Incomplete fusion versus breakup competition with weakly bound projectiles

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The importance of the breakup channel in the vicinity of the Coulomb barrier (1 < Ecm/Vc < 2) is investigated for the medium weight 6Li + 59Co system. Three-body final-state analysis of light-particle coincident data was carried out to disentangle, for the first time, the breakup contributions from other competing mechanisms. α − d angular correlations show incomplete fusion components as significant as that from breakup process. Their strong coupling to total fusion is discussed within a comparison with predictions of continuum discretized coupled-channel calculations.

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The study of fusion reactions in the vicinity of the Coulomb barrier provides a fascinating challenge for theories of quantum tunneling leading to an irreversible complete fusion (CF) of the interacting nuclei into the compound nucleus (CN) 1. 2. The fusion probability is sensitive to the internal structure of the interacting ions as well as to influence of the other competing mechanisms such as nucleon transfer and/or breakup (BU) which are known to affect the fusion. The fusion cross section enhancement generally observed at sub-barrier energies is understood in terms of dynamical processes arising from couplings to collective inelastic excitations of the target and/or projectile. However, in the case of reactions where at least one of the colliding ions has a sufficient low binding energy so that BU becomes an important process, conflicting experimental 3 4 5 6 and theoretical results are reported 6 7 8 9.

A great experimental effort, involving both (loosely bound) stable and unstable nuclei, has been devoted to investigate the specific role of the BU channel 2 10 11. The weak binding of these systems can also lead to incomplete fusion (ICF)/transfer (TR) processes playing an important role. Several attempts to clearly identify ICF in 6Li and 9Be induced fusion with fissile targets 4 5 12 13 and medium-mass targets 14 15 have been made. CF requires the formation of CN containing all the nucleons of both projectile and target. If only part of the projectile fuses with the target, with remaining fragment emerging from the interaction region, then ICF is defined (in this case, the BU process is followed by fusion) 16. A transfer-reemission process may proceed to a final state similar to ICF 17.

The recent availability of light-mass radioactive ion beams such as 6He 18 19 20 21, 11Be 22, and 17F 23, and the renewed interest on reactions involved in astrophysical processes 24, motivated the investigation of fusion reactions involving very weakly bound and/or halo projectiles around and below the Coulomb barrier. Clearly a full understanding of the BU process and its effects on near-barrier fusion is fundamental in order to be able to understand the dynamics of reactions involving radioactive nuclei. This requires systematic and exclusive measurements covering a wide range of processes, systems and energies. We choose to study both the total fusion 25 and BU 26 of 6Li with the intermediate-mass target 59Co.

In this Letter we address the competition between the several reaction processes and CF. A three-body kinematics analysis, in which we separate the contribution of the BU and the ICF, is presented for the first time.

The experiments were performed at the University of São Paulo Physics Institute. The 6Li beam was delivered by the 8UD Pelletron accelerator with energies Elab = 18, 22, 26 and 30 MeV, and bombarded a 2.2 mg/cm2 thick 59Co target. The detection system consisted of a set of 11 triple telescopes 27 separated by 10°, for which light particles can be detected with a very low-energy threshold (0.2 MeV for d and 0.4 MeV for α particles). Inside this work we will concentrate on α − d coincidences, which are usually fully attributed to a “BU process” 28. Depending on the angular combination, we observe well defined peaks, in the total kinetic energy spectrum, corresponding to the sequential BU of 6Li in its first excited state with E* = 2.19 MeV. No other discrete excited states are observed. When analysing the α + d coincidence yields from the 6Li induced reaction, we have to consider the contributions of other processes than BU, leading to the same particles in the final state. The processes to be considered are:

i) 6Li + 59Co → 6Li* + 59Co → α + d + 59Co

ii) 6Li + 59Co → α + 61Ni* → α + d + 59Co

iii) 6Li + 59Co → d + 63Cu* → α + d + 59Co

iv) 6Li + 59Co → 65Zn* → α + d + 59Co

Process i) is identified as the sequential BU of 6Li. The
The final state can also be reached through a direct BU. Process ii) can be identified as incomplete fusion of $d + ^{59}$Co ($d$ ICF) with the subsequent reemission of a deuteron from the excited $^{61}$Ni. This process could also be considered as a $d$ transfer followed by a $d$ reemission from the $^{61}$Ni nucleus. The same observations are valid regarding process iii), for which either incomplete fusion of $\alpha + ^{59}$Co ($\alpha$ ICF) or $\alpha$ transfer could occur and an $\alpha$ particle is reemitted. Process iv) corresponds to the $\alpha-d$ sequential decay of the $^{63}$Zn CN. The contribution of CN decay is considered negligible, as confirmed by predictions from statistical model codes.

In order to investigate the competition of the above processes, we performed a complete three-body kinematics analysis. As we know the detection angle and energies of both the $d$ and the $\alpha$ particle, from the three-body kinematics equations we can determine the energy and emission angle of the remaining $^{59}$Co nucleus and from this, all the quantities of interest, such as $Q$-values and relative energies. By generating $Q$-value spectra, we observe from the data, for most of the events in the final state $\alpha + d + ^{59}$Co, the residual $^{59}$Co nucleus mostly in its ground state, in which the events were gated. Products from the sequential $^6$Li BU $\alpha + d$, are focused inside an angular cone. If we assume that process i) is occurring, the relative energy $E_{\alpha-d}$ between $\alpha + d$ and $d$ in the rest frame of $^6$Li can be calculated. By fixing for instance, the detection angle of the $\alpha + d$ particle and varying the $d$ detection angle, we can follow the behavior of the relative energy $E_{\alpha-d}$. In Fig. 1(a) is shown, for $E_{\text{lab}} = 29.6$ MeV (corrected for the energy loss to the center of the target), the relative energy $E_{\alpha-d}$ as a function of the deuteron detection angle $\theta_d$, for a fixed angle $\theta_\alpha = 45^\circ$ of the $\alpha$ particle. It is interesting to notice that, within the angular range where the sequential BU of $^6$Li in its first excited state is kinematically allowed (delimited by the two vertical dashed lines), the relative energy $E_{\alpha-d}$ is constant. The $E_{\alpha-d}$ value is consistent with the sequential BU of $^6$Li in its first excited state. Outside this region it is no longer constant, which suggests the presence of other processes. In addition to ICF or TR, a direct BU occurring close to target with strong nuclear field could also give values where the quantity $E_{\alpha-d}$ is not constant.

In Fig. 1(b) we show the behavior of the laboratory $\alpha$ particle kinetic energy $E_\alpha$ as a function of $\theta_d$ for a fixed angle $\theta_\alpha = 45^\circ$, and for $E_{\text{lab}} = 29.6$ MeV. Here, $E_\alpha$ is taken as the centroid of the experimental coincidence spectra. We observe that the average energy $E_\alpha$ is constant (independent of the momentum of the deuteron), except in the angular range where the sequential BU of $^6$Li is present. Considering now process ii), if this binary process is occurring with an intermediate stage, for a given angular combination $\theta_\alpha$ and $\theta_d$ the energy $E_\alpha$ is uniquely determined once the $^{61}$Ni excitation energy is defined. We can then conclude from Fig. 1(b) that if process ii) is dominant over the angular range where $E_\alpha$ is constant, the average $^{61}$Ni excitation energy is also constant, and in this case $E_{^{61}Ni} = 25$ MeV. This is a very important result as a clear indication of a CN-type reaction. This constant value is consistent with the assumption of an ICF $d + ^{59}$Co where the $d$ has the projectile velocity. As a consistency check, we also calculated the $d$ energy in the rest frame of the decaying $^{61}$Ni as a function of $\theta_d$. The angles with two experimental points correspond to two kinematical solutions for the sequential BU.

![FIG. 1: (a) Relative energy $E_{\alpha-d}$ as a function of the detection angle $\theta_d$. (b) Average $\alpha$ energy $E_\alpha$ as a function of the deuteron detection angle $\theta_d$. (c) $d$ energy in the rest frame of the decaying $^{61}$Ni as a function of $\theta_d$. The angles with two experimental points correspond to two kinematical solutions for the sequential BU.](image-url)
cited the rotating axis is normal to the reaction plane, then
the equatorial plane and decreases toward the poles. If
Due to the centrifugal force, the yield is concentrated in
\[ [29] \]. It consists of a classical model for emission from
reemission, a model can be utilized to describe the de-
follows is based on an ICF picture.

As mentioned above, a priori, events from TR and ICF
process are indistinguishable due to the fact that the in-
termediate nucleus, in both cases, is populated in the
process are indistinguishable due to the fact that the in-
geometrical determination of the detector solid angles.

In order to quantify the contribution from processes
\( i, ii \) and \( iii \), we constructed the \( \alpha - d \) angular corre-
lation functions through calculation of the double dif-
ferential cross sections \( d^2\sigma/(d\Omega _\alpha d\Omega _d) \). The absolute cross
sections, the product of the number of particles in the
target per unit area and number of particles in the beam
\( (N_\alpha N_B) \) for each run, was calculated and normalized to
the elastic scattering data we measured. The uncertain-
ties in the experimental points (about 10% to 40%) are
due to statistics, the determination of \( N_\alpha N_B \) and, the
geometrical determination of the detector solid angles.

As mentioned above, a priori, events from TR and ICF
process are indistinguishable due to the fact that the in-
termediate nucleus, in both cases, is populated in the
continuum, and a statistical description for these pro-
cesses seems adequate \[ 28 \]. The model we propose as
an ICF shape presented in Fig. 2(b)

\[ Y(\psi) = Y_0 \exp(X\sin^2\psi) \] (1)

where \( Y_0 \) is a normalization factor and \( X \) is the ratio of
rotational kinetic energy to the thermal nuclear energy:

\[ X = 0.5(J + \frac{1}{2})^2/2IT \] (2)

where \( J \) is the spin of the rotating nucleus, \( I = \mu R^2 \) is
the moment of inertia, and the temperature \( T \) can be
estimated from \( E^* = aT^2 \), with \( a \) being the level density
parameter.

The angle between the rotational axis and the \( z \) axis
which is normal to the reaction plane, is defined to be \( \gamma \).
The angle \( \gamma \) is assumed to be gaussian distributed. From
Eq. (1), the angular distribution is:

\[ W(\theta, \phi) = \int d\gamma \exp(-\gamma^2/2\gamma_0^2)Y(\psi) \] (3)

with \( \cos\psi = \cos\gamma\cos\phi + \sin\gamma\sin\phi\sin\theta \).

The angular distribution \( W(\theta, \phi) \) is the same as the
experimental quantity \( d^2\sigma/(d\Omega _\alpha d\Omega _d) \) in the rest frame of
the rotating nucleus. In the laboratory reference frame,
\( W(\theta, \phi) \) is centered at the recoil direction in the primary
process. It is important to remark that by using this
model, the angular correlation \( \phi \) dependence is also taken
into account. Therefore, the integration is performed in
a better way than assuming an isotropic \( \phi \) dependence.

For \( d \) and \( \alpha \) emission, the best values for \( Y_0, X \) and
\( \gamma_0 \) are obtained from \( \chi^2 \) fits to the angular distributions
provided by the statistical code STATIS \[ 17, 30 \]. For
the calculations, a fusion process \( d + {\text{^{59}Co}} \to {\text{^{61}Ni}}^\ast \) or
\( \alpha + {\text{^{59}Co}} \to {\text{^{63}Cu}}^\ast \) was assumed, with a bombarding
energy forming the excited CN in an excitation energy
corresponding to the most probable value observed ex-
perimentally.

In Fig. 2(a) we show the \( \alpha - d \) angular correlation for
a fixed \( \theta_\alpha = 45^\circ \) and \( E_{lab} = 29.6 \text{ MeV} \), together with the
model predictions for the \( d \) ICF and \( \alpha \) ICF. The shape of
the \( \alpha \) ICF correlation is obtained from the model pre-
dictions for the angular correlations with \( \theta_d \) fixed. In the
same manner, the \( d \) ICF shape presented in Fig. 2(b)
is obtained from the predictions for the angular correla-
tions with \( \theta_d \) fixed. The sequential and direct BU con-
tribution is also shown in Fig. 2. It is obtained through
the subtraction of the incoherent sum of the \( d \) and \( \alpha \)
ICF contributions, from what would be the best fit to
the data. The two peaks lying around \( 45^\circ \) correspond to
the sequential BU of the \( 2.19 \text{ MeV} \) unbound state of \(^6\text{Li}\).

By numerically integrating the angular correlation
function in \( \theta \) and \( \phi \), for each process, the differential cross
section \( d\sigma/d\Omega _\alpha \) \((d\sigma/d\Omega _d)\) is obtained for the fixed \( \theta_\alpha \)
\((\theta_d)\). The procedure is repeated for all the other angular
correlations with different fixed \( \theta_\alpha \) or \( \theta_d \).
The BU cross section is obtained with the utilization of the $d$ singles cross sections. We assume that the $d$ singles spectra present predominantly the contribution of BU, $d$ ICF and $\alpha$ ICF. The total BU cross section for a given bombarding energy is then obtained by the difference between the total $d$ singles cross section and the total $d$ ICF + $\alpha$ ICF cross sections.

The exclusive BU cross sections for the resonant states in $^6$Li have been calculated by the CDCC formalism using a cluster folding model with potentials that describe well the measured elastic scattering angular distributions. The CDCC calculations for $^6$Li were performed with the code FRESCO assuming an $\alpha + d$ cluster structure, similar to that described in [22]. The binding potentials between $\alpha + d$ were taken from [22] and the $\alpha + d$ continuum was discretized into series of momentum bins of width $\delta k = 0.2 \text{ fm}^{-1}$ (up to $k = 0.8 \text{ fm}^{-1}$) for $L = 0,1,2$ for $^6$Li, where $\hbar k$ denotes the momentum of the $\alpha + d$ relative motion. All couplings, including continuum-continuum couplings, up to multipolarity $\lambda = 2$ were incorporated [22]. The total calculated BU cross-sections for $^6$Li were obtained by integrating contributions from states in the continuum up to 11 MeV. The results of full CDCC calculations are displayed in Fig. 3. The solid line corresponds to the final results of the BU CDCC calculations, and the symbols represent the experimental excitation functions obtained for the $d$ singles, and for the $d$ ICF, $\alpha$ ICF and the BU processes. The $d$ ICF and $\alpha$ ICF cross sections are comparable to the BU cross sections for all the bombarding energies.

In summary, we have presented a three-body kinematics analysis of coincidence measurements with the aim of disentangling the contribution of BU and competing processes in reactions with weakly bound nuclei. From the analysis of $\alpha - d$ coincidences of $^6$Li + $^{59}$Co at several near-barrier energies, we observed a significant contribution from the ICF process, with a cross section comparable to the one from BU process. This suggests that ICF should be accounted for in the coupled channels calculations to explain the fusion of weakly bound nuclei inhibition and/or enhancement at near-barrier energies.

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