NUCLEON TRANSFER REACTION STUDIES AT GANIL USING RADIOACTIVE NUCLEAR BEAMS[★]

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A series of experiments with both stable and radioactive nuclear beams were very recently performed at GANIL using, for the first time, the trio of detectors: TIARA, VAMOS and EXOGAM. Such a combination of devices provides an outstanding opportunity to study single-particle structure of exotic nuclei via the well known technique of nucleon transfer reactions. TIARA is a very compact array of position sensitive silicon strip detectors (400 μm thick) covering ~ 90% of 4π and which is designed for the study of nucleon transfer reactions in inverse kinematics using radioactive beams. Particle identification is made using the kinematic correlation between the angle and deposited energy of the target-like particle measured in coincidence with the beam-like particle recorded in the high acceptance and high energy resolution spectrometer VAMOS. An array of four segmented clover EXOGAM Ge detectors surrounding TIARA is also used to measure coincident gamma-rays and to provide good energy resolution for final excited states.

A detailed description of the setup and the status of the analysis for the reaction ^{24}Ne + d at 10 MeV/nucleon will be described. Simulations of the entire TIARA system undertaken with the code GEANT4 will be also discussed.

INTRODUCTION

With the recent development of radioactive nuclear beams such as those delivered by SPIRAL at GANIL, it is now feasible to study the shell structure of

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very exotic nuclei in detail using single-nucleon transfer reactions [1]. This means the opportunity is now offered to collect crucial information on new aspects of nuclear structure observed in exotic nuclei such as the formation of neutron haloes and neutron skins, the disappearance of shell gaps, the evolution of nuclear shape and the new form of nucleon pairing. A series of nucleon transfer reactions with both stable and radioactive nuclear beams was very recently performed at GANIL using three state-of the-art detectors. In this paper, after a brief description of the setup and GEANT4 simulations, preliminary results on the nucleon transfer reaction d(^{24}Ne,^{25}Ne)p are discussed.

EXPERIMENTAL SETUP

To study transfer reactions like (p,d), (d,p), (d,^{3}He), etc. with radioactive nuclear beams it is necessary to use inverse kinematics, with the proton or deuteron becoming the target. This aspect leads actually to severe requirements for the experimental setup in order to study energy levels with good energy resolution [2, 3, 4]. Our experimental setup consists of the detectors TIARA, VAMOS and EXOGAM coupled all together for the first time.

A very interesting feature of inverse kinematics [3] is that the energy-angle systematics of the target-like particle have very little dependence on the mass and energy of the beam particle provided the mass is large compared to the mass of the target nucleus and the Q-value is not too large. The TIARA design [4] is mainly based on this feature. The full TIARA array is display in Fig. 1. It is a very compact array of 400 μm silicon detectors manufactured using 6-inch technology by Micron [5]. With a central barrel made of 8 detectors with 4 resistive strips (98.8 mm long and 24.6 mm wide), plus two forward and one backward doubled sided silicon detectors, it covers ~90% of 4π. Thus, target-like particles emitted in pickup or stripping reactions as well as in elastic or inelastic scattering can be measured during a same experiment (Fig. 1b). Particle identification is by kinematical correlation between the angle and deposited energy of the target-like fragment. The identification of charge and mass of the beam-like particle is provided in coincidence by the VAMOS spectrometer tuned at zero degree [6]. The energy resolution of such setup is limited to ~ 300 keV. However, the TIARA vacuum chamber has also been designed to be placed in the middle of a compact array of four segmented Ge gamma-ray EXOGAM detectors [7]. In this configuration of EXOGAM, the Ge detectors are placed around the barrel at only 5 cm from the target. This provides for the excitation energies of the final nuclei an energy resolution limited only by the Doppler broadening (~ 30 keV at 1.332 MeV). Furthermore, this allows the use of thicker targets, compensating the γ-ray efficiency (~ 15% at 1.332 MeV) and the relatively low intensity (~ 10^{4} pps) of radioactive nuclear beams.

For the experiment discussed in this paper, the beam of ^{24}Ne was produced at 10.6 MeV/nucleon by the ISOL technique with the SPIRAL facility at GANIL and was directed onto a 1mg/cm^2 plastic polymer $(CD_2)_n$ target.

GEANT4 SIMULATIONS

The response of the TIARA array has been simulated using the GEANT4 Simulation Code developed at CERN laboratory. As shown in Fig. 1(a), the entire TIARA geometry has been defined in the code. The results of the simulation for several exit channels of the reaction ^{24}Ne + d at 10.6 MeV/ nucleon are displayed in Fig. 1(b). In the spectrum *deposited energy versus laboratory angle* of the target-like particle, we can see the different regions that are populated for the different exit channels and different excited states. Note that, in these simulations, the kinematical energy-angle correlation of the target-like particle is taken into account and the angular distribution of the differential cross section $d\sigma/d\Omega$ is assumed to be flat for all exit channels. Also, at this stage of the simulation code development, the effect of the target thickness on the energy and angular resolution hasn't been yet taken into account. The spectrum in Fig. 1b can be directly compared to the spectrum in Fig. 2a recorded during the experiment. The position of the two forward annular detectors was chosen with the purpose of covering the region of small laboratory angles to study the ^{3}He exit channel. It results in a gap between the barrel and the first forward annular detector that is clearly observed both in simulations and in the data spectra for laboratory angles between 28 and 36 degrees.

PRELIMINARY RESULTS

The TIARA energy-angle spectrum of the target-like particle, in Fig. 2a, has been recorded with a gate on any beam-like particle detected in coincidence in the focal plane in VAMOS. At the stage of our current analysis, the elastic scattering (d,d) and the one-neutron transfer reaction (d,p) to several known states of ^{25}Ne are clearly observed. However, due to lower cross sections, the (d,t) and (d,^{3}He) channels are not observed yet, and for those, further analysis is certainly required on particle identification and trajectory reconstruction in VAMOS.

According to simulations (Fig. 1b), events in region R1 (Fig. 2a) correspond to protons emitted in neutron transfer to ^{24}Ne to give ^{25}Ne in its ground state. Indeed, an additional gate on any gamma ray in EXOGAM shows that this region of events disappears. The differential cross section $d\sigma/d\Omega$ obtained with DWBA calculations with optical potential parameters from [8], is compared to

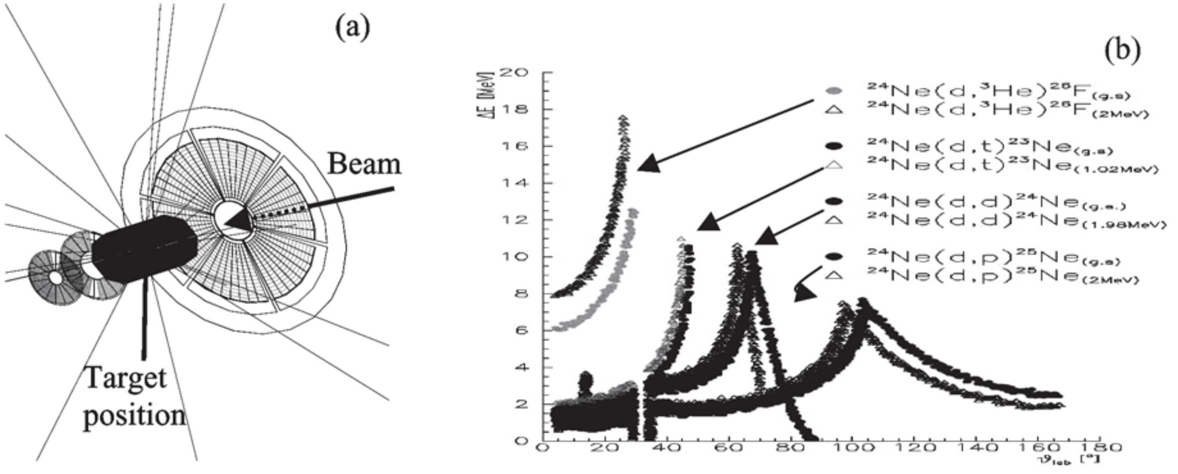

Fig. 1. – (a) Geometry of the TIARA detector defined in the simulation code. Tiara is made of an octagonal silicon barrel surrounding the target, plus 2 forward and1 backward silicon annular detectors. (b) Simulation of deposited energy versus laboratory angle of light particles emitted in inverse kinematics reactions: ^{24}Ne(d,d), ^{24}Ne(d,p), ^{24}Ne(d,t) and ^{24}Ne(d,^{3}He), see text.

$\ell = 2,$

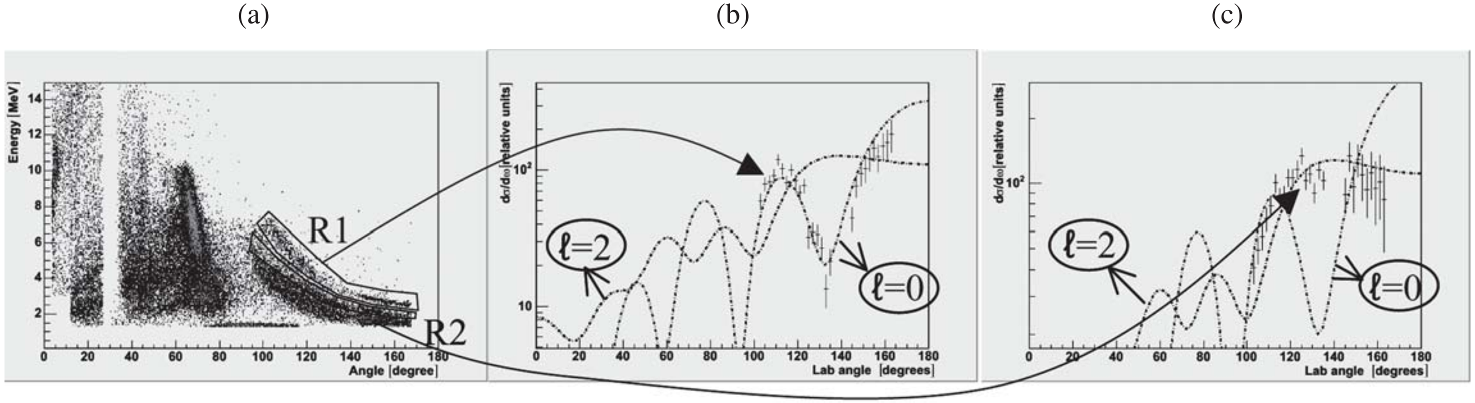

Fig. 2. – Preliminary Results. (a) Deposited Energy versus laboratory angle of target-like particles recorded in TIARA for ^{24}Ne + d reaction. The spectrum is gated on VAMOS. (b & c) Differential cross section $d\sigma/d\Omega$ for a transferred neutron orbital momentum $\ell = 0$ and respectively. Cross symbols represent the data and lines represent DWBA calculations.

the one measured experimentally in Fig. 2b. The shape of the measured angular distribution corresponds to a transferred orbital momentum quantum number $\ell = 0$ for the neutron. This result is also consistent with the spin 1/2 of the ^{25}Ne ground state predicted by the shell model using the USD interaction [9]. Protons in region R2 (Fig. 2a) correspond to a neutron transferred to ^{24}Ne in the first excited states of ^{25}Ne observed at ~1.7 MeV [10, 11, 12]. Indeed, in coincidence with these protons, peaks at ~1.6 and ~2 MeV are observed in the gamma energy spectrum. In addition, according to our DWBA calculations the shape of the differential cross section (Fig. 2c) is consistent with a transferred orbital momentum quantum number $\ell = 2$ for the neutron. This is in agreement with the predicted spin of these levels of 3/2 or 5/2 [9]. Clearly, below region R2, there are higher energy levels of ^{25}Ne that are populated in the (d,p) channel, but the resolution in TIARA and the low statistics in EXOGAM make the analysis more difficult.

CONCLUSION

It has been demonstrated that the coupling of the detectors TIARA, VAMOS and EXOGAM with radioactive beams from SPIRAL is an excellent tool to study nucleon transfer reactions in inverse kinematics. This has potentially a vast field of applications in nuclear physics. Our preliminary results on the (d,p) reaction channel are already very promising. Further detailed analyses is required for the (d,t) and (d,^{3}He) reaction channels. Our GEANT simulations of the TIARA detector are very helpful for the analysis, and the code is currently being developed to include the EXOGAM and VAMOS detectors.

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