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Selection of different reaction channels in ^{6}Li induced fusion reaction by a powerful combination of a charged particle array and a high-resolution gamma spectrometer

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Abstract. Investigation of the breakup and transfer effect of weakly bound nuclei on the fusion process has been an interesting research topic in the past several years. In comparison with radioactive ion beam (RIB), the beam intensities of stable weakly bound nuclei such as ^{6,7}Li and ^{9}Be, which have significant breakup probability, are orders of magnitude higher. Precise fusion measurements induced by these nuclei have already been performed. However, the conclusion of reaction dynamics was not clear and has contradiction. In order to have a proper understanding of the influence of breakup and transfer of weakly bound projectiles on the fusion process, the ^{6}Li+^{89}Y experiment with incident energies of 22 MeV and 34 MeV was performed on Galileo array in combination with Si-ball EUCLIDES at Legnaro National Laboratory (LNL) in Italy. Using the coincidence by the charged particles and γ-rays, the different reaction channels can be clearly identified.

1 Introduction

Investigation of the breakup effect of weakly bound nuclei on the fusion process has been an interesting research topic in the past several years [1–3]. Several experiments and theoretical calculations have focused on this subject. The fusion reactions induced by these nuclei are more complicated with respect to tightly bound nuclei. Different processes can occur after the breakup of weakly bound nuclei (usually the projectiles). The whole projectile can also fuse with the target nucleus without breakup, and this process is named as direct complete fusion (DCF). When all the fragments fuse with target nucleus one by one, this process is called sequential complete fusion (SCF). Experimentally, the residues formed in SCF cannot be distinguished from ones from DCF due to the same compound nucleus. Therefore, in the experiment the complete fusion (CF) cross sections include the contributions of both SCF and DCF. When only part of the fragments fuses with the target nucleus, this process is called incomplete fusion (ICF). When any fragments are not captured, this process is called non-capture breakup (NCBU). The total fusion (TF) cross section is equal to the sum of CF and ICF, $\sigma_T = \sigma_{CF} + \sigma_{ICF}$. Besides the above processes, transfer process can also occur such as one neutron stripping and pickup. In ICF and transfer processes, the same residual nuclei can be formed. However, in these two processes the light charged particles with different energies can be emitted. In coincidence with the light charged particles, these two processes can be separated.

In comparison with radioactive ion beam (RIB), the beam intensities of stable weakly bound nuclei such as ^{6,7}Li and ^{9}Be, which have significant breakup probability, are orders of magnitude higher. Precise fusion measurements have already been performed, and the effect of breakup of those nuclei on the fusion process has been extensively studied. Experimental fusion cross sections induced by RIB on different target nuclei have been reported. In ^{8}He+^{197}Au experiment [4], by measuring γ rays which are emitted from the evaporated residual nuclei, fusion and transfer cross sections were obtained. In comparison with the cross sections of these two processes, it is indicated that the sub-barrier total reaction cross section is dominated by one and two neutron stripping. In the case of reactions with neutron-rich radioactive ion beams, the coupling to transfer is found to be important. Recently for the first time in ^{7}Li+^{198}Pt reaction [5] at energies near the Coulomb barrier, the α-capture cross sections were measured by in-beam exclusive measurements of prompt γ-rays from the heavy-residues with various light charged particles (α, t, d and p). The cross sections of the residues

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resulting from the processes of fusion, *t*-capture and neutron transfer channels were measured by off-beam γ methods. The integrated cross sections for the above several channels were obtained. The different processes were distinguished including breakup fusion and the nucleon transfer. The result of a classical dynamic model [6–8] gave a good agreement with the experimental data and explained the critical role of different cluster structures of ^{7}Li in the dynamics of reaction mechanism for the first time. The present results are useful for the theoretical developments. It is important to carry out a systematic investigation on various targets especially for unstable weakly bound nuclei.

2 Experiments and results

The ^{6}Li+^{89}Y experiment was performed at the Tandem-XTU accelerator of LNL-INFN, Italy. A ^{6}Li^{3+} beam with E_{lab}=34 MeV and 22 MeV and an average beam intensity of 1.0 enA impinged on a ^{89}Y target of 550 μg/cm^2 backed with a 340 μg/cm^2 ^{12}C foil. The schematic of the experimental setup is shown in Fig. 1. The GALILEO array is composed of 25 Compton-Suppressed HPGe detectors, with 5 detectors placed at 152° , 5 at 129°, 5 at 119° and ten detectors at 90° with respect to the beam direction [9]. In Fig.1 the EUCLIDES is one of the key ancillary detectors of the GALILEO spectrometer [10–12] to detect the light-charged particles. It consists of 40 ΔE/E Si telescopes of different shapes with an angular coverage close to 4π. A single silicon telescope is usually assembled using a thin ΔE (130 μm) detector and a thick E (1 mm) detector. The most forward telescopes in the array are segmented into 4 sectors to sustain a higher counting rate. Each telescope is placed at distances around 6.5 cm from the target position. The solid angle of each telescope is about 0.2 sterad and the angular coverage is ≈11°.

An ^{89}Y target was mounted on the target holder and was put at the center of target chamber. An aluminum cylindrical absorber was inserted inside EUCLIDES and along the beam direction to protect the silicon detectors from the ions elastically scattered. Thickness of the absorber can be adjusted according with the beam-energy conditions and the reaction kinematics. In the commissioning experiment a ^{6}Li beam of 34 MeV and 22 MeV was sent on a ^{89}Y target. In that situation the thickness of the cylinder was 200 μm and the backward angles larger than 150° were unshielded by the absorber, see the Fig. 1 for further details of the setup.

3 Selection of reaction channels

For ^{6}Li+^{89}Y, many reaction channels can produce ^{90}Zr such as,

$$\begin{aligned}&\text{CF Process, } {}^6\text{Li} + {}^{89}\text{Y} \rightarrow {}^{95}\text{Mo} \rightarrow {}^{90}\text{Zr} + \alpha + \text{n}\\ &\text{ICF Process, } {}^2\text{H} + {}^{89}\text{Y} \rightarrow {}^{91}\text{Zr} \rightarrow {}^{90}\text{Zr} + \alpha + \text{n} \qquad (1)\\ &\text{Transfer Process, } {}^6\text{Li} + {}^{89}\text{Y} \rightarrow {}^{90}\text{Zr} + \alpha + \text{n}\end{aligned}$$

Since α particles can be from CF, ICF and transfer processes, even if one uses $\alpha - \gamma$ coincident method, it is impossible to distinguish these three reaction channels.

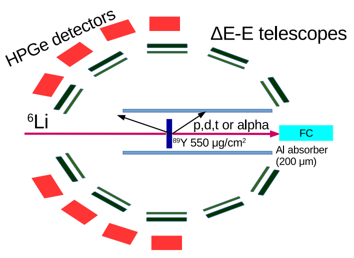

Figure 1. (color online). The schematic of the experimental setup (sectional view). HPGe detectors and ΔE-E telescopes present the schematic of a part of GALILEO and EUCLIDES arrays, respectively

So the reaction channels in fusion reactions induced by weakly bound nuclei cannot be separated by only using single γ energy spectra and even the charged particles-γ coincidence method without any limitation.

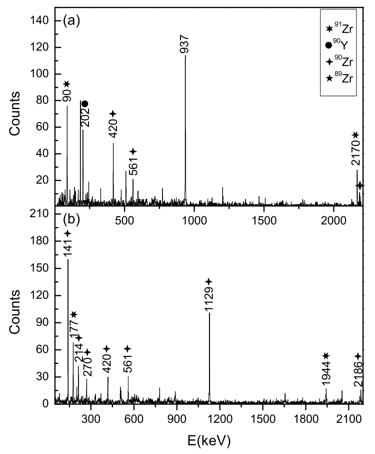

Figure 2. γ energy spectra in coincidence with the α particles of the angular ranges covered by aluminum absorber (a) and unshielded by aluminum absorber (b).

It is well known that the angular distributions and energy distributions of emitted charge particles from CF, ICF and transfer processes are different. To select the different channels and explore the different reaction mechanisms in fusion process induced by weakly bound nuclei, the method of γ energy spectra in coincidence with charged particles of different angular regions is applied. In Fig. 1 the aluminum absorber has a 200 μm thickness, and the ^{6}Li beam with an incident energy of 34 MeV or 22 MeV cannot pass it. In this setup, the α particles that have been observed in the telescope of angular ranges covered by the absorber were tentatively deemed to be mainly from transfer processes and the evaporated α particles cannot be detected. This conclusion is verified by the statistical evaporation model.

The γ-ray spectrum in coincidence with the α particles at angular ranges covered by the absorber is shown in Fig. 2 (a). The γ rays from ^{90}Zr (1p stripping), ^{91}Zr (1d stripping) and ^{90}Y (1n stripping) are present. In the calculation of statistic evaporation model for complete fusion (CF) and incomplete fusion (ICF), ^{90}Y is not predicted and the yield of ^{91}Zr can be neglected. Therefore, ^{91}Zr and ^{90}Y are expected from 1d and 1n stripping reactions, respectively. In the angular range unshielded by the absorber the alpha-gated γ spectrum clearly shows the presence of ^{90}Zr and ^{89}Zr as shown in Fig. 2(b). In such uncovered ranges the α particles are mainly from evaporation processes from the compound nucleus in CF process. Therefore, they are related to the components of the fusion evaporation residues. In the two spectra of Fig. 2, the γ peaks of ^{90}Zr are visible. However, in the backward silicon range, in the alpha-gated γ spectrum the peaks related to the high-lying states in ^{90}Zr while in the covered range other states from ^{90}Zr are present. This indicates that the populated states of ^{90}Zr are coming from the different reaction kinematics. Therefore, according to the present experimental setup, the different reaction channels can be clearly identified by charged particles-γ coincident method.

4 summary

An experiment to explore the fusion reactions of weakly bound nuclei was performed with the GALILEO array in combination with the Si-ball EUCLIDES at the Legnaro National Laboratory (LNL), Italy. By the time coincidence measurement of light-charged particles and γ rays, the different channels can be separated. As the γ energy spectra in coincidence with the light-charged particles allow a clean selection of the reaction channels, we can derive the cross sections for the different reaction channels. The detailed analysis is still ongoing.

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