Identification of different reaction channels in ^{6}Li + ^{89}Y experiment by the particles-γ coincidence measurement

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Abstract. This short paper presents the investigation of reaction mechanism induced by ^{6}Li through a particle-γ coincidence measurement. The data have been taken from a ^{6}Li+^{89}Y experiment which is performed in INFN-LNL, Italy. In this experiment, the light charged particles are detected by a Si-ball, named EUCLIDES, and the γ rays are collected by a HPGe detector array, called GALILEO. In this contribution, scientific motivations, experimental details and some results, such as α-γ analysis, are presented.

1 Introduction

Study of fusion reaction induced by weakly bound nuclei has been one of hot research topics for nuclear physics in the past several decades [1, 2]. Compared with unstable nuclei, the stable ones, such as ^{6}Li, ^{7}Li, and ^{9}Be, have more advantages, such as higher beam intensity, smaller beam spot and so on. Therefore, plenty of works have been devoted into the reaction mechanisms induced by stable weakly bound nuclei [3, 4].

Due to the cluster structure and low breakup threshold in stable weakly bound nuclei, the total fusion (TF) processes include the contributions from complete fusion (CF) and incomplete fusion (ICF), corresponding to the ones without and following the breakup of projectile, respectively. The $\frac{ICF}{TF}$ or $\frac{1-CF}{TF}$ is called CF suppression factor. Such factor is proved to be mainly governed by the breakup thresholds of the weakly bound projectiles, and is independnent with atomic numbers of the target nuclei [5, 6]. For example, Wang et al. [7] pointed out that the CF cross sections induced by ^{6}Li on many heavy targets, have an average suppression factor around 40% at energies slightly above the Coulomb barrier. However, in a recent measurement of ^{6}Li + ^{64}Ni system, the CF suppression factor was determined as $(13\pm7)\%$ experimentally [8]. Therefore, more investigations on fusion pro-

cesses induced by ^{6}Li should be performed, especially on the light target.

Usually, the residues survived from fusion-evaporation process can be identified and collected by measuring their characteristic γ rays. However, the residues produced from different CF and ICF processes may overlap with each other, if the total atomic number of the whole reaction system (both projectile and target) is around or less than 40. The reason is ascribed to the fact that the evaporation of charged particles is allowed when the Coulomb barrier of the fusion system becomes relatively low. Under such condition, it is impossible to clearly separate CF and ICF by simply measuring the γ rays. Furthermore, direct reation channel, such as transfer reaction, may be dominant at energies near the Coulomb barrier, which has been observed in many cases, such as ^{8}He + ^{197}Au [9] and ^{6}Li + ^{96}Zr [10].

In our previous studies, fusion processes have been investigated in ^{6}Li + ^{96}Zr [11] and ^{6}Li + ^{154}Sm [12] systems through in-beam γ-ray method at HI-13 Tandem Accelerator of China Institute of Atomic Energy (CIAE), Beijing, China. A smaller CF suppression factor around 25% was found for ^{6}Li + ^{96}Zr system, and an average suppression about 35% is found for ^{6}Li + ^{154}Sm system. Such results indicate that the systematic behaviors of the CF suppression factors for fusion processes induced by ^{6}Li are different in various situations. On the other hand, only γ rays

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were measured in these experiments, thus the CF and ICF cross sections may be ambiguous to some extent for the ^{6}Li + ^{96}Zr system in which the evaporation of charged particles becomes possible. Therefore, the conclusion needs to be further investigated both theoretically and experimentally.

The first exclusive measurement, in which both γ rays and light charged particles (proton, deuteron, triton and α) are collected, has been applied in ^{7}Li + ^{198}Pt system [13] at energies near the Coulomb barrier. Through particle-γ coincidence measurement, different breakup fusion processes are identified qualitatively, such as α-capture, triton-capture, ^{5}He-capture and ^{6}He-capture processes. The absolute cross sections of different breakup fusion processes and neutron stripping reactions are measured by the collection of the γ rays in different residues. However, such method may also encounter some limitations in the identification of reaction mechanism. Taking the yields of ^{199}Au as an example: in the α-gated γ-ray spectrum (see Fig. 2(a) in Ref. [13]), the main γ rays arise from ^{198,199}Au, which are assigned as the residues from triton-capture ICF process. However, one proton stripping reaction can also generate the target-like fragment ^{199}Au, as well as projectile-like fragment ^{6}He, which disassociates into α + 2n if the ^{6}He is excited to the continuum states through the one-proton-stripping reaction. Furthermore, the theoretical prediction of ^{199}Au cross section in which only triton-capture ICF is considered, would underestimate the experimental results, as shown in Fig. 4(a) [13]. As a conclusion, the existence of one-proton-stripping reaction cannot be excluded, and simple particle-γ coincidence measurement cannot separate it from other ICF processes.

According to the above analysis, particle-γ coincidence measurement is powerful in the separation of different ICF processes, but still has many limitations. It is deserved to develop a new particle-γ coincidence measurement in order to distinguish all the reaction mechanisms, including CF, ICF and nucleon (proton or neutron) transfer processes.

2 Experimental details

A ^{6}Li + ^{89}Y experiment was performed at the Laboratori Nazionali di Legnaro, INFN, Italy. A ^{6}Li^{3+} beam with an average intensity of 1.0 enA was accelerated to 34 MeV by the XTU Tandem-ALPI accelerator. The ^{89}Y target with a thickness of 550 μg/cm^2, was backed on a 340 μg/cm^2-thick ^{12}C foil in order to stop all the reaction products. The GALILEO array, which consists of 25 Compton-Suppressed Ge detectors, was employed for the collection of γ-ray. A 4π Si-ball detector array, named EUCLIDES, was used to measure the light charged particles. The EUCLIDES array was made up of 40 ΔE-E telescopes, where the thickness of ΔE and E detectors were 130 and 1000 μm, respectively. A typical particle identification plot measured by EUCLIDES was shown in Fig. 2 from Ref. [14]. The detailed information on the GALILEO and EUCLIDES arrays can be found in Refs. [12,13].

The schematic view of the current experimental setup can be found in Fig. 1 from Ref. [14]. Since the Si detectors are sensitive to radiation damage, a 200-μm-thick Al absorber was inserted between the target and EUCLIDES array to stop the elastically scattered ^{6}Li. The absorber shielded all the Si detectors excepted for those located at the angles more than 148°.

## 3 Results and discussions
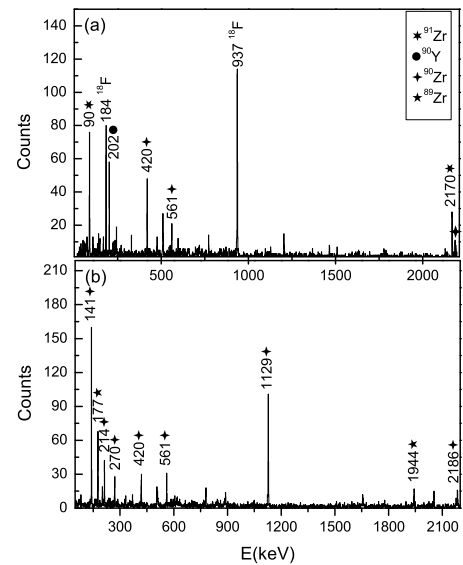
Figure 1. Gamma-ray energy spectra measured in coincidence with α detected by the shielded (a) and unshielded (b) Si detectors. Taken from Ref. [16].

The γ-ray energy spectra measured in coincidence with α which are detected in the shielded and unshielded (by Al absorber) Si-detectors are shown in Figs. 1 (a) and (b), respectively. Figure. 1 (a) shows the characteristic γ rays from ^{90}Y, ^{90}Zr and ^{91}Zr, corresponding to the products produced from one neutron, proton and deuteron stripping reactions, respectively. On the other hand, the characteristic γ rays from ^{89}Zr and ^{90}Zr, which can be ascribed evaporation residues from the deuteron-capture ICF process, are observed in Fig. 1(b).

It is noted that the γ rays in ^{90}Zr have observed simultaneously in Figs. 1(a) and (b). However, the reaction mechanisms of the productions of ^{90}Zr in Figs. 1(a) and (b) are totally different. In Fig. 1(a), the γ rays at 561 and 420 keV are the transitions which deexited the 3$^-$ (2747 keV) and 4$^-$ (2739 keV) states in ^{90}Zr, which is consistent with result of the (p, d) reaction in Ref. [15]. Meanwhile, the γ rays of ^{90}Zr which are shown in Fig. 1(b), are related to the transitions de-exiting the high-lying states, such as 141-, 270-, and 214-keV γ rays, being a typical feature of fusion-evaporation residues.

In addition, the energy distribution of α measured by the shielded Si-detectors is plotted in Fig. 2(a). The γ-ray spectra gated by α particles with different energies are shown in Figs. 2(b) and (c). As a result, the γ-ray spectrum
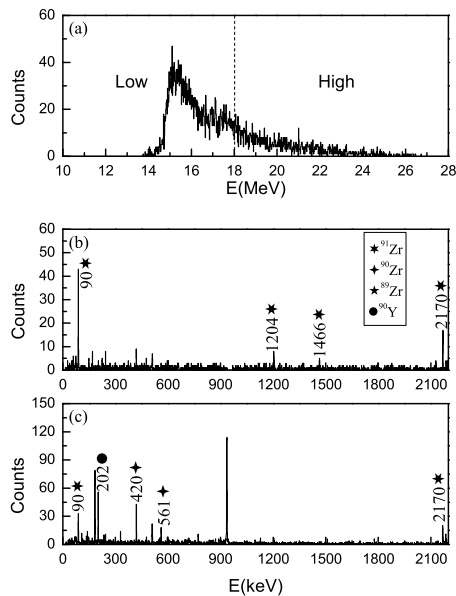
Figure 2. (a): Alpha energy spectrum measured by the shielded Si-detectors. (b) and (c): Gamma-ray energy spectra gated by α with energies higher and lower than 18 MeV, respectively. It is noted here the energies of α are the remaining ones after penetrating the absorber. Taken from Ref. [16].

this experiment, such as α-γ analysis which is discussed in this article. More information on the reaction mechanisms is expected to be obtained from other particle-γ analysis, including proton-γ, deuteron-γ and triton-γ coincidence analyses.

Acknowledgments

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with a gate on higher energy α only shows the characteristic γ rays in ^{91}Zr, being consistent with the fact that the Q value of 1d- (deuteron) stripping reaction is higher than that of 1n- (neutron) and 1p- (proton) stripping reactions. The detailed analysis of α-γ coincidence measurement can be found in earlier publication [16].

The other particle-γ analyses are still undergoing, such as proton-γ, deuteron-γ and triton-γ coincidence analyses. The detailed results will be published elsewhere soon.

4 Summary

A ^{6}Li+^{89}Y experiment has been performed at the INFN-LNL in Italy. The light charged particles and γ rays are collected by EUCLIDES and GALILEO array, respectively. The particle-γ coincidence measurement is powerful in the identification of various reaction mechanisms in