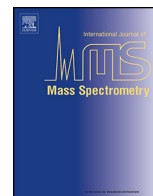




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## Aluminum hydride cluster cations: A mass spectrometric and computational study

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## ABSTRACT

A combined study using mass spectrometry and density functional theory (DFT) was conducted to investigate aluminum hydride cluster cations,  $Al_nH_m^+$  ( $1 \leq n \leq 5$ ,  $0 \leq m \leq 12$ ). The mass spectra revealed about 20 previously-unknown aluminum hydride cluster cations. Among these species, several showed high mass spectral intensities, suggesting that they had unusual stabilities. Density functional theory calculations were conducted to investigate the geometric structures of these clusters. Many of these clusters can be viewed as being composed of smaller, stable units, such as  $Al^+$ ,  $AlH_3$ ,  $Al_2^{+/0}$ ,  $H^+$  and  $H_2$ .

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## 1. Introduction

Though boron forms many hydrides, i.e., the boranes, its sister element, aluminum was thought, until a few years ago, to form only a few. The known chemistry of aluminum hydrides had long been limited to  $AlH_3$  and  $Al_2H_6$  seen in cryogenic matrices and perhaps in the gas phase, to alane,  $(AlH_3)_n$ , a polymeric solid, and to  $AlH_4^-$  as a moiety in alkali metal salts, e.g.,  $LiAlH_4$ . [1–4]. However, with the discovery of  $Al_4H_6^-$  cluster anions in the gas phase [5], the known chemistry of aluminum hydrides expanded dramatically. Over subsequent years, hundreds of aluminum hydride cluster anions were discovered. [5–15] Most of these had been prepared in unique ion sources, identified by mass spectrometry, and in some cases studied by a combination of photoelectron spectroscopy and theoretical computations.

Despite the growing family of aluminum hydride cluster anions, research on their cations has been surprisingly scarce. The first report on aluminum hydride cations appeared a half century ago with the observation of  $AlH_3^+$  and  $Al_2H_6^+$ , these having been prepared by slow evaporation of aluminum into hydrogen gas followed by ionization [16]. Subsequently, observation of  $AlH_{1,2,4}^+$  and  $AlH_2^+$

were reported [17,18]. Theoretical work found  $Al_3H_6^+$  to form a non-planar structure [19].

Aluminum is electron deficient by nature, this being the principal reason why aluminum hydride clusters tend to capture electrons and form a large variety of anions. Its cation chemistry, however, is not well understood. With this near void of information available, we studied aluminum hydride cluster cations using a unique ion source to prepare them, mass spectrometry to identify them, and theoretical computations to elucidate their structures. We observed ~20 previously unseen  $Al_nH_m^+$  clusters in our mass spectra. We carried out density functional theory (DFT) computations on the species with relatively high ion intensities, these including  $Al_3H_4^+$ ,  $Al_3H_6^+$ ,  $Al_4H_3^+$ ,  $Al_4H_6^+$ ,  $Al_4H_9^+$ ,  $Al_5H_6^+$ , and  $Al_5H_{12}^+$ .

## 1.1. Experimental methods

In the present work, the aluminum hydride cations were generated using a pulsed arc cluster ionization source (PACIS), which has been described in detail elsewhere [20]. The PACIS source has been proven to be a powerful tool for generating metal and metal hydride cluster anions [20–31]. In this study, however, we used it to generate cations. Briefly, a ~30  $\mu s$  long, 150 V, 1000 A electrical discharge, applied across an anode and the aluminum sample cathode, vaporized aluminum atoms. Almost simultaneously, 200 psi of ultra-high purity hydrogen gas was injected into the discharge region, where it

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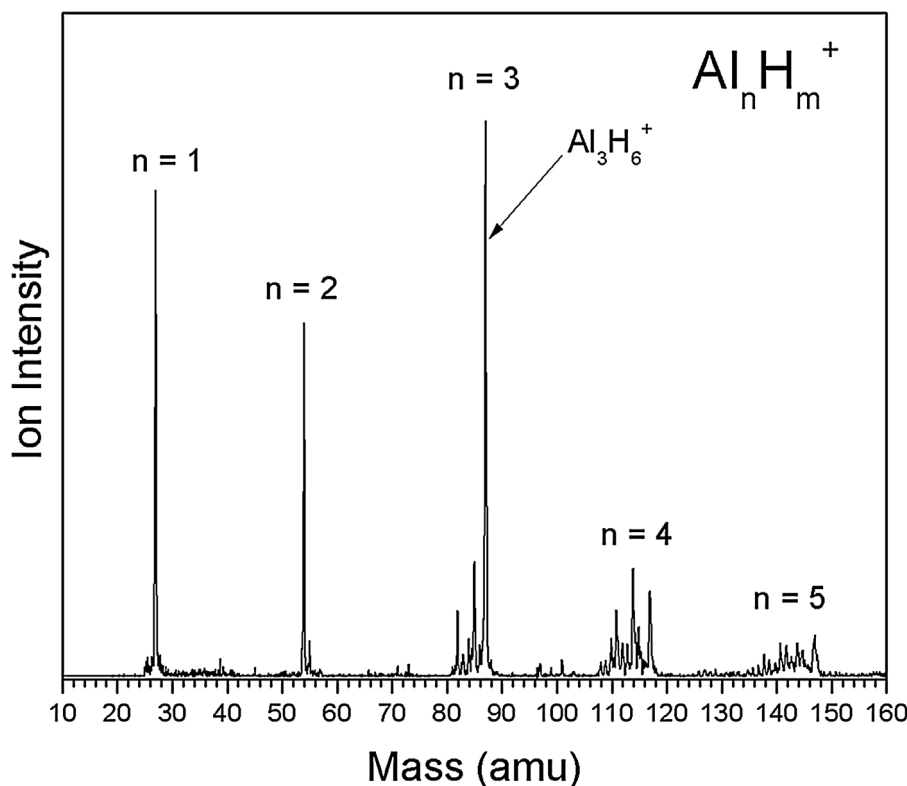


Fig. 1. The entire mass spectrum of  $\text{Al}_n\text{H}_m^+$  cluster cations as measured in this study.

was dissociated into hydrogen atoms. The pressure of  $\text{H}_2$  was optimized to obtain best ion signal. The resulting mixture of atoms, ions, and electrons then reacted and cooled as it flowed along a 20 cm tube before exiting into high vacuum. Hence, the reactions were due to the recombination of aluminum and hydrogen atoms/ions to form stable cations upon cooling and not by reactions between aluminum clusters and  $\text{H}_2$  molecules. The resulting cations were then extracted and analyzed by mass spectrometer.

## 1.2. Computational methods

The lowest and the higher energy isomers of the cationic clusters,  $\text{Al}_3\text{H}_4^+$ ,  $\text{Al}_3\text{H}_6^+$ ,  $\text{Al}_4\text{H}_3^+$ ,  $\text{Al}_4\text{H}_6^+$ ,  $\text{Al}_4\text{H}_9^+$ ,  $\text{Al}_5\text{H}_6^+$  and  $\text{Al}_5\text{H}_{12}^+$  were obtained using an unbiased systematic structure search based on the genetic algorithm (GA) [32]. In this method, initial structures were generated through a random population (parents) and subsequently allowed to cross-breed (children). Each successful “generation” becomes parents to breed the next set of children and so on. This process continued until no more mutations were possible. In our method, all levels of each structure were fully optimized without any constraints, using the BP functional and def2-SV(P) basis set [33], all employing TURBOMOLE [34]. The validity of this method had been tested against known aluminum hydride structures, and it correctly identified global minima for all of the previously studied  $\text{Al}_n\text{H}_m^-$  clusters. [6] The most stable structures were further optimized using the B3LYP functional [35–37] with the 6–311+G\*\* basis set. [38,39] Furthermore, frequency calculations were carried out at the same level of theory to verify the nature of the stationary points. All structures reported here were found to be minima on potential energy surfaces. All these calculations were carried out using the Gaussian 09 program. [40]

## 2. Results and discussion

The full-range mass spectrum showing  $\text{Al}_n\text{H}_m^+$  species observed in this study is presented in Fig. 1. Fig. 2(a)–(e) presents magnified, shorter-range versions of these mass spectra for  $n=1$ –5. Distinct hydride formation trends were observed depending on the number of aluminum atoms present in the clusters. For  $n=1$ , no hydride was formed; only the aluminum atomic cation was observed in the mass spectra, and it was intense. Aluminum hydride cations began to be seen at  $n=2$ . However, the peak of  $\text{Al}_2\text{H}^+$  was weak compared to the  $\text{Al}_2^+$  peak [see Fig. 2(b)]. The tendency for aluminum hydride cluster cations to form changed dramatically at  $n=3$ , and that trend continued for  $n=4$  and  $n=5$ . For  $\text{Al}_3\text{H}_m^+$  species, all  $m$  numbers from 1 to 7 were represented, although some  $\text{Al}_3\text{H}_m^+$  clusters had relatively weak signals [Fig. 2(c)].  $\text{Al}_4\text{H}_m^+$  and  $\text{Al}_5\text{H}_m^+$  clusters continued the pattern, with the number of hydrogen atoms going as high as  $m=9$  for  $\text{Al}_4\text{H}_m^+$  and up to  $m=12$  for  $\text{Al}_5\text{H}_m^+$  [Fig. 2(d, e)].

Let us first consider  $\text{Al}_3\text{H}_4^+$  in the  $n=3$  series. The five most stable isomers of  $\text{Al}_3\text{H}_4^+$ , as identified by our unbiased-DFT-GA method, are shown as structures, (1–5), in Fig. 3. The most stable isomer of  $\text{Al}_3\text{H}_4^+$  is (1). It has three bridging H atoms ( $\text{H}_b$ ) between two Al atoms, with the remaining H and Al atoms occupying terminal positions ( $\text{H}_t$ ) at both ends. All the isomers of  $\text{Al}_3\text{H}_4^+$  (1–5), including (1), its global minimum (GM), can be viewed as two Al atoms, either separately (2, 3) or as a unit (1, 4, 5), interacting with their tetrahedral- $\text{AlH}_4$  moieties in various ways. For example, the second most stable isomer, (2), which is only 0.09 eV higher in energy than the GM, has two Al atoms each interacting with two of the four H atoms on  $\text{AlH}_4$ . The bonding in these structures and in all other  $\text{AlH}$ -cations discussed here can be understood as follows:  $\text{Al}-\text{H}_t$  and  $\text{Al}-\text{H}_b-\text{Al}$  form 2c-2e and 3c-2e bonds, respectively; moreover for a terminally-bonded aluminum atom, one electron can be donated, while the other two exist as a lone pair. With this

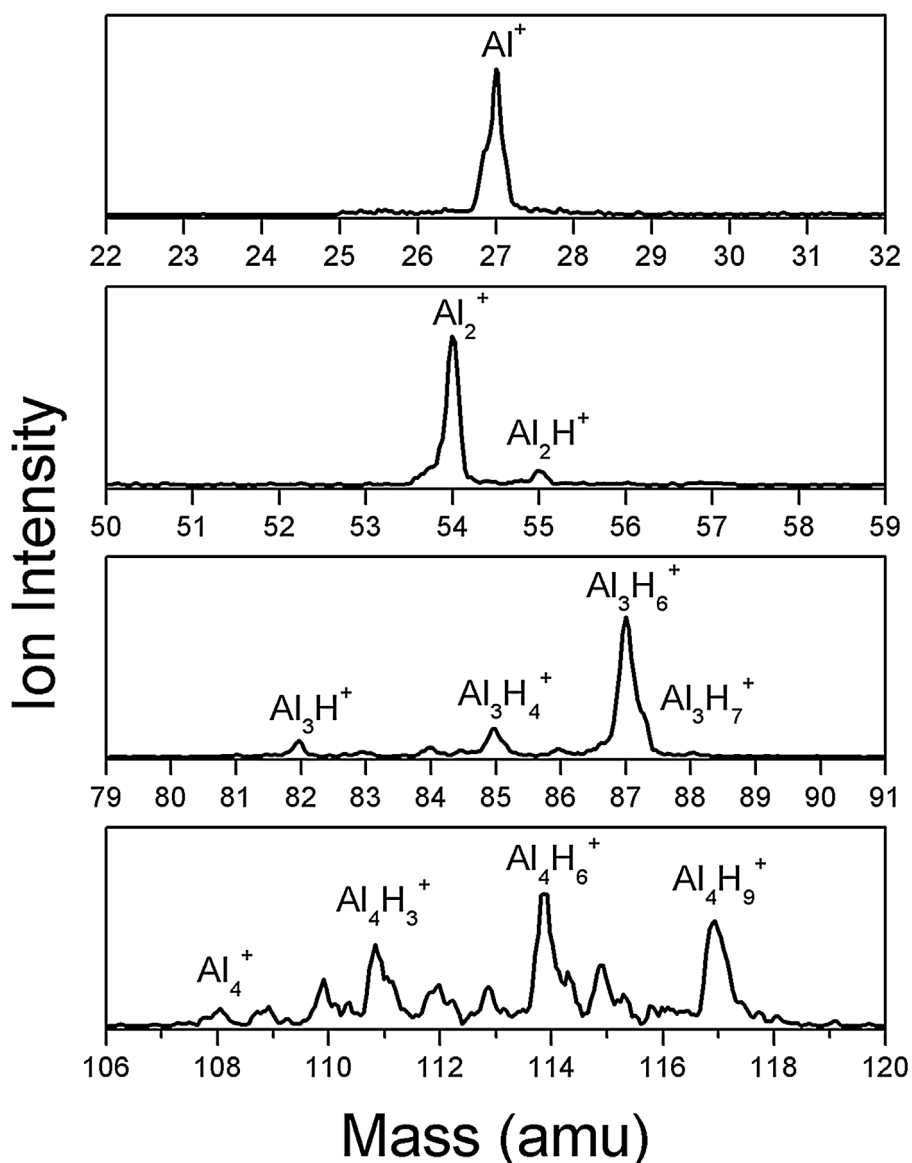


Fig. 2. The magnified, shorter mass range versions of  $\text{Al}_n\text{H}_m^+$  mas spectra,  $n=1$  to 5.

in mind, the chemical bonding, and thus the stability, of (1) with its 12 valence electrons ( $3 \times 3 + 4 - 1$ ) can be understood as follows: there are three 3c-2e bonds which account for 6 electrons, one 2c-2e bond via one Al-H<sub>t</sub> which accounts for 2 electrons, one Al-Al 2c-2e bond which accounts for 2 electrons, with the remaining 2 electrons existing as a lone pair on the terminal Al atom. Natural bond orbital (NBO) analysis confirms this bonding picture. The stability of (1) can be attributed to the fact that two of the three Al atoms exist in tetrahedral bonding environments, despite the presence of one monovalent Al atom. As we will demonstrate below, not only in  $\text{Al}_3\text{H}_4^+$  but also in other AlH cationic clusters as well, there is strong tendency to maximize the number of tetrahedral Al centers. This observation is not entirely surprising. We showed in previous work that the tetrahedral  $\text{AlH}_4^-$  anion is unusually stable with a very high vertical detachment energy. [14] The preference for tetrahedral Al bonding environments is energetically preferable over other bonding modes.

Among all these aluminum hydride cluster cations,  $\text{Al}_3\text{H}_6^+$  exhibited the highest ion intensity in the entire mass spectrum shown in Fig. 1, suggesting that this cluster cation is unusually stable. Fig. 3 presents the lowest-energy structure of  $\text{Al}_3\text{H}_6^+$  (6),

along with other higher energy isomers (7–10). The most stable structure (6) has  $C_{2v}$  symmetry, four H-bridges, two tetravalent Al atoms, and one divalent Al atom. Structure (6) can be viewed as a diborane-like- $\text{Al}_2\text{H}_6$  species, [41] interacting with an  $\text{Al}^+$  cation. Its bonding can be described as consisting of two 2c-2e Al-H<sub>t</sub> bonds, four 3c-2e Al-H<sub>b</sub>-Al bonds, and one Al atom with a lone electron pair. Interestingly, the corresponding borane analog,  $\text{B}_3\text{H}_6^+$  was predicted to have a completely different structure in which every borane atom is bonded to three hydrogen atoms. [19] This is due to the fact that *sp* hybridization in aluminum is not as pronounced as in the case of boron. [42] Thus, the 3s electrons of aluminum do not participate in bonding, i.e., they remain as a lone pair. As a result, aluminum can be either a three valence electron or a one valence electron system. This enhanced flexibility in aluminum, which is absent in boron, allows aluminum hydrides to adopt diverse structural patterns, some of which are not possible for the corresponding boranes.

The mass peaks for the  $\text{Al}_4\text{H}_3^+$ ,  $\text{Al}_4\text{H}_6^+$  and  $\text{Al}_4\text{H}_9^+$  clusters displayed the highest ion intensities among the  $\text{Al}_4\text{H}_m^+$  series, while the mass peaks for  $\text{Al}_5\text{H}_6^+$  and  $\text{Al}_5\text{H}_{12}^+$  clusters exhibited the highest ion intensities among the  $\text{Al}_5\text{H}_m^+$  series. In all these cases, their

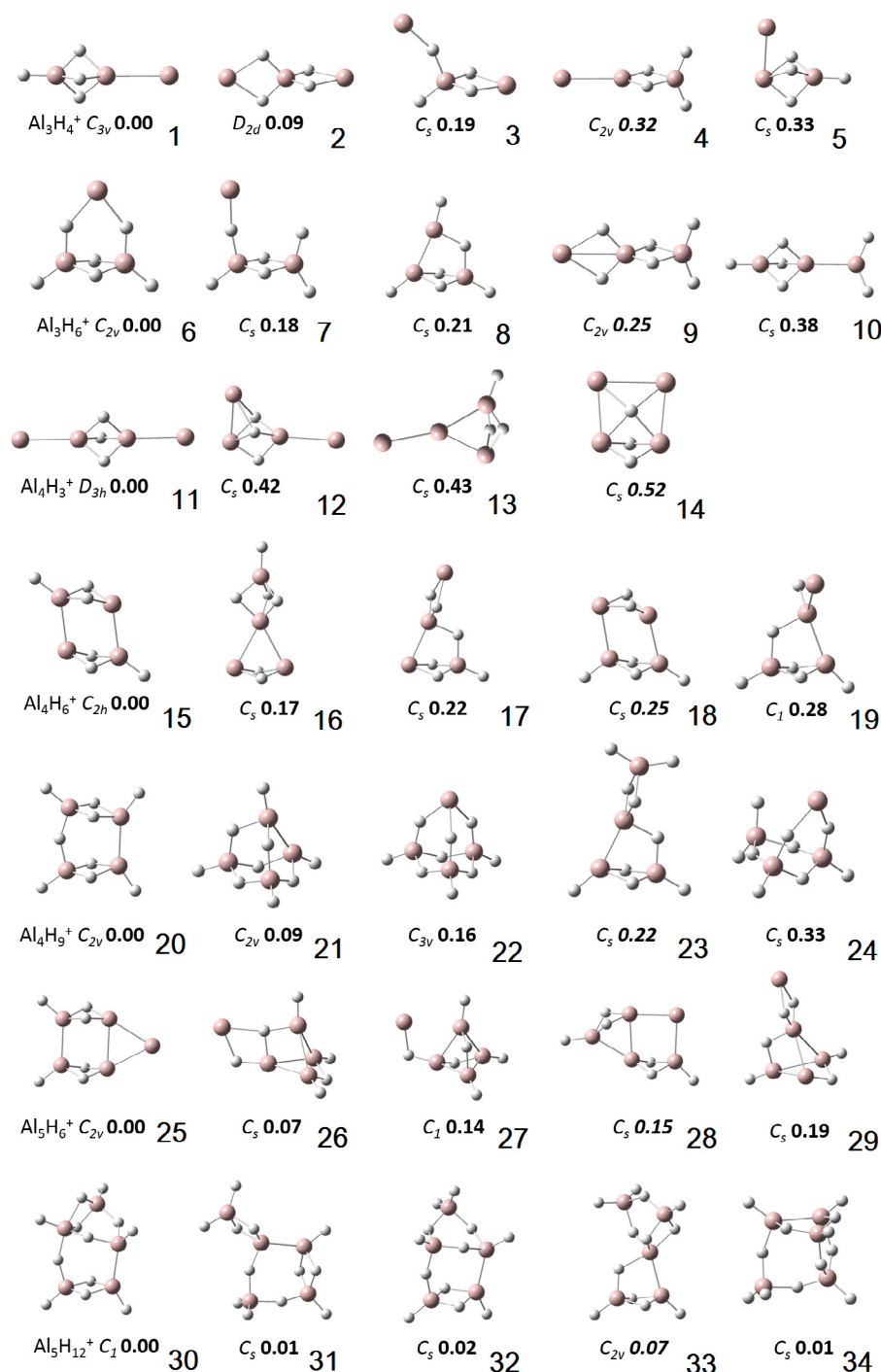


Fig. 3. Calculated structures of  $\text{Al}_3\text{H}_4^+$ ,  $\text{Al}_3\text{H}_6^+$ ,  $\text{Al}_4\text{H}_3^+$ ,  $\text{Al}_4\text{H}_6^+$ ,  $\text{Al}_4\text{H}_9^+$ ,  $\text{Al}_5\text{H}_6^+$  and  $\text{Al}_5\text{H}_{12}^+$ . Al atoms are presented by pink spheres, and H atoms are shown as white spheres.

prominent ion intensities suggest that they enjoy significant stability. The GM structure of  $\text{Al}_4\text{H}_3^+$  (**11**) can be viewed as an  $\text{Al}_3\text{H}_4^+$  (**1**) structure, in which its terminal H atom has been replaced by an Al atom. This gives  $\text{Al}_4\text{H}_3^+$   $D_{3h}$  symmetry. The GM structure of  $\text{Al}_4\text{H}_6^+$  (**15**) is a cage, in which two Al atoms are tetra-coordinated. The GM structure of  $\text{Al}_5\text{H}_6^+$  (**25**) is a cage with  $C_{2v}$  symmetry. There, four Al atoms are connected by four bridging H atoms, one Al atom bonds to two Al atoms, and two H atoms bond radially to the cage.

In the GM structures of  $\text{Al}_4\text{H}_9^+$  (**20**) and  $\text{Al}_5\text{H}_{12}^+$  (**30**), all of the Al atoms are tetra-coordinated either to H atoms or to neighboring Al atoms. In  $\text{Al}_4\text{H}_9^+$  (**20**), four Al atoms and five bridged  $\text{H}_b$  atoms form a  $C_{2v}$  cage structure, with the other four  $\text{H}_t$  atoms radially

bonded to Al atoms. In  $\text{Al}_5\text{H}_{12}^+$  (**30**), five Al atoms and seven bridged  $\text{H}_b$  atoms form an even larger cage, with the other five  $\text{H}_t$  atoms radially bonded to Al atoms. These structures reinforce the idea that tetrahedral-coordinated aluminum is key to stabilizing  $\text{Al}_n\text{H}_m^+$  cluster cations.

Lastly, Fig. 4 presents the structural evolution diagram for  $\text{Al}_n\text{H}_m^+$  cluster cations. Please note that the structural evolutions here are not chemical reactions that occurred in the source region, but merely a schematic way for understanding the stability of the cluster cations that were formed as well as the electron counting stated above. Notice that they are all inter-connected. All of them can be viewed as assemblies of smaller, more stable units, e.g.,  $\text{Al}^+$ ,

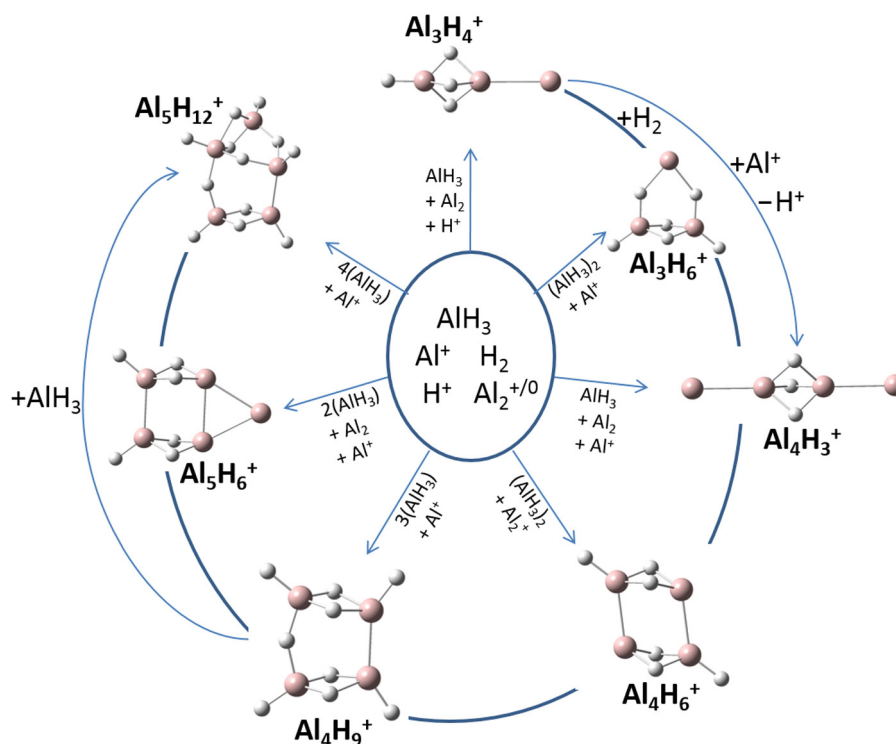


Fig. 4. Structural evolution of Al<sub>n</sub>H<sub>m</sub><sup>+</sup> cluster cations.

Al<sub>2</sub><sup>+0</sup>, AlH<sub>3</sub>, H<sup>+</sup> and H<sub>2</sub>. Furthermore, each cluster is connected to other clusters by these smaller units. Thus, the evolution of stable Al<sub>n</sub>H<sub>m</sub><sup>+</sup> stoichiometries can be additive. This study has expanded our knowledge of aluminum hydride clusters by focusing on their cations.

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### References

- [1] L. Andrews, X. Wang, *Science* 299 (2003) 2049.
- [2] F.A. Kurth, R.A. Eberlein, H. Schnöckel, A.J. Downs, C.R. Pulham, *J. Chem. Soc.* 1302 (1993) 1302.
- [3] J.W. Turley, H.W. Rinn, *Inorg. Chem.* 8 (1969) 18.
- [4] F.A. Cotton, G. Wilkinson, *Advanced Inorganic Chemistry*, 2 ed., Interscience, New York, 1966.
- [5] X. Li, A. Grubisic, S.T. Stokes, J. Cordes, G.F. Ganteför, K.H. Bowen, B. Kiran, M. Willis, P. Jena, R. Burgert, H. Schnöckel, *Science* 315 (2007) 356.
- [6] B. Kiran, P. Jena, X. Li, A. Grubisic, S.T. Stokes, G.F. Ganteför, K.H. Bowen, R. Burgert, H. Schnöckel, *Phys. Rev. Lett.* 98 (2007) 256802.
- [7] A. Grubisic, X. Li, G.F. Ganteför, K.H. Bowen, B. Kiran, P. Jena, R. Burgert, H. Schnöckel, *J. Am. Chem. Soc.* 129 (2007) 5969.
- [8] A. Grubisic, X. Li, S.T. Stokes, K. Vetter, G.F. Ganteför, K.H. Bowen, P. Jena, B. Kiran, R. Burgert, H. Schnöckel, *J. Chem. Phys.* 131 (2009) 121103.
- [9] X. Li, A. Grubisic, K.H. Bowen, A.K. Kandalam, B. Kiran, G.F. Ganteför, P. Jena, *J. Chem. Phys.* 131 (2009) 121103.
- [10] B. Kiran, A.K. Kandalam, J. Xu, Y.H. Ding, M. Sierka, K.H. Bowen, H. Schnöckel, *J. Chem. Phys.* 137 (2012) 134303.
- [11] P.J. Roach, A.C. Reber, W.H. Woodward, S.N. Kjanya, A.W. Jr. Castleman, *Proc. Natl. Acad. Sci. U.S.A.* 104 (2007) 14565.
- [12] L.F. Cui, X. Li, L.-S. Wang, *J. Chem. Phys.* 124 (2006) 054308.
- [13] X. Zhang, H. Wang, E. Collins, A. Lim, G. Ganteför, B. Kiran, H. Schnöckel, B. Eichhorn, K.H. Bowen, *J. Chem. Phys.* 138 (2013) 124303.
- [14] J.D. Graham, A.M. Buytendyk, X. Zhang, E.L. Collins, K. Boggavarapu, G. Ganteför, B.W. Eichhorn, G.L. Gutsev, S. Behera, P. Jena, K.H. Bowen, *J. Phys. Chem. A* 118 (2014) 8158.
- [15] I.A. Popov, X. Zhang, B.W. Eichhorn, A. Boldyrev, K.H. Bowen, *Phys. Chem. Chem. Phys.* 17 (2015) 26079.
- [16] P. Breisacher, B. Siegel, *J. Am. Chem. Soc.* 86 (1964) 5053.
- [17] M. Hara, K. Domen, T. Onishi, H. Nozoye, *J. Chem. Phys.* 65 (1991) 6.
- [18] K. Franzreb, R.C. Sobers Jr., J. Lorincik, P. Williams, *Appl. Surf. Sci.* 231 (2004) 82.
- [19] G.N. Srinivas, A. Anoop, E.D. Jemmis, T.P. Hamilton, K. Lammertsma, J. Leszczynski, H.F. Schaefer III, *J. Am. Chem. Soc.* 125 (2003) 16397.
- [20] X. Zhang, Y. Wang, H. Wang, A. Lim, G. Ganteför, K.H. Bowen, J.U. Reveles, S.N. Khanna, *J. Am. Chem. Soc.* 135 (2013) 4856.
- [21] A.S. Ivanov, X. Zhang, H. Wang, A.I. Boldyrev, G. Ganteför, K.H. Bowen, I. Černušák, *J. Phys. Chem. A* 119 (2015) 11293.
- [22] J. Joseph, K. Pradhan, P. Jena, H. Wang, X. Zhang, Y.J. Ko, K.H. Bowen, *J. Chem. Phys.* 136 (2012) 194305.
- [23] X. Zhang, B. Visser, M. Tschurl, E. Collins, Y. Wang, Q. Wang, Y. Li, Q. Sun, P. Jena, G. Ganteför, U. Boesl, U. Heiz, K.H. Bowen, *J. Chem. Phys.* 139 (2013) 111101.
- [24] A. Buytendyk, J. Graham, H. Wang, X. Zhang, E. Collins, Y.J. Ko, G. Ganteför, B. Eichhorn, A. Regmi, K. Boggavarapu, K.H. Bowen, *Int. J. Mass Spectrom.* 365–366 (2014) 140.
- [25] H. Wang, X. Zhang, J. Ko, A. Grubisic, X. Li, G. Ganteför, H. Schnöckel, B. Eichhorn, M. Lee, P. Jena, A. Kandalam, B. Kiran, K.H. Bowen, *J. Chem. Phys.* 140 (2014) 054301.
- [26] H. Wang, Y. Ko, X. Zhang, G. Ganteför, H. Schnöckel, B.W. Eichhorn, P. Jena, B. Kiran, A.K. Kandalam, K.H. Bowen, *J. Chem. Phys.* 140 (2014) 124309.
- [27] X. Zhang, P. Robinson, G. Ganteför, A. Alexandrova, K.H. Bowen, *J. Chem. Phys.* 143 (2015) 094307.
- [28] H. Wang, X. Zhang, Y. Ko, G.F. Ganteför, K.H. Bowen, X. Li, K. Boggavarapu, A. Kandalam, *J. Chem. Phys.* 140 (2014) 164317.
- [29] X. Zhang, H. Wang, G. Ganteför, B. Eichhorn, K. Bowen, *Int. J. Mass Spectrom.* 404 (2016) 24.
- [30] X. Zhang, G. Ganteför, A.N. Alexandrova, K. Bowen, *Phys. Chem. Chem. Phys.* 18 (2016) 19345.
- [31] X. Zhang, G. Liu, K. Meiwes-Broer, G. Ganteför, K. Bowen, *Angew. Chem. Int. Ed.* 55 (2016) 9644.
- [32] D.M. Deaven, K.M. Ho, *Phys. Rev. Lett.* 75 (1995) 288.
- [33] F. Weigenda, R. Ahlrichs, *Phys. Chem. Chem. Phys.* 7 (2005) 3297.
- [34] TURBOMOLE V6.2 2010, a development of University of Karlsruhe and Forschungszentrum Karlsruhe GmbH, 1989–2007, TURBOMOLE GmbH, since 2007; available from <http://www.turbomole.com>.
- [35] A.D. Becke, *Phys. Rev. A* 38 (1988) 3098.
- [36] A.D. Becke, *J. Chem. Phys.* 98 (1993) 5648.
- [37] C. Lee, W. Yang, R.G. Parr, *Phys. Rev. B* 37 (1988) 785.
- [38] R. Krishnan, J.S. Binkley, R. Seeger, J.A. Pople, *J. Chem. Phys.* 72 (1980) 650.
- [39] A.D. McLean, G.S. Chandler, *J. Chem. Phys.* 72 (1980) 5639.
- [40] M.J. Frisch, G.W. Trucks, H.B. Schlegel, G.E. Scuseria, M.A. Robb, J.R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G.A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H.P. Hratchian, A.F. Izmaylov, J. Bloino, G. Zheng, J.L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J.A. Montgomery, Jr., J.E.

Peralta, F. Ogliaro, M. Bearpark, J.J. Heyd, E. Brothers, K.N. Kudin, V.N. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J.C. Burant, S.S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J.M. Millam, M. Klene, J.E. Knox, J.B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R.E. Stratmann, O. Yazyev, A.J. Austin, R. Cammi, C. Pomelli, J.W. Ochterski, R.L. Martin, K. Morokuma, V.G. Zakrzewski, G.A. Voth, P. Salvador, J.J. Dannenberg, S. Dapprich, A.D. Daniels, Ö. Farkas, J.B. Foresman, J.V. Ortiz, J. Cioslowski, D.J.

Fox, 09 Gaussian D.01 Revision, Gaussian, Inc., Wallingford, CT, 2009.

- [41] B.K. Rao, P. Jena, S. Burkart, G. Ganteför, G. Seifert, Phys. Rev. Lett. 86 (2001) 692.

- [42] X. Li, H. Wu, X.-B. Wang, L.-S. Wang, Phys. Rev. Lett. 81 (1998) 1909.