Feasibility study of time-inverse measurement of the stellar reaction ^{22}Mg(α,p)^{25}Al

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The reaction rate for ^{22}Mg(α,p)^{25}Al, which is of interest for the (α,p) process that powers Type I X-ray bursts, is currently under investigation at the Cyclotron Institute.

Type I X-ray bursts (XRBs) are the most frequent thermonuclear explosions observed in the galaxy. It is thought that an XRB occurs in binary star systems where a neutron star accretes matter from its companion star [1]. As the accreted hydrogen- and helium-rich matter builds up on the surface of the neutron star the temperature and the pressure increase and a thermonuclear runaway occurs reaching peak temperatures of T ~ 1.5 GK, and is observed as X-ray burst. The fact that the bursts do not destroy the binary star system makes X-ray binaries useful as a way to study matter under extreme temperature and density conditions. The principal nuclear reaction sequences in XRBs have recently been presented in detail by Fisker et al. [2]. They are mainly characterized by helium burning via the (α,p)-process (a sequence of alternating (α,p) reactions and (p,γ) reactions) and hydrogen burning via the rp-process (a sequence of *rapid proton* capture reactions and β-decays). Reactions like ^{22}Mg(α,p)^{25}Al, ^{26}Si(α,p)^{29}P, ^{30}S(α,p)^{33}Cl, and ^{34}Ar(α,p)^{37}K are considered to play a significantly important role in determining the nucleosynthetic path for the (α,p) process in XRBs and for understanding XRB light-curve evolution [3]. Moreover, current sensitivity studies on XRB nucleosynthesis have identified the reaction ^{22}Mg(α,p)^{25}Al as being influential for the XRB total energy output [4].

We report here on a feasibility test performed in November 2012 to measure the experimentally unknown cross section of the ^{22}Mg(α,p)^{25}Al reaction at astrophysical relevant energies. The measurement was performed in inverse kinematics for the study of the time-inverse reaction ^{25}Al(p,α)^{22}Mg. A low-temperature oven coupled to the ECR2 ion source at the Texas A&M University Cyclotron Institute was operated at a temperature of ~540 °F to extract a ^{25}Mg^{10+} primary beam for the first time at the newly refurbished K150 cyclotron. The primary beam was accelerated at 11 MeV/nucleon, the highest energy available at the time due to the maximal operational K150 deflector voltage of 62.6 kV, and bombarded a cryogenic gas cell to produce the secondary beam ^{25}Al at ~7 MeV/nucleon via the ^{25}Mg(p,n) reaction. The entrance and exit windows of the gas cell were made of Havar foil of 4 μm thickness and the pressure in the gas cell was p = 1 atm. Out of a total current of 80 nA for the ^{25}Mg^{10+} primary beam, a current of 15 nA for a fully stripped ^{25}Mg^{12+} primary beam was transmitted on the primary target. As illustrated in Fig. 1, the resulting ^{25}Al beam separated by the Momentum Achromat Recoil Separator (MARS) had a purity of ~94.6% and was produced at a rate of about 1.4×10^4 pps.

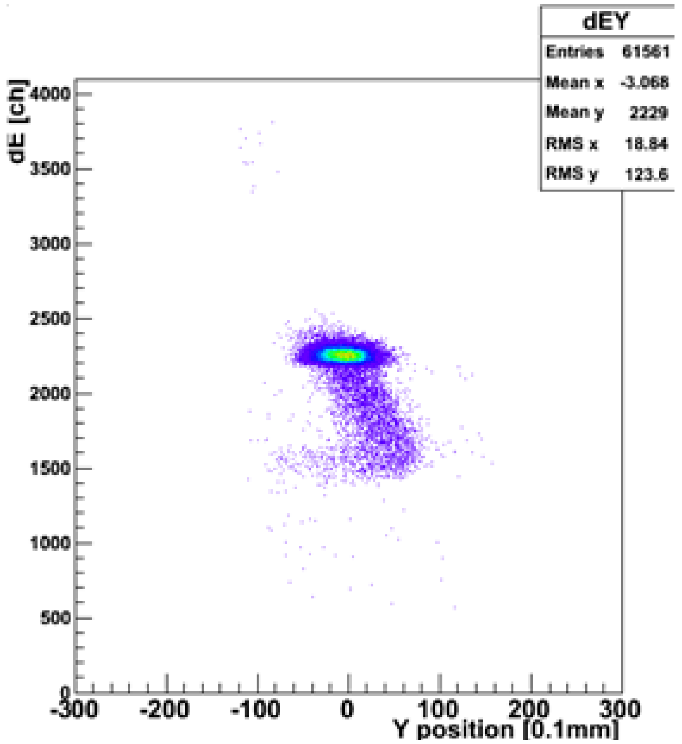

FIG. 1. Plot of energy versus y position in the MARS target detector.

The beam-spot size measured with the MARS silicon position sensitive target detector was about 4 mm × 4 mm (FWHM). A solid CH_2 target of ~1 mg/cm^2 thickness was used as reaction target and was located at the final focal plane of MARS. To disentangle the reaction induced-background due to the carbon present in the target, additional measurements using a pure carbon target, of ~2 mg/cm^2 thickness, were carried out.

We used an experimental setup that provided reaction channel selection and particle scattering angle determination. It consisted of four modular ΔE-E silicon telescopes (of 5 × 5 cm^2 active area) arranged in a symmetrical ‘cross’ configuration, as illustrated in Figure 2. The front ΔE detectors were 16-strip position-sensitive detectors, 140-μm thick (the vertical detectors) and 65-μm thick (the horizontal detectors). The back E residual detectors had the same area coverage of 5 × 5 cm^2 but the vertically positioned detectors were 1000-μm thick while the horizontal ones were 500-μm thick. A plastic scintillator detector was placed at 0° downstream of the reaction target and the Si-detector array and served for beam normalization of the reaction cross section evaluation.

For laboratory energies of ~7 MeV/nucleon at which the ^{25}Al secondary beam was produced here, the corresponding maximum laboratory angular range for the reaction products of interest – alpha particles and ^{22}Mg – was 18° and 3.3°, respectively. To accommodate these angular ranges for the detection of both alpha particles and ^{22}Mg heavy ions, the measurements were carried out at two distances from the CH_2 target to the cross-silicon detector array: 18 cm and 58 cm. At the shorter distance of 18 cm, the angular coverage in the *vertical detectors* was between ~4° and ~19° while in the horizontal detectors was between ~16° and ~30°. At the further distance of 58 cm, the angular coverage in the *vertical* *detectors* was between ~1° and ~6° while in the horizontal detectors was between ~5° and ~30°. In regard to the possible energy ranges for the two main reaction products of interest here, the energies for the alpha particles span from 3 MeV/nucleon up to 11 MeV/nucleon while for the ^{22}Mg heavy ions from ~6 MeV/nucleon up to 7 MeV/nucleon. Taking into account the thicknesses of the Si detectors in the 'cross'-array and the two target-detector distances at which the measurements were performed, the heavy ions could only be detected in the vertical ΔE detectors when the 'cross'-array was positioned at the 58 cm distance from the reaction target. Because the energy loss range for heavy ions is more than one order of magnitude higher than energy loss range for the alpha particles, we chose to sacrifice the 'bottom'-ΔE detector by lowering its amplification settings to allow the detection of ^{22}Mg-alpha particle coincidences between the 'bottom'-ΔE detector and any of the other three ΔE detectors, our signature that the reaction channel of astrophysical interest here was identified.

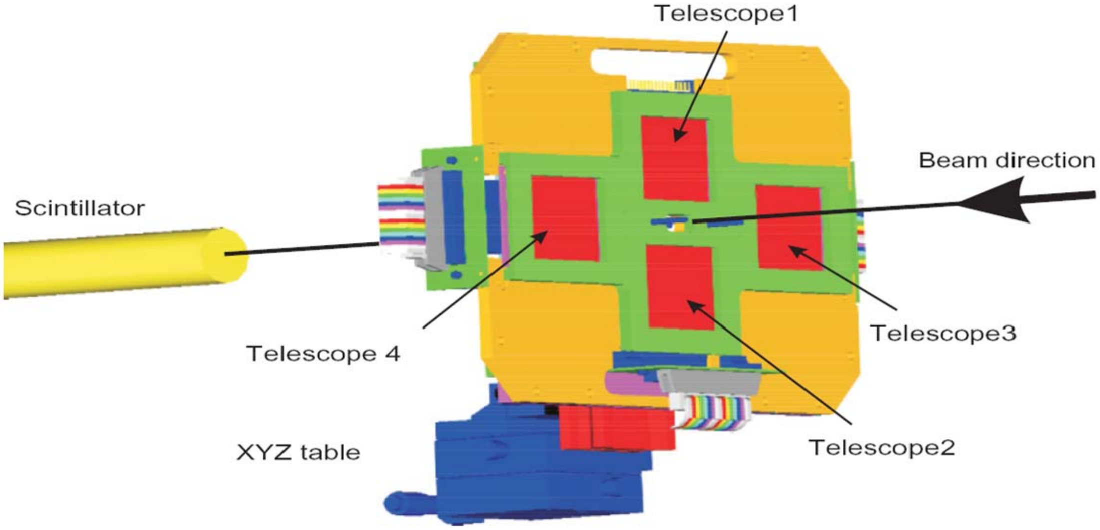

FIG. 2. A 3-dimensional view of the detector assembly employed: the 'cross'-silicon-detector array and a plastic scintillator detector. See text for details.

For a total of about 5-beam-on-target days, we were able to acquire coincidence data for ~36 hours. When comparing the coincidence data taken on the CH_2 target vs. the pure Carbon target, we did observe heavy ions of appropriate energy loss in the 'bottom'ΔE detector of the 'cross-array, as we would expect for the ^{22}Mg heavy ions, only for the CH_2-target data. While data analysis is currently in progress, it remains to be determined the nature and the origin of the heavy ions we did detect in coincidence with light particles.

In conclusion, we have successfully conducted a feasibility test for the time-inverse measurement of the stellar reaction ^{22}Mg(α,p)^{25}Al in which we achieved the production for the first time at the K150 cyclotron of both the primary and secondary beams of interest, ^{25}Mg and ^{25}Al, respectively. Preliminary results of the data analysis seem to validate our experimental approach. The ^{25}Al secondary beam was produced at laboratory energy of ~7 MeV/nucleon corresponding to a relative energy in the center of mass for the system ^{22}Mg-alpha of 3MeV, which is very close to the astrophysically relevant energy regime of 1.7 – 3.2 MeV for the X-ray burst peak temperature of 1.5 GK. Because of the very small cross sections at the astrophysically relevant energy regime, we plan next to perform measurements of the time-inverse reaction ^{25}Al(p,α)^{22}Mg at higher laboratory energy for the ^{25}Al beam than 7 MeV/nucleon such that we can be sure that we indeed identified the ^{22}Mg-alpha reaction channel of astrophysical interest. An increase of at least one order of magnitude is also expected for the production rate of the ^{25}Al secondary beam using either of the K150 or K500 cyclotrons available at TAMU.

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