

(NH₄)₃C₆₀: A New C₆₀ Superconductor?

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The enthalpy of formation (ΔH_f) of the ionic solid (NH₄⁺)₃C₆₀³⁻ is assessed. The solid is found to be stable with respect to the standard state reactants (N₂(g), H₂(g), and C₆₀(s)), with a ΔH_f of -1.82 eV/mol. For comparison, this enthalpy of formation is less than the enthalpy of formation of, e.g., K₃C₆₀ (-6.27 eV/mol). There are several attractive features of (NH₄⁺)₃C₆₀³⁻ as a new ionic solid and potential superconductor, if it can be synthesized. It is well-known that the size of the NH₄⁺ cation is almost exactly the same as that of Rb⁺. Among the M₃C₆₀ superconductors, Rb₃C₆₀ has the second highest superconducting transition temperature, with T_c = 28 K, which suggests that the T_c of a superconducting (NH₄)₃C₆₀ could be higher than yet achieved for C₆₀ superconductors, of which Cs₃C₆₀(s) has the highest T_c of 40 K. There is a 28% relative mass change when the NH₄⁺ counterion is replaced by ¹⁵ND₄⁺, which is a much larger relative change than can be achieved with the alkali metal atoms, which is important for study of the isotopic substitution effect on T_c . There is also the possibility of unique dynamics in which the ammonium ion rotates in the lattice; the presence of a molecular ion, rather than an atomic ion, could play a role in the mechanism of superconductivity, if the solid is superconducting. Finally, alternative methods to produce such an ammonium salt of C₆₀, such as electrosynthesis or direct synthesis in liquid ammonia, would be required in contrast to the method of the production of M₃C₆₀ (M = alkali atom) based on vapor phase transport of M via sublimation in sealed tubes.

Introduction

When the interstitial sites of fcc C₆₀(s) are doped with alkali atoms, superconducting solids can be formed.¹ Examples include M₃C₆₀(s) (M = K, Rb, and various mixtures of alkali atoms)¹ and M₅C₆₀(s) (M = Ca).² Such solids have been synthesized in a variety of ways, for example, mixing by sublimation in a sealed glass tube,³ reaction in liquid ammonia,⁴ and electrosynthesis.⁵ The highest T_c superconductor is Cs₃C₆₀, for which a T_c of 40 K has recently been measured.⁶ C₆₀-based superconductors are of interest for a variety of reasons, including the desire to understand in detail the mechanism of superconductivity; M₃C₆₀ (M = alkali) are isotropic solids, in contrast to the highly anisotropic "high T_c " cupric oxide systems. Also, there is the possibility of achieving higher T_c values.

Like all the fullerenes, C₆₀ is very electronegative, with an electron affinity of 2.65 eV,⁷ to date, all C₆₀-based superconductors are based on doping of interstitial sites with very electropositive elements. In some sense, one might suggest that the highest T_c has in fact been achieved with admixtures of the electropositive elements, because scientists have tried many possibilities;¹ however, note comments in ref 8 about the new class of binary alkali M₂NaC₆₀ or M₁Na₂C₆₀ (M = Rb, Cs). For example, the alkali and alkaline earth groups have been extensively studied. The highly electropositive lanthanides have been suggested as possible superconductors,⁹ but little synthesis effort has been expended on them. This is largely due to the very high temperatures required to achieve significant fluxes of lanthanide atoms (with the exception of the elements Sm, Eu, and Yb, which behave more like alkaline earths and have in fact been the subject of recent studies);^{10,11} the typical method of production of M_xC₆₀ by sublimation of M (vapor phase transport) is therefore very difficult. With the caveat that the high melting point, higher boiling point lanthanide elements deserve experimental effort, we may ask: Has the periodic table been "exhausted" as far as electropositive elements, and if so

are there are alternatives for formation of ionic solids that have interstitial sites occupied by a new type of cation?

A worthwhile exercise has been calculation by a Born–Haber (B–H) thermodynamic cycle of the enthalpy of formation, ΔH_f of (assumed) ionic solids such as (M⁺)₆C₆₀⁻⁶ (M = alkali) (see ref 12 for an extended discussion of the method of the B–H cycle calculation). Recent differential scanning calorimetry measurements by Chen et al. for ΔH_f of M₆C₆₀ (M = Na, K, Rb, Cs)¹³ agree to within a few percent (Na, Rb) and within 10% (K, Cs) with the values obtained from the B–H cycle calculation. This close agreement suggests that the M₆C₆₀ solids are in fact ionic solids with essentially full transfer of six electrons to C₆₀, a conclusion suggested by photoemission spectra of K-doped C₆₀ thin films,¹⁴ electrical conductivity measurements,¹⁵ and LDA calculations.¹⁶

The close agreement between experimental and B–H cycle calculated ΔH_f for these M₆C₆₀ solids also shows that the calculation of ΔH_f with the B–H cycle is essentially quantitatively correct. There is strong indirect evidence from experiment^{1,14} that the M₃C₆₀ solids (M = Na, K, Rb, Cs) are also completely ionic and therefore of the form (M⁺)₃C₆₀³⁻; these conclusions are supported by the B–H cycle treatment (close agreement of calculated and experimental lattice constants, calculated and experimental stability trends between M₃C₆₀ and M₆C₆₀, and calculated and experimental zero-pressure bulk modulus values), which assumed full electron transfer from M to C₆₀;¹² this picture is also strongly supported by extensive LDA calculations of the M₃C₆₀ solids.^{1,16} ΔH_f values have not yet been experimentally determined for the M₃C₆₀ solids (M = alkali); however, the very close agreement between the B–H calculated and experimentally determined ΔH_f for the M₆C₆₀ solids very strongly suggests that the calculated B–H cycle ΔH_f values for the M₃C₆₀ solids are also correct to a few percent or so. This serves as an important assumption in the analysis of the ΔH_f of (NH₄⁺)₃C₆₀³⁻ presented below, and I have therefore outlined the basis for this assumption in such detail. It is worth noting as an aside that the ΔH_f of M₃C₆₀ could likely be

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accurately determined by exploiting the “titration” or “back reaction” of M_6C_{60} with C_{60} to yield M_3C_{60} . The enthalpies of formation of M_6C_{60} and C_{60} are now known, so measurement of the enthalpy change for the reaction



would yield the ΔH_f of M_3C_{60} .

Results and Discussion

Fifty years ago Bleick used the method of Born and Mayer to calculate the lattice energy, U , of the ammonium halides NH_4X ($X = Cl, Br, I$) with the assumption of a fully ionic crystal, that is, $NH_4^+X^-$.¹⁷ He obtained from use of his calculated U and a B–H cycle, for each NH_4X , derived values for the proton affinity (PA) of NH_3 , which are (in kcal/mol) 206.3 (Cl), 206.6 (Br), and 206.2 (I). The extremely close agreement for the derived proton affinity from each cycle for these three different halogens demonstrated that the lattice energy calculations were accurate and that the ammonium halide crystals indeed were ionic. The proton affinity of NH_3 has since been determined to be 204 kcal/mol.¹⁸

In his lattice energy calculations, Bleick needed to calculate the repulsive potential $B(R_0)$, and to do so he needed the ionic radii. He noted that the lattice distances of the NH_4X (in the NaCl, i.e., rock salt structure) were almost identical to those of RbX ; at the time of his calculation, ionic radii were available for Rb^+ but not for NH_4^+ . Bleick assumed that the ionic radius of NH_4^+ was identical to that of Rb^+ , and his assumption is strongly supported by the internal consistency of the treatment (mentioned in the paragraph above) and also by modern data: the value presented for the ionic radius of NH_4^+ is identical to that of Rb^+ and is 1.48 Å.¹⁹

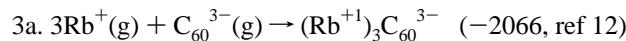
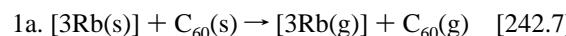
Thus, although NH_4^+ is isoelectronic with Na^+ , it is identical in size to Rb^+ . The bulk moduli, B_0 (units: GPa) of NH_4Cl (18.5) and NH_4Br (16.6) are closer to those of KCl (16.7) and KBr (14.3) than to those of $RbCl$ (16.2) and $RbBr$ (13.8).²⁰ However, care is needed in comparing these numbers, because the B_0 values for NH_4Cl and NH_4Br are for the CsCl low-temperature structure, whereas the values for the alkali halide salts are all for the NaCl crystal structure. That the structural change influences the crystal stiffness can be seen by comparing the trends in B_0 for a series of alkali chlorides: $NaCl$ (25.8 GPa), KCl (18.2), $RbCl$ (16.2), $CsCl$ (16.7);²¹ the Na , K , and Rb halides all crystallize in the NaCl structure and can be converted to the CsCl structure with pressure. The NH_4X ($X = Cl, Br, I$) all have the CsCl structure at low temperature and the less dense NaCl structure at high temperature. The obvious break in the monotonic decrease in B_0 values between $RbCl$ and $CsCl$ suggests that a naive assumption of the ion being more similar to K^+ than to Rb^+ in its compressibility is incorrect. In any case the compressibility of NH_4^+ is close to that of both K^+ and Rb^+ .

The bulk modulus of an ionic crystal, if available, is normally used to fit the energy terms in the Born–Mayer calculation of the lattice energy.¹⁷ Bleick assumed a repulsive parameter that is identical for all the alkali atoms (standard method, as discussed in ref 12) and with an identical radius as Rb^+ for the NH_4^+ , obtained the correct enthalpy of formation of NH_4X ($X = Cl, Br, I$) and proton affinity of NH_3 .¹⁷ In our previous B–H cycle treatment of the M_3C_{60} and M_6C_{60} solids, only the bulk modulus of K_3C_{60} was used as a constraint to obtain the repulsive parameter; ΔH_f of all other M_3C_{60} and M_6C_{60} solids were calculated on the basis of this constraint.¹² Note that the formation enthalpies of K_3C_{60} , Rb_3C_{60} , and Cs_3C_{60} as calculated

with this approach are (per alkali atom) −2.09, −2.12, and −2.10 eV, respectively.¹² Placing the compressibility of the NH_4^+ ion as “closer to K^+ or closer to Rb^+ ” is therefore of secondary importance in a treatment of the lattice energy, and I have outlined the issue at this length to demonstrate that one does not need *a priori* knowledge of the bulk modulus of $(NH_4)_3C_{60}$ to obtain a good estimate of the lattice energy. However, the reader may wish to speculate on the influence of pressure, where the “hardness” of the counterion may eventually make an important contribution.

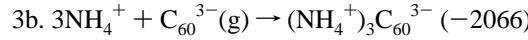
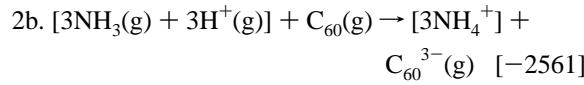
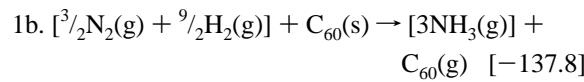
Estimation of the ΔH_f of $(NH_4)_3C_{60}^{3-}$. On the basis of the discussions above, it is clear that an excellent estimate for ΔH_f of $(NH_4)_3C_{60}^{3-}$ can be made using, but modifying, the B–H cycle calculated for $(Rb^+)_3C_{60}^{3-}$. The modification is straightforward and involves replacement of the steps where $Rb(s)$ is converted to $Rb^+(g)$, with the steps involving formation of $NH_4^+(g)$ from $N_2(g)$ and $H_2(g)$. The full cycle for Rb_3C_{60} is shown in steps 1a–3a and the cycle for $(NH_4)_3C_{60}$ is shown in steps 1b–3b. Numbers in brackets and parentheses are in kilojoule energy units.²²

Rb_3C_{60} :



$$\Delta H_f Rb_3C_{60} = -613.7 \text{ kJ} = -6.36 \text{ eV} \quad (\text{ref 12})$$

$(NH_4)_3C_{60}$:



$$\Delta H_f (NH_4)_3C_{60} = -176 \text{ kJ} = -1.82 \text{ eV}$$

The energy changes related to formation of the counterion only are shown in brackets (the energy changes for C_{60} are the same in each cycle) in eqs 1a–3a and 1b–3b.

On the basis of the discussions above about the strong similarity, in ionic crystals, of the ionic radius and hardness (from bulk modulus data) of NH_4^+ to Rb^+ and of the calculated lattice energies of NH_4X ($X = Cl, Br$, and I) and RbX ($X = Cl, Br$, and I), the lattice energies in steps 3a and 3b are assumed to be the same. The difference in ΔH_f between Rb_3C_{60} and $(NH_4)_3C_{60}$ is then the difference in ΔH_f of three $NH_4^+(g)$ from $N_2(g)$ and $H_2(g)$, and of ΔH_f of three $Rb^+(g)$ from $Rb(s)$, relative to the ΔH_f of Rb_3C_{60} . As shown above, ΔH_f of $(NH_4)_3C_{60}$ is negative and therefore stable with respect to the constituents in their standard states.

Can $(NH_4)_3C_{60}$ Be Made? Kadish and co-workers have made C_{60} -based superconductors such as Cs_3C_{60} by electro-synthesis.⁵ This is one method that could possibly synthesize $(NH_4)_3C_{60}$.

An important question is, what is the likelihood of proton transfer from NH₄⁺ to C₆₀ⁿ⁻ ($n = 0, 1, 2, 3$) during synthesis attempts? The proton affinity (which is by definition a "gas phase" value) of C₆₀ has been bracketed by observation of proton transfer to C₆₀ from MH⁺ for M = NH₃ (PA = 204 kcal/mol), but not for M = hexamethylbenzene (PA = 207 kcal/mol).²³ Note that an obvious correlation has never been made between *gas phase* proton affinities and proton transfer energetics *in solution or in solids*. For example, it is well known that proton transfer between NH₃ and HCl occurs readily in the bulk, with precipitation of the ionic salt NH₄Cl; however, the dimer between monomers in the gas phase is not NH₄⁺Cl⁻(g), but rather a H-bonded dimer with orientation H₃N...HCl.²⁴ Thus the slightly larger proton affinity of C₆₀ compared with that of NH₃ should not be taken as any sort of argument that (NH₄)₃C₆₀ cannot be made. In fact, Zhou et al. have studied C₆₀⁻ in ammonia solutions and state that "addition of strong acid (NH₄⁺) did not affect the cyclic voltammogram behavior, indicating lack of protonation of the radical anion in this solvent".²⁵

Although not the main point of this paper, we point out one significant aspect of the electrochemical measurements by Zhou et al., which is that they showed that, on the time scale of the electrochemical measurement, proton transfer from NH₄⁺ to C₆₀⁻ does not occur. This result means that it is likely that the remarkable polymeric chains observed for M₁C₆₀ (M = Na, K, Rb, Cs)²⁶ can also be observed with counterion M⁺ replaced by NH₄⁺. Either electrosynthesis or synthesis in liquid ammonia looks to be a useful method for production of NH₄C₆₀; the author feels that the dynamics of an ammonium ion trapped between neighboring C₆₀ monoanions and comparison of the NH₄C₆₀ linear polymer formed with that of M₁C₆₀ (M = Na, K, Rb, Cs) make synthesis attempts worthwhile.

Cliffel and Bard also recently studied proton transfer to the mono- and dianion of C₆₀ in dichlorobenzene solution and concluded that C₆₀⁻ is a weak base but that C₆₀²⁻ is a fairly strong base, capable of deprotonating relatively weak acids like benzoic acid.²⁷ This suggests that electrochemical production of C₆₀³⁻ in the presence of NH₄⁺ may be difficult. In this regard, we may consider the possibility of synthesizing (NH₄)₃C₆₀ by step wise replacement of (say) Rb in (Rb)₃C₆₀ by NH₄⁺. Mixed salts of type (M)₂NH₄C₆₀ or M(NH₄)₂C₆₀ (M = Na, K, Rb, Cs) are also possibilities. The ΔH_f of these ionic solids, if they can be made, will lie between the ΔH_f of M₃C₆₀ and that of (NH₄)₃C₆₀ and will therefore all be more stable than (NH₄)₃C₆₀; the ΔH_f value of M_x(NH₄)_{3-x}C₆₀ can be estimated quite accurately²⁸ by

$$\Delta H_f = x(\Delta H_f)(M_3C_{60}) + (3 - x)\Delta H_f((NH_4)_3C_{60}) \quad (4)$$

For example, the ΔH_f of Rb₃C₆₀ is -6.4 eV, and those of (Rb)₂NH₄C₆₀ and Rb(NH₄)₂C₆₀ are -4.9 and -3.3 eV, respectively. As stated above, the ΔH_f of (NH₄)₃C₆₀ is calculated to be -1.8 eV.

Ziebarth and co-workers recently suggested that metathesis reactions which exploit the relative solubilities of M₃C₆₀ (M = alkali) and LX (L = counterion, X = halide anion) in liquid ammonia may be a method of incorporation of larger counterions into the lattice;²⁹ for example, KRb₂C₆₀ has been synthesized by reaction of 3 equiv of RbCl with K₃C₆₀ in liquid ammonia. The liquid ammonia synthesis approach was also recently used by Palstra and coworkers to synthesize (Cs)₃C₆₀, whereas vapor phase transport by sublimation of Cs in sealed capillary tubes had not allowed synthesis of (Cs)₃C₆₀.⁶ Another possibility may be cation transfer by intimate contact of an ionic solid involving C₆₀ (for example, Rb₃C₆₀) and a simple ammonium halide salt.

Conclusions

A number of similarities have been noted between ammonium halide and rubidium halide salts; these similarities support the assumption that the lattice energy of ionic solids (Rb)₃C₆₀ and (NH₄)₃C₆₀ is the same. The enthalpy of formation of (NH₄)₃C₆₀ is calculated to be -1.8 eV/mol, which demonstrates that (NH₄)₃C₆₀ is stable with respect to the standard state reactants but less stable than Rb₃C₆₀, for which $\Delta H_f = -6.3$ eV/mol. Although (NH₄)₃C₆₀ is stable with respect to the standard state reactants, proton transfer may occur to the di- or trianion of C₆₀, which would make synthesis impossible. Three techniques seem relevant for attempting synthesis of (NH₄)₃C₆₀: electrosynthesis, synthesis in liquid ammonia, and solid/solid ion exchange reaction. Direct reaction may not work and an indirect method involving stepwise replacement of alkali counterions, for example, Rb₃C₆₀, may succeed.

Independent from success or failure of synthesis of (NH₄)₃C₆₀, it is likely that the remarkable polymeric chains observed for M₁C₆₀ (M = Na, K, Rb, Cs) can also be observed with counterion M⁺ replaced by NH₄⁺. Either electrosynthesis or synthesis in liquid ammonia looks to be a useful method for production of NH₄C₆₀. Synthesis of NH₄C₆₀ may also provide insight into how to produce (NH₄)₃C₆₀ or M_x(NH₄)_{3-x}C₆₀.

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