Fe at 110 MeV.



α-spectra for ^{28}Si+^{51}V.(a)ℓ_{max}= 56ħ(b) ℓ_{max} = 30ħ



Neutron spectra with a = A/8 and r_0 = 1.25 for ^{31}P + ^{45}Sc with ℓmax = 39ℏ at E_{lab} = 112 MeV.



Neutron spectra using r_0 = 1.25 and a = A/8 for ^{12}C + ^{64}Zn with ℓmax = 39ℏ at E_{lab} = 85 MeV.

Effect of energy variation on the dissipative evolution of the system in heavy-ion fusion reactions

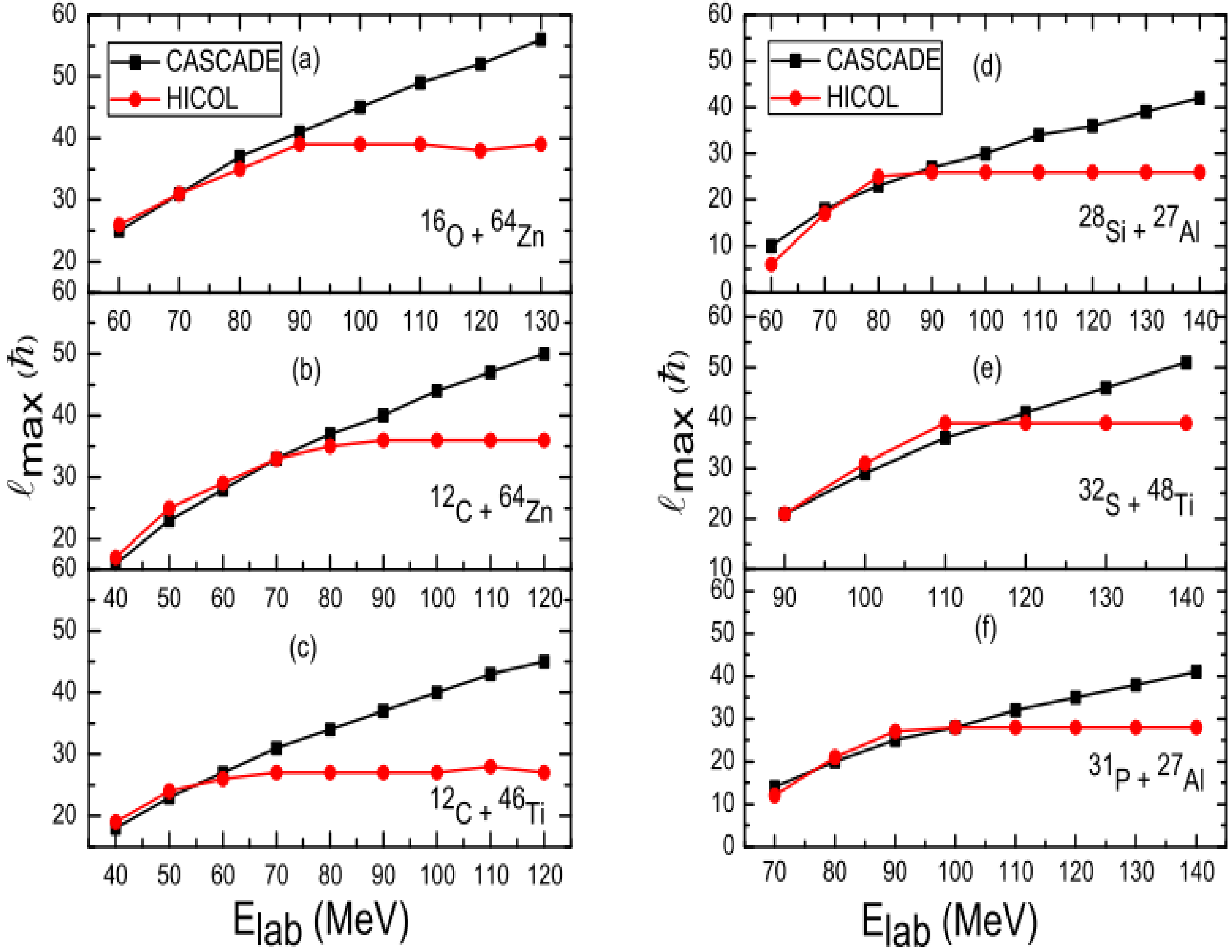
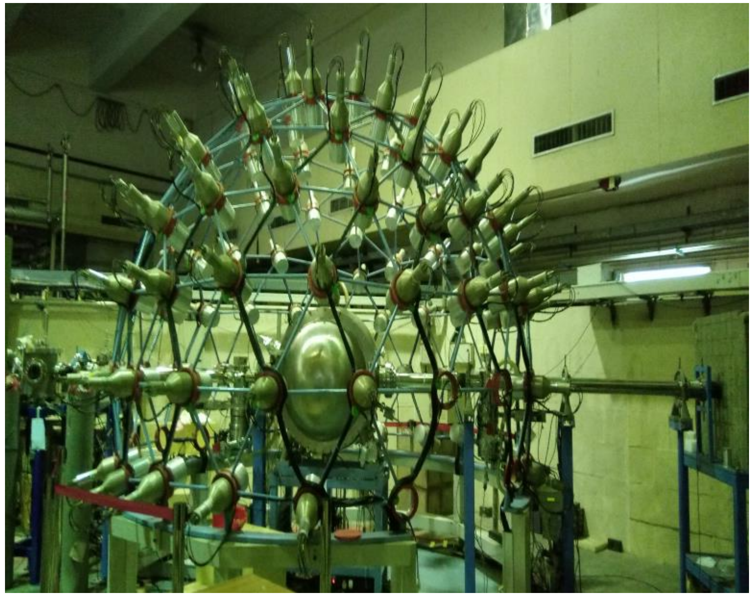


FIG. 4. Variation of angular momentum l_{max} with respect to incident energy E_{lab} for asymmetric systems (a)–(c) and symmetric systems (d)–(f).

N.K. Rai and **Ajay Kumar**, Phys. Rev. C **98**, 024626 (2018).

- ➢ **Dissipation in the entrance channel increases with the projectile energy and causes the angular momentum hindrance in both the symmetric and asymmetric systems at the higher energy.**
- ➢ **The dissipative behavior of the fusing nuclei also depends on the entrance channel parameters.**
- ➢ **We observed that with increasing value of mass asymmetry angular momentum hindrance decreases linearly, and angular momentum hindrance increases linearly with an increase in the coulomb interaction term (ZpZt).**

Measurement of neutrons multiplicity to investigate the role of entrance channel parameters on the nuclear dissipation



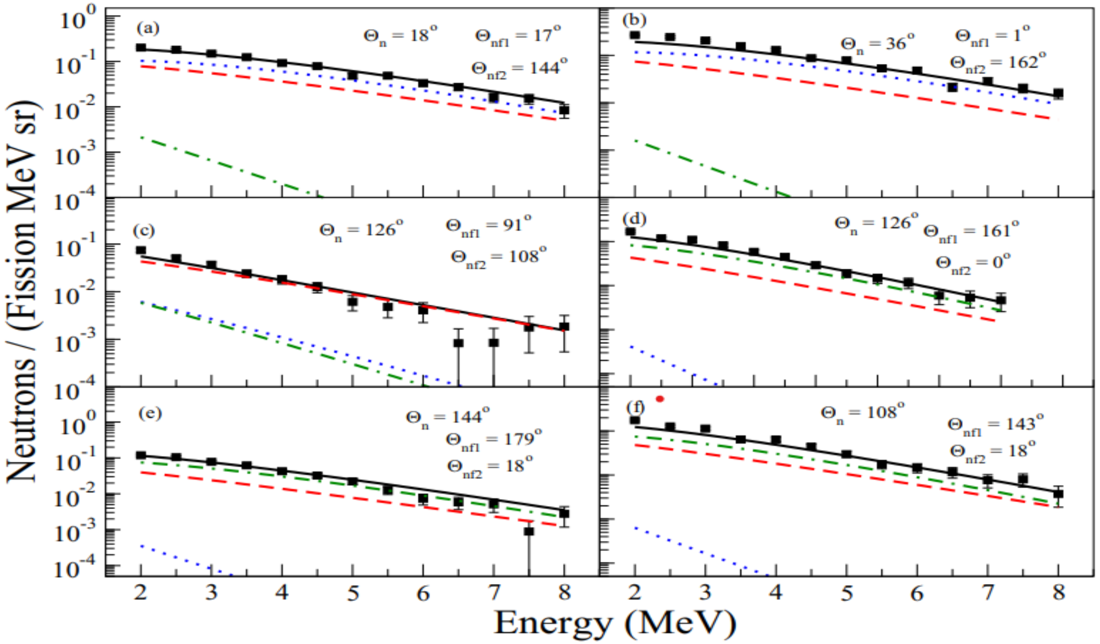
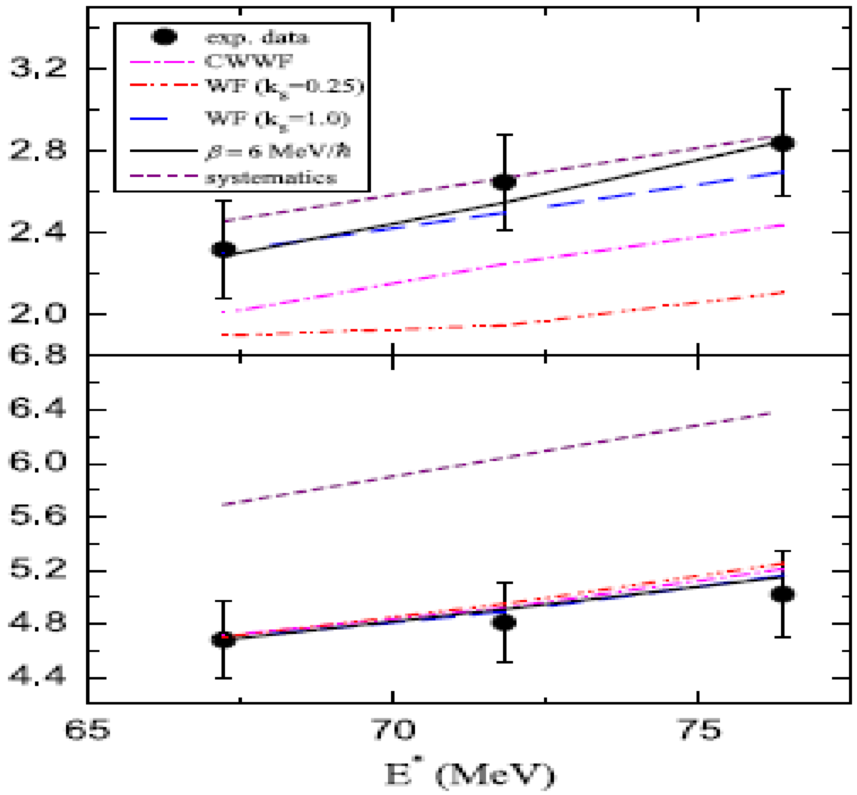


FIG. 1. Neutron multiplicity spectra (filled squares) at various angles for the reaction ^{18}O + ^{186}W at $E_{\mathrm{lab}} = 106.51$ MeV along with the fits for the pre-scission (dashed lines) and post-scission contributions from the one fragment (dotted lines) and that from the other (dotted-dash lines) are shown. Here, the solid black line represents the total contribution.

Measured the pre- and post-scission neutron multiplicity for18O + 186W and compared with 16O + 181Ta, existing in the literature. Nuclear dissipation decreases with the increasing value of the entrance channel mass asymmetry. . In the present case, it was also verified that nuclear dissipation increases with the increasing value of the Coulomb factor ZPZT as mentioned in our theoretical work (PRC 2018).

N.K. Rai and **Ajay Kumar**, Phys. Rev. C **100**, 014614 (2019).

Inference on fission timescale from neutron multiplicity measurement in ^{18}O + ^{184}W



N.K. Rai, and **Ajay Kumar,** Journal of Physics G: Nuclear and Particle physics, **49**, 035103 (2022).

- **The study establishes the role of dynamics in the fission process. Particularly, the predicted large fission time and its behaviour with the excitation energy are shown to depend strongly on the neutron evaporation process and the associated dynamical delays.**

Experimental work based on neutron induced reaction with different target material at PURNIMA, BARC, Mumbai, India

Table.1 Experimentally determined cross section with their uncertainty and correlation matrix at a neutron energy 14.92 ± 0.02 MeV.

Reaction	Present data (b)	Correlation matrix		
$^{65}Cu(n,\alpha)^{62m}Cu$	0.00404 ± 0.00059	1.000		
$^{41}K(n,\alpha)^{38}Cl$	0.02509 ± 0.00260	0.1451	1.000	
$^{65}Cu(n,2n)^{64}Cu$	1.03082 ± 0.11776	0.1237	0.2119	1.000

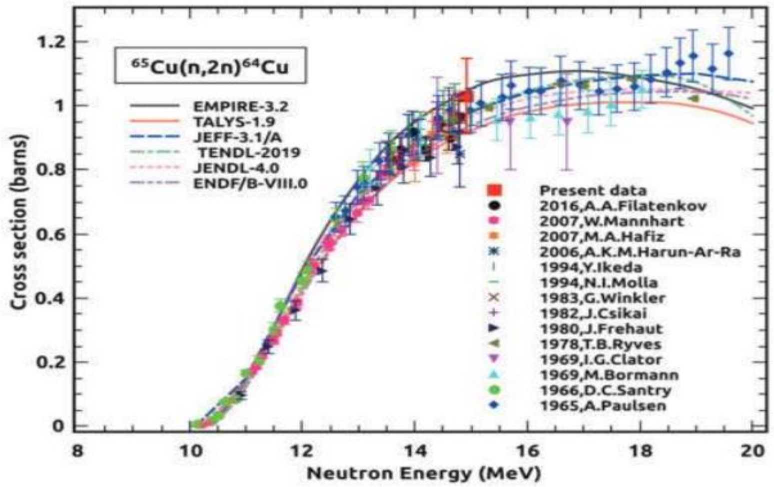


Fig. 1 Comparison of the experiment result of the 65Cu(n,2n)64Cu reaction with the literature data, theoretically predicate results and evaluated nuclear data. (CPC 46, 014002, 2022)

List of Publications from experimental work at PURNIMA, BARC, Mumbai.

1. Measurement of (n,γ), (n,p), and (n,2n) reaction cross sections for sodium, potassium, copper, and iodine at neutron energy 14.92 ± 0.02 MeV with covariance analysis, A. Gandhi & **Ajay Kumar**. Physical Review C 102, 014603 (2020).
2. Measurement of (n,α) and (n,2n) reaction cross sections at a neutron energy 14.92 ± 0.02 MeV for potassium and copper with uncertainty propagation, A. Gandhi & **Ajay Kumar**. Chinese Physics C 46, 014002 (2022).

Fig. 2 PURNIMA neutron generator (Experimental set up).

Experimental work based on neutron induced reaction with different target material at Folded Tandem Ion Accelerator, BARC, Mumbai, India

E_n (MeV)	Present data (mb)	Correlation matrix		
1.67 ± 0.14	10.8476 ± 1.1544	1.000		
2.06 ± 0.14	12.2408 ± 0.9994	0.1503	1.000	
2.06 ± 0.14	8.2430 ± 0.7168	0.1163	0.1587	1.000

1. Measurements of neutron capture cross sections on 109Ag at 0.53, 1.05, 1.66 MeV, M Upadhyay & **Ajay Kumar**. IEEE, 1-4, 2023.
2. Measurement of neutron induced reaction cross-section of ^{99}Mo, M. Upadhyay & **Ajay Kumar**. Journal of Physics G: Nuclear and Particle Physics, (September 2023).
3. Neutron radiative capture cross section for sodium with covariance analysis, A. Gandhi & **Ajay Kumar**. The European Physical Journal A 57, 1 (2021).
4. Neutron capture reaction cross section measurement for iodine nucleus with detailed uncertainty quantification, A. Gandhi & **Ajay Kumar**. The European Physical Journal Plus 136, 819 (2021).
5. Measurement of neutron induced reaction cross-section of ^{99}Mo, **Ajay Kumar** et al, Journal of Phys G, Oct 17, 2023

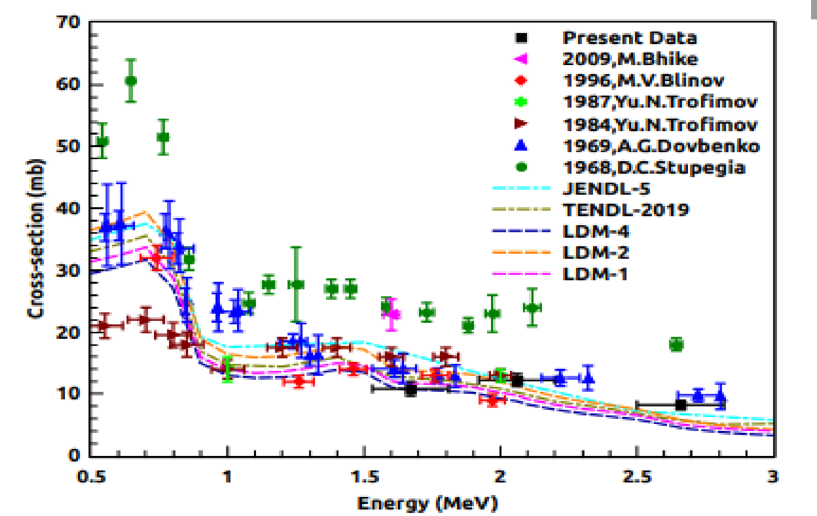


Fig.1 Cross-section of 98Mo(n,γ) 99Mo reaction measured in the present work compared with Exfor database, different level density models and different evaluated data libraries. (JPG, September, 2023)

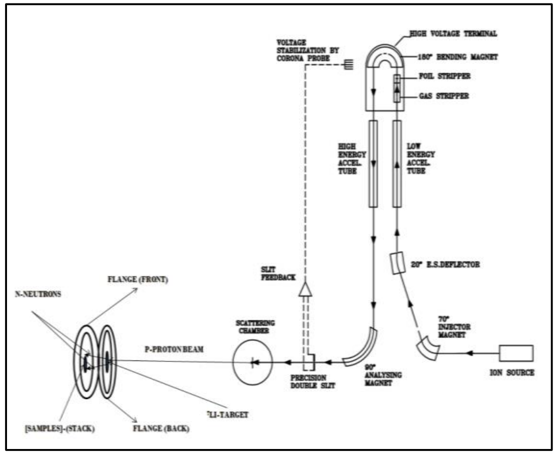
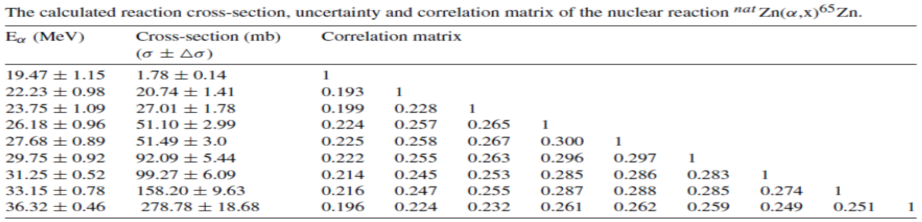


Fig. 2 FOTIA tandem accelerator (Experimental set up).

Fig. 3 Experimental set-up for the offline γ-ray spectroscopy using HPGe detector system.

Experimental work based on alpha indued reaction with different targets at Variable Energy Cyclotron Center (VECC), Kolkata, India from 2022 to till now

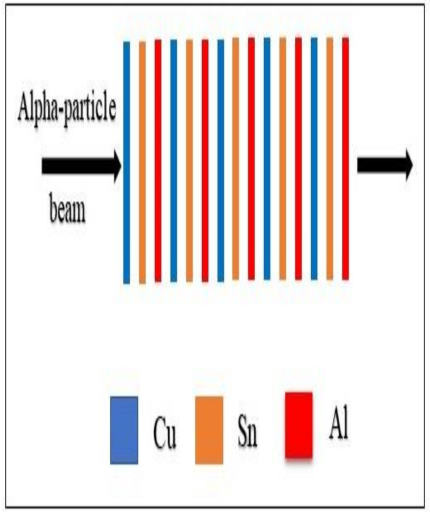
Table.1



The calculated reaction cross-section, uncertainty and correlation matrix of the nuclear reaction $^{nat}Zn(\alpha,x)^{65}Zn$.

E_α (MeV)	Cross-section (mb) ($\sigma \pm \Delta\sigma$)	Correlation matrix								
19.47 ± 1.15	1.78 ± 0.14	1								
22.23 ± 0.98	20.74 ± 1.41	0.193	1							
23.75 ± 1.09	27.01 ± 1.78	0.199	0.228	1						
26.18 ± 0.96	51.10 ± 2.99	0.224	0.257	0.265	1					
27.68 ± 0.89	51.49 ± 3.0	0.225	0.258	0.267	0.300	1				
29.75 ± 0.92	92.09 ± 5.44	0.222	0.255	0.263	0.296	0.297	1			
31.25 ± 0.52	99.27 ± 6.09	0.214	0.245	0.253	0.285	0.286	0.283	1		
33.15 ± 0.78	158.20 ± 9.63	0.216	0.247	0.255	0.287	0.288	0.285	0.274	1	
36.32 ± 0.46	278.78 ± 18.68	0.196	0.224	0.232	0.261	0.262	0.259	0.249	0.251	1

1. Measurement of alpha-induced reaction cross-sections on ^{nat}Mo with detailed covariance analysis, M Choudhary & **Ajay Kumar.** The European Physical Journal A 58(5), 1-10 (2022).
2. Measurement of excitation functions for $^{nat}Cu(\alpha, x)$ reactions with detailed covariance analysis, M Choudhary & **Ajay Kumar.** Journal of Physics G: Nuclear and Particle Physics 50(1), 015103 (2022).
3. Measurement of alpha-induced reaction cross-sections for ^{nat}Zn with detailed covariance analysis, M Choudhary & **Ajay Kumar.** Nuclear Physics A 1038, 122720 (2023).
4. Excitation functions of alpha-particle induced nuclear reactions on ^{nat}Sn, M Choudhary & **Ajay**



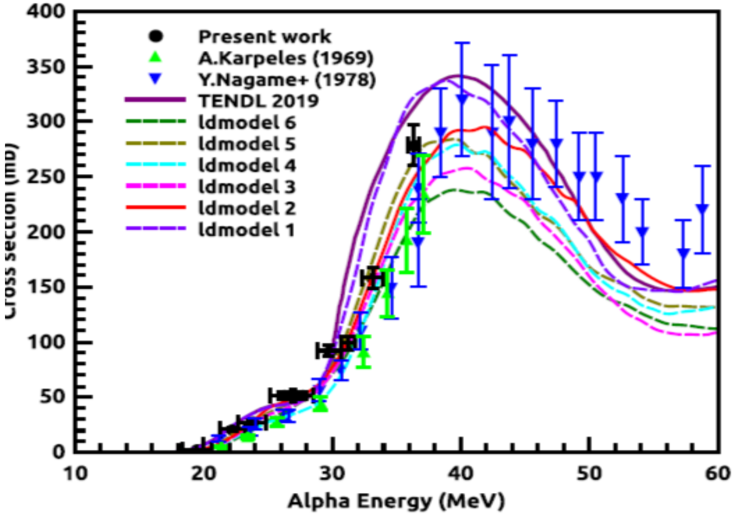
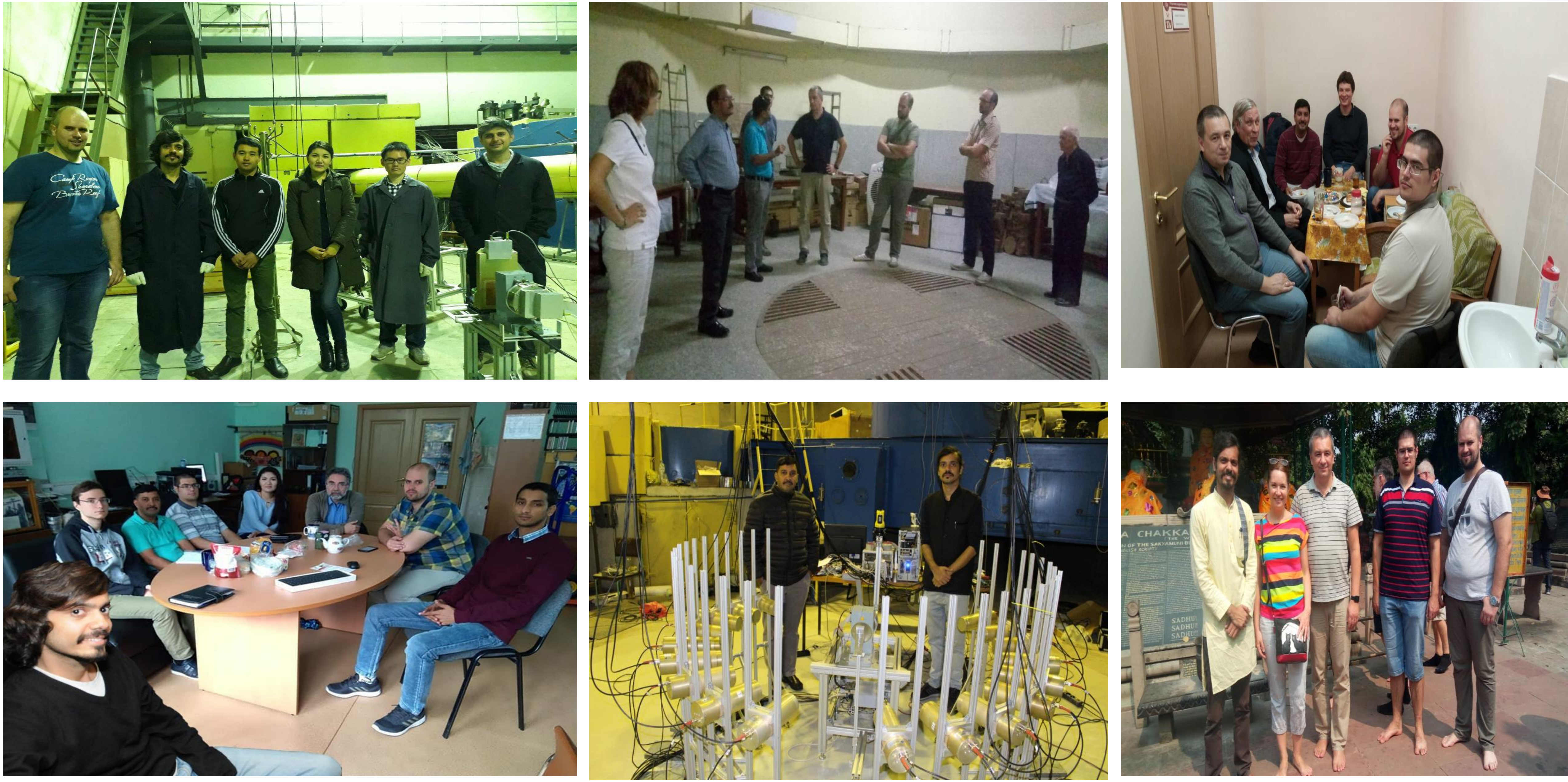


Fig.1 Cross sections for $^{nat}Zn(\alpha,x)^{65}Zn$ reaction from this study in comparison of the available experimental data from EXFOR and theoretical calculation from TALYS. (Nuclear Physics A, 1038, 122720.)

Fig. 2 A close view photograph of the beam line

Fig. 3 A picture during the experiment at VECC, Kolkata, India

Some pictures of the work under BHU-Russian Collaboration



List of Publications under Indo-Russian Collaboration

1. Studying of 14.1 MeV neutrons inelastic scattering on light nuclei, N.A. Fedorov, T.Y. Tretyakova, D.N. Grozdanov, V.M. Bystritskiy, Y.N. Kopatch, I.N. Ruskov, V.R. Skoy, N.I. Zamyatin, D. Wang, F.A. Aliev, C. Hramco, A. Gandhi, **A. Kumar**, M.G. Sapozhnikov, Y.N. Rogov, E.A. Razinkov and S.Dabylova, Memoirs of the Faculty of Physics, 2, (2018).

2. Measurements of the gamma-quanta angular distributions emitted from neutron inelastic scattering on 28Si, N.A. Fedorov, D.N. Grozdanov, V.M. Bystritskiy, Yu.N. Kopach, I.N. Ruskov, V.R. Skoy, T.Yu. Tretyakova, N.I. Zamyatin, D. Wang, F.A. Aliev, C. Hramco, A. Gandhi, **A. Kumar**, S. Dabylova, E.P. Bogolubov and Yu.N. Barmakov, EPJ web conferences, 177, P02002, (2018).

3. Measurement of Angular Distributions of Gamma Rays from the Inelastic Scattering of 14.1-MeV neutrons by Carbon and Oxygen Nuclei, D.N. Grozdanov, N.A. Fedorov, V.M. Bystritski, Yu.N. Kopach, I.N. Ruskov, V.R. Skoy, T.Yu. Tretyakova, N.I. Zamyatin, D. Wang, F.A. Aliev, C. Hramco, A. Gandhi, **A.Kumar**, S. Dabylova, E.P. Bogolubov, Yu.N. Barmakov, Physics of Atomic Nuclei, Vol. 81, No. 5, pp. 588–594 (2018).

4. Evaluation of the nuclear excitation functions of fast neutron-induced reactions on 52Cr and 56Fe isotopes A. Gandhi, V. Kumar, N. K. Rai, P. K. Prajapati, B. K. Nayak, A.Saxena, B. J. Roy, N. L. Singh, S. Mukherjee, Yu. N. Kopatch, I. N. Ruskov, D. N.Grozdanov, N. A. Fedorov & **A. Kumar**, Indian J. Phys 93(10) 1345–1351 (2019).

5. Cross section calculation of (n,p) and (n,2n) nuclear reactions on Zn, Mo and Pb isotopes with ~ 14 MeV neutrons, A. Gandhi, A. Sharma, Yu. N. Kopatch, N. A. Fedorov, D. N. Grozdanov, I. N. Ruskov, and **A. Kumar**, Journal of Radioanalytical and Nuclear Chemistry 322: 89–97 (2019).

6. Investigation of Inelastic Neutron Scattering on 27Al Nuclei, N. A. Fedorov, T. Yu. Tretyakova, V. M. Bystritsky, Yu. N. Kopach, I. N. Ruskov, V. R. Skoy, D. N. Grozdanov, N. I. Zamyatin, W. Dongming, F. A. Aliev, K. Hramco, **A. Kumar**, A. Gandhi, S. Dabylova, D. I. Yurkov, Yu. N. Barmakov, Physics of Atomic Nuclei 82 (4), 343 -350 (2019).

7. Measurement of the yield and angular distributions of γ-rays originating from the interaction of 14.1 neutrons with chromium nuclei, D. N. Grozdanov, N. A. Fedorov, Yu. N. Kopach, V. M. Bystritsky, T. Yu. Tretyakova, N. Ruskov, S. Dabylova, F. A. Aliev, K. Hramco, N.A. Gundorin, D. I. Dashkov, E.P. Bogolyubov, D. I. Yurkov,I.V. Zverev,A. Gandhi and **A. Kumar**, Physics of Atomic Nuclei 83 (3), 384–390, (2020).

8. Measuring the yields and angular distributions of gamma quanta from the interaction between 14.1 MeV neutrons and magnesium nuclei, N. A. Fedorov, D. N. Grozdanov, Yu. N. Kopach, V. M. Bystritsky, T. Yu. Tretyakova, I. N. Ruskov, V.R. Skoy, S. Dabylova, F. A. Aliev, K. Hramco, N.A. Gundorin, D. I. Dashkov, E.P. Bogolyubov, D. I. Yurkov, I.V. Zverev, A. Gandhi and **A. Kumar**, Bulletin of the Russian Academy of Sciences: Physics, 84(4) 367 (2020).

9. Response function of a BGO detector for γ-rays with energies in the range from 0.2 MeV to 8 MeV, D N Grozdanov, N A Fedorov, Yu N Kopatch, I N Ruskov, S B Dabylova, F A Aliyev, V R Skoy, C Hramco, T Yu Tretyakova, **A Kumar**, A Gandhi, A Sharma, D Wang, S K Sakhiyev & TANGRA Collaboration, Indian Journal of Pure & Applied Physics, Vol. 58(5), 427-430 (2020).

10. Inelastic scattering of 14.1 MeV neutrons on iron, N. A. Fedorov, D. N. Grozdanov, Yu. N. Kopatch, T. Yu. Tretyakova, I. N. Ruskov, V. R. Skoy, I. D. Dashkov, F. A. Aliyev, S. Dabylova, C. Hramco, **A. Kumar**, A. Gandhi, D. Wang, E. P. Bogolyubov, D. I. Yurkov & TANGRA collaboration, European Physical Journal A, 57, 194 (2021).

11. TANGRA multidetector systems for investigation of neutron-nuclear reactions at the JINR Frank Laboratory of Neutron Physics, I. Ruskov, Yu. Kopach, V. Bystritsky, V. Skoy, D.N. Grozdanov, N.A. Fedorov, T.Yu. Tretyakova, F. Aliev, C. Hramco, V. Slepnev, N. Zamyatin, A. Gandhi, D. Wang, **A. Kumar**, E. Zubarev, E. Bogolubov, Yuri Barmakov and TANGRA collaboration, EPJ web of conferences, EDP Sciences, 256, 00014 (2021).

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Letter

Deterministic sampling approach for the propagation of uncertainties in nuclear reaction models

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Uncertainty propagation of model parameters through nuclear reaction models is critical for nuclear data evaluation and other applications. Nuclear reaction models generally contain nonlinear functions of the model parameters, making the process of uncertainty propagation difficult. Usually stochastic approaches like the Monte Carlo method are employed to propagate the uncertainties through nuclear reaction models. The Monte Carlo method does provide proper results, but it takes a lot of computational power and time, which makes the process of uncertainty propagation difficult. Deterministic sampling approaches may provide results with accuracy using less computational time making the process of uncertainty propagation fast. In this study we have explored the use of a deterministic sampling approach called the unscented transform method for the uncertainty propagation in the nuclear reaction models. As a test case we have propagated the uncertainties of correlated optical model parameters through the optical model calculations for total and reaction cross sections of the $n + {}^{56}$Fe reaction. The results obtained using the unscented transform method are then compared with the results of the Monte Carlo method. It has been observed that the unscented transform method provides results practically similar to the Monte Carlo method in less computational time. It is concluded in this study that the unscented transform method can propagate uncertainties effectively through optical model calculations and there should be further investigation of the use of this method for other nuclear reaction models.

DOI: 10.1103/PhysRevC.106.L041601

Nuclear reaction data of good quality with a covariance matrix are crucial for safer and more advanced nuclear facilities, and this field has seen much progress in the past few decades [1–3]. Experimental measurement of nuclear reaction observables like cross sections, angular distributions, differential cross sections, etc., is a challenging and expensive task. Measuring all the physical quantities experimentally for a variety of nuclear reactions over a wide range of projectile energies is not feasible. Also some reactions of high importance may be impossible to measure directly due to the unavailability of targets or projectiles [4–6]. Therefore the use of the theoretical models is inevitable in this kind of situation, also such theoretical models are regularly used to interpolate and extrapolate the data in the absence of the experimental measurements, making them an integral part of the nuclear data evaluation [1,7]. Theoretical predictions are also associated with the uncertainties and may be correlated similarly to the experimentally measured data. These uncertainties can be attributed to different sources, e.g., uncertainties in the model parameters, uncertainties due to model deficiencies, algorithmic uncertainties, etc. [8,9]. Hence the quantitative knowledge of such sources of uncertainties and their effect on the final predictions of the model is very important.

In recent years there have been a renewed interest in the field of uncertainty quantification in low energy nuclear reactions [10–13]. Uncertainty quantification problems can be broadly classified into two categories, one is inverse problems; in which the model parameter uncertainties or model uncertainty itself are quantified using the well known final outcomes. The second is the forward problems, which are concerned with the determination of the uncertainties in the final outcomes of the models due to uncertainties in the input parameters [1]. In this study we will be focusing only on the forward uncertainty propagation of the model parameters. Input parameter uncertainties need to be propagated through nuclear reaction models, which generally contain nonlinear functions of the input parameters. When the statistical moments of the input parameters are known then there are two distinct approaches for calculating the statistical moment of the model outputs, these are the stochastic approach and deterministic approach [1,14]. In this study, we will be using a stochastic approach called the Monte Carlo method of uncertainty propagation, which provides accurate results even if the model functions are highly nonlinear [7,9]. In this method the input model parameters are sampled randomly from their joint probability distribution function and these random samples of the input parameters are then used to propagate the uncertainties through the theoretical model. But this method requires a very large number of random samples to be drawn so that it can give reliable results, which makes this method computationally expensive if the model calculations itself take large computational time. Deterministic sampling approaches may provide satisfactory results in less calculations as compared to the Monte Carlo method [15]. In this study we have also used a deterministic sampling approach called the unscented transform method [16–19]. This method was first proposed

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Estimation of optical model parameters and their correlation matrix using Unscented Transform Kalman Filter technique

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A R T I C L E I N F O

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A B S T R A C T

In the present study, we have optimized the optical model parameters and also calculated their correlation matrix using the Unscented Transform Kalman Filter technique for the first time. We have used n+^{56}Fe, n+^{45}Sc and n+^{59}Co reactions for this study in order to verify the application of this method. We have used the experimental differential cross section data for the elastically scattered neutrons from the EXFOR data library and DWBA calculations to determine the parameters. In this study we have assumed that the optical model provides correct results and the uncertainties come from the variation of fitting parameters only. We have used the TALYS nuclear reaction code for the DWBA calculations. The optical model parameters determined through this study, reproduce the calculations which are consistent with the experimental trends for the elastically scattered neutrons and total reaction cross sections. Also the correlations calculated in this work are consistent with the earlier study of n+^{56}Fe reaction.

1. Introduction

A good quality nuclear reaction data over a wide range of the projectile energy is one of the primary ingredients for the development of the future nuclear technologies. But the direct measurements of nuclear reactions are not possible for all the projectile energies and all the target mass range, because of the practical issues like projectile energy resolution, stable target availability etc. In such kind of situation, one has to rely more on the theoretical predictions for producing the evaluated nuclear data files like ENDF/B-VII.1, CENDL-3.1 and JENDL-4.0 etc. Nowadays, more importance is being given to the better estimation of nuclear data uncertainties and covariance, as these are of high importance for calculating the uncertainties in the design parameters of the nuclear facilities.

There are number of nuclear reaction models which are used to predict and interpret the experimental data. These models use set of parameters, which are normally determined by comparing the model predictions with the available experimental data. Hence the quality of these parameters will affect the quality of the model predictions. Information about the uncertainties and correlations between these model parameters is also important. These uncertainties of the parameters can be used to estimate the uncertainties and covariance matrix associated with the model predictions using Total Monte Carlo (TMC) method [1]. Few efforts in this direction have been made since the past decade, and some information about the model parameters uncertainties along with their correlations have also been included in the RIPL-3 library [2]. It uses Monte Carlo method for producing these estimations, but this study is in its early stage, and the provided estimates are proof of the principle only, which means there is enough room to explore and discuss other methods. The uncertainty quantification of the model parameters is also very important from the perspective of the nuclear reaction theory as it provides a deep understanding about the uncertainties within the models [3].

There are different techniques used in the literature for the parameter estimation and uncertainty quantification, e.g. Extended Kalman Filter [4], χ^2 minimization [3,5], Monte Carlo techniques [6] etc. The EMPIRE-KALMAN approach [4] used for the parameter correlation estimation and optimization uses the extended Kalman filter technique (EKFT). Hence it is required to calculate the partial derivatives of the model with respect to all the parameters i.e. sensitivity matrix. This is a cumbersome process and also approximates the uncertainties only up to the first order of the Taylor series expansion. In an another study correlated and uncorrelated χ^2 minimization functions have been used to calculate the correlations between the optical model parameters [3]. But this method also requires to calculate the Jacobian matrix of model functions with respect to the parameters, hence has the limitations similar

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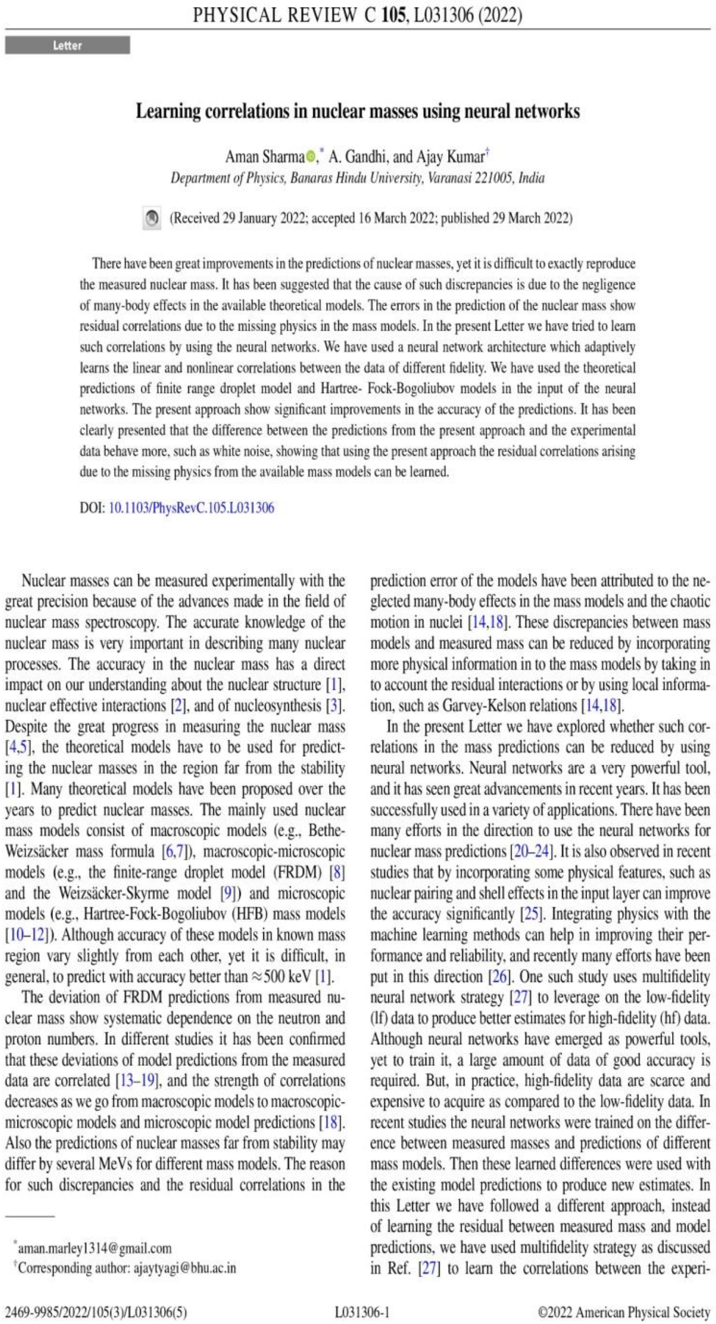

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Letter

Learning correlations in nuclear masses using neural networks

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There have been great improvements in the predictions of nuclear masses, yet it is difficult to exactly reproduce the measured nuclear mass. It has been suggested that the cause of such discrepancies is due to the negligence of many-body effects in the available theoretical models. The errors in the prediction of the nuclear mass show residual correlations due to the missing physics in the mass models. In the present Letter we have tried to learn such correlations by using the neural networks. We have used a neural network architecture which adaptively learns the linear and nonlinear correlations between the data of different fidelity. We have used the theoretical predictions of finite range droplet model and Hartree- Fock-Bogoliubov models in the input of the neural networks. The present approach show significant improvements in the accuracy of the predictions. It has been clearly presented that the difference between the predictions from the present approach and the experimental data behave more, such as white noise, showing that using the present approach the residual correlations arising due to the missing physics from the available mass models can be learned.

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Nuclear masses can be measured experimentally with the great precision because of the advances made in the field of nuclear mass spectroscopy. The accurate knowledge of the nuclear mass is very important in describing many nuclear processes. The accuracy in the nuclear mass has a direct impact on our understanding about the nuclear structure [1], nuclear effective interactions [2], and of nucleosynthesis [3]. Despite the great progress in measuring the nuclear mass [4,5], the theoretical models have to be used for predicting the nuclear masses in the region far from the stability [1]. Many theoretical models have been proposed over the years to predict nuclear masses. The mainly used nuclear mass models consist of macroscopic models (e.g., Bethe-Weizsäcker mass formula [6,7]), macroscopic-microscopic models (e.g., the finite-range droplet model (FRDM) [8] and the Weizsäcker-Skyrme model [9]) and microscopic models (e.g., Hartree-Fock-Bogoliubov (HFB) mass models [10–12]). Although accuracy of these models in known mass region vary slightly from each other, yet it is difficult, in general, to predict with accuracy better than ≈500 keV [1].

The deviation of FRDM predictions from measured nuclear mass show systematic dependence on the neutron and proton numbers. In different studies it has been confirmed that these deviations of model predictions from the measured data are correlated [13–19], and the strength of correlations decreases as we go from macroscopic models to macroscopic-microscopic models and microscopic model predictions [18]. Also the predictions of nuclear masses far from stability may differ by several MeVs for different mass models. The reason for such discrepancies and the residual correlations in the prediction error of the models have been attributed to the neglected many-body effects in the mass models and the chaotic motion in nuclei [14,18]. These discrepancies between mass models and measured mass can be reduced by incorporating more physical information in to the mass models by taking in to account the residual interactions or by using local information, such as Garvey-Kelson relations [14,18].

In the present Letter we have explored whether such correlations in the mass predictions can be reduced by using neural networks. Neural networks are a very powerful tool, and it has seen great advancements in recent years. It has been successfully used in a variety of applications. There have been many efforts in the direction to use the neural networks for nuclear mass predictions [20–24]. It is also observed in recent studies that by incorporating some physical features, such as nuclear pairing and shell effects in the input layer can improve the accuracy significantly [25]. Integrating physics with the machine learning methods can help in improving their performance and reliability, and recently many efforts have been put in this direction [26]. One such study uses multifidelity neural network strategy [27] to leverage on the low-fidelity (lf) data to produce better estimates for high-fidelity (hf) data. Although neural networks have emerged as powerful tools, yet to train it, a large amount of data of good accuracy is required. But, in practice, high-fidelity data are scarce and expensive to acquire as compared to the low-fidelity data. In recent studies the neural networks were trained on the difference between measured masses and predictions of different mass models. Then these learned differences were used with the existing model predictions to produce new estimates. In this Letter we have followed a different approach, instead of learning the residual between measured mass and model predictions, we have used multifidelity strategy as discussed in Ref. [27] to learn the correlations between the experi-

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Future Plans

1. To study the effect of shell closure in fusion-fission dynamics. (at IUAC, New Delhi)

2. Study the effects of N/Z in heavy ion fusion-fission dynamics. (at TIFR Mumbai)

3. Surrogate reactions a tool to study nuclear reactions without using neutrons. (at IUAC, New Delhi)

4. Mapping of dissipation and entrance channel effects in heavy ion induced fusion reactions. (at IUAC, New Delhi)

5. To determine the 58Co(n p) cross section taking 61Ni(n p) as the reference reaction using surrogate ratio method. (at IUAC, New Delhi)

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- **BARC, Mumbai**
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- **VECC, Kolkata**

Thanks

(d+D $\longrightarrow$ B*+b $\longrightarrow$ c+C), let δ be the entrance channel (d+D) of this reaction. The probability that the compound nucleus B* is formed and decayed through desired exit channel χ in a surrogate reaction, can be given using following equation.

$$P_{\delta\chi}(E^*) = \sum_{J\pi} F_{\delta}^{CN}(E^*, J, \pi) G_{\chi}^{CN}(E^*, J, \pi) \tag{3}$$

Where $F_{\delta}^{CN}(E^*, J, \pi)$ is the formation probability of the desired compound nucleus (B^*) in the surrogate reaction. The application of this method can be greatly simplified by using Weisskopf-Ewing approximation (35), which states that the branching ratios of the compound nucleus are spin and parity independent, therefore $P_{\delta\chi}(E^*) = G_{\chi}^{CN}(E^*)$; since $\sum_{J\pi} F_{\delta}^{CN}(E^*, J, \pi) = 1$ (9). $P_{\delta\chi}(E^*)$ can be measured in a surrogate experiment by detecting the ejectile (b) and decay particle (c) in coincidence as $P_{\delta\chi}(E^*) = \frac{N_{\delta\chi}}{N_{\delta}\epsilon_{\chi}}$, where N_{δ} is the total number of surrogate events, ($N_{\delta\chi}$) is the number of coincidence counts b and c, and ϵ_{χ} is the detection efficiency of the particle c in the surrogate experiment. Using this decay probability the desired cross sections can be determined using following equation.

$$\sigma_{\alpha\chi}(E^*) = \sigma_{\alpha}^{CN}(E^*) P_{\delta\chi}^{CN}(E^*) \tag{4}$$

We will refer the above method in Eq. (4) as the “Weisskopf-Ewing” approximation in this manuscript. There is another