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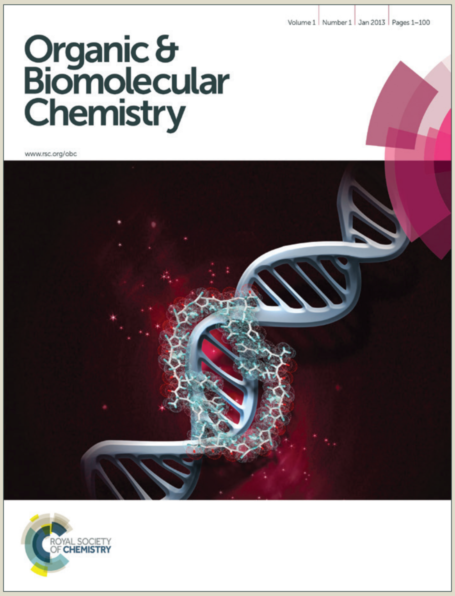

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Gas phase Chemistry of *N*-benzylbenzamides with silver(I) cation: Characterization of benzylsilver cation†

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The benzylsilver cation emerged from the collisional dissociation of silver(I)/*N*-benzylbenzamides complexes was characterized by deuterium-labeling experiments, theoretical calculations, breakdown curve along with substituent effect. Nucleophilic attack of carbonyl oxygen on α-hydrogen takes responsibility for the generation of benzylsilver cation, which is competitive to the AgH loss with the α-hydrogen.

Introduction

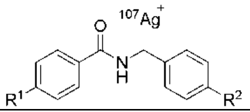
With the growing interest in the use of organosilver reagents,[1] it is inevitable to come down to the study on the intrinsic mechanism of these metal-mediated reactions, which encounters great challenge for the difficulties in isolation and storage of the transient organometallic intermediates.

Through great efforts, new methodologies based on those unique species have been developed with the application of mass spectrometry, especially electrospray ionization mass spectrometry (ESI-MS), which readies organometallates for investigation by isolating and storing them in an ion trap without marring of solvent effects, aggregation phenomena, etc.[2] So far, mass spectrometry has not only made contributions in detection of organometallte intermediates, but also in exploration of their reactivities in gas phase,[3] either by directly transferring from liquid phase or gaseous synthesizing.

Formation of target organometallates via direct electrospray ionization is scarcely possible, except the silver alkynyl cluster cation.[4] For now though, there are still two effective gaseous synthetic strategies for organometallates based on collision-induced dissociation (CID). When subjected to collisional activation, metal/diazomalonates complexes carry out consecutive Wolf rearrangement and generate corresponding metallocarbenoid,[5] while metal carboxylate ions tend to undergo decarboxylation reaction with the formation of organo-metal bond, such as dialkylmetallates in the anionic systems[6] and alkyl metal cluster cations in the cationic systems.[7]

Those gaseous synthetic strategies are operative in the generation of dialkylsilver ion (such as $[MeAgCH_2Ph]^-$). However, none of them works for the gaseous formation of neat benzylsilver ion, let alone in condense phase. Neat alkylsilver species are extremely unstable and would undergo quick decomposition even below 0 □, although addition of salts (such as LiBr, $MgBr_2$) could benefit their stability. That is the reason why Hu et al. can not succeed in directly observing the benzylsilver intermediate in gas phase or liquid phase, which is crucial in their proposed mechanism for homocoupling reaction of gem-difluoroalkenes.[8]

Table 1. Major ions in the CID mass spectra of the $[M + Ag]^+$ ions of the *N*-benzylbenzamides (Exicitation amplitude = 2.00 V).



Cmpd	R¹	R²	$[M+Ag]^+$	Ion **A**	Ion **B**	Ion **C**
1	H	H	318	210 (89 ± 3)[a]	197 (24 ± 4)	105 (100 ± 0)
2	OCH_3	H	348	240 (9 ± 1)	197 (15 ± 3)	135 (100 ± 0)
3	Cl	H	352	244 (85 ± 6)	197 (11 ± 2)	139 (100 ± 0)
4	Br	H	396	288 (81 ± 6)	197 (12 ± 2)	183 (100 ± 0)
5	NO_2	H	363	255 (100 ± 0)	197 (8 ± 4)	150 (27 ± 2)
6	F	H	336	228 (70 ± 5)	197 (10 ± 5)	123 (100 ± 0)
7	H	Cl	352	244 (100 ± 0)	231 (21 ± 2)	105 (73 ± 5)
8	H	CH_3	332	224 (100 ± 0)	211 (8 ± 1)	105 (55 ± 4)

[a] *m/z* (Mean of relative abundance ± SD, %)

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To address this deficiency, we have successfully synthesized the neat benzylsilver cation in gas phase from the collisional activation of silver(I)/*N*-benzylbenzamides complexes (Table 1), which not only makes a big breakthrough in the gaseous synthesis of alkylsilver, but also provides an opportunity for further study on the reactivity of benzylsilver cation in gas phase.

Results and discussion

In the CID mass spectra of all the silver(I)/*N*-benzylbenzamides complexes studied (Table 1, *N*-benzylbenzamides were obtained in the same way as in a previous paper[9]), the generation of $[C_7H_6Ag]^+$ (ion **B**, corresponding to $[M+Ag-121]^+$) is the most notable among the elimination of AgH (ion **A**),[10] formation of benzoyl cation (ion **C**) and silver cation (*m/z* 107).

For simplification, the argentinated *N*-benzylbenzamide is used as the model complex. All fragment ions in the spectrum of the model complex (Figure 1a) has been confirmed by accurate mass using a Q-TOF mass spectrometer (Table S1).

When the hydrogen atoms on methylene are replaced by deuterons (as depicted in Figure 1b), one deuterium atom is exclusively eliminated during the formation of ion **A** and ion **B**. Apparently, the hydrogen required for the elimination of AgH (ion **A**) is from methylene. On the other hand, the signal of ion **B** remains unchanged at *m/z* 197 no matter how the substituent on the benzoyl phenyl ring changes (Table 1), providing confirmative evidence that the benzyl moiety is employed in the building of $[C_7H_6Ag]^+$ with one α-hydrogen eliminated.

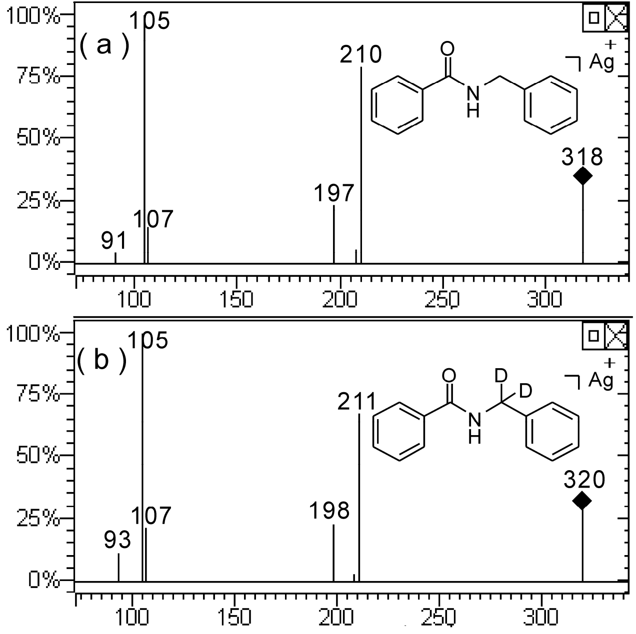
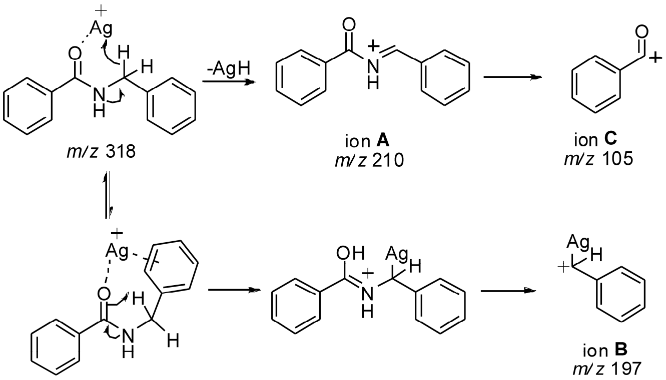


Figure 1. CID mass spectra of argentinated (a) *N*-benzylbenzamide and (b) *N*-(benzyl-α',α'-d_2)benzamide.

Based on present results, plausible mechanism is proposed in Scheme 1. Ion **A** is the result of the 1,2-elimination of AgH carrying one α-hydrogen, while ion **B** is the consequnce of 1,5-proton transfer from α-site to the carbonyl oxygen. For the formation of ion **C**, both direct dissociation of precusor ion and rupture of ion **A** (Figure S1a) take responsibilities.



Scheme 1. Proposed fragmentation pathways for argentinated *N*-benzylbenzamide.

Hereto, questions about the stucture of ion **B** arise: whether the proposed ion **B** is stable as benzylsilver cation (ion **B** in Figure 2), or rearrange to another isomer, such as tropyliumsilver cation (ion **B**' in Figure 2).

To evaluate the stability of ion **B**, theoretical calculations on the fragmentaion of argentinated *N*-benzylbenzamide were performed and potential energy surfaces were obtained in Figure 2. The produced ion **A** in the process of AgH elimination possesses the energy of 158 kJ mol^{-1}, which is 83 kJ mol^{-1} lower than that of ion **B** (241 kJ mol^{-1}) from elimination of benzimidic acid (the energy needed for loss of benzamide is much higher, see Figure S2 for details). Moreover, the overall energy barrier for the elimination of AgH in path **A** is 165 kJ mol^{-1} (**TS1-1**), lower by 96 kJ mol^{-1} than that in path **B** (**TS2-2**, 261 kJ mol^{-1}). Thus, the model complex prefers the elimination of AgH, no matter considering from the energies of the products or transition states. This theoretical result is in well accordance with the experimental distribution of the product ions (Figure 1a), where the abundance of ion **A** (*m/z* 210) is much higher than that of ion **B** (*m/z* 197).

The formation of ion **C** from further rupture of ion **A** is applicable for the whole required energy is 291 kJ mol^{-1}. On the contrary, the transition-state energy barrier (429 kJ mol^{-1}) for the conversion of benzylsilver cation to tropylium one is too high to surmount, though tropylium form (ion **B**' of 235 kJ mol^{-1}) is a little more stable than benzylium one (241 kJ mol^{-1}), which rules out the existance of tropylium form (ion **B**'). Other alternative isomers of $C_7H_6Ag^+$ (ion **B**) have been investigated by DFT calculations as well, including 2-phenyl-2-yliummethyl silver cation and isomers where the silver is attached on the phenyl ring (Figure S3). All those isomers possess higher energies than that of benzylsilver cation, especially for 2-phenyl-2-yliummethyl silver cation, which is higher by the amount of 177 kJ mol^{-1}. The results from theoretical calculations strongly suggest that $C_7H_6Ag^+$ (ion **B**) prefers the structure of benzylsilver cation rather than others.

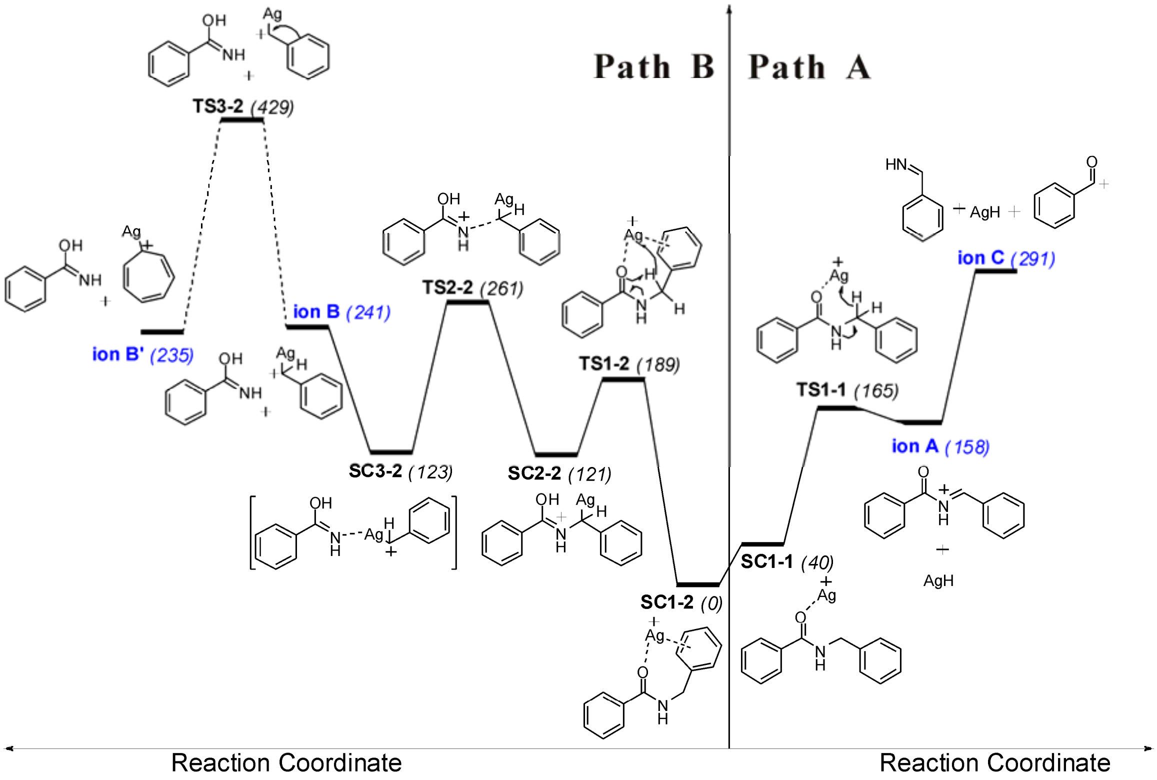


Figure 2. DFT potential energy surfaces of different pathways for fragmentation of *N*-benzylbenzamide. All energy values are in kJ mol^{-1}.

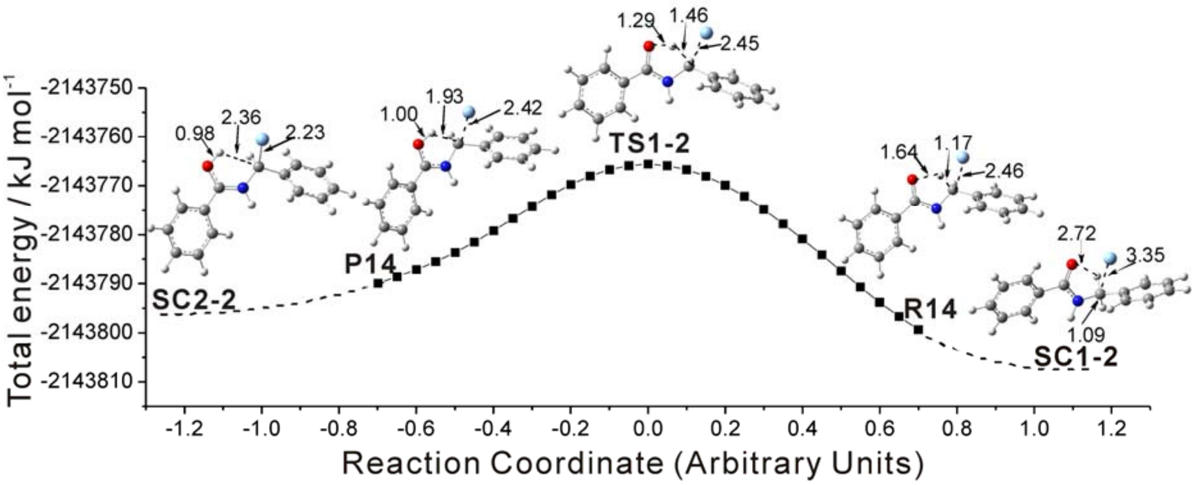


Figure 3. IRC plots for TS**1-2** using the RB3LYP hybrid method: LANL2DZ basis set for silver while 6-311+G(*d,p*) basis set for the other atoms. The length of the chemical bonds is given in Å.

To intuitively present how the covalent C$^{\alpha}$-Ag bond comes into being, intrinsic reaction coordinate (IRC) for **TS1-2** has been plotted out in Figure 3, which clearly authenticates a smooth transition from R14 to P14 along the potential energy surface. Further optimization on the structures of R14 and P14 gives rise to **SC1-2** and **SC2-2** respectively, illustrating that IRC traces the reation pathway backward to **SC1-2** and forward to **SC2-2**. The reaction path involves α-hydrogen migrating to carbonyl oxygen, where the bond length of C$^{\alpha}$-H$^{\alpha}$ increases from 1.09 Å in **SC1-2** to 2.36 Å in **SC2-2** and the bond length of O-H$^{\alpha}$ decrease from 2.72 Å to 0.98 Å. At the same time, the distance of C$^{\alpha}$-Ag shrinks from 3.35 Å to 2.23 Å, ascertaining the generation of covalent C$^{\alpha}$-Ag bond from the silver complex.

Other than theoretical calculations, evaluation of breakdown curves can provide valuable information on the fragmentation mechanism, such as between competitive and consecutive fragmentation pathways, the stability of product ions. The breakdown graph for the model complex shows that ion **A** (*m/z* 210) is the dominant product at low collision energies with ion **C** (benzoyl cation at *m/z* 105) increasing in importance as the collision energy increases. This behavior fits well to the consecutive fragmentaion of ion **A** to ion **C**. Meanwhile, the fractional abundance of ion **B** (*m/z* 197) is stable when collision energy varies from low to high, which is the same situation to the fractional abundace of the sum of ion **A** and ion **C** (*m/z* 105 + *m/z* 210). This observation proves that ion **B** is produced from the pathway different from that of ion **A** and ion **C**.

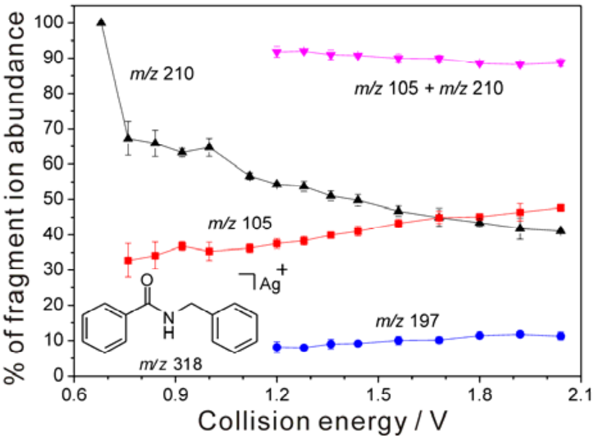


Figure 4. Breakdown curve for argentinated *N*-benzylbenzamide. Each point represented the mean ± SD ($n = 4$).

At last, to experimentally explore the relationship between the carbonyl oxygen and the formation of ion **B**, the mass spectrometry of a series of argentinated *N*-benzylbenzamides with different substituent on *para* site of the phenyl ring of benzoyl moiety were characterized. It was found that electron-donating groups are in favor of producing ion **B**, whereas electron-withdrawing groups favor formation of ion **A**, as indicated in Table 2. This competitive relationship between the formation of ion **A** and ion **B** is closely related with the nucleophilicity of the carbonyl oxygen, as proposed in Scheme 1. When an electron-donating group is present on the phenyl ring of benzoyl moiety, the electron density of the carbonyl oxygen is elevated, which makes the nucleophilic attack by carbonyl oxygen on the *α*-hydrogen more easily and promotes the formation of ion **B**. Meanwhile, electron-withdrawing group decreases the nucleophilicity of carbonyl oxygen and thus hinders the generation of ion **B**.

Table 2. Relationship[a] between ln (**A**/**B**) and the σ substituent constants for fragmentation of argentinated Cmpd **1-5** (Excitation amplitude = 1.10 V).

Cmpd	R^1	σ_p^+	ln (**A**/**B**)
2	OCH_3	-0.78	-0.69
1	H	0	1.25
3	Cl	0.11	1.50
4	Br	0.15	1.75
5	NO_2	0.79	2.40

[a] linear fitting equation $y = 2.02\ x + 1.13$, $R^2 = 0.94$.

Besides the observation of benzylsilver cation in collisional activation of argentinated *N*-benzylbenzamide, similar organosilver cations have been “synthesized” as well when the benzyl moiety of the model complex is replaced by furylmethyl, thienylmethyl, naphthylmethyl or 3-methyl-2-butenyl (Figure S4). Even argentinated *N*-alkylbenzamides are able to produce trace signal peaks corresponding to organosilver cations, which are under detailed study by our group at present.

Conclusions

In a nutshell, the collisional activation of argentinated *N*-benzylbenzamides presents an intriguing formation of benzylsilver cation by using ESI-MS^2 equipped with an ion trap cell. The results from tandem mass spectrometry together with deuterium-labeling experiments suggest that the generation of benzylsilver cation lays in the nucleophilic attack on the *α*-hydrogen by carbonyl oxygen. The stability of benzylsilver is theoretically proved by DFT calculations and experimentally verified by the breakdown curve, while the relationship between nucleophilicity of carbonyl oxygen and the formation of benzylsilver cation is further consolidated by the study on substituent effect. Here the generation of benzylsilver cation from argentinated *N*-benzylbenzamides in tandem mass spectrometry not only enriches our knowledge on the gaseous fragmentaion, but even more importantly, provides an alternative gaseous synthetic method for organosilver ions, which sets the stage for an examination of their gas-phase bimolecular and unimolecular reactivity.

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Notes and references

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