

In situ synthesis of volatile carbonyl complexes with short-lived nuclides

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Abstract Rapid in situ formation of metal carbonyl complexes with short-lived nuclides has been demonstrated to be feasible with recoiling ions formed in nuclear fusion and fission reactions. These carbonyl complexes are highly volatile and can be transported rapidly in a gas-stream to counting or chemistry devices. This method was already successfully applied in the chemical investigation of the superheavy element seaborgium ($Z = 106$) and appears

promising for various fields of nuclear research. In this article, we give an overview on the current status of metal carbonyl complex studies with short-lived d-element isotopes.

Keywords Metal carbonyl complexes · Superheavy elements · Nuclear fission products · Nuclear fusion products · Physical pre-separation · Seaborgium

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Introduction

Various fields of radiochemistry benefit from fast chemical reactions and separation techniques. For example, the production of nuclides for different applications requires rapid (in the ideal case fully automated) chemical separation procedures [1–3]. For radioactive beam developments with the ISOL technique, a crucial point is the fast and selective transfer of ions of interest out of the target to the ion source. Rapid chemical methods help solving some of the associated problems [4]. In superheavy element chemistry research, special challenges are the nuclear properties of these elements including the short half-lives (typically a few milliseconds up to several seconds) and low production rates (between a few atoms per hour and one atom per month) as well as huge amounts of unwanted nuclear by-products [5].

We have recently investigated the in situ synthesis of carbonyl complexes with short-lived nuclides of refractory d-elements. Thus, we were able to directly synthesize carbonyl complexes with the recoiling nuclear reaction products and transport these complexes rapidly in a gas stream to counting and chemistry devices. So far, our method gave access to volatile carbonyl complexes of the groups 6 to group 9 elements, including the transactinoid seaborgium (Sg, $Z = 106$). The method allows the separation of these elements from other refractory elements, e.g. the elements of group 4 and group 5. In this paper, we give an overview on the current status of in situ synthesis of carbonyl complexes with short-lived isotopes and highlight the perspectives for possible applications of this technique.

Metal carbonyl complexes

The compound class of carbonyl complexes was discovered more than 100 years ago. Mond reported on the synthesis of nickel tetracarbonyl [6]. Since that time numerous carbonyl complexes have been synthesized, and many of them became important for applied and fundamental science [7]. Common techniques to synthesize these complexes involve applying high carbon monoxide pressure [8]. Multinuclear and mixed carbonyl complexes are formed by almost all transition metals. Elements of group 6 and group 8 as well as nickel are known to form volatile, highly symmetric, binary carbonyl complexes [8]. Therefore, group 6 and group 8 appeared promising for superheavy element research. Characteristic for carbonyl complexes is the σ -donation bond from the highest occupied molecular orbital (HOMO) of the carbonyl ligand to the orbitals of the transition metal in σ -symmetry (s or $p_{1=2}$ orbitals) and the π -backbonding from the orbitals of the metal in p-symmetry to the lowest unoccupied molecular

orbital LUMO of the carbonyl ligand [9]. In transactinoids, the bonding situation in carbonyl complexes is especially interesting. In all carbonyl complexes of 3d, 4d, and 5d transition metals, the σ -donation bond is stronger than the π -backbond. In superheavy elements, the influence of relativistic effects on the chemical properties of the elements is much stronger than in lighter elements [10]. In the recent literature, predictions can be found that seaborgium hexacarbonyl is stable, however, due to relativistic effects the σ -symmetric orbitals as the $p_{1=2}$ and the s contract, causing the overlap with the HOMO of the carbonyl ligand to be weaker. On the other hand, the d-orbitals are better shielded from the charge of the atomic nucleus, they expand and the overlap with the LUMO of the carbonyl ligand increases. The π -backbonding becomes stronger [11], [12]. Thus, the strength of the carbon–metal bond in tungsten hexacarbonyl and seaborgium hexacarbonyl is predicted to be similar [11], [12]. Furthermore, seaborgium hexacarbonyl and tungsten hexacarbonyl are predicted to have the same adsorption properties on a silicon dioxide surface [13].

Investigations of the carbonyl complex formation with fission products

Carbonyl complex synthesis with fission products applying hot-atom chemistry methods was reported by Baumgärtner and Reichold [14]. They mixed $^{235}\text{U}_2\text{O}_3$ with $\text{Cr}(\text{CO})_6$ and irradiated the powdered mixture with neutrons. Fission Mo isotopes were found to replace the Cr in the hexacarbonyl complex. The volatile carbonyl complexes could be separated from the powder by evaporation.

In experiments at the Swiss spallation neutron source SINQ at PSI, Switzerland, neutron induced fission of ^{235}U was used to produce the isotopes $^{83-87}\text{Se}$. The fission products were thermalized in a He/CO mixture. The formation of volatile SeCO was observed, which was transported in a gas stream to a collection station [15, 16]. Transition metals were not in the focus of these studies.

In experiments at the TRIGA Mainz research reactor, we explored the possibility of a continuous synthesis of transition metal carbonyl complexes with short-lived isotopes combined with a rapid transport [17, 18]. A ^{249}Cf target was placed in a recoil chamber near the reactor core and irradiated with a neutron flux of $9.8 \times 10^{10} \text{ n}/(\text{cm}^2 \text{ s})$. The target chamber was flushed with a N_2/CO gas mixture. The fission products recoiled out of the target, they were thermalized in the N_2/CO atmosphere and reacted with the CO. Volatile compounds and fission products were rapidly transported in the gas stream through a capillary out of the reactor to a charcoal filter. The filter was monitored with a HPGe γ -detector. The transported isotopes and their

daughter nuclides were identified by the energy of their γ -lines. In addition to the elementally volatile fission products I, Se, and Xe, also the refractory elements Mo, Tc, Ru, and Rh were transported. The transport yield of Se significantly increased due to the formation of SeCO as in the studies reported in [15, 16]. Obviously, the transition metals Mo, Tc, Ru, and Rh reacted with the CO and formed volatile compounds. Precursor effects complicate the unambiguous identification of the transported species: in many cases it remains unclear, if a detected element was indeed transported as a carbonyl complex, or if transport of the β^- -decay precursor occurred, which decayed to its daughter in the charcoal filter [18]. Thus, a quantitative analysis of this data is challenging [18].

The results of these experiments were reproduced with ^{252}Cf -fission sources at the Institute of Modern Physics (IMP) in Lanzhou, in China [19] and at the Miss Piggy fission source [20] at the University of Bern, Switzerland. The transport of these refractory elements is most likely due to the formation of carbonyl complexes. Molybdenum is known to form stable volatile molybdenum hexacarbonyl $\text{Mo}(\text{CO})_6$ and ruthenium is known to form volatile pentacarbonyl $\text{Ru}(\text{CO})_5$. However, no binary, stable, mononuclear carbonyl complexes of technetium, and rhodium are known. As the experiments are performed on an atom-at-a-time level, formation of multinuclear complexes can be excluded. We currently consider the formation of radical type complexes or of mixed carbonyl complexes with impurities of the gases as the most likely explanation for our results. Partial efficiencies for complex formation and transport depend strongly on the geometry of the target chamber, the pressure conditions, and the composition and purity of the gas-mixture.

Investigations of the carbonyl complex formation with nuclear fusion products

Unlike in the experiments with fission products, heavy-ion induced fusion reactions open a possibility to study various transition metals without the problems associated with precursor effects from radioactive decay. However, several other experimental challenges need to be taken into account. In heavy-ion induced fusion reactions a thin target is irradiated with a high intensity ion beam. If a recoil chamber is placed directly behind the target and flushed with an inert gas/carbon monoxide mixture, this chamber will heat up, and at high beam intensities a plasma will form. These harsh conditions do not allow synthesis of compounds that are unstable at high temperatures. Furthermore, the carbon monoxide molecules are destroyed in the plasma and carbon clusters are

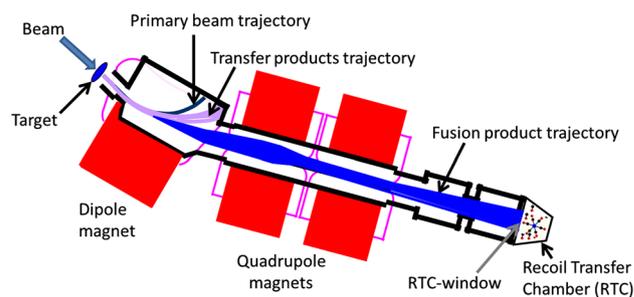


Fig. 1 Schematic drawing of TASCA as an example for a physical preseparator. The beam from the accelerator hits the target. The primary beam passes the target and is deflected by the field of the dipole magnet to the beam dump. The transfer products are predominantly deflected by the dipole magnet. Fusion products are guided by the dipole magnet and focused by a quadrupole doublet to the separator's focal plane, where they pass the RTC window. The RTC is continuously flushed with an inert gas/CO mixture. The fusion products are thermalized inside the RTC. Thus, carbonyl complexes can be formed under ambient conditions in the RTC and can be transported from there with the gas mixture to chemistry or detection devices

formed [19, 21]. Thus, for first tests of the synthesis of carbonyl complexes with fusion products a combination of physical preseparation [22–24] and in situ chemistry was applied. In the method of physical preseparation [25], recoiling evaporation residues (ERs), are separated in-flight from the primary beam and unwanted by-products using ionoptical separators (based on electric and/or magnetic deflection components in either in vacuum or gas-filled operation). The ERs are focused by ion-optics into the focal plane of the separator, where a recoil transfer chamber (RTC) [26] is attached. The ERs pass a thin vacuum window (e.g. a Mylar window) and are thermalized in the RTC at ambient conditions. Figure 1 shows a scheme of the gas-filled, physical TransActinide Separator and Chemistry Apparatus (TASCA) at GSI.

Pioneering work applying this method for online chemical synthesis was performed at the Berkeley gas-filled Separator (BGS) [23, 27]. At GSI, TASCA was optimized from the design phase on for this purpose [26, 28]. For the GAs-filled recoil isotope separator (GARIS) [29] at RIKEN a RTC and gas-jet system was developed to establish chemistry experiments with preseparated isotopes [30]. Carbonyl chemistry studies were performed at TASCA [17, 18] and at GARIS [31]. All these separators are of the gas-filled type and are operated with He filling gas at a pressure of around 1 mbar. Thus, small leakage through the RTC window foil is less critical. Recently, we were able to demonstrate that it is also possible to combine a vacuum separator in which electrical fields are applied, and where high vacuum conditions are critical, with a RTC. At the separator for heavy ion reaction products (SHIP) [32] at GSI, carbonyl complex formation of 5d-elements was investigated [33].

Carbonyl complex chemistry studies at TASCA

As mentioned in the previous paragraph, TASCA (see Fig. 1) is a gas-filled separator optimized for chemical studies of transactinoids. It consists of a dipole magnet and two quadrupole magnets. The ions recoiling from the target interact with the helium gas in TASCA, following a trajectory determined by the average charge state due to the many charge changing collisions with the gas atoms [34]. Within the dipole field the ions are separated. The ions of interest are focused to the focal plane by the two quadrupole magnets. In experiments at TASCA, the formation of carbonyl complexes of W, Re, Os, and Ir under conditions relevant for transactinide chemistry experiments was investigated [17, 18].

The isotopes ^{163}W ($t_{1/2} = 2.75$ s) and ^{164}W ($t_{1/2} = 6.0$ s) were synthesized in the reaction $^{144}\text{Sm}(^{24}\text{Mg},4-5n)$. The isotopes ^{170}Os ($t_{1/2} = 7.3$ s), ^{171}Os ($t_{1/2} = 8.0$ s), and ^{172}Os ($t_{1/2} = 19.2$ s) were synthesized in the reaction $^{152}\text{Gd}(^{24}\text{Mg},4-6n)$. These isotopes partially decay through α -emission. For the investigation of the transport and adsorption properties of Os and W, the Cryo-online multidetector for physics and chemistry of transactinides (COMPACT) [35] was used. COMPACT is a thermochromatography detector which was developed for gas-phase chemical studies of volatile species of superheavy elements and the investigation of their decay properties under low background conditions. A COMPACT array consists of two panels of 32 silicon positive intrinsic negative (PIN) diodes each. The panels are mounted facing each other so that the PIN diodes form a 32 cm long channel with a cross section of $(1.0 \times 0.06 \text{ cm}^2)$. The gas passes through this channel. The exit side is kept at temperatures around -140 °C by a copper finger which is cooled with liquid nitrogen, thus establishing a negative temperature gradient along the chromatography column. The Os and W isotopes were thermalized in the RTC, which was flushed continuously with a He/CO mixture. Thus, Os and W formed volatile complexes which were transported to COMPACT. The volatile Os and W species were adsorbed in the last third of COMPACT at temperatures below -30 °C. From this observation, the formation of $\text{W}(\text{CO})_6$ and $\text{Os}(\text{CO})_5$, which physisorbed on the surface in COMPACT, was concluded. These results showed that an experiment with the heavier homologs Sg and hassium (Hs, $Z = 108$) are feasible [17]. The experiments with fission products gave evidence that also Tc and Rh form volatile complexes. However, as no stable, binary mononuclear complexes of Tc and Rh are known and the influence of precursor effects could not be completely excluded, the heavier homologs Re and Ir formed in fusion-neutron evaporation reaction, thus avoiding the precursor formation, were investigated at TASCA [18]. The isotopes

$^{178-179}\text{Ir}$ were produced in the reaction $^{159}\text{Tb}(^{24}\text{Mg},4-5n)$ and $^{170-172}\text{Re}$ were produced in the reaction $^{\text{nat}}\text{Eu}(^{24}\text{Mg},xn)$. These isotopes decay through β - and γ -emission but do not emit α -particles. To unambiguously identify the Re and Ir isotopes by their γ -lines, COMPACT was replaced by a charcoal filter. The filter was monitored with a HPGe γ detector. Ir and Re also formed volatile complexes with CO and they were transported in the gas-stream to the filter. Hence, it could be demonstrated that under the chosen experimental conditions, Re and Ir also formed volatile carbonyl complexes. The exact species was not determined. Stable, mononuclear, binary carbonyl complexes are not known from literature. The transported species may be mixed carbonyl complexes, which were formed with impurities present in the gas. The Ir and Re complexes were studied with isothermal chromatography. They adsorbed on quartz at low temperatures, which indicates a physisorption process. Furthermore, their thermal stability was studied, and they were found to decompose at temperatures above 300 °C passing a quartz surface [18]. Although the complex formation of group 7 and group 9 elements is not fully understood yet, in situ carbonyl chemistry is also a suitable method for fast transport and investigations of these elements opening up, e.g., perspectives for the first chemical investigation of meitnerium (Mt, $Z = 109$).

First chemical investigation of seaborgium hexacarbonyl at GARIS

The studies at TASCA laid the basis for the synthesis of the first transactinoid carbonyl compound— $\text{Sg}(\text{CO})_6$. ^{265}Sg appeared as a good candidate for the first carbonyl chemistry experiment with a transactinoid element. The synthesis and decay properties of this isotope were revealed by a meta-analysis of all existing data [36]. The results of the meta-analysis were recently fully confirmed at the GARIS separator in the reaction $^{248}\text{Cm}(^{22}\text{Ne},5n)$, which has a relatively high cross section of 380 pb [37]. ^{265}Sg has two isomeric states, which decay through α -emission with half-lives of $14.4^{+3.7}_{-2.5}$ s and $8.5^{+2.6}_{-1.6}$ s, respectively [37].

For the chemical investigation of $\text{Sg}(\text{CO})_6$ the COMPACT detector [35] was connected with an aerosol particle-free gas-jet system [30] to the GARIS separator. To compare Sg with its lighter homologs short-lived isotopes of Mo and W were produced in the reactions $^{\text{nat}}\text{Zn}(^{24}\text{Mg},xn)^{87,88}\text{Mo}$ and $^{144}\text{Sm}(^{24}\text{Mg},4n)^{164}\text{W}$. Like in the experiments at TASCA, the recoiling isotopes were separated from the primary beam in the magnetic fields of GARIS and guided to the end of the separator, where they passed a Mylar window and were thermalized in an RTC. The RTC was flushed continuously with a He/CO mixture, and the volatile species were transported in the gas-stream

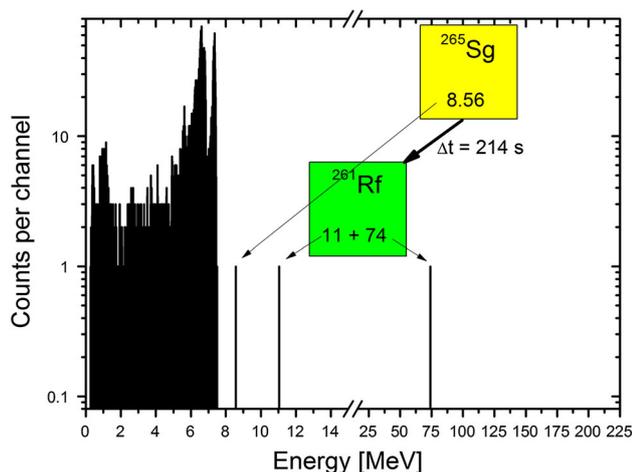


Fig. 2 Sum spectrum of all 32 detector pairs. The spectrum was collected while 4.35×10^{17} ^{22}Ne particles hit the target. All energies are given in MeV

to a COMPACT detector and adsorbed at characteristic temperatures. W could be identified by the energy of the emitted α particle. The investigated Mo isotopes undergo β^+ decay. To unambiguously identify the Mo isotopes, they were first collected on an activated charcoal filter, which was monitored by a HPGe γ -detector. Thus, the isotopes $^{87-90}\text{Mo}$ were identified by their γ lines. Afterwards, the Mo-isotopes were collected in COMPACT. The β particles emitted by the decaying nuclides can be registered with COMPACT, and the isotopes $^{87,88}\text{Mo}$ were identified by their half-lives. To identify Sg, a search for correlated decay chains of ^{265}Sg was performed. In the data analysis, we searched for α -particles with energies between 7.4 and 10.0 MeV, followed within 1 hour by the detection of a fission fragment or a second α -particle in the same or a neighboring detector. Thus, 15 correlated chains were found, which were assigned to the decay of ^{265}Sg or its daughter nuclides. The likelihood that these decay chains originated from background was less than 10^{-5} . Additionally, three uncorrelated spontaneous fission (SF) events were registered with the COMPACT detector. As there was no fission background in the detector during the experiment and these three events were observed in the same part of the chromatography channel as the other 15 decay chains, these SF events were also assigned to the decay of ^{265}Sg or its daughter nuclides. All 18 decays assigned to originate from Sg or its daughter nuclides were observed in the last third of the COMPACT detector array [31].

Figure 2 shows a typical sum spectrum of all 32 detector pairs. During the period, when this spectrum was collected, the target was irradiated with 4.35×10^{17} ^{22}Ne particles. As it is clearly seen, the spectra are very clean in the interesting energy range above 7.5 MeV. The α peaks at energies below 7.5 MeV originate from the decay of ^{219}Rn

and its daughter isotopes ^{215}Po and ^{211}Bi , as a ^{227}Ac -emanation source was connected to the gas-loop to allow calibrating the COMPACT detectors.

In the spectrum shown in Fig. 2, one α event (in detector No. 29 bottom) was followed 214 s later by a SF, where both fragments were detected in the same detector pair (detector No. 29 top and No 29 bottom) in coincidence. The α particle had an energy of 8.56 MeV. One fission fragment had a registered energy of 11 MeV, while the other fragment had an energy of 74 MeV, where the energies are not corrected for pulse height defect. The relatively low energy of 11 MeV of one of the fission fragments can be explained by the energy it lost when traversing the gas-filled COMPACT chromatography channel and the dead layer of the detector. Random coincidence can be excluded as the spectrum is free from background in the region of interest. However, it is for the first time that an α -SF correlation with such a long SF lifetime was observed in the decay of ^{265}Sg . It is worth noticing that previous experiments on the observation of ^{265}Sg , ^{261}Rf , and their decay products [37–44], were not sensitive to such long correlation times. So far, the α -decay of $^{265\text{a,b}}\text{Sg}$ into the two isomers of ^{261}Rf has been observed [36, 37]. The isomer $^{261\text{a}}\text{Rf}$ is an α -emitter with an half-life of 68 s, the upper limit for a SF-branch is $b_{\text{SF}} \leq 13\%$ [44], while $^{261\text{b}}\text{Rf}$ has a half-life of 1.9 s and decays through a emission or SF with $b_{\text{SF}} = 82\%$ [37]. Thus, the question arises, if there is an unknown SF-branch in $^{261\text{a}}\text{Rf}$, or if one of the ^{261}Rf -isomers also has an electron-capture branch feeding ^{261}Lr . ^{261}Lr is an isotope with an half-life of 39 min [45]. In Ref. [45] the reactions $^{248}\text{Cm}(^{18}\text{O},5n)^{261}\text{Rf}$ and $^{248}\text{Cm}(^{18}\text{O},\text{p}4n)^{261}\text{Lr}$ were investigated, and thus an upper limit for an electron capture branch in ^{261}Rf of 14 % was determined based on the comparison of the reaction cross sections. Further investigations under zero-background conditions like in the carbonyl chemistry experiments are required to help answering the question which of the scenarios is responsible for the observed decay-chain.

All Sg events were observed in the last third of the COMPACT detector array. Also, Mo and W were mainly deposited in this part of the detector array. This led to the interpretation that all three elements formed hexacarbonyl complexes, which have the same volatility. The deposition patterns were compared to Monte Carlo simulations [46]. The systematic uncertainties of this method are about (± 6 kJ/mol). Adsorption enthalpies of (-50 ± 2 kJ/mol) for $\text{Mo}(\text{CO})_6$, (-49 ± 2 kJ/mol) for $\text{W}(\text{CO})_6$, and (-50 ± 4 kJ/mol) for $\text{Sg}(\text{CO})_6$, respectively, were determined [31]. These values are identical within the statistical uncertainty limits, which is in agreement with theoretical predictions [13]. Figure 3 shows the experimental distributions of Mo, W and Sg in COMPACT as well as the

2 mm to a filter of activated charcoal filter. The volatile compounds adsorbed on the charcoal filter, which was monitored with a γ -detector. The bottom panel of Fig. 4 shows a typical spectrum. The sample was collected for 30 min on the charcoal filter and measured during collection. W and Re isotopes were identified, which confirmed the results obtained in the experiments performed at TA-SCA [17, 18] and GARIS [31]. γ -lines from ^{214}Pb originate from natural background. However, no Ta and Hf isotopes were observed in the spectra. Thus, it was demonstrated that Ta and Hf do not form volatile carbonyl complexes with CO under these experimental conditions. Gas phase carbonyl chemistry is therefore an appropriate tool to separate group 4 and 5 elements from group 6 and 7 elements. With respect to future experiments, carbonyl chemistry can thus be used as a second separation step behind a physical separator and can serve for the separation of isobaric nuclei.

Attempts to synthesize carbonyl complexes without preseparation

The most significant disadvantage of the combination of physical preseparation and carbonyl chemistry is that the overall efficiency is limited by the finite transmission of the isotopes through the physical preseparator. In the case of ^{265}Sg produced in the reaction $^{248}\text{Cm}(^{22}\text{Ne},5n)$, the transmission through GARIS was estimated to be 13 % [37]. It would thus be favorable to avoid using a preseparator. However, carbonyl chemistry with fusion products without a physical preseparation turned out to be problematic for the reasons mentioned above (see paragraph “[Investigations of the carbonyl complex formation with nuclear fusion products](#)”).

In Ref. [19], the isotopes ^{173}W and ^{179}Os were produced in the reactions $^{159}\text{Tb}(^{19}\text{F},5n)$ and $^{165}\text{Ho}(^{19}\text{F},5n)$. The recoiling isotopes as well as transfer products were thermalized directly behind the target in a recoil chamber, which was flushed with a He/CO mixture. All transported species were collected on a charcoal filter, which was monitored by a γ -detector. In the spectra, also γ -lines of non-volatile, projectile-like transfer products such as ^{21}Na and ^{25}Na appeared. Furthermore, the Teflon chromatography column was covered after the experiments with a yellow deposit. Due to the plasma created by the ion beam the CO molecules were destroyed and carbon clusters were formed. This led to a chemically non-selective transport also of species that do not form volatile complexes with CO.

In another experiment at RIKEN [21], the same phenomenon was observed. Several $^{\text{nat}}\text{Ta}$ targets were placed in a chamber, which was flushed with a He/CO mixture. The targets were irradiated with a 24-MeV deuteron beam.

Thus, the nuclear reaction products were thermalized in the surrounding gas-atmosphere. One product was $^{179\text{m}}\text{W}$, which could be transported in the gas-stream to a charcoal filter. Placing a glass fiber filter, which retains aerosol particles, between the target chamber and the collection station reduced the transport efficiency of $^{179\text{m}}\text{W}$ drastically. Thus, it was demonstrated that under these conditions a mixed transport of W, partially as a volatile complex and partially adsorbed to aerosol particles, takes place.

Summary and outlook

In the last few years, exploration of the possibilities to synthesize metal-carbonyl complexes with short-lived isotopes has started and led to the discovery of the first transactinoid carbonyl complex. It was demonstrated that the in situ carbonyl complex chemistry is an efficient method to volatilize the refractory fission products Mo, Tc, Ru, and Rh. Furthermore, the 5d-elements W, Re, Os, and Ir produced in nuclear fusion reactions were shown to form volatile complexes upon thermalization in a CO-containing atmosphere. Physical preseparation of the fusion products from the primary beam is needed, as the primary beam forms a plasma in the gas-filled recoil chamber, which destroys the CO molecules and leads to carbon cluster formation. Hence, at the moment the combination of physical preseparation with in situ carbonyl chemistry is the method of choice.

The combination of physical preseparation and carbonyl chemistry also turned out to be a powerful tool to perform nuclear decay spectroscopy of single atoms under background-free conditions, thus being an useful approach for nuclear structure studies. It can even be used in specific cases to suppress isobaric contamination in nuclear physics experiments. It bears the potential to become of interest in radioactive beam production with the ISOL technique. Isotope production for applied sciences might also benefit from this technique.

The approach of carbonyl chemistry behind a preseparator allowed the first chemical investigation of a transactinoid carbonyl complex— $\text{Sg}(\text{CO})_6$. Furthermore, based on our studies the chemical investigation of carbonyl complexes of the elements bohrium (Bh, $Z = 107$), hassium (Hs, $Z = 108$) and meitnerium (Mt, $Z = 109$) are now in reach, thus marking a new chapter in superheavy element chemistry. Good candidates for these experiments are isotopes with half-lives in the range of seconds. The isotopes ^{266}Bh ($t_{1/2} \approx 2$ s) and ^{267}Bh ($t_{1/2} = 17.6^{+14}$ s) can be synthesized in the reactions $^{249}\text{Bk}(^{22}\text{Ne},5n)$ with a cross-section of $\sigma = 25\text{--}250$ pb and $^{249}\text{Bk}(^{22}\text{Ne},4n)$ with $\sigma = 96^{+55}_{-25}$ pb [48]. As Bk is not an easily available target material due to its

half-life of 320 days, the reaction $^{248}\text{Cm}(^{23}\text{Na},4\text{-}5\text{n})$ with $\sigma \approx 50$ pb is a good alternative [49]. For the studies of hassium, the isotopes ^{269}Hs ($t_{1/2} = 12$ s) and ^{270}Hs ($t_{1/2} = 7.6$ s), which can be synthesized in the reactions $^{248}\text{Cm}(^{26}\text{Mg},5\text{n})$ $\sigma \approx 7$ pb and $^{248}\text{Cm}(^{26}\text{Mg},4\text{n})$ $\sigma \approx 3$ pb [50], appear to be promising candidates. However, no Mt isotope with a half-life in the range of seconds has been synthesized directly in a nuclear fusion reaction, so far. From the decay chains of element 117 synthesized in the reaction $^{249}\text{Bk}(^{48}\text{Ca},3\text{n})^{294}117$, the isotope ^{278}Mt with $t_{1/2} = 4.4^{+3.6}_{-1.4}$ s is known [51, 52]. No method to synthesize ^{278}Mt directly is known and therefore it is not suitable for carbonyl studies with the recently developed technique. Mt isotopes near the closed neutron subshell ($N = 162$) might be better candidates. ^{270}Mt ($N = 161$) has a half-life of $t_{1/2} = 0.69^{+0.95}_{-0.26}$ s, thus it could still be a suitable isotope for carbonyl chemistry studies. So far, only three decays of ^{270}Mt have been experimentally observed in the decay-chain of $^{278}113$ [53], thus further investigations on its decay properties and the direct synthesis are required. Also ^{271}Mt ($N = 162$) might be a good candidate, its half-life might be in the range of seconds due to the neutron subshell closure. ^{271}Mt has not been discovered, yet. A possibility to investigate ^{270}Mt and ^{271}Mt is the reaction $^{248}\text{Cm}(^{27}\text{Al},4\text{-}5\text{n})$. The cross section of this reaction is estimated to be $\sigma \approx 1$ pb based on extrapolation of the production cross sections of fusion evaporation reactions with a ^{248}Cm -target [37].

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