Partial fusion of a weakly bound projectile with heavy target at energies above the Coulomb barrier

Z.H. Liu¹,a, C. Signorini², M. Mazzocco², M. Ruan¹, H.Q. Zhang¹, T. Glodariu²,b, Y.W. Wu¹, F. Soramel³, C.J. Lin¹, and F. Yang¹

¹ China Institute of Atomic Energy, P.O. Box 275(10), Beijing 102413, PRC
² Physics Department of the University and INFN, Via Marzolo 8, 35131, Padova, Italy
³ Physics Department of the University and INFN, Udine, Via delle Scienze 208, 33100, Udine, Italy

Received: 21 July 2004 / Revised version: 20 June 2005 / Published online: 28 October 2005 © Società Italiana di Fisica / Springer-Verlag 2005

Abstract. Partial-fusion cross-sections for the systems ⁶Li + ²⁰⁸Pb, ⁹Be + ²⁰⁹Bi have been determined. The effect of breakup on fusion for weakly bound projectiles ⁶Li and ⁹Be incident on ²⁰⁸Pb or ²⁰⁹Bi targets has been discussed comparing experimental fusion cross-section excitation functions to those evaluated with a semi-classical approach. It is shown that complete fusion of a weakly bound projectile with heavy target is reduced, whereas the breakup process has very little influence on the total-fusion cross-section for some of the studied systems at energies above the Coulomb barrier.

PACS. 25.70.Ji Fusion and fusion-fission reactions – 25.70.Mn Projectile and target fragmentation

1 Introduction

The availability of Radioactive Ion Beams (RIBs) has opened many new perspectives to nuclear physics studies. One example is the behavior of light-mass RIBs (either weakly bound or with a halo structure) in the fusion process. In fact, during the interaction with a heavy stable target these nuclei drive the process towards different paths: The two nuclei undergo a complete-fusion (CF) process, alternatively the radioactive nucleus breaks in lighter nuclei (breakup) and one of the fragments is captured by the target nucleus resulting in an incomplete- or partial-fusion (ICF) process. Several theoretical [1–6] and experimental [7–17] works have been published on this subject. From the theoretical point of view two different conflicting scenarios have been foreseen; one [5] predicts a fusion enhancement with respect to reactions involving stable nuclei, the other [1–4] predicts a fusion cross-section suppression due to the reaction flux lost in the breakup channel. Recently, Hagino et al. [6] performed an improved coupled-channels calculation with the aim of reconciling the two conflicting scenarios; they predicted a complete-fusion cross-section enhancement at energies below the Coulomb barrier and a suppression at energies above the Coulomb barrier. These different theoretical predictions call for precise and reliable measurements as a watershed among various theories. To this goal, many experiments have been performed with halo (⁶He, ¹¹Be) [7–11] and weakly bound (⁶Li, ⁹Be, ¹⁷F) [12–17] projectiles. The experimental results obtained with ⁶Li and ⁹Be projectiles have been compared to different theoretical predictions and, in any case, despite the reference model, a sizable reduction of the complete-fusion cross-section has been observed. The aim of this paper is to analyze the data for ⁶Li and ⁹Be pointing out the relation between partial and complete fusion at energies above the Coulomb barrier.

2 Incomplete-fusion data

Our first step has been to examine the four systems ⁶Li, ⁹Be + ²⁰⁸Pb, ²⁰⁹Bi to get information on the ICF cross-section. For the systems ⁶Li + ²⁰⁹Bi [13] and ⁹Be + ²⁰⁸Pb [14] we had already an ICF cross-section measurement, while for the systems ⁶Li + ²⁰⁸Pb and ⁹Be + ²⁰⁹Bi the ICF cross-sections were deduced from a new analysis of data collected during previous experiments. In the following we define the total-fusion cross-section (σfuₚ) as the sum of complete-fusion cross-section (σCF) and incomplete-fusion cross-section (σICF), i.e., σfuₚ = σCF + σICF.
These cross-section data are given in table 2 and plotted.

In this experiment [15] the charged particles were detected using Si-ΔE and CsI(Tl)-E_{res} arranged all around the target in a spherical geometry. The collected data allowed to extract the differential and total cross-sections for α, d, and p (σ_{α}, σ_{d}, σ_{p}) production at four beam energies, as well as the cross-section for α-d and α-p coincidences (σ_{α-d}, σ_{α-p}). Combining the cross-sections and assuming that

- the α-particle never breaks since it has a large binding energy,
- the evaporation cross-sections for d and α from the compound nucleus are, as predicted from the PACE4 code, negligible if compared to the measured cross-sections,
- the α, d and p transfer cross-sections are negligible, too, (FRESCO code),

we could extract α and d capture cross-sections:

\[
\sigma_{d}^{\text{capture}} = \sigma_{a} - \sigma_{α-d} - \sigma_{α-p}, \quad (1)
\]
\[
\sigma_{α}^{\text{capture}} = \sigma_{d} - \sigma_{α-d} - \sigma_{α-p}. \quad (2)
\]

The sum of the two capture cross-sections gives the ICF cross-sections of table 1 and fig. 1a.

### 2.1 The \( ^6\text{Li} + ^{208}\text{Pb} \) system

In this experiment, described in more detail in [18], the light charged particles were detected in the SπLP setup of LNL [19] using 126 two-stage telescopes, Si-ΔE and CsI(Tl)-E_{res} arranged all around the target in a spherical geometry. The collected data allowed to extract the differential and total cross-sections for α, d, and p (σ_{α}, σ_{d}, σ_{p}) production at four beam energies, as well as the cross-section for α-d and α-p coincidences (σ_{α-d}, σ_{α-p}). Combining the cross-sections and assuming that

- the α-particle never breaks since it has a large binding energy,
- the evaporation cross-sections for d and α from the compound nucleus are, as predicted from the PACE4 code, negligible if compared to the measured cross-sections,
- the α, d and p transfer cross-sections are negligible, too, (FRESCO code),

we could extract α and d capture cross-sections:

\[
\sigma_{d}^{\text{capture}} = \sigma_{α} - \sigma_{α-d} - \sigma_{α-p}, \quad (1)
\]
\[
\sigma_{α}^{\text{capture}} = \sigma_{d} - \sigma_{α-d} - \sigma_{α-p}. \quad (2)
\]

The sum of the two capture cross-sections gives the ICF cross-sections of table 1 and fig. 1a.

### 2.2 The \( ^9\text{Be} + ^{208}\text{Pb} \) system

In this experiment [15] the charged particles were detected using E(Si) detectors placed at backward angles. The α-particles emitted in the largest of the various evaporation residues produced in the reaction were identified through their characteristic decay energies. The only ICF channel we could clearly identify is the one that, following the fusion of \(^4\text{He} + ^{208}\text{Pb}\) (\(^9\text{Be} + ^{208}\text{Pb}\)) with the \(^{212}\text{At}\) target, populated the \(^{111}\text{At}\) residual nucleus after \(1n(2n)\) evaporation following \(^4\text{He} + ^{208}\text{Pb}\) incomplete fusion. These cross-sections data are given in table 2 and plotted in fig. 1b together with σ_{ICF} data. We underline that these data, far from exhausting the σ_{ICF} of the \(^9\text{Be} + ^{208}\text{Pb}\) system, most likely do represent the largest contribution to σ_{ICF}, as already found for the system \(^9\text{Be} + ^{209}\text{Bi}\) [14]. We can conclude that for \(^9\text{Be} + ^{209}\text{Bi}\) the σ_{ICF} data we have deduced are 30-40% lower than the real σ_{ICF}. The \(^6\text{Li} + ^{208}\text{Pb}\) ICF cross-section is large, while for the \(^9\text{Be} + ^{209}\text{Bi}\) system it is smaller but not negligible.

### 3 Fusion data and analysis

It is well known that fusion near and below the Coulomb barrier is strongly affected [20] by the intrinsic degrees of freedom of the interacting nuclei, whose coupling with the relative motion causes an energy splitting of the single uncoupled fusion barrier. This gives rise to a distribution of barrier heights [21], that manifests itself as an enhancement of the fusion cross-sections at energies near and below the Coulomb barrier. Above the Coulomb barrier this effect becomes less important and, at energies well above the Coulomb barrier, it can be neglected. Fusion cross-section of tightly bound nuclei can be satisfactorily described with the semi-classical approach formula

\[
\sigma_{fus}(E_{c.m.}) = \pi R_B^2 \left[1 - \frac{V_B}{E_{c.m.}}\right], \quad (3)
\]