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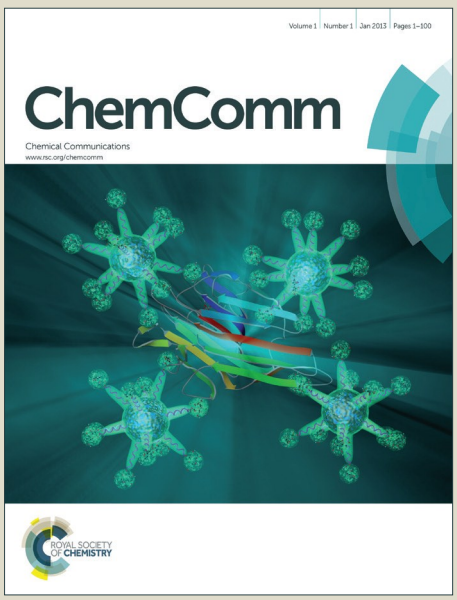

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Possible Isomers in Ligand Protected Ag_{11} Cluster Ions Identified by Ion Mobility Mass Spectrometry and Fragmented by Surface Induced Dissociation

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This communication reports the identification of gas phase isomers in monolayer-protected silver clusters. Two different isomers of $Ag_{11}(SG)_7^-$ (SG-gulathione thiolate) with different drift times have been detected by combined electrospray ionization (ESI) and ion mobility (IM) mass spectrometry (MS). Surface induced dissociation (SID) of the 3^- charge state of such clusters shows charge stripping to give the 1^- charged ion with some sodium attachment, in addition to fragmentation. SID and collision induced dissociation (CID) for $Ag_{11}(SG)_7^-$ suggest different pathways being accessed with each method. SID was introduced first time for the study of monolayer protected clusters.

Atomically precise monolayer protected clusters (MPCs) of gold and silver belong to a fascinating area of research due to their unique optoelectronic properties and wide range of applications in materials, electronics, catalysis and biology[1-3]. Several clusters have been synthesized and many of them have been crystallized including $Au_{25}(SR)_{18}$[4, 5], $Au_{30}S(SR)_{18}$[6], $Au_{36}(SR)_{24}$[7], $Au_{38}(SR)_{24}$[8], $Au_{68}(SR)_{32}$[9] and $Au_{102}(SR)_{44}$[10]. Some of the silver clusters have also been crystallized including $[Ag_{14}(SR)_{12}(PPh_3)_8]$[11], $[Ag_{16}(DPPE)_4(SR)_{14}]$[12], $[Ag_{32}(DPPE)_5(SCR)_{24}]$[12] (DPPE: 1,2-Bis(diphenylphosphino)ethane), $Ag_{44}(SR)_{30}$[13, 14] and most recently, $Ag_{25}(SR)_{18}$[15] (SR correspond to various thiolate ligands). Crystal structures of some of the alloy clusters consisting of Au/Ag[13, 16] and Au/Cu[17] have also been solved. While some of the clusters could be crystallized, there are several others which were identified by optical spectroscopy and mass spectrometry (MS) along with structural insights from theoretical calculations, mainly density functional theory (DFT) [18-35]. Only a few clusters are known to show well defined mass spectrometric signatures namely, $Ag_9(MSA)_7$[18], $Ag_{11}(SG)_7$[36], $Ag_{15}(SG)_{11}$[37], $Ag_{31}(SG)_{19}$[37], $Ag_{32}(SG)_{19}$[27], $Ag_{44}(SR)_{30}$[19], $Ag_{75}(SG)_{40}$[38], etc., where SG refers to the thiolate form of glutathione. Some of the clusters have been well characterized by electrospray ionization (ESI) MS and their fragmentation patterns have been studied using collision induced dissociation (CID). $Au_{25}(SR)_{18}$ is one of the most widely and systematically studied systems from both experimental and theoretical points of view[5, 28, 34, 39-41]. The crystal structure reveals the presence of an Au_{13} core and 6 $Au_2(SR)_3$ staple motifs[4, 5]. Fragmentation from the core as well as the staple has been identified by an ESI MS/MS study by Angle *et al.* [39] In another theoretical study, Liu *et al.* have identified the stepwise fragmentation of the stable motifs as the most favourable fragmentation pathway for $Au_{25}(SR)_{18}$[42]. These researchers have shown different isomeric structures of the core which can be responsible for fragmentation and catalytic properties of the clusters.

Due to the core as well as ligand orientation, MPCs can have isomeric forms. However, no isomeric structures have been reported to date for ions in the gas phase. In this context, ion mobility-mass spectrometry (IM-MS) which can separate ions based not only on their mass and charge but also on their size and shape, known as their rotationally averaged collision cross section (CCS) has great potential. Different conformations can be separated by this process based on differences in their CCS, as evident from several studies on proteins and other biomolecules[43-45]. There are a few reports on the use of IM-MS on monolayer protected Au clusters and nanoparticles.[46-50] For example, $Au_{25}(SR)_{18}$ cluster fragments were identified by ion mobility.[39] Symmetric drift time distribution of these clusters suggested the presence of only one structure or interconverting isomers[39]. There is no report on monolayer protected silver clusters which were separated by IM-MS.

Here, we report the first observation of the presence of ligand induced isomers of $Ag_{11}(SG)_7^-$ by ESIIM-MS where two isomers can be distinguished by their different drift times. We also introduce surface induced dissociation (SID) as a method of

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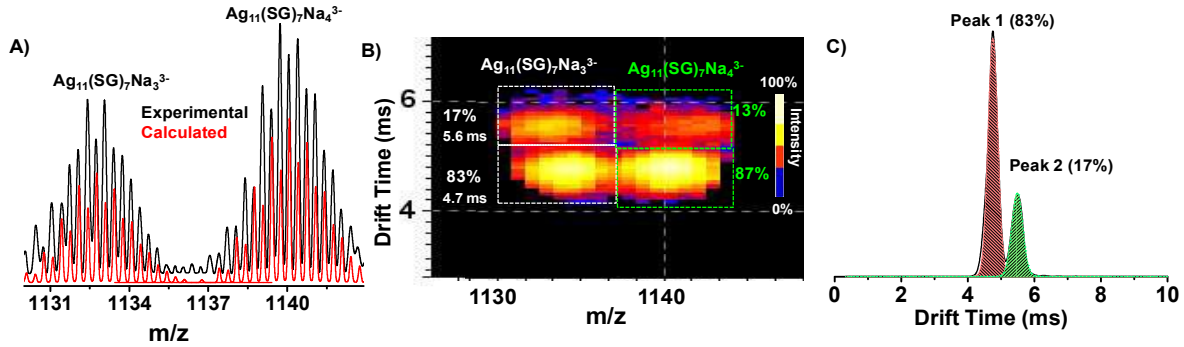


Figure 1: *A) Zoom in view of the ESI MS of $Ag_{11}(SG)_7$ showing 3- charged ion with three and four attachments. The peaks are matching exactly with the theoretically calculated pattern. B) Plot of ion mobility drift time versus m/z of $Ag_{11}(SG)_7Na_3^{3-}$ and $Ag_{11}(SG)_7Na_4^{3-}$ is showing presence of two isomeric species. Relative abundances of the isomers found from the drift profiles are labelled. Drift profile of $Ag_{11}(SG)_7Na_3^{3-}$ is shown in C where two clear peaks indicate the presence of two isomeric structures. Relative abundances of the isomers were found by calculating the area under each peak.*

fragmentation to study such clusters for the first time where charge stripping can generate deprotonated peaks from a higher charged species, in addition to fragmentation. SID is known to result in significantly different fragmentation pathways for protein complexes in comparison to CID. We observed different types of fragmentation in SID and CID for $Ag_{11}(SG)_7Na_n^{3-}$ suggesting that different pathways are being accessed with each method.[51, 52]

This $Ag_{11}(SG)_7$ was synthesized by a recently reported method.[36] Briefly, a 1:5 ratio of silver nitrate ($AgNO_3$) and glutathione (GSH) were mixed together in ice-cold MeOH to form silver(I)glutathionate which was subsequently reduced by chilled aqueous $NaBH_4$. As-synthesized cluster precipitates out in the solution due to the presence of excess MeOH. These red luminescent (λ_{em}=705 nm) clusters showed three distinct absorption peaks at 487, 437 and 393 nm in the optical absorption spectrum. As-synthesized clusters are of high purity as confirmed from polyacrylamide gel separation. ESI MS of these clusters showed 3- and 2- charged species with multiple Na attachments (see Figure S1). Detailed MS/MS analyses were carried out to study the fragmentation pattern.

An ion mobility study of the clusters using a Waters Synapt G2S instrument capable of measuring drift times and mass spectra simultaneously is presented here. The instrument was in-house modified to incorporate an SID device before the IM cell.[53] Figure 1A shows a zoom in plot of ion drift time versus m/z obtained, highlighting the species of interest, namely $Ag_{11}(SG)_7Na_n^{3-}$ (where n = 3 and 4). This is the prominent peak observed for the species. About 2-7 Na attached peaks were observed among which 3 and 4 Na additions are the most intense, and are shown in Figure 1B; the isotope distributions of which match well with their theoretically calculated distribution. For each ion, there are two species with slightly different structures. This is reflected in the similarity of their drift times, as shown in the plot of ion drift time versus m/z (Figure 1A) as well as in the drift profile (Figure 1C); in both cases two distributions can be observed.

A sharp peak in the drift time at 4.7 ms is due to the main structural isomer. However, another one appears around 5.6 ms which is due to a structural isomer of lower intensity. The relative abundance of the peaks were calculated from the area under each peak. Note that in the previous study of $Au_{25}(SCH_2CH_2Ph)_{18}^-$ a symmetric drift profile was observed indicating the absence of isomers. DFT calculations of the present clusters suggested an Ag_7 core, one $Ag_2(SG)_3$ staple and two $Ag(SG)_2$ staples. Six possible structures were reported in the previous work, which are discussed in the supplementary information. Considering the energies and HOMO-LUMO gaps along with the observed absorption spectrum, the two structures are of similar energy and stability. Therefore, it is indeed possible that both the structures can co-exist leading to two isomeric forms as seen in IM-MS. The structures are described in Supplementary Information (see Figure S7) in detail. Between these two structures, one is more compact compared to the other considering inward and outward projection of the ligands. These structures were calculated considering SMe instead of the whole GSH as ligand. In the case of isomers, the structures should be calculated with intact GSH ligand but due to large number of atoms ($Ag_{11}C_{70}H_{102}N_{21}O_{42}S_7$ for intact $Ag_{11}SG_7$ cluster) it is difficult. Being a tripeptide, GSH has inherent tendency to make H-bonds with adjacent ligands which can also lead to isomerism. The two peaks with different drift times may be ascribed to isomers having different structures of the glutathione moieties on identical AgS backbones. The coulomb repulsion between the ligands of multiply charged $Ag_{11}(SG)_7$ may induce isomerization as in the case of multiply-charged proteins in the gas phase. Considering all these possibilities, the presence of multiple isomers in IM measurements is understandable.

These clusters show good mass spectral signatures which allowed us to proceed further to see the fragmentation pattern from a specific charge state. The instrument is capable of dissociating any of these ions in both SID and CID modes. In the CID mode, we observed the usual fragments of $Ag_{11}(SG)_7Na_n^{3-}$ (which is actually $[Ag_{11}(SG)_7\text{-}nH+nNa]^{3-}$). AgSG-loss was apparent as the main fragmentation pathway to give $Ag_{10}(SG)_6Na_n^{2-}$ at the lowest collision energy (Figure 2A). The fragment $AgSG^-$ is detected at the lower mass range. With increasing collision energy, lower mass fragments were observed. Mostly the fragmentation occurs via $AgSG^-$ loss.

The smallest fragment observed was $AgSG^-$ at the highest

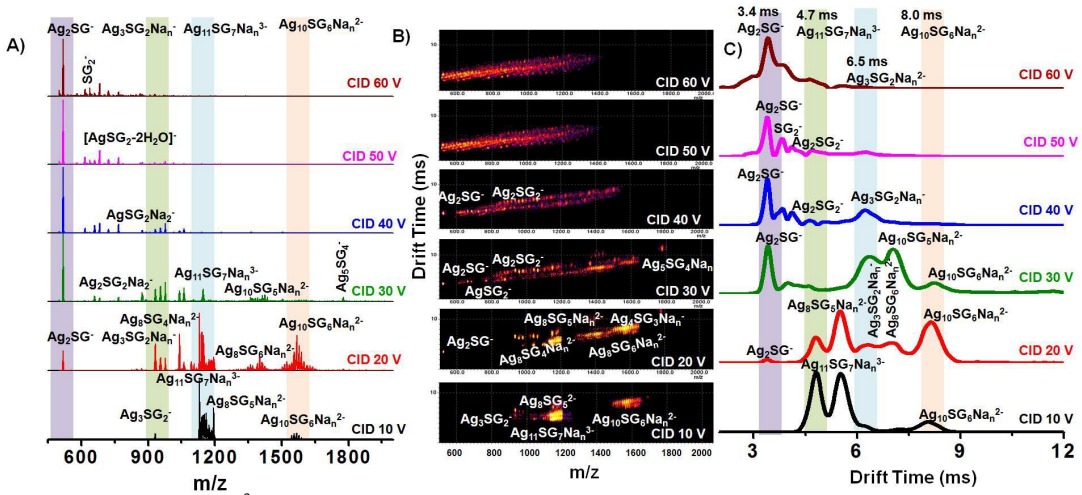
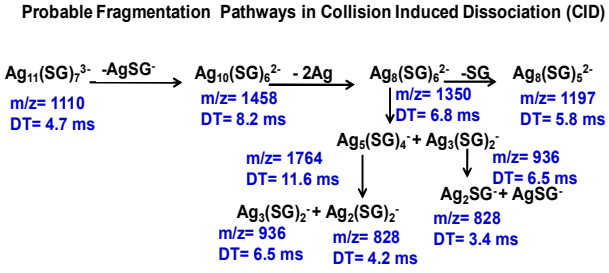


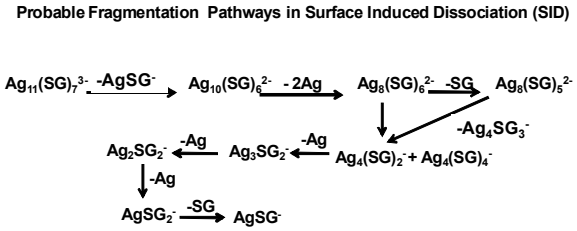
Figure 2: *A) CID of $Ag_{11}(SG)_7Na_n^{3-}$ with major products labeled. Corresponding drift time plots of ion mobility drift time versus m/z are shown in B) and the respective peaks are labeled. Corresponding drift time profiles are shown in C. Each of these plot of ion drift time versus m/z and the mass spectra are shown separately in Figure S2-S5. Major fragments are marked with highlight.*

collision energy (Figure 2A, additional details are in Figure S2-S5) at the mass range studied. However, at lower mass range (<500 Da), $AgSG^-$ is seen as a major peak along with SG^- and its fragments from SG^-. A corresponding change is also observable from the drift time profile where shorter drift times imply smaller, more compact fragments as shown in Figure 2. Interestingly, one ligand loss from the parent ion gives $Ag_{10}(SG)_6Na_n^{2-}$ with a drift time of 8.2 ms, causing a loss of isomeric structure (only one peak in drift profile) which implies that the isomerism is ligand induced in this case. Only one isomeric structure seen for the fragment could also be due to annealing of the ion as a result CID. Another ligand loss at slightly higher energy resulted in $Ag_{10}(SG)_5Na_n^{2-}$ (drift time 7.0 ms) where no isomeric structure has been observed. This fragmentation is due to the loss of one $Ag(SG)_2$ staple which might be responsible for the disappearance of the isomeric structure. Each of these staples is directly linked to two Ag atoms of the core. Therefore, loss of one staple will directly affect the core conformation and hence the isomeric structure. Other smaller fragments observed in CID also do not exhibit any isomers. A probable fragmentation pathway is shown in Scheme 1 along with drift time of the resulting fragments. The peaks are assigned to respective ions in Figure 2B. The plot of ion mobility drift time versus m/z s shown in the inset of Figure



Scheme 1: *Probable fragmentation pathways in CID.*

2B for each CE is expanded in the supplementary information (Figure S2-S5). Note that, all the data presented for the plot of I on drift time versus m/z are as obtained from Driftscope V2.8 software and are presented without any change. SID of the same species on a fluorocarbon self assembled monolayer (SAM) grown on a gold-coated surface showed completely different type of fragmentation. SID differs from CID in the sense that fragmentation results from a single collision with the surface, as opposed to multiple collisions as in the case of CID. Details of the instrumental parameters are listed in Supporting Information. In SID at the lowest energy used here, one AgSG loss was observed for $Ag_{11}(SG)_7Na_n^{3-}$ as seen for CID (see Figure 2). We have observed two isomeric species of $Ag_{10}(SG)_6Na_n^{3-}$, with drift time of 8.2 ms as the major component and a smaller peak at 8.6 ms as the minor one, which was absent in CID. This may be explained in terms of different types of fragmentation channels of isomeric $Ag_{11}(SG)_7Na_n^{3-}$ precursor upon different internal energy transfer. As we increase the energy, more and more fragmentations to smaller thiolates were observed. Unlike CID, at similar energy (ΔV) in SID, a wide range of fragment ions were observed including the main precursor ion. SID at 30V, we observed charge stripping of the ion from -3 to -2. Upon SID at 40V, the -1 peak was also observed. Charge stripping from a higher charged species to a lower charge was not observed before for any other cluster (both Au and Ag) although this is commonly seen for proteins. Fragments and probable fragmentation pathways observed are shown in Scheme 2.



Scheme 2: *Probable fragmentation pathways in SID.*

In this study, we have shown the presence of isomers of glutathione protected silver clusters for the first time by combined ESI IM MS.

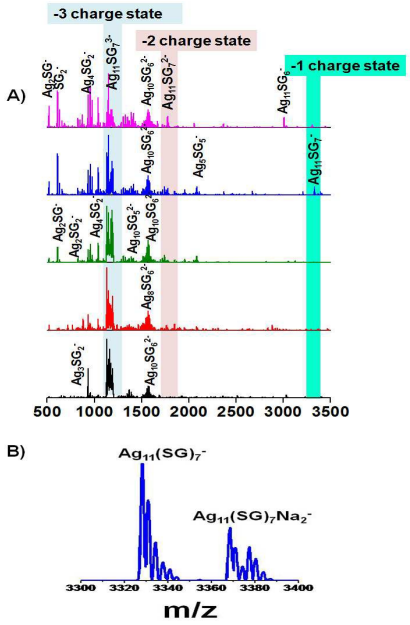


Figure 3: *A) SID of $Ag_{11}(SG)_7Na_n^{3-}$ at increased voltage shows multiple fragmentations at all the energies, unlike in CID. At higher voltages, charge stripping was observed to give a -2 charged species and finally at SID 40, -1 ion peak was observed. Two Na attached peaks were also observed as expanded in B).*

Ligand induced isomerism was confirmed from the proposed structures as well as CID. SID showed the presence of two structural isomers which might be due to different types of configurations of the cluster, which fragment differently upon colliding the surface. At higher voltages (in SID), charge stripping of -3 charged ions resulted in the deprotonated ion, which has not been observed in any cluster system. Similar studies may be used to identify the presence of isomeric clusters which will expand the science of noble metal clusters.

Notes and references

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