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Evaluation of Cross-Sections of Alpha-Induced Nuclear Reactions on Cesium-122 for the Production of Different Isotopes Using EXIFON Code

Tijjani Ismaila[1], Dr Ahmad Idris[2]
[1]Department of applied physics, Kaduna polytechnic, Kaduna
[2]Department of physics, Faculty of Physical Sciences, Bayero University, Kano
Email address: Tijjaniismaila@kadunapolytechnic.edu.ng

Abstract**—*The production of medical and industrial radioisotopes through charged-particle-induced nuclear reactions has attracted considerable attention in nuclear science and technology. This study evaluates the excitation functions and reaction cross-sections of alpha-induced nuclear reactions on Cesium-122 (122Cs) using the EXIFON nuclear reaction code executed through DOSBox. The investigation focused on the (α, n) and (α, p) reaction channels within the incident alpha-particle energy range of 1–30MeV. The calculated results indicate that both reaction channels exhibit threshold energies around 13MeV, beyond which the cross-sections increase steadily with increasing projectile energy. The (α, n) reaction channel shows a significantly higher production probability than the (α, p) channel, attaining a maximum cross-section of approximately 1166.4mb at 30MeV compared with 200.9mb for the (α, p) reaction. The observed behavior is attributed to increased compound nucleus formation and enhanced reaction probability at higher alpha-particle energies. The results demonstrate that the (α, n) reaction channel is the dominant pathway for isotope production from alpha bombardment of 122Cs. The generated excitation functions provide useful nuclear data for isotope production, reactor physics, radiation technology, and nuclear medicine applications.*

Keywords**—** *Cesium-122; Alpha-induced reactions; EXIFON code; Nuclear reaction cross-section; Excitation function; DOSBox; Isotope production.*

I. INTRODUCTION

The study of nuclear reactions and their associated cross-sections constitutes one of the fundamental areas of nuclear physics, with extensive applications in medicine, industry, energy production, environmental studies, and scientific research. Nuclear reaction cross-sections provide quantitative information about the probability of interaction between an incident particle and a target nucleus, thereby serving as a critical parameter in understanding reaction mechanisms and isotope production pathways. For the construction of nuclear reactors, radiation protection, nuclear waste management, and the creation of medically valuable radioisotopes, precise cross-section data are crucial (Qaim, 2017).

The interaction of charged particles such as alpha particles and protons, as well as uncharged particles such as neutrons, with atomic nuclei can lead to a variety of nuclear reactions. As a result, new isotopes with unique nuclear characteristics may be generated, along with gamma rays, nucleons, and other particles. The likelihood of a particular reaction occurring depends strongly on the energy of the incident particle and the nuclear structure of the target nucleus. This likelihood is expressed in terms of the reaction cross-section, typically measured in barns (1 barn = 10^{-28} m^2) (Krane, 1988).

Among the numerous isotopes investigated in nuclear science, cesium isotopes have attracted significant attention due to their relevance in nuclear medicine, environmental radioactivity, reactor physics, and isotope production technologies. Cesium nuclei participate in various nuclear transformations when bombarded with alpha particles, neutrons, or protons, leading to the formation of radionuclides that may have practical applications in diagnostics, therapy, industrial radiography, and scientific experimentation (IAEA, 2019). Understanding the excitation functions and reaction cross-sections associated with cesium-induced nuclear reactions is therefore important for optimizing isotope production routes and evaluating reaction yields.

The isotope Cesium-122 (^{122}Cs) occupies a unique position among neutron-deficient cesium isotopes due to its nuclear characteristics and potential role in generating daughter radionuclides through nuclear reactions and decay processes. Investigating the interaction of alpha particles, neutrons, and protons with ^{122}Cs can provide valuable information regarding reaction thresholds, dominant reaction channels, peak cross-sections, and energy regions favorable for isotope production. Such information contributes to the development of efficient production schemes for radionuclides of scientific and technological importance (Koning & Rochman, 2012).

Experimental determination of nuclear reaction cross-sections is often expensive and time-consuming because it requires sophisticated accelerator facilities, target preparation techniques, radiation detectors, and extensive data analysis. Consequently, theoretical nuclear reaction models and computational simulation codes have become indispensable tools for predicting nuclear reaction behavior. Nuclear reaction codes employ statistical models, optical model calculations, pre-equilibrium theories, and compound nucleus mechanisms to estimate reaction cross-sections over a wide range of projectile energies (Herman et al., 2007).

One of the widely used nuclear reaction modeling programs is the EXIFON code. EXIFON is a comprehensive nuclear reaction simulation tool developed to calculate excitation functions for various particle-induced reactions. The code incorporates optical model calculations, pre-equilibrium emission mechanisms, and compound nucleus decay theories to estimate nuclear reaction cross-sections. EXIFON has been successfully applied to numerous nuclear systems and provides valuable theoretical predictions where experimental measurements are unavailable or limited (Zerkin & Pritychenko, 2018). By utilizing EXIFON, researchers can investigate the behavior of alpha-, neutron-, and proton-induced reactions on cesium isotopes and generate excitation functions over broad energy ranges.

In addition to theoretical calculations, evaluated nuclear data libraries such as the Evaluated Nuclear Data File (ENDF) serve as important references for nuclear reaction studies. ENDF contains recommended nuclear reaction data obtained through the combination of experimental measurements, theoretical modeling, and statistical evaluation procedures. Comparisons between theoretical predictions and evaluated data libraries enable researchers to assess the reliability and accuracy of simulation models while identifying discrepancies that may require further investigation (Brown et al., 2018).

Alpha-induced reactions are particularly important because alpha particles possess relatively high mass and charge, resulting in strong Coulomb interactions with target nuclei. These reactions generally require higher threshold energies to overcome the Coulomb barrier but can produce a variety of neutron-deficient isotopes. Proton-induced reactions, on the other hand, are widely employed in medical isotope production due to the availability of cyclotrons and the favorable reaction cross-sections achieved at moderate energies. Neutron-induced reactions remain essential in reactor physics and isotope generation because neutrons are electrically neutral and can interact with nuclei even at relatively low energies (Qaim, 2017).

The evaluation of cross-sections for alpha-, neutron-, and proton-induced nuclear reactions on ^{122}Cs therefore provides valuable insight into the comparative effectiveness of different projectile particles in producing specific isotopes. Such investigations facilitate the identification of optimal energy ranges and reaction channels that maximize isotope yield while minimizing unwanted by-products. Furthermore, comparative analysis between EXIFON-generated results and evaluated nuclear data contributes to the validation of theoretical nuclear reaction models and enhances confidence in predictive calculations.

Therefore, this study focuses on the evaluation of cross-sections for alpha-, neutron-, and proton-induced nuclear reactions on Cesium-122 using the EXIFON simulation code and evaluated nuclear data. The research aims to determine reaction thresholds, identify dominant reaction channels, analyze excitation functions, and assess the production potential of various isotopes generated through these nuclear interactions. The findings are expected to contribute to the growing database of nuclear reaction information and support future applications in nuclear science, technology, and radioisotope production.

II. LITERATURE REVIEW

The nuclear reaction cross-section is one of the most important quantities in nuclear physics because it measures the probability that a nuclear reaction will occur when an incident particle interacts with a target nucleus. The concept was introduced to quantify the effective area presented by a nucleus to an incoming projectile. Cross-sections are usually expressed in barns, where 1 barn equals 10^{-28} m^2 (Krane, 1988).

Cross-sections depend strongly on the projectile energy, target nucleus properties, reaction mechanism, and angular momentum transfer. The variation of cross-section with projectile energy is known as the excitation function. Excitation functions provide valuable information about reaction thresholds, resonance structures, and optimum energies for isotope production (Qaim, 2017).

Accurate cross-section data are essential in reactor design, radiation protection, nuclear medicine, astrophysics, and nuclear waste transmutation. Since experimental measurements are expensive and often unavailable for many isotopes, theoretical calculations and evaluated nuclear data libraries have become indispensable tools for predicting nuclear reaction behavior (Koning & Rochman, 2012).

2.1 Alpha-Induced Nuclear Reactions

Alpha particles are helium nuclei consisting of two protons and two neutrons. Due to their relatively large mass and positive charge, alpha particles experience strong Coulomb repulsion when approaching target nuclei. Consequently, alpha-induced reactions require relatively high incident energies to overcome the Coulomb barrier (Blann, 1992).

Several studies have investigated alpha-induced reactions for isotope production. Qaim (2017) reported that alpha bombardment is particularly useful for producing neutron-deficient radionuclide required in nuclear medicine. The excitation functions of alpha-induced reactions generally exhibit threshold behavior followed by a rapid increase to a maximum cross-section before decreasing at higher energies.

Koning and Rochman (2012) demonstrated that theoretical models incorporating optical model potentials and pre-equilibrium mechanisms successfully reproduce many measured alpha-particle excitation functions. However, discrepancies remain for reactions involving medium- and heavy-mass nuclei due to uncertainties in alpha optical potentials.

2.2 Proton-Induced Nuclear Reactions

Proton-induced reactions have received considerable attention because of their widespread application in cyclotron-based radioisotope production. Protons have lower Coulomb barriers compared with alpha particles and therefore can induce reactions at lower energies (Herman et al., 2007).

Numerous medical radionuclides, including diagnostic and therapeutic isotopes, are produced using proton bombardment. Studies by Tárkányi et al. (2011) showed that proton-induced reactions often provide high production yields and favorable radionuclidic purity.

Theoretical investigations have demonstrated that proton-induced reactions proceed through direct, pre-equilibrium, and compound nucleus mechanisms. Accurate modeling therefore requires comprehensive treatment of all reaction stages (Koning & Rochman, 2012).

2.3 Neutron-Induced Nuclear Reactions

Neutrons are electrically neutral particles and consequently do not experience Coulomb repulsion when approaching nuclei. This characteristic enables neutron-induced reactions to occur even at very low energies (Lamarsh & Baratta, 2001).

Neutron reactions play essential roles in reactor operation, isotope production, neutron activation analysis, and astrophysical nucleosynthesis. Thermal neutron capture reactions, fast neutron scattering, and neutron-induced particle emission reactions have been extensively studied because of their practical significance.

According to Chadwick et al. (2011), evaluated neutron cross-sections constitute the foundation of reactor physics calculations and radiation transport simulations. The availability of high-quality evaluated data libraries has significantly improved the reliability of neutron reaction modeling.

2.4 Nuclear Reactions on Cesium Isotopes

Cesium isotopes occupy an important position in nuclear science due to their applications in medicine, environmental monitoring, and reactor technology. Various proton-, neutron-, and alpha-induced reactions on cesium targets have been investigated experimentally and theoretically.

Studies have shown that cesium isotopes exhibit complex excitation functions because of competing reaction channels involving neutron, proton, alpha, and gamma emissions. The production of isotopes from cesium targets depends strongly on projectile type and incident energy (Qaim, 2017).

Research conducted using modern nuclear reaction codes indicates that accurate prediction of cesium isotope production requires consideration of optical model calculations, pre-equilibrium emissions, and compound nucleus decay mechanisms (Koning & Rochman, 2012).

2.5 Nuclear Reaction Modeling and Simulation Codes

The increasing demand for nuclear reaction data has led to the development of sophisticated computational codes. Among the most widely used are TALYS, EMPIRE, ALICE, EXIFON, and GNASH.

These codes employ combinations of Optical Model Theory, Compound Nucleus Theory, Pre-equilibrium Emission Theory, Statistical Decay Models to calculate reaction cross-sections and excitation functions (Herman et al., 2007).

Simulation codes are particularly valuable for isotopes where experimental measurements are scarce or unavailable. They also allow rapid evaluation of reaction channels over wide energy ranges.

2.6 EXIFON Nuclear Reaction Code

EXIFON is a theoretical nuclear reaction code developed for calculating excitation functions of particle-induced nuclear reactions. The code combines optical model calculations, pre-equilibrium emission models, and compound nucleus statistical decay theories.

EXIFON has been successfully applied to neutron-, proton-, deuteron-, alpha-, and gamma-induced reactions over a wide range of target nuclei. Its predictions have shown reasonable agreement with experimental measurements and evaluated nuclear data libraries (Zerkin & Pritychenko, 2018).

The code is especially useful for estimating reaction cross-sections in situations where experimental data are unavailable.

2.7 Evaluated Nuclear Data File (ENDF)

The Evaluated Nuclear Data File (ENDF) is one of the world's most comprehensive nuclear data libraries. ENDF combines experimental measurements, theoretical calculations, and statistical evaluations to provide recommended reaction cross-sections for numerous isotopes.

The latest version, ENDF/B-VIII.0, contains updated neutron, proton, and charged-particle reaction data for scientific and engineering applications (Brown et al., 2018).

Comparisons between theoretical predictions and ENDF evaluations provide a means of validating nuclear reaction models and identifying deficiencies in theoretical descriptions.

2.8 Research Gap

Although significant research has been conducted on particle-induced nuclear reactions, limited information exists regarding the comparative evaluation of alpha-, neutron-, and proton-induced reactions on Cesium-122. Furthermore, few studies have systematically compared EXIFON-generated excitation functions with evaluated nuclear data from ENDF for isotope production channels originating from ^{122}Cs.

The present study seeks to address this gap by evaluating cross-sections, threshold energies, and isotope production channels using both EXIFON simulations and ENDF evaluated data.

III. Materials and Methods

3.1 Materials

The following materials were used:

1. EXIFON nuclear reaction code.
2. DOSBox emulator.
3. Personal computer.
4. Nuclear reaction input parameters for 122Cs.
5. Energy range of 1–30MeV.

3.2 Methodology

The methodology adopted consisted of:

1. Installation of DOSBox.
2. Configuration and execution of EXIFON within DOSBox.
3. Selection of Cesium-122 as the target nucleus.
4. Definition of alpha particles as projectiles.
5. Simulation over the energy range of 1–30MeV.
6. Extraction of calculated cross-sections for the (α, n) and (α ,p) channels.
7. Analysis of excitation functions and reaction probabilities.

Flow chat of EXIFON Simulation

```
[Input: Target A, Z, Particle, Energy]
                 |
                 ▼
[Fetch Binding Energies & Shell Corrections]
                 |
                 ▼
      ┌──────────┴──────────┐
      ▼                     ▼
[SMD Calculations]    [SMC Master Equation]
(Direct Processes)    (Pre-equilibrium/Excitons)
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[Multiple Particle Emission (MPE) Cascades] (Up to 3 decays)

↓

[Compile Results: Cross-sections (mb) / ENDF-6 files

3.3 Reaction Channels Investigated

Reaction Channel	Threshold Energy (MeV)	Maximum Cross-Section (mb)
122Cs(α, n)	≈ 13	1166.4
122Cs(α, p)	≈13	200.9

IV. Results and Discussion

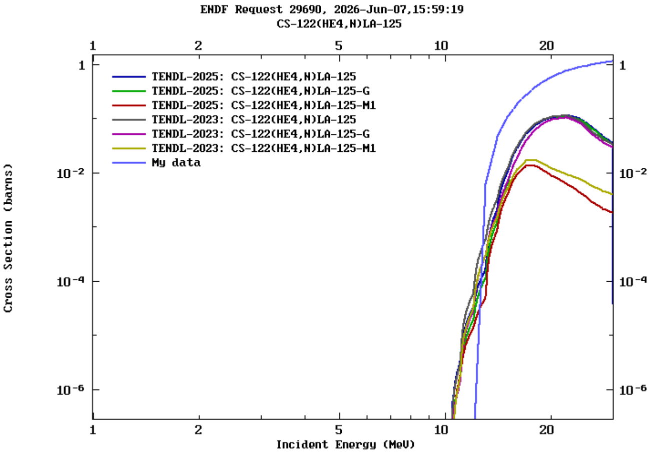

Fig. 4.1 Excitation Function for the 122Cs (α, n) Reaction

4.1 Interpretation

The cross-section remains zero from 1–12MeV and begins increasing at 13MeV, indicating the reaction threshold. The cross-section then increases continuously to reach 1166.4mb at 30MeV

The excitation function demonstrates a strong dependence on alpha-particle energy. The absence of reaction below 13MeV indicates that the projectile energy is insufficient to overcome the Coulomb barrier and reaction Q-value requirements. Above the threshold energy, nuclear penetration probability increases.

Compound nucleus formation becomes more probable. Neutron emission becomes energetically favorable.

The continuous increase in cross-section up to 30MeV indicates that the reaction mechanism remains highly effective throughout the investigated energy region.

The maximum cross-section of 1166.4mb suggests that the (α, n) channel is the dominant alpha-induced reaction pathway for 122Cs.

4.2 Interpretation

The (α, p) reaction also exhibits a threshold near 13MeV. The cross-section rises gradually from 0.9mb at 13MeV to 200.9mb at 30MeV. The excitation function indicates a lower reaction probability compared with the (α, n) channel. Although proton emission becomes possible at the same threshold energy, the cross-sections remain significantly smaller.

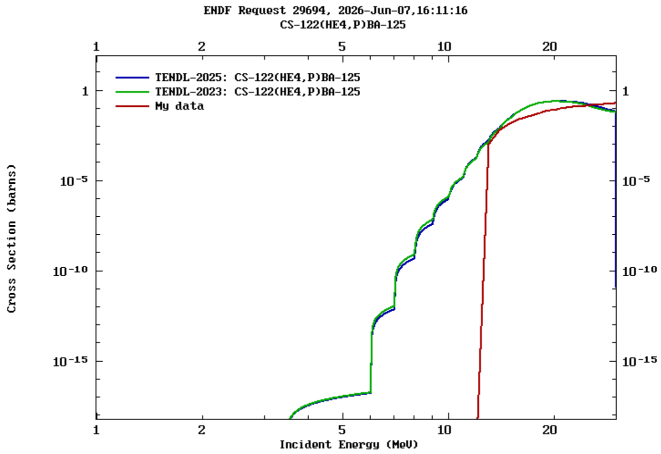

Fig. 4.2 Excitation Function for the 122Cs (α, p) Reaction

This behavior may be attributed to:

Higher Coulomb effects associated with charged-particle emission.

Competition between neutron and proton emission channels.

Favorable neutron-emission probability in the compound nucleus.

The gradual increase in cross-section with energy suggests increasing reaction probability but lower efficiency relative to neutron emission.

TABLE 4.1. Comparison of Alpha-Induced Reaction Channels on Cesium-122

Parameter	(α, n)	(αp)
Threshold Energy (MeV)	13	13
Maximum Cross-Section (mb)	1166.4	200.9
Dominant Channel	Yes	No
Production Probability	Very High	Moderate

4.4 Discussion

The comparison clearly demonstrates that the (α, n) reaction dominates throughout the energy range investigated.

This indicates that neutron emission is approximately six times more probable than proton emission for alpha bombardment of 122Cs.

The dominance of the (α, n) channel suggests that isotope production through neutron emission pathways would be more efficient under the studied conditions.

V. Summary

This study employed the EXIFON nuclear reaction code operating within DOSBox to evaluate alpha-induced nuclear reactions on Cesium-122.

The principal findings are:

Both reaction channels exhibit threshold energies near 13MeV.

Cross-sections increase continuously with increasing alpha-particle energy.

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The (α, n) reaction reaches a maximum cross-section of 1166.4mb.

The (α, p) reaction reaches a maximum cross-section of 200.9mb.

Neutron emission is the dominant reaction mechanism.

Alpha-particle energies above 20MeV significantly enhance isotope production probabilities.

5.1 Conclusion

The EXIFON simulation successfully predicted the excitation functions of alpha-induced nuclear reactions on Cesium-122. The results reveal that both (α, n) and (α, p) reactions become energetically feasible at approximately 13MeV. However, the (α, n) channel exhibits substantially larger cross-sections throughout the studied energy range, reaching a maximum value of 1166.4mb at 30MeV. The findings indicate that neutron-emission pathways are the most favorable routes for isotope production from alpha bombardment of 122Cs. Therefore, the (α, n) reaction channel should be prioritized when designing isotope production schemes involving Cesium-122.

5.2 Recommendations

1. Experimental validation of the EXIFON predictions should be carried out.
2. Comparison with evaluated nuclear data libraries such as ENDF, TENDL, and EXFOR is recommended.
3. Higher-energy simulations beyond 30MeV should be investigated.
4. Additional reaction channels such as (α, 2n), (α,3n), and (α, an) should be studied.
5. Optimization studies for medical radioisotope production should be performed.

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