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IDENTIFICATION OF PROJECTILE SEQUENTIAL DECAY AND TRANSFER-REEMISSION REACTION CHANNELS IN THE $^{16}O+^{28}Si$, $^{16}O+^{27}Al$ AND $^{10}B+^{27}Al$ SYSTEMS AT 4-5 MeV/A

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ABSTRACT

In plane angular correlations have been investigated in the $^{28}Si(^{16}O,^{12}C-\alpha)$, $^{27}Al(^{16}O,^{12}C-\alpha)$ and $^{27}Al(^{10}B,^{6}Li-\alpha)$ reactions at 64, 64 and 48 MeV, respectively. Two sequential processes have been clearly identified, namely: transfer-reemission through the formation of intermediate nuclei and projectile sequential decay. The analysis is based on three body kinematics and model fits of experimental angular correlation functions.

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Over the last few years studies of light particles emission were used to probe early stages of heavy ion reaction mechanisms yielding both to inclusive and coincidence data. There has been increasing interest in unambiguous identification of projectile fragmentation, pre-equilibrium emission and incomplete fusion mechanisms[1-4]. The controversy found in the literature concerning the identification of these mechanisms and their competition in light systems[5,7] reflects the experimental difficulties and calls for alternative methods. The $^{27}Al(^{16}O,^{12}C-\alpha)$ system has received most of the attention, although no conclusive interpretation has been drawn. While some authors pointed out the dominance of α-transfer like processes followed by pre-equilibrium[5] or equilibrium emission[6] by an intermediate $^{31}P^*$ nucleus, others suggested the occurrence of incomplete fusion processes[7]. A different approach, which does not allow for a clear identification has been adopted by Sasagase et al.[8] by temptativelly pointing out the coexistence of two different sequential processes. Therefore systematic studies, based on exclusive measurements revealing projectile and target dependence of these mechanisms, are necessary in order to establish an unified picture for sequential processes in light heavy ion reactions.

In this letter we are reporting the study of $^{28}Si(^{16}O,^{12}C-\alpha)$, $^{27}Al(^{16}O,^{12}C-\alpha)$ and $^{27}Al(^{10}B,^{6}Li-\alpha)$ reactions. The experiments were performed using ^{16}O

(E_{Lab} = 64 MeV) and ^{10}B (E_{Lab} = 48 MeV) beams supplied by the University of São Paulo -Pelletron Accelerator. Self-supporting ^{27}Al (1mg.cm^{-2}) and ^{Nat}Si (750μg.cm^{-2}) targets were used. Carbon and Lithium particles were identified with a 2.3 msr solid angle telescope consisting of a 15μm E and a 1mm E solid state detectors fixed at +30° and +20°, for C and Li, respectively. Alpha particles were detected, in the reaction plane, at angles varying from -120° to +60°, using three (ΔE-E) telescopes (ΔE=20μm, E=2mm), each of them subtending a 5 msr solid angle. At forward angle measurements the elastically scattered particles were suppressed by using thin Ta absorbers located in front of light particle detectors.

Experimental angular correlation functions are shown in Figure 1. These functions have well defined maxima at negative angles, nearby the beam direction, and are asymmetric. This asymmetry could, in principle, be attributed to contributions from different processes. In order to characterize these contributions we have performed kinematical and model analysis for the following three body final contributions:

i) Projectile Sequential Decay (PSD)

$$^{16}O+^{28}Si \rightarrow {}^{16}O^*+^{28}Si \rightarrow {}^{12}C+\alpha+^{28}Si$$
$$^{16}O+^{27}Al \rightarrow {}^{16}O^*+^{27}Al \rightarrow {}^{12}C+\alpha+^{27}Al$$
$$^{10}B+^{27}Al \rightarrow {}^{10}B^*+^{27}Al \rightarrow {}^{6}Li+\alpha+^{27}Al$$

ii) Transfer-Reemission (TR)

$$^{16}O+^{28}Si \rightarrow {}^{12}C+^{32}S^* \rightarrow {}^{12}C+\alpha+^{28}Si$$
$$^{16}O+^{27}Al \rightarrow {}^{12}C+^{31}P^* \rightarrow {}^{12}C+\alpha+^{27}Al$$
$$^{10}B+^{27}Al \rightarrow {}^{6}Li+^{31}P^* \rightarrow {}^{6}Li+\alpha+^{27}Al$$

iii) Massive Transfer-Reemission (MTR)

$$^{16}O+^{28}Si \rightarrow \alpha+^{40}Ca^* \rightarrow \alpha+^{12}C+^{28}Si$$
$$^{16}O+^{27}Al \rightarrow \alpha+^{39}K^* \rightarrow \alpha+^{12}C+^{27}Al$$
$$^{10}B+^{27}Al \rightarrow \alpha+^{33}S^* \rightarrow \alpha+^{6}Li+^{27}Al$$

Contributions due to MTR processes were found to be negligible, as compared with PSD and TR ones. This result can be easily understood in terms of reduction of exit channel Coulomb barrier penetrabilities, very low Q-values involved and expected inhibition of the correlation function for the angular configuration of the particle detectors[9].

Relative kinetic energies in the rest frame of the recoiling proposed intermediate nuclei, with all final components in the ground state, were extracted from measured α and ^{12}C(^{6}Li) energies, and are shown in Figure 2 as a function of α-particle detection angles, θ_α^{Lab}. These energies appear to be constant at backward negative angles when α-^{28}Si (α-^{27}Al) configurations are assumed. This behaviour indicates that a sequential process, like TR, via an intermediate nucleus $^{32}S^*$ ($^{31}P^*$) is dominant for

$\theta_\alpha^{Lab} \lessgtr -20°$. On the other hand, since relative energies tend to a constant value in the remaining angular range when α-^{12}C (α-^{6}Li) configurations are considered, the PSD mechanism via $^{16}O^*$ ($^{10}B^*$) is established.

These conclusions are supported by the fact that E_{rel} vs θ_α^{Lab} kinematical trajectories predicted for TR (PSD), in the angular range where they have been experimentally found to be constant, are well reproduced by straight lines if PSD (TR) is supposed to occur in that angular range (dot-dashed line in fig.2). Moreover excitation energies for $^{32}S^*$ ($^{31}P^*$), obtained from extracted constant values of the relative energies in the angular range where TR dominates, agree with expected values for a direct α-transfer with an optimum Q-value (Table 1). This result indicates that a direct transfer followed by the emission of an α-particle instead of a projectile break-up followed by the fusion with the target nucleus of an α-particle, having beam velocity most likely occurs as a first stage of the reactions.

The above mentioned findings, concerning the nature of the sequential process, can be confirmed by model estimatives of angular correlation functions. Let us first start with the TR channel. The first stage of TR is described by direct transfer reactions $^{28}Si(^{16}O,^{12}C)^{32}S^*$, $^{27}Al(^{16}O,^{12}C)^{31}P^*$ and $^{27}Al(^{10}B,^{6}Li)^{31}P^*$. The excitation energies and recoil angles of intermediate $^{32}S^*$ or $^{31}P^*$ nuclei are determined by ^{12}C or ^{6}Li kinetic energies at

$\theta_C^{Lab}=+30°$ or $\theta_{Li}^{Lab}=+20°$. The double differential cross section $d^2\sigma/d\Omega_{C(Li)}d\Omega_{C(Li)}$ will weight the cross sections associated with a first stage. A second stage is described by the statistical emission of an α-particle from equilibrated $^{32}S^*$ or $^{31}P^*$, intermediate nuclei. The corresponding α-particle angular distributions as a function of $^{32}S^*$ ($^{31}P^*$) center of mass angle and excitation energy, are obtained from standard Hauser-Feshbach calculations[10]. The resulting TR angular correlation is given by[9]:

$$\frac{d^2\sigma}{d\Omega_{HF}d\Omega_\alpha}(\theta_\alpha^{Lab}) = \sum_{Q_{HF}} P(Q_{HF},\ _{HF})\left(\frac{d\sigma}{d\Omega}\right)_\alpha(Q_{HF},\theta_{HF},\theta_\alpha^{Lab}) \qquad (1)$$

where $P(Q_{HF},\theta_{HF}) = (d^2\sigma/d\Omega_{HF}\ dQ_{HF})/(d\sigma/d\Omega_{HF})$ denotes the probability for excitation of the intermediate nucleus $^{32}S^*$($^{31}P^*$) and the index HF refers to the Heavy Fragments, i.e. C or Li nuclei.

In the case of a PSD the observed ^{12}C (^{6}Li) nuclei are not produced by a primary process and therefore for each ^{12}C (^{6}Li) kinetic energy a set of scattering angles and excitation energies of $^{16}O^*$ ($^{10}B^*$), is allowed by kinematical conditions. For every θ_α^{Lab}, the double differential cross section $d^2\sigma/d\Omega_{C(Li)}d\Omega_\alpha$ is obtained from the sum of the product of two factors. The first, $d^2\sigma/d\Omega_{C(Li)}dE^*_{^{16}O^*(^{10}B^*)}$ supplies a set of n allowed excitation energies[9] and scattering angles of the intermediate $^{16}O^*$ ($^{10}B^*$) nucleus. The second is the differential cross section $d\sigma/d\Omega_{^{16}O^*(^{10}B^*)}$ for the projectile inelastic scattering which can be parametrized by a gaussian, in good agreement with coupled channel calculations[9]. The final PSD angular correlation is given by the expression[9]:

$$\frac{d^2\sigma}{d\Omega_{HF}d\Omega_\alpha}(\theta_\alpha^{Lab})=\sum_n \sum_{Q_{HF}} P(Q_{HF},\theta_{HF},n)\left(\frac{d\sigma}{d\Omega}\right)_{^{16}O^*(^{10}B^*)}\left(\theta_{^{16}O^*(^{10}B^*)}(Q_{HF},\theta_{HF},n,\theta_\alpha^{Lab})\right) \tag{2}$$

The experimental angular correlation functions were fitted by adding incoherently TR and PSD contributions, although the data may indicate the existence of interference effects. The best χ^2-fits are shown in Figure 1.

The results of the analysis can be summarized by:

i) the angular dependence of relative energies, points clearly out the existence of a sequential reaction mechanism;

ii) the fit of angular correlation functions, allows for the identification of two different processes, namely: Transfer-Reemission and Projectile Sequential Decay.

Concerning the influence of nuclear structure effects upon TR and PSD, we can conclude that while TR results show a target-dependence, PSD results display a projectile-dependence. It should also be noted that the results shown in figure 2 suggests that the present technique might be a convenient tool for studying cluster structure in light heavy-nuclei[9].

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REFERENCES

1. P.L. Gonthier, H. Ho, M.N. Namboodiri, J.B. Natowitz, L. Adler, S. Simon, K. Hagel, S. Kniffen and A. Khodai
   Nucl.Phys. A411, 289 (1983).

   H. Ho, P.L. Gonthier, G.Y. Fan, W. Küan, A. Pfoh, L. Schad, R. Wolski, J.P. Wurm, J.C. Adlogg, D. Disdier, A. Kamili, V. Rauch, G. Rudolf, F. Scheibling and A. Strazzeri
   Phys.Rev. C27, 584 (1983).

2. W.D.M. Rae, A.J. Cole, B.G. Harvey and R.G. Stokstad
   Phys.Rev. C30, 158 (1984).

3. R.K. Browmik, J. Van Driel, R.H. Siemssen, G.J. Balster, P.B. Goldhoorn, S. Gongrijp, Y. Iwasaki, R.V.F.Janssens, H. Sakai, K. Siwek-Wilczynska, W.A. Starrenburg and J. Wilczynski
   Nucl.Phys. A390, 117 (1982)

4. H. Morgenstern, W. Bohne, W. Galster and K. Grabisch
   Z. Phys. A324, 443 (1986)

5. J.W. Harris, T.M. Cormier, D.F. Geesaman, L.L. Lee Jr., R.L. McGrath and J.P. Wurm
   Phys.Rev.Lett. 38, 1460 (1977)

6. M.B. Tsang, W.G. Lynch, R.J. Puigh, R. Vandenbosch and A.G. Seamster
   Phys.Rev. C23, 1560 (1981)

7. S.J. Padalino and L.C. Dennis
   Phys.Rev. C31, 1794 (1985)

8. M. Sasagase, M. Sato, S. Hanashima, K. Furuno, Y. Nagashima, Y. Tagishi, S.M. Lee and T. Mikuno
   Phys.Rev. C27, 2630 (1983)

9. N. Carlin Filho et al.
   To be published

10. R.G. Stokstad
    Wright Nuclear Structure Laboratory
    Yale University, Internal Report n°. 52 (1972)

FIGURE CAPTIONS

Figure 1. In plane angular correlation functions for (^{12}C-α) and (^{6}Li-α) measured at $\theta_C=+30°$, $\theta_{Li}=+20°$. Fits based on TR and PSD mechanisms are shown by dashed and dash-dotted lines, respectively. Total contributions are indicated by solid lines.

Figure 2. Relative kinetic energies, E_{rel}, for the channels: a) (α-^{28}Si), b) c) (α-^{27}Al), closed circles and a) b) (α-^{12}C), c) (α-^{6}Li), open circles, as a function of the α particle detection angles, θ_α^{Lab} Angular intervals, kinematically allowed, corresponding to different projectile excited states $^{16}O^*$ ($^{10}B^*$) are denoted by dashed lines labeled with the excitation energies of these states. For the meaning of dot-dashed lines see the text.

TABLE CAPTION

Table 1. a) Effective bombarding energies taking into account the energy-loss in the targets.

Most probable excitation energy for the intermediate nucleus:

b) Obtained using the relative energies from figure 2 (E^*_{TR}).

c) Obtained on the basis of a $Q_{optimum}$-value for the α-transfer ($E^*_{optimum}$).

d) Expected for an incomplete fusion process of a beam velocity α-particle taking into account the binding energies.

TABLE 1

SYSTEM	$E_{Lab}(E^{eff}_{Lab})_{a)}$ (MeV)	E^*_{TR} $(MeV)_{b)}$	$Q_{optimum}$ (MeV)	$E^*_{optimum}$ $(MeV)_{c)}$	E^*_{IF} $(MeV)_{d)}$
$^{16}O + ^{28}Si$	64 (63)	12.5 ± 1.0	-10.7	10.5	19.2
$^{16}O + ^{27}Al$	64 (62)	15.0 ± 1.0	-10.5	13.0	21.6
$^{10}B + ^{27}Al$	48 (47.6)	21.7 ± 1.0	-15.7	20.9	24.9

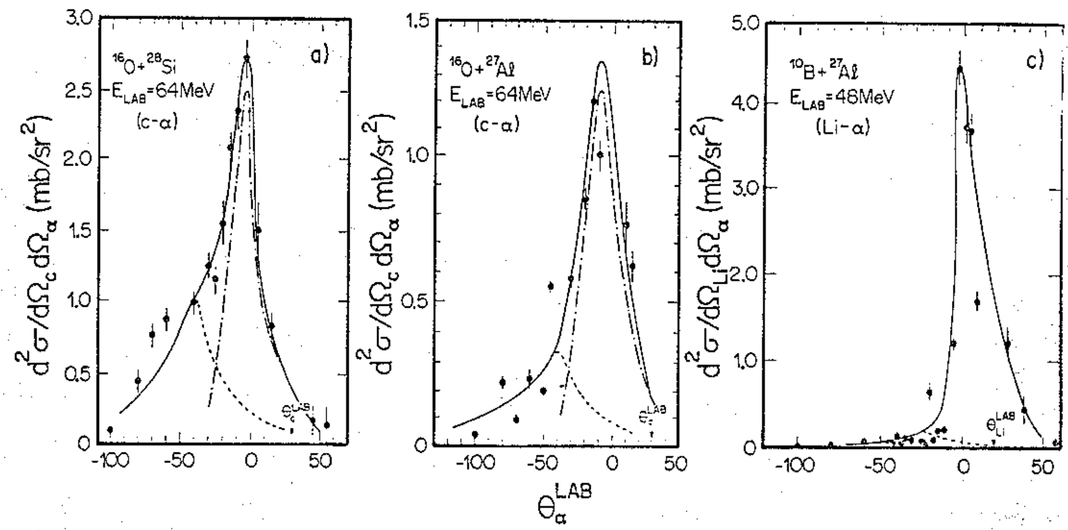

FIG. 1

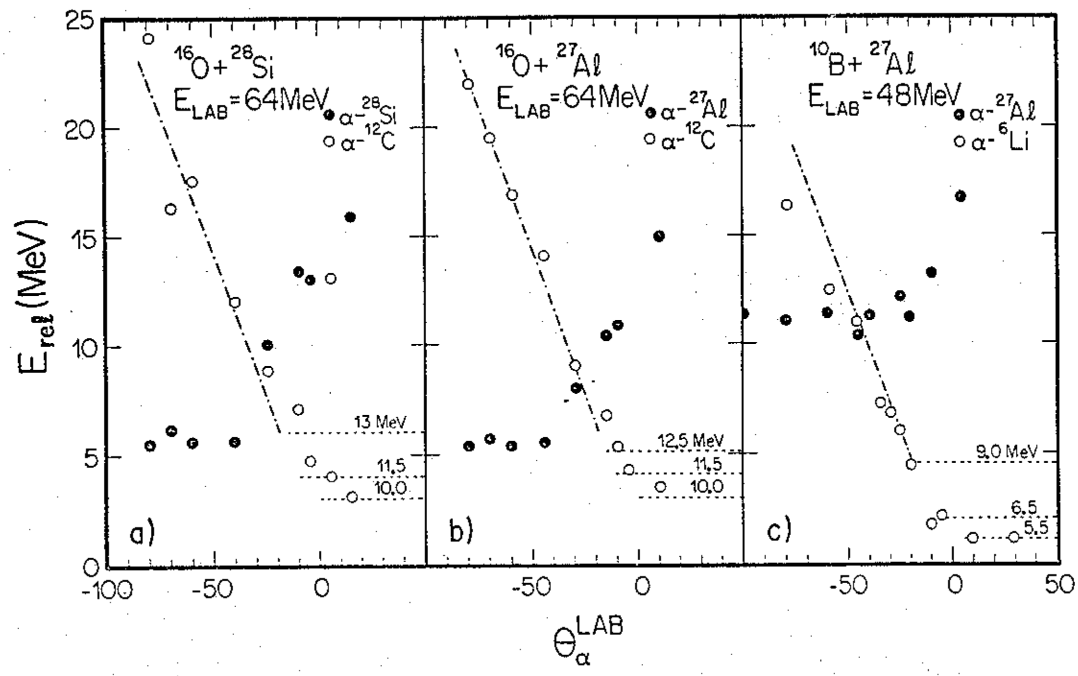
$^{16}O+^{28}Si$
$E_{LAB}=64MeV$
$\alpha-^{28}Si$
$\alpha-^{12}C$
13 MeV
11.5
10.0
a)
$^{16}O+^{27}Al$
$E_{LAB}=64MeV$
$\alpha-^{27}Al$
$\alpha-^{12}C$
12.5 MeV
11.5
10.0
b)
$^{10}B+^{27}Al$
$E_{LAB}=48MeV$
$\alpha-^{27}Al$
$\alpha-^{6}Li$
9.0 MeV
6.5
5.5
c)
E_{rel} (MeV)
Θ_{α}^{LAB}
0
5
10
15
20
25
-100
-50
0
50

FIG. 2