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Study and analysis of nuclear cross section for Cu^{64}- Medical radioisotope through proton induced reaction on Ni^{64} using EMPIRE 3.2.3 code

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Abstract

This study aims to analyze and measure the nuclear cross section for Cu^{64} radioisotope through proton induced reaction on Ni^{64} using the EMPIRE 3.2.3 code theoretically from energy range up to 25 MeV. EMPIRE code accounts for the major nuclear reaction models, such as optical model, Coupled Channels and DWBA (distorted wave born approximations). EMPIRE code contains both the quantum mechanical and classical model to describe pre- equilibrium reactions. In this study, we have focused on Cu^{64} which is a medically important radioisotopes used in positron emission tomography (PET) imaging and molecular radiotherapy. Several production methods have been investigated to obtain Cu^{64}, including cyclotron based methods and reactor-based methods. Among these, the proton induced nuclear reaction on Ni^{64} has gained significant attention due to its potential for high specific activity and relatively low production costs. The aims of our study is to explore the current state of knowledge regarding the production of Cu^{64} through proton induced nuclear reaction on Ni^{64}. Here, we have studied the experimental data from literature and compare this experimental data with theoretical calculations using EMPIRE code.

Introduction

The study and analysis of nuclear cross section plays a crucial role in various fields, including nuclear energy, radiotherapy, and nuclear medicine. Accurate cross section data is essential for the design and optimizations of nuclear reactions, the development of radioisotopes for medical applications, and understanding nuclear reactions. Cu^{64} is a widely used radioisotope in medical applications such as positron emission tomography imaging and targeted radionuclide therapy. The Production of Cu^{64} can be achieved through various methods including proton – induced nuclear reaction on Ni^{64} and the reaction is $Ni^{64}(p,n)Cu^{64}$. The literature review aims to provide an overview of previous studies related to the production, study and analysis for Cu^{64} through proton induced nuclear reaction on Ni^{64} using the EMPIRE code. The nuclear cross section is a measure of the probability of a specific reaction occurring when a target nucleus is bombarded by a projectile particle. It is typically represented by the symbol (σ) and is measured in barns (1barn $=10^{-24}\,cm^2$).The cross section depends on various factors such as the projectile energy, target nucleus, and reaction mechanism. Several experimental studies have been conducted to measure the nuclear cross section for Cu^{64} production through proton induced reactions on Ni^{64}. These measurements provide valuable experimental data for validating theoretical models and codes.

Proton induced reactions involve the interaction of protons with a target nucleus, resulting in various reaction products. These reactions are of particular interest due to their relevance in nuclear energy production, and medical applications. Proton- induced reaction on Ni^{64} leading to Cu^{64} production have been extensively studied to understand the underlying reaction mechanisms and to obtain accurate cross section data.

Several experimental studies have been done for proton induced reaction on Ni^{64}. Some of them are studied in this paper by using NNDC (National Nuclear Data Center) EXFOR. EXFOR is the library and format for the collection, storage, exchange and retrieval of experimental nuclear reaction data. The EXFOR library contains an extensive compilation of experimental nuclear reaction. Neutron reactions have been compiled systematically since the discovery of the neutron, while charged particle and photon reactions have been discovered less extensively. The basic unit of EXFOR is an entry, which corresponds to one experiment which is usually described in one or more bibliographic references. An entry contains the numerical data.

- EXFOR is not a bibliographic system but contains numerical data with cross references to pertinent publications.
- EXFOR "entry" represents the results of a work performed at a given laboratory at a given time.[1]

The experimental nuclear reaction data (EXFOR) for proton induced Ni^{64} and energy is ranges up to 1 – 25 MeV as shown in fig.1.

Literature Review:

Experimental studies for Ni^{64} (p,n) Cu^{64} reaction by following authors:

1. Adel (2020):

Typical nickel proton- induced nuclear cross section of Ni^{64}(p,x)$Co^{56,57,58}$ and Ni^{nat}(p,x) Ni^{64}, have been experimentally measured by their centre up to 17 Mev proton energy. Stacked foil technology combined with HPGe gamma ray spectroscopy. Three codes such as ALICE- IPPE, EMPIRE CODE 3.2.3 and TENDL.2017 were used in the theoretical calculations. Nickel is an important element used as a construction material in nuclear technology and as a target material in medical radio nuclides production. Current results are compared with previous experimental data and codes were carried out. The graph is plotted between energy and cross section. [2]

2. Uddin (2016):

A newly developed facility on a 3MeV tandem accelerator in Dhaka to measure the proton induced cross-section in the energy region below 5MeV is described and beam measurements are described. The results were confirmed by comprehension with the positive value of the work function of the Ni^{64}(p,n)Cu^{64} reaction. Excitation function for the Ni^{nat}(p,x)$Cu^{60,61}$,Ni^{nat}(p,x)$Co^{55,57}$ and Ni^{nat}(p,x)Ni^{57} reactions were also measure from the threshold to 16 MeV using the stacked foil technique. Here, irradiation was carried out using 5MeV proton from the tandem accelerator in Julich, Germany and 16.7MeV proton from the BC 1710 cyclotron. Radioactivity was measured with the HPGe gamma rays detector. In particular Ni^{nat}(p,x)Cu^{61} reaction below 3MeV can be used as a light source. The graph is plotted between them as given below.[3]

3. R. Adam Rebel (2009):

The radioisotope in which a growing interest exists in nuclear medicine is Cu^{64}. The branched decay makes is suitable for both diagnostic and therapeutic purposes. Activation cross sections of the proton induced reaction on enriched Ni^{64}have been studied using the stacked foil technique up to 24MeV. The experimental cross sections are compared with values available from literature. [4]

4. Avila – Rodrigu (2007):

Cu^{64} and Co^{61} radio nuclides were produced simultaneously with the enrichment of Ni^{64} by irradiation of a low energy pure proton cyclotron. Ni targets where prepared by electro deposition of enriched Ni^{64} at a temperature up to 25-225 mg/cm^2 thickness. Irradiate with 11.4 MeV protons for 8 hours using a water cooled target. Radiochemical separation of Cu^{64} and Co^{61} from Ni^{64} was achieved in greater than 95% yield by 1 step chloride complex chromatography using an anion exchange column. Using this formula, Ni targets were reused and recycled for further production efficiency of greater than 96%. The excitation function of the Ni^{64}(p,n) Cu^{64} reaction were measured and compared with the published value.[5]

5. Szelecsenyi (1993):

Excitation function were measured by using stacked foil technique for Ni^{61}(p,n) Cu^{61} and Ni^{61}(p,2n)Cu^{60} nuclear reaction utilizing 88.84% improved Cu^{61} and Ni^{64}(p,n)Cu^{64} utilizing 95% improved Ni^{64} from 18.6MeV. The strength range for the result of two together Cu^{61} and Cu^{64} was expected 12-9MV. At 95% advancement of the material Cu^{64} yield total 6.38mCi and Cu^{61} pollutions are 10.01 and 0.41% individually. An ion exchange, chromatographic method for triggered Ni. The Ni^{61} (p,n)Cu^{61} and Ni^{64}(p,n)Cu^{64} processes are the result of Cu^{61} and Cu^{64} at a narrow atom.[6]

6. Sevior (1983):

Cross can be measured for Cu^{64}, Ni^{64} and Cu^{63} over the proton energy range of 1.05-4.70Mev respectively, for (p,n) reactions over proton energy range from threshold 4.86MeV and for Cu^{63}(p,p`)Cu^{63} over a protn enegy range of 1.5- 4Mev. All the data are compared with global statistical model calculation. [7]

7. Tanaka (1972):

Excitation functions have been measured for several nuclear events involving nickel isotopes and protons with energies between 5 and 56 MeV. The peak's cross-sections were calculated as follows: Ni^{58}(p, 2p)-21mb, Ni^{60}(p, n)-320mb, Ni^{61}(p, n)-480mb, Ni^{62}(p, n)-480mb, Ni^{64}(p, n)-670 mb. Up to E_p =64, the cross-sections for the following reactions were calculated: Ni^{58}(p, p2n),Ni^{60}(p, p3n) and Ni^{61}(p). Cross-sections of Co^{60} formation from natural nickel were also measured.[8]

8. Moses (1971):

The total neutron yields of Cr^{54}(p, n)Mn^{54} and Ni^{64}(p, n)Cu^{64} of the differential cross sections of Cr^{64}(p, p)Cr^{64} and Ni^{64} were measured in the analogs of the third excited state of Cr^{55} and the first excited state of Ni^{65}. The total energy spread for these measurements is approximately 300–400eV. The data has been increase in the neutron widths of the fine-structure resonances connected to these analog states. No neutron widths can be observed. [9]

9. Blooser (1955):

Twenty (p,n)cross sections on elements with atomic numbers ranging from 21 to 58 were measured, and the results are presented. When interpreted in terms of a wholly black square well potential at a depth of 20 Mev, the findings show total reaction cross sections, which equate to a potential radius of 1.55 to 1.65 $A^{1/3}10^{-13}$ cm.[10]

10. Blaser(1991):

It also calculated the energy and Cross sections. The graph is plotted between between incident energy and Cross section. Data is compared with other authors.[11]

Selected experimental data is extracted from literature Review. We have studied research papers. The graph is plotted between incident energy and Cross section. Different research paper shows different values of the cross-section at different energies. The result shows that the increase and decrease of the cross-section curve are almost at same peak. In all the research papers that we have studied, the higher value of cross-section was between 10-12 MeV. Once this value was reached, the cross-section curve started decreasing. We collected some information for our project work by comparing theoretical calculations with these experimental data to evaluate or check the accuracy of our results through EMPIRE code. The data for energy versus cross section as shown in Figure 1.

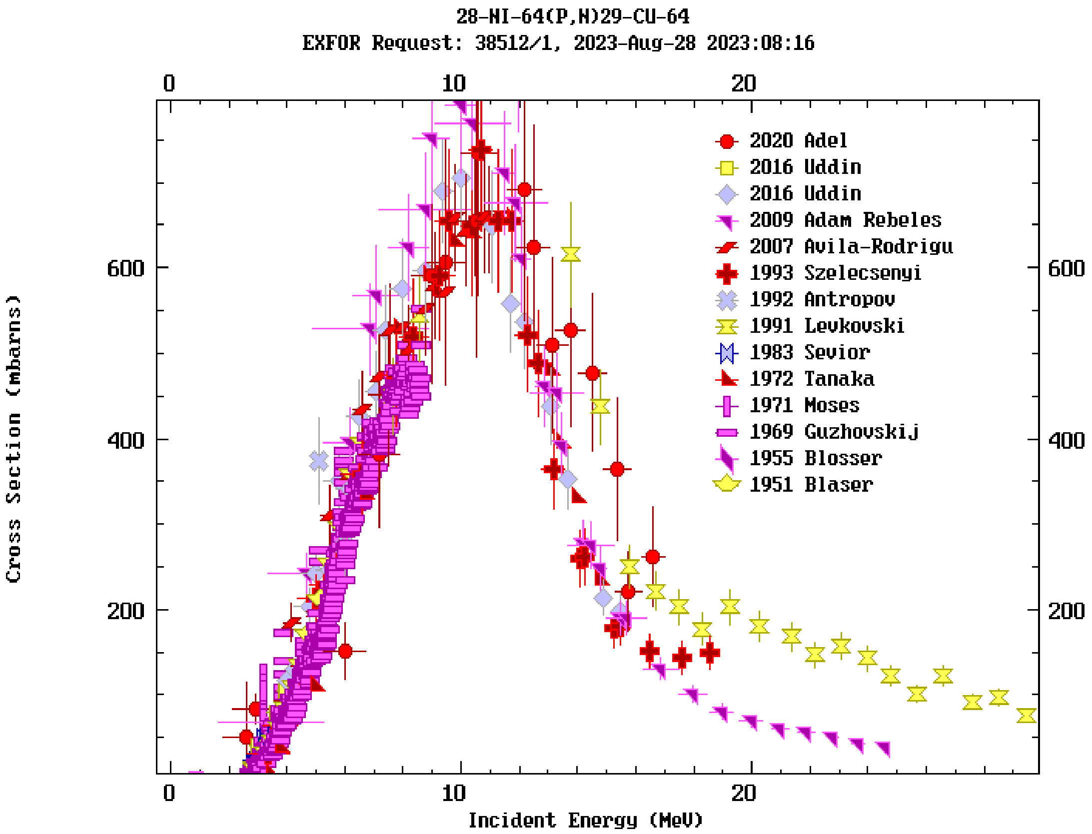

Fig 1: Selected experimental data Cross section for Ni^{64} (p,n) Cu^{64} reaction

Theoretical calculations of the nuclear cross section for Cu^{64} through proton induced reaction Ni^{64} using the EMPIRE 3.2.3 code.

EMPIRE stands for "Energy dependent model for the prediction of nuclear reaction and emission of particles." It's used to predict cross-sections for nuclear reactions, which are essential for understanding how particles and nuclei interact in various scenarios, including nuclear reactors, particle accelerators, astrophysical processes.

Theoretical calculations of nuclear cross-section are essential for understanding various nuclear reactions and processes. The cross-section of proton induced reactions on Ni^{64} were experimentally measured for Ni^{64}(p,n) Cu^{64} from their respective threshold up to 25 MeV energy. On the basis of our data result between incident energy and cross-section a graph have plotted. We compared our data with the experimental data to validate the accuracy of the calculations and assess the reliability of the EMPIRE code for this specific reaction Ni^{64}(p,n) Cu^{64}. The reaction is:-

$$p + Ni^{64} \rightarrow Cu^{64} + n$$

The EMPIRE code is computational code used in nuclear physics and nuclear engineering. It is a system designed for modeling and simulating nuclear reaction and interactions, particularly in the context of nuclear reaction analysis, cross-section calculations and related research. EMPIRE code is a complex system of codes, linked through a series of scripts and graphical interfaces, designed for modeling nuclear reactions. The system is general and flexible, and can been applied to the calculation.

EMPIRE code is a modular system of nuclear reaction codes, comprising various nuclear models, and designed for calculations over a broad range of energies and incident particles. The system can be used for theoretical investigations of nuclear reactions as well as for nuclear data evaluation work. The code accounts for the major nuclear reaction models, such as optical model, Coupled Channels and DWBA, Multi-step Direct. EMPIRE provides a natural environment for implementing the covariance evaluation capabilities. EMPIRE code contains both the quantum mechanical and classical model to describe pre- equilibrium reactions. The code is designed to simulate and analyze a variety of nuclear reactions, including neutron-induced reactions, photonuclear reactions, and particle induced reactions. It utilizes a Monte Carlo approach, where random numbers are used to simulate the statistical nature of nuclear reactions. The package contains the full EXFOR library of experimental data in computational format C4 that are automatically retrieved during the calculations.

The EMPIRE code incorporates several theoretical models and methods to calculate and predict the behavior of nuclear reactions, including compound nucleus reactions, direct reactions and more. The user has to supply only those input parameters that the code cannot know. These are the incident energy, the projectile, the target and the number of emitted particles to be followed.

EMPIRE code belongs to a new generation of nuclear reaction codes, and is intended as a general theoretical tool to be used in basic research and nuclear data evaluation over a broad range of incident energy and projectiles. It was designed to contain up to date nuclear reaction models as well as being easy to use. It consists of a number of FORTRAN codes, input parameters, and experimental data library EXFOR operated through the Graphic User Interface. Comprehensive library of input parameters and graphic user interface facilitate preparation of the input and operation of the code.

EMPIRE is the result of an international cooperation towards open source software, as so successfully promoted by the General Public License. It is built around a physics core designed for modeling low- to-intermediate energy nuclear reactions. It incorporates an extensive set of nuclear reaction models able to describe all relevant reaction mechanisms, each of them conveniently coupled to the up-to-date library of input model parameters. The code is also suitable for massive calculations, is easy to use, has readily available default input values for all parameters, and is applicable to a wide range of target nuclei and incident energies. Results may be stored and subsequently plotted against experimental data for verification.

In this code is an edited input for reaction Ni^{64}(p,n) Cu^{64} with changing energy, has been used and all the parameters have kept default for this direct reaction.

After the EMPIRE code completes the calculation; it generates output files containing the calculated cross section. These files can be analyzed to extract the desired information as shown in Table: 1. The cross-section can be plotted as a function of energy and compared with experimental data and other theoretical calculation.

Theoretical calculated data by EMPIRE code:

Table 1 Theoretical cross section by EMPIRE code for Ni^{64}(p,n) Cu^{64}

Energy (MeV)	Cross-section EMPIRE (mb)
2	1.59
3	41.72
4	166.8
5	240.03
7	418.29
10	612.82
12	511.41
14	318.38
15	233.91
17	136.45
20	47.48
21	40.48
22	30.91
23	22.31

These values are calculated using EMPIRE 3.2.3 code and graph is plotted using NNDC. Graph is plotted between incident energy (MeV) and cross- section (mb) as shown in Fig. 2.

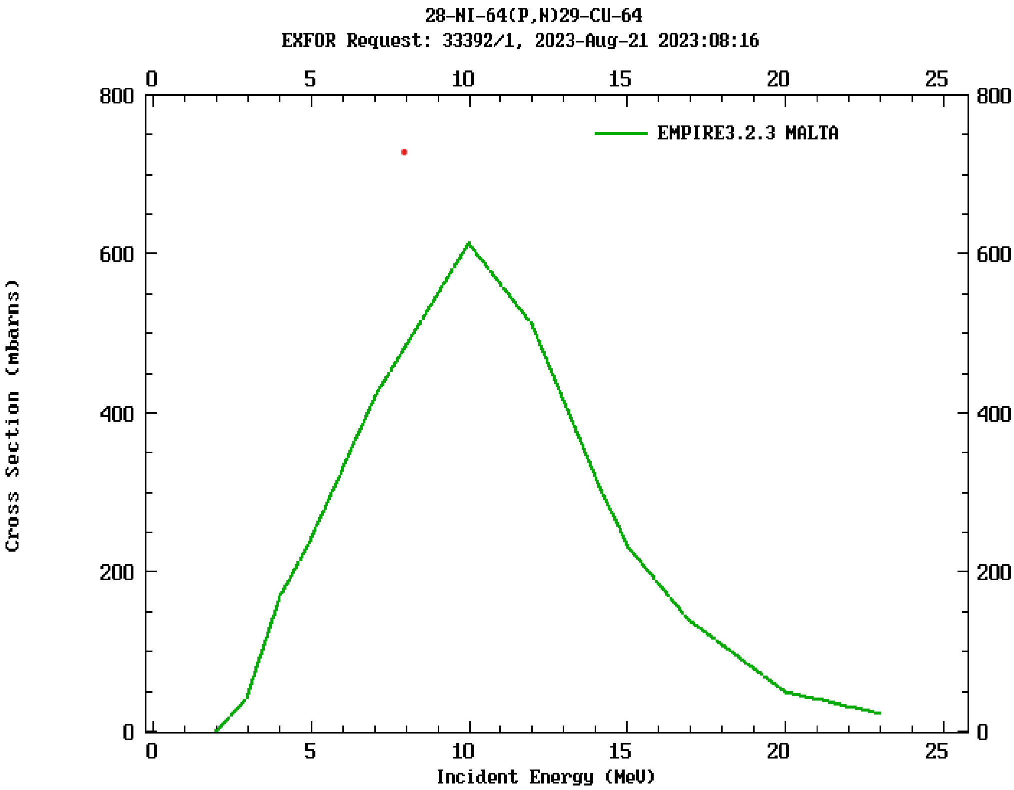

Fig.2. Theoretical calculations using the EMPIRE nuclear model code for Ni^{64}(p,n)Cu^{64}

Compared experimental data with theoretical calculations:

In this step, the selected experimental data was compared with theoretical cross section calculation. We analyze the selected experimental data from the literature review and calculate the theoretical cross section calculations using the EMPIRE3.2.3 code. This step helps us to validate our calculation and to evaluate the dependability of EMPIRE for this particular reaction Ni^{64}(p,n)Cu^{64} as shown in Figure 3.

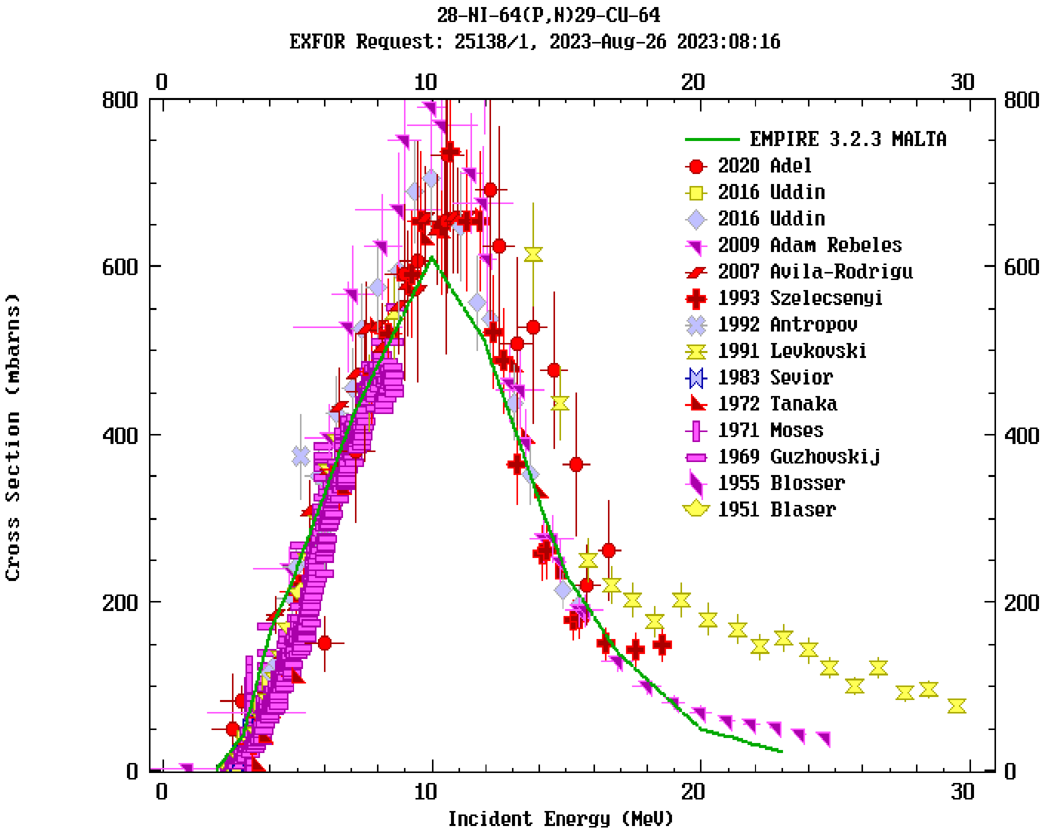

Fig 3. Selected experimental along with the result of theoretical calculations using the nuclear model codes EMPIRE for the $Ni^{64}(p,n)Cu^{64}$

This study compared several experimental data with theoretical calculations. The initial step of the calculation was to take the lowest energy values, after which the cross sectional curve began to increase. At 10-12 MeV, the curve reached its maximum value, after which it began to decrease. The results of the study showed that the EMPIRE code accurately predicted the cross sections and production yields of Cu^{64} by comparing the experimental data.

Result and Conclusion

The cross sections of proton induced reaction on Ni^{64} were theoretically measured for Ni^{64}(p,n)Cu^{64} from their energy up to 25MeV. Selected experimental data are extracted from the literature and compare our theoretical data with these experimental data. Both experimental data and theoretical data were comparable. In this study, we concluded that around 10 MeV, our cross-section curve reached at its maximum and after this value, the curve started decreasing. These results may help in the development of effective methods to produce medical imaging applications.

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