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Measurement of the ^{86}Kr(α,n)^{89}Sr cross section at energies relevant for the weak r-process

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Abstract. The r-process has been shown to be robust in reproducing the abundance distributions of heavy elements, such as europium, seen in ultra-metal poor stars. In contrast, observations of elements $26 < Z < 47$ display overabundances relative to r-process model predictions. A proposed additional source of early nucleosynthesis is the weak r-process in neutrino-driven winds of core-collapse supernovae. It has been shown that in this site (α,n) reactions are both crucial to nucleosynthesis and the main source of uncertainty in model-based abundance predictions. Aiming to improve the certainty of nucleosynthesis predictions, the cross section of the important reaction ^{86}Kr(α,n)^{89}Sr has been measured at an energy relevant to the weak r-process. This experiment was conducted in inverse kinematics at TRIUMF with the EMMA recoil mass spectrometer and the TIGRESS gamma-ray spectrometer. A novel type of solid helium target was used.

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1 Background

The main r-process is a nucleosynthesis process responsible for producing around half of the elements heavier than iron. While there remains some ambiguity over the site(s) of the r-process, the observation of strontium in the first observed kilonovae (AT2017gfo) [1] indicates that r-process nucleosynthesis can at least occur in neutron star mergers. As a primary process, the r-process does not require the existence of pre-existing heavy nuclei, unlike the s-process which requires seed nuclei to be present in a star's composition in order to function. Therefore, the further back in the history of the universe, the greater the proportion of the heavier than iron elements was made via the r-process. Ultra-Metal Poor (UMP) stars formed so early in the universe that the r-process is expected to have produced most of the elements heavier than iron detected in their atmospheres [2].

This assumption is supported by studies that compare observed elemental abundances in UMP stars to predictions made based on models of r-process nucleosynthesis. Here, observations for elements $Z > 47$ agree well with model predictions; however, observations of elements $26 < Z < 47$ show a significant enrichment relative to model predictions [2]. Due to the good agreement for the heavier elements, it has been suggested that these additional lighter heavy elements, are produced by a separate, and as of yet unknown, mode of nucleosynthesis; one proposed site is the weak r-process in neutrino-driven winds of core-collapse supernovae [3].

Models predict that the potential for nucleosynthesis in the neutrino-driven winds of core-collapse supernovae is limited to nuclei $A < 130$ [4], making it a candidate for the source of the overabundant lighter heavy nuclei in UMP stars. The exact physical conditions in this site are unknown however, the value for electron fraction Y_e (the ratio of the number of protons to the total number of protons and neutrons) has been shown to have a significant impact on the predictions for nucleosynthesis. In the case that the electron fraction is slightly neutron rich (0.40—0.49), simulations have shown that (α,n) reactions are the most important for moving matter to higher atomic numbers [3]. These (α,n) reactions are also the primary source of uncertainty in models of weak r-process nucleosynthesis [3]. This uncertainty arises from significant disagreements in Hauser-Feshbach cross section predictions upon which, models of nucleosynthesis must be based as there are few cross section measurements in literature for (α,n) reactions on the lighter heavy elements within the energy range of interest ($T_9 = 2 - 5$ GK) [3].

2 Experiment

In order to reduce the uncertainty in nucleosynthesis predictions for the weak r-process, a measurement of the reaction ^{86}Kr(α,n)^{89}Sr was conducted at the TRIUMF ISAC-II facility using the EMMA recoil mass spectrometer [5] and the TIGRESS gamma-ray spectrometer [6]. This reaction was chosen as it has been identified as affecting final elemental abundances under many astrophysical conditions [7, 8]. The reaction was studied in inverse kinematics at two beam energies, 2.6 AMeV and 3.1 AMeV: the former being a measurement within the range of interest for the weak r-process and the latter allowing for a comparison with a previous study that, while failing to produce a cross section, succeeded in measuring the gamma-ray spectrum for the reaction [9]. The recoiling ^{89}Sr nuclei were detected in the focal plane of EMMA at a position determined by the mass-to-charge ratio of each recoiling nucleus. This ratio allows for the identification of the detected nuclei which can be used to set gates on the gamma-rays detected by TIGRESS: only gamma-rays detected in coincidence with recoiling nuclei that had a measured position consistent with that of $^{89}Sr^{20+}$ were used to plot a gamma-ray spectrum. The gates used in the analysis of part one of the experiment (2.6 AMeV) are shown in Figure 1. In this experiment, the act of gating on the time-of-flight peak cut 90% of the total rate in EMMA. The real-to-random events ratio (i.e., the height of the time-of-flight peak above the random coincidence rate) is further improved by the EMMA mass-gate as the ^{89}Sr nuclei have a smaller spread on the focal plane that the random events.

The targets used in this experiment were of a novel design and consisted of helium contained within a silicon matrix; they were made using magnetron sputtering and have a density comparable to gas targets [10]. This work represents their first use in a nuclear astrophysics experiment.

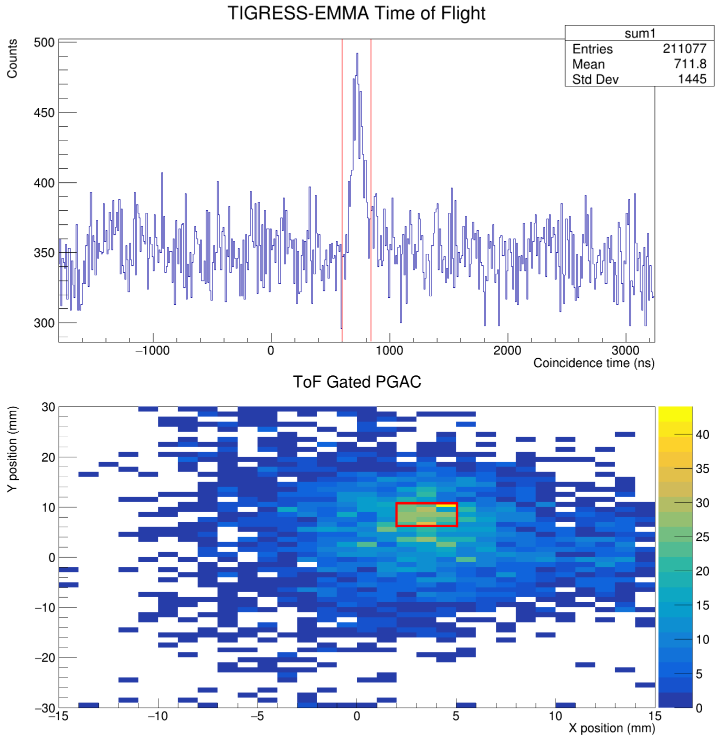

Fig. 1. Above: coincidence time gate between events in EMMA and events in TIGRESS. Below: focal plane gate set on the recoils measured by the EMMA PGAC (position-sensitive parallel grid avalanche counter).

3 Results

Analysis of the data collected in both experiments are underway and a gamma-ray spectrum from the 3.1 AMeV measurement can be seen in Figure 2. The aim is to use the measured counts of individual gamma-rays to deduce the number of times that low lying excited states in ^{89}Sr were populated and from there to infer a cross section based on theoretical predictions for the population of excited states in ^{89}Sr and their decay. Gamma-rays from the de-excitation of the second excited state ($E_x = 1473$keV) were observed at both beam energies. Gamma-rays that occur in random coincidence with events in EMMA can be observed in red on figure 2 and correspond to the background that remains after gating on the EMMA PGAC. These time random counts can be estimated by setting a second gate on the time-of-flight between EMMA and TIGRESS, this time excluding the signal peak (shown in figure 1) then normalising.

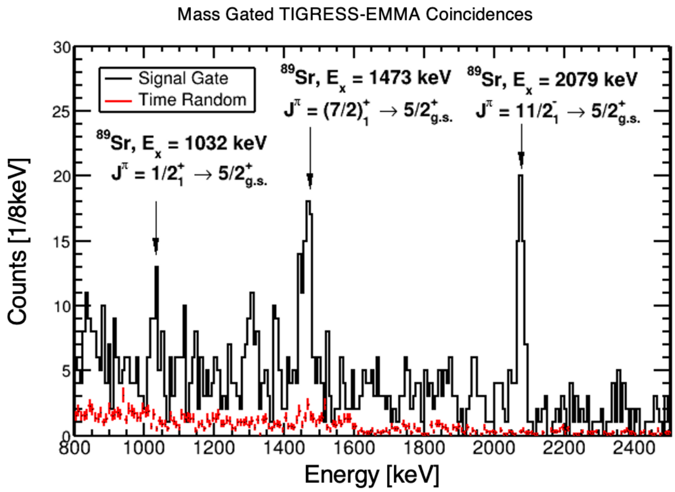

Fig. 2. Gamma spectrum resulting from the ^{86}Kr(α,n)^{89}Sr reaction with a beam of ^{86}Kr at an energy of 3.1 AMeV measured by TIGRESS after recoil mass-gating with EMMA.

4 Summary

This experiment aimed to measure the cross section of the important reaction ^{86}Kr(α,n)^{89}Sr at energies relevant to the weak r-process in the neutrino-driven winds of core-collapse supernovae in order to reduce uncertainty in model predictions for nucleosynthesis in this site. The experiment was conducted at the TRIUMF ISAC-II facility using the EMMA recoil mass spectrometer and the TIGRESS gamma-ray spectrometer along with a novel solid helium target. Analysis is ongoing.

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