EPJ Web of Conferences **275**, 02003 (2023) https://doi.org/10.1051/epjconf/202327502003
11th European Summer School on Experimental Nuclear Astrophysics

Experimental study of $^{37}Cl(\alpha, n)^{40}K$ reaction in order to constrain the reaction rate of destruction of ^{40}K in stars

Nikolaos Dimitrakopoulos[1,5,*], *Georgios* Perdikakis[1,3,5]*Pelagia* Tsintari[1,5], *Carl R.* Brune[2,5], *Thomas N.* Massey[2,5], *Zach* Meisel[2,5], *Alexander* Voinov[2,5], *David C.* Ingram[2,5], *Panos* Gastis[4,5], *Yenuel* Jones-Alberty[2,5], *Shiv K.* Subedi[2,5], *Justin* Warren[2,5], *Kristyn H.* Brandenburg[2,5], *Nisha* Singh[2,5], and *Lauren P.* Ulbrich[1,5]

[1]Department of Physics, Central Michigan University, Mt. Pleasant, MI 48859, USA
[2]Department of Physics & Astronomy,Ohio University, Athens, OH 45701, USA
[3]Facility for Rare Isotope Beams, East Lansing, MI 48824, USA
[4]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[5]Joint Institute for Nuclear Astrophysics –Center for the Evolution of the Elements, East Lansing, MI 48824, USA

Abstract. ^{40}K is one of the main isotopes responsible for the radiogenic heating of the mantle in Earth-like exoplanets [1] and hence, plays a very important role in the internal geophysical dynamics of a planet. The abundance of ^{40}K in the mantle and the core of such planets is not always possible to be determined by astrophysical observations, although constraining the nuclear reaction rates of ^{40}K during stellar evolution can also lead to constraining the present amount of ^{40}K in these planets, which will improve our understanding on the habitability potential of Earth-like exoplanets. This study aims to constrain the ^{40}K(n,α)^{37}Cl reaction rate, one of the two major destruction paths of ^{40}K in stellar nucleosynthesis, by measuring the reverse reaction ^{37}Cl(α,n)^{40}K and applying the principle of detailed balance as we have done before for the ^{40}K (^{40}K(n,p)^{40}Ar reaction rate) [2]. During the first set of measurements we performed differential cross-section measurements of the ^{37}Cl(α,n$_1\gamma$)^{40}K, ^{37}Cl(α,n$_2\gamma$)^{40}K and ^{37}Cl(α,n$_3\gamma$)^{40}K reaction channels, for six different center of mass energies in the range between 5.1 and 5.4 MeV. The experiment took place at the Edwards Accelerator Laboratory of Ohio University. The gamma rays from the reaction channels mentioned above were detected by two LaBr3 scintillators. Using the swinger facility to change the angle of the beam-target system with respect to the detection system, we were able to take measurements for the differential cross-section at six different angles between 20° and 120° in the lab system.

*e-mail: dimt2n@cmich.edu

1 Introduction

Nuclei in the intermediate-mass region are of great interest for nuclear astrophysics [3], yet there is a great experimental deficiency. The unstable isotope of ^{40}K is one of the four main isotopes responsible for the radiogenic heating of the mantle in Earth-like exoplanets, in fact it dominates the planetary heat production about 5 Gyr after galaxy formation [1]. In addition, small quantities of the isotope may be present in the earth's core. The radiogenic heat keeps the mantle and the outer core (consisting mainly of molten iron and nickel) in a state of turbulent convection. The heat-induced motion of the core's outer layers generates the earth's magnetic field, which is essential for developing a habitable environment [4]. In addition, the heating of the mantle controls the formation of plate tectonics, the development of the volcanic activity, and the recycling of carbon on a planet, by controlling the amount of heat it will be extracted from the outer core to the mantle. The abundance of ^{40}K in a planet depends on the composition of the interstellar medium from which it was formed. Thus, nuclear reactions that determine the amount of ^{40}K during stellar evolution (both creation and destruction mechanisms) are not only crucial for understanding the fundamental mechanisms of potassium nucleosynthesis but may also play an essential role in understanding the habitability potential of earth-like exoplanets.

^{40}K is mainly created through three astrophysical processes: hydrostatic carbon shell burning, s-process, and explosive oxygen burning in type Ia supernovae [6, 7]. On the other hand, there are two main destruction paths for ^{40}K, the (n,p) and the (n,α) reactions. In this study, we aim to constrain the (n,α) destruction path, by measuring the time reverse reaction (^{37}Cl(α,n)^{40}K) and applying the principle of detailed balance.

2 Experimental setup

The experiment took place at the 4.5 MV tandem accelerator of the Edwards Acceleration Laboratory using the beam swinger capability of the facility [5]. A DC alpha particle beam was accelerated at energies between 5.65 and 5.95 MeV. The beam impinged into a thin ^{nat}KCl (1.1×10^{18} KCl/cm^2) target that was evaporated on a thin Au layer (1.34×10^{18} Au/cm^2). The composition and thickness of the target were determined via Rutherford Backscattering Spectroscopy, performed in the same facility after the experiment.

In this first measurement, we obtained the gamma rays originating from the de-excitation of the residual nucleus, hence we were able to perform differential cross section measurements for three reaction channels that corresponds to the three first excited states of ^{40}K, namely the ^{37}Cl(α,n$_1\gamma$)^{40}K, ^{37}Cl(α,n$_2\gamma$)^{40}K and ^{37}Cl(α,n$_3\gamma$)^{40}K. The three gamma rays that were measured, along with all the energeticaly allowed excited states of the residual nucleus are presented n Figure 1

For the gamma-ray detection, we placed two 2"x2" $LaBr_3$ detectors radially at 16 and 17 cm from the target, respectively. Both detectors were mounted on a stand to ensure a 52° relative angle between the two detectors in respect to the target. Finally, to determine the gamma-ray angular distribution for each of the reaction channels measured, the swinger magnet of the facility, which allows the beam axis to rotate around the target center, was utilized (Figure 2) enabling the measurement of gamma rays at 20°,45°, 60°,72°,95°, and 122°. Finally, to determine the efficiency of the $LaBr_3$ detectors, various gamma ray source measurements were performed after the experiment.

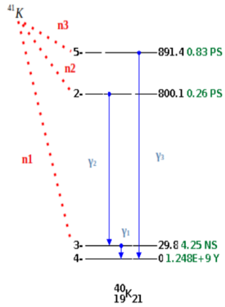

Figure 1. Energetically allowed excited states of the residual nucleus along with the three measured gamma rays .

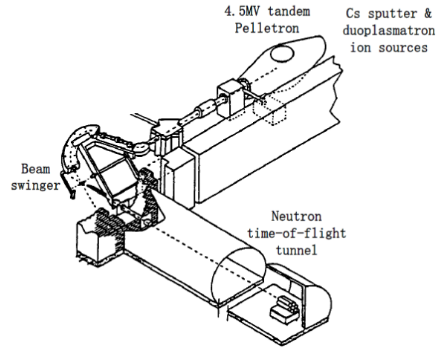

Figure 2. Beam swinger magnet diagram, Edwards Acceleration Laboratory.

3 Preliminary results and future perspectives

In this final section, some preliminary results are presented, along with the future plans for this ongoing study. In Figure 3 the differential cross sections for the reaction channels ^{37}Cl(α,n$_2\gamma$)^{40}K and ^{37}Cl(α,n$_3\gamma$)^{40}K at four different energies and six different angles are shown.Counting statistics is the primary source of the relative uncertainties, which range from 4 to 8 percent for each of these measurements. Furthermore, the gamma ray angular distributions for the two aforementioned reaction channels in two different alpha beam energies are presented in Figure 4. On the left plot, the angular distribution of the gamma rays originating from the de-excitation of the second energy level of ^{40}K at an alpha beam energy of 5.85 MeV is presented. The right plot shows the angular distribution for gamma rays from the third excited state when the target was irradiated with 5.95 MeV alpha particles. In both cases, the function used to fit the data was the first two even terms of Legendre polynomials, and in agreement with older measurements[8], the quadrupole radiation is dominant. The angular uncertainties are due to the diameter of the detectors and their distance from the target.

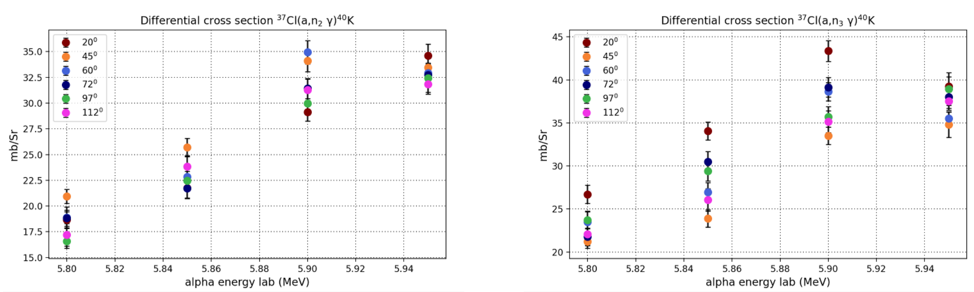

Figure 3. Differential cross sections for ^{37}Cl(α,n$_2\gamma$)^{40}K (left) and ^{37}Cl(α,n$_3\gamma$)^{40}K (right) reaction channels.

https://doi.org/10.1051/epjconf/202327502003

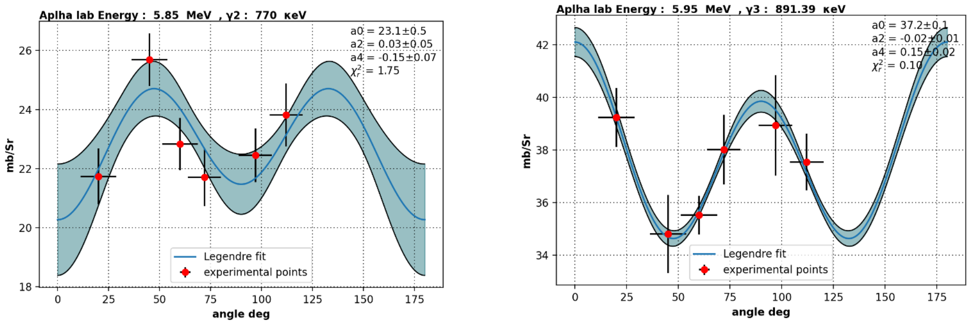

Figure 4. Gamma ray angular distributions from gamma rays originating from ^{37}Cl(α,n$_2\gamma$)^{40}K and ^{37}Cl(α,n$_3\gamma$)^{40}K reaction channels.

Our future perspectives for this work include performing an additional measurement. Along with the existing gamma ray detectors, an array of neutron detectors, namely organic liquid scintillators, will be used. Due to their excellent neutron gamma discrimination capabilities and their efficiency, we will be able to measure the ^{37}Cl(α,n$_0$)^{40}K reaction channel, that was impossible to measure with our current setup and ^{37}Cl(α,n$_1\gamma$)^{40}K. As for the latter, the internal self-activity of the $LaBr_3$ detectors imposed difficulties integrating the corresponding 29.8 keV gamma ray peak. Additionally, a code that reduces LaBr self activity, using a NaI as a reference detector, is currently under development[9]. Once we have measured the differential cross section for all the energetically available reaction channels of ^{37}Cl(α,n)^{40}K, we will be able to integrate them to obtain the total cross section and finally constrain the reaction rate of ^{37}Cl(α,n)^{40}K using the principle of detailed balance. Lastly, we will theoretically investigate the results and the alpha optical potential using Talys code [10], and the final results of this work will be presented in a future publication.

References

[1] Elizabeth A. Frank, Icarusl **243**, 274-286 (2014)
[2] Gastis P., Phys. Rev. C **101**, 16 (2020)
[3] Howard A. J, The Astrophysical Journal **188**, 131-139 (1974)
[4] U.R.Rao, Pramana-J Phy **15**, 33-43 (1980)
[5] Meisel Z., Conference on the Application of Accelerators in Research and Industry, Elsevier B.V (2016)
[6] Iliadis C. *Introduction to Nuclear Astrophysics*
[7] Truran J., The Astrophysical Journal **160**, 181 (1970)
[8] Wechsung R., Nuclear physics A **170**, 557-570 (1971)
[9] Ding Yuan, NIM-A **644**, 33-39 (2011)
[10] A.J. Koning,Proceedings of the International Conference on Nuclear Data for Science and Technology, 211-214 (2008)