Alpha-particle capture reactions in inverse kinematics relevant to p-process nucleosynthesis


Abstract. The first feasibility study of an α-particle capture reaction in inverse kinematics at energies relevant to the p-process was performed at the Wien Filter of the LISE spectrometer at GANIL. Hereby, the $^4\text{He}(^{40}\text{Kr},\gamma)^{82}\text{Sr}$ reaction was investigated using as target an $^4\text{He}$-implanted thin Al foil. The analysis of the data has shown that the determination of $(\alpha,\gamma)$ reaction cross sections at rather low energies around 2 MeV/u in inverse kinematics is indeed feasible regarding the high rejection rate of the primary beam, which in the present work was better than a factor of $10^9$. However, the expected position of the recoils of interest was completely masked by particles of currently unknown origin that could hardly be attributed to scattering of the primary beam. The most probable explanation for the origin of these “pollutants” could be microscopic dust particles of $10^{-5}$ diameter and less, that are extremely difficult to avoid in standard experimental conditions. Hence, the use of a gas-jet target instead of a solid one is compulsory.

Keywords: p process, inverse nuclear capture reactions, $^4\text{He}$-implanted targets.

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MOTIVATION

The synthesis in cosmos of the so-called p nuclei requires a special mechanism known as p process [1] according to which p nuclei are taken to originate from the “burning” of pre-existing more neutron-rich nuclei at stellar environments of very high temperatures ranging from $\approx 1.5$ to $\approx 3.5$ billion degrees Kelvin. Such temperature conditions are expected to be fulfilled in the Oxygen/Neon rich layers of massive stars during their explosion as type II supernovae. The term “p nuclei” refers to the 35 stable proton-rich nuclides which lie “north-west” of the stability valley between $^{74}\text{Se}$ and $^{198}\text{Hg}$. In contrast to all the other nuclei that are heavier than iron, p nuclei cannot be synthesized “conventionally”, i.e. by the two neutron capture processes referred to
as $s$ and $r$ processes. The production of $p$ nuclei via these processes is blocked by stable ("seed") nuclei that shield them from the beta decay of more neutron-rich isobars. Hence, $p$ nuclei are typically 10-100 times less abundant than the corresponding more neutron-rich isotopes.

So far, all the models of $p$-process nucleosynthesis are able to reproduce most of the $p$-nuclei abundances within a factor of 3, but they fail completely in the case of the light $p$ nuclei. Abundance calculations, however, make an extensive use of the nuclear statistical model for the calculation of the reaction rates (reactions/cm$^3$/sec) needed for the solution of an extended reaction network involving over 20000 nuclear reactions on $\approx$2000 nuclei. Since it is impossible to measure the cross sections of all these reactions, the majority of which refer to unstable target nuclei, all extended network calculations have to rely on cross-section predictions by the Hauser-Feshbach (HF) theory. Comparison with ($p,\gamma$) and/or ($n,\gamma$) cross sections indicate that the aforementioned reaction rates can be predicted by the HF theory within a factor of two. However, some of the very few ($\alpha,\gamma$) data show that the reaction rates calculated using phenomenological alpha-particle optical potentials can be wrong by a factor of ten or more. These uncertainties might be reduced substantially by putting constraints in the alpha-nucleus optical potentials that are so far poorly known at low energies ($E<12$ MeV), especially in regions of unstable proton-rich nuclei.

Under these conditions, systematic cross-section measurements of $\alpha$-particle capture reactions at energies between 1.5 and 3 MeV/u are necessary. To achieve this goal, there exist different approaches, amongst which the ($\alpha,\gamma$) measurements at sub-Coulomb energies in inverse kinematics using detectors combined with velocity filters is very transparent and, from the experimental point of view a challenging one. Such measurements are proposed to be carried out mainly in the $A=80\div140$ and $A=170\div200$ mass regions, since detailed theoretical studies [2] of this problem have shown that these are the most sensitive regions to distinguish between different alpha-particle optical potentials. The study of $\alpha$-particle capture reactions in inverse kinematics requires either $^4$He-gas targets or $^4$He-implanted solid-state targets. Recent experimental studies [3] have shown that it is feasible to implant $^4$He ions on thin $^{27}$Al foils with fluences ranging from $10^{17}$ to $10^{18}$ atoms/cm$^2$. Such fluences correspond to target thicknesses that are suitable to perform cross-section measurements of $\alpha$-particle capture reactions in inverse kinematics. In such measurements, cross sections can in principal be determined by counting the produced compound nuclei using, e.g., the Wien Filter (WF) of the LISE3 spectrometer at GANIL. In the present work we report on the $^4$He($^{78}$Kr,$\gamma$)$^{82}$Sr reaction, the first feasibility study of an $\alpha$-particle capture reaction in inverse kinematics at energies relevant to the $p$ process.

THE EXPERIMENTAL SETUP

The $^4$He($^{78}$Kr,$\gamma$)$^{82}$Sr reaction was investigated at an energy of 1.76 MeV/u using the LISE3 spectrometer installed at GANIL. Prior to the GANIL runs, several $^4$He-implanted targets were produced at the 6.4 GHz ECR source of the Cyclotron Laboratory of the University of Jyväskylä (JYFL). The target employed at GANIL consisted of $\approx1.3\times10^{17}$ atoms/cm$^2$ of Helium implanted into a 50 µg/cm$^2$ Al foil. Given
the cross-section expected for the reaction of interest (≥ 100 μb), the difference between the velocity of the \( \text{Kr} \) beam and the compound nucleus \( \text{Sr} \) is ≈5% only. Such a small velocity difference is a real challenge for the separation of the recoiling nuclei and the beam.

The 12 meters long block of Wien Filter (WF) of the LISE spectrometer was used for the separation of the \( \text{Sr} \) nuclei from the primary stable beam \( \text{Kr} \). The major advantage of this device is the fact that the selection of the nuclei of interest is based on the velocity and not on the charge state of the ions. The intensity of the primary beam was \( 7.8 \times 10^9 \) pps. The main part of the primary beam was stopped on the “61W” slits located in the center of the WF and the rest was stopped on the “62” slits located at the end of the spectrometer, as shown in fig. 1.

In this setup the velocity acceptance was 0.55% and the average angular acceptance was 32 mrad. The angular straggling was ≈3 mrad and the energy (velocity) straggling of the \( \text{Sr} \) was 0.3% (0.15%) and for the beam the momentum straggling depends practically only on accelerator emittance which was ≈0.1%. Due to very restrictive experimental conditions, especially keeping in mind that the difference of the velocities between the beam and the compound nucleus is ≈5%, extensive ion optics simulations were necessary. As the LISE WF has a peculiar shape of fringe fields, it was not possible to use some standard ion optics codes such as TRANSPORT or COSY INFINITY. Thus we used the “raytrace” type of code ZGOUBI, version 5.1.0. Beside the WF, it was necessary to have a fine tuning of the quadrupoles as well.

**RESULTS AND CONCLUSION**

The analysis of the data has shown that the measured rejection factor of the primary beam is very good, i.e. higher than \( 10^9 \). However, we have also observed particles at \( 84 \) MeV that cannot be explained neither by energy loss and scattering in the target (see figure 2) nor by the scattering elsewhere in the separator. Since the target is very thin, the most probable reason for this energy discrepancy is microscopic dust deposited on the target. The dust particles of diameter from 10 μm down to 1 μm are
present in the atmosphere with density of ≈1 cm⁻³. There is a high probability for them to be attached to the target, especially if we consider the possible influence of the static electricity.

![Image 1](image1.png)

**FIGURE 2.** The time of flight vs. energy graph

![Image 2](image2.png)

**FIGURE 3.** SRIM simulation of the beam scattering at the target: The energy and the counting rate of the locus 84 MeV cannot be explained by the straggling in the target. The SRIM simulation of 5x10⁶ particles doesn’t show a single event, inside the average acceptance angle (< 32 mrad) with an energy around 117 MeV (which corresponds to 84 MeV after passing through two MCPs).

The measured energy spread of the locus (from now on called the locus 84 MeV) of an unknown contribution is approximately 5 MeV with a centroid around 84 MeV. Actually, an energy of 84 MeV measured by the silicon detector is degraded by two MCP detectors which means that the energy of the beam through the WF was 117 MeV, i.e., relatively close (1% difference) to the selected velocity. This difference can come due to the fact that the final energy is a folding between the energy (velocity), angular distribution and the ion optics transmission function. The energy of 117 MeV could correspond to an energy loss of the primary beam passing through 2.5 µm and 2.0 µm of PVC for example. Thus we performed a simplified model of a spherical PVC dust particle of 2.5 µm in diameter deposited on the surface of the target. If such particle is placed at the beam spot on the target, it can produce the energy seen at the locus 84 MeV. The shaded (yellow) area of the dust particle (figure 4) would induce such energy loss that the beam would have energies in the range 81.5 – 86.5 MeV. The effective surface of the shaded (yellow) area seen by the beam is ≈ 1.5 µm². The beam spot on the target has diameter of ≈3 mm which corresponds to ≈7.1 mm². The ratio of
this area and the beam spot area on the target multiplied by the beam intensity ($\approx 8 \times 10^9$ pps - 10 nA of $^{78}\text{Kr}^{+}$) gives the yield of a beam of $\approx 2000$ pps with energy in the range 81.5 – 86.5 MeV, which is more or less what we observed. This calculation is quite crude; nevertheless it shows that the dust problem cannot à priori be neglected; instead it appears to play a crucial role.

During the experiment, we experienced an unexpected problem of two energy peaks of the primary beam on several silicon detectors. Such behavior is seldom encountered. We explained this problem by a coupling of two effects – the channeling and the recombination. This behavior was already noticed in few experiments [4] and had a same explanation as ours. Although this problem is encountered also at high energies it is probable that it will be encountered more often at low energies (the energies of astrophysical interest), which should be considered in the future.

![FIGURE 4. Dust particle of PVC attached to the target, proposed as an example of possible origin of the locus 84 MeV. The shaded area is a part of the dust particle where the primary beam should pass in order to have energy in the range 81.5 – 86.5 MeV. The effective surface of the shaded area is 1.5 $\mu$m$^2$, giving for the yield of $\approx 2000$ pps for the given beam intensity.]

In conclusion, it was not possible to separate any events attributed to the $^{82}\text{Sr}$ (see figure 2), mainly due to two reasons: the high presence of the background at our zone of interest coming from the locus 84 MeV and the slight discrepancy between the velocity selected by the WF and the expected velocity of the $^{82}\text{Sr}$. Such type of experiment requires extensive ion optics simulations, which, besides the WF, have to include the fine tuning of the quadrupoles. The obtained rejection factor was quite good, i.e. higher than $10^9$. Regarding the high risk of the scattering on the dust deposited on the solid target, the use of the gas windowless target seems to be indispensable. Considering the achieved rejection factor of the primary beam and the possibility of the usage of the windowless gas target, this type of experiment appears very promising.

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REFERENCES
