Nuclear Data Requirements, Challenges and need for New Experimental Measurements

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1. Introduction

Nuclear data comprises of experimental data of all physical observables of nuclear structure, decay data, fission, reactions of all nuclei over the nuclides chart. Major interest is of the nuclear reaction data with projectiles such as neutrons, protons, deuterons, α, γ, also heavy ion transfer reactions populating stable and unstable nuclei at high excitation energies. Nuclear database plays a vital role in power reactors, industrial and medical applications, waste transmutation, post irradiation radiation levels and decay heat from materials and spent fuel and esstimation of ^{232}U in thorium fuel cycle. Precision nuclear data is very critical for cutting edge technology applications such as the design and safe operation of Generation IV nuclear reactors, fusion technology, Accelerator-Driven Subcritical Systems (ADSs) [1–8].

Presently, the database of neutron induced reactions is required for the neutron energies in the range of below thermal up to 20 MeV. Materials in fusion reactor face up to 14MeV neutrons and up to ~100MeV spallation neutrons in ADSs. The current reaction database is incomplete and this opens up many opportunities to measure the reaction cross sections data over periodic table for stable and unstable nuclides. In addition, measurements of γ-strength functions and nuclear level densities up to high excitation energies will be crucial for transfer and capture reactions. For fission database, neutron induced fission cross sections of actinides, Prompt Fission Neutron Spectra (PFNS) and Gamma spectra (PFGS) are required. The γ-induced reactions are important part of nuclear data. Mono energetic γ-sources of variable energies are not easily available. For bremsstrahlung γ-induced reactions, spectral averaged data is useful for medical isotopes production, further high energy electrons produce secondary neutrons which useful for applications.

Neutron induced fission of actinides is important for basic science as well as applications to nuclear technology. In a recent report R. Capote *et. al.,* presented Prompt Fission Neutron Spectra (PFNS) evaluations with uncertainties quantifications and new data for neutron-induced fission [9]. PFNS measurements were carried out for ^{238}U(n,f) [10] and recently of ^{232}Th(n,f) at FOTIA facility at BARC. PFNS measurements are time consuming due to the requirements of neutron time of flight and coincidence events with sufficient statistics. The integral quantities such as average neutron multiplicities and total gamma energy per fission versus incident neutron energy, with or without fragment mass resolved, are sufficient for the fission database. For this, ^{6,7}Li projectiles may be useful as a surrogate route for estimating the neutron, proton induced fission cross sections on actinides targets when the targets are not naturally available. A few experiments are being planned using surrogate route to measure fission cross sections and average neutron multiplicity in the actinide region.

2. Fast neutron induced reactions of actinides, structural materials and Evaluations.

Neutron induced reaction cross sections of structural materials such as Zr, Nb, Fe, Co, Ni and Cr are important from the point of view of neutron economy for advanced reactor designs and choice of reactor grade materials. The available reaction data reported over last 75 years in various journals and conferences covering millions of cross sections data is compiled in IAEA EXFOR reaction database, whereas applications use only evaluated data. Evaluated data libraries are key inputs for many fields and many such libraries are available such as ENDF/B-VIII.0, JENDL 4.0, JEFF-3.2, ROSFOND-2010, EAF, TENDL-2017. Meghna Karkera *et. al.*, carried out measurements, covariance analysis, evaluation of ^{232}Th(n, 2n)^{231}Th reaction cross sections and compared with the values of several evaluated nuclear data files and the results from TALYS-1.9 code [11]. The measurements were performed at the BARC-TIFR Pelletron accelerator facility and the PURNIMA neutron generator facility. This evaluation of ^{232}Th(n, 2n)^{231}Th nuclear reaction data is first time in India, performed as a part of BRNS project important for AHWRs [7]. Sangeeta Prasanna *et. al.*, from VESIT, Mumbai and Vidya Devi from Baddal, Ropar Chandigarh have also taken up evaluation projects. Presently, the nuclear data covariances are routinely included in the many published reports of experimental data from India, started first by Manipal University gorup. Several experiments of neutron and proton induced reactions have been performed in the last 10 years using BARC and TIFR facilities. For example, neutron capture cross sections were measured at FOTIA for ^{70}Zn by Punte *et. al.,* [12], ^{96}Zr(n, γ)^{97}Zr reaction cross sections by S. Badwar *et. al.,* [13] and neutron induced reaction cross section measurements at PURNIMA facility for gallium isotopes by Rebecca Pachuau *et. al.,* [14]. These reports included covariance analysis for the uncertainty propagation and comparison to various evaluated data libraries. Siddhrath Parashari *et. al.,* made several measurements and especially derived systematics of (n,p), (n,2n) cross sections in medium mass region [15].

3 Surrogate Reaction method for nuclear data

Large number of radionuclides are produced in fusion reactor by 14 MeV neutrons interacting with various structural and other materials during reactor operation. The neutron induced reaction cross sections for these produced radio isotopes is essential for neutronics purpose as well as H, He gases production causing damage structural integrity of the materials due to (n,p) and (n,α) reactions. Following surrogate reaction ratio method, the cross sections for ^{55}Fe(n,p) were measured and reported by Bhawna Pandey *et. al.,* [16], the ^{59}Ni(n, xp) reaction cross sections by Jyoti Pandey *et. al.,* [17] and ^{53}Mn(n,xp) by Ramanadeep Gandhi *et. al.,* [18]. These are important data on radio nuclides for fusion technology and are important for future evaluations. The following experiments are urgently needed for fusion technology applications:

^{65}Zn(n,p) by ^{63}Cu(^{7}Li,α)^{66}Zn->^{65}Cu+p, ^{62}Ni(^{6}Li,d)^{66}Zn -->^{65}Cu+p, ^{57}Co(n,p) by ^{56}Fe(^{6}Li,α)^{58}Co -->^{57}Fe+p, ^{58}Co(n,p) by ^{57}Fe (6Li,α)^{59}Co-->^{58}Fe+p, ^{60}Co(n,p) by ^{58}Fe(^{7}Li,α)^{61}Co->^{60}Co+p.
Further, data is required for ^{63}Ni(n,x), ^{59}Fe(n,p), ^{77}Se(n,p).

As discussed by Forrest [8], there is need for cross sections measurements of the following listed reactions. There is no experimental data for most of these reactions or data for some reactions have discrepancies.

^{20}Ne(n,p)^{20}F, ^{22}Ne(n,α)^{19}O, ^{36}S(n,2n)^{35}S, ^{46}Ca(n,2n)^{45}Ca, ^{72}Ge(n,2n)^{71}Ge, ^{78}Kr(n,α)^{75}Se, ^{84}Kr(n,2n)^{83m}Kr, ^{104}Pd(n,2n)^{103}Pd, ^{132}Xe(n,α)^{129}Te, ^{176}Lu(n,n')^{176m}Lu, ^{180}W(n,γ)^{181}W, ^{190}Os(n,2n)^{189m}Os, ^{196}Pt(n,2n)^{195m}Pt, ^{207}Pb(n,n'α)^{203}Hg.
^{34}S(n,α)^{31}Si, ^{37}Cl(n,p)^{37}S, ^{58}Ni(n,t)^{56}Co, ^{60}Ni(n,2n)^{59}Ni, ^{90}Zr(n,p)^{90}Y, ^{94}Mo(n,p)^{94}Nb, ^{177}Hf(n,n')^{177m}Hf, ^{180}Hf(n,2n)^{179m}Hf.

4. Nuclear Data needs for Medical Isotopes.

Experiments were carried out for finding alternate routes for production of medical isotopes at BARC [19,20,21]. Conventionally these isotopes are abundantly produced in reactors. Production of medical isotopes ^{99}Mo and ^{64}Cu in a mixed field of bremsstrahlung γ and neutrons in a 15MV clinical electron linear accelerator was explored [20], neutron irradiations of Zn for therapeutic radionuclide ^{67}Cu [21] and for ^{99m}Tc using proton irradiation of ^{100}Mo at PLF, TIFR were carried out. Other radio nuclides we will pursue are ^{32}S(n,p)^{32}P, ^{45}Ti(n,p)^{47}Sc, ^{64}Zn(n,p)^{64}Cu, ^{67}Zn(n,p)^{67}Cu. Towards these nuclear data requirements, it is necessary to initiate Nuclear Data Evaluations program in India and its importance can be appreciated from the detailed review of Brown *et. al.,* [22].

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