Available online at www.sciencedirect.com
SCIENCE DIRECT®
International Journal of Mass Spectrometry 231 (2004) 69–75
International Journal of Mass Spectrometry
www.elsevier.com/locate/ijms

# Substituent effect on ion–molecule reaction of disubstituted benzenes with acetone plasma

Zhili Li [a,*], Shuying Liu [b]

[a] *Shandong Non-Metallic Material Research Institute, Jinan, Shandong 250031, PR China*
[b] *Changchun Institute of Applied Chemistry, Chinese Academy of Sciences, Changchun, Jilin 130022, PR China*

Received 16 August 2002; accepted 16 August 2002

**Abstract**

We investigated the ion–molecule reactions of disubstituted benzenes with acetone or acetone-$d_6$ as reagent gases under chemical ionization conditions, and the fragmentation reactions of the adduct ions (mostly acetyl ion and protonated acetone adducts) using collision-induced dissociation (CID) technique. The CID results of $[M + A_dD]^+$ ions of phenylamine derivatives suggest that the phenylamine derivatives have higher proton affinities than acetone. Our experiments also suggest: (1) electron-releasing substituents favor the adduct reactions, while electron-withdrawing groups do not; (2) the position and properties of substituting groups have an effect on the relative abundances of the adduct ions; (3) the fragmentation reaction of the acetyl adduct ion formed by the reaction of *ortho*-phenylenediamine with acetyl ion is similar to the reductive alkylation reaction in the liquid phase.


*Keywords:* Disubstituted benzene; Ion–molecule reaction; Substituent effect; Collision-induced dissociation; Acetone

## 1. Introduction

Chemical ionization (CI) is most commonly used to study ion–molecule reactions in analytical mass spectrometry. Reactions other than proton transfer, such as methylation, acetylation and formation of an ion–neutral complex, may result in the formation of high mass adduct ions, which can give more characteristic spectral information than those obtained from protonated substrates [1–3]. Acetone was initially used as chemical ionization reagent to distinguish some monosaccharide isomers that form the adduct ions $[M + 41]^+$ and $[M + 59]^+$ with the ion system of acetone. The ratio $[M + 41]/[M + 59]^+$ is characteristic for each stereoisomer [4]. Later, the relationship between the proton affinities of the monosubstituted aromatic substrates and acetone in the formation of the $M^{+\bullet}$, $[M + H]^+$, and $[M + CH_3CO]^+$ ions using acetone as chemical ionization reagent was established [5]. The results of ion–molecule reactions of disubstituted benzenes with acetyl chloride under chemical ionization conditions showed that all $[M + CH_3CO]^+$ ions are proton-bound complexes [6].

Intramolecular functional group interactions play an important role in gas phase ion–molecule reactions and in the fragmentation reactions of their product ions [7–18]. The fragmentation reactions of the odd-electron molecular ions of benzoic acid [19], phenylacetylene [20], phenylsulfide [21], nitrobenzene [22], methoxybenzaldehyde [23] and acetophenone [24], clearly showed evidence for the *ortho* effect. The fragmentation properties of the protonated molecules and other even-electron adduct ions of *o*-, *m*- and *p*-methoxy-acetophenone, *o*-, *m*- and *p*-hydroxyacetophenone, *o*-, *m*- and *p*-methoxybenzaldehyde and *o*-, *m*- and *p*-hydroxybenzaldehyde have been reported [25,26]. The *ortho* effect also has been observed for even-electron ions derived from other disubstituted benzenes under collision-induced dissociation (CID) conditions. It has been shown that the properties of the functional groups have an effect on the fragmentation pathways of the adduct ions [6,27,28].

In this paper, we report the ion–molecule reactions of 33 disubstituted benzenes with acetone or acetone-$d_6$ as reagent gases under chemical ionization conditions, and the CID reaction properties of the adduct products.

* Corresponding author. Present address: Department of Pharmacology, Yale University School of Medicine, 333 Cedar Street, New Haven, CT 06520-8066, USA. Fax: +1-203-785-7670.
*E-mail address:* Zhililiyale@yahoo.com (Z. Li).

1387-3806/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.ijms.2002.08.001

## 2. Experimental

### 2.1. Instrumental

All the experiments were performed using a triple stage quadrupole mass spectrometer (Finnigan TSQ-70B, Finnigan MAT, San Jose, CA) equipped with a chemical ionization ion source. The CID spectra were measured by using the first quadrupole to select the precursor ions according to their mass, which were focused into an r.f.—only quadrupole collision cell containing research-grade helium collision gas maintained at an estimated pressure of $2.06 \times 10^{-3}$ Pa, low enough to ensure essentially single-collision conditions. The laboratory frame collision energy was restricted to 10 eV, which, together with use of He as collision gas, ensured that the center-of-mass collision energy was sufficiently low that only the reaction channels of lowest critical energy were accessed. The CID reactions and the surviving precursor ions were monitored by scanning the second quadrupole analyzer over the desired mass range. The acetone or acetone-$d_6$ was introduced into the ion source through the gas chromatography/mass spectrometer (GC/MS) interface. The flow rate was controlled by the fine metering valve to maintain a stable ion current inside the ion source. The samples were introduced into the ion source by the direct inlet probe. Taking into account the melting points of the samples, the probe temperatures were set up to obtain stable ion currents of the ions of interest.

### 2.2. Chemicals

All the samples, supplied by Aldrich Chemical Co. and Sigma Chemical Co., Inc. USA, were commercially available.

## 3. Results and discussion

### 3.1. The ion–molecule reactions of disubstituted benzenes with the ion system of acetone or acetone-$d_6$

Under CI conditions, the reaction products of acetone (or acetone-$d_6$) self-chemical ionization are mainly the protonated acetone, the proton-bound complexes of acetone with ketene, and the proton-bound dimer of acetone [29]. The major product ions formed by the ion–molecule reactions of 33 disubstituted benzenes with acetone or acetone-$d_6$ as chemical reagent gases, along with the corresponding relative abundances, are listed in Tables 1 and 2.

Based on the data in Tables 1 and 2, the major ions for phenylamine derivatives (substrates 1–15) are $[M]^{+\bullet}$, $[M+H]^+$, $[M+CH_3CO]$, and $[M+AH]^+$, where A denotes a molecule of acetone. Under acetone/CI conditions, the disubstituted benzenes studied here showed variation in the formation of adducts and $[M+H]^+$ with respect to the properties and the position of functional groups. As the property of the functional group was changing from electron-releasing to electron-withdrawing (e.g., the second functional group from amino or hydroxyl to methyl) the number of different adduct ions formed, and their corresponding relative abundances, were changing. In the acetone/CI mass spectra, the relative abundance of $[M + CH_3CO]^+$ (or $[M + CD_3CO]^+$) ions and $[M+H]^+$ (or $[M+D]^+$) ions of phenylamine derivatives gradually decreases as the second functional group is changed from $NH_2$, $N_2O$, OH, Cl to $CH_3$. An increase in the relative abundances of $[M + A_2H]^+$ (or $[M + (A_d)2D]^+$) ions as the second functional groups $NH_2$, $N_2O$, or OH is replaced with Cl or $CH_3$ is observed. Then, the relative abundances of $[M + AH]^+$ (or $[M + A_dD]^+$) almost keep constant as the second functional groups $NH_2$, $N_2O$, or OH is replaced with Cl or $CH_3$ (shown in Tables 1 and 2). The chloroaniline and toluidine isomers (substrates 10–15) could not form the abundant adduct $[M + CH_3CO]^+$ ions, and the *ortho*-chloroaniline and *ortho*-toluidine yielded no adduct ions. We infer that the properties of the two functional groups and the relative position on the ring have an effect on the adduct reactions. For phenol derivatives (substrates 16–21), there are abundant adduct ions $[M + CH_3CO]^+$ in the acetone/CI mass spectra. However, the relative abundances of $[M + CD_3CO]^+$ (or $[M + CH_3CO]^+$) ions for compounds 22–24 are weak. These results indicate that the active hydrogen atom of the hydroxyl group is involved in the adduct reactions between phenyl derivatives and acetyl ion, and the nitro-group does not favor the formation of the adduct ions $[M + CD_3CO]^+$. The unique $[M + A]^{+\bullet}$ ions of phenol derivatives further suggest that the hydrogen atom of the hydroxyl group is involved in the reaction of phenyl derivatives with acetone. For nitrobenzenes derivatives (substrates 25–33), there are only three adduct ions, and their relative abundances are weak because the two functional groups are both electron-withdrawing. In conclusion, the data in Tables 1 and 2 show that the electron-releasing groups favored the adduct reaction, and that the differences in the relative abundances of the adduct ions are generated by the relative position and properties of the functional groups.

### 3.2. CID reactions of $[M + CH_3CO]^+$ and $[M + CD_3CO]^+$ ions of substrates 1–24

The CID reaction products of $[M + CH_3CO]^+$ and $[M + CD_3CO]^+$) ions of substrates 1–24 are listed in Table 3.

The $[M + CH_3CO]^+$ ions formed under acetone/CI conditions has been reported in mass spectral studies of many substrates such as alkenes [30], alcohols [31], amines [32], esters [33], and amino acids and nucleobases [34]. For most of the substrates the structure of the $[M + CH_3CO]^+$ ions was found to involve covalent bonding, and the site of acetylation depended on the functional groups present in the substrate molecules. According to the data in Table 3, the dominant fragmentation pathways for the adduct ions $[M + CH_3CO]^+$ (or $[M + CD_3CO]^+$) were those producing either the protonated molecules or the acetyl ion. During the former

Table 1
Major product ions formed by 33 disubstituted benzenes with the ion system of acetone and their corresponding relative abundances

| | Substrate | Major ions (*m/z*) and their relative abundance (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $M^{+\bullet}$ | $[M+H]^+$ | $[M+CH_3CO]^+$ | $[M+AH]^+$ | $[M+CH_3CO+A]^+$ | $[2M+H]^+$ | $[M+A_2H]^+$ | $[M+A]^+$ |
| 1 | 1,2-Phenylenediamine | 108 (71) | 109 (100) | 151 (50) | 167 (65) | 209 (2) | 217 (3) | | |
| 2 | 1,3-Phenylenediamine | 108 (15) | 109 (100)* | 151 (30) | 167 (60) | | | 225 (3) | |
| 3 | 1,4-Phenylenediamine | 108 (27) | 109 (78)* | 151 (15) | 167 (100) | 209 (2) | 217 (4) | 225 (5) | |
| 4 | 1,2-Aminophenol | 109 (18) | 110 (58)* | 152 (12) | 168 (100) | 210 (4) | 219 (2) | 226 (3) | |
| 5 | 1,3-Aminophenol | 109 (70) | 110 (52)* | 152 (10) | 168 (100) | 210 (6) | 219 (4) | 226 (6) | |
| 6 | 1,4-Aminophenol | 109 (30) | 110 (54)* | 152 (14) | 168 (100) | 210 (5) | | 226 (4) | |
| 7 | 1,2-Nitroaniline | 138 (34) | 139 (100)* | 181 (25) | 197 (50) | 239 (4) | 277 (4) | 255 (2) | |
| 8 | 1,3-Nitroaniline | 138 (70) | 139 (100)* | 181 (20) | 197 (95) | 239 (8) | 277 (5) | 255 (4) | |
| 9 | 1,4-Nitroaniline | 138 (40) | 139 (100)* | 181 (24) | 197 (60) | 239 (5) | 277 (4) | 255 (2) | |
| 10 | 1,2-Chloroaniline | 127 (100) | 128 (12)* | | 186 (32) | | 255 (4) | 244 (32) | |
| 11 | 1,3-Chloroaniline | 127 (100) | 128 (39)* | 170 (4) | 186 (84) | | 255 (2) | 244 (78) | |
| 12 | 1,4-Chloroaniline | 127 (28) | 128 (20)* | 170 (11) | 186 (60) | 228 (36) | 255 (2) | 244 (100) | |
| 13 | 1,2-Toluidine | 107 (100) | 108 (20)* | | 166 (70) | 208 (5) | 215 (10) | 224 (70) | |
| 14 | 1,3-Toluidine | 107 (45) | 108 (25)* | 150 (5) | 166 (100) | 208 (4) | 215 (4) | 224 (34) | |
| 15 | 1,4-Toluidine | 107 (30) | 108 (28)* | 150 (8) | 166 (100) | 208 (4) | 215 (6) | 224 (48) | |
| 16 | 1,2-Dihydroxybenzene | 110 (100) | 111 (40)* | 153 (30) | 169 (4)* | 211 (5) | | | 168 (25) |
| 17 | 1,3-Dihydroxybenzene | 110 (100) | 111 (40)* | 153 (28) | 169 (6)* | 211 (4) | | | 168 (20) |
| 18 | 1,4-Dihydroxybenzene | 110 (100) | 111 (35)* | 153 (22) | 169 (2)* | 211 (3) | | | 168 (20) |
| 19 | 1,2-Cresol | 108 (100) | 109 (95)* | 151 (60) | 167 (34)* | 209 (50) | | | 166 (100) |
| 20 | 1,3-Cresol | 108 (100) | 109 (96)* | 151 (32) | 167 (30)* | 209 (48) | | | 166 (100) |
| 21 | 1,4-Cresol | 108 (100) | 109 (98)* | 151 (54) | 167 (28)* | 209 (56) | | | 166 (100) |
| 22 | 1,2-Nitrophenol | 139 (100) | 140 (22)* | 182 (6) | 198 (6)* | | | | 197 (18) |
| 23 | 1,3-Nitrophenol | 139 (100) | 140 (43)* | 182 (9) | 198 (10)* | | | | 197 (16) |
| 24 | 1,4-Nitrophenol | 139 (40) | 140 (100)* | 182 (10) | 198 (8) | | | | |
| 25 | 1,2-Chloronitrobenzene | 157 (100) | 158 (4)* | 200 (12) | 216 (6) | | | | |
| 26 | 1,3-Chloronitrobenzene | 157 (100) | 158 (5)* | 200 (10) | 216 (3) | | | | |
| 27 | 1,4-Chloronitrobenzene | 157 (100) | 158 (16)* | 200 (18) | 216 (10) | | | | |
| 28 | 1,2-Bromonitrobenzene | 201 (100) | 202 (10)* | 244 (8) | 260 (4) | | | | |
| 29 | 1,3-Bromonitrobenzene | 201 (100) | 202 (11)* | 244 (7) | 260 (5) | | | | |
| 30 | 1,4-Bromonitrobenzene | 201 (100) | 202 (9)* | 244 (8) | 260 (6) | | | | |
| 31 | 1,2-Iodonitrobenzene | 249 (100) | 250 (14)* | 292 (3) | | | | | |
| 32 | 1,3-Iodonitrobenzene | 249 (100) | 250 (16)* | 292 (2) | | | | | |
| 33 | 1,4-Iodonitrobenzene | 249 (100) | 250 (20)* | 292 (3) | | | | | |

(*) denotes the contribution from the relative abundance of isotope; A denotes the molecule of acetone.

Table 2
Major product ions formed by 33 disubstituted benzenes with the ion system of acetone-$d_6$ and their corresponding relative abundances

| | Substrate | Major ions (*m/z*) and their relative abundance (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $M^{+\bullet}$ | $[M + D]^+$ | $[M + CD_3CO]^+$ | $[M + A_dD]^+$ | $[M + CD_3CO + A_d]^+$ | $[2M + D]^+$ | $[M + A_{d2}D]^+$ | $[M + A_d]^+$ |
| 1 | 1,2-Phenylenediamine | 108 (76) | 110 (100)* | 154 (45) | 174 (62) | 218 (2) | 218 (5) | | |
| 2 | 1,3-Phenylenediamine | 108 (19) | 110 (100)* | 154 (27) | 174 (55) | | | 238 (4) | |
| 3 | 1,4-Phenylenediamine | 108 (32) | 110 (75)* | 154 (17) | 174 (100) | 218 (5) | 218 (3) | 238 (6) | |
| 4 | 1,2-Aminophenol | 109 (20) | 111 (62)* | 155 (14) | 175 (100) | 219 (4) | 220 (2) | 239 (5) | |
| 5 | 1,3-Aminophenol | 109 (67) | 111 (56)* | 155 (15) | 175 (100) | 219 (5) | 220 (4) | 239 (7) | |
| 6 | 1,4-Aminophenol | 109 (33) | 111 (59)* | 155 (17) | 175 (100) | 219 (8) | | 239 (3) | |
| 7 | 1,2-Nitroaniline | 138 (36) | 140 (100)* | 184 (28) | 204 (55) | 248 (8) | 278 (9) | 268 (4) | |
| 8 | 1,3-Nitroaniline | 138 (68) | 140 (100)* | 184 (23) | 204 (90) | 248 (12) | 278 (5) | 268 (2) | |
| 9 | 1,4-Nitroaniline | 138 (42) | 140 (100)* | 184 (27) | 204 (63) | 248 (10) | 278 (7) | 268 (5) | |
| 10 | 1,2-Chloroaniline | 127 (100) | 129 (16)* | | 193 (34) | | 256 (7) | 257 (36) | |
| 11 | 1,3-Chloroaniline | 127 (100) | 129 (40)* | 173 (4) | 193 (89) | 237 (35) | 256 (4) | 257 (72) | |
| 12 | 1,4-Chloroaniline | 127 (30) | 129 (25)* | 173 (11) | 193 (66) | 217 (6) | 256 (6) | 257 (100) | |
| 13 | 1,2-Toluidine | 107 (100) | 109 (24)* | | 173 (75) | 217 (8) | 216 (13) | 237 (75) | |
| 14 | 1,3-Toluidine | 107 (50) | 109 (20)* | 153 (10) | 173 (100) | 217 (10) | 216 (6) | 237 (38) | |
| 15 | 1,4-Toluidine | 107 (36) | 109 (23)* | 153 (8) | 173 (100) | 220 (4) | 216 (8) | 237 (54) | |
| 16 | 1,2-Dihydroxybenzene | 110 (100) | 112 (45)* | 156 (33) | 176 (4)* | 220 (3) | | | 174 (30) |
| 17 | 1,3-Dihydroxybenzene | 110 (100) | 112 (40)* | 156 (26) | 176 (3)* | 220 (2) | | | 174 (26) |
| 18 | 1,4-Dihydroxybenzene | 110 (100) | 112 (38)* | 156 (26) | 176 (4)* | 218 (54) | | | 174 (25) |
| 19 | 1,2-Cresol | 108 (100) | 110 (92)* | 154 (65) | 174 (30)* | 218 (44) | | | 172 (100) |
| 20 | 1,3-Cresol | 108 (100) | 110 (92)* | 154 (37) | 174 (33)* | 218 (52) | | | 172 (100) |
| 21 | 1,4-Cresol | 108 (100) | 110 (91)* | 154 (52) | 174 (32)* | | | | 172 (100) |
| 22 | 1,2-Nitrophenol | 139 (100) | 141 (32)* | 185 (8) | 205 (10)* | | | | 203 (20) |
| 23 | 1,3-Nitrophenol | 139 (100) | 141 (48)* | 185 (13) | 205 (15)* | | | | 203 (16) |
| 24 | 1,4-Nitrophenol | 139 (45) | 141 (100)* | 185 (13) | 205 (10) | | | | 203 (2) |
| 25 | 1,2-Chloronitrobenzene | 157 (100) | 159 (6)* | 203 (12) | 223 (3) | | | | |
| 26 | 1,3-Chloronitrobenzene | 157 (100) | 159 (7)* | 203 (15) | 223 (2) | | | | |
| 27 | 1,4-Chloronitrobenzene | 157 (100) | 159 (13)* | 203 (20) | 223 (6) | | | | |
| 28 | 1,2-Bromonitrobenzene | 201 (100) | 203 (8)* | 247 (7) | 267 (3) | | | | |
| 29 | 1,3-Bromonitrobenzene | 201 (100) | 203 (8)* | 247 (3) | 267 (4) | | | | |
| 30 | 1,4-Bromonitrobenzene | 201 (100) | 203 (6)* | 247 (5) | 267 (9) | | | | |
| 31 | 1,2-Iodonitrobenzene | 249 (100) | 251 (16)* | 295 (7) | | | | | |
| 32 | 1,3-Iodonitrobenzene | 249 (100) | 251 (14)* | 295 (5) | | | | | |
| 33 | 1,3-Iodonitrobenzene | 249 (100) | 251 (22)* | 295 (4) | | | | | |

(*) denotes the contribution from the relative abundance of isotope; $A_d$ and D denote the molecule of acetone-$d_6$ and deuterium atom, respectively.

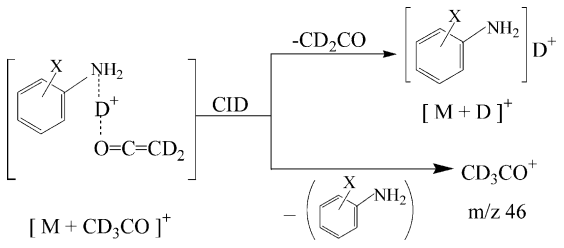
Table 3
CID products of $[M + CH_3CO]^+$ ($[M + CD_3CO]^+$) ions of substrates 1–24

| | Substrate | Precursor ions (*m/z*) | | Product ions (*m/z*) | |
|---|---|---|---|---|---|
| | | $[M + CH_3CO]^+$ ($[M + CD_3CO]^+$) | $[M + H]^+$ ($[M+D]^+$) | $[CH_3CO]^+$ ($[CD_3CO]^+$) | $[M + CH_3CO\text{-}H_2O]^+$ ($[M + CD_3CO\text{-}H_2O]^+$) |
| 1 | 1,2-Phenylenediamine | 151 (154) | 109 (110) | 43 (46) | 133 (136)[a] |
| 2 | 1,3-Phenylenediamine | 151 (154) | 109 (110) | 43 (46) | |
| 3 | 1,4-Phenylenediamine | 151 (154) | 109 (110) | 43 (46) | |
| 4 | 1,2-Aminophenol | 152 (155) | 110 (111) | 43 (46) | |
| 5 | 1,3-Aminophenol | 152 (155) | 110 (111) | 43 (46) | |
| 6 | 1,4-Aminophenol | 152 (155) | 110 (111) | 43 (46) | |
| 7 | 1,2-Nitroaniline | 181 (184) | 139 (140) | 43 (46) | |
| 8 | 1,3-Nitroaniline | 181 (184) | 139 (140) | 43 (46) | |
| 9 | 1,4-Nitroaniline | 181 (184) | 139 (140) | 43 (46) | |
| 11 | 1,3-Chloroaniline | 170 (173) | 128 (129) | 43 (46) | |
| 12 | 1,4-Chloroaniline | 170 (173) | 128 (129) | 43 (46) | |
| 14 | 1,3-Toluidine | 150 (153) | 108 (109) | 43 (46) | |
| 15 | 1,4-Toluidine | 150 (153) | 108 (109) | 43 (46) | |
| 16 | 1,2-Dihydroxybenzene | 153 (156) | 111 (112) | 43 (46) | |
| 17 | 1,3-Dihydroxybenzene | 153 (156) | 111 (112) | 43 (46) | |
| 18 | 1,4-Dihydroxybenzene | 153 (156) | 111 (112) | 43 (46) | |
| 19 | 1,2-Cresol | 151 (154) | 109 (110) | 43 (46) | |
| 20 | 1,3-Cresol | 151 (154) | 109 (110) | 43 (46) | |
| 21 | 1,4-Cresol | 151 (154) | 109 (110) | 43 (46) | |
| 22 | 1,2-Nitrophenol | 182 (185) | 140 (141) | 43 (46) | |
| 23 | 1,3-Nitrophenol | 182 (185) | 140 (141) | 43 (46) | |
| 24 | 1,4-Nitrophenol | 182 (185) | 140 (141) | 43 (46) | |

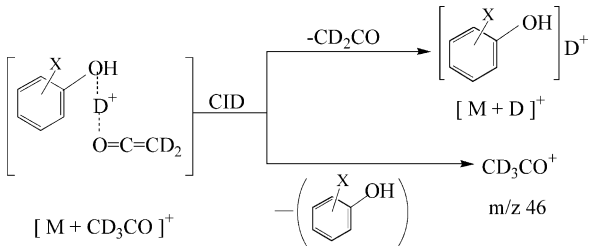
[a] The CID spectra of the ions at *m/z* 133 (136) were further obtained.

dissociation process, a proton must be transferred from the acetyl ion to the neutral molecule. The competing reaction generates the acetyl ion. These results strongly suggest that the structure of the $[M + CH_3CO]^+$ ions can be represented as a proton-bound complex of M and ketene. The proposed fragmentation reaction mechanisms of $[M + CD_3CO]^+$ of phenylamine derivatives and phenol derivatives are shown in Schemes 1 and 2, respectively.

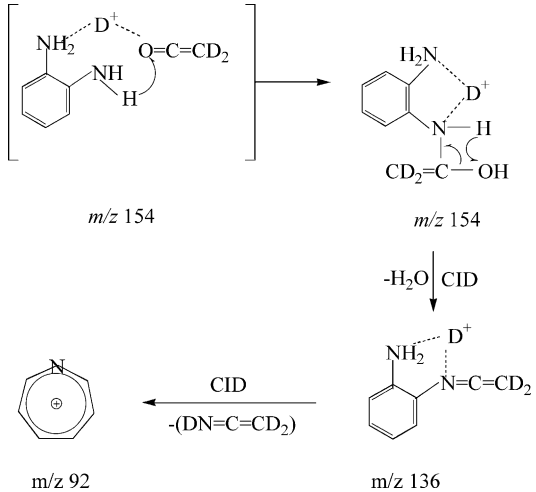
The unique dissociation pathway of the 1,2-phenylenediamine adduct ions $[M+CD_3CO]^+$ (or $[M+CH_3CO]^+$) yielded the fragment ion at *m/z* 136 (or 133) corresponding to loss of 18 Da neutral species. The fragment ion at *m/z* 136 (or 133), as the precursor ion, could further fragment to generate the ion at *m/z* 92 with loss of a 44 (or 41) Da neutral species (data not shown). In terms of the CID results of the precursor ions $[M + CD_3CO]^+$ (*m/z* 154) and $[M + CH_3CO]^+$ (*m/z* 151), we infer that the 18 Da neutral specie is $H_2O$, the two hydrogen atoms coming




Scheme 1. Proposed fragmentation mechanism of the adduct ions $[M + CD_3CO]^+$ of substrates 1–15 (phenylamine derivatives) (X = $NH_2$, OH, $NO_2$, Cl and $CH_3$).




Scheme 2. Proposed fragmentation mechanism of the adduct ions $[M + CD_3CO]^+$ of substrates 16–24 (phenol derivatives) (X = OH, $CH_3$ and $NO_2$).




Scheme 3. Proposed fragmentation mechanism of the adduct ion $[M + CD_3CO]^+$ of 2-phenylenediamine.

Table 4
CID reaction products of adduct ions of substrates 1–15

| | Substrate | Precursor ions (*m/z*) | Product ions (*m/z*) |
|---|---|---|---|
| | | $[M + AH]^+$ ($[M + A_dD]^+$) | $[M + H]^+$ ($[M + D]^+$) |
| 1 | 1,2-Phenylenediamine | 167 (174) | 109 (110) |
| 2 | 1,3-Phenylenediamine | 167 (174) | 109 (110) |
| 3 | 1,4-Phenylenediamine | 167 (174) | 109 (110) |
| 4 | 1,2-Aminophenol | 168 (175) | 110 (111) |
| 5 | 1,3-Aminophenol | 168 (175) | 110 (111) |
| 6 | 1,4-Aminophenol | 168 (175) | 110 (111) |
| 7 | 1,2-Nitroaniline | 197 (204) | 139 (140) |
| 8 | 1,3-Nitroaniline | 197 (204) | 139 (140) |
| 9 | 1,4-Nitroaniline | 197 (204) | 139 (140) |
| 10 | 1,3-Chloroaniline | 186 (193) | 128 (129) |
| 11 | 1,3-Chloroaniline | 186 (193) | 128 (129) |
| 12 | 1,4-Chloroaniline | 186 (193) | 128 (129) |
| 13 | 1,3-Toluidine | 166 (173) | 108 (109) |
| 14 | 1,3-Toluidine | 166 (173) | 108 (109) |
| 15 | 1,4-Toluidine | 166 (173) | 108 (119) |

$A_d$ and D denote acetone-$d_6$ and deuterium atom, respectively.

from the amino group. Then, 44 and 41 Da neutral species lost on further fragmentation are $NC_2D_3$ and $NC_2H_3$, respectively. The proposed fragmentation mechanism of the ion $[M + CD_3CO]^+$ of 1,2-phenylenediamine, involving an *ortho* effect on the covalently bound dimer intermediate, is shown in Scheme 3. This reaction is similar to the reductive alkylation reactions of amine in the liquid phase [35].

### 3.3. CID reactions of $[M + AH]^+$ ($[M + AD]^+$) and $[M + A_2H]^+$ ($[M + (A_d)_2D]^+$) ions of substrates 1–15

The main CID product ions of $[M + A_dD]^+$ (or $[M + AH]^+$) are the protonated molecular ions (Table 4). These results suggest that the proton affinities of substrates 1–15 (phenylamine derivatives) are higher than that of acetone (the proton affinities of 1,2-phenylenediamine: 896.5, 1,3-phenylenediamine: 929.9, 1,4-phenylenediamine: 905.9, 1,2-aminophenol: 898.8, 1,3-aminophenol: 898.8, 1,4-nitroaniline: 866.0, 1,4-chloroaniline: 868.1, 1,3-chloroaniline: 873.8, 1,2-toluidine: 890.9, 1,3-toluidine: 895.8, 1,4-toluidine: 896.7, and acetone: 812.0 kJ/mol [36]). It is worth pointing out that the adduct ions $[M + A_dD]^+$ have the proton-bound dimer intermediate between the nitrogen atom of the amino group of substrates and the oxygen atom of acetone molecules.

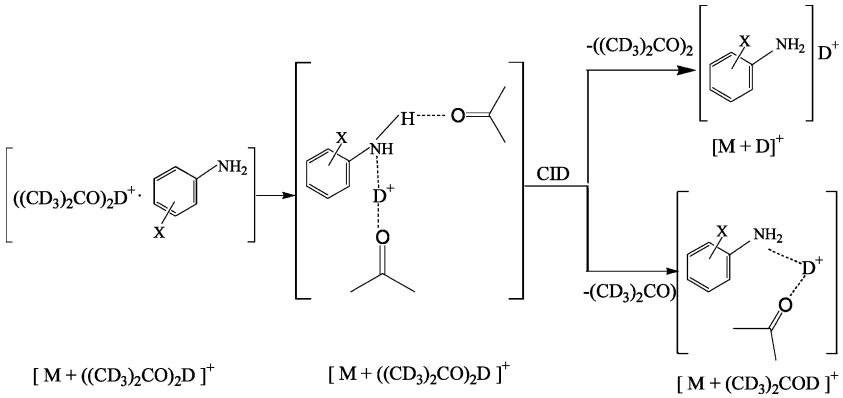
Table 5
CID reaction products of $[M + A_2H]^+$ ($[M + (A_d)_2D]^+$) ions of substrate 10–15

| | Substrate | Precursor ions (*m/z*) | Product ions (*m/z*) | |
|---|---|---|---|---|
| | | $[M + A_2H]^+$ ($[M + (A_d)D]^+$) | $[M + AH]^+$ ($[M + A_dD]^+$) | $[M + H]^+$ ($[M + D]^+$) |
| 10 | 1,3-Chloroaniline | 244 (257) | 186 (193) | 128 (129) |
| 11 | 1,3-Chloroaniline | 244 (257) | 186 (193) | 128 (129) |
| 12 | 1,4-Chloroaniline | 244 (257) | 186 (193) | 128 (129) |
| 13 | 1,3-Toluidine | 224 (237) | 166 (173) | 108 (109) |
| 14 | 1,3-Toluidine | 224 (237) | 166 (173) | 108 (109) |
| 15 | 1,4-Toluidine | 224 (237) | 166 (173) | 108 (109) |

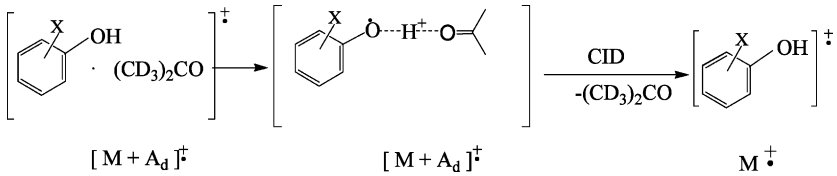
The structure of the $[M+A_2H]^+$ (or $[M+(A_d)_2D]^+$) ions of substrates 10–15, which fragmented to give the product ions $[M + AH]^+$ (or $[M + A_dD]^+$) and $[M + H]^+$ (or $[M + D]^+$) (Table 5), probably involves two kinds of bonding of substrate with the two acetone molecules, i.e., a hydrogen bond and a proton-bound dimer. The proposed fragmentation mechanism of $[M + (A_d)_2D]^+$ ions is shown in Scheme 4.

### 3.4. CID reactions of $[M + A]^{+\bullet}$ and $[M + A_d]^{+\bullet}$ ions of substrates 16–23

The unique adduct ions for substrates 16–23 (phenol derivatives) are $[M + A]^{+\bullet}$ (or $[M + A_d]^{+\bullet}$) in acetone/CI mass spectra. The adduct ions fragmented to give only the product ions $M^{+\bullet}$ (Table 6). The data in Table 6 indicate that the adduct ions are ion–molecule complexes rather than covalently bound adducts. These results are similar to that of $[M + A]^{+\bullet}$ of phenol formed under acetone/CI condition [37]. The proposed fragmentation mechanism of the adduct ions $[M + A_d]^{+\bullet}$ is shown in Scheme 5.




Scheme 4. Proposed fragmentation mechanism of the adduct ions $[M + (A_d)_2D]^+$ of substrates 10–15 (X = Cl and $CH_3$).




Scheme 5. Proposed fragmentation mechanism of the adduct ions $[M + A_d]^{+\bullet}$ of phenol derivatives (X = OH, $CH_3$ and $NO_2$).

Table 6
CID reaction products of $[M + A]^{+\bullet}$ ($[M + A_d]^{+\bullet}$) ions of substrates 16–23

| | Substrate | Precursor ions (*m/z*) | Product ion (*m/z*) |
|---|---|---|---|
| | | $[M + A]^+$ ($[M + A_d]^+$) | $M^{+\bullet}$ ($M^{+\bullet}$) |
| 16 | 1,2-Dihydroxybenzene | 168 (174) | 110 (110) |
| 17 | 1,3-Dihydroxybenzene | 168 (174) | 110 (110) |
| 18 | 1,4-Dihydroxybenzene | 168 (174) | 110 (110) |
| 19 | 1,2-Cresol | 166 (172) | 108 (108) |
| 20 | 1,3-Cresol | 166 (172) | 108 (108) |
| 21 | 1,4-Cresol | 166 (172) | 108 (108) |
| 22 | 1,2-Nitrophenol | 197 (203) | 139 (139) |
| 23 | 1,3-Nitrophenol | 197 (203) | 139 (139) |

## 4. Conclusion

The trends observed in the ion–molecule reactions of a wide selection of disubstituted benzenes under acetone/CI conditions provide good examples of detecting the effect of some functional groups for ion–molecule reactions of multiple functional substrates. The behaviors of the various adduct ions formed by the ion–molecule reactions of disubstituted benzenes with the ion system of acetone under acetone/CI conditions, indicate that the structure of most adduct ions is proton-bound hetero-dimers or trimers. However, the fragmentation mechanism of the 1,2-phenylenediamine adduct ions $[M + CD_3CO]^+$, which produced the fragment ion at *m/z* 136, involved a covalently bound intermediate.

## References

[1] J.S. Brodbelt, Mass Spectrom. Rev. 16 (1997) 91.
[2] S. Prabhakar, M. Vairamani, Mass Spectrom. Rev. 16 (1997) 259.
[3] Z. Li, S. Liu, L.S. Long, Chinese Chem. Lett. 10 (1999) 833.
[4] G. Wang, Y. Sha, Z. Xu, J. Pan, Anal. Chem. 57 (1985) 2283.
[5] M. Vairamani, Org. Mass Spectrom. 28 (1993) 1498.
[6] Z. Li, F. Song, S. Liu, Rapid Commun. Mass Spectrom. 15 (2001) 1893.
[7] D. Aue, H. Web, M. Bowers, J. Am. Chem. Soc. 95 (1973) 699.
[8] M. Meot-Ner, J. Am. Chem. Soc. 105 (1983) 906.
[9] I. Dzidic, J. McCloskey, J. Am. Chem. Soc. 93 (1971) 955.
[10] R. Weinkam, J. Gat, Org. Mass Spectrom. 11 (1976) 188.
[11] P. Ashkenazi, W. Blum, B. Domon, J. Am. Chem. Soc. 109 (1987) 325.
[12] M. Meot-Ner, J. Am. Chem. Soc. 105 (1983) 912.
[13] T. Morton, J. Beauchamp, J. Am. Chem. Soc. 94 (1972) 671.
[14] D. Mueller, B. Domon, W. Blum, Org. Mass Spectrom. 24 (1989) 157.
[15] D. Ramana, N. Sundarom, M. George, Org. Mass Spectrom. 25 (1990) 161.
[16] P. Vainiotalo, P. Malkonen, Org. Mass Spectrom. 22 (1987) 493.
[17] A. Harrsion, R. Kallury, Org. Mass Spectrom. 15 (1980) 277.
[18] E. Kingston, J. Shanlon, M. Lacey, Org. Mass Spectrom. 18 (1983) 183.
[19] J. Riley, T. Baer, G. Marbury, J. Am. Soc. Mass Spectrom. 1 (1990) 69.
[20] D. Ramana, H. Ramakrishna, Org. Mass Spectrom. 24 (1989) 317.
[21] D. Ramana, N. Sundaram, M. George, Org. Mass Spectrom. 23 (1988) 63.
[22] J.T. Bursey, M.M. Bursey, G.G.I. Kingston, Chem. Rev. 73 (1973) 191.
[23] U. Filges, H.F. Grutzmacher, Org. Mass Spectrom. 21 (1986) 673.
[24] U. Filges, H.F. Grutzmacher, Org. Mass Spectrom. 22 (1987) 44.
[25] T. Donovan, J. Liu, J.S. Brodbelt, J. Am. Soc. Mass Spectrom. 3 (1992) 47.
[26] T. Donovan T, J.S. Brodbelt, Org. Mass Spectrom. 27 (1992) 9.
[27] J.L. Olear, L.G. Wright, R.G. Cooks, Org. Mass Spectrom. 22 (1987) 348.
[28] Z. Li, S. Liu, F. Song, Z. Liu, Y. Zhou, Rapid Commun. Mass Spectrom. 12 (1998) 105.
[29] Z. Li, S. Liu, Chinese Chem. Lett. 9 (1998) 675.
[30] M. Vairamani, K.V.S. Kumar, G.K.V. Rao, Org. Mass Spectrom. 25 (1990) 263.
[31] M. Vairamani, K.V.S. Kumar, G.K.V. Rao, Ind. J. Chem. 31B (1992) 9.
[32] M. Pykalainen, A. Vainiotalo, T.A. Pakkanen, P. Vainiotalo, J. Mass Spectrom. 31 (1996) 716.
[33] M. Vairamani, M. Saraswathi, K.V.S. Kumar, Org. Mass Spectrom. 27 (1992) 27.
[34] S. Prabhakar, P. Krishna, M. Vairamani, Rapid Commun. Mass Spectrom. 11 (1997) 1945.
[35] J. March, 1977. Advanced Organic Chemistry, 2nd ed. McGraw-Hill, New York, p. 441.
[36] NIST Standard Reference Database Number 6–9 July 2001 Release.
[37] S.H. Hoke II, S.S. Yang, R.G. Cook, D.A. Hrovat, W.T. Borden, I. Am. Chem. Soc. 116 (1994) 4888.