Superheavy Element Chemistry — Achievements and Perspectives

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Superheavy elements have been synthesized and chemically characterized one-atom-at-a-time up to element 108. Presently, the quest for element 112 is one of the hottest topics in this field. The transactinide elements 104 to 108 are members of group 4 to 8 of the Periodic Table and element 112 belongs into group 12. Chemical properties of some of these elements, like elements 104 and 105, show stunning deviations from simple extrapolations within their respective group while others exhibit great similarities with their lighter homologues elements. First experiments to investigate seaborgium (Sg, element 106) in aqueous solution were performed. Again, in large international collaborations at the GSI, several gas-phase chemistry experiments were performed with hassium (Hs, element 108). Recently, the highly efficient and very clean separation of Hs was applied for nuclear studies of various Hs nuclides investigating their cross section and their nuclear decay properties in the region of the doubly-magic ^{270}Hs ($Z = 108$, $N = 162$). To overcome certain limitations of the presently used on-line chemical separations the new **T**rans**A**ctinide **S**eparator and **C**hemistry **A**pparatus (**TASCA**) — with a gas-filled recoil separator as a front-end tool — was designed and built at the GSI in a collaborative effort. Presently in its commissioning phase, TASCA shall be a key instrument for a big leap into quantitatively and qualitatively new experiments in the region of superheavy elements.

1. Introduction

The number of chemical elements has considerably increased over the last decades. But how many elements are sufficiently chemically characterized to justify their position in the Periodic Table and are their chemical properties significantly modified by increasingly strong relativistic effects? These are key questions chemists like to answer in addition to the central question of how many elements can exist. Already the first pioneering chemical studies showed that rutherfordium and dubnium (Rf, element 104, and Db, element 105, respectively) belong into group 4 and 5 of the Periodic Table. These elements, which can only be produced one-atom-at-a-time in heavy-ion reactions, mark the beginning of a remarkable series of chemical elements; from a chemical point of view they are transactinide elements and from a nuclear point of view they can be called superheavy elements (SHE).[1] It was only in recent years, that a large number of experiments did not only shed light on many fascinating and sometimes surprising chemical properties of Rf and Db but allowed to stepwise climb up the exceedingly difficult path to the subsequent elements seaborgium (Sg, element 106), bohrium (Bh, element 107) and hassium (Hs, element 108); see References 1–4 for a comprehensive coverage of this development.

Most chemical experiments of lighter transactinides depend on the problematic cluster (aerosol) jet-transport. This technique was applied to investigate Rf (see References 5 and 6 and references therein for a large number of very detailed, recent Rf studies), Db, and Sg in aqueous solution. For Sg, the heaviest element investigated in aqueous solution,[7,8] until now only two studies were performed. These will be described in an exemplary way. Contrary to the transport of the refractory lighter transactinides with a cluster jet a rather volatile compound of element 108 is directly formed in the recoil chamber and is transported to the chemistry/detector device. This unique approach allowed unprecedented chemical studies of

Hs (References 9 and 10) and yielded exciting nuclear results for the most neutron-rich Hs isotopes and their daughter nuclides. Chemical and nuclear aspects of Hs studies will be discussed in more detail. Recently the quest for element 112 and beyond became one of the hottest and most challenging topics in heavy element research with chemical methods.[11,12] Studies with element 112 constitute a transition from a more traditional approach in SHE chemistry — to form a chemical compound and chemically investigate this compound — towards studies of an element in its atomic state. The success in SHE chemistry was only feasible because of an enormous progress in many fields. Therefore, experimental developments, their scientific outcome, and perspectives for the future SHE chemistry research will be discussed in an exemplary way.

These very successful chemistry experiments, however, at the same time clearly demonstrated the limits of these techniques. To move on to new frontiers, including heavier elements and so far inaccessible chemical systems, "physical" recoil separators are presumably ideal front-end "tools" for SHE chemistry. Ground-breaking experiments began at the Berkeley Gas-filled Separator.[13,14] A large international community is presently building and commissioning TASCA, the TransActinide Separator and Chemistry Apparatus,[15] at the GSI. Characteristic features of this gas-filled recoil separator, which will be very instrumental in chemical and in nuclear oriented experiments in the SHE region, will be outlined while discussing perspectives of SHE research.

2. Nuclear Syntheses and Properties of Superheavy Elements

Heavy-ion fusion reactions of medium-heavy projectiles with Pb and Bi targets produce short-lived nuclides. They are, maybe with one or two exceptions,[13] not useful for chemical investigations. In contrast to these so-called "cold-fusion" reactions superheavy element chemistry experiments usually exploit an advantage of "hot-fusion" reactions which lead to the synthesis of the most neutron-rich, longest-lived isotopes of a given element. To this end, the most neutron-rich available iso-

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tope of an actinide element, e.g., ^{248}Cm, is irradiated with a neutron-rich light ion beam like ^{18}O, ^{22}Ne, and ^{26}Mg. These reactions produce SHE one-atom-at-a-time — decreasing from about one atom per minute for element 104 and 105, and a few atoms per hour for element 106, to about one atom per day for element 108.[1,2] This leads to the most extreme situation one can envision in chemistry; only single atoms or molecules, which are rapidly vanishing due to their radioactive decay, are at hand for chemical investigations. As all nuclides used and investigated in recent chemical studies of transactinides decay by emission of characteristic α-particles a clear identification of the separated nuclide (and element) was feasible after chemical isolation.

More elements and longer-lived nuclides are on the horizon and a challenge for chemical studies. In reactions between ^{48}Ca as a projectile and targets made of ^{233,238}U, ^{242}Pu, and ^{248}Cm, Oganessian et al.[16] reported on the observation of elements up to 116. This opens up a thrilling region for heavy element chemists to probe the influence of increasingly strong relativistic effects and the structure of the Periodic Table at its extreme limit; see Figure 1. As all nuclear decay chains observed from these ^{48}Ca induced reactions are terminated by spontaneous fission (SF) no "genetic" link into the region of known nuclides can be established. Therefore, an unambiguous identification of these new elements still remains open as the presently available physical techniques do not allow for a clear detection of the atomic number. Chemistry — in addition to unraveling exciting chemical properties of these elements — may again become a crucial tool in elemental identification. The first steps towards a chemical separation and identification of element 112 — directly produced or as decay product of element 114 — have been made.[11,12] Those chemical experiments to search for ^{283}112 produced directly in the ^{48}Ca on ^{238}U reaction[11] at the GSI will be discussed in the next section in more detail together with chemical aspects of element 112. While these experiments did not identify ^{283}112 (only upper-limit cross sections were obtained),[11] a recent report from a similar experiment performed at the Flerov Laboratory of Nuclear Reactions (FLNR), Dubna, making use of the ^{48}Ca on ^{242}Pu reaction and searching for ^{283}112 as an α-decay daughter of ^{287}114, indicates the observation of element 112 after chemical separation.[12]

Chemistry experiments on Sg and Hs, which were performed at the GSI and will be discussed in more detail, use ^{22}Ne and ^{26}Mg beams to synthesize and investigate ^{265}Sg and ^{269,270,271}Hs

in reactions with ^{248}Cm. While the main emphasis in the Sg experiments[7,8] was to unravel chemical properties of Sg, recent Hs experiments exploited the unique and very clean Hs chemistry to study nuclear reaction and nuclear structure aspects. The rotating ^{248}Cm target wheel ARTESIA[1] was irradiated with high intense ^{26}Mg beams at five different energies between E_{lab} =130 MeV and 150 MeV covering the range from below the maximum of the 4n channel producing the new isotope ^{270}Hs (Reference 17) to an energy well beyond the maximum of the 5n channel (^{269}Hs). Measured cross sections are in good agreement with calculations using the code HIVAP.[18] At the lower irradiation energies, surprisingly enough, evidence for the observation of ^{271}Hs — produced in the 3n-evaporation channel (!) — was obtained.[17] Most interesting, the decay of these Hs isotopes — their α-decay energies and partial SF half-lives — allows for a crucial test of theoretical model predictions of the $N = 162$ neutron-shell strength. The deduced Q_α-value[17] of the doubly-magic ^{270}Hs$_{162}$ is in good agreement with macroscopic-microscopic model predictions.[19] In addition, also the decay properties of the Sg isotopes, observed as the Hs α-decay daughter nuclides, provide important data for this comparison. Most recently, a ^{25}Mg beam was used in a search for the unknown isotope ^{268}Hs. The sensitivity of this chemistry experiment was well below one picobarn for an assumed ^{268}Hs half-life of one second or longer.

3. Chemical Properties of Superheavy Elements

After the first chemical studies have shown that Rf and Db are transactinides and member of group 4 and 5 of the Periodic Table (see Figure 1), more detailed chemical studies were performed over the last two decades; see References 1–4 for a comprehensive summary. It soon became clear that simple extrapolations of chemical properties within a given group of elements in the Periodic Table are not trustworthy. Especially Rf and Db exhibit chemical properties which are often very much different from extrapolations in group 4 and 5. Studies in the liquid phase, which concentrated on the aspects of hydrolysis and complex formation, were mainly performed in pure and mixed mineral acid solutions. First detailed studies of Db in mixed HCl/HF solutions yielded a surprisingly non-Ta-like behavior.[20] Only subsequent experiments,[21] which were carried out in pure acid solutions, showed a Db behavior in agreement with theoretical predictions[22] including relativistic effects. In recent years, the aqueous phase behavior of Rf was investigated in greater detail[5,6,23,24] using first the Automated Rapid Chemistry Apparatus (ARCA)[25] and most recently the much more advanced AIDA[23,26] which includes automated sample preparation and transfer of the sample into the detector chamber. For the first time, this allowed to measure a Rf elution curve.[24] A number of surprising results were obtained in a large number of detailed Rf studies; e.g., the fluoride complexation[6] of Rf revealed stunning differences between Rf and Zr and Hf. These kind of experimental findings still remain a challenge for theoretical model descriptions.

Aqueous chemistry with ARCA has reached Sg for which only two very basic chromatographic studies exist;[7,8,27] both performed with a cation-exchange resin. The one carried out with 0.1 M HNO$_3$/5 × 10^{-4} M HF showed that Sg elutes within 10 s from a 1.6 × 8 mm cation-exchange column (Aminex A6, 17.5 ± 2 μm). Therefore, under these conditions Sg behaves similarly to Mo and W in group 6 of the Periodic Table and distinctively different from hexavalent U which forms uranyl-ions.[27] This return to an expected behavior — after all the surprises with Rf and Db chemistry — was termed occasionally "oddly ordinary seaborgium." However, this does NOT allow a statement like "seaborgium reaffirms periodic table's predictive ability." As not only relativistic effects but also other effects, like shell effects, on the atomic and molecular electrons

Figure 1. Periodic Table of the Elements. The IUPAC accepted transactinide elements 104 through 111 shall take the positions of the seventh period transition metals below Hf in group 4 and Au in group 11. While chemical studies have justified placing the elements Rf through Hs into group 4 to 8 of the Periodic Table, the "chemically unknown" heavier elements (chemical symbols for "known" elements and open symbols for yet unconfirmed reports) still need to be investigated. The arrangement of the actinides reflects that the first actinide elements still resemble, to a decreasing extent, the chemistry of d-elements.

can cancel each other with the result of surprisingly similar properties — or, in other cases, they can all act in such a direction that strong deviations from expected properties can be observed. Already the second Sg experiment,[8] which was performed in pure 0.1 M HNO_3, indicated a non-W-like behavior of Sg. Contrary to W, Sg was not eluted from the cation-exchange column. From this, it was concluded that neutral or anionic oxofluoride complexes like SgO_2F_2 or $SgO_2F_3^-$ were likely to be formed and eluted in the first experiment. Without the presence of complexing fluoride anions Sg was retained on the resign in cationic form, presumably, as $Sg(OH)_4(H_2O)_2^{2+}$ or $SgO(OH)_3(H_2O)_2^+$ present in dilute HNO_3 due to the lower tendency of Sg to hydrolyze[28] as compared to that of W.

The recent success in SHE chemistry in the liquid phase and in the gas phase was only feasible because of an enormous progress in many fields to meet a large number of physical, chemical, technological, and metrological challenges. Intense and stable heavy ion beams became available and technologies like the rotating target wheel ARTESIA[1] were developed to stand high heat loads on windows, actinide target, and backings. In recent experiments at the GSI, e.g., Mg beams were produced from the ECR source with very low consumption of 0.5 mg/h or less of isotopically enriched material. This made "pulse" beam intensities of 4×10^{13} particles per second available in the 5-ms long UNILAC macropulse. At a 50 Hz repetition rate this corresponds to 1.5 particle-μA DC beam. With these high beam intensities traditional He/cluster-jet transport systems reach their limits and become inefficient as transport yields sharply drop. Not only to circumvent these problems but to exploit a number of advantages, the formation of a volatile oxide directly in the recoil chamber and its transport to a combined chemistry and detector device[29,30] was applied in all Hs experiments.[9,10,17] Before, gas-adsorption chromatographic studies of the lighter transactinides were mainly performed with volatile halide or oxohalide complexes formed in a remote reaction chamber after a cluster-jet transport; see Reference 31 for a compilation.

Two kinds of gas-adsorption experiments have been performed with HsO_4 (References 9 and 10) both showing a typical group 8 behavior of Hs. Firstly and typical for its lighter homologue Os, all experiments demonstrated, as expected,[32] the formation of a stable and at room temperature volatile tetroxide of Hs in an oxygen containing gaseous environment. However, in the thermochromatographic experiments[9] — in which the deposition temperature of Os and Hs compounds was measured by registering characteristic α-decays in detector arrays mounted along a temperature gradient — a theoretically unexplained[32] higher adsorption temperature — or lower volatility — was measured for HsO_4 in comparison with OsO_4. From the observation of seven molecules of HsO_4 and their adsorption position at (-44 ± 6) °C, in comparison with the one of OsO_4 at (-82 ± 7) °C, the following adsorption enthalpies ($\Delta H_a°$) on silicon nitride were deduced from the first Hs experiment:[9] $-\Delta H_a^{°(T)}(HsO_4) = (46 \pm 2)$ kJ/mol for HsO_4 and $-\Delta H_a^{°(T)}(OsO_4) = (39 \pm 1)$ kJ/mol for OsO_4. Although the difference between the theoretically predicted[32] and experimentally observed and recently confirmed HsO_4 volatility is small on an absolute scale of adsorption temperatures it remains unclear why the inverse order of volatilities $HsO_4 < OsO_4$ is observed experimentally as compared with the theoretical prediction $OsO_4 \leq HsO_4$. Most recently, a Hs-chemistry experiment showed that a sub-picobarn cross section limit can be reached in superheavy element chemistry — a crucial prerequisite to explore the chemistry of SHE in the region around element 114.

As in the preceding experiment, also in the second Hs experiment[10] tetroxides were formed in a recoil chamber and in its hot (600 °C) outlet section. Contrary to the preceding experiment, which had to meet the challenge of using very dry

gases to avoid early ice formation in the cold part of the detector, in this second experiment water was added (2 g H_2O per kg gas) to the O_2 containing He. Within 3–4 s volatile products were transported to a set of four detector boxes kept at room temperature. Each box contained a linear array of four PIN-diode detectors facing at a NaOH coated stainless steel plate. Computer controlled, always three detector boxes in a row were measuring while the fourth box was refurbished and freshly prepared NaOH was mounted. Simultaneously produced and transported OsO_4 was used as a monitor. Due to the formation of an osmate (VIII) with the chemically reactive NaOH surface more than 50% of the Os is found in front of detector one and the rest exhibits a significant tailing. Six decay chains of Hs, centered at detector number three, were detected in the first five detectors.[10] The low statistics does not allow drawing any conclusion about a possible lower reactivity of the HsO_4 as compared to OsO_4. However, the observation (i) confirms the formation and stability of the volatile HsO_4 compound, and (ii) shows the similarity in chemical reactivity between HsO_4 and OsO_4. Presumably, the deposition of Hs is, in analogy to a well-known behavior of Os, the result of the formation of a hassate (VIII) according to: $2NaOH + HsO_4 \rightarrow Na_2[HsO_4(OH)_2]$. For the first time, an acid-base chemical reaction was performed with HsO_4.

Recent attempts to get a first glimpse on the chemistry of element 112 are most exciting and most challenging. Since the mid-70's possible chemical properties of element 112 have attracted a lot of attention, mainly because of strong relativistic effects and the $6d^{10}7s^2$ closed-shell configuration. Very early on, especially the question how closely element 112 would resemble the chemistry of Hg — its lighter homologue in group 12 — was in the focus; see Reference 33 for a summary of early theoretical works. A wide span of volatilities has been predicted for element 112. One group of predictions is based on theoretical model calculations including relativistic effects[33–35] while others rest on empirical extrapolations.[36,37] While earlier predictions did not exclude a highly volatile and chemically inert element 112, possibly even resembling an inert gas like behavior,[34] recent calculations are discussing a more Hg-like behavior[35] but still with a higher volatility for element 112. A very recent fully-relativistic treatment of the interaction of element 112 with metallic surfaces such as Au and Pd predicts weaker adsorption of 112 than Hg on these metals.[35] These calculations predict that the adsorption temperature of element 112 on (ideal) Au surfaces will be 93 K below the one for Hg. In addition it is pointed out that element 112 will form some metal-metal bonding with Au and, therefore, element 112 will adsorb at much higher temperatures than Rn. Adsorption enthalpies of element 112 on metal surfaces obtained from an empirical model also indicate a weak chemical bond formed on Au surfaces and a "volatile noble metal" character of element 112 was predicted.[36–38] The element 112 volatility was expected to be much higher than that of Hg.

Recent experiments[11,39] on element 112 constitute a transition from a more traditional approach in SHE chemistry — to form a chemical compound and chemically investigate this compound — to studies of an element in its atomic state. However, several experiments to study the volatility of element 112 in its atomic state gave partially controversial and inconclusive results.[11,39] Still unpublished, a most recent press release[12] claims a successful chemical separation and identification of element 112. Unfortunately, a number of controversial reports[11,16,40–43] from different experiments about the cross section to synthesize $^{283}112$ in the ^{48}Ca on ^{238}U reaction and about the nuclear decay properties of $^{283}112$ leave parts of the scientific community in a state of confusion; see Table 1 for a summary.

After first chemistry experiments[39] performed at the FLNR an international collaboration carried out a second series of

TABLE 1: Experiments to synthesize ^{283}112 in the ^{48}Ca + ^{238}U reaction and their results

E_{proj} / MeV (middle of target)	Events assigned to ^{283}112 α ; SF	E_α / MeV or SF	Technique	Half-life	Cross section[a] / pb	Reference
231	0 ; 2	SF	VASSILISSA	$(1.4^{+2.5}_{-0.5})$ min	$5.0^{+6.3}_{-3.2}$	40
238	0 ; 0	–			<7.3	
231	0 ; 0	–	VASSILISSA		<2.2	41
234	0 ; 2	SF		$(5.1^{+3.5}_{-1.5})^e$ min	$3.0^{+4.0}_{-2.0}$	
233	0 ; 7	SF	"Rn-like" chemistry	>3 min assumed ^{f}	$2.0^{+0.9}_{-0.7}$	39
230	0 ; (1)^g		DGFRS	3.4 s	$0.5^{+1.2}_{-0.4}$	16
234	4 ; (2)^g	9.54		$(4.0^{+1.3}_{-0.7})$ s	$2.5^{+1.8}_{-1.1}$	
230	0 ; 0	–	BGS		<0.8^b , <1.6^c	43
236	0 ; 0	–			<0.96^b, <2.0^c	
233	0 ; 0	–	SHIP		<0.8^b	42
236	0 ; (1)^h	SF		$(5.2^{+25.1}_{-2.4})^h$ s	$(0.7^{+1.6}_{-0.6})^h$	
239	0 ; 0	–			<0.6^b	
231	– ; 0	–	"Hg-like" chemistry	*5 min (SF) assumed* ^{f}	<0.8^d	
	– ; 0	–	"Rn-like" chemistry	*5 min (SF) assumed* ^{f}	<1.9^d	11
235	0 ; 0	–	"Hg-like" chemistry	*4 s (α)^f ; 5 min (SF)^f*	<2.3^d ; <1.7^d	
	0 ; 0	–	"Rn-like" chemistry	*4 s (α)^f ; 5 min (SF)^f*	<2.7^d ; <7.6^d	

^{a}Error bars and upper limit sensitivities at 68% c.i. if not otherwise specified.

^{b}"One-event" limits without statistical fluctuation.

^{c}Upper limit sensitivity at 84% c.i.

^{d}Upper limit sensitivity at 95.45% c.i.

^{e}Mean value including previously observed events.

$^f T_{1/2}$ not measured in chemistry experiment, for cross section calculation assumed $T_{1/2}$.

^{g}Interpreted as SF from the daughter nucleus after missing the α-event from the mother decay.

^{h}No assignment made to a specific isotope.

experiments at the GSI.[11] The ^{48}Ca on ^{238}U reaction was selected to produce ^{283}112. Simultaneously, ^{220}Rn was produced as a transfer product from U and $^{184-186}$Hg from small amounts of Nd in the target. These experiments were aiming at measuring the adsorption behavior of element 112 in comparison with Hg and Rn on Au. Along the Au surface, a temperature gradient from +35 °C to about –185 °C was established in a modified version of the Cryo On-Line Detector (COLD), which was successful in the Hs experiment.[9] A schematic view of this setup is shown in Figure 2. In the first somewhat slow GSI experiment, concentrating on a then believed 5-min SF decay for ^{283}112, a Au-catcher was facing an array of 32 silicon PIN-diodes. Although some events were observed which could have been interpreted as SF from ^{283}112 small imperfections and open
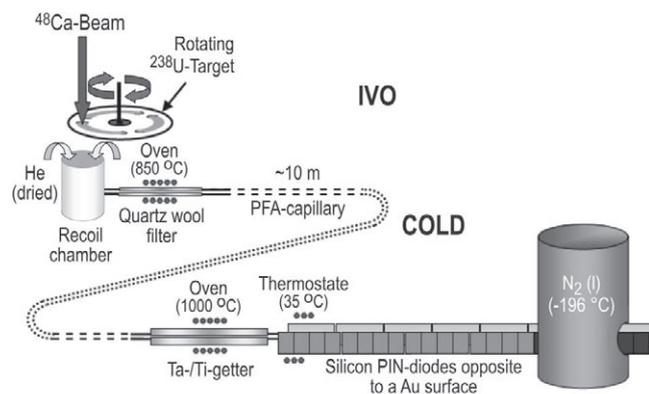

Figure 2. Schematic view of the experimental set up used in the first experiment on element 112 at the GSI. The upper left part depicts the In-situ Volatilization (IVO) part attached to the rotating target wheel. It is coupled to the Cryo On-Line Detector (COLD) with its Si PIN-diodes monitoring the opposite Au-coated side of the thermochromatographic channel. Figure from Reference 1.

questions led the international collaboration agree to first repeat this experiment under improved conditions to substantiate the findings. An improved version was developed and applied in the second experiment which allows measuring much more efficiently in (almost) 4π-geometry.[11] Further improvements made the second experiment also much more sensitive to shorter half-lives in the region of a few seconds. Also the second experiment, which in addition to longer-lived SF decays concentrated on shorter-lived α-SF-decay sequences, did not detect any decay pattern which could be unambiguously attributed to a superheavy element over a broad range of adsorption properties between its group 12 homologue Hg and the noble gas Rn. The upper limit sensitivity levels reached in both GSI experiments are listed in Table 1 for two different assumed decay modes and half-lives and for two different assumed volatilities. The levels reached in these experiments are not low enough to clarify contradictions between previously published results on the cross section and on the decay of ^{283}112.

4. Perspectives

Many of the very successful experiments on the chemistry of SHE at the same time clearly demonstrated limits of the applied techniques. A totally new quality of chemical studies is on the horizon when combining chemical techniques with gas-filled recoil separators. They are ideal front-end tool to overcome the unwanted interaction of the primary heavy-ion beam with anything present in the recoil chamber and to preseparate unwanted nuclear reaction products. Ground-breaking experiments began at the Berkeley Gas-filled Separator[13,14] (BGS). Coupled to the BGS, the first Rf separation with SISAK,[13,44] which is a fast and continuously operating liquid-liquid extraction technique, was successful. Preseparated 4.7-s ^{257}Rf was stopped in the gas of a Recoil Transfer Chamber[14,30]

(RTC) — the key interface with a thin window between the gas filled separator and any chemistry set up — and was transported via a He/KCl-jet to the SISAK system. The α decay of ^{257}Rf was registered on-line with a rather unspecific liquid-scintillator being part of the flowing organic phase. Though resolution is very low preseparation enabled a clear Rf identification. The SISAK technique in combination with preseparation allows further improvements to study the extraction behavior of even heavier elements in aqueous solution. Under development are also alternative approaches like the use of crown ethers[45] to widen the scope of chemical investigations or to extend the studies of SHE in aqueous solution beyond Sg. For this region electrochemical deposition techniques are under preparation. In addition, in the field of SHE chemistry previously unknown, completely new techniques and compounds will become accessible in gas-phase experiments; e.g., the use of organometallic compounds,[46] when performing chemical reactions with preseparated SHE to produce and investigate volatile species.

Most recently, the TransActinide Separator and Chemistry Apparatus[47] (TASCA) was built at the GSI and a large international community is presently commissioning all components of the separator and its peripheral components. The goal of building TASCA was to provide the community with a gas-filled separator with maximized transmission (efficiency) for transactinide research making use of hot-fusion reactions and actinide targets to produce the most neutron-rich, longest-lived nuclides. While chemical investigations of preseparated SHE are in the focus and shall play a major role in the upcoming program a rich nuclear reaction and nuclear structure research is envisaged making use of TASCA. As it can be operated with different gas fillings like, e.g., H_2 or N_2 as an alternative to He as the standard gas, basic research on the interaction of slow moving ions of the heaviest elements in different gases and the determination of their charge states may become an interesting research aspect. Some central components of the 3.5-m long gas-filled separator TASCA use components from a former separator.[48] To optimize all components, ion-optical calculations[49] were performed based on the model fusion reaction of 5–6 MeV/u ^{48}Ca on 0.5 mg/cm^2 actinide targets (^{238}U, ^{244}Pu). The DQQ configuration with a 30-degree dipole magnet and a quadrupole doublet, which was selected as the best choice, allows operation in two possible modes. While the DQ_hQ_v mode gives the highest possible transmission the smallest image size results from the DQ_vQ_h mode (Q_h and Q_v denote horizontally and vertically focusing quadrupoles). New ducts were designed, built and installed for the dipole and the quadrupoles to maximize the transmission in both modes. According to first model calculations,[47,49] a horizontal and vertical acceptance of about ±110 and ±40 mrad was achieved for the "high transmission" DQ_hQ_v mode which corresponds to a solid angle of ≈14 msr. This is at least 50% higher as compared with the solid angle of the Dubna Gas-Filled Recoil Separator (DGFRS) which has a 35–40% transmission[16,50] for the Ca on Pu reaction. From this one can estimate that the TASCA transmission should be about 50% higher than the DGFRS one; i.e., in the "high transmission" mode of TASCA we are expecting up to 60% transmission for evaporation residues produced Ca on U or Pu reactions. This is very similar to the best values given for the BGS.[43] TASCA will combine two advantages of these two separators, i.e., the large transmission of the BGS and the small dispersion of the DGFRS. In the DQ_vQ_h mode, a reduced horizontal acceptance of ±34 mrad will presumably reduce the transmission by a factor of ≈0.6. However, an extraordinarily small image area should be achievable — a key issue to build small recoil transfer chambers for a fast transport of products into any chemistry setups and something unique for TASCA.[47,49]

To make use of the highest presently obtainable beam inten-

sities at the UNILAC and the even higher intensities which will become available with the implementation of a new 28 GHz SC-ECR source in a few years, a windowless differential pumping section was installed and is successfully in operation.[51] A new target chamber was designed and built which accommodates (i) the rotating actinide target wheel in an easily removable cassette taking care of the safety aspects while working with highly radioactive material, (ii) the newly built drive, (iii) collimators, and (iv) beam diagnostic components. A beam current transformer upstream of the target shall allow for continuous monitoring of the beam current. Equipped with a separator like TASCA and combining it with the tools which were developed over the last decade to study superheavy elements promises a big leap ahead and gives hope for a new quality in SHE research.

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