Fast timing with FATIMA - From νBall at ALTO to DESPEC at GSI

P.-A. Söderström[1,2], M. Rudigier[3], T. Arici[2], S. Bottoni[4], M. Brunet[3], R. Canavan[3], N. Cieplicka-Oryńczak[5], S. Courtin[6], D. Doherty[3], J. Gerl[2], M. Gorska[2], K. Hadyńska-Klęk[3], M. Heine[6], Ł. W. Iskra[5], N. Jovančević[7], V. Karayonchev[8], A. Kennington[3], I. Kojouharov[2], P. Koseoglou[1,2], M. Lebois[7], N. Kurz[2], C. Lizarazo[1,2], G. Lorusso[3,9], G. Lotay[3], M. Nakhostin[3], C.R. Niță[10], S. Oberstedt[11], N. Pietralla[1], S. Pietri[2], Zs. Podolyák[3], L. Qi[7], P.H. Reagan[3,9], J.-M. Régis[8], S. Saha[1,2], H. Schaffner[2], R. Shearman[3], J. Vesić[2], J. Wilson[7], W. Witt[1,2]

[1]TU-Darmstadt, Darmstadt, Germany; [2]GSI, Darmstadt, Germany; [3]University of Surrey, Guildford, U.K.; [4]University of Milano, Milano, Italy; [5]Institute of Nuclear Physics, PAN, Kraków, Poland; [6]IPHC, Strasbourg, France; [7]IPN, Orsay, France; [8]Universität zu Köln, Köln, Germany; [9]NPL, Teddington, UK; [10]IFIN-HH, Magurele, Romania; [11]European Commission, Geel, Belgium

Lifetime measurements of excited states using fast $LaBr_3$ scintillators is a strongly emerging field within nuclear physics that has gained significant popularity in recent years. Most of the experiments performed to date have taken place using γγ-coincidences at stable beam facilities [1]. With the upcoming generation of high-intensity radioactive ion beam facilities, this technique is becoming increasingly used to study the structure of more exotic nuclei [2]. For example, in one of the recent experiments at RIKEN, βγ-coincident fast-timing with $LaBr_3$ and plastic scintillators have been very successful [3,4]. This type of experiment will be one of the foci of the upcoming DESPEC beam times.

Implementing FATIMA with νBall

In November 2017 the first experiment with the new mixed EUROBALL HPGe and FATIMA $LaBr_3$ spectrometer, νBall, was performed in Orsay. It's aim was to measure the lifetime of the low-lying states in ^{166}Dy as well as to search for a predicted 4^- isomer. The experiment was performed using a pulsed ^{18}O beam from the ALTO tandem to induce two-neutron transfer reactions on a ^{164}Dy target as well as fusion-evaporation reactions to reach high-spin states in ^{178}W. One of the key features in this experimental setup is the possibility to use the high resolution pulsed beam to extract lifetimes from beam radiofrequency-γ coincidences. A typical example of the spectra obtained is shown in Figure 1. Within the data from this experiment the transitions of interest in ^{166}Dy were clearly observed in singles and in γγ-coincidences, the lifetime of the first excited state in the Coulex of ^{164}Dy was well reproduced, and γ rays originating from the decay of the high-spin isomers of ^{178}W could also be identified. The full data from this experiment is currently under analysis. However, the data already shows stable operation and a high quality of the output data from FATIMA.

Experiments within DESPEC in 2018

For the DESPEC campaign the FATIMA detectors will be moved to GSI in spring 2018. One of the proposed experiments at GSI is the study of neutron-rich Hf, W, and Os isotopes. The advanced implantation detector AIDA will be used as an active stopper consisting of three layers of silicon detectors. AIDA will be complemented by thin plastic scintillators for electron tagging and these will be read out via regular or silicon photomultipliers. FATIMA will be configured into three rings upstream, and for high-resolution spectroscopy an array of HPGe detectors will be installed; currently proposed as seven DEGAS triple-clusters. The proposed readout of FATIMA will consist of 10-bit resolution and 1 GS/s V1751 8-channel digitizers, and V1290 16-channel multihit TDCs. These electronic units will be integrated into the GSI readout system MBS via a RIO4 CPU, TRIVA trigger module, and a VULOM4b VME universal logic module. The results and experience from these experiments will be crucial for future implementation of NUSTAR at FAIR.

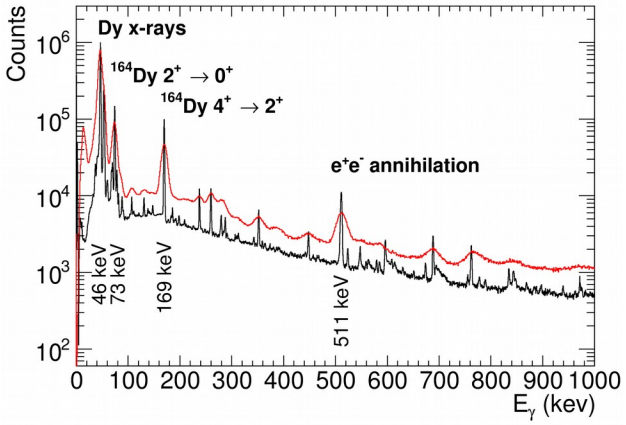

Figure 1: Example spectra of γ rays detected in the HPGe (black) and $LaBr_3$ (red) detectors. The most intense features are labelled.

References

[1] N. Mărginean, et al., Eur. Phys. J. A 46 (2010) 329
[2] P. H. Regan, et al., EPJ Web Conf. 63 (2013) 01008
[3] F. Browne, et al., Phys. Lett. B 750 (2015) 448
[4] F. Browne, et al., Phys. Rev. C 96 (2017) 024309

Characterization of a Sunpower CryoTel CT cooling engine for DEGAS

W. Witt[1,2], P. Koseoglou[1,2], P.-A. Söderström[1,2], E. Adamska[3], J. Gerl[2], I. Kojouharov[2], N. Pietralla[1]

[1]TU Darmstadt, Darmstadt, Germany; [2]GSI, Darmstadt, Germany; [3]University of Warsaw, Warsaw, Poland

As one of the four experimental pillars of the FAIR project the NUSTAR collaboration aims at investigating exotic beams provided by the accelerator through the Super-FRS. This includes the decay spectroscopy setup DESPEC, which is to be located at the low-energy branch of the facility. To obtain maximum output from DESPEC, new detector systems for high-efficiency measurements are being developed and adapted to the facility's requirements. One of the key instruments is the DEGAS germanium-array, which, due to its compact design, makes the standard liquid nitrogen cooling impossible. Therefore, new technology based on compact electrical coolers of the type Cryotel CT by Sunpower is under development [1].

One of the main obstacles in the application of electrical cooling are the vibrations originating from the Stirling engine, which transfer directly to the Ge-crystal to be cooled and affect its energy resolution. To characterize the thermal properties of the cooler and, in particular, to quantify the vibrations and explore possible countermeasures, several measurements were performed at the Helmholtz-Institut Mainz during summer 2017. The purpose of this measurements was to observe time-dependent temperature and acceleration developments at the cooling point during the cooling-down process and the effect of different mechanical holding structures on the oscillations.

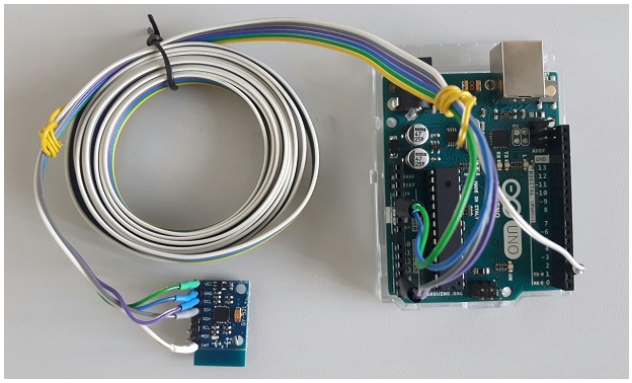

Figure 1: The MPU6050 sensor connected to an Arduino Uno Board for readout.

The thermal measurement performed with a PT-100 sensor showed a gradual cooling-down process towards the operating temperature of 77K, which was achieved within 150 minutes. The power consumption did not exceed 170 W and remained at 60 W at 77K. These properties met the expectations and requirements for the DEGAS cooling.

The accelerometry was performed using an Arduino Uno Board and a MPU6050 sensor [2], as shown in Fig. 1. The MPU6050 sensor is equipped with an accelerometer and a gyroscope and the Arduino Uno board was programmed to read the values from the sensor and stream them to a computer at 500 kbps. The effective sampling frequency was determined globally for the full setup by the sampling frequency of the sensor, and the internal clocks of the sensor and the Arduino board. The maximum sampling frequency of the MPU6050 sensor's accelerometer is 1 kHz and the highest sampling frequency reached during these measurements was around 600 Hz. The acceleration measuring range was set to ±16 G.

The obtained data were analysed using a three-dimensional Fast Fourier Transform (FFT), including a low-pass filter. One main product of these measurements can be seen in Fig. 2. showing the vibration frequency as a function of time during 30 minutes of the cooling-down phase. Besides lower-intensity vibrational features four strong bands are dominant, which coincide with the frequency of the cooler's gear (60 Hz) [3] and it's harmonic modes (120 Hz, 180 Hz, 240 Hz).

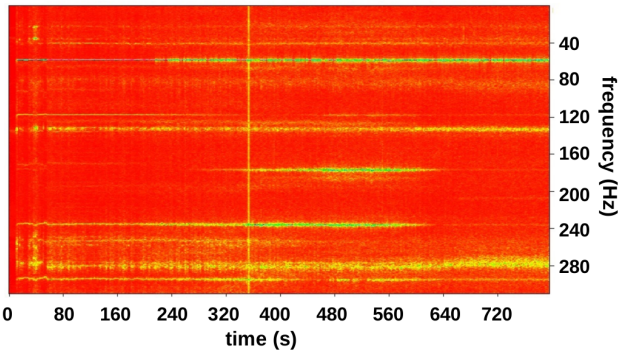

Figure 2: Typical frequency-time spectrum of oscillations at the cooling point of the Cryotel CT during the cool-down process.

In previous tests of the cooler [1], the malfunction or wrong setting of the AVC (active vibration cancellation, a mechanical attachment to the cooler to perform anti-phase oscillations for a net-zero vibration of the cooler) remained unclear. This was ruled out in this work. The AVC was shown to work correctly and dampen the oscillations slightly.

Furthermore, accelerometry was performed after changing the properties of the cooler's holding structure (damping legs, Styrofoam, additional weight on top), cp. Fig. 3. The structure variation proved to have a potentially damping effect on the measured oscillations and, hence, the adaption of the holding structure in terms of mechanical decoupling of the cooler from the cooling point, e.g. employed in [4], was persued.

 DOI:10.15120/GR-2018-1

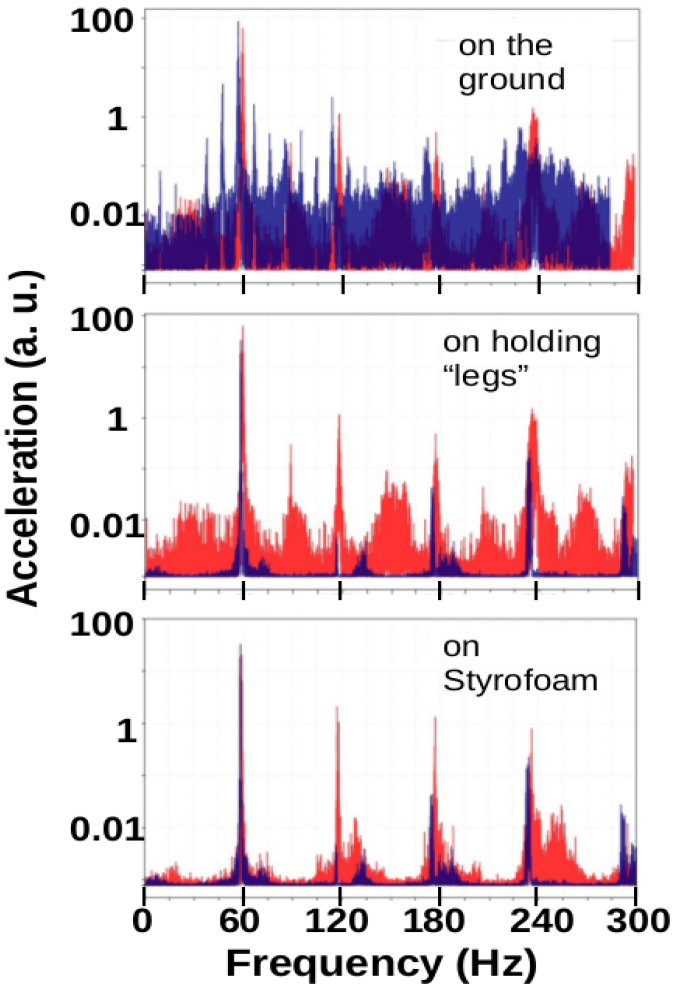

Figure 3: Variation of the cooler oscillations with changing holding structure and with (blue) /without (red) lead on top.

The design and manufacture company Ortec could be convinced to design and produce such adapted holding structure. A first draft of the design based on vacuum bellows and flexible copper rods for the decoupling is shown in Fig. 4. The production is planned to be finished in April 2018.

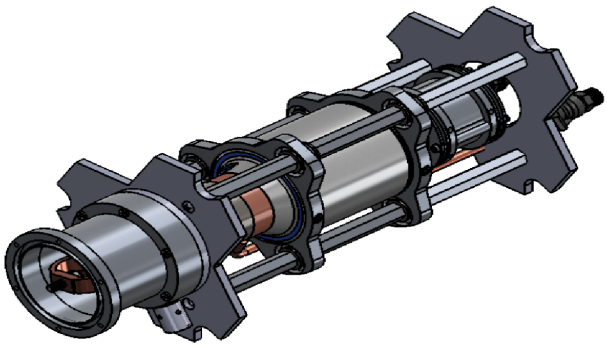

Figure 4: New Cryotel CT holding structure as designed by Ortec employing oscillation-decoupling mechanics.

Further tests will show the efficiency of the modifications. Should the oscillations prove to be sufficiently reduced, the electrical Cryotel CT coolers will be used in the DEGAS array as foreseen starting Fall 2018 with the FAIR-0 DESPEC experiments.

This work was supported by HGS-HIRe and the German ministry for education and research (BMBF) within the project NUSTAR R&D under grant no. 05P15RDFN1.

References

[1] W. Witt et al., GSI Scientific Report 2016, 186 (2017)
[2] http://www.arduino.cc/ accessed in September, 2017
[3] Sun Power CryoTel User Manual V.7 (2012)
[4] G. Raskin et al., Compact Stirling cooling of astronomical detectors, Instr. and Meth. for Astrophys. (2013)

First spectroscopy of neutron-rich Sc isotopes using FAIR instrumentation in the third SEASTAR campaign

P. Koseoglou[1,2], V. Werner[1], P.-A. Söderström[1,2], M. Lettmann[1], N. Pietralla[1], P. Doornenbal[3], A. Obertelli[1,4,3], N. Achouri[4], H. Baba[3], F. Browne[3], D. Calvet[4], F. Château[4], S. Chen[5,6,3], N. Chiga[3], A. Corsi[4], M. L. Cortés[3], A. Delbart[4], J-M. Gheller[4], A. Giganon[4], A. Gillibert[4], C. Hilaire[4], T. Isobe[3], T. Kobayashi[7], Y. Kubota[3,8], V. Lapoux[4], H. Liu[4,9], T. Motobayashi[3], I. Murray[3,10], H. Otsu[3], V. Panin[3], N. Paul[4], W. Rodriguez[11,3], H. Sakurai[3,12], M. Sasano[3], D. Steppenbeck[3], L. Stuhl[8], Y. L. Sun[4], Y. Togano[13,3], T. Uesaka[3], K. Wimmer[12,3], K. Yoneda[3], O. Aktas[9], T. Aumann[1], L. X. Chung[14], F. Flavigny[10], S. Franchoo[10], I. Gasparic[3,15], R.-B. Gerst[16], J. Gibelin[17], K. I. Hahn[18], D. Kim[18], T. Koiwai[12], Y. Kondo[19], J. Lee[6], C. Lehr[1], B. D. Linh[14], T. Lokotko[6], M. MacCormick[10], K. Moschner[16], T. Nakamura[19], S. Y. Park[18], D. Rossi[1], E. Sahin[20], D. Sohler[21], S. Takeuchi[19], H. Törnqvist[1], V. Vaquero[22], V. Wagner[1], S. Wang[23], X. Xu[6], H. Yamada[19], D. Yan[23], Z. Yang[3], M. Yasuda[19] and L. Zanetti[1].

[1]Institut für Kernphysik, Technische Universität Darmstadt; [2]GSI Helmoltzzentrum für Schwerionenforschung GmbH; [3]RIKEN Nishina Center; [4]IRFU, CEA, Université Paris-Saclay; [5]School of Physics, Peking University; [6]Department of Physics, The University of Hong Kong; [7]Department of Physics, Tohoku University; [8]Center for Nuclear Study, the University of Tokyo; [9]Department of Physics, Royal Institute of Technology; [10]Institut de Physique Nucléaire Orsay, IN2P3-CNRS; [11]Universidad Nacional de Colombia; [12]Department of Physics, University of Tokyo; [13]Department of Physics, Rikkyo University; [14]Institute for Nuclear Science & Technology, VINATOM; [15]Rudjer Boskovic Institute, Zagreb; [16]Institut für Kernphysik, Universität zu Köln; [17]LPC Caen, ENSICAEN, Université de Caen; [18]Ewha Womans University; [19]Department of Physics, Tokyo Institute of Technology; [20]Department of Physics, University of Oslo; [21]MTA Atomki; [22]Instituto de Estructura de la Materia, CSIC; [23]Institute of Modern Physics, Chinese Academy of Sciences.

Recent results for the level structure of ^{54}Ca have shown evidence for the existence of a new magic neutron number N=34 [1]. At the same time there might not be a corresponding shell gap in Ti isotopes [2, 3]. Scandium isotopes lie between calsium and titanium. In scandium isotopic chain the valence proton occupies the $\pi f_{7/2}$ orbital, interacting with the $\nu f_{5/2}$ orbital in $^{55-61}$Sc. The evolution of the proton orbitals of these isotopes can reveal the nature of both the magic number N=34, recently proved to vanish in ^{55}Sc [4], and the N=40 *pf*-shell closure.

Gamma-ray spectroscopy of the neutron-rich $^{55-61}$Sc isotopes was performed at the Radioactive Isotope Beam Factory (RIBF) in Wako-shi, Japan, as part of the third SEASTAR campaign [5]. A ^{70}Zn beam at 345 MeV/u, delivered from the RIBF accelerator complex, produced a cocktail of secondary radioactive beams by impinging on a 10-mm-thick ^{9}Be target. The secondary beams, that were identi ed and separated by the BigRIPS fragment separator [6], produced the isotopes of interest by knock-out reactions in the MINOS target system [7], consisting of a 150-mm-thick LH_2 target surrounded by an active TPC. The emitted gamma-quanta of the isotopes produced were measured by the DALI2+ array [8], consisting of 226 NaI(Tl) detectors, surrounding MINOS. The reaction products were reconstructed event-by-event in SAMURAI [9] using two drift chambers and a hodoscope plastic-scintillator array. Additionally, NeuLAND [10] and NEBULA [11] were used for neutron detection. The experimental set-up is shown in Figure 1.

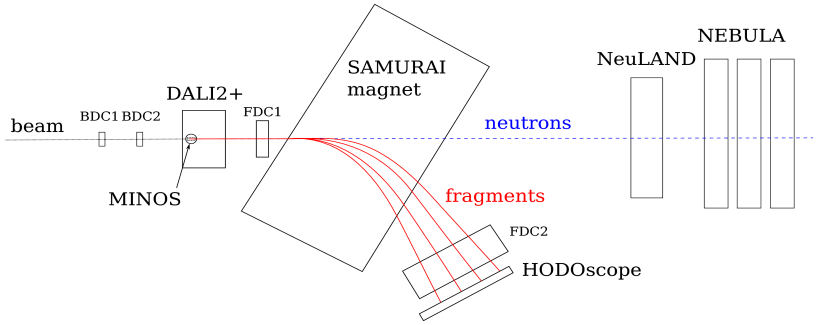

Figure 1: Experimental set-up of the 3rd SEASTAR campaign at RIBF.

 DOI:10.15120/GR-2018-1

The γ transitions reported previously for ^{55}Sc in Ref. 4 have been already identified in the current early state of our data analysis from the neutron knock-out reaction, ^{56}Sc(p,pn)^{55}Sc. The analysis for $^{55\text{-}61}$Sc is on-going. Figure 2 shows the particle identification in BigRIPS after gating on $^{55\text{-}61}$Sc nuclei in SAMURAI.

The large number of detectors together with the BigRIPS fragment separator and the SAMURAI magnet formed a complex experimental set-up similar to the planned NUSTAR HISPEC/DESPEC experiments at FAIR.

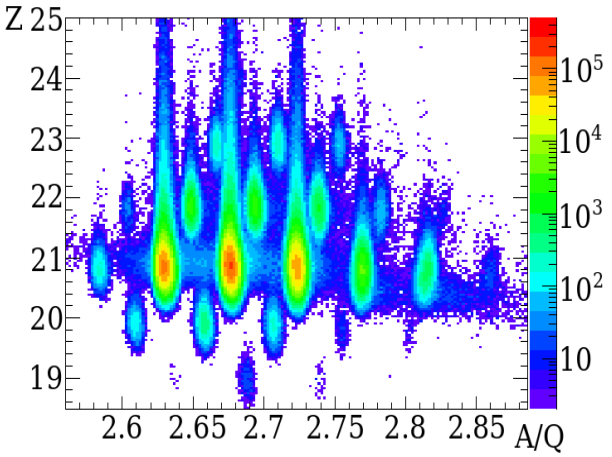

Figure 2: The particle identification in BigRIPS after gating on $^{55\text{-}61}$Sc in SAMURAI.

The first author would like to thank the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe) for FAIR for its support though the HGS-HIRe abroad program.

References

[1] D. Steppenbeck, et al., Nature **502**, 207-210 (2013).
[2] D.-C. Dinca, et al., Phys. Rev. C **71**, 041302(R) (2005).
[3] S. N. Liddick, et al., Phys. Rev. Lett. **92**, 072502 (2004).
[4] D. Steppenbeck, et al., Phys. Rev. C **96**, 064310 (2017).
[5] P. Doornenbal and A. Obertelli, RIKEN Proposal for Scientific Program (2013).
[6] T. Kubo, et al., Prog. Theor. Exp. Phys. 2012, 03C003 (2012).
[7] A. Obertelli, et al., Eur. Phys. J. A **50**, 8 (2014).
[8] S.Takeuchi, et. al., Nucl. Instr. and Meth., A **763** (2014) 596-603.
[9] T. Kobayashi, et. al., Nucl. Instr. and Meth., B **317** (2013) 294-304
[10] NeuLAND-TDR, https://edms.cern.ch/document/1865739.
[11] T. Nakamura, Y. Kondo, Nucl. Instr. Meth. B **376**, 1 (2015).

Fuzzy Bayes Tracking – Experimental results

P. Napiralla[1,2], H. Egger[3], P. R. John[1], N. Pietralla[1], M. Reese[1], and C. Stahl[1]

[1]Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany; [2]GSI, Darmstadt, Germany;
[3]AG Numerik und wissenschaftliches Rechnen, Technische Universität Darmstadt, Darmstadt, Germany

The Advanced GAmma Tracking Array AGATA [1] will be the key instrument for nuclear structure investigations in the upcoming HISPEC and DESPEC experimental campaigns at the Facility for Antiproton and Ion Research FAIR. Due to its germanium shell without any Compton-shielding, γ-ray tracking algorithms are essential for experiments with high reaction rates.
Based on the mathematical framework of the *Bayes-Tracking* (see [2]), the Fuzzy Bayes Tracking (FBT) adds a geometrical clustering algorithm into the framework. This clustering algorithm is based on a *Fuzzy c-means* algorithm (see [4]), which forms simple geometrical clusters via a minimization process. These clusters are then either physically confirmed or torn further by the Bayesian analysis of the tracking algorithm, if a higher amount of clusters is more likely. This is achieved by comparing all possible sub-combinations of observed clusters via *marginalization* [3]

$$P(cluster) = \sum_{n=1}^{N} P(cluster|n)\,P(n)$$

where n is the number of possible sub-clusters and N is the number of observed interaction points. For each sub-cluster, the probability $P(cluster|n)$ is calculated using known cross sections of Compton scattering and photo-electric absorption. In addition, the plausibility of the resulting photon paths are considered by comparing geometrical scattering angles with energetic Compton scattering angles under the metrological restraints of the AGATA detectors. Comparing all possible probabilities $P(cluster|n)$, the most probable sub-clusters are chosen and their respective total deposited energies are set as the tracked energies.

Using ^{60}Co source data from the AGATA-Demonstrator experiment 09.08 conducted at LNL in 2011, a first benchmark test of the Fuzzy Bayes Tracking can be made. The achieved performance of the Fuzzy Bayes Tracking can be seen in Figure 1. By suppressing cluster formation with very low probabilities (mostly belonging to escaped photons), the tracked spectrum can be cleaned significantly (see Fig. 1).

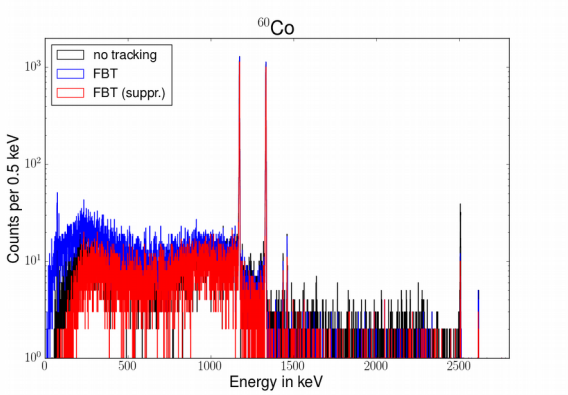

Figure 1: Performance of the Fuzzy Bayes Tracking on a ^{60}Co spectrum. Black is without any tracking, blue the tracked spectrum without suppression and red with suppression.

Comparing the Peak-to-Total ratios with and without the Fuzzy Bayes Tracking yields:

- no tracking: 38 %
- FBT: 31 %
- FBT with suppression: 43 %

To improve the Fuzzy Bayes Tracking further, future work will focus on merging FBT's methods with the reconstruction methods mentioned in [2]. In addition, further improvements of the geometrical clustering process will be made.

References

[1] A. Akkoyun *et. al.*, AGATA – Advanced Gamma Tracking Array, Nuclear Instruments and Methods in Physics Research A, 668:26-58, 2012.
[2] P. Napiralla *et. al.*, Bayes-Tracking – A novel approach to γ-ray tracking, GSI Scientific Report 2016, 2016.
[3] D. Sivia and J. Skilling, Data Analysis – A Bayesian Tutorial, volume 2, Oxford University Press, Oxford, 2006.
[4] M.S. Yang and Y. Nataliani, Robust-learning fuzzy c-means clustering algorithm with unknown number of clusters, Pattern Recognition, 71:45-49, 2017.

Experiment beamline: none
Experiment collaboration: NUSTAR-DESPEC-HISPEC
Experiment proposal: none
Accelerator infrastructure: none
PSP codes: 1.2.2.8
Grants: BMBF 05P15RDFN1, BMBF 05P15RDFN9
Strategic university co-operation with: Technische Universität Darmstadt

 DOI:10.15120/GR-2018-1

Position sensitive Ge detector

T. Arici[1], I. Kojouharov[1], J. Gerl[1]

[1]GSI, Darmstadt, Germany

Position sensitivity of gamma-ray detection is required for a wide range of applications. In order to achieve good position sensitivity, segmentation of the contacts of the crystal must be applied. Recently, segmentation of HPGe has been applied to coaxial crystals, such as the AGATA detectors, results in a position resolution of 3-5 mm with a high energy resolution [1]. Despite the impressive results obtained by these detectors, the demand for increased position resolution of 1 mm requires focusing on segmented planar detectors. Nevertheless, having a superior position resolution, the physics of the operation and the feasible technical solutions resulted in a large dead volume in the crystal and large insensitive space around it, which affects negatively the performance of a planar detectors array. To solve the problem, a new geometry, namely the semi-planar detector geometry, which severely minimizes this layer, has been proposed.

Detector Test

The project proposed is aimed at development of semi-planar detector with point contacts as a segmentation tool. This includes a detailed study by numerically simulating the electric field and the charge transport inside the detection crystal and a search for the optimal geometry.
The crystal processing is supposed to be carried out by an industrial partner and the detector to be scanned by the GSI Detector Scanner. The main idea is to make several point read-outs on a planar crystal which are sensitive to certain area. The distribution and number of these points can be estimated by performing simulations taking the electric field and charge transportation into account. In this framework, semi-planar HPGe detector with a single point contact read-out was studied in order to characterize the behaviour of such a novel contact technology replacing the segmentation of the crystal. A non-segmented p-type HPGe crystal with a dimension of 33.2x33.2x15.5 mm^3 and Carrier concentration of 3.3x109 atom/cm^3 was used for the test purposes. The charge signal was extracted from the p+ electrode. The detector was operated at 100 V and 1.2 pA leakage current was observed. Sudden increase of the leakage current when increasing the bias voltage caused the saturation of the pre-amplifier which is related to the type of the coupling used for the signal read-out. Detector was tested using ^{57}Co and ^{60}Co sources in order to cover the low and high energy regions. For each source different shaping times were tested. Experimental data was fitted using an exponentially modified Gaussian function and the results for two different shaping times are given in Figure 1 for ^{60}Co source. Using the ^{57}Co source, 2.1 keV and 2.3 keV energy resolutions at 122 keV line was obtained respectively for 3 µs and 6 µs shaping times. While with ^{60}Co source, 4.5 keV and 4.3 keV energy resolution was obtained for the 1332 keV transition respectively for 3 µs and 6 µs shaping times.

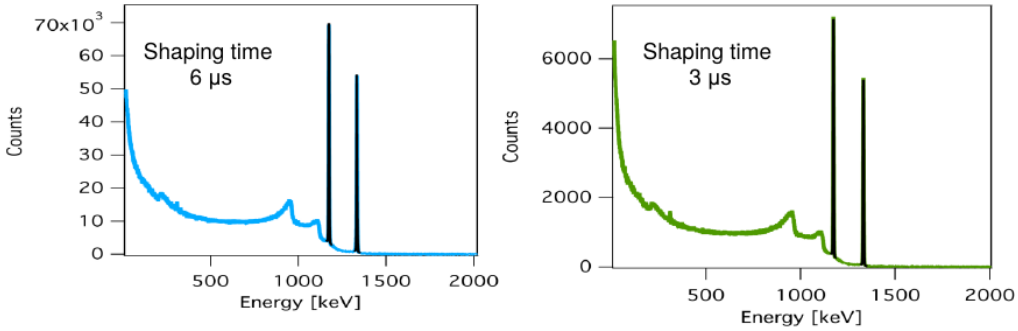

Figure 1: The observed energy spectrum with ^{60}Co source. The spectrum on the left side was recorded using 6 µs shaping time while the one on the right side obtained with 3 µs shaping time.

References

[1] S. Akkoyun and A. Algora, "AGATA – Advanced Gamma Tracking Array", NIM volume 668, 26-58 2012

Experiment beamline: Gamma-Spectroscopy
Experiment collaboration: NUSTAR-DESPEC-HISPEC
Grants: ENSAR2

Fast-timing lifetime measurement of ^{152}Gd with FATIMA-type $LaBr_3$ detectors

J. Wiederhold[1], R. Kern[1], C. Lizarazo[1,2], W. Witt[1,2], V. Werner[1], N. Pietralla[1], D. Bucurescu[3], N. Florea[3], D. Ghita[3], T. Glodariu[3], R. Lica[3], N. Marginean[3], R. Marginean[3], C. Mihai[3], R. Mihai[3], I.O. Mitu[3],A. Negret[3], C. Nita[3], A. Olacel[3], S. Pascu[3], L. Stroe[3], S. Toma[3], A. Turturica[3]

[1]Institut für Kernphysik,TU Darmstadt, Germany; [2]GSI, Darmstadt, Germany, [3]IFIN-HH, Bucharest, Romania

In preparation of the upcoming DESPEC campaign at FAIR with the Fast TIMing Array (FATIMA), experiments were performed at the 9-MV FN Tandem of the National Institute for Physics and Nuclear Engeneering Horia Hulubei in Bucharest. The experimental setup at IFIN-HH for γ-ray spectroscopy uses the RoSphere Array [1] consisting of 11 FATIMA-type $LaBr_3$ detectors and 14 HPGe detectors, which is similar to the planned setup for the upcoming DESPEC campaign in 2018/19 with the DEGAS and FATIMA detectors.

Fast electronic scintillation timing (FEST)

The lifetime of an excited nuclear state is determined using FEST by measuring the time di erence between a start and a stop signal. The respective time signals originate from the detection of γ quanta from nuclear transitions feeding and depopulating the state of interest. The resulting time-di erence distribution is a convolution of the prompt response of the experimental setup and the exponential decay of the excited nuclear state. Lifetimes in the range of dozens of ps can be determined by measuring the centroid shift of the time-di erence distribution after a correction for the energy dependent time-walk of the experimental setup is applied. A more detailed overview of the experimental technique and the setup can be found in [1-3].

Lifetimes of ^{152}Gd

The region around neutron number N=90 is a well-known example for a rather rapid change in structure as a function of the nucleon number, i.e., a rst order quantum phase transition (QPT) [4]. Excited states of ^{152}Gd (N=88 neutrons) were populated via the ^{149}Sm(α,n)^{152}Gd reaction and lifetimes were measured using FEST. In particular, the lifetime of the second 0^+ was investigated, searching for a possible new signature of a QPT [5]. Figure 1 shows the obtained energy spectrum of the HPGe detectors. Many transitions of ^{152}Gd can be identi ed.

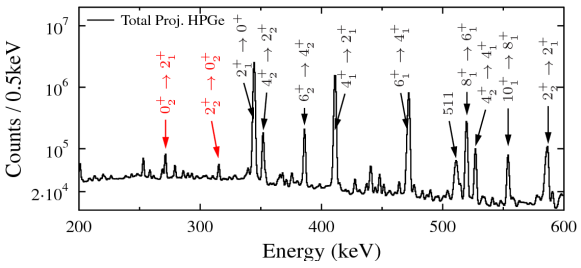

Figure 1: Partial energy spectrum of the HPGe detectors.

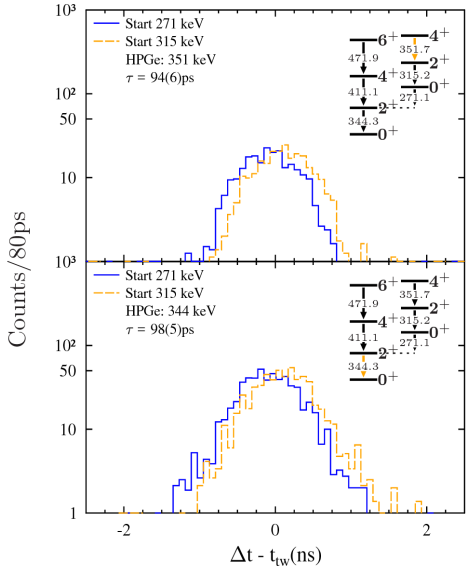

Figure 2: Time-di erence spectra for the combination of gates on the 2^+_2 0^+_2 and 0^+_2 2^+_1 transitions of ^{152}Gd.

Figure 2 shows the nal time-di erence spectrum for the combination of gates on the populating (315 keV) and decaying (271 keV) transitions of the second 0^+ state of ^{152}Gd. Additional gates were set in the pulse-height spectra from the HPGe detectors, selecting the cascade of interest and eliminating background contributions.

The newly determined mean lifetime of the second 0^+ state of ^{152}Gd of τ=96(6) ps [5] turned out to be nearly two times larger than the literature value of 53(12) ps [6] with direct implications for the charaterization of the QPT in the Gd isotopic chain [5].

Supported by the BMBF under the grants 05P15RDFN1 and 05P15RDFN9 and by HIC for FAIR.

References

[1] D. Bucurescu *et al.*, Nucl. Instrum. Methods Phys. Res. A **837**, 1 (2016).
[2] N. Marginean *et al.*, Eur. Phys. J. A **46**, 329 (2010).
[3] J.-M. Régis *et al.*, Nucl. Instrum. Methods. Phys. Res. A **726**, 191 (2013).
[4] R. Casten, Nature Physics **2**, 811 (2006).
[5] J. Wiederhold *et al.*, Phys. Rev. C **94**, 044302 (2016).
[6] N. R. Johnson *et al.*, Phys. Rev. **C** 26, 1004 (1982).

 DOI:10.15120/GR-2018-1

Activities in superheavy element research at SHIP and TASCA

H. David[1], Ch.E. Düllmann[1,2,3], M. Götz[1,2,3], S. Götz[1,2,3], E. Jäger[1], J. Khuyagbaatar[1,3], J. Krier[1], L. Lens[1,2], A. Di Nitto[1,2], V. Pershina[1] , J. Runke[1,2], B. Schausten[1], A. Yakushev[1,3,] for the SHE Chemistry department and the TASCA Collaboration,

M. Block[1,2,3], P. Chhetri[4,1], M. Eibach[5,1], F. Giacoppo[1,3], F. P. Hessberger[1,3], O. Kaleja[2,6], M. Laatiaoui[2,3], J. Maurer[1], A. K. Mistry[1,3], T. Murböck[1], S. Raeder[1,3] for the SHE Physics department and the SHIP/SHIPTRAP Collaborations.

[1]GSI, 64291 Darmstadt, Germany; [2]Universität Mainz, 55099 Mainz, Germany [3]Helmholtz Institut Mainz, 55099 Mainz, Germany; [4]Technische Universität Darmstadt, 64289 Darmstadt, Germany; [5] Universität Greifswald, 17489 Greifswald, Germany; [6]MPIK Heidelberg, 69117 Heidelberg, Germany

In the year 2017, efforts of the Superheavy Element Chemistry department focused on analysis of data obtained in the past UNILAC beamtime period. Major modifications to the experimental setups were performed: i) an upgrade of the cave X8 (TASCA) to install improved shielding, ii) the installation of a new, more flexible TASCA detector chamber, iii) a relocation of the TASCA control room in anticipation of major refurbishment of the SE building, which currently houses the control room, and iv) the design and implementation of a next generation TASCA Control System. Thus, best use was made of the extended shutdown period at GSI.

Selected experiments were performed at other facilities, including the Cyclotron Institute at Texas A&M University, College Station, USA.

'For the superheavy element physics department the activities concentrated on the analysis of data obtained in the past UNILAC beamtime period and preparations of the different experimental setups for the planned experiments in the beamtime period 2018 at GSI.

In parallel, several technical developments were advanced, for example, the completion of the decay spectroscopy system COMPASS, the construction of the single-ion mass measurement setup SHIPTRAP-2, and the design of a novel setup for gas-jet laser spectroscopy.

The specific activities are discussed briefly in the following sections.

Nuclear reaction studies

The drastic reduction of fusion-evaporation cross sections for reactions that form the heaviest elements cannot be understood without knowledge of the competing quasifission (QF) process, which hinders the fusion. Generally, this competition is studied by measuring fission fragments originating from QF and fusion-fission (FF). However, quantitative descriptions of experimental results become complex as many degrees of freedoms are involved and observables for FF and QF can overlap significantly. In collaboration with the Australian National University (ANU), Canberra, Australia, several experiments have been carried out in recent years at ANU's Heavy Ion Accelerator Facility (HIAF). Here, a large range of beam-target configurations was examined in order to investigate how QF/FF competition evolves with changes in entrance channels, taking advantage of the wide angular range available for fission-fragment detection with the CUBE detector setup. These data, together with data on fusion-evaporation reactions (e.g., measured at TASCA and SHIP), provide a comprehensive dataset for describing the QF and FF [Khu17]. In particular, measurements of varying QF probabilities in the ^{48}Ti+^{204,208}Pb and ^{50}Ti+^{206,208}Pb reactions have shed light on the strong influence of nuclear structure on the fusion process. Observed differences for ^{48}Ti+^{208}Pb and ^{50}Ti+^{206}Pb, providing distinct experimental evidence that even reactions that form the same compound nucleus and share the same charge product ($Z_p \cdot Z_t$) can exhibit different levels of QF, cannot be explained by current theories. In addition, data collected using beams of ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{58}Fe and ^{64}Ni incident on actinide targets has yielded a clear systematic picture of a strong dynamical evolution when moving from ^{48}Ca to heavier beams. The data are currently under final analysis. To obtain a conclusive picture concerning the choice of the most preferable beam-target combination for the synthesis of new elements beyond Z=118, fusion-evaporation cross-section measurements of ^{50}Ti-induced reactions on any actinide is suggested. Such measurements are planned to be performed, e.g., at RIKEN, Japan and Dubna, Russia.

Nuclear Structure

Construction of the novel ALpha-BEta-GAmma (ALBEGA) multi-coincidence spectroscopy setup for chemically separated samples [DiN15] continued. Advanced prototypes of the two ALBEGA core detectors, whose inner surfaces are covered with a thin Al and SiO_2 layer, respectively, have been tested. They were developed to provide i) improved energy resolution and sensitivity to low energy signals produced by electrons, ii) higher photon detection efficiency, and iii) better mechanical stability against pressure differences. The tests performed with several radioactive sources including ^{241}Am (α particles) and ^{133}Ba (conversion electrons) confirmed performance according to specifications, including the uniformity and desired very thin thickness of the dead layers, as well as the sensitivity to the low energy signals. In a next step, the detectors will be mounted in a sandwich configuration to produce the final version of the ALBEGA core detector that will be characterized in 2018.

Nuclear decay spectroscopy data collected in parasitic ^{48}Ca beamtime was examined as part of the commissioning of the new Compact Decay Spectroscopy Setup (COMPASS) [Ack18] detection system at SHIP. Initially, the upgrade of using a higher granularity implantation

detector in the form of a double-sided silicon strip detector was assessed, with long correlation times from the decay ^{254}No→^{250}Fm (~30 min) →^{246}Cf measured [Mis18]. In addition, the ability to perform α-γ coincidences was successful, with excited states in ^{249}Fm populated following the decay of ^{253}No. Secondly, with the use of new digital electronics (FEBEX3A) [Hof12], the heavy neutron deficient region around *Z*=92-94 was explored. The use of such a fast timing system (20 ns time resolution) enables full chains to be acquired from a region of fast decaying nuclei, where with a conventional analogue system chain members could not be recorded due to dead time of the electronics system. A successful product of this investigation was synthesis of the previously unconfirmed isotope ^{225}Np. Development work on improvements to the detector system included upgrading to FEBEX4A (10 ns timing resolution) and enhancements to the escape 'box' detectors to maximize efficiency.

Mass measurements for nuclear structure studies

The nuclear structure studies by direct mass spectrometry with SHIPTRAP will be further extended to heavier and more exotic nuclides in the next beamtime period at GSI in 2018. Facing the challenge of ever-lower production rates, it has been worked on measures for a further increase in efficiency and sensitivity. To this end in the recent years, a cryogenic gas cell for SHIPTRAP has recently been built. In the commissioning beamtime in 2015 an increase of the overall efficiency by almost one order of magnitude was achieved [Kal15]. In 2017, additional offline studies were performed with radioactive sources. We studied the extraction of different elements from the gas cell and to optimize the transport of ions to the SHIPTRAP Penning traps following the 2016 relocation of the complete setup [Gia17]. The phase imaging (PI-ICR) measurement technique [Eli13] was further optimized at SHIPTRAP studying systematic uncertainties, exploring the achievable mass resolving power and improving the long-term stability for measurements with lowest yield. The PI-ICR technique has become the new standard for on-line mass measurements of radionuclides worldwide. However, challenges for direct mass spectrometry of the heaviest elements remain. In the next measurement campaign at GSI the identification of low-lying isomeric states in No-, Lr-, and Rf-isotopes is planned. In this mass region the various types of isomeric states are known, many of which have low excitation energies and similar half-lives to the ground state rendering their identification by means of conventional nuclear spectroscopy difficult. The high mass resolving power of the PI-ICR method makes it an ideal choice for this. A mass resolving power of about 100,000 for only 100 ms measurement time has also been reached for heavy ions.

Atomic Physics

The pioneering laser spectroscopy work on nobelium performed at the GSI in recent years led to the observation of more than 30 atomic states in the nobelium atom, among them several Rydberg states [Laa16]. From the convergence of the observed Rydberg series, we eventually obtained the ionization potential based on a two-step laser ionization scheme with high accuracy. However, the presence of buffer gas collisions led to the population of long-lived metastable states below the $^1P_1$ state that was directly excited by the first-step laser. The second laser excitation had sufficient energy to ionize the nobelium atoms from either of the two states. Thus, the identification of the different series was crucial for the IP determination. This was accomplished based on the delayed ionization signal obtained when the second step laser was delayed compared to the first one. In the case of the $^1P_1$ state that features a lifetime of only about 2 ns this signal decayed rapidly, whereas a longer-lived component with a lifetime of tens of ns was observed indicating the population of the lower-lying metastable state. In 2017, the data analysis was completed, and a rate equation model was developed that allowed us to describe the experimental data for nobelium as well as corresponding data for the homolog ytterbium perfectly [Chh17]. Consequently, the first ionization potential of nobelium was determined two orders of magnitude more accurately than before [Chh18].

The analysis of the hyperfine spectroscopy data for ^{253}No was supported by three different sets of atomic structure calculations that provided the mass shift and field shift constants as well as the hyperfine parameters. The results support the ground state spin and parity assignment of $9/2^-$, previously derived from in-beam gamma spectroscopy, and furthermore provide the magnetic and quadrupole moment of this odd-*A* nucleus accurately. Recently, state-of-the-art density functional calculations reproduced the differential charge radii of lighter actinides [Mar14, Rei17]. These calculations are also in excellent agreement with the nobelium data on differential charge radii. This confirms the theoretical prediction of maximum deformation in the nobelium isotopic chain around neutron number N = 152. It also substantiates the claim of a sizeable central depression in the proton distribution of ^{254}No, a feature that is only found in superheavy nuclei and originates from their strong Coulomb repulsion. The hyperfine spectroscopy results have been submitted for publication [Rae18].

Chemistry

In the past beamtime periods, experiments to study the chemical behavior of Fl and Nh in comparison with Hg, Tl, Pb, and Rn were performed at TASCA [Blo16]. In addition, the volatility and reactivity of these elements towards surfaces like SiO_2 and Au were measured. The comprehensive analysis of these results was continued. For Nh, experimental results [Blo16, Aks17] indicate a reduced volatility and enhanced reactivity compared to Cn and Fl. To render assistance to these gas-phase experiments, calculations of the adsorption energies of these elements and their lighter homologs on a Au(111) surface have been performed using a periodic ADF BAND code. Such periodic calculations of adsorption energies have been performed for the first time for superheavy element systems adsorbing on gold. The results have shown that Cn should indeed be the most volatile element out of

 DOI:10.15120/GR-2018-1

those under consideration. In addition, Fl should interact with gold at room temperature. Nh, should very strongly interact with gold. Such a different adsorption behavior allows for a good separation between all of these elements using a combination of quartz and gold surfaces [Per17a]. In addition, molecular properties of group-13 hydroxyls (of Tl and Nh) needed for predictions of their reactivity with quartz and gold have been calculated with the use of most advanced relativistic methods. In difference to the conclusion from the earlier predictions, NhOH is expected to be less volatile than TlOH [Per18]. To study Nh under improved conditions, advanced setups for optimized transport of the element under study to the detection setup are under development also allowing investigation of less volatile species. One such approach involves the direct connection of the existing COMPACT detection array [Yak14] to the TASCA Recoil Transfer Chamber (RTC). Another possibility involves the coupling of COMPACT to a recoil separator by employing a buffer-gas stopping cell instead of a classical RTC. First studies of the extraction efficiency of ^{219}Rn ions obtained from a ^{223}Ra recoil ion source installed in the SHIPTRAP buffer gas stopping cell [Neu06] into a COMPACT detector array were measured in off-line experiments at GSI. A first on-line experiment with such a setup was performed at the Cyclotron Institute, Texas A&M University, College Station, USA. The buffer gas stopping cell was coupled to the Momentum Achromat Recoil Spectrometer (MARS) [Fol12]. The isotopes ^{182,183}Hg and ^{199,200}At were produced in the reactions ^{40}Ar + ^{147}Sm and ^{40}Ar + ^{165}Ho, isolated in MARS, thermalized in the buffer gas stopping cell, and extracted into the COMPACT by using electric fields. The final analysis of the obtained extraction efficiencies and transport times is currently ongoing.

The studies related to volatile transition metal carbonyl complexes with short-lived isotopes have been continued. Currently, the method of choice is the isolation of the studied isotopes in a recoil separator, followed by their thermalization in an RTC that is flushed with CO-containing carrier gas [Eve14]. As the fusion-evaporation products of asymmetric fusion reactions needed for the productions of sufficiently long-lived isotopes of the elements of interest like Sg, Bh, and Hs, have a relatively large angular and energy spread, transmission efficiencies through a recoil separator like TASCA or GARIS at RIKEN are rather moderate, around 10-15%. Thus, the overall efficiency for the synthesis of carbonyl complexes in combination with physical preseparation is rather low. Therefore, possibilities for the chemical investigation of these compounds without a physical preseparator are currently explored. First experiments performed at the Tandem accelerator at JAEA Tokai, Japan, suggested that the successful synthesis of Os and W carbonyl complexes is feasible if the thermalization of the evaporation residues is spatially decoupled from the chemical synthesis. In that way it is needed, that the formation of the carbonyl complexes takes place in the absence of the beam, which is a strict requirement [Wan14]. In experiments with fission products at the research reactor TRIGA Mainz, the partial efficiencies for the flush-out transfer of non-volatile products from the thermalization chamber into the chemical synthesis chamber were measured and confirm that such an approach allows obtaining higher efficiencies than with preseparation. To support gas-phase experiments on studies of the stability and volatility of carbonyls of the heaviest elements, calculations of the electronic structures and properties of group-6 carbonyls [Ili17] and group-7 carbonyls, including those of Bh, were performed using the most advanced relativistic quantum-chemical methods (ADF BAND, X2c-DFT, DIRAC). The work considers all possible formation reaction scenarios of the single species that do not exist in macrochemistry. The formation mechanisms have been found and the volatile species that should form at the experimental conditions are suggested. Accordingly, the detailed properties of the $M(CO)_5H$ species (M= Tc, Re and Bh) have been calculated, including radicals $M(CO)_5$. Volatilities of these species and first bond dissociation energies have been predicted [Per17b].

Further activities, including those centered at the Helmholtz Institute Mainz, are described in more detail in the contribution to the Annual Report 2018 of the Helmholtz Institute Mainz [HIM18].

References

[Ack18] D. Ackermann, A.K. Mistry, F.P. Hessberger et al., Nucl. Instrum. Meth. A, accepted, in publication (2018).
[Aks17] N.V. Aksenov et al., Eur. Phys. J. A 53, 158 (2017).
[Blo16] M. Block et al., GSI Sci. Rep. 2016, p. 197-199, RESEARCH-NUSTAR-SHEP-1.
[Chh17] P. Chhetri et al., Eur. Phys. J. D 71,195 (2017).
[Chh18] P. Chhetri et al., in preparation (2018).
[DiN15] A. Di Nitto et al., GSI Sci. Rep. 2014, p. 184, MU-NUSTAR-SHE-C-06 (2015).
[Eli13] S. Eliseev et al., Phys. Rev. Lett. 100, 082501 (2013)
[Eve14] J. Even et al., Science 345, 1491 (2014).
[Fol12] C.M. Folden III et al., NIMA 678, 1 (2012).
[Gia17] F. Giacoppo et al., Acta Phys. Pol. B 48, 423 (2017).
[HIM18] SHE section of the 2017 HIM Annual Report (2018).
[Hof12] J. Hoffmann et al., GSI Scientific Report 2011, 253, (2012).
[Ili17] M. Iliaš and V. Pershina, Inorg. Chem. 56, 1638 (2017).
[Kal15] O. Kaleja et al., xxx
[Khu17] J. Khuyagbaatar, EPJ Web Conf., 163, 00030 (2017).
[Laa18] M. Laatiaoui et al., Nature 538, 495 (2016).
[Mar14] J. A. Maruhn et al., Comput. Phys. Commun. 185, 2195 (2014).
[Mis18] A. K. Mistry et al., Acta Phys. Pol., accepted, in publication (2018).
[Neu06] J.B. Neumayr et al., NIMB 244, 489 (2006).
[Per17a] V. Pershina, Relativistic Quantum Chemistry for Chemical Identification of the Superheavy Elements, In: Handbook of Relativistic Quantum Chemistry, Ed. W. Liu, Springer, (2017) pp. 857-899.

[Per17b] V. Pershina and M. Iliaš, J. Chem. Phys. 146, 184306 (2017).
[Per18] V. Pershina and M. Ilias, Chem. Phys. Lett. 694, 107 (2018).
[Rae18] S. Raeder et al., in publication (2018).
[Rei17] P.-G. Reinhard and W. Nazarewicz, Phys. Rev. C 95, 064328 (2017).
[Wan14] Y. Wang et al., Radiochim. Acta 102, 69 (2014).
[Yak14] A. Yakushev et al., Inorg. Chem. 53, 1624 (2014).

Experiment beamline: SHIP-SHIPTRAP / TASCA
Experiment collaboration: NUSTAR-SHE / NUSTAR-LASPEC / NUSTAR-MATS
Experiment proposal:
[U259,U288,U295,U308,U312,U313,U314]
Accelerator infrastructure: UNILAC
Grants: [EU H2020 contract No. 654002 / TNA]
Strategic university co-operation with: JGU Mainz

 DOI:10.15120/GR-2018-1