Commissioning of the TIARA for Texas experimental station

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Single- and multi nucleon transfer reactions such as (d, p) and (^{6}Li, d) are valuable tools for obtaining spectroscopic information on nuclei away from stability. Their sensitivity to excitation energies, orbital angular momenta, and single-particle (or pair/cluster) strengths make them ideal tools for studying the evolution of nuclear structure away from the valley of stability and for constraining the strengths of key, isolated resonances involved in stellar nucleosynthesis. Transfer reactions performed in forward kinematics using the MDM spectrometer have played a key role in the scientific program at the TAMU Cyclotron Institute for many years. A prime example is the long and successful program of constraining astrophysical reactions using the ANC technique. Looking towards the future, the anticipation of re-accelerated rare isotope beams (RIBs) from the light- and heavy-ion guide upgrades motivates the development of new experimental stations which are optimized for studying transfer reactions in inverse kinematics, with the short-lived RIBs impinging on light targets.

In order to study transfer reactions in inverse kinematics with re-accelerated RIBs, the TIARA (transfer and inelastic scattering all-angle reaction array) experimental setup [1] has been moved from its former home at GANIL in Caen, France and re-commissioned at the Cyclotron Institute, where it is commonly referred to as “TIARA for Texas” (T4T). TIARA consists of two silicon detector arrays which are optimized for detecting the target-like ejectiles emitted from transfer and elastic scattering reactions in inverse kinematics. The first detector array is 16-strip annular DSSD which can be placed either upstream or downstream of the target depending on the desired reaction kinematics. The second detector array is compact silicon “barrel” composed of position-sensitive resistive strip detectors which surrounds the reaction target covering laboratory angles from 30^o – 145^o. Together these detector arrays provide good angular coverage and resolution for both the ejectiles emitted in the transfer reaction under study and elastically-scattered target nuclei which are used for the absolute cross section normalization. At the Cyclotron Institute, TIARA is installed at the target position of the MDM magnetic spectrometer and further coupled to four HPGe clovers borrowed from the HYPERION array. This setup allows beam-like recoils to be detected in the focal plane of the MDM, in coincidence with reaction events in the TIARA Si detectors. This coincidence technique virtually eliminates any background from fusion-evaporation reactions. Furthermore, the coupling with HPGe detectors allows measurement of the gamma-rays emitted in the de-excitation of states populated in transfer reactions, allowing states which are nearly degenerate in energy to be separated in the data analysis. The HPGe detectors are arranged in a compact geometry surrounding the target to maximize efficiency, which is around 10% for gamma rays with an energy of ~1 MeV.

Following its installation the T4T setup was commissioned in a series of stable beam experiments performed in the Fall of 2016, each targeted at constraining key resonance strengths involved in astrophysical nucleosynthesis. The first two experiments, ^{19}F(d,p)^{20}F and ^{23}Na(d,p)^{24}Na are aimed at studying the mirrors of important proton-capture resonances affecting nucleosynthesis in classical novae.

For more details on the latter reaction, see the report “Studying the ^{23}Na(d,p)^{24}Na reaction to constrain the astrophysical ^{23}Mg(p,γ)^{24}Al reaction rate”. The other two experiments were aimed at constraining the properties of resonances in ^{26}Mg which affect the overall rate of the ^{22}Ne(α,n)^{25}Mg reaction in AGB stars. This reaction is one of only two sources of neutrons for the slow neutron capture process which is partially responsible for the formation of elements heavier than iron. Resonant states in ^{26}Mg were populated and studied using both the ^{25}Mg(d,p)^{26}Mg and ^{22}Ne(^{6}Li, d)^{26}Mg reactions. See the report “Study of the astrophysical α + ^{22}Ne reaction using ^{6}Li(^{22}Ne,^{26}Mg)d alpha transfer with TIARA and the MDM spectrometer”.

The data from these four experiments are in the early stages of analysis; however, at present a number of key features demonstrating the performance of the system can already be identified. Figure 1 demonstrates the performance of the T4T system in making spectroscopic measurements of the ^{19}F(d,p)^{20}F reaction. As can be seen in panel a), the system displays good particle identification from

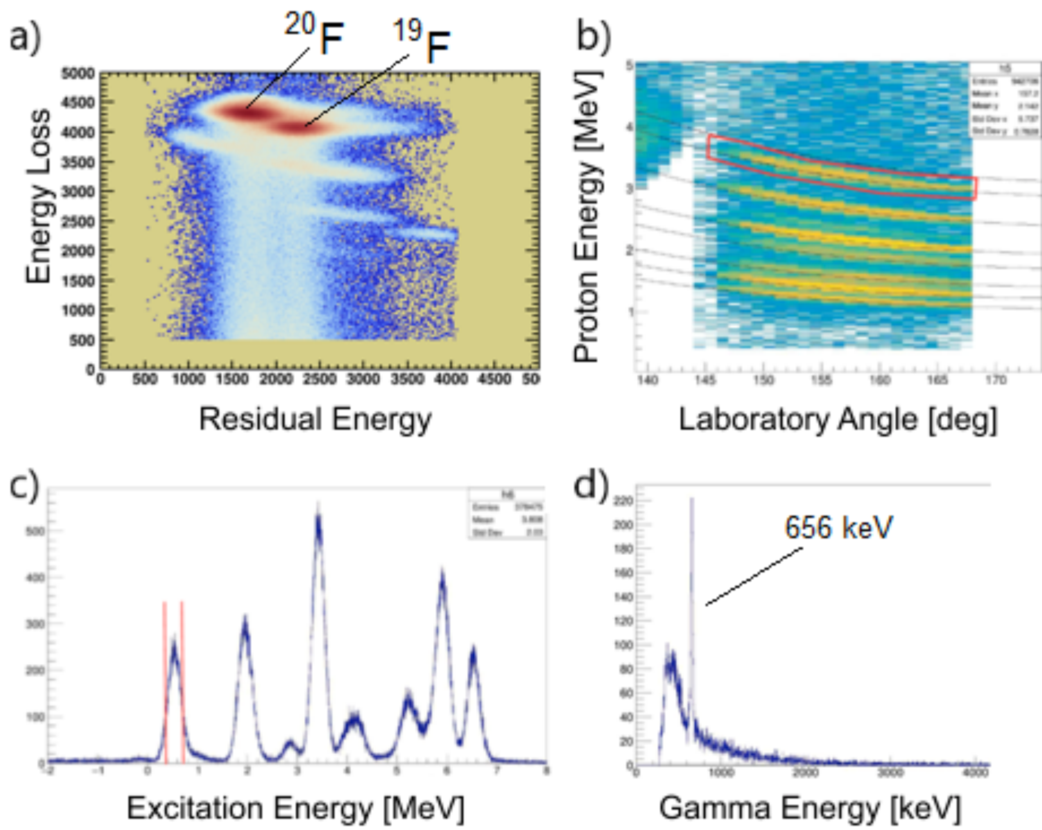

FIG. 1. Sample plots showing the performance of the T4T spectroscopic system. All plots are from data taken on the ^{19}F(d,p)^{20}F reaction. a) Sample E-ΔE particle ID plot in the Micromega detector at the MDM focal plane. b) Proton kinematic lines observed in the backward-angle annular Si detector. c) Excitation energy spectrum of ^{20}F observed in the backward-angle annular Si detector. d) Gamma-ray energy spectrum, gated on the first excited state in ^{20}F at 656 keV.

measurements of E-ΔE in the MICROMEGA detector at the focal plane of the MDM, with the loci of ^{20}F recoils and ^{19}F beam clearly separated. Panel b) shows kinematic lines observed in the backward-angle Si detector, with the expected kinematic curves from ^{19}F(d,p)^{20}F superimposed and matching well with the data. Panel c) shows the ^{20}F excitation energy spectrum calculated from the measured proton energies and angles in the annular Si detector. Excited states in ^{20}F are clearly present, and the excitation energy resolution is approximately 200 keV FWHM (these data were taken with a 200 μg/cm^2 CD_2 target). Panel d) demonstrates the performance of the gamma-ray detection system, showing the Doppler-corrected HPGe spectrum gated on the 656 keV first excited in ^{20}F. The 656 keV peak from the direct decay of this state to the ground state is clearly evident. The resolution for the Doppler-corrected gamma-rays in this energy regime is approximately 10 keV FWHM.

Fig. 2 demonstrates the performance of the system for measuring the target-like products of elastic scattering, which is essential for determining the beam + target luminosity needed to extract absolute cross sections. Panel a) shows the Si barrel energy vs. angle plots observed by impinging ^{25}Mg at 10A MeV on a CD_2 target. A kinematic curve from d(^{25}Mg, ^{25}Mg)d elastic scattering is clearly evident on top of background from fusion-evaporation. Panel b) shows a projection onto the angle axis, for a narrow slice in energy. The peak from elastic scattering is clearly identifiable, and in the final analysis its area can be extracted from a simple Gaussian + polynomial background fit.

Analysis of the data from all of the TIARA stable-beam experiments is ongoing, and it is expected that absolute differential cross sections will be obtained for the states of astrophysical interest. Future experiments with TIARA will focus on astrophysically-motivated (d,p) reactions performed both with RIBs from the light-ion guide upgrade, as well as long-lived radioactive isotopes of nickel and iron placed directly into the K500 ion source.

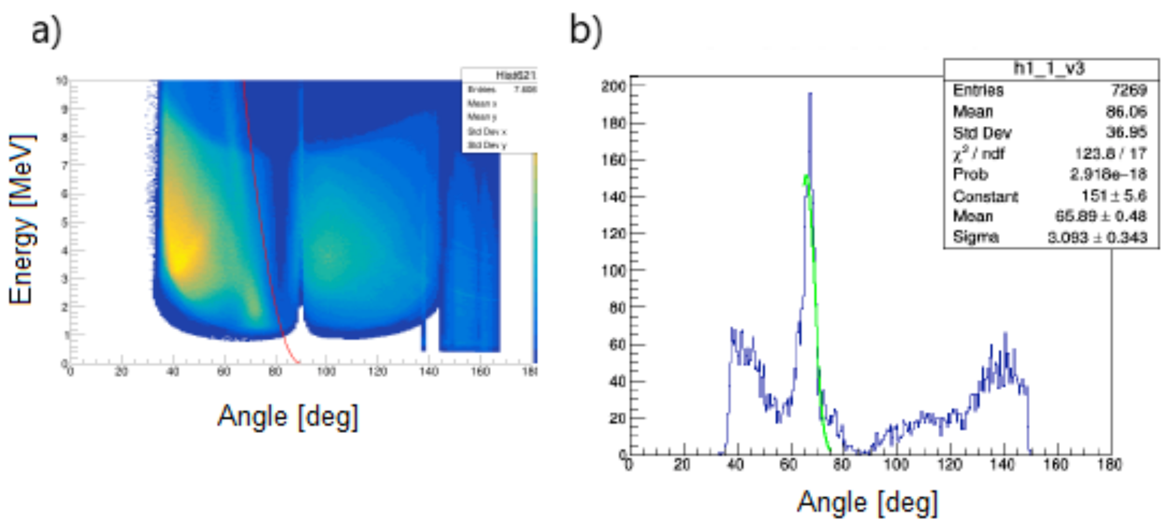

FIG. 2. Sample plots demonstrating the performance of the Si barrel detector for measuring d(^{25}Mg, ^{25}Mg)d elastic scattering. Panel a) shows the elastic scattering kinematic curve sitting on top of a background from fusion-evaporation. Panel b) shows a projection onto the angle axis of the plot in panel a), gated on a narrow slice in energy. The peak from elastically-scattered deuterons is clearly evident on top of fusion-evaporation background.

[1] M. Labiche *et al.*, Nucl Instrum. Methods Phys. Res. **A614**, 439 (2010).