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Study of Reaction Mechanisms in α + ^{69}Ga reaction at ≈10 – 50 MeV

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COMPLETE code;

Reaction channel;

Excitation function

ABSTRACT

The excitation functions of ^{69}Ga(α, n)^{72}As, ^{69}Ga(α, 2n)^{71}As, ^{69}Ga(α, 3n)^{70}As, ^{69}Ga(α, x)^{69}Ge, ^{69}Ga(α, x)^{68}Ga and ^{69}Ga(α, x)^{67}Ga reactions produced in the interaction of α-projectile with ^{69}Ga-target were studied at ≈ 10-50 MeV. The produced nuclei were different isotopes of As, Ge, and Ga, some of which have important medical applications. The theoretical model predictions were based on the statistical code COMPLETE, and the predicted results were compared and discussed with existing experimental data. Good agreement between the theoretical predictions and experimental results were obtained. Pearson's relational statistics showed moderate to strong positive correlations between the theoretically predicted and experimentally measured reaction cross-sections. Furthermore, the present investigation revealed significant pre-compound contributions in the studied energy range. Therefore, it is important to consider the admixture of pre-equilibrium and equilibrium modes of reactions when predicting the reaction cross-sections.

INTRODUCTION

Advances in accelerator technology and cyclotrons have enabled the use of light- and heavy-charged nuclei as projectiles in nuclear reactions. This development has improved our understanding of the reaction mechanism and nuclear structure at various energies near and above the Coulomb barriers (Cavinato *et al*., 1995; Amorini *et al*., 1998; Gadioli *et al*., 1998). For example, at moderate excitation energies, reactions induced by nucleons and light-charged projectiles are found to proceed through the equilibrium (EQ) and pre-equilibrium (PE) mode reactions (Baure *et al*., 1995;Agrawal *et al*., 2001; Patronis *et al*., 2007; Johari and Saxena, 2015). To understand these reaction mechanisms, reaction cross-section data evaluation is essential. Accordingly, comparative studies based on experimental data and theoretical predictions are demanding. In this regard, nuclear reaction model-based computer codes can swiftly help to predict unknown reaction cross-sections and thus improve computer code predictions.

Studies of light-charged induced nuclear reactions help better understand the reaction mechanisms and test the validity of various available and newly evolving computer codes. Furthermore, in light-charged induced nuclear reactions, the processes of PE and EQ particle(s) emissions are vital in comprehending and characterizing the reaction mechanisms, attributable to the strong competition between PE and EQ mode of reactions at moderate excitation energies.

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In the past, several light-charged induced comparative reaction mechanisms studies between theoretically predicted and experimentally measured reaction cross sections have been done (Agarwal *et al*., 2002; Abhishek *et al*., 2008; Amanuel *et al*., 2011; Yigit and Tel, 2014; Asres *et al*., 2018; Asres *et al*., 2019; Amanuel, 2021) in attempts to explain these reaction mechanisms. However, reasonable comparative reaction mechanisms studies between theory and experiment of ^{72}As, ^{71}As, ^{70}As, ^{69}Ge, ^{68}Ga, and ^{67}Ga reaction products produced in α-projectile induced reactions on ^{69}Ga-target at ≈10 – 60 MeV, have not been investigated efficiently; therefore, further investigations and scientific evidence are required (Ismail 1990; Rezvi *et al*., 1989; Didik *et al*., 1994). Furthermore, understanding the reaction mechanisms induced by a light-charged projectile, such as in α + ^{69}Ga reaction helps to investigate new works on producing pure and optimized ^{72}As and $^{68,\ 67}$Ga radionuclides that are useful in medical applications embracing the present and possible future needs.

The present work investigates the reaction mechanisms involved in the interaction of α-projectile with ^{69}Ga-target at ≈10 - 50 MeV. Excitation functions of ^{69}Ga(α, n)^{72}As, ^{69}Ga(α, 2n)^{71}As, ^{69}Ga(α, 3n)^{70}As, ^{69}Ga(α, x)^{69}Ge, ^{69}Ga(α, x)^{68}Ga and ^{69}Ga(α, x)^{67}Ga reactions were predicted using the statistical model code COMPLETE. The corresponding experimental data were collected from the EXFOR database (Levkovski, 1991).The COMPLETE computer code has proven effective in reaction mechanism studies, particularly for light- and medium-nuclei induced reactions(Agarwal *et al*., 2002; Asres *et al*., 2018; Asres *et al*., 2019).

THEORETICAL BACKGROUND

Several theoretical nuclear reaction model-based computer codes have been used to predict reaction cross-sections (Abhishek *et al*., 2008; Yigit and Tel, 2014; Amanuel, 2021). The nuclear reaction mechanisms change with light-charged projectile energies near and above the Coulomb barrier. The reaction mechanism is considered to proceed through EQ as well as PE emission of particles at moderate excitation energies (≈10- 60 MeV) (Baure *et al*., 1995; Agrawal *et al*., 2001; Pal *et al*., 2005; Johari *et al*. 2015; Asres *et al*., 2019). The EQ mode of reaction mechanism dominates in the low energy region (in general, below 20 MeV). Furthermore, this reaction mechanism occurs in a nuclear reaction time scale of about 10^{-16} to 10^{-18} s. In the EQ mode of reactions, the projectile is captured by the target nucleus, and its energy is shared and re-shared among the nucleons, losing their identity and forming a single excited complex system that eventually leads to a fully equilibrated compound nucleus (CN). The EQ emissions of nuclear reactions are usually treated using statistical models. For example, the Hauser-Feshbach (Hauser and Feshbach, 1952) formalism considers the angular momentum and the nuclear level structure to define the EQ emission spectrum. On the other hand, in the Weisskopf-Ewing (Weisskopf and Ewing, 1940) EQ emission formalism, angular momentum, and parity are not considered.

The PE mode of reaction mechanism becomes increasingly crucial at a relatively high energy region (above ≈20 MeV). Therefore, the PE emissions of nuclear reactions occur before the thermalization of a composite system and are usually treated using non-statistical models; and the popular models used for the description and calculations of the PE mode of the reaction mechanism are the exciton model (Griffin, 1966; Blann, 1975; Agassi *et al*., 1975), hybrid model (Blann, 1971), and geometry-dependent hybrid model (Blann and Vonach, 1983).

Various computer codes were developed for years based on different nuclear reaction models that helped study nuclear structure and reaction mechanisms (Young *et al*., 1992; Uhl and Strohmaier, 1976; Strohmaier and Uhl, 1980). The ALICE-91 (Blann, 1991) analytic code developed by Blannwas also vastly used over the years to predict reaction cross-sections in the intermediate energy regions. The computer code COMPLETE (Ernst, 1997) is an advanced modified version of the ALICE-91 code family and has been successfully applied to the calculation of EQ and PE reaction cross-sections(Aydin *et al*., 2010; Asres *et al*., 2018; Asres *et al*., 2019; Amanuel, 2021).

COMPLETE code

The computer code COMPLETE with new corrections and capabilities has successfully predicted nuclear reaction cross-sections, especially for reaction mechanisms studies (Asres *et al*., 2018; Asres *et al*., 2019; Amanuel *et al*., 2011). This code employs the Weisskopf-Ewing formalism (Weisskopf and Ewing, 1940) for the EQ reaction component and Hybrid (H) model (Blann, 1971) as well as the Geometric Dependent Hybrid (GDH) model of Blann (Blann and Vonach, 1983) for the PE reaction component. Based on Bohr's independence hypothesis, the nuclear reaction cross-section for entrance channel α and exit channel β, can be expressed according to the Weisskopf-Ewing model as follows:

$$\sigma_{\alpha\beta} = \sigma_{CN}(\alpha)\frac{\Gamma_\beta}{\Gamma} \qquad (1)$$

Where $\sigma_{CN}(\alpha)$ is the cross-section for the formation of the CN and Γ_β, Γ, respectively, represent the energy average width for the decay of the CN in channel β, and the energy averaged total width. In Eq. (1) Γ_β can be given as:

$$\Gamma_\beta = \frac{2S_\beta + 1}{\pi h^2}\mu_\beta \int d\varepsilon \sigma_\beta^{inv}(\varepsilon)\varepsilon \frac{\omega_1(U)}{\omega_1(E)}$$

Where μ_β and D_β represent the ejectile's reduced mass and spin, respectively, the quantity $\sigma_\beta^{inv}(\varepsilon)$ represents the inverse reaction cross-section, and U the excitation energy of the residual nucleus. $\omega_1(E)$corresponds to the total single-particle level density at excitation energy, E.

The H model formulation of Blann and Vonach (Blann and Vonach, 1983) for PE reaction differential cross-section is given by:

$$\frac{d\sigma_v(\varepsilon)}{d\varepsilon} = \sigma_R P_v(\varepsilon) \qquad (2)$$

$$P_v(\varepsilon)d\varepsilon = \sum_{\substack{n=n_0 \\ \Delta n=+2}}^{\bar{n}} \left[\frac{X_{\upsilon} N_n(\varepsilon,U)}{N_n(\varepsilon)}\right] g_v d\varepsilon \left[\frac{\lambda_c(\varepsilon)}{\lambda_c(\varepsilon)+\lambda_+(\varepsilon)}\right] D_n, \qquad (3)$$

Here,$\sigma_R$represents the reaction cross-section, and $P_{v(\varepsilon)d\varepsilon}$ represents the number of particles of the type ν emitted into the unbounded continuum with channel energy between ε and ε+dε. The quantity in the first set of the square bracket of Eq. (3) represents the number of particles to be found (per MeV) at a given energy "ε" with respect to the continuum for all scattering processes leading to an "n" excition configuration. The nucleon-nucleon scattering energy partition function, $N_n(\varepsilon, U)$ represents the number of combinations with which n exciton may share the excitation energy, E_{ex} and x_v represent the exciton number of ν type nucleon for a given total exciton state n.$g_v$corresponds to the single-particle level density for nucleon of the"ν" type. The second set of a square bracket in Eq. (3) represents the fraction of the ν type particles at energy ε, which should undergo emission into a continuum rather than making an inter-nuclear transition. TheD_n represents the average fraction of the initial population surviving the treated exciton number.The quantity $\lambda_c(\varepsilon)$ represents the continuum emission rate for particles with "ε" channel energy, and $\lambda_+(\varepsilon)$ represents the intranuclear transition rate. The quantities U and E represent the residual nucleus and composite system excitation energies, respectively.

The GDH hybrid model has successfully reproduced a wide range of nuclear reaction data (Blann, 1972; Blann and Vonach, 1983; Harp *et al.*, 1966). The GDH model is a modified version of the H model in which the nuclear geometry effects are considered. In addition, the GDH model considers the reduced matter density, hence the shallow potential. Accordingly, the PE decay formalism incorporated the diffused surface properties sampled by higher impact parameters.

The differential cross-section for PE emission in the GDH model is formulated as follows:

$$\frac{d\sigma_v(\varepsilon)}{d\varepsilon} = \pi\lambda^2 \sum_{l=0}^{\infty}(2l+1)T_l P_v(l,\varepsilon) \quad (4)$$

The quantity T_l represents the transmission coefficient for the l^{th} partial wave, and $P_l(l,\varepsilon)$ represents decay probability at channel energy "ε" and orbital angular momentum "l". λ is the reduced de-Broglie wavelength.

Pearson's correlation coefficient

The prediction quality of our optimization in fitting COMPLETE code using essential input parameters for the experimental reaction cross sections available in the literature was evaluated using the statistical Pearson's coefficient, R(Sedgwick, 2012; Wang, 2012; Patrick, 2018). In addition, the present work used Pearson's correlation coefficient to provide information on the linear relational strength between the COMPLETE predicted and experimentally measured reaction cross-sections.

Pearson's correlation coefficient, R, is given by:

$$R = \frac{N\left(\sum_{i=1}^{N} x_{T_i} x_{E_i}\right) - \left(\sum_{i=1}^{N} x_{T_i}\right)\left(\sum_{i=1}^{N} x_{E_i}\right)}{\sqrt{\left[N\sum_{i=1}^{N} x_{E_i}^2 - \left(\sum_{i=1}^{N} x_{E_i}\right)^2\right]\left[N\sum_{i=1}^{N} x_{T_i}^2 - \left(\sum_{i=1}^{N} x_{T_i}\right)^2\right]}} \quad (5)$$

Where N is the number of the theoretical and experimental data points,$X_{T_i}$and$X_{E_i}$are the theoretical and experimental cross-section of the i^{th} value, respectively. Eq. (5) returns unitless valuesfor R between -1 and +1, where +1 indicates a strong positive relationship,-1 indicates a strong negative relationship; and 0 indicates no relationship. If $0 < R < 0.3$, the correlation is weak and positive, if $0.3 \le R < 0.7$ the correlation is moderate and positive; and if$0.7 \le R < 1$ the correlation is strong and positive.

RESULTS AND DISCUSSION

Excitation functions of $^{69}Ga(\alpha, n)^{72}As$, $^{69}Ga(\alpha, 2n)^{71}As$, $^{69}Ga(\alpha, 3n)^{70}As$, $^{69}Ga(\alpha, x)^{69}Ge$, $^{69}Ga(\alpha, x)^{68}Ga$ and $^{69}Ga(\alpha, x)^{67}Ga$ reactions produced via EQ and PE processes were considered at ≈ 10-50 MeV. The experimentally measured excitation functions were compared with the theoretical model code COMPLETE predictions, which account for both EQ and PE processes. In this code, the level density parameter a, which predominantly affects the EQ components of a cross-section, is calculated from the expression a = A/K MeV^{-1}, where A is the nucleon number of a CN and K is an adjustable constant. K may vary to match the experimental data. The initial exciton number n_o (n_o=n+p+h, which is described by the number of neutrons (n), the number of protons (p) in excited states, and the number of holes (h) after the first collision) that governs the PE component, represents the initial configuration of the number of particles in the excited states and the number of holes after the first collision.

In the present work, to match the experimental data, the values of important input parameters K(K=8, 10, 12) and n_o (n_o=4, 5, 6) were varied for a representative ^{69}Ga(α, n)^{72}As Reaction. Figure 1 displays the experimentally measured excitation functions and theoretical predictions using different K and n_o values for ^{69}Ga(α, n)^{72}As Reaction.

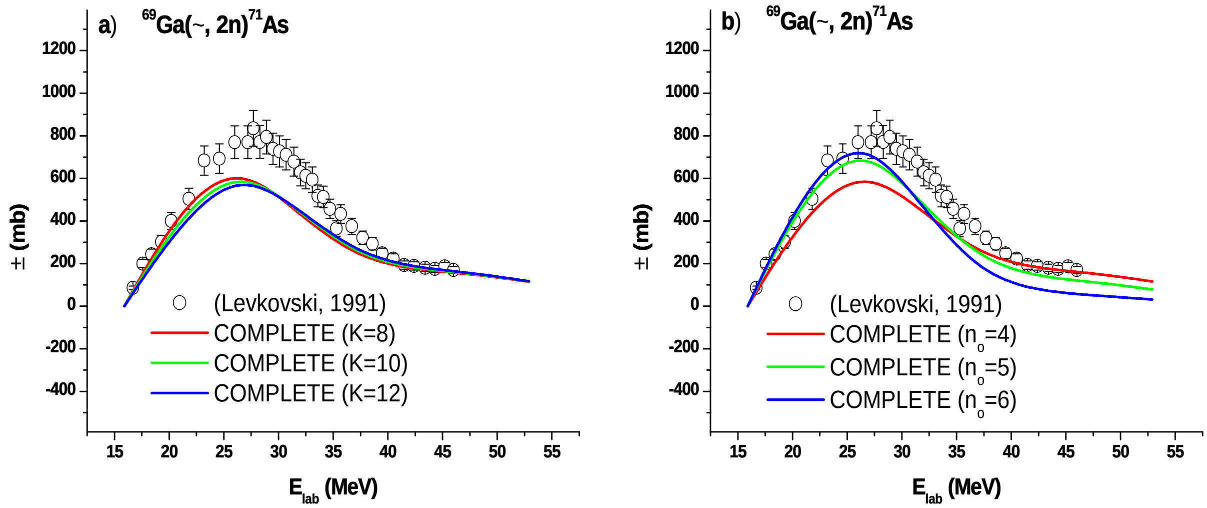


Figure 1: Experimentally measured and theoretically calculated excitation functions for ^{71}As residue.

The curves represent the theoretical predictions (admixture PE and EQ) for different values of K (K = 8, 10, and 12) in panel (a) and n_o (n_o = 4, 5, and 6) in panel (b). The open circles represent the experimental cross-sections.

As this figure indicates, the measured excitation function is well reproduced by COMPLETE code for values of K=8 and n_o=5. It may be observed from Fig 1(a) that the predicted excitation functions for different K values are similar; if they differ, the differences are minimal. For other reaction channels populated in the interaction of α-projectile with ^{69}Ga-target, a combination of K=8 and n_o=5 has been consistently used to predict the reaction cross-sections.

A) ^{9}Ga(α, n)^{72}As Reaction

When α-projectile bombarded ^{69}Ga-target, a composite [^{73}As]* nucleus is produced in excited states. The excited [^{73}As]* nucleus then emits a neutron leaving the ^{72}As nucleus as a residue, i.e., $\alpha + {}^{69}\text{Ga} \longrightarrow [{}^{73}\text{As}]^* \longrightarrow n + {}^{72}\text{As}$

Figure 2(a) displays the experimentally measured excitation function and the COMPLETE code predictions for ^{69}Ga(α, n)^{72}As reaction. As shown in Figure 2(b), the experimentally measured excitation function is relatively higher than the theoretically predicted excitation functions (with and without PE contribution), though the shapes of the two excitation functions showed a similar trend. The observed enhancement on the measured cross-section may be attributable to impurity contributions from the heavier residue(s). In addition, Pearson's correlation coefficient between theoretically predicted and experimentally measured production cross-sections has a value of R=0.96. Hence, the theoretical results indicated a strong and positive correlation with the experimental.

B) ^{69}Ga(α, 2n)^{71}As Reaction

In the case of ^{69}Ga(α, 2n)^{71}As reaction, the residue ^{71}As may be produced following the emission of two neutrons from an excited composite nucleus, [^{73}As]*, i.e.,

$$\alpha + {}^{69}\text{Ga} \longrightarrow [{}^{73}\text{As}]^* \longrightarrow 2n + {}^{71}\text{As}$$

Fig. 2(b) shows the theoretically predicted excitation functions (with and without the contribution of PE reaction) along with the experimentally measured excitation function for ^{69}Ga(α, 2n)^{71}As Reaction. As shown in this figure, the predictions of the COMPLETE code, after incorporating the PE reaction, agree with the measured excitation function. Furthermore, Pearson's correlation coefficient value (R ≈ 0.94) indicated a strong and positive correlation between theoretically predicted and experimentally measured production cross-sections.

C) ^{69}Ga(α, 3n)^{70}As reaction

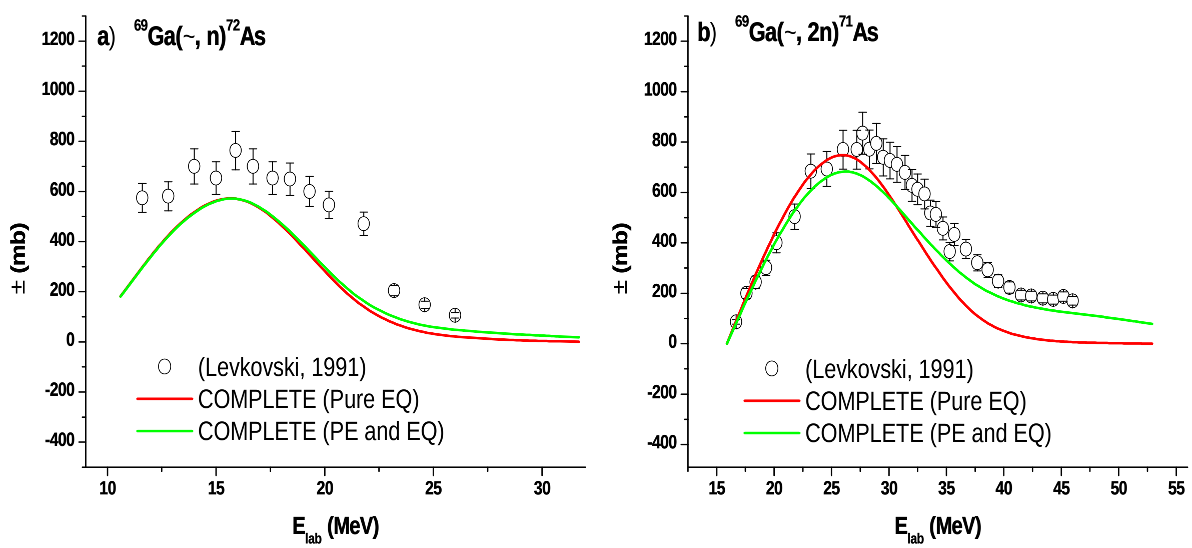
The measured excitation function and theoretical predictions obtained from COMPLETE code for ^{70}As residue populated via (α, 3n) channel are shown in Figure 2(c). Note that in the ^{69}Ga(α, 3n)^{70}As reaction, the residue ^{70}As may be formed through the reaction:

$$\alpha + {}^{69}\text{Ga} \longrightarrow [{}^{73}\text{As}]^* \longrightarrow 3n + {}^{70}\text{As}$$

It may be observed from Figure 2(c) that up to 40 MeV (up to the peak portion), the predicted excitation function after incorporating PE contribution, in general, reproduced the measured excitation function satisfactorily. However, above 40 MeV (in the tail portion of the excitation function), the predicted values are higher than the experimental data. Moreover, Pearson's correlation coefficient between theoretically predicted and experimentally measured reaction cross-sections has a value of R=0.86. Hence, the theoretical results indicated a strong and positive correlation with the experimental.

D) ^{9}Ga(α, x)^{69}Ge reaction

In ^{69}Ga(α, x)^{69}Ge reaction, ^{69}Ge residue may be formed through the emissions of unidentified particles, x from the composite nucleus, [^{73}As]* via (α, x) complex channel. As seen in Figure 2(d), the predicted excitation functions with the inclusion of PE contribution is in good agreement with the measured excitation function.



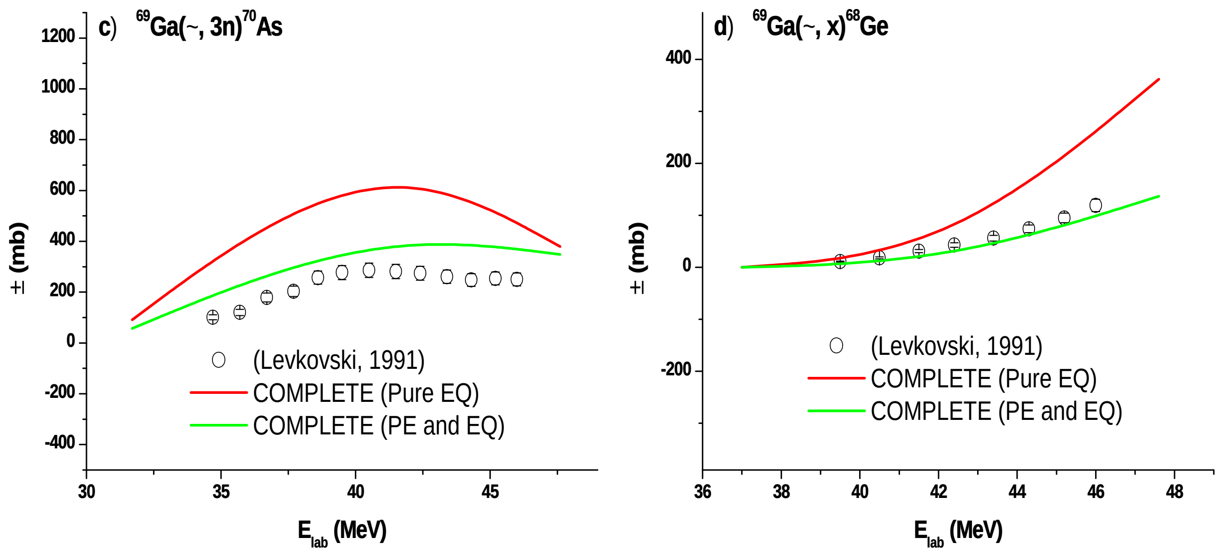


Figure 2. Experimentally measured and theoretically calculated excitation functions for 72As, 71As, 70As, and 69Ge residues.

The curve represents the theoretical prediction, and the symbols represent the experimental cross-sections.

Pearson's correlation coefficient between theoretically predicted and experimentally measured production cross-sections is R ≈ 0.99. This result indicated a strong positive association between the predicted and measured production cross-sections.

A) ^{9}Ga(α, x)^{68}Ga reaction

^{68}Ga residue is produced when unidentified particles (x) are emitted from an excited composite nucleus [^{73}As]* via ^{69}Ga(α, x)^{68}Ga complex reaction channel. Figure 3(a) shows the theoretically predicted excitation and experimentally measured excitation functions.

It may be observed from Figure 3(a) that the predicted (pure EQ) excitation function is in good agreement with the measured one. Furthermore, Pearson's correlation coefficient between the predicted (pure EQ) and measured cross-sections have a value of R ≈ 0.5, indicating a moderate and positive correlation between the measured and the predicted excitation functions.

B) ^{69}Ga(α, x)^{67}Ga reaction

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The measured excitation functions, along with the theoretical predictions (with and without the contribution of PE reaction) for ^{69}Ga(α, x)^{67}Ga complex reaction channel, are shown in Figure 3(b). Note that ^{67}Ga residue is produced when unidentified particles (x) are emitted from an excited composite nucleus [^{73}As]* via ^{69}Ga(α, x)^{67}Ga complex reaction channel.

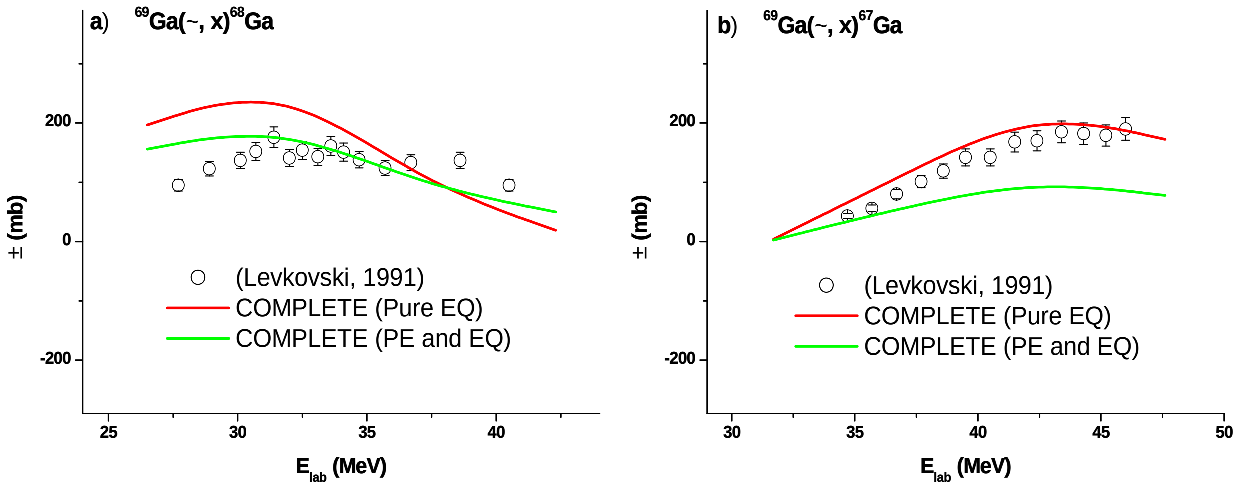

Figure 3. Experimentally measured and theoretically calculated excitation functions for ^{68}Ga and ^{69}Ga residues.

The curve represents the theoretical prediction, and the symbols represent the experimental cross-sections.

Figure 3(b) shows that the pure EQ-predicted excitation function agrees with the experimentally measured excitation function. Furthermore, Pearson's correlation coefficient value (R≈0.98) indicated a strong and positive correlation between theoretically predicted and experimentally measured reaction cross-sections.

CONCLUSION

Excitation functions of ^{69}Ga(α, n)^{72}As, ^{69}Ga(α, 2n)^{71}As, ^{69}Ga(α, 3n)^{70}As, ^{69}Ga(α, x)^{69}Ge, ^{69}Ga(α, x)^{68}Ga and ^{69}Ga(α, x)^{67}Ga reactions populated in the interaction of α-projectile with ^{69}Ga-target were studied at ≈10 -50 MeV. Except for ^{69}Ga(α, x)^{68}Ga reaction, the theoretically predicted (admixture of PE and EQ reactions) reaction cross-sections using the statistical model code COMPLETE with the K=8 and n_o=5, in general, were found to be in good agreement with the experimentally measured excitation functions.

Furthermore, Pearson's correlation coefficients showed moderate to strong positive correlations between the theoretically predicted and experimentally measured excitation functions for investigated reaction channels. The present results also disclosed a significant contribution from a pre-equilibrium reaction, particularly in the tail sections of the excitation functions. Thus, the admixtures of pre-equilibrium and equilibrium modes of reactions must be considered when predicting total reaction cross-sections.

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