A Study of Reaction Dynamics in the Interaction of ^{14}N+^{59}Co System at ≈32-56 MeV

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Abstract

The present work was done to investigate the reaction mechanisms involved in the interaction of ^{14}N projectile with ^{59}Co target at beam energies ~32-56 MeV. The experimentally measured excitation functions available in the literature [2] were compared and analyzed with the statistical model code PACE4 calculation. For non-α emitting channels populated via complete fusion reaction, the measured excitation functions, after correcting them for possible contributions coming from higher charge isobaric precursor decays, were in general found to be in good agreement with theoretical predictions. However, for α-emitting channels, the experimentally measured excitation functions had more production cross-sections than what PACE4 predicted. The observed enhancement in the present case may be attributable to process of incomplete fusion from break-up of ^{14}N projectile. It may be pointed out that incomplete fusion reaction increases with increase in projectile energy. The observation of high incomplete fusion reaction is attributable to the prompt breakup of ^{14}N projectile into α-cluster.

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Introduction

Nuclear physics is the science of the components of the nucleus of atoms, that is protons and neutrons, and related fundamental particles .Interactions that split atomic nuclei, or fuse them together, are part of nuclear physics. Initially back around 1920, the known particles were proton, neutrons, and electrons, Nuclear physics, sometimes called particle physics, and now has a standard model with 17 particles. The one most recently discovered is the Higgs Boson [6]. Each proton and neutron, for example, is made of three quarks. All nuclear interactions are governed by two forces, the strong nuclear force and the weak nuclear force. Nuclear physics also explains the nuclear fusion that powers the sun and makes H-bombs; and the nuclear fission that powers nuclear power plants and is used to make A-bombs. It also explains why some atoms are radioactive and how phenomena like radio carbon dating work. Now days the study of the interaction of heavy ions is atopic which has acquired a central place in nuclear physics research (1, 2). This is possible with the availability of the accelerated beams of heavy ions. Recent studies show that there are different reaction mechanisms in heavy ion reactions at energies around the coulomb barrier to well above it. These reaction mechanisms have been discussed in recent papers (2, 3). A nuclear reaction (14-20) is a process in which the structure and energy content of an atomic nucleus are changed by interaction with another nucleus or particle. There are important features of fusion reactions: For light particles and low incident energies the fusion cross section may be a considerable fraction of the reaction cross section. The second important feature is, with increasing charge of the increasing ions the fusions probability falls abruptly. The other feature of fusion reaction is the fusion cross section at first increases linearly with $1/E_{cm}$ reaches a maximum and there after decreases linearly with $1/M_{cm.}$ ICF reactions only a part of the projectiles fuses with the target nucleus , leading to the formation of the exited incomplete fusion(ICF) fused composite systems with amass and /or charge lower than that of the CN ,while the remaining part escapes in forward cone with approximately the beam velocity .The exited composite system formed as a result of fusion fragment of the incident with the target may also undergo de-excitation by emission of the particle and /or gamma rays. The common features of ICF reaction are: The outgoing particles have forward peaked angular distribution and energy spectrum at beam velocity. The recoil range distribution of heavy residues shows allows range of the components, suggesting incomplete momentum transfer. The spin distribution of evaporation residues populated via ICF is found to be distinctly different from those of CF [13].The study of the interaction of two heavy ions has required central place in nuclear physics research [1, 2].This is possible with the availability of the accelerated beams of the heavy ions .The recent studies shows that there are different reaction mechanisms in heavy ion reactions at energies around the coulomb barrier to well above it. These reaction mechanisms have been discussed in recent papers [2].The formation of compound nucleus is the dominant process at lower excitation energies. In compound nuclear formation reactions, the projectile is captured by the target nucleus and its energy is shared and re shared among the nucleons of compound nucleus until it reaches a state of statistical equilibrium. After time much longer than the time required by the projectile to cross the nucleus, a nucleon or a group of nucleons near the surface may, by statistical fluctuation, receive enough energy to escape, just as a molecule may evaporate from a heated drop of liquid. At moderate excitation energies, however there are indications that pre-equilibrium emission (where there is emission a particle long before the attainment of statistical equilibrium) also contributes to the reactions processes. Late experimental studies [2, 3] have Shawn the CF and ICF reactions play important roles in the heavy ion reactions .In CF reaction process the projectile with target, the projectile completely fuses with the target nucleus .In case ICF reactions, only apart the incident ion fuses with the target and the remaining part moves in the direction of the incident beam with almost the velocity .In this case, the fraction of the momentum transferred depends on the mass of the fused fragment. In the past a number of reaction mechanisms studies were carried out by different scholars in the field.

Even though a number of studies done in the past a clear and robust modeling of ICF processes is still lacking, especially at relatively low bombarding energies ≈ 4–8 MeV/nucleon, where a clear systematic study and compiled data are available for only a few projectile-target systems.

In view of this, in the present work the dynamics of reaction mechanisms involved in the interaction of ^{14}N+^{59}CO.sytem. This is accomplished by study the excitation functions of residues produced in ^{14}N+^{59}CO system.

Methodology

The study of this research work was conducted mixed methods that mean quantitative with qualitative approach using computer base PACE4 code software. The data was gathered (obtained) from an IAEA data source in searching Google engine. The experimental data information was generated by the bombarded projectile as a nitrogen particle with target nuclide different cobalt isotopes using a PACE4 computer-based software package.

Computer Code and Formulation

The nucleus is a tightly bound system of protons and neutrons which is held together by strong nuclear forces that are not normally detectable in nature because of their extremely short range .The small size , strong nuclear forces , and many particles in nucleus result in a highly complex and unique quanta system .The nucleus is highly complex with various degrees of freedom being excited at small excitation energy and often strongly mixed .The density of the quantum mechanical states increases rapidly with excitation energy and soon becomes very large and complex .Even at lower beam energy were nuclear reactions can be initiated with charge particles , many states are available for the compound nucleus. This compound nucleus in excited energy state subsequently can decay through many different ways since separate study of each states very complex. The models based on statistical approaches are not only appropriate, the way essential for understanding and predictions of various nuclear phenomena. In studying and other collisions processes we are always interested in a quantitative measure of the probability with which the collision process occur [21-25].

This quantitative measure is always expressed through a parameter called cross-section.

Studies of nuclear reactions deal with the analysis of cross-section data in terms of statistical model for the formation and decay of the compound nucleus. Models developed by Bethe [27], Weisskopf and Ewing [26] were based on Bohr's independent hypothesis for the formation and decay of compound nucleus. However, these models neglect a direct influence of angular momentum imparted by the projectile to the composite system and party. As such, these models are convenient for the study of nuclear reactions mechanism with light ion induced, where the angular momentum affects are small due to low mass of the projectile. Advances in accelerator technologies enabled to use heavy-ions as beams in the late 1950s where the introduction of large angular momentum due to the large mass the beam had various consequences therefore, in order to incorporate the angular momentum effects in the nuclear level density expansions these models were modified by Hauser and Feshback [26, 28]. Several models have been proposed to understand nuclear reactions dynamics and nuclear structure and various computer codes were developed for the predictions and analysis of various products of CN decay. These computer codes can now be used to verify the reaction mechanisms formation and decay, to determine angular momentum and to search for non-statistical aspects of nuclear structure at higher excitation energies and high angular momentum [28]. There are two broad classifications in calculation and computer code as single-steps (SS) and multi-step (MS) calculations. In SS calculations the excited nucleus has energy sufficient for a single decay or it is only the emission of the first particle that is of interest. However, in case of MS calculations the spectra of gamma rays and light particles contains contributions from successive decays and the distribution of heavy residues is arrived at through several or many successive decays. This problem can be treated in two ways namely Multi Step Gridded Method (MSGR) and Multi Step Monte Carlo (MSMC) method. In MSGR a grid is constructed in Z and A, for each nucleus, a population distribution over a two dimensional grid in excitation energy and angular momentum. The size of the grid in Z and A continues to expand for successive daughter nuclei until further decay is energetically forbidden. However, MSMC method follows the decay of individual compound nuclei in an initial ensemble by Monte Carlo techniques until the residual nucleus can no longer decay. The great advantage of the Monte Carlo method is that it can predict energy spectra, angular distributions and multi particle correlations in laboratory system. In the present work we have used the statistical model codes PACE4 [29, 30] for excitation functions predictions.

Precursor Formulation

The cumulative cross-section, (σ_{cum}) of the given residue is the sum of
i) Its independent production cross-section (σ_{ind}), deduced from the measured cumulative cross- section
ii) Cross-section for independent production of its precursor (σ_{prec}) multiplied by a numerical coefficient F_{prec}[15] which is formulated as

$$\sigma_{cumul}=\sigma_{ind}+F_{prec}\cdot\sigma_{prec} \text{--} (3.12)$$

The value of F_{prec}depends on the branching ratio for higher charge isobaric precursor (HCIP) as:

$$F_{prec}=B.T_{ind}/T_{ind}-T_{prec} \text{---}(3.13)$$

where,*Tind* and *Tprec* are half-life of residue and precursor respectively as such, the cumulative cross-section is:

$$\sigma_{cuml}=\sigma_{ind}+B.T_{ind}/T_{ind}-T_{prec}.\sigma_{prec} \text{---} (3.14)$$

the value of branching ratio and half-life required for this obtaining this result is taken from the table of nuclear wallet card [14]. By using this formulation, the independent cross-section can be separate out from the cumulative cross-section as

$$\sigma_{ind}=\sigma_{cuml}-+B.T_{ind}/T_{ind}-T_{prec}.\sigma_{prec} \text{---} (3.15)$$

where, σ_{prec} can be taken from PACE4 code. The precursor may also be populated by
the decay of (HCIP). Since, the precursor has relatively shorter half-life compared to the corresponding residue. The precursor has a contribution to separate out the independent cross-section on the HCIP decay process.

Results and Discussions

Analysis of Excitation Functions of Residues Populated In ^{14}N+59Co System

In this work the measured EFs of ^{14}N+^{59}Co system available in the literature[1]were evaluated and analyzed using the theoretical prediction of the statistical model code PACE4[2].In this code the value of level density parameter , a ,which is an important parameter largely affects the equilibrium components of a cross section is calculated by a=A/K ,where A is the nucleon number of a CN and K is an adjustable parameter ,which can be varied to fit the experimental data. The measured EFs were compared to the predictions of PACE4 using different level density parameter values for residues populated via CF and /or ICF processes .In these calculations the de-excitation processes which used 300000 de-excitation cascades was followed by a Monte-Carlo procedure, And the statistical errors in the maxima of the EFs for all residues populated in the interaction of the of ^{14}N projectile with the ^{59}Co target were less than 10 % .

The measured EFs have been compared with theoretical predictions based on computer code PACE4.The PACE4 [2] is based on statistical approach. In this program the de-excitation of the compound nucleus is followed by a Monte-Carlo procedure. The angular momentum projectiles are calculated at each stages of the de-excitation which enables the de-excitation of the angular distribution of the emitted particles. The level density parameter is an important which may be varied to match the experimental data.

Residues Populated via non-α-contaminated channels

Figures 4.1(a-d) below displayed the experimental measured EFs along with the PACE4 prediction for ^{69}As, ^{70}As, ^{72}Se and ^{69}Ge residues populated via (^{14}N, 2np) (14N, 3np) (^{14}N, p) and (^{14}N, 2n2p)Cannels respectively. In this channels there is no like hood of ICF reactions occurring and therefore, these channels are populated only by CF processes. As can be seen from these figures, the PACE4 predictions with K=7.5, in general reproduced satisfactorily the experimental measured EFs, after correcting for possible contributions from higher charged isobaric precursor decay.

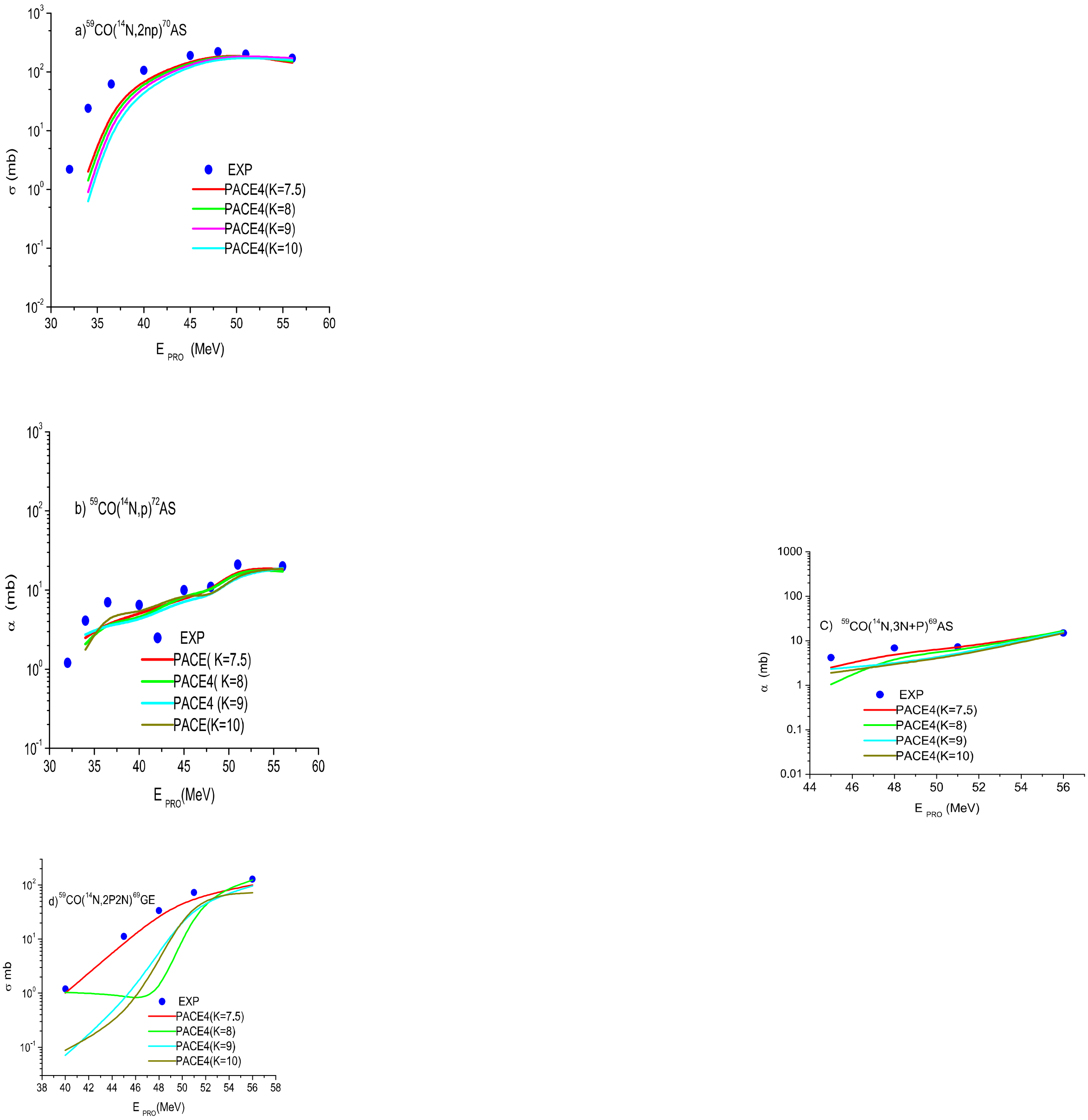

Figure: 4.1(a-d) Experimentally measured and theoretically calculated EFs for ^{70}As, ^{72}Se, ^{69}As and ^{69}Ge residues populated via the CF channels of (^{14}N,P2n), (^{14}N,P3n), (^{14}N,P) and (^{14}N,2P2n) in the ^{14}N+^{59}Co system. The circle symbol indicates the experimentally measured data and the curve represent the theoretically calculated data at different residues of K (=7.5,8,9 and 10).

Residues Populated via α-contaminated channels

The fact that measured fusion cross section (σ) for non α-emitting channels in the ^{14}N+^{59}Co system could be reproduced satisfactorily by PACE4 predictions , gives confidence in the input parameters chosen to fit the EFs for all (measurable) α-emitting channels considered in the ^{14}N+^{59}Co system. For residues populated via α-contaminated channels, which are expected to be produced via CF and/or ICF processes the same set of input parameter, K=7.5 is consistently used.

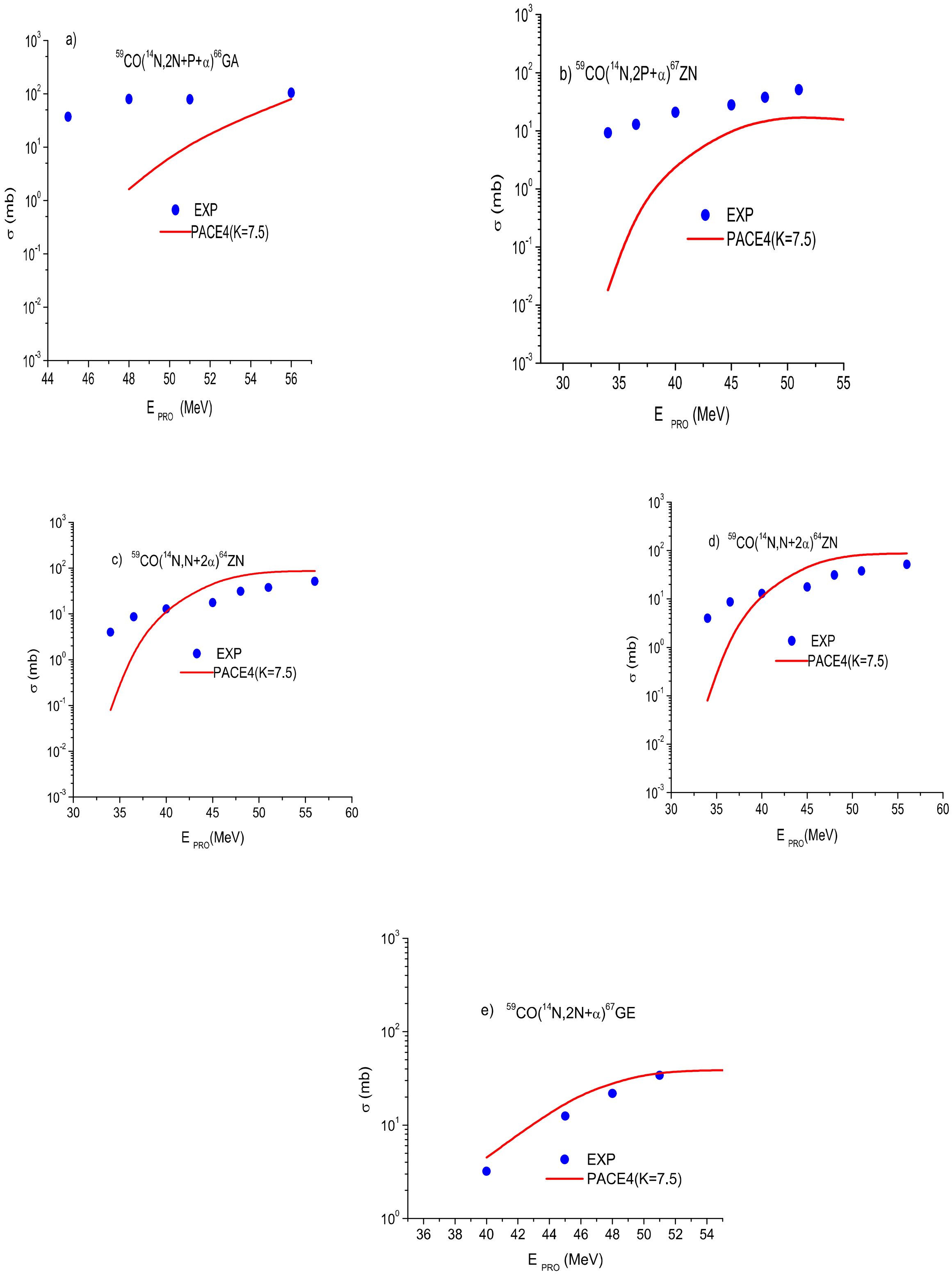

Figure: 4.2(a-e) Experimentally measured and theoretically calculated EFs for ^{66}Ga, ^{67}Zn, ^{64}Zn, ^{68}Ge and ^{67}Ge residues populated CF and /or ICF in the interaction of ^{14}N+^{59}Co system.

a) Residue of ^{66}Ga

The measured EFs along with the PACE4 prediction for ^{66}Ga residue is populated via α-emitting (^{14}N, 2npα) channel is shown in the figure 2(a). ^{66}Ga residue is populated through CF and/or ICF processes as:

1) Complete fusion ^{14}N, i.e.

$^{14}\mathrm{N}+^{59}\mathrm{Co} \rightarrow (^{73}\mathrm{Se})^{*} \rightarrow ^{66}\mathrm{Ga}+2np$

2) Incomplete fusion

$^{14}\mathrm{N}\ (^{10}\mathrm{B}+\alpha) +^{59}\mathrm{Co} \rightarrow (^{69}\mathrm{Ge})^{*}+\alpha \rightarrow ^{66}\mathrm{Ga}+\alpha+2pn$,

Where, α as spectator

It may observed from figure 2(a) above, the experimentally measured cross section were greater than theoretically calculated cross section using PACE4 with K =7.5 , especially at lower energy points. The observed disagreement between the experimental and theoretical data could be inferred to the contribution coming from the incomplete fusion.

b) **Residues of ^{67}Zn and ^{64}Zn**

The residue ^{67}Zn shown with the figure 2(b) may be formed via complete and/or incomplete of ^{14}N with ^{59}Co, ^{73}Se residue populated via of CF and /or ICF reactions as:

1) Complete fusion of ^{14}N, i.e

$^{14}\mathrm{N}+^{59}\mathrm{Co} \rightarrow (^{73}\mathrm{Se})^{*} \rightarrow ^{67}\mathrm{Zn}+np\alpha$

2) Incomplete fusion

$^{14}\mathrm{N}\ (\alpha+^{10}\mathrm{B}) +^{59}\mathrm{Co} \rightarrow (^{69}\mathrm{Ge})^{*}+\alpha$,

$(^{69}\mathrm{GE})^{*} \rightarrow ^{67}\mathrm{Zn}+Pn$

Where, α-as spectator

The residue ^{64}Zn indicated with the figure 2(c) may also formed by CF and /or ICF reaction as :

1) Complete fusion of ^{14}N, i.e.

$^{14}\mathrm{N}+^{59}\mathrm{Co} \rightarrow (^{73}\mathrm{Se})^{*} \rightarrow ^{64}\mathrm{Zn}+N+2\alpha$

2)Incomplete fusion

$^{14}\mathrm{N}(\alpha+\alpha+^{6}\mathrm{Li}\ )+^{59}\mathrm{CO} \rightarrow (^{65}\mathrm{GA})^{*}+2\alpha$,

$(^{65}\mathrm{GA})^{*} \rightarrow ^{64}\mathrm{ZN}+n$, where (α- as spectator)

The experimentally measured EFs, compared with PACE4 prediction using level density parameter K =7.5 for (^{14}N, npα) and (^{14}N, n2α) channels populated by CF and or ICF processes. In (^{14}N, npα) channel, the residue may be formed by two different processes:

$^{14}\mathrm{N}+^{59}\mathrm{Co} \rightarrow (^{73}\mathrm{Se})^{*} \rightarrow ^{67}\mathrm{Zn}+np\alpha$ and

$^{67}\mathrm{Ga}+\mathrm{EC}/B^{+} \rightarrow ^{67}\mathrm{Zn}$,

From higher charge isobaric precursor parent

The cumulative and independent is related using equation (3.14) we obtained:

$\sigma_{\mathrm{Cumul}}\ (^{67}\mathrm{ZN}) = \sigma_{\mathrm{Ind}}\ (^{67}\mathrm{ZN}) + 1.008\ \sigma_{\mathrm{prec}}\ (67\mathrm{GA})$ -- (4.1)

Figure: 4.2 (b) and (c) display the predicated EFs along with the measured cross section, after correcting for possible contribution coming from higher charge isobaric precursor decay. As can be seen from the figure (b) and (c) the predicated EFs with K=7.5 in general does not reproduced significantly the experimentally measured EFs. It may be further seen from this figure that the measured EFs for ^{64}ZN residue at lower energy points and for ^{67}ZN residue in the entire the energy ranges shown significant enhancement as compared to the theoretical perdition, since PACE4 does not take in to account, therefore the observed enhancement in the experimentally measured production cross section may be attributed to the contribution coming from ICF of ^{14}Nwith target nucleus.

C) **Residues of ^{68}Ge and ^{67}Ge**

The residue ^{68}GE EF indicated with the figure 2(d), it may formed via CF and/or ICF OF ^{14}N with ^{59}CO , ^{73}SE of the compound nucleus is produced .The ^{68}GE residue populated through CF and /or ICF reaction as:

1) Complete fusion of ^{14}N i.e.

$^{14}\mathrm{N}+^{59}\mathrm{CO} \rightarrow (^{73}\mathrm{SE})^{*} \rightarrow ^{68}\mathrm{Ge}+n\alpha$

3) Incomplete fusion reaction

$^{14}\mathrm{N}\ (\alpha+^{10}\mathrm{B}) +^{59}\mathrm{CO} \rightarrow (^{68}\mathrm{Ge})^{*}+\alpha n$,

$(^{68}\mathrm{GE})^{*} \rightarrow ^{67}\mathrm{Ge}+n$ Where,(α-as spectator).

With similar way to ^{68}Ge, the residue ^{67}Ge which indicated with the figure 2(e) it may also form by CF and /or ICF reactions as:

1) Complete fusion of ^{14}N i.e.

$^{14}\mathrm{N}+^{59}\mathrm{CO} \rightarrow\ (^{73}\mathrm{Se})^{*} \rightarrow\ ^{68}\mathrm{Ge}+n\alpha$

2) Incomplete fusion reaction

^{14}N (α+^{10}B) +^{59}CO $\rightarrow$(^{67}GE)*+2nα,
(^{68}GE)*$\rightarrow$^{66}GE+2n
Where, (α-as spectator)
The experimentally measured EFs compared with PACE4 predictions using the level density parameter value K=7.5 for (^{14}N, nα) and (^{14}N,2nα) channels populated by CF and /or IC reactions that the cumulative and independent cross section using equation [3.14] gives: -

σ_{CUMUL} (^{68}Ge) = σind(^{68}Ge) +1.006σ_{prec} (^{68}As) --- (4.2)

σCumul (^{67}Ge) =σ_{Ind} (^{57}Ge) +1.038σprec (^{67}As) -- (4.3)

Figure4.2(d) and (e) displays the predicated EFs along with the measured cross section, after correcting for possible contribution coming from the high charge isobaric precursor decay. As can be seen from figur4.2 (d) and (e), the predicated EFs with K=7.5, in general does not reproduced satisfactorily the experimental measured EFs. I.e. As can be seen from the figure the measured EFs for ^{68}Ge residue at lower energy points satisfied and at higher energy points the excitation EFs does satisfy, since the experimentally measured value above the theoretically measured values. In the case of ^{67}Ge residue, it may observed that at lower and higher energy points the experimentally measured value below from theoretical measured PACE4. Value (K=7.5), the observed disagreement between the experimental and theoretical data could be inferred to the contribution coming from the ICF reaction of ^{14}N with the target nucleus. The independent and cumulative yields of these residues are also displayed. The cumulative cross section, (σ_{cumul}) of given residue is the sum of:

- Its independent production cross section, σ_{ind} deduced from the measured cumulative cross section by using the relationship (equation 1-2 above). And
- Cross section for independent production of its precursor σ_{prec} multiplied by a numerical coefficient F_{prec} [32].

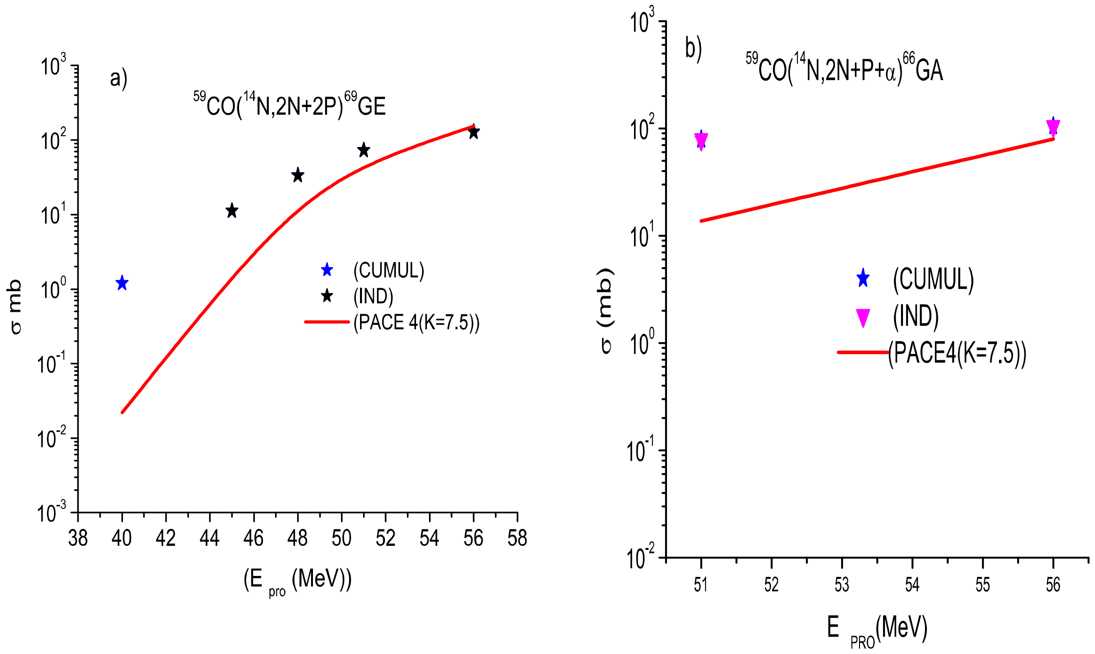

Figure: 4.3 experimentally measured and theoretically calculated EFs for ^{69}Ge (2n2p) and ^{66}Ga (2npα) residues populated in cumulative and independent interaction of the ^{14}N+^{59}Co system.

Incomplete fusion contribution

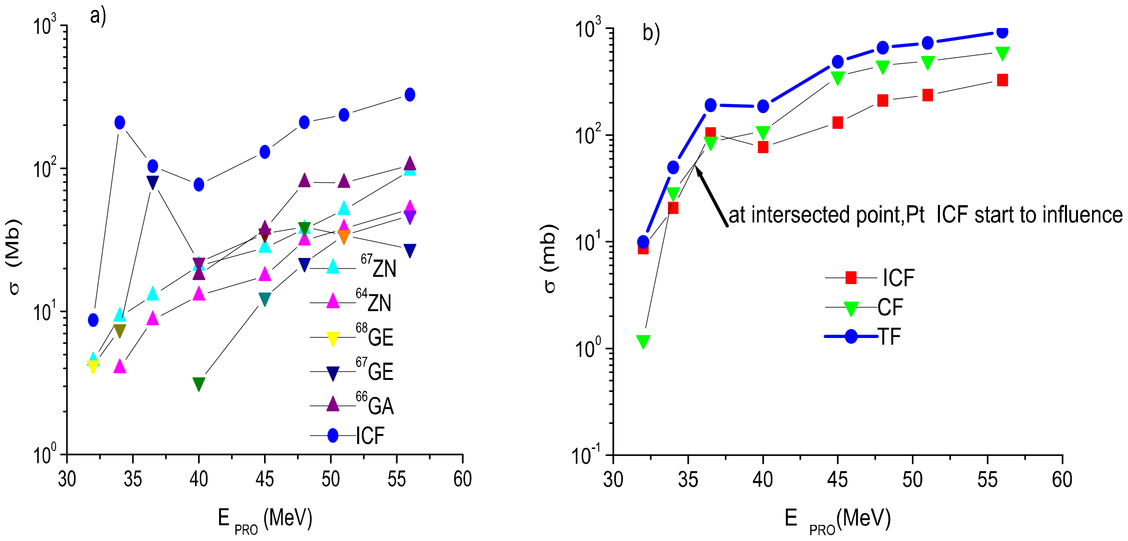

Figure: 4.4(a) Above ICF contributions for individual residue along with the total sum of ICF cross section, ∑ICF for ^{14}N+^{59}CO system. It may be observed from this figure the contribution of ICF increase with projectile energy. Figure 4.4 (b) the total sum of the measured TF and the total sum of the CF cross section, ∑CF along with the total sum of ICF cross section at various energy for the ^{14}N+59COsystem.

Figure 4.4(a) and (b),the HICP decay corrected total ICF cross section (∑ICF)and total CF reaction(∑CF) =$\sum\alpha - emitting$ (exp)+$\sum\alpha - emitting\ (theo)$ were plotted along with the total fusion cross section ,TF (TF=∑CF+∑ICF) for all(measurable) evaporation residue populated in the 14N+^{59}co system. As it was seen from the figure 4. 2(a-e), the experimentally measured cross section is greater than the PACE4 perdition cross section and vice versa. The reason for this difference is that for α-emitting channels the PACE4 simulation considered α-as spectator on ICF reactions ,the ICF does not to be considered byPACE4. Due to this reason the gap is occurred between experimental and theoretical measured cross sections. As can be seen the the figure 4.4(b), the ICF starts to influence at projectile energy 36 MeV point (36MeV), thus the relative contribution of ICF is about 14.4% of the total fusion cross section at the point ICF start to influence and increase to 37 % at projectile energy 39 MeV point (39MeV). It was observed from the figure 4.4(b) that, ICF contribution increase with increasing at higher energy, ICF cross section were highly closer to the CF cross section.

Conclusion

In the present work, the study of excitation functions of ^{68}Ge, ^{67}Ge, ^{66}Ga, ^{67}Zn and ^{64}Zn residues populated in the interaction of ^{14}N projectile with ^{59}Co target were studied for the energy range of ≈32-56 MeV by using an excitation model with computer PACE4 code software. The measured excitations available in the literature [2] were compared with theoretical prediction of statistical model code PACE4.

For non-α emitting channels, after correcting them for possible contributions from higher charge isobaric precursor decay, the measured excitation functions in general revealed an agreement with the values predicted by PACE4 within the error bar. The measured excitation functions for α-emitting channels were in general higher than the PACE4 predictions. The observed enhancement in the measured cross-sections is attributable to the contribution coming from incomplete fusion, which is not taken into account in prediction of PACE4. The approximate incomplete fusion contribution was found to be less than 14.4% at the starting point (≈ 36 MeV), but at the highest energy point (≈39 MeV) it reached approximately 37% of the total fusion. It may be pointed out that incomplete fusion increases with increase in projectile energy. The observation of high incomplete fusion reaction is attributable to the prompt breakup of the projectile into α-cluster wherein the projectile, breaks up into ^{14}N (^{10}B +^{4} He and/or ^{4}He +^{4} He +^{6} Li), leading to an ICF reaction. It was found that the probability of breakup increases with an increase in the incident projectile energy.

Declarations

Availability of data and materials

The present work is totally my idea without considering citation of reference which means that there was no conflict of interest among the researchers. Theoretical data tool from IAEA, EXFOR data and to generate experimental data COMPLETE code is used.

Authors' contributions

Research article conceived and designed the study. The Author has done study validation, formal analysis, investigation resources, reaction mechanism and more gave attention to research to the nuclear science technology

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