Developments for performing the $^{16}O(n,\alpha)^{13}C$ reaction using HIRA

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1. Introduction: Measurements of the reaction cross-section of $^{13}C(\alpha,n)^{16}O$ are one of the topmost priorities in low-energy nuclear physics. It is evident from the fact that APS assigned this as one of the 11 most important experiments in physics[1]. The scientific motivation for the measurements is that the neutrons emitted in this reaction are the primary source for the S-process in the low-mass AGB (Asymptotic Giant Branch) Stars. Sergio et. al, have shown that isotopic abundances of certain elements can vary as much as 100% with a 10% variation of the neutron strength [2]. Thus, the cross-section of this reaction provides a key input to an accurate and precise understanding of the isotopic abundances of the universe.

We are investigating the $^{16}O(n,\alpha)^{13}C$ reaction to derive the cross-section of the $^{13}C(\alpha,n)^{16}O$ reaction using TRM (time reversal method). The theoretical formulation of the TRM was pioneered by Sergio et. al [2]. A quick review of the current status of the (n,α) measurements shows experimental errors of 30%, which exceeds the desired goal of <10%. In this regard, we refer to (i) the measurements at Los Alamos using the LANSCE facility. This measurement improved the errors to a ~30% level compared to the earlier >50% [3] and (ii) latest measurements at CERN using the n_ToF facility by Sergio et. al. which also had difficulties [2,5]. We assess that both investigations were performed using Spallation Neutron Sources (SNS): LANSCE and n_ToF at CERN. While both of these are state-of-the-art SNSs, there are inherent challenges to using an SNS for such measurements. This includes (i) the generation of photon flash along with neutrons as the proton pulse strikes the target which interferes with the signals and (ii) issues in determining the absolute normalization.

We are proposing a novel technique to minimize these errors and conduct the measurements at IUAC. The proposal was recently approved by IUAC PAC (AUC75328). We also benefited from the discussions with the collaboration led by Sergio who is also part of this experiment. In this paper, we will discuss two key aspects of our efforts (i) the production of a monochromatic neutron beam of desired quality and (ii) the optimization of the experimental setup.

2. Monochromatic neutron source: From the discussions above, it is apparent that the fundamental requirement for the investigation is a neutron source with beam characteristics comparable to LANSCE or CERN. As India does not have such a source, we are proposing a new idea to develop the neutron beam using entirely existing equipment: HIRA and RIB instrumentations in new ion optics, Rotating target system(RTS), MD-slit system and an ASSD (annular Si strip detector). The details of these including publications and photographs are available on the HIRA webpage[6]. The neutrons will be produced using the reaction $^{1}H(^{7}Li,^{7}Be)n$ in inverse kinematics. The geometry of the ASSD and the ^{16}O-containing target is optimized such that for each neutron emitted, the corresponding

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$^7Be^{4+}$ ion will also be detected in the HIRA focal plane with MWPC & IC[6]. The RTS will be used to mount a large area $(CH_2)_N$ foil as the proton target. The design characteristics of the neutron source are beam energy (E_n) = 3-7 MeV, flux (ϕ_n)~10^4-10^5/s, energy/angular spread of ΔE_n~300 keV and $\Delta\theta_n$=±2°. ΔE_n can be further reduced by measuring the ^{7}Be energy or ToF.

The neutron flux is the most important criterion for a source. We developed a GEANT4 model of the source to get an accurate estimate of neutron flux. The validity of the model parameters is verified by simulating the Orsay neutron source flux and comparing it with data [7]. From Fig.1 (top panel) we see that neutron flux is reproduced for the entire range of measured angles. The neutron and ^{7}Be energy spectrum at E(^{7}Li)=15 MeV are shown (bottom panel). Simulations of HIRA ion optics to obtain (n,^{7}Be) coincidence efficiencies are in progress. A beam test to verify the predicted neutron flux and source characteristics (AUC71368) was delayed due to COVID-19 and is expected to be scheduled soon.

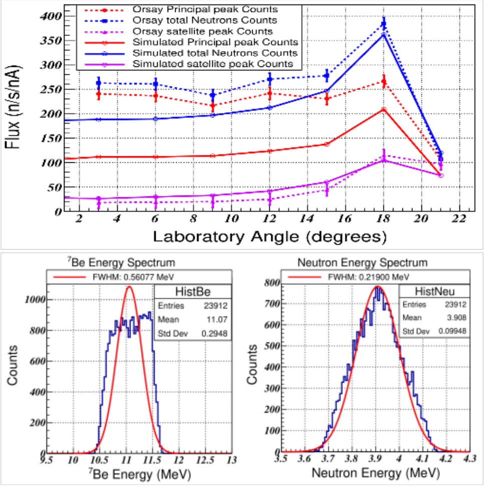

Fig. 1: GEANT4 simulation for ORSAY

3. The experimental setup for $^{16}O(n,\alpha)^{13}C$: A ring-shaped ^{16}O target and an ASSD will be placed along the beam axis (Fig. 2). HIRA will be operated at 0°, and neutrons within the narrow cone of 8.43°-12.43° will be incident on the ^{16}O target. The corresponding ^{7}Be angles will be within 1.9°-2.69°. This is within the solid angle of acceptance for HIRA(10 mSr).The ASSD will detect the α-particles in coincidence with ^{7}Be. The method we are adopting for the absolute normalization of neutron flux is to count the ^{7}Be rate at the HIRA focal plane. The coincidence between a detected ^{7}Be and an α-particle in the ASSD will ensure the genuineness of the event.

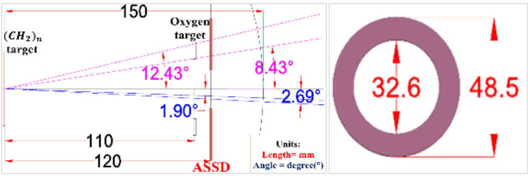

Fig. 2: The proposed experimental setup (left) and the ring-shaped ^{16}O target(Li_2CO_3). The target is not fabricated yet.

4. Estimation of data rates: Neutron flux on the ^{16}O target ($\Delta\theta_n$=±2°) is estimated to be ~5×10^4/ sec for 10 pnA beam. As GEANT4 simulations were only completed now, we originally estimated the neutron flux using ^{7}Li(^{1}H,^{7}Be)n cross-section data from BARC (at θ_{Lab} =30° and E_p=2.5 MeV). For inverse kinematics, E_{beam} = 17.5 MeV, neutron flux is obtained by performing a Jacobian transformation on the BARC data. Neutrons of 4.053 MeV and 4.175 MeV will populate the $1/2^+$ and $3/2^+$state of the ^{17}O compound nucleus. In Fig.3, the decay through α+^{13}C channel is shown. The α rates have been calculated using LANSCE data of the same reaction [4]. Our goal is ~10% accuracy.

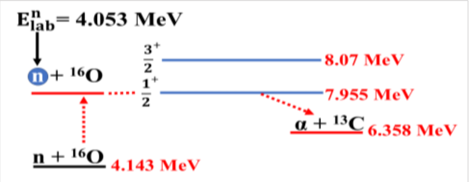

Fig. 3: Resonance of $1/2^+$ state of ^{17}O for4.053 MeV neutron

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