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^{40}Ar proposed as probe of neutron-induced reactions in a high-density stellar-like plasma at the National Ignition Facility

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Abstract. The thermodynamical conditions and the neutron density produced in a laser-induced implosion of a deuterium-tritium (DT) filled capsule at the National Ignition Facility (NIF) are the closest laboratory analog of stellar conditions. We plan to investigate neutron-induced reactions on ^{40}Ar, namely the ^{40}Ar$(n, 2n)^{39}$Ar($t_{1/2}$ =268 y), the ^{40}Ar$(n, \gamma)^{41}$Ar(110 min) and the potential rapid two-neutron capture reaction ^{40}Ar$(2n, \gamma)^{42}$Ar(33 y) in an Ar-loaded DT capsule. The chemical inertness of noble gas Ar enables reliable collection of the reaction products.

1 Introduction

Reactions of astrophysical interest in the *s*-process regime have been extensively studied in the laboratory [1] but *r*-process rapid neutron captures occurring in explosive nucleosynthesis at very high neutron densities (in the range 10^{22}–10^{25} neutrons/cm^3) [2] have been beyond the realm of terrestrial experiments. Deuterium-tritium (DT) inertial confinement fusion implosions at laser facilities like the National Ignition Facility (NIF) are a unique environment for approaching the conditions of explosive nucleosynthesis in the laboratory. High-power laser beams, directed to a DT-filled capsule at the center of a large chamber, compress and heat the DT fuel to thermodynamical conditions (density, temperature, and pressure) comparable to or exceeding those in the center of stars. Recent experiments at NIF first passed the burning-plasma threshold [3–6], where self-heating exceeds the external heating applied to the fuel, and then produced record fusion yields of > 1 MJ [6], see also [7] for a review article. Neutrons are produced by the DT thermonuclear process in a volume with a radius of

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≈ 50 μm within ≈ 100 ps, representing neutron fluxes of 10^{31} cm^{-2}s^{-1} and a neutron density approaching 10^{22} cm^{-3}, for the first time close to those of the astrophysical *r* process [2] in a laboratory setting. Although DT neutrons are produced at ≈ 14 MeV (unlike stellar neutrons in the energy range of 10–100 keV), they are partly energy-downgraded by scattering in the high-density environment (> 1000 g/cm^3) of the NIF implosion. The study of neutron capture reactions, which have a strong energy-dependence, is expected to reveal the extent of the neutron thermalization in the medium and provide also information on areal density, a critical implosion parameter.

A laser shot and experiment dedicated to these studies was approved as part of the Discovery Science program at NIF and was performed in October 2022 (not yet analyzed). Our experiment is aimed specifically at the study of neutron-induced reactions on ^{40}Ar seeds incorporated in the DT-filled capsule. Noble gas argon was selected for its chemical inertness ensuring reliable collection of its gaseous isotopic reaction products after dispersion of the capsule debris. The ^{40}Ar$(n, 2n)^{39}$Ar$(t_{1/2} = 268$ y), the ^{40}Ar$(n, \gamma)^{41}$Ar(110 min) and ^{40}Ar$(2n, \gamma)^{42}$Ar(33 y), a potential rapid two-neutron capture reaction, will be investigated. Long-lived ^{39,42}Ar products can be detected at ultra-high sensitivity by the Noble Gas Accelerator Mass Spectrometry (NOGAMS) technique (see [8] for details) and ^{41}Ar by γ spectrometry,

2 Capsule and laser shot design and collection of argon reaction products

For our NIF experiment, the argon dopant is loaded inside the DT-filled capsule, imploding in a so-called indirect drive and shown schematically in Fig. 1. The NIF lasers (1.8 MJ, 400 TW) irradiate the inside of a small high-Z cell, termed ‘hohlraum’, cantilevered at the center of the large NIF vacuum chamber (10 m diameter). The hohlraum has 3.45 mm diameter apertures on either end through which the laser beams enter. The laser energy is converted into a thermal X-ray bath inside the hohlraum, which drives a high-density-carbon (HDC) capsule located at the center. Ablation of the HDC compresses by inertial confinement the DT fuel to fusion conditions. The fuel is equimolar DT gas at 4mg/cc with 0.1% atomic Ar dopant. As the implosion stagnates and fusion conditions are reached, the D and T react producing 14 MeV neutrons, which irradiate the Ar.

After the capsule implosion, the remaining target capsule explodes outward, releasing residual target gases (D, T, H atoms or molecules, He and the gaseous reaction products from the Ar component) into the NIF target chamber. To help the collection of the reaction products, a 15-30 cm^3 STP stable isotope carrier containing enriched ^{38}Ar and ^{nat}Ar (^{38}Ar/Ar≈ 1/3) is released into the NIF chamber 10 seconds after the shot time. The ^{38}Ar component is needed for differentiation from Ar present in the residual gas of the NIF chamber. The chemical inertness of noble gas argon enables reliable collection of the Ar isotopic products and the Ar carrier gas. The Radiochemical Analysis of Gaseous Species (RAGS) diagnostic system at NIF [9] collects gas from the target chamber for up to 15 minutes after shot execution. Based on the ^{39}Ar abundance sensitivity of the NOGAMS technique (^{39}Ar/Ar $\lesssim 10^{-15}$) [8, 10], the experiment is able to detect Ar reaction products down to the range of 10^4-10^5 atoms.

3 Detection of ^{39}Ar from the ^{40}Ar$(n, 2n)^{39}$Ar reaction

In order to establish conditions of the NOGAMS analysis of ^{39}Ar produced in the NIF shot, the following samples were prepared in separate *ad hoc* irradiations and analyzed. They will be used as calibration samples in our NIF-shot experiment.

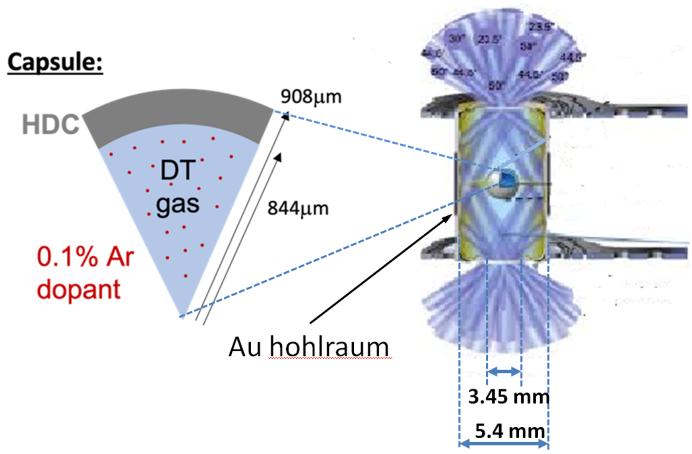


Figure 1: Target used for the NIF experiment: the hohlraum is made of Au, with a HDC capsule at the center. The laser beams are depicted to enter the hohlraum through the top and bottom apertures. The capsule is filled with DT gas that contains a 0.1% Ar dopant. The figure is adapted from [7].

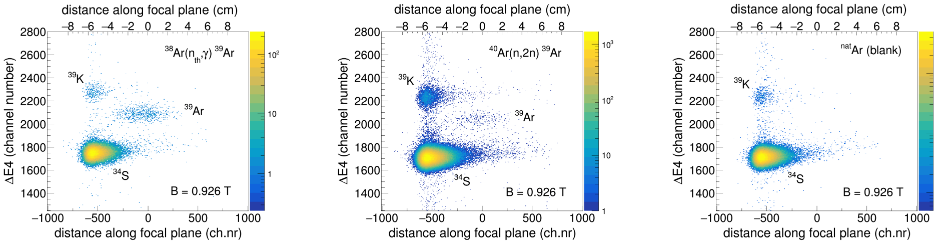
A ^{39}Ar sample was produced at Soreq NRC (Israel) by thermal neutron activation of enriched ^{38}Ar (99.961%) contained in a quartz ampoule. The sample (denoted by SNRC) was diluted with ^{38}Ar and ^{40}Ar (^{38}Ar/^{40}Ar= 9.5%) to produce a sample measurable by AMS with a ratio ^{39}Ar/Ar$\approx 10^{-12}$.

A 20 mm diameter stainless steel spherical ampoule (denoted by HZDR) made of thin stainless steel (0.5 mm thickness) was cryogenically filled with Ar gas enriched in ^{40}Ar. The sphere was activated during four hours in the 14 MeV neutron flux of the DT generator [11] of Technical University Dresden at Helmholtz Zentrum Dresden Rossendorf, together with appropriate neutron monitors (Al, Zr, Nb) to produce ^{39}Ar by the ^{40}Ar$(n, 2n)$ reaction.

Fig. 2 shows identification spectra for the SNRC, HZDR and the blank (non-irradiated) Ar samples in a NOGAMS experiment performed at Argonne National Laboratory for ^{39}Ar accelerated at charge state 8+ under conditions similar to those described in [10, 12]. The newly commissioned MONICA detector [13] was used in this experiment. The ^{39}Ar group is clearly identified, both in position and in ΔE4 energy loss and separated from beam contaminants (^{34}S accelerated as ^{34}S^{7+} nearly identically as ^{39}Ar^{8+} ($\delta(m/q)/(m/q) \approx 0.4\%$) and stable ^{39}Kr isobar partly deflected outside the detector acceptance). The results are currently being analyzed to extract the ^{40}Ar$(n, 2n)^{39}$Ar reaction cross section.

A recent test experiment was conducted at NIF before the dedicated October 2022 laser shot in a configuration similar to that shown in Fig. 1 with an Ar content of 0.05% in the DT capsule. A first signal of ^{39}Ar, produced by the ^{40}Ar$(n, 2n)^{39}$Ar reaction within the inertially-confined fusion environment, was observed and is illustrated in Fig. 3. The signal is being studied quantitatively together with possible background production of ^{39}Ar.

In future experiments, we aim to search for a ^{42}Ar signal produced by the rapid two-neutron capture ^{40}Ar$(2n, \gamma)$ reaction. The detection of ^{42}Ar by the NOGAMS technique was demonstrated for the first time in a calibration sample produced in a high-fluence thermal neutron irradiation of ^{40}Ar. Preliminary results were presented in [13].



(a) (b) (c)

Figure 2: Identification spectra (energy loss vs. focal-plane position) of ions accelerated to 5.5 MeV/u and detected in the focal plane of the Argonne Enge gas-filled spectrograph (see [8, 12] for details): ^{39}Ar ions detected in (a) sample SNRC thermal-neutron activated ^{38}Ar (^{39}Ar/^{40}Ar= 6.3×10^{-12}); (b) 14-MeV neutron-activated ^{40}Ar (sample HZDR); (c) non-activated (blank) ^{nat}Ar under same conditions in (a), (b).

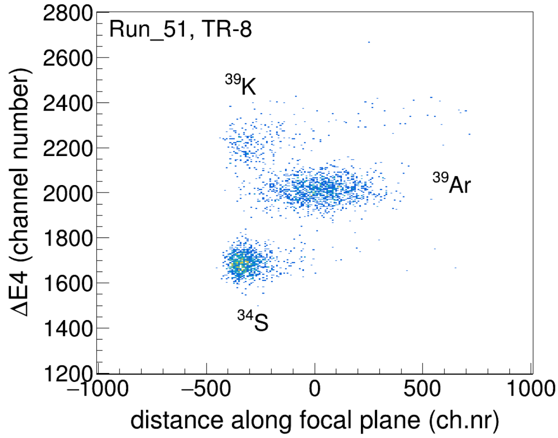


Figure 3: First signal of ^{39}Ar produced by the ^{40}Ar$(n, 2n)^{39}$Ar reaction in a NIF laser shot on a DT-Ar(0.05 at%) filled capsule. The axes in the figure are the same as in Fig. 2.

4 Summary

We described an experimental platform based on Noble-Gas Accelerator Mass Spectrometry (NOGAMS) for the study of neutron-induced reactions in the high-density plasma of a NIF implosion of a DT-Ar filled capsule. ^{39}Ar produced in calibration samples by the ^{38}Ar$(n,\gamma)^{39}$Ar and the ^{40}Ar$(n, 2n)^{39}$Ar reactions were identified. A first signal of ^{39}Ar produced by the ^{40}Ar$(n, 2n)^{39}$Ar reaction in a NIF shot on an DT-Ar filled capsule was observed. The results are under quantitative analysis.

5 Acknowledgements

This talk was dedicated to the memory of our long-time collaborator Franz Käppeler whose enthusiasm and approach to laboratory nuclear astrophysics remain for us as a beacon of guidance.

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