Investigation of nuclear reaction mechanisms of Nickel isotopes at various energies induced by alpha particles

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Abstract

The excitation functions of $^{58}\text{Ni}$($\alpha, n + 2p + \alpha$)$^{55}\text{Fe}$, $^{58}\text{Ni}$($\alpha, n + 3p$)$^{58}\text{Co}$, $^{58}\text{Ni}$($\alpha, n + p$)$^{60}\text{Cu}$, $^{58}\text{Ni}$($\alpha, n + p + + \alpha$)$^{66}\text{Co}$, $^{58}\text{Ni}$($\alpha, p$)$^{61}\text{Cu}$, $^{58}\text{Ni}$($\alpha, p + \alpha$)$^{57}\text{Co}$ and $^{58}\text{Ni}$($\alpha, 2n + p + + \alpha$)$^{55}\text{Co}$ reactions were studied for particle energies up to 70 MeV. The aim of this study is to investigate the reaction mechanisms of $^{58}\text{Ni}$ isotopes induced by alpha particle using computer code COMPLET and EXFOR database. Calculated results of the excitation functions are discussed and compared with the experimental data taken from database. Comparisons of theoretical nuclear reaction cross-section calculations give remarkable agreements with the experimental data taken from EXFOR database.

1. Introduction

Experimental techniques developed to obtain, detect neutrons and charged particles of different energies and measure different particle of induced reactions \cite{1, 2}. The reaction mechanism is considered to proceed through equilibrium (EQ) as well as pre-equilibrium (PE) emission of particles at moderate excitation energies \cite{3, 4}.

Nuclear data evaluation is carried out based on experimental data and theoretical calculations using computer code \cite{2, 5}. It is both practically and economically impossible to measure necessary cross-sections for all isotopes for a wide range of energies \cite{6}. Computer code calculations frequently needed to provide predictions of reaction cross-sections if the experimental data are not available or unable to measure the cross-sections due to experimental difficulties \cite{4, 7}. Besides, these calculated data are necessary to develop more up-to-date theoretical nuclear codes in order to explain nuclear reaction mechanisms and the properties of the excited states in different energy ranges \cite{1, 4}. Equilibrium and pre-equilibrium particle emissions during the decay process of a compound nucleus are very important for a better understanding of the nuclear reaction mechanism induced by medium energy particles \cite{4, 5}.

Contributions of equilibrium and pre-equilibrium reaction mechanisms investigated different reaction calculations \cite{3}. The theoretical excitation functions of $^{58}\text{Ni}$($\alpha, n + 2p + \alpha$)$^{55}\text{Fe}$, $^{58}\text{Ni}$($\alpha, n + 3p$)$^{58}\text{Co}$, $^{58}\text{Ni}$($\alpha, n + p$)$^{60}\text{Cu}$, $^{58}\text{Ni}$($\alpha, n + p + + \alpha$)$^{66}\text{Co}$, $^{58}\text{Ni}$($\alpha, p$)$^{61}\text{Cu}$ and $^{58}\text{Ni}$($\alpha, p + \alpha$)$^{57}\text{Co}$ were obtained using computer code COMPLET \cite{7}. EXFOR library were preferable in order to gather the experimental database in the literature \cite{8}.

Different researchers studied comparison of experimental and theoretical nuclear reaction cross-sections, but they still need scientific evidences \cite{9–11}. Based on this research gap, the aim of this study is to investigate the reaction cross-section mechanisms of $^{58}\text{Ni}$ isotopes induced by alpha particle using computer code COMPLET and EXFOR database. The results of theoretical excitation function have been compared with the available experimental data taken from EXFOR database \cite{12}.
2. Materials and methods

2.1. EXFOR data centre
The EXFOR (ExchangeFormat) format was designed for the collection, exchange and dissemination of microscopic neutron-induced reaction data based on a combination of coded information [13]. It is the library and format for the collection, storage, exchange and retrieval of experimental nuclear reaction data [14]. The format is flexible in order to record all the necessary information and explain the measured data by defining computer readable coded information.

EXFOR compiled experimental nuclear reaction data regularly through the network of nuclear reaction data centres. Nuclear Reaction Data Centres (NRDC) has played a crucial role for collection, exchange and dissemination of nuclear reaction data [15–17]. The quality of the database increases by the removal of compilation error, and improve accessibility for researchers.

2.2. Computer code ‘COMPLET’ and description of parameters
Computer code COMPLET employed Weisskopf-Ewing model for the statistical component and Hybrid as well as geometry dependent hybrid model of Blann for PE emission [7, 14, 18]. It is a modified and advanced computer code [19]. This code is capable of calculating equilibrium and pre-equilibrium reaction cross-sections. This computer code system is used for the analysis and prediction of nuclear reactions and helped researchers to determine both the compound and pre-compound excitation functions [20]. In computer code COMPLET, the particles in the initial configuration (\(n = \text{Ex}_1 + \text{Ex}_2 + \text{Ex}_3\)) can be neutron, proton or alpha particle represented by the exciton numbers \(\text{Ex}_1\), \(\text{Ex}_2\) and \(\text{Ex}_3\) respectively [19, 21, 22].

2.3. Computer code ‘COMPLET’ formalism
In pre-equilibrium emission calculations, the initial excitation configurations and level density parameters are very essential quantities [7]. The nuclear level density influences the shape and the height of the calculated excitation functions [21, 23]. The expression for nuclear reaction cross-section may be written from the consideration of decay rate equation governing nuclear transformation and decay of the activated products [23].

2.4. Theoretical calculations with computer codes
The reaction cross-sections of the investigated reactions compared with the data given in the on-line EXFOR library [24–26]. This library is based on both default and adjusted computer code COMPLET calculations [2, 21, 25]. To achieve a better description of available data for \((\alpha, n + p)\) reactions in these codes, a phenomenological energy dependent enhancement factor was introduced based on cross sections for medium and heavy nuclei. This study describes a new way of providing basic experimental and theoretical nuclear reaction information and new approaches towards nuclear data library production/evaluation, validation and uncertainty propagation are developed [25, 26].

In this study, the researchers tested the prediction capability of the theoretical nuclear reaction cross-section using computer code COMPLET. The code run with the default input parameters by considering all possible reactions involved including the reaction thresholds at the given bombarding energies [12, 18]. Calculations for the experimental cross-section were made by using EXFOR datacentre in the literature. Spreadsheet was used for data tabulation and graphical representation of the results of this study [7, 25].

2.5. Comparisons of theoretical results with experimental values
The theoretical and experimental reaction cross sections are plotted against the projectile energies and are shown in tables 1–7 and figures 1–7 [23, 27]. The excitation functions for the theoretical calculations are shown by a solid line (equil) for the pre-equilibrium reactions and with a solid line (pre-equil) for the equilibrium one while the experimental results are shown by a solid line (exp) [4, 7]. The results obtained were done by varying level density and exciton number parameters of the reaction cross sections [14, 24].

To compare the theoretical and experimental cross-section results, the researchers use Pearson’s correlation coefficient (R).

\[
R = \frac{\sum_{i=1}^{N} (X_{Ti} - \langle X_T \rangle)(X_{Ei} - \langle X_E \rangle)}{(N - 1)(S_{XT})(S_{XE})},
\]

Where, R is correlation coefficient and unit less, \(\langle X_{Ti} \rangle\) and \(\langle X_{Ei} \rangle\) are the mean theoretical and experimental cross-sections of the ith values respectively, N is number of the theoretical and experimental data, and \(S_{XT}\) and \(S_{XE}\) are the standard deviations of the theoretical and experimental cross-sections respectively [2].
Table 1. Theoretical evaluation of $^{58}\text{Ni} (\alpha, p)^{61}\text{Cu}$ reaction cross-section computed with experimental data.

| Energy (MeV) | $\sigma$ (exp) | $\sigma$ (pre-comp) | $\sigma$ (comp) |
|--------------|----------------|---------------------|-----------------|
| 9.0          | 150            | 119.7 ± 0.09        | 119.7 ± 0.091   |
| 14.0         | 360            | 714.0 ± 0.037       | 713.5 ± 0.037   |
| 17.0         | 401            | 745.9 ± 0.036       | 747.4 ± 0.036   |
| 23.0         | 201            | 163.7 ± 0.078       | 154.6 ± 0.08    |
| 25.0         | 95             | 100.6 ± 0.099       | 89.65 ± 0.10    |
| 29.0         | 46             | 58.29 ± 0.131       | 49.33 ± 0.142   |
| 36.0         | 16             | 21.54 ± 0.21        | 12.74 ± 0.28    |
| 40.0         | 13             | 15.47 ± 0.78        | 8.62 ± 0.34     |

Table 2. Theoretical evaluation of $^{58}\text{Ni} (\alpha, p + \alpha)^{57}\text{Co}$ reaction cross-section computed with experimental data.

| Energy (MeV) | $\sigma$ (exp) | $\sigma$ (pre-comp) | $\sigma$ (comp) |
|--------------|----------------|---------------------|-----------------|
| 21.9         | 5.2            | 79.09 ± 0.44        | 166.4 ± 0.08    |
| 24.3         | 47             | 134.9 ± 0.15        | 195.7 ± 0.07    |
| 25.5         | 108            | 157.5 ± 0.1         | 199.6 ± 0.07    |
| 27.4         | 175            | 183.3 ± 0.08        | 214.3 ± 0.07    |
| 30.5         | 240            | 208.2 ± 0.06        | 229.9 ± 0.07    |
| 32.5         | 250            | 221.7 ± 0.06        | 229.8 ± 0.07    |
| 33.2         | 260            | 200.8 ± 0.06        | 196.8 ± 0.07    |
| 35           | 235            | 200.8 ± 0.07        | 150.2 ± 0.08    |
| 35.7         | 250            | 216.3 ± 0.06        | 164.6 ± 0.08    |
| 36.5         | 190            | 206.9 ± 0.07        | 127.9 ± 0.09    |
| 38           | 245            | 189.3 ± 0.06        | 106.10 ± 0.07   |
| 38.2         | 220            | 176.4 ± 0.07        | 80.17 ± 0.11    |
| 39.3         | 170            | 160.2 ± 0.08        | 60.17 ± 0.13    |
| 40.7         | 190            | 154.4 ± 0.07        | 47.64 ± 0.14    |
| 41.5         | 135            | 134.2 ± 0.09        | 35.58 ± 0.17    |
| 43           | 132            | 132.5 ± 0.09        | 27.74 ± 0.19    |
| 43.9         | 140            | 116 ± 0.08          | 19.74 ± 0.23    |
| 44.4         | 113            | 121.2 ± 0.09        | 21.30 ± 0.22    |
| 45.1         | 102            | 105.3 ± 0.10        | 14.69 ± 0.26    |
| 47           | 100            | 72.89 ± 0.10        | 7.80 ± 0.36     |

Table 3. Theoretical evaluation of $^{58}\text{Ni} (\alpha, n + 2p + \alpha)^{55}\text{Fe}$ reaction cross-section computed with experimental data.

| Energy (MeV) | $\sigma$ (exp) | $\sigma$ (pre-comp) | $\sigma$ (comp) |
|--------------|----------------|---------------------|-----------------|
| 48.7         | 1.1            | 25.42 ± 0.20        | 177.9 ± 0.67    |
| 51.2         | 20             | 52.5 ± 0.14         | 251.4 ± 0.61    |
| 53.8         | 37             | 92.31 ± 0.10        | 335.1 ± 0.57    |
| 56.10        | 57             | 117.5 ± 0.09        | 339.1 ± 0.55    |
| 58.4         | 75             | 150.70 ± 0.08       | 360.4 ± 0.53    |
| 60.6         | 86             | 174.2 ± 0.08        | 337 ± 0.52      |
| 62.8         | 96             | 200 ± 0.07          | 327.2 ± 0.52    |
| 64.9         | 103            | 212.5 ± 0.07        | 282.9 ± 0.51    |
| 67.1         | 119            | 217.4 ± 0.07        | 239.2 ± 0.51    |

The whole excitation functions of $^{58}\text{Ni}$ isotopes re-measured and compared with the recommended experimental data taken from EXFOR library using Pearson’s correlation coefficient.

3. Results and discussion

This study describes new calculations on the excitation functions of $^{58}\text{Ni} (\alpha, n + 2p + \alpha)^{55}\text{Fe}$, $^{58}\text{Ni} (\alpha, n + 3p)^{58}\text{Co}$, $^{58}\text{Ni} (\alpha, n + p)^{60}\text{Cu}$, $^{58}\text{Ni} (\alpha, n + p + \alpha)^{56}\text{Co}$, $^{58}\text{Ni} (\alpha, p)^{61}\text{Cu}$ and $^{58}\text{Ni} (\alpha, n + p + \alpha)^{57}\text{Co}$ in the range of 12.3 MeV to 70 MeV alpha incident energy [7, 8, 19]. Each reaction has a
peculiar structure and all reaction mechanisms must be interpreted separately [7]. The pre-equilibrium reaction calculation on the excitation functions were carried out with computer code COMPLET for hybrid model and the geometry-dependent hybrid model [19, 24, 28].

The comparison of the computations and experimental results have been given in tables 1–7 and figures 1–7 [5, 8, 27]. The theoretical calculations have been done by taking the first initial exciton number $n_0 = 4$ with configuration $(2n + 2p + 0 \ h)\ PLD$, the level density parameter, PLD = CAN 8, has been checked to ensure and know its effects on calculated values of excitation functions [19, 24, 29].

### 3.1. $^{58}$Ni ($\alpha$, $p$) $^{61}$Cu nuclear reaction

The calculation for the excitation function of $^{58}$Ni ($\alpha$, $p$) $^{61}$Cu reaction is compared with the reported experimental values as in table 1 and figure 1 [27, 30].

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**Table 4.** Theoretical evaluation of $^{58}$Ni ($\alpha$, $2n + p + \alpha$) $^{58}$Co reaction cross-section computed with experimental data.

| Energy (MeV) | $\sigma$(exp) | $\sigma$(pre-equl) | $\sigma$(comp) |
|-------------|---------------|---------------------|----------------|
| 46.1        | 0.9           | 1.68 ± 0.77         | 23.03 ± 0.21   |
| 47.4        | 1.4           | 2.743 ± 0.06        | 32.21 ± 0.18   |
| 48.7        | 2.8           | 5.476 ± 0.43        | 53.42 ± 0.14   |
| 49.8        | 3.4           | 9.484 ± 0.32        | 84.42 ± 0.11   |
| 51.2        | 7.1           | 16.93 ± 0.24        | 116.9 ± 0.09   |
| 52.3        | 11            | 23.97 ± 0.2         | 148 ± 0.08     |
| 53.8        | 10            | 40.32 ± 0.16        | 224.9 ± 0.07   |
| 54.7        | 15            | 64.91 ± 0.12        | 206.2 ± 0.06   |
| 56.1        | 17            | 65.5 ± 0.12         | 300 ± 0.06     |
| 56.9        | 22            | 95.58 ± 0.10        | 340.8 ± 0.05   |
| 58.4        | 24            | 92.6 ± 0.10         | 333.5 ± 0.05   |
| 59.1        | 27            | 114.5 ± 0.09        | 358.7 ± 0.05   |
| 60.6        | 31            | 125.9 ± 0.09        | 360.7 ± 0.05   |
| 61          | 29            | 160.5 ± 0.08        | 394.3 ± 0.05   |
| 62.8        | 37            | 149.7 ± 0.08        | 331.9 ± 0.05   |
| 63.3        | 32            | 189 ± 0.07          | 338.9 ± 0.05   |
| 64.9        | 43            | 178.5 ± 0.07        | 308.9 ± 0.06   |
| 65.7        | 42            | 184.4 ± 0.07        | 279.3 ± 0.06   |
| 67.1        | 49            | 192.5 ± 0.07        | 255.9 ± 0.06   |
| 67.8        | 53            | 109.9 ± 0.07        | 223.9 ± 0.07   |

**Table 5.** Theoretical evaluation of $^{58}$Ni ($\alpha$, $n + p + \alpha$) $^{58}$Co reaction cross-section computed with experimental data.

| Energy (MeV) | $\sigma$(exp) | $\sigma$(pre-equl) | $\sigma$(comp) |
|-------------|---------------|---------------------|----------------|
| 46.1        | 136           | 382 ± 0.05          | 673.4 ± 0.04   |
| 47.4        | 137           | 446.6 ± 0.05        | 587.5 ± 0.04   |
| 48.7        | 150           | 455 ± 0.05          | 534.7 ± 0.04   |
| 49.8        | 143           | 475.6 ± 0.05        | 488.4 ± 0.05   |
| 51.2        | 158           | 487 ± 0.05          | 436.5 ± 0.05   |
| 52.3        | 170           | 487.8 ± 0.05        | 378.7 ± 0.05   |
| 53.8        | 130           | 475.7 ± 0.05        | 259.7 ± 0.05   |
| 54.7        | 138           | 461.3 ± 0.05        | 268.6 ± 0.06   |
| 56.1        | 122           | 442.6 ± 0.05        | 176.4 ± 0.06   |
| 56.9        | 124           | 443.6 ± 0.05        | 187.9 ± 0.08   |
| 58.4        | 106           | 412.7 ± 0.05        | 119.3 ± 0.07   |
| 59.1        | 91            | 373.9 ± 0.05        | 93.27 ± 0.09   |
| 60.6        | 91            | 374.1 ± 0.05        | 77.72 ± 0.10   |
| 61          | 79            | 373.5 ± 0.05        | 79.26 ± 0.11   |
| 62.8        | 80            | 326.1 ± 0.06        | 48.9 ± 0.14    |
| 63.3        | 59            | 339.8 ± 0.05        | 52.2 ± 0.14    |
| 64.9        | 71            | 293.4 ± 0.06        | 31.55 ± 0.18   |
| 65.7        | 65            | 270.5 ± 0.06        | 24.2 ± 0.20    |
| 67.1        | 70            | 247.9 ± 0.06        | 22.14 ± 0.21   |
| 67.8        | 71            | 239.8 ± 0.06        | 19.49 ± 0.023  |
Table 6. Theoretical evaluation of $^{58}\text{Ni} (\alpha, n + 3p) ^{58}\text{Co}$ reaction cross-section computed with experimental data.

| Energy (MeV) | $\sigma$(exp) | $\sigma$(pre-equi) | $\sigma$(comp) |
|--------------|---------------|--------------------|----------------|
| 46.1         | 34            | 29.8 ± 0.18        | 226.4 ± 0.07   |
| 47.4         | 40            | 43.4 ± 0.15        | 276.4 ± 0.06   |
| 48.7         | 70            | 56.69 ± 0.13       | 317.4 ± 0.06   |
| 49.8         | 90            | 71.9 ± 0.12        | 353 ± 0.05     |
| 51.2         | 113           | 88.42 ± 0.11       | 372.7 ± 0.05   |
| 52.3         | 148           | 152.5 ± 0.08       | 437.2 ± 0.05   |
| 53.8         | 142           | 155 ± 0.08         | 469.7 ± 0.05   |
| 54.7         | 168           | 181.6 ± 0.07       | 480.9 ± 0.05   |
| 56.1         | 170           | 191.1 ± 0.07       | 481.2 ± 0.05   |
| 56.9         | 194           | 223.9 ± 0.07       | 482.5 ± 0.05   |
| 58.4         | 191           | 226.3 ± 0.06       | 465.3 ± 0.05   |
| 59.1         | 195           | 252.9 ± 0.06       | 452.2 ± 0.05   |
| 60.6         | 193           | 252.2 ± 0.06       | 401 ± 0.05     |
| 61           | 170           | 285.9 ± 0.06       | 412 ± 0.05     |
| 62.8         | 189           | 277.4 ± 0.06       | 347.9 ± 0.05   |
| 64.9         | 192           | 285.7 ± 0.06       | 280.9 ± 0.06   |
| 65.7         | 175           | 306.3 ± 0.06       | 289.6 ± 0.06   |
| 67.1         | 198           | 291.6 ± 0.06       | 222.6 ± 0.07   |
| 67.8         | 212           | 309.2 ± 0.06       | 226 ± 0.07     |

Table 7. Theoretical evaluation of $^{58}\text{Ni} (\alpha, n + p) ^{60}\text{Cu}$ reaction cross-section computed with experimental data.

| Energy (MeV) | $\sigma$(exp) | $\sigma$(pre-equi) | $\sigma$(equi) |
|--------------|---------------|--------------------|----------------|
| 18           | 15.1          | 2.8 ± 0.59         | 12.8 ± 0.28    |
| 19.4         | 51.9          | 35.8 ± 0.17        | 213.8 ± 0.07   |
| 20.9         | 76            | 108.3 ± 0.10       | 378.8 ± 0.05   |
| 21.9         | 110           | 176.3 ± 0.08       | 527 ± 0.04     |
| 22           | 93.3          | 181.7 ± 0.07       | 523.5 ± 0.04   |
| 23.4         | 189           | 299.9 ± 0.06       | 638.2 ± 0.04   |
| 24.6         | 234           | 307.4 ± 0.06       | 721.8 ± 0.04   |
| 26           | 226           | 544.4 ± 0.04       | 820.3 ± 0.03   |
| 27           | 250           | 640.5 ± 0.04       | 842 ± 0.03     |
| 27.2         | 242           | 622 ± 0.04         | 717 ± 0.04     |
| 28.5         | 390           | 657.7 ± 0.04       | 692.9 ± 0.04   |
| 30.2         | 305           | 739.6 ± 0.04       | 594.8 ± 0.04   |
| 33           | 260           | 613.2 ± 0.04       | 272.7 ± 0.06   |
| 33.5         | 224           | 576.3 ± 0.04       | 150.9 ± 0.08   |
| 38           | 175           | 412.5 ± 0.05       | 51.5 ± 0.14    |

Figure 1. The $^{58}\text{Ni} (\alpha, p) ^{61}\text{Cu}$ excitation functions computation with EXFOR Experimental database.
Figure 2. The $^{58}\text{Ni}(\alpha,p+\alpha)^{57}\text{Co}$ excitation functions computation with EXFOR experimental database.

Figure 3. The $^{58}\text{Ni}(\alpha,n\,2\,p+\alpha)^{55}\text{Fe}$ excitation functions computation with EXFOR experimental database.

Figure 4. The $^{58}\text{Ni}(\alpha,2n+p+\alpha)^{55}\text{Co}$ excitation functions computation with EXFOR experimental database.

Figure 5. The $^{58}\text{Ni}(\alpha,n\,p+\alpha)^{59}\text{Co}$ excitation functions computation with EXFOR experimental database.
The evaporation residue nucleus $^{61}$Cu is radioactive and undergoes beta plus decay and its half-life is 3.33 hr $^{27}$.

The theoretical pre-equilibrium and equilibrium reaction cross-sections overlapped each other and are in good agreement with the experimental data between 9.0 MeV and 40 MeV. Pre-equilibrium reaction cross-sections reaches its maximum peak at 745.9 mb while equilibrium reaction cross-section attains its maximum peak value at 747.4 mb $^{7}$.

From table 1 and figure 1, it is evident that both the compound and pre-equilibrium nuclear reaction cross-section are good agreement with the experimental values up to an incident energy of 17 MeV. After an incident energy of 23 MeV and above, the pre-equilibrium reaction and compound cross-section give better agreement with the experimental data (correlation coefficient, $r = 0.95$).

3.2. $^{58}$Ni ($\alpha, p + \alpha$) $^{57}$Co nuclear reaction

The reaction channel $^{58}$Ni ($\alpha, p + \alpha$) $^{57}$Co of table 2 and figure 2 is obtained by the emission of one proton and one alpha particles, and $^{57}$Co is radioactive (unstable) which undergoes electron capture.

The calculated excitation function for $^{58}$Ni ($\alpha, p + \alpha$) $^{57}$Co reactions compared with the experimental values as shown in table 2 and figure 2 $^{27}$. Both the pre-compound and compound nuclear reaction mechanisms are far from the experimental values $^{7, 27}$. This confirms that there is no formation of both pre-compound and compound nuclear reaction mechanisms, but it could be direct/pickup reaction mechanisms $^{7}$.

The correlation coefficient of the reaction cross section of experimental and pre-equilibrium nuclear reactions is calculated to be $r = 0.87$ for the lower energy region and it is good agreement. Above an incident energy of 33.2 MeV, the pre-equilibrium reaction mechanism better agrees with the experimental data than the pure equilibrium reaction mechanism as shown in table 2 and figure 2 $^{18}$.

3.3. $^{58}$Ni ($\alpha, n + 2p + \alpha$) $^{55}$Fe nuclear reaction

The calculated excitation function of $^{58}$Ni ($\alpha, n + 2p + \alpha$) $^{55}$Fe reactions generated by the emission of one neutron, two protons and one alpha particle are compared with the experimental values as shown in table 3 and figure 3 $^{27}$.

The equilibrium calculations of $^{58}$Ni ($\alpha, n + 2p + \alpha$) $^{55}$Fe reactions are in acceptable agreement with the experimental value in the energy of 48.7 MeV with 177.9 mb and it continues increasing as the projectile energy...
increases [27]. For $^{58}$Ni ($\alpha$, n + 2p + $\alpha$) $^{55}$Fe reaction, the pre-equilibrium calculations are in good agreement with the experimental values in the energy range of 48.7 MeV with 25.42 mb and it continues increasing as the energy of the alpha particle’s energy increases [18, 27]. From table 3 and figure 3, it is evident that the pre-equilibrium and compound nuclear reaction mechanisms are both far from the experimental values throughout the course of the incident energies [7]. Hence, the reaction takes place pickup/direct reaction channels. The correlation coefficient for the pre-equilibrium theoretical nuclear reaction values and the experimental one is calculated to be $r = 0.99$ which is a strong and positive relation [2, 7].

3.4. $^{58}$Ni ($\alpha$, 2n + p + $\alpha$) $^{55}$Co nuclear reaction

The other reaction channel $^{58}$Ni ($\alpha$, 2n + p + $\alpha$) $^{55}$Co is obtained by the emission of two neutrons, one proton and one alpha particles, and $^{55}$Co is radioactive (unstable) and it undergoes beta plus decay to be formed [27].

The theoretical pre-compound reaction cross section values are started from the bottom of the assigned value of projectile energy of 46.1 MeV with a cross section of 1.68 mb and it continues to be increased as the energy of the alpha particles is increasing [7, 18]. Experimental results show that the graph starts at 0.9 mb with the same projectile energy and it remains increased as the bombarding energy also increases. The correlation coefficient of the cross section of experimental and pre-equilibrium nuclear reactions is calculated to be $r = 0.97$ [2, 7, 18]. From table 4 and figure 4, the pre-equilibrium nuclear reaction mechanisms best agree with the experimental values between the projectile energy of 46.1 MeV to 61.1 MeV, and after the projectile energy of 61.1 MeV the pre-equilibrium reaction mechanisms become far and far away from the experimental values. This confirmed that there is no formation of pre-compound nuclear reaction mechanisms [7, 18].

From table 4 and figure 4, it is also evident that the compound nuclear reaction mechanisms go far from the experimental values thought the course of the incident energies which in turn confirms that the is no formation of compound nuclear reaction mechanisms under the specified incident energies. This indicates that after an incident energy of 61.1 MeV, the reaction can be neither compound nuclear reaction nor pre-equilibrium nuclear reaction, but it could be direct/pickup reaction mechanisms [7, 25].

3.5. $^{58}$Ni ($\alpha$, n + p + $\alpha$) $^{56}$Co nuclear reaction

The reaction channel $^{58}$Ni ($\alpha$, n + p + $\alpha$) $^{56}$Co is obtained by the emission of one neutron, one proton and one alpha particle, and $^{56}$Co is radioactive (unstable) which undergoes beta plus decay [27].

The theoretical pre-compound reaction cross section values started from the bottom of the assigned projectile energy of 46.1 MeV with a cross section of 382.0 mb and it continues increasing as the energy of the alpha particle’s energy increases [12]. Experimental results show that the graph starts at 136 mb with the same projectile energy of the theoretical reaction cross-section and it remains increasing up to the bombarding energy of 67.8 MeV. and then the graph almost decreases by making a long tail. The correlation coefficient of the cross section of experimental and pre-equilibrium nuclear reactions is calculated to be $r = 0.89$ and the correlation coefficient between the experimental and the compound cross section nuclear reactions is calculated to be $r = 0.84$ which describes the strong positive correlation between the theoretical and experimental total cross-section values [4, 12].

From table 5 and figure 5, it is evident that both the pre-equilibrium and compound nuclear reaction mechanisms are far from the experimental values thought the specified incident energies [12]. Compound reaction cross section shows that the graph starts at 673.6 mb and then the graph almost decreases by making a long tail. In the energy range, alpha particles pick up one neutron and one proton from the target nucleus of $^{58}$Ni and as the of this pickup/ direct reaction takes place

3.6. $^{58}$Ni ($\alpha$, n + 3p) $^{58}$Co nuclear reaction

The evaporation residue nucleus $^{58}$Co is radioactive (unstable) and it undergoes beta plus decay to form the daughter nucleus $^{58}$Co [27].

The theoretical pre-compound reaction cross section values started from 46.1 MeV and it continues increasing as the energy of the alpha particle’s energy increases [12]. Experimental results show that the graph starts at 34 mb with the same projectile energy of the theoretical reaction cross-section and it almost remains increasing throughout the course of the specified incident energies. The correlation coefficient of experimental and pre-equilibrium reactions cross-sections is $r = 0.93$ and shows good agreement [4, 12]. The compound nuclear reaction is far from the experimental values showing that no formation of compound nuclear reaction mechanisms.

From table 6 and figure 6, the pre-equilibrium nuclear reaction mechanisms in the energy range of 46.1 to 56.9 MeV best agrees with the experimental values confirming the formation of the pre-equilibrium nuclear
reaction mechanisms [12]. The equilibrium reaction mechanisms becomes far and far from the experimental values, hence the reaction can be explained by pickup/direct reaction mechanisms [12].

3.7. $^{58}\text{Ni} (\alpha, n + p)^{60}\text{Cu}$ nuclear reaction

The evaporation residue nucleus $^{60}\text{Cu}$ is radioactive (unstable) and it undergoes beta plus decay to form the daughter nucleus $^{60}\text{Cu}$ [27]. The theoretical prediction and the experimental data for $^{58}\text{Ni} (\alpha, n + p)^{60}\text{Cu}$ nuclear reactions are shown in table 7 and figure 7 [26].

The theoretical pre-compound nuclear reaction cross section starts from the bottom of the assigned projectile energy of 18 MeV with 2.842 mb, reached its maximum peak at (30.2 MeV, 739.6 mb). It starts to fall down for the increasing value of the projectile energy by making long tail [3, 12, 19]. The equilibrium reaction mechanisms moved far and far from the experimental values and reached its maximum peak at (26 MeV, 820.5 mb). Hence, it falls down rapidly for the increasing value of the projectile energy by making long tail.

The calculation for the excitation function of $^{58}\text{Ni} (\alpha, n + p)^{60}\text{Cu}$ reaction is compared with the reported experimental data as in table 7 and figure 7 [3]. After an incident energy of 24.6 and above, both the compound and pre-compound nuclear reaction mechanisms are far from the experimental values confirming that the formation of direct/pickup reaction mechanisms under the specified incident energies [3].

The correlation coefficient of the cross section of experimental and pre-equilibrium nuclear reactions is calculated to be $r = 0.91$, which describes a strong and positive correlation between the theoretical and experimental reaction cross-sections [4, 12].

The theoretical excitation functions computed by adjusting level density parameters and exciton numbers for both the compound and pre-equilibrium calculations using computer code COMPLET [7, 14]. The excitation functions of $^{58}\text{Ni} (\alpha, n + 2p + \alpha)^{56}\text{Fe}$, $^{58}\text{Ni} (\alpha, n + 3p)^{57}\text{Co}$, $^{58}\text{Ni} (\alpha, n + p + \alpha)^{56}\text{Co}$, $^{58}\text{Ni} (\alpha, n + p + \alpha)^{60}\text{Cu}$, $^{58}\text{Ni} (\alpha, n + p + \alpha)^{61}\text{Cu}$ and $^{58}\text{Ni} (\alpha, p + \alpha)^{55}\text{Co}$ are tabulated and plotted as shown in figures 1–7 and tables 1–7 using spreadsheet.

The results of the theoretical excitation functions for the pre-equilibrium reaction generally agree with the experimental results [7, 19].

3.8. Error analysis and calculations

All measurements in science have an uncertainty (or error) associated with them. The error is the quotient of the difference of the theoretical pre-equilibrium and experimental values and the experimental one times 100%. The sum of all the experimental values to the specified range is 4400 and the pre-equilibrium ones is to be 4367.

$$\text{Percent error} = \frac{\text{Experimental value} - \text{Theoretical Value}}{\text{Theoretical value}} \times 100\%$$

The calculated percent error indicates that the collected data are acceptable.

4. Conclusion

Using computer code COMPLET, the theoretical excitation functions are computed by supplying standard input parameters of the problem and the adjustable free parameters for both the compound and pre-equilibrium calculations. The theoretical calculations were done using different arrangements for the description of the nuclear level density and exciton numbers. The results of theoretical and experimental have no appreciable changes with the variation of level density parameter, especially in pre-equilibrium region. However, the results of theoretical excitation function changed considerably with the change of exciton numbers, showing that the excitation functions depended on the exciton numbers.

Calculated results of $^{58}\text{Ni}$ reaction cross sections the seven induced by alpha particle were in reasonable agreements with experimental database and strongly correlated.

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