University of Groningen

Experimental techniques for in-ring reaction experiments

Mutterer, M.; Egelhof, P.; Eremin, V.; Ilieva, S.; Kalantar-Nayestanaki, N.; Kiselev, O.; Kollmus, H.; Kroell, T.; Kuilman, M.; Chung, L. X.

Published in:
Physica Scripta

DOI:
[10.1088/0031-8949/2015/T166/014053](https://doi.org/10.1088/0031-8949/2015/T166/014053)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2015

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Mutterer, M., Egelhof, P., Eremin, V., Ilieva, S., Kalantar-Nayestanaki, N., Kiselev, O., Kollmus, H., Kroell, T., Kuilman, M., Chung, L. X., Najafi, M. A., Popp, U., Rigollet, C., Roy, S., von Schmid, M., Streicher, B., Traeger, M., Yue, K., Zamora, J. C., & EXL Collaboration (2015). Experimental techniques for in-ring reaction experiments. *Physica Scripta*, (T166), [014053]. <https://doi.org/10.1088/0031-8949/2015/T166/014053>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Experimental techniques for in-ring reaction experiments

M Mutterer^{1,3}, P Egelhof¹, V Eremin², S Ilieva³, N Kalantar-Nayestanaki⁴, O Kiselev¹, H Kollmus¹, T Kröll³, M Kuilman⁴, L X Chung⁵, M A Najafi⁴, U Popp¹, C Rigollet⁴, S Roy⁴, M von Schmid³, B Streicher^{1,4}, M Träger¹, K Yue^{1,6} and J C Zamora³ for the EXL Collaboration

¹ GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany

² Ioffe Physical Technical Institute, Russian Academy of Science, 194021 St. Petersburg, Russia

³ Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany

⁴ KVI-CART, Rijksuniversiteit Groningen, 9747 AA Groningen, The Netherlands

⁵ Institute for Nuclear Science and Technology, Vietnam Atomic Energy Institute, Hanoi, Vietnam

⁶ Institute of Modern Physics, Chinese Academy of Science, 730000 Lanzhou, People's Republic of China

E-mail: M.Mutterer@gsi.de

Received 21 November 2014

Accepted for publication 22 January 2015

Published 26 November 2015

Abstract

As a first step of the EXL project scheduled for the New Experimental Storage Ring at FAIR a precursor experiment (E105) was performed at the ESR at GSI. For this experiment, an innovative differential pumping concept, originally proposed for the EXL recoil detector ESPA, was successfully applied. The implementation and essential features of this novel technical concept will be discussed, as well as details on the detectors and the infrastructure around the internal gas-jet target. With $^{56}\text{Ni}(p, p)^{56}\text{Ni}$ elastic scattering at 400 MeV u^{-1} , a nuclear reaction experiment with stored radioactive beams was realized for the first time. Finally, perspectives for a next-generation EXL-type setup are briefly discussed.

Keywords: in-ring experiments, UHV technology, differential pumping, radioactive beams, elastic proton scattering, $^{56,58}\text{Ni}$

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years, nuclear reaction studies with storage rings have attracted much interest since they give access to scattering processes at very low momentum transfer. The present work focuses on the implementation of complex granular detector arrays for nuclear reaction experiments in the UHV environment of a storage ring. The concept to be presented here was borne out when designing the detection system for the upcoming project 'EXotic nuclei studied in Light ion induced reactions (EXL)' [1, 2] at the New Experimental Storage Ring (NESR) as a part of the future FAIR facility. By means of reaction experiments in inverse kinematics, EXL provides for studying various physics phenomena in unstable nuclei [3–5]. The crucial part of EXL is the 4π ball-shaped detector for recoil particles, ESPA (figure 1). This detector

array consists of telescope-like segments which, depending on the different angular ranges, house pairs of double-sided silicon strip detectors (DSSDs) for particle tracking and identification, and the subsequent thick silicon pad and Si(Li) detectors, as well as CsI scintillator crystals, for the spectroscopy of higher-energy particles. The innermost spherical arrangement of DSSDs should enable detection of light recoil particles (i.e., p, d, t, ^3He and α) down to about 100 keV energy, as required for particular reactions at low momentum transfer. From a technical point of view, a major challenge is to install so many (up to 700) detectors together with related front-end electronics, connectors and cables, and possibly cooling circuits, around the beam–target interaction zone of the NESR where the need of an UHV below the order of 10^{-10} mbar requires low-outgassing and bakeable materials.

Figure 1. *Left:* sketch of the future 4π EXL silicon particle array ESPA around the gas-jet target zone of the NESR [1, 2]. *Right:* illustration of the differential pumping concept for ESPA. The inner shell of DSSDs isolates the UHV in the storage ring from less stringent auxiliary vacuum (AV) housing the other ESPA instrumentation.

Figure 2. (a) UHV scattering chamber with detectors, slit aperture and calibration source used in the E105 experiment. (b) Exploded view of the DSSD1 detector telescope with a pair of cooled Si(Li)s (drawings by Lindemulder, KVI-CART).

2. Experimental techniques for the EXL project

2.1. Vacuum concept for the silicon particle array (ESPA)

For the operation of all detectors in the NESR environment, a new differential pumping concept was envisaged where the UHV interconnected with the storage ring is maintained inside the innermost sphere of DSSDs which is acting as a vacuum barrier to an outer volume with an auxiliary vacuum (AV) (see figure 1) [6]. The AV can tolerate much less stringent vacuum quality and may, thus, contain all subsequent layers of detectors, as well as all unbakeable and thus outgassing electronic components and supporting material. Since the vacuum barrier serves at the same time the purpose of an active window it enables the detection of recoil particles down to the lowest energies required by EXL.

2.2. Experimental set-up for measuring elastic scattering of stored $^{56,58}\text{Ni}$ ions on protons at the ESR storage ring

Since the NESR will not be part of the first construction phase of FAIR, a start-up EXL experiment (E105) was performed at the ESR at GSI. As proof of concept for the innovative vacuum design for the ESPA detection system, based on the differential pumping idea, it was realized inside a dedicated UHV scattering chamber built for the internal gas-jet target section of the ESR. The experiment aimed at (i)

commissioning with stable ^{58}Ni beam on H_2 and ^4He targets [7], (ii) studying ^{20}Ne at 50 MeV u^{-1} on H_2 target (experiment E87) [8] and, in particular, (iii) accurately measuring $^{56}\text{Ni}(p, p)^{56}\text{Ni}$ at 400 MeV u^{-1} , as a first nuclear reaction study with radioactive beams in a storage ring [4, 9, 10]. The measured elastic-scattering cross section provides insight into the radial distribution of nuclear matter and the rms radius of the doubly-magic ^{56}Ni nucleus.

In the following, the implementation and essential features of this novel technical concept will be discussed, as well as some adjacent UHV compatible equipment used, such as a silicon PIN diode array positioned at forward angles, a remote-controlled slit aperture operated at the gas-jet target, and a removable α -particle calibration source.

For the E105 experiment, the dedicated UHV compatible scattering chamber was installed at the gas-jet target position of the ESR (figure 2). Two large-size ($64 \times 64 \text{ mm}^2$) DSSDs measure scattered particles at an angular range of $73^\circ < \theta_{\text{lab}} < 88^\circ$ for DSSD1, and $27^\circ < \theta_{\text{lab}} < 38^\circ$ for DSSD2, respectively. They serve as an active vacuum barrier for the AV restricted to two stainless-steel tubes in this case. As seen on the right in figure 2, the DSSD1 assembly contains a pair of Si(Li) pad detectors, which are not bakeable and thus not UHV compatible. The 6.5 mm thick Si(Li) detectors, fabricated by SEMIKON Detektor GmbH, Jülich, Germany, have an active area of $\sim 50 \text{ mm}$ times $\sim 92 \text{ mm}$ with a 8-pad

structure on their boron implanted and below $1\ \mu\text{m}$ thick p⁺-contacts. These detectors were cooled with an external recirculating liquid cryostat during the bake-out cycle of the scattering chamber, and operated at $-10\ ^\circ\text{C}$ during the measurements for reducing reverse current. Extended chamber tests for the temperature distribution during baking of the detectors composing the DSSD1 telescope were performed prior to the installation in the ESR. This was needed to ensure, on the one hand, reasonable cooling of the Si(Li)s and, on the other hand, high enough temperature at the outer tube surface and the DSSD for proper bake-out.

The DSSD sensor, designed at the Ioffe Physical Technical Institute, St. Petersburg, Russia⁷, with an active area of $64 \times 64\ \text{mm}^2$ and thickness of $285\ \mu\text{m}$ used in our experiment has 128 vertical strips of $0.5\ \text{mm}$ width on the p-side (UHV side) and 64 horizontal strips of $1\ \text{mm}$ width on the n-side (AV side). The size and number of strips represent the detectors specified for the final EXL design. This sensor is housed in a specially designed printed circuit board (PCB) that was manufactured from aluminium nitride (AlN) ceramic [6, 11]. This material was chosen for its low outgassing, good dielectric properties, high thermal conductivity and thermal expansion coefficient close to that of silicon. The DSSD sensor was hermetically glued into a laser-cut gap of the PCB using a low-outgassing EPO-TEK H77 [11] two-component glue which has a total mass loss less than 0.22% at $250\ ^\circ\text{C}$. The detector strips were manually bonded to the pads printed on both PCB sides. The signal lines from the PCB side facing the UHV pass through the AlN material via laser-drilled holes covered with a glass layer to assure vacuum tightness. This ensures that the UHV side is entirely made up of UHV compatible material. All signals are derived, by vacuum compatible spring-pin connectors with bodies fabricated from PEEK material [6, 11] and PTFE ribbon cables, from the AV side of the boards.

The layout of the PCB with total dimension of $113 \times 95\ \text{mm}^2$ is depicted in figure 3. The DSSDs were particularly designed with thin entrance windows for low-energy detection [12]. The dead layer on the p-side was measured to be $0.06\text{--}0.08\ \mu\text{m}$ (equivalent silicon thickness), which results in a lower cut-off energy of $2\text{--}3\ \text{keV}$ for α particles, and $1.5\ \text{keV}$ for protons, respectively. The thicker n-side dead layer of $3.6\ \mu\text{m}$ is still adequate for a transmission measurement. In practice, the low-energy limit for the measurement was not governed by the entrance window but by electronic noise, at a level of about $20\ \text{keV}$ when the preamplifiers were placed outside of the scattering chamber. In the E105 experiment, low-energy α particles were registered with DSSD2 for the $^{58}\text{Ni}(\alpha, \alpha')^{58}\text{Ni}$ reaction at $100\ \text{MeV}\ \text{u}^{-1}$, providing evidence for ISGMR and ISGDR excitation, for the first time from an experiment with stored beam [7]. The option of placing proper front-end electronics such as ASICS inside the well-shielded AV volume is expected to considerably reduce the electronic noise level and improve measurements at low energies.

⁷ DSSD supplier: Maxwell, Severny pr. 73/2-54, 195257 St. Petersburg, Russia.

Figure 3. AlN PCB with mounted $64 \times 64\ \text{mm}^2$ DSSD, with p-side (red) and n-side (green) strip lines (layout by May, GSI). The position of the Helicoflex® seals is indicated.

Special care was taken for mounting the AlN ceramic PCB onto the stainless-steel tube ends. The problem was to cope with the large difference in thermal expansion coefficients between both materials (4.5 (or 3.6) for AlN (or Si), and 17 for SS-304, all in units of $10^{-6}\ \text{m/m}^\circ\text{C}$). In order to guarantee mechanical stability and minimize shear stress, so-called spring-energized metal seals, low-load Helicoflex® HNV Delta seals [11], were applied on both PCB surfaces which, compared to previously used welded aluminium wires, are very planar and have small and well-defined contact surfaces. In addition, the surface quality of the PCBs was improved for a residual roughness below $0.5\ \mu\text{m}$ (before: $<5\ \mu\text{m}$) and flatness below $50\ \mu\text{m}$ (before: $250\ \mu\text{m}$). Finally, cup washers were used at all fixation screws, to guarantee a uniform contact pressure of $10\ \text{N}$ per mm length over the total circumference of $355\ \text{mm}$ of the seals. With these precautions, all vacuum windows in use have worked properly over a number of baking cycles. In a series of tests performed prior to the final run, an AV level up to $10^{-4}\ \text{mbar}$ could be tolerated, with the vacuum level at the UHV side being safely kept below $10^{-10}\ \text{mbar}$. In the course of the E105 experiment, below $10^{-7}\ \text{mbar}$ pressure was achieved for the AV in both tubes, compared to about $10^{-10}\ \text{mbar}$ in the chamber. This tells that there is still wide scope for tolerating supplemental components (e.g. ASICS) in the AV that might contribute to additional gas-load.

A special issue of the experiment was a mechanical slit aperture (optionally 1 or $2\ \text{mm}$ width) (figure 4) in front of DSSD1. The slit plate was retracted from the beam region during filling of the ESR about every two hours and, after beam cooling, positioned with absolute accuracy of $<5\ \mu\text{m}$ at an operating position close to the target. Remotely-controlled

Figure 4. *Left:* sketch of the slit aperture for DSSD1. *Right:* energy of recoil protons versus scattering angle in the $^{56}\text{Ni}(p, p)^{56}\text{Ni}$ reaction at 400 MeV u^{-1} , without and with a 1 mm wide aperture. Energy ranges of the different detectors are indicated.

two-dimensional movement of the slit plate up to 50 mm travel is achieved by piezo-based nanopositioners from Attocube AG, München [13]. The stainless steel version of this device is bakeable to 150°C and, thus, well capable for operating in the UHV. As for the connecting wires, UHV capable Kapton-insulated ribbon cables from Ag-plated Cu were coupled inside the chamber to a UHV sub-D vacuum feed-through. The aperture permits considerable improvement in scattering angular resolution and, in case of elastic scattering, assessment of a well-defined target-detector geometry. The benefit of the slit aperture in front of DSSD1 and Si(Li)s is demonstrated in figure 4, for the relation of the energy of scattered protons with the scattering angle in the $^{56}\text{Ni}(p, p)^{56}\text{Ni}$ reaction. In contrast to the situation without slit, inserting the 1 mm wide aperture permits to fully separate elastic scattering from inelastic channels [9, 10]. For elastic scattering, there is an analytic relationship between recoil energy and scattering angle. Thus, the actual target-detector geometry could precisely be deduced by fitting, by the method of least squares, the measured energy-angle correlation to a calculated one, using a geometrical offset parallel to beam direction as the free parameter.

For coincidence measurement between the light recoils registered in DSSD1&2 and beam-like reaction products an array of six silicon detectors, each one with an area of $10 \times 10 \text{ mm}^2$ and $500 \mu\text{m}$ thickness, was mounted on a movable arm downstream before the first dipole magnet. Using again AlN ceramics as the PCB material, Kapton-insulated cables and stainless-steel mechanical parts, permitted standard baking cycles and thus full UHV compatibility without the need of placing the device inside a pocket made of stainless-steel membranes. Use of the in-ring detector in the E87 experiment is described in [8].

We finally mention that all silicon detectors were calibrated with the aid of a ^{241}Am α source deposited onto a stainless steel disc. The source was housed inside a UHV capable magnetic linear feedthrough system (see figure 2) and could be placed at the position of the beam–target interaction zone, without influencing the vacuum in the scattering chamber. Alpha particle calibration at 5.48 MeV energy was performed for all n-side and p-side strips of the DSSD1 and DSSD2 detectors. For the other detectors (Si(Li)1 and Si(Li)2

behind DSSD1, and the PIN diode array) their electronic chains were coupled to DSSD1 detector strips facing the source for calibration. This indirect calibration procedure needs to consider minor corrections only, e.g., for the ballistic deficit in case of the Si(Li)s which have much slower signal rise times than the DSSD pulses. For the higher energies, a PB5 precision pulse generator was used as a reference source.

2.3. Perspectives for a next-generation EXL-type experiment

For a short-term perspective towards EXL more extended detector installations fitting into the same scattering chamber as E105 were envisaged. For the assembly of a larger number of detectors different options were discussed. Figure 5 sketches, as examples, two possible experimental setups. The version shown on the left side keeps, as an option, the present concept of vacuum separation with a vacuum tight front array made of DSSDs, and possible placement of Si(Li)s behind. The simpler version shown on the right side, places all DSSDs in the UHV environment. Here, to do without vacuum-window technology needs all detectors to be baked. Here, as the thicker detectors, Si(Li)s have to be replaced by a few mm thick silicon pad detectors. For the purpose of updating the current experiment, up to 30 DSSDs and AlN boards have been purchased, as well as prototypes of 1 and 2 mm thick silicon pad detectors of comparable large sizes [12]. However, for a successful future experiment in the EXL campaign, considerable R&D is still needed with respect to readout electronics on the basis of ASICS, and the development of internal gas-jet targets with small dimensions [14].

3. Summary

As a first step of the EXL project scheduled for the NESR at FAIR a first EXL-type experiment with a radioactive beam (E105) was commissioned at the ESR of GSI. An innovative differential pumping concept, originally proposed for the EXL recoil detector ESPA, was successfully applied. For the first time (world wide) a nuclear reaction experiment, namely $^{56}\text{Ni}(p, p)^{56}\text{Ni}$ at 400 MeV u^{-1} , with stored radioactive beams was successfully performed. The experimental concept with

Figure 5. Optional detector arrangements for a next-generation EXL-type experiment, (a) with and (b) without vacuum-window technology (see text) (drawings by Lindemulder, KVI-CART).

UHV capable detectors and infrastructure around the internal target was proven to be successful. The technology of piezo-drive nanopositioners was used for the first time in a storage-ring experiment for precise positioning of items inside UHV, such as the slit aperture close to the target. A UHV compatible silicon PIN diode array was placed down-stream in the beam line, and a calibration alpha source was inserted into the UHV chamber. We believe that the various technical concepts realized in the present work can potentially be applied also outside of the EXL project for experiments requiring the usage of complex detector systems in the UHV environment of storage rings.

Acknowledgments

We acknowledge technical support by A Glazenberg-Kluttig, M Lindemulder, P Schakel and H Timersma (KVI-CART, Groningen) and J Cavaco, G May, J P Meier and L Urban (GSI, Darmstadt). Work supported by HIC for FAIR, GSI-TUD cooperation agreement, GSI-RUG/KVI collaboration agreement, the European Community FP7-Capacities, contract ENSAR no 262010, and BMBF (06DA9040I, 05P12RDFN8). L X Chung has partly been supported by NAFOSTED of Vietnam under grant 103.01-2011-17.

References

- [1] (www.gsi.de/work/forschung/nustarenn/kernreaktionen/activities/exl.htm)
- [2] FAIR Baseline Technical Report 2006 (www.faircenter.eu/fileadmin/fair/publications/FAIR/FAIR_BTR_4.pdf)
- [3] Egelhof P, Kisselev O, Münzenberg G, Neumaier S R and Weick H 2003 *Phys. Scr.* **T104** 151–9
- [4] Egelhof P *et al* 2015 First nuclear reaction experiment with stored radioactive ^{56}Ni beam and internal hydrogen and helium targets *JPS Conf. Proc.* **6** 020049
- [5] Kiselev O *et al* 2015 *Phys. Scr.* **T166** 014004
- [6] Streicher B, Egelhof P, Ilieva S, Kalantar-Nayestanaki N, Kollmus H, Kröll T, Mutterer M, von Schmid M and Träger M 2011 *Nucl. Instrum. Methods Phys. Res. A* **654** 604–7
- [7] Zamora J C *et al* 2015 *Phys. Scr.* **T166** 014006
- [8] Doherty D *et al* 2015 *Phys. Scr.* **T166** 014007
- [9] von Schmid M *et al* 2014 First EXL experiment with stored radioactive beam: proton scattering on ^{56}Ni *EPJ Web Conf.* **66** 03093
- [10] von Schmid M *et al* 2015 *Phys. Scr.* **T166** 014005
- [11] PCB manufacturer (www.lust-hybrid.de); Glue producer (www.epotek.com); Spring pin producer (www.idinet.com); Seal producer (www.helicoflex.com)
- [12] Eremin V 2011 private communication
- [13] (ECS3080/StSt/NUM/UHV) by AttoCubeSystems (www.attocube.com/attomotion/)
- [14] Petridis N, Grisenti R E, Litvinov Y A and Stöhlker T 2015 *Phys. Scr.* **T166** 014051