Theoretical Calculations of Excitation Function of Cobalt and Manganese Isotopes using Empire Nuclear Reaction Code for Medical Applications

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Abstract:- The excitation function for the Ni(d, x) ^{52,54}Mn and ^{55,57}Co reactions in the energy range of 0-24 Mev were measured using Nuclear reaction code, EMPIRE code Malta 3.2. The optical, pre-equilibrium and compound nucleus models were employed for the statistical calculations. The evaluated cross-sections were compared with the recent experimental data retrieved from EXFOR library. The results show good agreement with the EXFOR data.

Keywords:- *Excitation function, Cross-section,^{52}Mn, ^{54}Mn,^{55}Co, and ^{57}Co, EMPIRE code.*

I. INTRODUCTION

One of the most important activities of nuclear technology is the production of medical radioisotopes.The recent increase in carcinogenic cases has led to more quest for the production of ^{52}Mn,^{55}Co and ^{57}Co radioisotopes that are used for various applications in nuclear medicine. The need for understanding processes taking place when a nuclear reaction occurs are to produce nuclear data for various application using nuclear reaction codes. Different experimental and theoretical investigations were carried out and compared with evaluated data for accuracy. The majority of these radioactive isotopes are produced through various nuclear processes. Variety of radioactive isotopes are employed for medical purposes, in diagnosis and therapy (Aikawa*et al.,* 2018). Radioactive isotopes produced through bombardment of metallic target by light- charged particles has attracted significant attention, due to the rising applications in various fields such as nuclear medicine, environmental science, agricultural science and many different industrial procedures. The high demand of radioactive isotopes is leading to more quest for greater accuracy of data, optimized production and alternative production methods (Usman *et al.,* 2016). Excitation functions and nuclear reaction mechanisms are explored in many researches for simulation of the production of various radioisotopes in the TALYS, EMPIRE, and AlICE reaction codes, after which parameters and various models of nuclear level density as one of the most important components in statistical reaction models, are adjusted for effective production of desired radioactive yields (Nasrabadi and Sepiani 2015). Due to a lack of experimental data, nuclear reaction models have been designed to estimate reaction cross-sections (Sahan*et al.,* 2017).

In the present study, reaction cross section calculations of ^{52}Mn,^{54}Mn,^{55Co} and ^{57}Co radioisotopes were investigated using nuclear reaction code model EMPIRE-3.2 Malta. Several important cobalt (Co) radioisotopes were produced from irradiation of Nickel (Ni) with deuteron particle beam from various experiments. The radioisotopes are used for various application in nuclear medicine and other research fields due to their suitable decay characteristics. ^{55}Co is applicable in labelling bleomycin and in examining cerebral and cardiac disorder via PET, ^{57}Co found important application as a calibration standard in gamma ray spectrometry and tomography (SPECT) (Usman *et al.,* 2016).^{52}Mn has significant applications in cell radiolabeling, PET imaging and liposomal Nano medicine (Qawne*et al.,* 2018).

II. MATERIALS AND METHOD

The materials employed in this work are computer system and the Software: Microsoft Windows 7, Microsoft excel, EMPIRE code 3.2.3 (MALTA).The parameters required for the nuclear models to calculate the excitation functions have been taken from the RIPL-3 library. The RIPL-3 includes the nuclear masses, discrete levels and decay schemes, neutron resonances, optical model parameters, level densities, gamma-ray strength function and fission barriers.

A. EMPIRE CALCULATION

In our work the direct reaction is calculated with default spherical optical model that uses the ECIS06 code and which have been used to calculate the particle transmission coefficient.(Koning*et al.,* 2005) proposes the OM potential parameter used in this calculation. The Statistical Hauser-Feshbach model is use for the calculation of the compound nucleus decay.

The exciton model (PCROSS code) is employed for pre-equilibrium emission that describes particle and gamma-emission and calculate pre-equilibrium emission with default mean free path multiplier PCROSS 1.5. The contribution from all three mechanisms make total cross-section and maximum contribution comes from the CN decay with an addition of some pre-equilibrium mechanism. The effect of pre-equilibrium contribution increases with increase in incident energy.

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Empire code incorporated four level density models to calculate cross-section, LEVDEN 0, LEVDEN 1, LEVDEN 2 and LEVDEN 3 respectfully. LEVDEN 0 is employ in this calculation, which is the EMPIRE-specific level densities (EGSM RIPL-3), and it is a default model used in EMPIRE, adjusted to RIPL- 3 experimental Dobs and to discrete levels.This is Enhanced Generalized Super fluid Model (EGSM). The model uses super fluid model below critical excitation energy and the Fermi gas model above critical excitation energy.

III. RESULTS AND DISCUSSION

The computed cross-section of this work and the experimental cross-sections retrieved from EXFOR database are plotted against the incident projectile energy as shown in fig. 1. To 6. A (blue line) with circle pointonit Indicates the excitation function of the theoretical calculation. The experimental data by (Usman *et al.,* 2016) retrieved from EXFOR database is indicated by orange circle points.

Nuclide	Half-life	Contributing reaction	Reaction products	Q-value (MeV)	Threshold energy (MeV)
^{52}Mn	5.59 d	^{58}Ni(d,2α)^{52}Mn	^{52}Mn+2α	-1.24	1.28
^{54}Mn	312.12 d	^{60}Ni(d,2α)^{54}Mn	^{54}Mn+2α	-0.63	0.65
^{55}Co	17.53 h	^{58}Ni(d,n+α)^{55}Co	^{55}Co+n+α	-3.56	3.68
^{57}Co	271.74 d	^{60}Ni(d,n+α)^{57}Co	^{57}Co+n+α	-2.49	2.57

Table 1: Nuclear decay data relevant for this study extracted from Nudat 3.0 as well as Q-values and threshold energy extracted from Qtool, (NNDC) National nuclear data center

A. *^{58}Ni(d,2α)^{52}Mnreaction*

The medically important ^{52}Mn radionuclide is formed via the ^{58}Ni(d,2α)^{52}Mn reaction. Our evaluated cross-sections are almost the same as those of (Usman *et a.,l*2016) l. At lower energies the EXFOR cross-section are lower than our evaluated cross-section values, almost the same cross-section value of ~1.3 mb was produce at 8 MeV. Empire code produce cross-section beyond the experimental cross-section value of ~2.3 mb, while the code cross-section evaluation stop at ~3 mb, at an incident energyup to ~15.65 MeV.

B. *^{60}Ni(d,2α)^{54}Mn reaction*

The cross-section of the long live radionuclide ^{54}Mn ($T_{1/2}$=312.12 d) formed via ^{60}Ni(d,2α)^{54}Mn reaction fit well with the experimental at some certain energy levels below 11 MeV. Cross-section discrepancies are observe at energies above ~12 MeV as the experimental cross-section data stopped at a projectile energy of ~12 MeV, the EMPIRE code complete the cross-section evaluation at a projectile energy of ~15 MeV.

C. *^{58}Ni(d,n+α)^{55}Co reaction*

The computed cross-section of the short lived radioisotopes ^{55}Co ($T_{1/2}$= 17.53 h) formed via ^{58}Ni(d,n+α)^{55}Co reaction has a good agreement with the extracted experimental data retrieved from EXFOR data base. Empire code reproduce almost the same cross-section values as that of EXFOR at the energy range of ~4.85 MeV up to ~6 MeV. Cross-section data was produce by Empire code beyond the 14.68 MeV and ~24 mb which the highest incident energy and cross-section of the EXFOR.

D. *^{60}Ni(d,n+α)^{57}Co reaction*

The evaluated cross-sections of ^{57}Co confirm those measured from experimental data by (Usman*et al* 2016). The excitation function show the same cross-section value of 50mb at ~18 MeV, a similar result occur at ~22 MeV. The ^{57}Co experimental result has slightly higher values than the evaluated result from this work. The overall evaluated cross-section indicate a good agreement with the measured EXFOR data by (Usman *el al.,* 2016).

INCIDENT DEUTRON ENERGY (MeV)	CROSS SECTION (mb)			
	^{55}Co(mb)	^{57}Co(mb)	^{57}Co(mb)	^{54}Mn(mb)
1.07	0.02	0.09	0.09	0.20
1.80	0.51	0.13	0.13	0.42
2.00	0.52	0.19	0.19	0.52
3.27	1.01	0.15	0.15	0.57
4.03	3.01	0.18	0.18	1.16
4.85	7.75	0.20	0.20	1.07
5.50	10.0	0.28	0.28	1.51
8.00	15.01	0.31	0.31	1.65
9.80	17.94	0.05	0.05	1.84
10.25	18.94	0.90	0.90	1.95
11.91	22.0	7.2	7.2	1.99
13.30	23.0	12.03	12.03	2.01
14.65	25.1	30.01	30.01	2.02
15.20	22.9	49.40	49.40	2.04
16.01	23.06	52.60		
18.00		133		
18.54		162		
19.54		165		
21.10		185		
22.16		194		
22.35		212		
23.40		242		
24.10		249		

Table 2: Evaluated production cross-sections for ^{52,54}Mn and ^{55,57}Co radionuclides

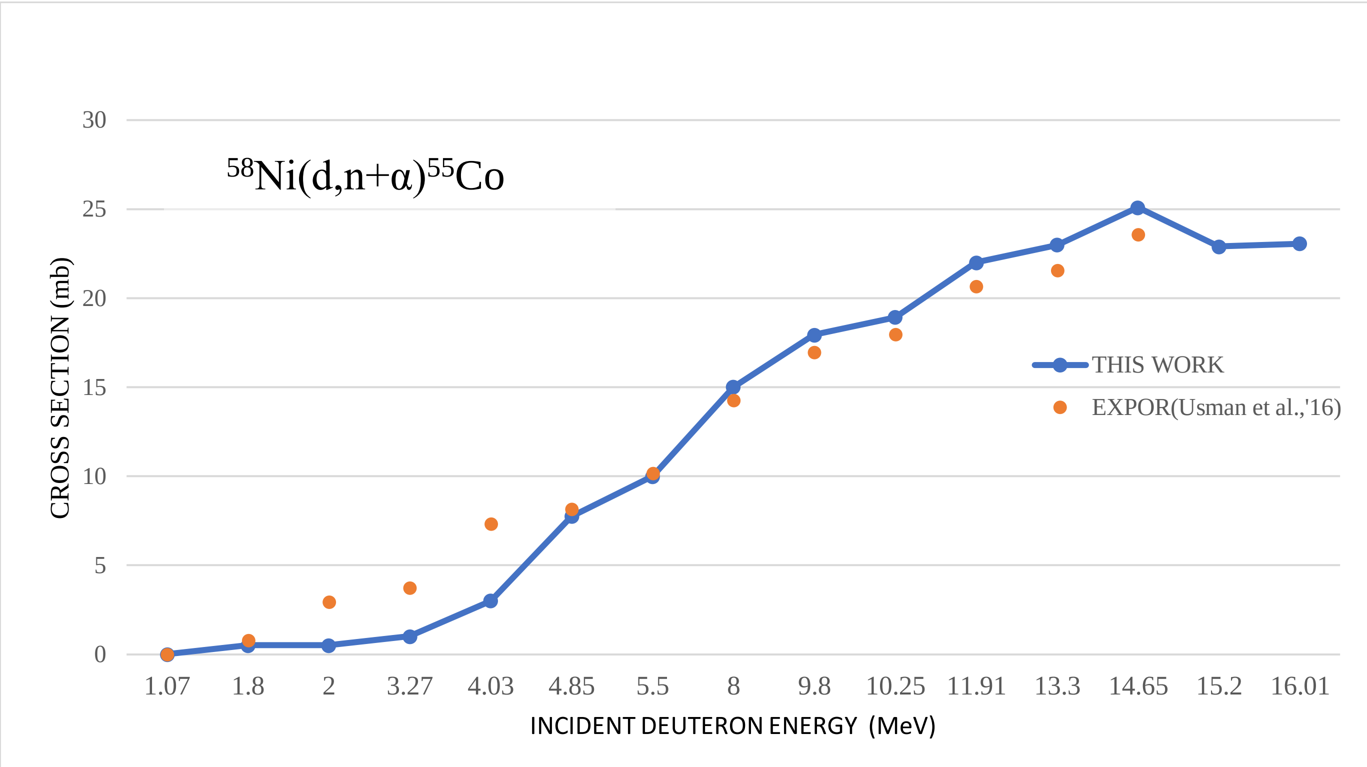

Fig. 1: Excitation function of ^{58}Ni(d,n+α)^{55}Co reaction at different deuteron energies estimated in present work and experimental data retrieve from EXFOR database.

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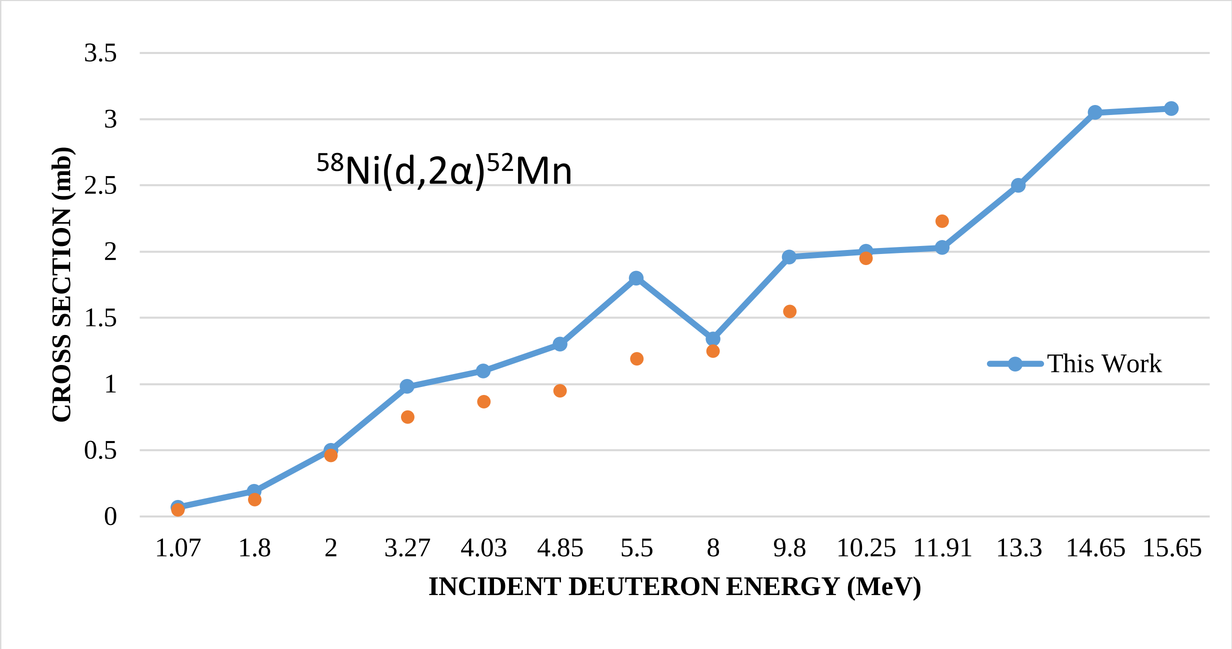

Fig. 2: Excitation function of $^{58}Ni(d,2\alpha)^{52}Mn$ reaction at different deuteron energies estimated in present work and experimental data retrieve from EXFOR database

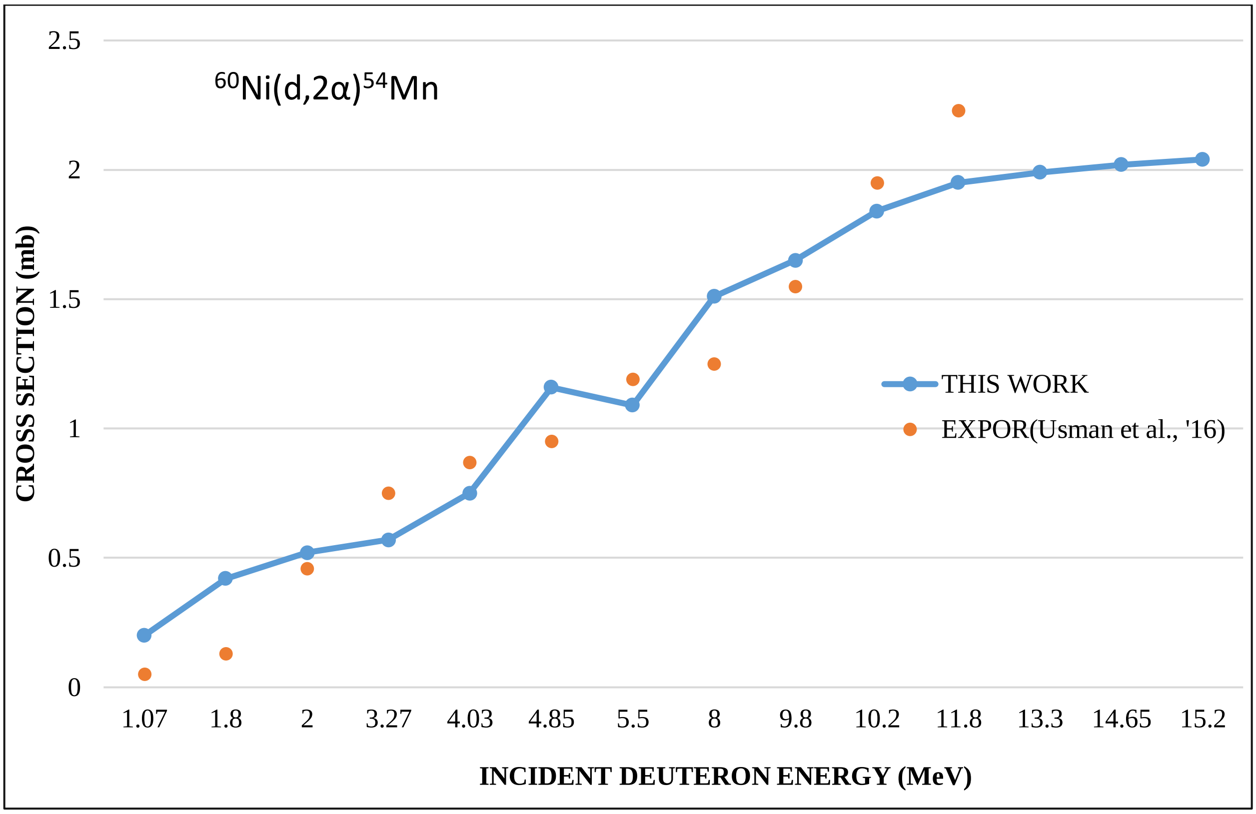

Fig. 3: Excitation function of $^{60}Ni(d,2\alpha)^{54}Mn$ reaction at different deuteron energies estimated in present work and experimental data retrieve from EXFOR database

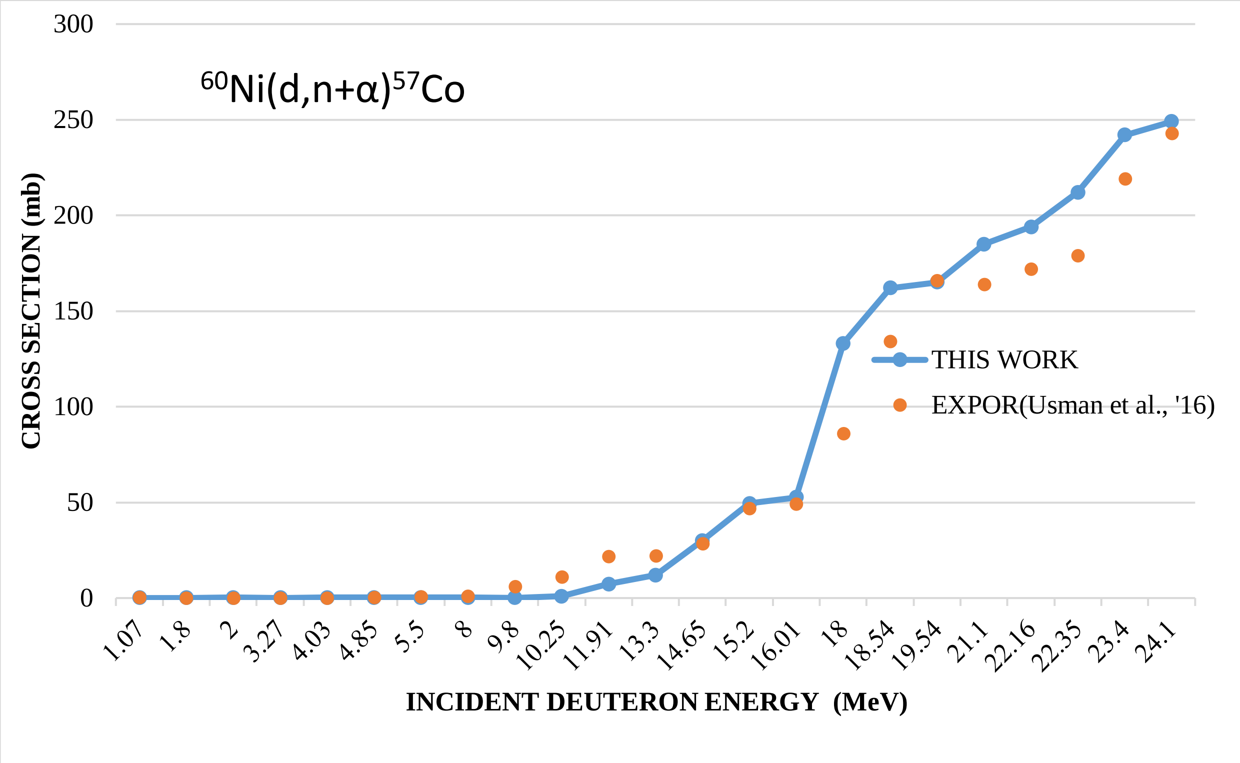

Fig. 4: Excitation function of ^{60}Ni(d,n+α)^{57}Co reaction at different deuteron energies estimated in present work and experimental data retrieve from EXFOR database

IV. SUMMARY AND CONCLUSION

The deuteron induced reaction cross-section for the reactions ^{58}Ni(d,2α)^{52}Mn, ^{60}Ni(d,2α)^{54}Mn, ^{58}Ni(d,n+α)^{55}Co,^{58}Ni(d,α)^{56}Co, ^{60}Ni(d,n+α)^{57}Co, ^{60}Ni(d,α)^{58}Co, over the deuteron energy range from threshold to 25 MeV, have been calculated using different models of EMPIRE code (MALTA). The spherical optical model, statistical hauser-feshbach model, Exciton model and the level density model employed show how sensitive the cross-section are to the excitation function. The evaluated results are in acceptable agreement with the experimental data retrieved from EXFOR database. The comparison of the computed cross-sections and the experimental data is essential in medical applications. Computation using all the three level density models, (LEVDEN 0, LEVDEN 1 and LEVDEN 2) will be helpful in assessing a more agreeable result with the EXFOR data.

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