Chemical studies of the heaviest known elements: nihonium (element 113), flerovium (element 114), and moscovium (element 115)

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All elements up to oganesson (element 118) have been discovered and officially accepted, filling up the 7th period of the periodic table of chemical elements. Experimental chemical investigations of the heaviest elements have also made tremendous progress in the last decades. Currently, the focus is on copernicium (Cn, element 112), nihonium (Nh, element 113), flerovium (Fl, element 114), and mocovium (Mc, element 115). Relativistic effects render Cn, Nh, and Fl more chemically inert than their lighter homologs due to the energetic stabilization and spatial contraction of the outermost $7s_{1/2}$ and $7p_{1/2}$ orbitals, which was realized already in the 1970s [1] and is confirmed in more current state-of-the-art molecular, cluster, and solid-state relativistic calculations (cf., e.g., [2]). Experimentally, such effects are explored using gas phase chromatographic techniques, which allow studying single atoms of these elements and probing their volatility and reactivity towards hetero-surfaces like silicon oxide or gold, also in relation to the properties of their lighter homologs as well as the noble gas radon [3,4].

Whereas the chemical properties of Cn have been reproducibly studied [4] and shown that the trend in adsorption strength on a Au surface established by the lighter group-12 homologs is followed by Cn [5], only fragmentary and unconfirmed information mostly gained in studies that suffered from considerable background is available on Nh [4,6]. For the past ten years, Fl has been in the focus of chemical studies, yet its chemical character is not clear. Results obtained at FLNR Dubna [7] and at GSI [8] were interpreted to point at a noble-gas-like and a metallic character, respectively. In the course to settling the question, the safe identification of its nuclear decay chains has proven to be difficult [4]. As was demonstrated [8,9], the coupling of chemistry setups to an electromagnetic separator provides the necessary suppression of the primary beam and of the products of multi-nucleon transfer reactions, and thus a gain in sensitivity for the unambiguous identification of single

atoms of the heaviest elements. This facilitates studies of chemical properties and even of the exploration of nuclear properties of superheavy elements in chemistry experiments [9].

At GSI Darmstadt, the gas filled TransActinide Separator and Chemistry Apparatus (TASCA) serving as a physical preseparator, along with its ancillary Cryo-Online Multidetector for Physics and Chemistry of Transactinides (COMPACT) and its upgraded version miniCOMPACT [6,11] have been used continuously improved during the last decade, e.g. [8,10]. The current focus of the superheavy element chemistry experiments behind TASCA is on nihonium, flerovium, and moscovium, using isotopes with half-lives down to ≈0.2 s. At the conference, further experimental data on Fl [12] as well as first data on Mc and its daughter Nh gained more recently at GSI Darmstadt will be discussed. To progress to the next heavier element, livermorium (Lv, element 116), developments towards a faster technique based on electrical field guidance rather than gas-flow extraction to transport the species of interest to the gas chromatography and detection system have started [11]. Preparatory experiments were performed at Texas A&M University and at GSI Darmstadt and show the path forward to chemical studies of yet heavier elements.

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