

Quantitative Structure-Activity Relationships in the Lithium and Sodium Affinities of *n*-Alkyl Fluorides

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Abstract: B3LYP/6-31+g (d, p) method was used to calculate the lithium and sodium affinities of *n*-alkyl fluoride. These affinities were found to obey the Holmes relationship, *i.e.* they correlate linearly with the quotient $n/(n+1)$, where n is the number of carbon atoms in the alkyl chain. From the correlation the limiting values of lithium and sodium affinities for very long alkyl chain were predicted to be -153.3 kJ/mol and -108.4 kJ/mol, respectively.

Keywords: Lithium affinity, sodium affinity, density functional theory, C-F...metal interaction, ion attachment.

With the development of supramolecular science, the coordination chemistry of C-F unit in fluorocarbons has attracted much attention recently¹. In fact, the interaction between C-F unit and metal cations not only has been successfully employed to construct novel host molecules for molecular recognition², but also has been effectively used to control the stereochemistry in organic synthesis³. However, as this interaction is usually very weak, little has been known about its strength, geometry, and thermodynamics.

Herein, we studied the lithium and sodium affinities of *n*-alkyl fluorocarbons with high-level theoretical calculations, which are apparently essential for the understanding of C-F...cation interactions. In addition to obtaining accurate affinity data for potential applications as recently the metal cation attachment has been found very useful in soft ionization mass spectrometry⁴, we are more interested to know if the non-conventional C-F...cation interaction can be described by certain quantitative structure-activity relationships (QSAR). Such relationships can offer important insights into the mechanism of the interaction, and with them a researcher can easily estimate the interaction energy in related systems without sophisticated experimental or theoretical work.

Methods

All the calculations were performed with GAUSSIAN 98⁵. The monomers and complexes were optimized with B3LYP/6-31+g (d, p) method, which has been shown reliable to calculate lithium affinities in a recent work⁶. For all the alkyl compounds the

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linear, all-anti form was adopted as the initial geometry in optimizing the structures. Frequency calculations were also performed at the same level of theory, which confirmed that the optimized complexes corresponded to true minima and yielded the zero-point energies (DE_{ZPE}). Interaction energy (DE_0) was computed as difference in energy between the complex and the sum of isolated monomers, and basis set superposition error (BSSE) was corrected by the counterpoise procedure of Boys and Bernardi⁷. The lithium or sodium affinity was finally calculated according to Eq. 1:

$$\Delta H_{298K} = \Delta E_0 + \Delta E_{thermal} + \Delta(PV) \quad (1)$$

where $\Delta(PV) = \Delta(nRT) = -2.5 \text{ kJ/mol}$ at 298K.

Results and discussion

In **Figure 1** is shown a typical structure of the complex between *n*-alkyl fluorocarbons and alkali-metal cations, for which it can be seen that the cations indeed form complexes with the fluorine atom of the fluorocarbons. The corresponding $\text{Li}^+ \dots \text{F}$ and $\text{Na}^+ \dots \text{F}$ distances and interaction energies are listed in **Table 1** and **Table 2**. Herein, it should be mentioned that the accuracy of the present calculations is acceptably good. In fact, the lithium affinity of HF has been calculated as -91.5 kJ/mol at MP4/aug-cc-pvQZ level⁸ (compared with -95.1 kJ/mol here), and the lithium affinity of CH_3F was calculated to be -125.8 kJ/mol at B3LYP/6-311+g (3df) level⁹ (compared to -123.1 kJ/mol here).

Figure 1 The structure of C-F...cation complex between *n*-butyl fluoride and Li^+

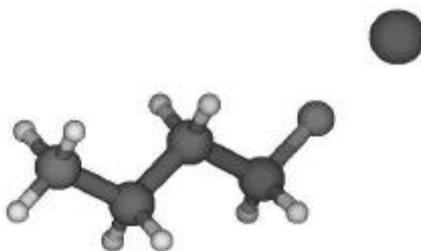


Table 1 The calculated structures and energies of the C-F... Li^+ complexes

<i>n</i>	$\text{Li}^+ \dots \text{F}$ distance (Å)	DE_0 (kJ/mol)	BSSE (kJ/mol)	$DE_{thermal}$ (kJ/mol)	$-DH_{298K}$ (kJ/mol)
0	1.811	-96.74	1.50	2.67	-95.1
1	1.760	-126.61	1.15	4.90	-123.1
2	1.743	-140.51	1.02	4.34	-137.7
3	1.738	-144.00	1.05	4.65	-140.8
4	1.735	-146.36	0.97	4.78	-143.1
5	1.733	-147.62	0.94	4.73	-144.4
6	1.733	-148.36	0.92	4.81	-145.1
7	1.732	-148.64	0.82	4.52	-145.8
8	1.732	-149.10	0.89	4.96	-145.8
9	1.732	-149.25	0.87	4.91	-146.0
10	1.731	-149.48	0.92	4.81	-146.2

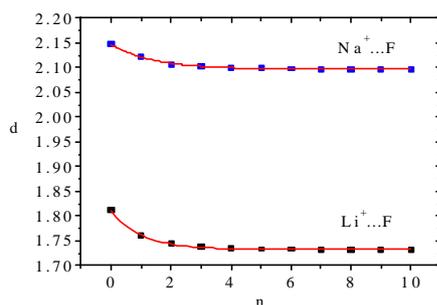
Table 2 The calculated structures and energies of the C-F...Na⁺ complexes

<i>n</i>	Na ⁺ ...F distance (Å)	<i>DE</i> ₀ (kJ/mol)	BSSE (kJ/mol)	<i>DE</i> _{thermal} (kJ/mol)	- <i>DH</i> _{298K} (kJ/mol)
0	2.147	-71.37	2.12	2.53	-69.2
1	2.123	-91.77	2.40	4.30	-87.6
2	2.107	-101.24	2.42	3.91	-97.4
3	2.103	-103.87	2.47	4.04	-99.9
4	2.100	-105.54	2.47	4.04	-101.5
5	2.100	-106.47	2.44	3.98	-102.6
6	2.098	-107.03	2.45	4.05	-103.0
7	2.097	-107.38	2.42	4.25	-103.2
8	2.097	-107.68	2.44	4.20	-103.5
9	2.097	-107.80	2.42	4.26	-103.6
10	2.097	-107.95	2.42	4.11	-103.9

According to **Table 1** and **2**, the cation...F distance is shorter in the lithium case, which is reasonable as the radius of lithium cation is smaller. Interestingly, the cation...F distances fit the following empirical equations (Eq. 2 and 3) quite well (**Figure 2**), which leads to a limiting value of lithium and sodium affinities for very long alkyl chains as 1.719 Å and 2.091 Å respectively. Such a relationship has been found before and is well known as the Holmes relationship¹⁰.

$$d_{Li^+ \dots F} = 1.807 - 0.088 \frac{n}{n+1} \quad (r = 0.990, sd = 0.004) \quad (2)$$

$$d_{Na^+ \dots F} = 2.148 - 0.057 \frac{n}{n+1} \quad (r = 0.993, sd = 0.002) \quad (3)$$

Figure 2 The dependence of the cation...F distances on the length of the alkyl chain.


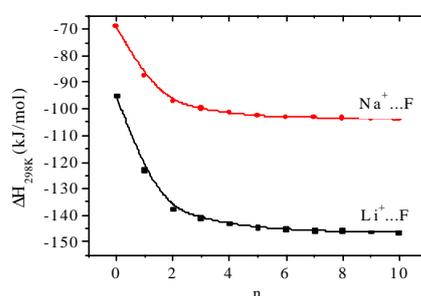
From **Table 1** and **2**, it is also apparent that C-F...Li⁺ interaction is usually stronger than C-F...Na⁺ interaction. The result is understandable as Li⁺ is a harder Lewis acid. Again, the Holmes relationship (**Figure 3**) is found applicable for the lithium and sodium affinities, which gives Eq. 4 and 5, respectively. It is notable that the standard deviations of the regressions are less than 2kJ/mol. Therefore, such QSAR should be very useful as we can quite accurately estimate the lithium or sodium affinity of any long *n*-alkyl fluoride. In addition, from the relationship the limiting values of lithium and sodium

affinities for very long alkyl chain were predicted to be -153.3 kJ/mol and -108.4 kJ/mol, respectively.

$$\Delta H_{Li^+ \cdots F} = -95.8 - 57.5 \frac{n}{n+1} \quad (r = 0.994, sd = 1.8) \quad (4)$$

$$\Delta H_{Na^+ \cdots F} = -69.4 - 39.0 \frac{n}{n+1} \quad (r = 0.995, sd = 1.1) \quad (5)$$

Figure 3 The dependence of the lithium or sodium affinity on the length of the alkyl chain



Conclusion

High-level density function theory calculations were performed to obtain the lithium and sodium affinities of *n*-alkyl fluoride. It turned out that these affinities obey the Holmes relationship. Thus, the lithium and sodium affinities of any *n*-alkyl fluoride can be reasonably and easily estimated, whose limiting values for very long alkyl chain were predicted to be -153.3 kJ/mol and -108.4 kJ/mol, respectively.

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References

- (a) H. Plenio, *Chem. Rev.*, **1997**, *97*, 3363. (b) H. J. Buschmann, J. Hermann, M. Kaupp, H. Plenio, *Chem. Eur. J.*, **1999**, *5*, 2566.
- (a) H. Takemura, N. Kon, M. Yasutake, H. Kariyazono, T. Shinmyozu, T. Inazu, *Angew. Chem. Int. Ed. Engl.*, **1999**, *38*, 959. (b) H. Takemura, S. Nakashima, N. Kon, T. Inazu, *Tetrahedron Lett.*, **2000**, *41*, 6105.
- T. Yamazaki, M. Ando, T. Kitazume, T. Kubota, M. Omura, *Org. Lett.*, **1999**, *1*, 905.
- (a) P.C. Liao, J. Allison, *J. Mass Spectrom.*, **1995**, *30*, 408. (b) T. Fujii, Y. Yashiro, H. Tokiwa, Y. Soma, *J. Am. Chem. Soc.*, **1997**, *119*, 12280.
- M. J. Frisch, G. W. Trucks, H. B. Schlegel, *et al.*, *Gaussian 98, Revision A.7*, Gaussian, Inc., Pittsburgh PA, **1998**.
- S. Arulmozhiraja, T. Fujii, *J. Phys. Chem. A*, **2000**, *104*, 9613.
- S. F. Boys, F. Bernardi, *Mol. Phys.*, **1970**, *19*, 553.
- J. E. D. Bene, *J. Phys. Chem.*, **1996**, *100*, 6284.
- F. M. Siu, N. L. Ma, C. W. Tsang, *Chem. Phys. Lett.*, **1998**, *288*, 408.
- (a) J. L. Holmes, F. P. Lossing, *Can. J. Chem.*, **1982**, *60*, 2365. (b) P. D. Pacey, Q. T. N. Tan, *J. Phys. Chem.*, **1995**, *99*, 17729. (c) A. P. Ligon, *J. Phys. Chem. A*, **2000**, *104*, 8739. (d) J. Evans, G. Nicol, B. Munson, *J. Am. Soc. Mass Spectrometry*, **2000**, *11*, 789.

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