Author(s): Romero, J.; Auranen, K.; Block, M.; Briscoe, A. D.; Eronen, T.; Gins, W.; Grahn, T.; Greenlees, P. T.; Illana, A.; Julin, R.; Joukainen, H.; Jutila, H.; Khuyagbaatar, J.; Krier, J.; Leino, M.; Louko, J.; Luoma, M.; Moore, I. D.; Mosat, P.; Ojala, J.; Ortiz-Cortés, A.; Pakarinen, J.; Papadakis, P.; Plaza, A. M.; Rahkila, P.; Raggio, A.; Ruotsalainen, P.; Sarén, J.; Sandzelius, M.; Tolosa-Delgado, A.; Uusitalo, J.; Zimba,

Title: Nuclear Reaction Studies and Prospects for the New MARA-LEB Facility

Year: 2023

Version: Published version

Please cite the original version:

Romero, J., Auranen, K., Block, M., Briscoe, A. D., Eronen, T., Gins, W., Grahn, T., Greenlees, P. T., Illana, A., Julin, R., Joukainen, H., Jutila, H., Khuyagbaatar, J., Krier, J., Leino, M., Louko, J., Luoma, M., Moore, I. D., Mosat, P., . . . Zimba, G. (2023). Nuclear Reaction Studies and Prospects for the New MARA-LEB Facility. Acta Physica Polonica B : Proceedings Supplement, 16, Article 4-A12. https://doi.org/10.5506/APhysPolBSupp.16.4-A12

Acta Physica Polonica B Proceedings Supplement **16**, 4-A12 (2023)

NUCLEAR REACTION STUDIES AND PROSPECTS FOR THE NEW MARA-LEB FACILITY*

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Received 30 November 2022, accepted 2 January 2023,
published online 22 March 2023

A Low Energy Branch for the MARA separator, MARA-LEB, is under construction at the University of Jyväskylä, Finland. It will be used to purify and study exotic beams initially via nuclear decay and laser spectroscopy. Two experiments have been performed using the MARA separator to determine the acceptance of the gas cell and to assess the feasibility of future experiments at the new facility. Products of different reaction mechanisms have been produced and their transmission from the focal plane of MARA into the LEB gas cell has been estimated. In one experiment, medium-mass nuclei have been produced in fusion–evaporation reactions. In a second experiment, with the primary goal of studying the non-fusion reaction dynamics, heavy target-like fragments from multi-nucleon transfer reactions have been produced. Production cross sections have been measured and are presented in this work.

DOI:10.5506/APhysPolBSupp.16.4-A12

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[*] Presented by J. Romero at the Zakopane Conference on Nuclear Physics, *Extremes of the Nuclear Landscape*, Zakopane, Poland, 28 August–4 September, 2022.

1. Introduction

The Low Energy Branch (LEB) [1] for the Mass Analysing Recoil Apparatus (MARA) [2] is a facility under construction in the Accelerator Laboratory of the University of Jyväskylä. MARA-LEB is designed to investigate exotic nuclei far from stability, taking advantage of MARA's high mass selectivity [2]. In the early conceptual design phase of the facility, the proton-rich $N \sim Z$ regions around ^{80}Zr, ^{94}Ag, and ^{100}Sn were highlighted due to their scientific interest. Their proximity to the $N = 50$ and $Z = 50$ magic numbers, the $N = Z$ line, and the proton dripline makes this region a fertile ground for the testing of nuclear models and their predictions [3, 4]. The rapid proton capture (rp) [5] and the neutrino-induced nucleosynthesis (νp) [6] processes traverse this region, thus accurately measuring the nuclear properties of these isotopes becomes crucial in the development and verification of astrophysical nucleosynthesis models.

The actinide elements ($89 \leq Z \leq 103$) have emerged as a new region of interest for MARA-LEB. These nuclei have grown in scientific significance in recent years, especially due to the technical and methodological developments of laser spectroscopy that have allowed access to ground-state nuclear structure properties of exotic species in this region [7]. Access to this region of nuclei can be achieved via fusion–evaporation (FE) reactions. Other reaction channels, such as multi-nucleon transfer (MNT), provide alternative access routes to the region. However, the reaction dynamics of these alternative paths are not yet fully understood and intensive experimental study is ongoing [8, 9]. The use of MNT reactions in combination with the MARA-LEB facility is foreseen as a promising future opportunity for experiments, opening up the possibility of laser spectroscopy of actinides.

2. The MARA-LEB facility

The MARA-LEB facility combines several ion manipulation techniques to purify low-energy radioactive beams produced and initially separated by MARA [1]. Reaction products, known as recoils, are focused by MARA into a small-volume gas cell, containing a laminar flow of a noble buffer gas (typically helium or argon). Recoils are stopped, thermalised, and neutralised in argon gas before being laser ionised via multi-step resonant laser ionisation. For experiments not involving laser ionisation, helium can be used for reduced extraction times, in a manner similar to operations at the IGISOL facility.

Multi-step laser ionisation of neutralised recoils allows for the selection of specific elements, while others remain neutral. Non-neutralised recoils are collected by electrodes before exiting the gas cell. Ionised recoils are extracted and accelerated to 30 kV by the use of radio-frequency quadrupole guides and ion-optical elements [10]. The ions are further mass and energy separated by the use of a dipole magnet and an electrostatic deflector operated at 90°, which also directs the ions towards experimental stations.

3. Experiments at MARA

The combination of ion-optical elements at MARA allows for recoils to be separated by their mass-over-charge (m/q) ratios, in addition to being focused onto a position-sensitive detector [2], usually a Multi-Wire Proportional Chamber (MWPC). The products of nuclear reactions are mass- and energy-selected and focused onto the focal plane detector system. They are detected by the MWPC in well-defined m/q clusters, known as charge states. The MARA ion-optical settings can be adjusted to centre a particular charge state or the midpoint between two consecutive charge states (referred to as focusing on a half-charge state) onto the middle of the MWPC. In both of these cases, adjacent charge state clusters can also be detected in the MWPC with the distance between them depending on the selected mass and energy of the recoils.

The MARA-LEB gas cell will be positioned at the focal plane of MARA, thus the design of its entrance window is dependent on the spatial distribution of recoils at the focal plane.

An experiment, designed to estimate the production of ^{94,96}Ag, was performed at the MARA facility using the ^{40}Ca(^{58,60}Ni, $p3n$)^{94,96}Ag fusion–evaporation reactions. The production of both silver isotopes of interest in this more limited, exploratory type of experiment proved insufficient for them to be clearly identified over other contaminants with higher production cross sections, further justifying the need for additional beam purification with MARA-LEB for studies in this region. Instrumental data, however, could be extracted from the experiment. Namely, by selecting a contaminant of mass number $A = 96$, the spatial distribution of recoils of this mass could be examined in order to make decisions on the design of the gas-cell window. ^{96}Pd was abundantly produced via ^{40}Ca(^{58}Ni, $2p$)^{96}Pd. By identifying it via γ-ray tagging and excluding all other recoils, an image of palladium ions at the focal plane could be produced. By analysing these images with different MARA focus settings, the influence of window size on gas-cell acceptance could be quantified.

Acceptance into the gas cell was analysed in terms of the radius of the windows while scanning across the position of the charge states on the window. The cases of two- and three-charge states being accepted into the gas cell were studied and are exemplified on the left and right, respectively, of Fig. 1. At a radius of 32 mm, centring the window on a half-charge state, the entirety of the clusters with charges 26 and 27 enter the gas

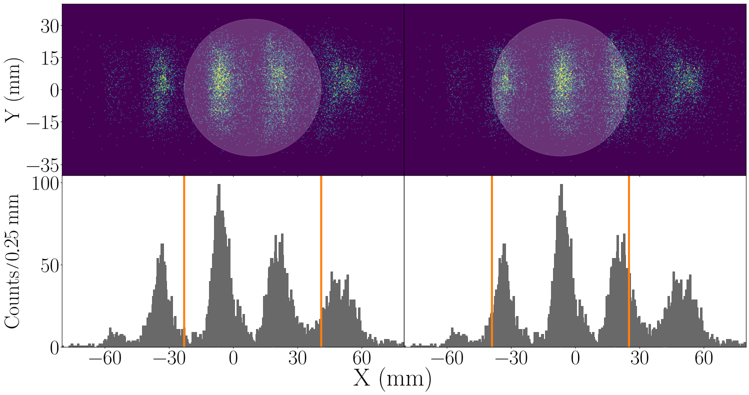

Fig. 1. 32 mm-radius gas-cell window superimposed onto the recoil image at the MARA focal plane (top) and its dispersive plane projection (bottom) for ^{96}Pd recoils. On the left, the window is centred between charge states 26 and 27, accepting two entire charge states. On the right, the window is centred onto charge state 27, accepting it entirely and most of the adjacent charge states.

cell (Fig. 1, left). This constitutes an acceptance of 58% of the ^{96}Pd recoils arriving at the MWPC. For a window of the same size, but centred on the most intense charge state, 63% of the recoils detected in the MWPC enter the gas cell, as an entire cluster and most of the immediate adjacent ones are accepted (Fig. 1, right).

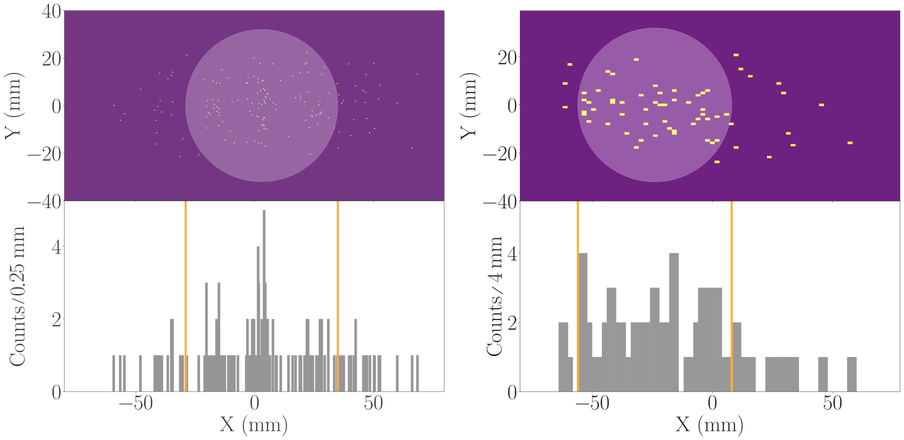

Fig. 2. 32 mm-radius gas-cell window superimposed onto the recoil image at the MARA focal plane (top) and its dispersive plane projection (bottom), centred on the most populated charge state. ^{213}Rn is shown on the left. ^{226}Th is shown on the right, with a coarser binning that allows for data to be more easily visualised.

Recently, experiments have been performed at MARA by the GSI-JYFL Collaboration aiming to study the dynamics of non-fusion reactions. The experimental data from these experiments are currently under evaluation [11].

In connection with MARA-LEB, the energy and position of certain reaction products were investigated. Figure 2 illustrates the position of ^{213}Rn and ^{226}Th, produced via the ^{65}Cu+^{209}Bi and ^{65}Cu+^{238}U reactions, respectively. Considering a gas-cell window with a radius of 32 mm, the acceptance into the gas cell as a percentage of the total number of recoils of the same species arriving at the MWPC is given in Table 1 for all reactions. These reactions were also used to estimate production yields for heavier isotopes which are now of interest for MARA-LEB. Table 2 shows the preliminary cross-section values for selected products of these reactions within the 10 msr acceptance of the MARA separator.

Table 1. Acceptance (α) of different recoils into the gas cell as a percentage of those that arrive at the MWPC, for different cases and number of charge states (n_{chst}) accepted into the window.

Case	n_{chst}	α [%]
^{96}Pd	2	58.5
^{96}Pd	3	62.7
^{213}Rn	3	70.6
^{226}Th	3	75.0

Table 2. Preliminary cross-section values (σ) for selected products within the MARA separator accepted solid angle.

Isotope	Target	σ [μb]
^{211}Po	^{209}Bi	2.9(2)
^{212}Rn	^{209}Bi	2.7(2)
^{213}Rn	^{209}Bi	2.2(2)
^{213}Fr	^{209}Bi	1.8(2)
^{221}Ac	^{238}U	1.6(3)
^{221}Ra	^{238}U	2.1(3)
^{223}Ac	^{238}U	1.9(3)
^{226}Th	^{238}U	2.4(3)

4. Conclusions

In addition to supporting the design of the MARA-LEB gas-cell window, the experiments described in this work have served as a proof of concept for experiments at the new facility. In particular, the production of recoils from FE and MNT reactions is a promising first step for new experimental possibilities for MARA-LEB.

Cross sections as low as 0.5 μb have proven to be sufficient for laser spectroscopy with primary beam intensities in the order of hundreds of particle nA [12]. Primary beam intensities of that order and similar target thicknesses can be expected in MARA-LEB experiments, thus laser spectroscopy of actinides and other heavy isotopes may well be feasible at the new facility, depending on the different efficiencies that will need to be determined once the facility is operational.

This project has received funding from the Academy of Finland under project number 315179 (In-gas-jet laser spectroscopy near the proton dripline) and the European Union's Horizon 2020 research and innovation programme under grant agreement number 861198-LISA-H2020-MSCA-ITN-2019.

REFERENCES

[1] P. Papadakis *et al.*, *Hyperfine Interact.* **237**, 152 (2016).
[2] J. Uusitalo, J. Sarén, J. Partanen, J. Hilton, *Acta Phys. Pol. B* **50**, 319 (2019).
[3] T. Faestermann, M. Górska, H. Grawe, *Prog. Part. Nucl. Phys.* **69**, 85 (2013).
[4] P. Gysbers *et al.*, *Nat. Phys.* **15**, 428 (2019).
[5] R.K. Wallace, S.E. Woosley, *Astrophys. J. Suppl. Ser.* **45**, 389 (1981).
[6] C. Fröhlich *et al.*, *Phys. Rev. Lett.* **96**, 142502 (2006).
[7] M. Block, M. Laatiaoui, S. Raeder, *Prog. Part. Nucl. Phys.* **116**, 103834 (2021).
[8] S. Heinz, H.M. Devaraja, *Eur. Phys. J. A* **58**, 114 (2022).
[9] A. Di Nitto *et al.*, *Phys. Lett. B* **784**, 199 (2018).
[10] P. Papadakis *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **463**, 286 (2020).
[11] J. Khuyagbaatar *et al.*, to be published.
[12] S. Raeder *et al.*, *Phys. Rev. Lett.* **120**, 232503 (2018).