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A Comprehensive Review of Fast Neutron-Induced (n,p) Reaction Excitation Functions and Their Applications

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ABSTRACT

One of the most important categories of nuclear reactions to study both nuclear structure, reaction mechanisms and applications in the field of nuclear engineering is (n,p) reactions caused by fast neutrons. Accurate excitation functions of this type of reactions provide the essential cross-section data required in any reactor design, fusion, radiation shielding and dosimetry, as well as in medical isotope production, activation analysis and nuclear astrophysics. Over the last few decades a lot of experimental work and theoretical calculations concerning (n,p) reactions have been done through the use of sources based on accelerators, while the availability of more advanced reaction codes such as TALYS, EMPIRE, CoH and ALICE has made the predictions of excitation functions better across wide ranges of neutron energy. The aim of this review is to present the knowledge available about the excitation functions of fast neutron-induced reactions and to result in the ranges of neutron energy, starting from threshold and going to nearly 30 MeV. Different experimental techniques like activation methods, time-of-flight spectroscopy and quasi-monoenergetic neutron production procedures are also dealt with together with their uncertainties and difficulties in measurement. Moreover, the evaluation of major nuclear data libraries including ENDF/B, JEFF, JENDL, TENDL, IRDFF and EXFOR is carried out in order to compare discrepancies of experimental databases and theoretical evaluations. The article also discusses the developments that are being made concerning reaction modelling, potential optical model theory, pre-equilibrium process, formation of compound nucleus and theories used in this area of study. Also there are discussions of using excitation functions of (n,p) reactions, where discussed applications include reactors and fusion energy systems, among others. Emerging trends involving machine learning will also be discussed here, while suggestions for future research will also be provided to enable improvements in both areas of experimental accuracy and theoretical reliability.

Introduction

Neutron-induced nuclear reactions are of great importance in nuclear physics and have helped the discipline develop both from a theoretical and practical viewpoint since the year when the neutron was first discovered by James Chadwick in 1932. Unlike other charged particles, neutrons are electrically neutral particles, and therefore they do not face Coulomb repulsion while approaching the atomic nuclei. Because of this property, neutrons can easily penetrate through matter and interact with target nuclei at various energies. The results of neutron interaction depend on the energy of the neutron and the specific nuclear structure of the target isotope. In particular, neutron interaction can take place via elastic scattering, inelastic scattering, neutron capture, fission, or other charged particle emission reactions. Of these processes, neutron-induced proton emission has been highlighted for its important position in studies of nuclear reactions, reactor physics, fusion technology, dosimetry, activation analysis, radiation protection, and isotope production (Capote *et al.*, 2009; Koning & Rochman, 2012). neutron-induced reactions are divided into thermal (<0.5 eV), epithermal (0.5 eV–100 keV), intermediate, fast (100 keV–20 MeV), and high energy (>20 MeV), depending on the kinetic energy of the neutrons. The fast neutron energy region is particularly interesting as neutrons in this range are present in neutron spectra of fission reactors, fusion reactors, accelerator-driven systems, and high intensity neutron generators.

Fast neutrons mainly interact with nuclei via various competing mechanisms, with relative significance of each of these depending on neutron energy and the nuclear structure. At low energies, neutron capture often leads to production of compound nucleus and the subsequent decays via statistical process into particles or emitting gamma radiation. As neutron energy increases, direct reaction mechanisms as well as pre-equilibrium processes start to play a significant role. Direct reactions happen in a very short time, about 10^{-22} seconds, in which only a few of nucleons participate in the process. The reaction process is similar in in the case of compound nucleus reactions, but there is complete energy equilibration in the nucleus before any particle is emitted. In case of pre-equilibrium reactions, the reaction process is in between the direct and compound reactions (Hauser & Feshbach, 1952, Kalbach, 1986). Understanding the relative importance of these reactions is vital for proper description of neutron induced (n,p) reaction cross sections in large ranges of energy. Among particles reaction types, the (n,p) reaction is very unique as it is the case of neutron being converted into proton from nuclear interaction. In a typical (n,p) reaction,

$$\frac{A}{Z}X + n \rightarrow^{A}_{Z-1} Y + p,$$

A target nucleus can absorb a neutron and release a proton to lower its atomic number by one. The mass number is unchanged due to nuclear reactions, which have a threshold energy determined by their Q-value and nuclear binding energy. Therefore, many (n, p) reactions occur only in the high-energy neutron region, which is important for the studies with fast neutrons (about 14-20 MeV) produced by D-T neutron generators. The threshold behavior of (n, p) reactions, energy dependence of the given processes, and peak values of cross-sections provide crucial information for studying level densities, transmission coefficients, optical potentials, and pre-equilibrium emission probabilities (Koning & Delaroche, 2003) etc. An important parameter for neutron-induced nuclear reactions is the excitation function which indicates the dependence of the reaction cross-section on the energy of the incident neutron. The excitation function gives full information on the threshold energies and maximum values of cross-sections, and the range of energies for different reaction mechanisms. Accurate measurements of the excitation function are essential in theoretical validations of neutron-induced reactions and evaluation of the nuclear data libraries. Since the probability of nuclear reaction depends on the energy of neutrons, the results of the excitation function are unequivocally necessary for reactor physics, neutron transport, isotopes' production planning, and shielding design (Qaim, 2012). In addition, the excitation functions enable comparisons between experimental data and theoretical predictions with the aid of contemporary computer codes on nuclear reactions including TALYS, EMPIRE, CoH, ALICE. The nuclear reaction cross-section describes the probability of a specific nuclear reaction occurring after neutrons interact with the target nucleus. The value of the cross-section is measured in barns (1 barn = 10-24 cm²) depending on the energy of the neutron, type of the target isotope, nuclear spin, parity, etc. Therefore, accurate cross-section measurements in experimental nuclear physics are of primary importance since the errors in nuclear data affect reactor design calculations, neutron dosimetry standards, fusion blanket developments, and predictions of activation. Significant improvements have been made in measures of neutron-induced reaction cross-sections using various activation methods, time-of-flight spectroscopy, quasi-monoenergetic neutron sources, and accelerator neutron facilities (Carlson *et al*., 2018). However, discrepancies between various experimental databases for a number of important (n, p) reactions remain highlighting the need for constant evaluation and theory improvement.

The significance of neutron-induced (n,p) processes is found not only in pure nuclear physics. In the domain of reactor technology, accurate cross sections for the (n,p) interactions serve multiple purposes in activating analyses, structural materials characterization, neutron flux measurement, and assessing radiation effects on materials. In fusion reactors, particularly those with deuterium–tritium fuel cycles, high-energy 14.1-MeV neutrons facilitate several (n,p) interactions in blanket, first-wall, and diagnostic materials. Hence, reliable activation functions have fundamental importance in forecasting material activation, transmutation, and radioactive inventory in future fusion reactors (Gilbert *et al*., 2019). Likewise, neutron dosimetry is dependent on well-characterized activation reactions such as 27Al(n,p)27Mg, 58Ni(n,p)58Co, and 56Fe(n,p)56 Mn, which can be conveniently used as neutron flux monitors for both reactors and accelerators. In addition to generating energy through nuclear reactions, there has been an increasing significance of neutron-induced (n,p) reactions in medical isotope manufacture, industry radiography, environmental surveillance, nuclear security, and nuclear astrophysics. Many medically important radionuclides can also be obtained through the activation by fast neutrons, and the effective activation cross sections can be utilized to conduct activation analyses for trace elements in biological, geological, and environmental samples. Moreover, the activation cross sections have played a key role in determination of the nucleosynthesis processes in the universe (Rauscher, 2011).

Difficulties persist in obtaining reliable data on (n,p) excitation functions, especially in the fast-neutron energy region for medium and heavy nuclear organs, notwithstanding the extensive studies on this subject that have been conducted over several decades. One of the factors that may lead to the inconsistencies among different evaluated nuclear data libraries (e.g., ENDF/B, JEFF, JENDL, CENDL, TENDL, and EXFOR), which often presents such inconsistencies is the variety of experimental methods employed and their associated statistical uncertainties as well as the ways of modeling nuclear phenomena of the different authors. With significant progress having been made in computational nuclear physics due to the implementation of TALYS and EMPIRE as well as the use of Bayesian nuclear data evaluation techniques, it is important to remember that verification through measurement is still needed.

This paper is a review of the (n,p) reaction excitation technique of fast neutrons, mainly around the neutron energy range of its threshold value up to around 20 MeV, for the which reaction is important in the nuclear science and technology field. This paper describes the experimental cross-section determination for the (n,p) reactions, availability of evaluated data libraries, and theoretical work done for evaluating current status and reliability of nuclear data. In this review paper, an analysis has been made on the major data repositories such as EXFOR, ENDF/B, JEFF, JENDL, and TENDL to find the consistency, inconsistency, and gap in data. The techniques available for the experimental determination of excitation function have also been discussed in this paper such as activation method, time of flight method, and usage of accelerator as a neutron source. The various nuclear reaction models based on TALYS and EMPIRE codes which are very popular, in the field of nuclear science has also been discussed in this paper. The application of (n,p) excitation function for different applications such as fission reactor, fusion reactor, neutron dosimetry, medical isotopes, etc has also been discussed. The problems which are still there such as lack of consistency and uncertainty with respect to the experimental determination of (n,p) excitation function and theoretical uncertainty in models and also inconsistency in evaluations and will be discussed in detail.

2. Fundamentals of Fast Neutron-Induced (N,P) Reactions

Fast neutron-induced (n,p) reactions are one of the most significant categories of the charged particle emission reactions in nuclear physics. (n,p) reactions take place when a neutron hits a target nucleus and a proton is released, which leads to the generation of a residual nucleus that possesses the same mass number as the target nucleus and one fewer proton. Due to the fact that neutrons are electrically neutral particles and as such can penetrate the atomic nucleus without feeling the effects of the repulsion force due to the electric charge, neutron-induced reactions are very good for the study of the structure of the nucleus and dynamics of the process through which nuclear reactions take place. In the fast neutron energy region (1–20 MeV), (n,p) reactions are governed by a number of mechanisms, which include compound nucleus creation, direct reactions, and pre-equilibrium emission, with each mechanism contributing differently, depending on the neutron energy as well as from the other characteristics of the target nucleus (Koning & Rochman, 2012). In order to understand these processes, nuclear reaction theory is to be applied through which it is possible to describe the process through which the neutron interacts with the nuclides in the target The crucial element that affects nuclear reaction is the so-called Q-value which is defined as the difference between the total rest-mass energies of reactants and products. It is understood that if the Q-value is positive it means energy is being released during the course of nuclear reaction while negative Q-value means that certain kinetic energy should be supplied from the outside. It has been mentioned earlier that all the reactions where neutrons trigger different nuclear reactions have negative Q-values, thus translating into what is referred to as threshold condition. Hence the process requires certain amount of energy received by neutrons before the nuclear reaction may occur. The amount of threshold energy depends on Q-value and masses of nuclei participating in nuclear reaction so it means that one cannot start these reactions without certain amount of energy supplied by neutrons. Essentially, almost all (n,p) reactions can only be accomplished at very high energies domain with respect to neutron energies where the aforementioned quantity is measured in several MeV. The effectiveness of this function shows the dependence what happens in terms of reaction cross section with respect to the energy of incoming neutrons. Excitation functions can be considered as the most crucial quantity in this respect as they contribute to the threshold points, resonance areas, maximum cross sections, and to some other aspects. Reaction cross-section is usually defined in barns (one barn eq. to 10-24 cm2) and refers to the probability of occurrence for any nuclear reaction when neutron hits nucleus. Cross-sections can be very diverse depending on the neutron energy, nucleus mass, isotope composition as well as reaction type, thus it is clear that proper estimation is very important in terms of nuclear engineering (Carlson *et al*., 2018). In order to make accurate predictions concerning excitation functions it is necessary to know exact structure of nucleus.

The optical model is also an important aspect of the neutron nucleus interactions as via a combination of real and imaginary potential which describes the reaction dynamics between neutrons and the nucleus. The actual potential describes the elastic scattering of neutrons while the imaginary potential describes the absorption to the inelastic product channels. The optical model parameters give the required transmission coefficients to carry the statistical calculations for the reactions and serve as a basis for various nuclear reaction codes which include EMPIRE and TALYS (Koning & Delaroche 2003). The neutron induced fast (n,p) reactions take place through three main processes. In the case of compound nuclear mechanism of interaction, the incident neutron is fully absorbed making an excited nucleus and stays long enough for it to reach the statistical equilibrium before it emits protons or other products. This method is very common when the neutron energies are quite low. On the other hand, the direct interaction happens when only a few nucleons are involved and hence the reaction occurs in a time frame of roughly 10^{-22} s leading to fast emission of protons and almost zero transfer of energy. The pre-equilibrium process of reaction is a method falling between the two methods and it results in the emission of particles whereby the nuclear system does not reach the total equilibrium yet. The pre-equilibrium nuclear reactions play an increasing role above about 10 MeV and influence all the excitation functions as fast neutron reactions (Kalbach 1986; Herman *et al*. 2007). To understand all these basic concepts is important for the interpretation of the experimental excitation functions and the evaluation of the nuclear models at the same time improving the evaluated nuclear databases. These principles are used in various fields including: reactor physics, fusion technology, neutron dosimetry, shielding from radiation and production of medical isotopes among others.

3. Experimental Measurement Techniques

The accurate determination of the excitation functions pertaining to fast neutron-induced (n,p) reactions is a paramount requirement for the development of dependable nuclear data useful in reactor physics, fusion technology, neutron dosimetry, and developing medical isotopes. In the present day, different neutron generating devices and detection methods are employed experimentally to measure the relevant reaction crosssections in a large energy range. It is worth mentioning that neutron generators represent the most common laboratory neutron sources because they can produce stable neutron outputs either monoenergetically or semi-monoenergetically (Qaim, 2012). The greatest neutron inputs arise from the deuterium-tritium neutron generator since this gives nearly monoenergetic neutrons at 14.1 MeV through the 3H(d,n)4He reaction. The basis of the successful use of neutron generators for crosssection measurement with very high neutron yield and energy stability is clear. Alternatively the deuterium-deuterium (D-D) neutron generator which makes it possible to utilize qualifying neutrons at 2.5 MeV (i.e., 2H(d,n)3He) also has the potential for crosssection studies (Carlson *et al*., 2018).

The time-of-flight (TOF) method is the most reliable method to determine neutron energy. Neutron energy is determined from time-of-flight measurements where the time of flight of neutrons from the neutron production target to the detector is measured. TOF measurements allow for high-precision excitation function measurements over a wide range of energies. For radioactive products of nuclear reactions, activation analysis is commonly used. After the sample is irradiated with neutrons, the activity produced is measured with gamma-ray spectrometry, usually using high-purity germanium (HPGe) detectors. HPGe detectors offer very good resolution making it possible to precisely identify and quantify the characteristic gamma rays emitted from the activity produced in the sample (Gilmore, 2008). In addition, reliable determination of cross sections requires adequate efficiency calibration of the detection system, using certified radioactive standards in the relevant energy range. Correction for detection efficiency is performed for all geometrical effects, attenuation of gamma rays, counting of coincident events, and the detection response. The final component of this process is a complete uncertainty analysis needed to determine the quality of the measurement. Major sources of uncertainty include neutron flux measurement, efficiency of the detector, amount of sample used, counting statistics, gamma emission probabilities, half-lives, dead-time correction, and the spread of neutron energy. Details of combining these uncertainties using statistical propagation methods are provided in international standards (ISO, 2008; Carlson *et al*., 2018).

4. Excitation Functions of Major (N,P) Reactions

The excitation functions for fast neutron-induced reactions on some of the most important materials. For example, the excitation functions for 27Al(n,p)27Mg have threshold and increasing cross-section as clearly seen in the experimental EXFOR data, and the ENDF/B predictions follow this trend. The same applies for the case of 56Fe(n,p)56Mn since EXFOR data is rather abundant; still one has to take discrepancies into account due to different energy spreading of neutrons in the data sets. In addition, the use of TENDL in that case provides additional calibration to the measurements obtained via experimental methods. Lastly, one can apply 58Ni(n,p)58Co reaction for neutron dosimetry and activation studies. The experimental data, as generally true for the previous cases, demonstrate strong fast neutron sensitivity, while the evaluated libraries show quite an agreement in the 14–15 MeV region. For the case of 59Co(n,p)59Fe (where the measured excitation functions are present significantly less), TENDL becomes important for determining the general shape of the excitation function and its behavior at high energies. Furthermore, it is also possible to use 63Cu(n,p)63Ni and 64Zn(n,p)64Cu reactions.

Medium-mass reactions such as 89Y(n,p) 89Sr, 93Nb(n,p) 93Zr, and 103Rh(n,p) 103 Ru are relevant to reactor materials, activation products, and nuclear technology. Their excitation functions often show stronger dependence on nuclear level density and pre-equilibrium emission. Experimental EXFOR datasets are limited for some energy regions, so evaluated libraries and TALYS-based calculations become essential for cross-section estimation. 107Ag(n,p) 107Pd and 115In(n,p) 115Cd are useful in activation and detector-related applications, although isomeric-state production and decay-data uncertainties may complicate interpretation. Finally, 197Au (n,p) 197 Pt is valuable because gold is frequently used as a reference material in activation measurements; however, proton-emission channels in heavy nuclei require careful treatment of Coulomb barriers and competing reactions. Overall, comparison of EXFOR, ENDF/B, TALYS, and TENDL indicates that light and medium-mass target nuclei generally show better agreement between experiment and evaluation than heavier nuclei. Discrepancies usually arise from neutron spectrum uncertainties, detector efficiency, decay-data corrections, competing reactions, and limitations in nuclear model parameters. Therefore, systematic comparison of experimental data with evaluated libraries remains essential for improving fast-neutron nuclear data reliability.

5. **Nuclear Data Libraries**

The importance of reliable nuclear data libraries must not be overlooked in the assessment, evaluation, and usage of excitation functions of fast neutron-induced nuclear reactions. The nuclear data libraries collect experimental and theoretical evaluations, along with cross-section data for radiation transport, reactor physics, activation analysis, and medical isotope generation based on standardized cross-section data. However, it is imperative to understand that every library has a particular purpose, methodology, and area of utilization. EXFOR is the main database globally maintained by the International Atomic Energy Agency (IAEA) in collaboration with various nuclear data centers. It comprises actual experimental data pertaining to nuclear reactions, which makes it the ideal repository for validating theoretical calculations and evaluated libraries (Zerkin & Pritychenko, 2018). ENDF/B-VIII.1 is the most recent evaluated nuclear data library developed by the U.S. Cross Section Evaluation Working Group, whereby it uses a combination of experimental observations and nuclear reactions to produce a composite library that is widely used for the purposes of nuclear design and shielding calculations (Brown *et al*., 2024). The JEFF library is similarly regulated by the OECD Nuclear Energy Agency to cater to nuclear fission and fusion applications in Europe. The JENDL, which is the Evaluated Nuclear Data Library of Japan, is intended for reactor technology, fusion systems, as well as radiation applications in Japan, while CENDL, which is the Evaluated Nuclear Data Library of China, serves the increasing nuclear energy project development as well as research programs of China. The BROND library that was developed in Russia, is meant for reactor calculation as well as neutron transport, while ROSFOND provides recently evaluated Russian nuclear data and has more covariance data for engineering applications. The IRDFF library on the other hand, specializes in neutron dosimetry and fusion neutron monitoring. It is an international recommended library of dosimetry cross-sections together with standard uncertainties related to this. Meanwhile, the TENDL, which is the TALYS Evaluated Nuclear Data Library is generated through the TALYS nuclear reaction code system which provides almost all evaluated nuclear data for stable and long-lived isotopes. The TENDL library is indeed very relevant in the areas where there might be limited experimental measurements since it provides the theoretical predictions of different reaction channels (Koning *et al*., 2019). All these libraries are basis for evaluation of nuclear data in modern age.

6. Nuclear Reaction Modelling

Precise assessment of (n,p) reaction excitation functions resulting from fast neutrons depends on refined methods of nuclear reactions that can account for the complex interactions between the incoming neutrons and the nuclei. Today's methods of nuclear reaction involve the use of many theoretical parts to estimate the different direct, compound, and other types of nuclear reactions across a wide range of energies. The models are useful in the formulation of standardized data for the state of nuclear reactions in areas where experimental data is missing and/or inadequate (Koning and Rochman, 2012). One of the most popular software used in nuclear reactions today is TALYS, which is capable of simulating nuclear reactions resulting from neutrons, protons, tritons, and other particles in the energy range of 1 keV to 200 MeV. TALYS uses optical model calculations, direct reactions, pre-equilibrium nuclear reactions, and fission reactions. TALYS serves as the basis of the TALYS Evaluated Nuclear Data Library (TENDL), which gives evaluated cross sections for almost all isotopes that are stable or of long half-life (Koning *et al*, 2019). Another existing software used in the processing of nuclear data is the EMPIRE code. EMPIRE incorporates many of the different reaction mechanisms, including optical model calculations, coupled-channel analysis, Hauser-Feshbach theory, indirect and direct reactions. Because EMPIRE is flexible in being able to deal with many of the complex types of reactions since it can handle various forms of reactions with ease, it is extensively applied in the formulation of ENDF and JEFF data (Herman *et al*, 2007). Other codes that are similar in nature to EMPIRE and offer the use of coupled-channel calculations are CoH (Coupled-channel Hauser-Feshbash), which performs statistical calculations of nuclear reactions using coupled-channel optical potentials. ALICE code is also another popular code that is capable of using the hybrid and geometry-dependent hybrid methods to estimate excitation functions. Finally, GNASH has played an important role in forming the different nuclear reactions by coupling Hauser-Feshbach and pre-equilibrium models, thereby influencing the development of nuclear methodology.

The optical model serves as the basis for nuclear reaction calculations. The optical model treats interactions of the incident neutron with the target nucleus as occurring via a complex potential, where the real part describes elastic scattering and the imaginary part describes absorption into non-elastic channels. The optical model parameters are important for accurate calculation of transmission coefficients for statistical calculations (Koning & Delaroche, 2003). Hauser-Feshbach statistical theory forms the basis for compound nucleus reactions. The theory assumes the formation of the compound nucleus upon interaction of the incident neutron with the target nucleus, which undergoes statistical equilibrium before subsequent reactions. The probabilities of all the reaction channels can be calculated as the result of the transmission coefficients and the nuclear level density (Hauser & Feshbach, 1952).

At intermediate neutron energies, the Kalbach systematics provides semi-empirical descriptions of the continuum emission for quantitative analysis using a combination of direct and pre-equilibrium emissions. The systematics help in making accurate predictions of the angular distributions and the emitted particle spectra (Kalbach, 1986). The pre-equilibrium models, especially the exciton model, predict particle emission due to pre-equilibrium processes. The pre-equilibrium models start to become significant at energies above 10 MeV, where both direct and compound processes take place. Therefore, the incorporation of pre-equilibrium emission into the calculations improves the agreement of the calculated excitation functions with the observed excitation functions for the fast neutron-induced (n,p) reactions. Thus, modern modeling of nuclear reactions combines experimental nuclear physics and the advanced theoretical approach, which enables obtaining correct predictions in terms of cross-sections that is necessary for improving evaluated databases.

7. **Applications Of Fast Neutron-Induced (N,P) Reaction Excitation Functions**

Fast neutron-induced (n,p) reaction excitation functions have extensive applications in nuclear science, engineering, medicine, and astrophysics because they provide reliable cross-section data required for neutron transport calculations, activation analysis, and radiation safety assessments. In nuclear reactors, accurate (n,p) reaction cross sections are essential for predicting neutron activation, material transmutation, radiation damage, and fuel-cycle performance. Structural materials such as iron, nickel, cobalt, and chromium undergo neutron-induced reactions that influence reactor lifetime and maintenance strategies (Chadwick *et al*., 2011).

Target Nuclide	**Reaction**	**Product Nuclide**	**Threshold Energy (MeV)**	**Major Application**
^{27}Al	(n,p)	^{27}Mg	1.89	Neutron dosimetry
^{56}Fe	(n,p)	^{56}Mn	4.12	Reactor materials
^{58}Ni	(n,p)	^{58}Co	0.40	Dosimetry
^{59}Co	(n,p)	^{59}Fe	2.35	Activation analysis
^{63}Cu	(n,p)	^{63}Ni	1.65	Radioisotope production
^{64}Zn	(n,p)	^{64}Cu	2.70	Medical isotope
^{89}Y	(n,p)	^{89}Sr	3.55	Reactor activation
^{93}Nb	(n,p)	^{93}Zr	1.52	Structural materials

^{103}Rh	(n,p)	^{103}Ru	2.84	Nuclear technology
^{107}Ag	(n,p)	^{107}Pd	2.30	Activation studies
^{115}In	(n,p)	^{115}Cd	1.18	Neutron detectors
^{197}Au	(n,p)	^{197}Pt	6.50	Reference activation

In fusion reactors, particularly deuterium–tritium (D–T) systems, high-energy 14.1 MeV neutrons induce numerous (n,p) reactions within blanket materials, first-wall components, and diagnostic systems. Reliable excitation functions are therefore required to estimate activation products, decay heat, helium production, and radioactive inventory during reactor operation (Gilbert *et al*., 2019). Similarly, accelerator-driven systems (ADS) employ high-energy neutron fields generated through spallation reactions, making accurate (n,p) cross sections indispensable for neutron transport simulations and subcritical reactor design. In radiation dosimetry, threshold reactions such as 27Al(n,p) 27Mg, 56Fe(n,p) 56Mn, and 58Ni(n,p) 58 Co serve as neutron flux monitors because of their well-characterized excitation functions. These reactions are widely used in reactor surveillance, neutron calibration facilities, and fusion experiments (IRDFF-II Collaboration, 2020). Medical isotope production also benefits from fast neutron-induced reactions, which provide alternative production routes for selected diagnostic and therapeutic radionuclides when conventional charged-particle methods are unavailable (Qaim, 2012).

The application of fast neutron activation is crucial for neutron activation analysis (NAA), which is a method used to analyze elements present in low concentrations in geological and biological matrices. The significance of excitation function information with regard to preventing radiation accidents in the design of radiation shielding must not be overlooked because the neutron activation of the shielding material must be calculated prior to its application in order to protect the individuals from harmful radiation exposure. In addition to nuclear waste disposal, other applications of excitation function data include utilization in the materials testing, where neutron activation experiments are employed to assess the degradation of materials due to exposure to reactor environment; and application of neutron activation in space radiobiology, where neutron activation of shielding materials is applied in evaluating space radiation effects on astronauts and materials in spacecrafts.

8. **Current Challenges and Future Perspectives**

Despite significant advances in experimental techniques and theoretical modeling, several challenges remain in the accurate determination and evaluation of fast neutron-induced (n,p) reaction excitation functions. One of the most critical issues is the limited availability of experimental data for many isotopes and neutron energy ranges. While commonly studied reactions such as 27Al(n,p) 27Mg and 58Ni(n,p) 58Co have extensive datasets, numerous medium- and heavy-mass nuclei still lack comprehensive experimental measurements. The scarcity of data above 14–20 MeV limits the validation of theoretical models and reduces the reliability of evaluated nuclear data libraries (Zerkin & Pritychenko, 2018). Another major challenge is data inconsistency among different experimental investigations. Variations in neutron source characteristics, detector efficiency, target purity, irradiation geometry, decay data, and neutron flux determination often produce discrepancies between independent measurements. Consequently, excitation functions reported in the EXFOR database may differ significantly, requiring careful evaluation before inclusion in recommended nuclear data libraries such as ENDF/B, JEFF, and JENDL (Carlson *et al*., 2018). These inconsistencies complicate nuclear data evaluation and introduce uncertainties into reactor physics and radiation transport calculations. Accurate high-energy neutron measurements present additional experimental difficulties. Producing monoenergetic neutrons above approximately 20 MeV requires sophisticated accelerator facilities and specialized detection systems, which are available only at a limited number of research laboratories worldwide. Furthermore, neutron energy spread, background radiation, competing reaction channels, and detector dead time increase measurement complexity and reduce experimental precision (Qaim, 2012). Reliable nuclear data also require rigorous uncertainty propagation and comprehensive covariance data. Although evaluated libraries provide recommended cross sections, uncertainty estimates and covariance matrices remain incomplete for many (n,p) reactions. The absence of detailed covariance information restricts sensitivity analyses, uncertainty quantification, and advanced reactor simulations, particularly in safety-critical applications (Chadwick *et al*., 2011).

Finally, model limitations continue to affect theoretical predictions. Modern nuclear reaction codes such as TALYS, EMPIRE, and CoH rely on optical model potentials, nuclear level density parameters, gamma-strength functions, and pre-equilibrium models, each of which introduces model-dependent uncertainties. Although these codes generally reproduce experimental trends, discrepancies remain for nuclei with complex level structures or limited experimental constraints. Continued improvements in nuclear reaction theory, combined with new high-precision measurements, are therefore essential for developing more accurate evaluated nuclear data libraries and enhancing the predictive capability of fast neutron-induced (n,p) reaction models.

Research on fast neutron induced (n,p) reactions has a bright future thanks to new neutron facilities, improved detector technology, advancements in nuclear data evaluation, and collaboration between various institutes. The increasing demand for high-quality nuclear data in advanced nuclear reactors, fusion technology, isotopes in medicine, radiation protection, and space applications makes the improvement of excitation function measurements important. Researchers hope to improve upon the challenges being faced in the area of experimental coverage, uncertainty analysis, and theoretical modeling to improve the quality and reliability of nuclear data libraries. Modern neutron sources, spallation sources, and high flux D-T generators will make data collection easier because they will provide better neutron intensity, resolution, and stability. Data acquired will give scientists a chance to perform cross-section measurements for isotopes that are currently lacking experimental data for energies greater than 20 MeV where little data exists. The facilities will also allow for research on isotopes and new materials for advanced nuclear reactors. Improvements in detector technology are expected. New, highly efficient high purity Ge detectors plus lanthanum bromide scintillator detectors and devices for digital signal processing will improve energy resolution, decrease background, increase counting efficiency, and increase collection speed thereby decreasing uncertainty in activation and gamma spectroscopy measurements. Automated calibration of detectors and real-time diagnostic techniques will further improve measurement reliability. New data evaluation methods will help scientists conduct nuclear evaluations in conjunction with experimental data and advanced theoretical simulations. Nuclear codes such as TALYS will be developed further through the use of advanced potential models, nuclear level density models, gamma strength functions, and pre-equilibrium nuclear reactions. Machine learning and artificial intelligence will further refine the models used and predict behaviors of nuclei where experimental data are scarce.

Future progress will depend heavily on hybrid experimental–theoretical approaches, in which new measurements are continuously used to validate and refine reaction models. Such integrated strategies reduce discrepancies between observed and calculated excitation functions while improving the reliability of nuclear data used in reactor simulations, radiation transport, fusion technology, and medical applications. Experimental benchmarking remains essential for constraining theoretical parameters and ensuring the consistency of evaluated libraries such as ENDF/B, JEFF, JENDL, TENDL, and CENDL.

Finally, international collaboration will remain fundamental to advancing fast neutron-induced (n,p) reaction research. Organizations such as the International Atomic Energy Agency (IAEA), the OECD Nuclear Energy Agency (OECD-NEA), the

National Nuclear Data Center (NNDC), and regional nuclear data centers play a central role in coordinating experimental programs, standardizing measurement methodologies, maintaining global nuclear databases, and developing evaluated data libraries. Collaborative initiatives involving shared experimental facilities, open-access databases, inter-laboratory comparison studies, and coordinated research projects will continue to improve the quality, consistency, and accessibility of nuclear data. Through sustained international cooperation and technological innovation, future research will significantly strengthen the accuracy of fast neutron-induced (n,p) reaction excitation functions and expand their applications across nuclear science, energy, medicine, and space technology.

Fast neutron-induced (n,p) reactions are among the most significant types of neutron-induced nuclear reactions due to the intrinsic importance of these reactions in the field of nuclear physics and their extensive application in nuclear science and technology. The excitation functions of such atomic interactions give important data on the probabilities of atomic reaction based on energy of neutrons, and thus should be included in modern nuclear data libraries. Comprehensive understanding of excitation functions is critical for the operation of nuclear reactors and the other applications like fusion processes, the use of accelerators, protection against radiation, dosimetry, radiation activation analysis, preparation of medical isotopes, or testing different materials. In this context, continuous developments in experimental methods and theoretical studies are essential for improving the reliability of nuclear databases and the predictive ability of calculations in nuclear engineering. The review aims at providing the theoretical frameworks responsible for fast neutron-induced nuclear (n,p) reactionsii, encompassing nuclear reaction theory, determination of Q-values, threshold energies, excitation functions etc. All these theories provide the basis for validation of experimental findings and for the development of modern nuclear reaction models that help in anticipating excitation functions over a range of neutron energies. Use of modern atomic reaction codes such as TALYS, EMPIRE, CoH, ALICE and GNASH has significantly enhanced the theoretical predictions through implementation of modern optical model potentials and Hauser-Feshbach statistical theory and pre-equilibrium emission models.The evaluation also looked at the primary experimental techniques used for the measurement of the excitation functions like neutron generators using D-T and D-D, neutron production using cyclotrons, spallation sources of neutrons, measurement through time-of-flight, neutron activation methods, and spectrometry of gamma rays using high-purity germanium detectors. Though all these methods have helped tremendously in improving the overall quality of experimental nuclear information, there still remain many problems because of the lack of data regarding several isotopes, the inconsistencies existing between the experimental data, difficulty related to uncertainty propagation, incomplete covariance data, etc. Henceforth, it is important to keep validating such applicable nuclear data libraries like EXFOR, ENDF/B, JEFF, JENDL, CENDL, BROND, ROSFOND, IRDFF, and TENDL. To advance the field, the applications related to the fast neutron-induced excitation functions (n,p) cannot only be confined to the subject of nuclear physics since they have many applications in reactor physics, and fusion energy development, isotopes production, dosimetry, activation analysis, nuclear waste management, etc. With nuclear energy systems advancing and new medical technologies coming up, the need for comprehensive information will grow in the future. Thus, there is going to be an even bigger need for comprehensive neutron reaction results therefore; the development of high power neutron sources, new detectors, good techniques for evaluation, combination of theory and experiments will be essential. Also, there is a rising trend towards the use of Bayesian statistics and machine learning methods in evaluations of nuclear data, which are going to improve the data quality significantly. Hence, all these databases will ultimately enable the field to produce accurate results.

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