An *ab initio* and DFT study of some halogen atom transfer reactions from alkyl groups to acyl radical†

Hiroshi Matsubara,*[a] Ilhyong Ryu[a] and Carl H. Schiesser[b,c]

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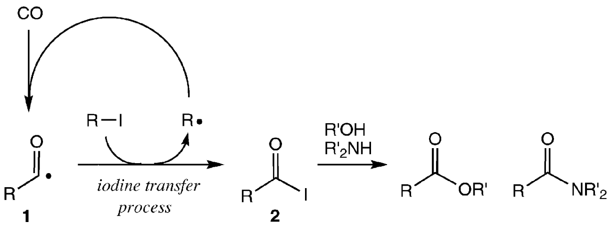
Ab initio calculations using the 6-311G**, cc-pVDZ, and (valence) double-ζ pseudopotential (DZP) basis sets, with (MP2, QCISD, CCSD(T)) and without (HF) the inclusion of electron correlation, and density functional (BHandHLYP, B3LYP) calculations predict that the transition states for the reaction of acetyl radical with several alkyl halides adopt an almost collinear arrangement of attacking and leaving radicals at the halogen atom. Energy barriers ($\Delta E^{\ddagger}$) for these halogen transfer reactions of between 89.2 (chlorine transfer from methyl group) and 25.3 kJ mol^{-1} (iodine transfer from *tert*-butyl group) are calculated at the BHandHLYP/DZP level of theory. While the difference in forward and reverse energy barriers for iodine transfer to acetyl radical is predicted to be 15.1 kJ mol^{-1} for primary alkyl iodide, these values are calculated to be 6.7 and -4.2 kJ mol^{-1} for secondary and tertiary alkyl iodide respectively. These data are in good agreement with available experimental data in that atom transfer radical carbonylation reactions are sluggish with primary alkyl iodides, but proceed smoothly with secondary and tertiary alkyl iodides. These calculations also predict that bromine transfer reactions involving acyl radical are also feasible at moderately high temperature.

Introduction

Atom transfer radical carbonylation (ATC) reactions are efficient methods for the preparation of aliphatic carboxylic acid esters, amides, and related heterocyclic compounds.[1–3] Alkyl iodides and carbon monoxide, both readily available materials, are employed in this reaction. Although the reactions with secondary and tertiary alkyl iodides proceed smoothly, ATC reactions with primary alkyl iodides progress sluggishly to afford the required compounds often in poor yield and requiring longer reaction times. These reactions also often compete with undesirable side reactions such as alkyl iodide decomposition, resulting in decreased product yields. Addition of palladium or manganese catalysts with photo-irradiation can often overcome the limitations of this process.[4] ATC reactions involve both radical and ionic steps as illustrated in Scheme 1. Acyl radical **1**, generated from alkyl radical and carbon monoxide, reacts in an iodine atom transfer reaction with the alkyl iodide to afford acyl iodide **2** and another chain-carrying alkyl radical (radical steps). The formed acyl iodide is easily quenched with alcohols or amines to give the corresponding esters or amides, respectively (ionic steps). The key step in the ATC process is the iodine atom transfer reaction, which is expected to be the rate-determining step in the process. Accordingly, ATC reactions involving primary alkyl iodides are sluggish, presumably due to the reduced leaving group ability of primary radicals compared with secondary and tertiary systems. Indeed, rate constants for halogen atom transfer to alkyl radicals are reported to be: (3 ± 2) × 10^{6}, (5.1–9.5) × 10^{5} and (1.7–3.4) × 10^{5} M^{-1} s^{-1} for tertiary, secondary and primary alkyl iodides, respectively.[5] However, the rate constants for primary iodides do not seem significantly smaller than those of secondary iodides, indicating that the poor outcomes of ATC reactions involving primary iodides cannot be explained well by rate constant data alone. It should also be noted that these data are for transfers to alkyl radicals, not acyl radicals; indeed, there are no kinetic data for halogen atom transfer reactions to acyl radicals.



Scheme 1

Work in our laboratories has been directed toward the understanding and utilization of free-radical homolytic substitution chemistry with the aim of developing novel synthetic methodology.[6] To that end, we have published recently several *ab initio* and DFT studies with the aim of increasing our understanding of the factors that affect and control the mechanism of homolytic substitution at several main-group heteroatoms.[7–10] Our mechanistic studies on homolytic substitution reactions at halogen atoms suggested that while 1,5-, 1,6- and 1,7-halogen transfer reactions in ω-haloalkyl radicals would be infeasible due to high energy barriers ($\Delta E^{\ddagger}$ > 100 kJ mol^{-1}),[7] homolytic substitution reactions of methyl radical at the halogen atom in

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[a] *Department of Chemistry, Graduate School of Science, Osaka Prefecture University, Sakai, Osaka, 599-8531, Japan*
[b] *School of Chemistry, The University of Melbourne, Victoria, 3010, Australia*
[c] *Bio21 Molecular Science and Biotechnology Institute, The University of Melbourne, Victoria, 3010, Australia*

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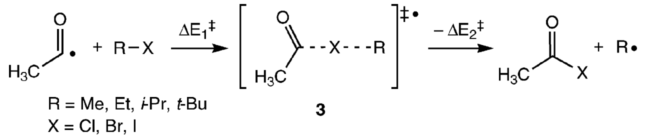
bromomethane and iodomethane as well as halogen atom transfer reactions from the methyl group to silyl, germyl and stannyl radicals in halomethanes can proceed.[8]

As part of our ongoing interest in homolytic substitution chemistry involving higher main group heteroatoms and in order to provide further insight into the mechanistic details of halogen atom transfer reactions from alkyl groups to acyl radicals,[11–13] we began to explore chlorine, bromine and iodine transfer reactions from methyl, ethyl, isopropyl and *tert*-butyl groups to acetyl radical (Scheme 2) through the use of *ab initio* and DFT calculations.



Scheme 2

Methods

Ab initio and DFT calculations were carried out on Compaq Personal Workstation 600au, Alpha Station DS10L, and Dell PowerEdge 400SC computers using the Gaussian 98 and Gaussian 03 programs.[14,15] Geometry optimizations were performed using standard gradient techniques at the SCF, MP2, BHandHLYP and B3LYP levels of theory using restricted (RHF, RMP2, RBHandHLYP and RB3LYP) and unrestricted (UHF, UMP2, UBHandHLYP and UB3LYP) methods for closed- and open-shell systems respectively.[16] All ground and transition states were verified by vibrational frequency analysis. Further single-point QCISD and CCSD(T) calculations were performed on each of the MP2-, BHandHLYP- and B3LYP-optimized structures. When correlated methods were used, calculations were carried out using the frozen core approximation. Values of $<s^2>$ never exceeded 0.89 before annihilation of quartet contamination (except for some UHF calculations). Where appropriate, zero-point vibrational energy (ZPE) corrections have been applied. Standard basis sets were used. In addition, the (valence) double-ζ pseudopotential basis sets of Hay and Wadt[17] supplemented with a single set of *d*-type polarization functions were used for the heteroatoms in this study, (exponents $d(\zeta)_{Cl} = 0.640$, $d(\zeta)_{Br} = 0.428$, and $d(\zeta)_{I} = 0.289$),[18] while the double-ζ all-electron basis sets of Dunning[19] with an additional set of polarization functions (exponents $d(\zeta)_C = 0.75$, $d(\zeta)_O = 0.85$ and $p(\zeta)_H = 1.00$) were used for C, O and H. We refer to this basis set as DZP throughout this work.[7–10] In previous work, results generated using DZP proved to be very similar to those obtained using 6-311G** for reactions involving chlorine[7,8] and silicon.[9,10]

Optimized geometries and energies for all transition structures in this study (Gaussian Archive entries) are available as Electronic Supplementary Information (ESI†).

Results and discussion

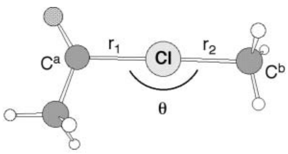
Atom transfer reaction of chlorine from methyl group to acetyl radical

Extensive searching of the C_3H_6ClO potential energy surface at all of the levels of theory employed for optimization in this study located hypervalent species **3** (X = Cl; R = Me), of C_s symmetry as transition states for the atom transfer reaction of chlorine from methyl group to acetyl radical (Scheme 2). The important geometric features of the transition states **3** (X = Cl; R = Me) are summarized in Fig. 1, while calculated energy barriers ($\Delta E_1^\ddagger$ and $\Delta E_2^\ddagger$, Scheme 2) together with the corresponding imaginary frequencies are listed in Table 1. Full computational details are available as ESI.

Inspection of Fig. 1 reveals that transition state **3** (X = Cl; R = Me) is predicted to adopt an almost collinear arrangement of the attacking acetyl radical and the leaving methyl radical at all levels of theory employed (C_s symmetry). The transition state

Table 1 Calculated energy barriers (in kJ mol^{-1}) for the forward ($\Delta E_1^\ddagger$) and reverse ($\Delta E_2^\ddagger$) atom transfer reactions of chlorine from methyl group to acetyl radical and imaginary frequencies (ν, in cm^{-1}) of transition state **3**

Method	$\Delta E_1^\ddagger$	$\Delta E_1^\ddagger$ + ZPE	$\Delta E_2^\ddagger$	$\Delta E_2^\ddagger$ + ZPE	ν
HF/6-311G**	131.2	127.3	129.2	138.2	610i
HF/DZP	132.5	128.3	139.3	147.8	623i
MP2/6-311G**	108.0	107.5	104.6	115.2	749i
MP2/DZP	113.3	112.4	121.3	131.8	796i
MP2/cc-pVDZ	103.3	102.8	104.8	115.3	751i
QCISD/6-311G**//MP2/6-311G**	102.9	—	92.6	—	—
QCISD/DZP//MP2/DZP	105.5	—	105.7	—	—
QCISD/cc-pVDZ//MP2/cc-pVDZ	97.2	—	91.6	—	—
CCSD(T)/6-311G**//MP2/6-311G**	92.8	—	84.5	—	—
CCSD(T)/DZP//MP2/DZP	95.8	—	99.5	—	—
CCSD(T)/cc-pVDZ//MP2/cc-pVDZ	87.8	—	84.5	—	—
BHandHLYP/6-311G**	90.6	88.4	79.7	88.7	551i
BHandHLYP/DZP	89.2	87.1	88.9	97.6	574i
BHandHLYP/cc-pVDZ	86.6	84.7	81.0	90.0	551i
QCISD/cc-pVDZ//BHandHLYP/cc-pVDZ	95.5	—	90.3	—	—
CCSD(T)/cc-pVDZ//BHandHLYP/cc-pVDZ	85.9	—	82.9	—	—
B3LYP/6-311G**	63.3	61.3	52.2	60.5	424i
B3LYP/DZP	60.8	59.0	60.6	68.9	446i
B3LYP/cc-pVDZ	59.4	57.7	53.6	61.8	427i
QCISD/cc-pVDZ//B3LYP/cc-pVDZ	95.5	—	89.7	—	—
CCSD(T)/cc-pVDZ//B3LYP/cc-pVDZ	86.1	—	82.6	—	—



Method	r_1	r_2	θ
HF/6-311G**	2.239 Å	2.217 Å	179.7°
HF/DZP	2.227 Å	2.210 Å	179.6°
MP2/6-311G**	2.080 Å	2.080 Å	180.0°
MP2/DZP	2.084 Å	2.078 Å	178.9°
MP2/cc-pVDZ	2.096 Å	2.089 Å	179.2°
BHandHLYP/6-311G**	2.145 Å	2.159 Å	180.0°
BHandHLYP/DZP	2.126 Å	2.135 Å	179.4°
BHandHLYP/cc-pVDZ	2.139 Å	2.149 Å	179.6°
B3LYP/6-311G**	2.145 Å	2.159 Å	180.0°
B3LYP/DZP	2.142 Å	2.161 Å	179.0°
B3LYP/cc-pVDZ	2.153 Å	2.181 Å	179.4°

Fig. 1 Optimized structure of transition state **3** (X = Cl; R = Me) for the atom transfer reaction of chlorine from chloromethane to acetyl radical at various levels of theory.

(C^a–Cl) separations (r_1) in **3** (X = Cl; R = Me) are predicted at all levels of theory to lie in the range: 2.080–2.239 Å, while the (Cl–C^b) distances (r_2) in **3** (X = Cl; R = Me) are calculated to be 2.078–2.217 Å. Interestingly, the Cl–C^a distances are predicted to be slightly longer than the Cl–C^b distances at the UHF and the MP2 levels of theory, while the Cl–C^a distances are calculated to be slightly shorter using the DFT methods. These distances are in the expected ranges when compared with our previous calculations of homolytic substitution reactions involving halogen atoms.[7,8]

Inspection of Table 1 reveals that the energy barrier ($\Delta E_1^\ddagger$) for the forward reaction (Scheme 2) associated with **3** (X = Cl; R = Me) is calculated to be 131.2 kJ mol^{-1} at the HF/6-311G** level of theory. As expected, electron correlation is important in these calculations; MP2/6-311G** serves to lower this energy barrier to 108.0 kJ mol^{-1} for **3** (X = Cl; R = Me), while inclusion of zero-point vibrational energy correction (ZPE) has little effect on these barriers. Further improvements in both basis set quality and levels of correlation provide values of $\Delta E_1^\ddagger$ for the reaction involving **3** (X = Cl; R = Me) that range from 103.3 (MP2/cc-pVDZ) to 102.9 (QCISD/6-311G**//MP2/6-311G**). At the highest level of theory used (CCSD(T)/cc-pVDZ//MP2/cc-pVDZ), an energy barrier ($\Delta E_1^\ddagger$) of 87.8 kJ mol^{-1} is predicted for the reaction involving **3** (X = Cl; R = Me). BHandHLYP/6-311G** and BHandHLYP/cc-pVDZ calculations provide energy barriers ($\Delta E_1^\ddagger$) of 90.6 and 86.6 kJ mol^{-1} for the reaction involving **3** (X = Cl; R = Me) respectively, while values of 63.3 and 59.4 kJ mol^{-1} are obtained at the B3LYP/6-311G** and B3LYP/cc-pVDZ levels of theory. The B3LYP method provided significantly smaller energy barriers than those obtained using other methods, and deserves special mention. Interestingly, single-point calculations on the geometries which were optimized on the B3LYP calculation provided very similar energy barriers to those on the structure optimized at the MP2 and the BHandHLYP levels of theory, indicating that while the B3LYP method is capable of providing reliable geometries, as has been observed previously,[13] it is incapable of providing reliable energy data.

It is interesting to note that the BHandHLYP/DZP level of theory performs well when benchmarked against higher, all-electron methods, such as CCSD(T). Given that the DZP basis set is required for calculations involving iodine, the BHandLYP/DZP method will be employed for subsequent calculations.

The data in Table 1 shows that the differences in energy barriers between for the forward and reverse processes ($\Delta E_1^\ddagger$and $\Delta E_2^\ddagger$) are small, indicating that this reaction is reversible under high temperatures. This is not surprising given that acyl radicals are known to be stabilized by resonance.[11]

Atom transfer reaction of chlorine from ethyl, isopropyl, and *tert*-butyl groups to acetyl radical

Extensive searching of the H_3C–CO–Cl–R (R = Et, *i*-Pr, *t*-Bu) potential energy surfaces at the BHandHLYP/DZP level of theory located hypervalent species **3** (X = Cl; R = Et, *i*-Pr, *t*-Bu) as transition states for the atom transfer reactions (Scheme 1). The important geometric features of the transition states **3** (X = Cl; R = Et, *i*-Pr, *t*-Bu) are summarized in Fig. 2, while calculated energy barriers ($\Delta E_1^\ddagger$and $\Delta E_2^\ddagger$, Scheme 2) together with the corresponding imaginary frequencies are listed in Table 2. Full computational details are available as ESI.

The structures in Fig. 2 bear a resemblance to those calculated for the analogous reactions with a methyl group on **3** (X = Cl, R = Me). Transition states **3** (X = Cl; R = Et, *i*-Pr, *t*-Bu) are also predicted to adopt an almost collinear arrangement of the attacking acyl radical and the leaving alkyl radical. Interestingly, while transition state **3** with an ethyl group is predicted to have C_s symmetry similar to the transition state involving a amethyl group, transition state **3** with a bulky group (isopropyl or *tert*-butyl) is calculated to have C_1 symmetry, As shown in Fig. 2, the transition

Table 2 BHandHLYP/DZP calculated energy barriers (in kJ mol^{-1}) for the forward ($\Delta E_1^\ddagger$) and reverse ($\Delta E_2^\ddagger$) atom transfer reactions of chlorine from ethyl, isopropyl and *tert*-butyl groups to acetyl radical, and imaginary frequencies (ν, in cm^{-1}) of transition state **3**

Alkyl group	$\Delta E_1^\ddagger$	$\Delta E_1^\ddagger$ + ZPE	$\Delta E_2^\ddagger$	$\Delta E_2^\ddagger$ + ZPE	ν
Et	88.2	86.2	86.4	93.4	559i
i-Pr	84.6	82.8	85.0	91.8	540i
t-Bu	78.5	77.3	84.6	88.0	518i

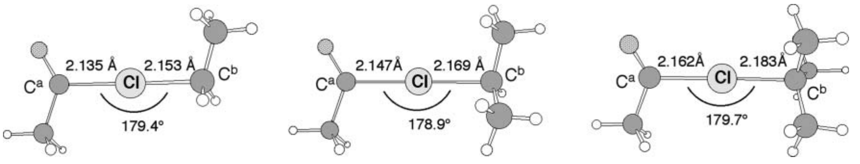


Fig. 2 BHandHLYP-optimized structure of transition states **3** (X = Cl; R = Et, *i*-Pr, *t*-Bu) for the atom transfer reaction of chlorine from ethyl, isopropyl and *tert*-butyl groups to acetyl radical.

state (C^a–Cl) and (Cl–C^b) separations in **3** (X = Cl; R = Et, *i*-Pr, *t*-Bu) are predicted be longer on changing the leaving radical from ethyl to isopropyl to *tert*-butyl, consistent with expectation on the basis of leaving group ability.

Inspection of Tables 1 and 2 reveals that energy barriers of the chlorine atom transfer reaction calculated on the BHandHLYP/DZP level lie in the range 79–89 kJ mol^{-1}. Calculated energy barriers for the forward reaction ($\Delta E_1^{\ddagger}$) decrease in the order methyl > ethyl > isopropyl > *tert*-butyl, while those for the reverse process ($\Delta E_2^{\ddagger}$) decrease only slightly in the same order of the leaving radical; the chlorine transfer reaction involving *tert*-butyl radical is calculated to be a significantly exothermic reaction. The computational data presented here indicate that atom transfer reactions of chlorine from alkyl groups to acetyl radical are predicted to be associated with high energy barriers in all cases, suggesting that these transformations are unlikely to be synthetically useful.

Atom transfer reaction of bromine and iodine from methyl, ethyl, isopropyl, and *tert*-butyl groups to acetyl radical

Extensive searching of the H_3C–CO–X–R (X = Br, I; R = Me, Et, *i*-Pr, *t*-Bu) potential energy surfaces at the BHandHLYP/DZP level of theory located hypervalent species **3** (X = Br, I; R = Me, Et, *i*-Pr, *t*-Bu), as transition states for the atom transfer reactions (Scheme 1). The important geometric features of the transition states **3** (X = Br, I; R = Me, Et, *i*-Pr, *t*-Bu) are summarized in Fig. 3, while calculated energy barriers ($\Delta E_1^{\ddagger}$and $\Delta E_2^{\ddagger}$, Scheme 2) together with the corresponding imaginary frequencies are listed in Table 3. Full computational details are available as ESI.

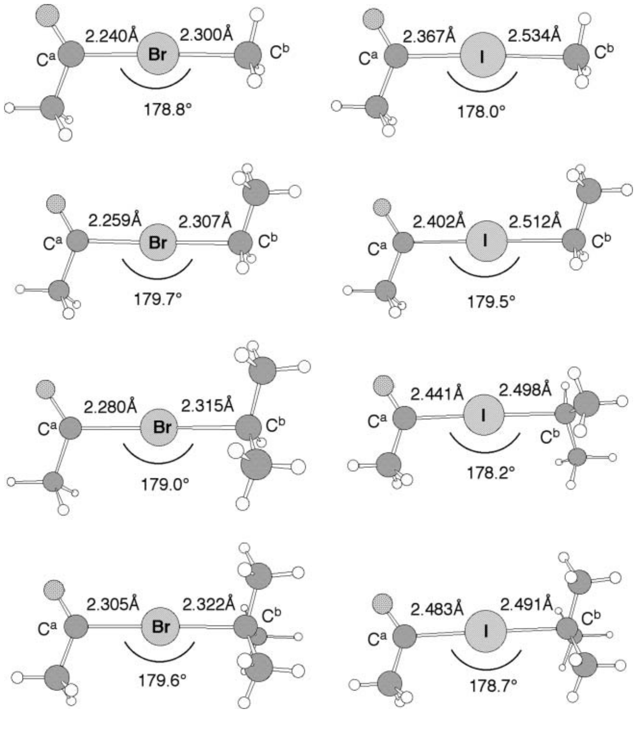


Fig. 3 BHandHLYP-optimized structure of transition states **3** (X = Br, I; R = Et, *i*-Pr, *t*-Bu) for the atom transfer reaction of bromine and iodine from methyl, ethyl, isopropyl and *tert*-butyl groups to acetyl radical.

Table 3 BHandHLYP/DZP calculated energy barriers (in kJ mol^{-1}) for the forward ($\Delta E_1^{\ddagger}$) and reverse ($\Delta E_2^{\ddagger}$) atom transfer reactions of bromine and iodine from methyl, ethyl, isopropyl and *tert*-butyl groups to acetyl radical, and imaginary frequencies (ν, in cm^{-1}) of transition state **3**

Alkyl halide	$\Delta E_1^{\ddagger}$	$\Delta E_1^{\ddagger}$ + ZPE	$\Delta E_2^{\ddagger}$	$\Delta E_2^{\ddagger}$ + ZPE	ν
MeBr	59.1	57.6	49.0	58.1	384i
EtBr	57.1	56.0	48.8	56.5	370i
i-PrBr	53.3	52.6	49.6	57.4	352i
t-BuBr	47.6	47.3	51.6	56.2	334i
MeI	42.0	40.3	20.4	29.2	279i
EtI	37.0	36.1	22.0	29.7	267i
i-PrI	31.8	31.4	25.1	33.3	253i
t-BuI	25.3	25.4	29.5	34.6	238i

Not unexpectedly, the structures in Fig. 3 bear a striking resemblance to those calculated for the analogous reactions involving chlorine. Again, transition states **3** (X = Br, I; R = Me, Et, *i*-Pr, *t*-Bu) are predicted to adopt an almost collinear arrangement with C_s symmetry for methyl and ethyl, and C_1 symmetry for isopropyl and *tert*-butyl. As shown in Fig. 3, (C^a–X) distances in **3** are calculated to lie between 2.240 Å (X = Br, R = Me) and 2.483 Å (X = I, R = *t*-Bu) at the level of theory employed, while X–C^b separations in **3** are predicted to be between 2.300 Å (X = Br, R = Me) and 2.534 Å (X = I, R = Me). Interestingly, while both calculated bond distances around the transferred halogen atom (C^a–X, X–C^b) generally increase in the order of methyl < ethyl < isopropyl < *tert*-butyl, X–C^b separations in **3** predicted in the transition states involving iodine decrease in the same order of the leaving radical.

Similar to the chlorine system, calculated energy barriers ($\Delta E_1^{\ddagger}$) for the forward reaction decrease in the order of methyl > ethyl > isopropyl > *tert*-butyl, while those ($\Delta E_2^{\ddagger}$) for the reverse process increase in the same order of the leaving radical. As a result, while bromine or iodine transfer reactions involving methyl, ethyl, and isopropyl groups are predicted to be endothermic, these reactions involving the *tert*-butyl group are calculated to be slightly exothermic.

As shown in Table 3, energy barriers ($\Delta E_1^{\ddagger}$) of the bromine and iodine transfer reaction calculated on the BHandHLYP/DZP level lie in the range 48–59 and 25–42 kJ mol^{-1}, respectively.[20] It would therefore seem that the inefficiency that primary alkyl iodides are afflicted with in ATC reactions is not well interpreted by the calculated energy barriers alone; however, it can be explained in terms of equilibria expected on the basis of the differences in calculated energy barriers (ΔE) between the forward and reverse reactions. Indeed, these differences for the bromine and iodine transfer processes involving the isopropyl or *tert*-butyl radicals are less than 7 kJ mol^{-1}. Irrespective of the endothermic or exothermic nature of these reactions, these reactions are predicted to be reversible under the usual reaction conditions. Once generated, the products of these atom transfer processes, acyl halides, would be expected to react quickly with nucleophiles such as alcohols or amines to give more stable products, such as esters or amides, respectively. If we focus on the reactions involving iodomethane and iodoethane, reactions known to be inefficient, the differences ΔE for iodine transfer to acetyl radical are calculated to be 22 and 15 kJ mol^{-1} respectively, favouring the reverse process, and consistent with experimental observation. In addition, the computational data presented in this work suggest that bromine transfer reaction from isopropyl and *tert*-butyl (and perhaps ethyl and methyl) groups to acetyl radical is reversible at high temperature. Consequently, we conclude that atom transfer reactions involving acyl radicals might occur not only for iodine but also for bromine under suitable conditions.

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References and notes

1 I. Ryu, *Chem. Soc. Rev.*, 2001, **30**, 16.

2 K. Nagahara, I. Ryu, S. Minakata, M. Komatsu and N. Sonoda, *J. Am. Chem. Soc.*, 1997, **119**, 5465; I. Ryu, K. Nagahara, N. Kambe, N. Sonoda, M. Kreimerman and M. Komatsu, *Chem. Commun.*, 1998, 1953; S. Kreimerman, I. Ryu, S. Minakata and M. Komatsu, *Org. Lett.*, 2000, **2**, 389; S. Kreimerman, I. Ryu, S. Minakata and M. Komatsu, *C. R. Acad. Sci., Ser. IIc: Chim.*, 2001, **4**, 497; I. Ryu, *Chem. Rec.*, 2002, **2**, 1691.

3 M. Sugiura, H. Hagio and S. Kobayashi, *Chem. Lett.*, 2003, 898; O. Itsenko, T. Kihlberg and B. Långström, *J. Org. Chem.*, 2004, **69**, 4356; O. Itsenko and B. Långström, *J. Org. Chem.*, 2005, **70**, 2244; O. Itsenko and B. Långström, *Org. Lett.*, 2005, **7**, 4661; O. Itsenko, K. Kihlberg and B. Långström, *Synlett*, 2005, 3160; O. Itsenko, T. Kihlberg and B. Långström, *Eur. J. Org. Chem.*, 2005, 3830.

4 I. Ryu, S. Kreimerman, F. Araki, S. Nishitani, S. Oderaotoshi, S. Minakata and M. Komatsu, *J. Am. Chem. Soc.*, 2002, **124**, 3812; T. Fukuyama, S. Nishitani, I. Inouye, K. Morimoto and I. Ryu, *Org. Lett.*, 2006, **8**, 1383; T. Fukuyama, T. Inouye and I. Ryu, *J. Organomet. Chem.*, 2007, **692**, 685.

5 M. Newcomb, R. M. Sanchez and J. Kaplan, *J. Am. Chem. Soc.*, 1987, **109**, 1195.

6 C. H. Schiesser and B. A. Smart, *Tetrahedron*, 1995, **51**, 6051; C. H. Schiesser, B. A. Smart and T.-A. Tran, *Tetrahedron*, 1995, **51**, 10651; C. H. Schiesser and B. A. Smart, *J. Comput. Chem.*, 1995, **16**, 1055; M. C. Fong and C. H. Schiesser, *Tetrahedron Lett.*, 1995, **36**, 7329; C. H. Schiesser and M. A. Skidmore, *Chem. Commun.*, 1996, 1419; M. A. Lucas and C. H. Schiesser, *J. Org. Chem.*, 1996, **61**, 5754; M. C. Fong and C. H. Schiesser, *J. Org. Chem.*, 1997, **62**, 3103; M. J. Laws and C. H. Schiesser, *Tetrahedron Lett.*, 1997, **38**, 8429; I. Ryu, T. Okuda, K. Nagahara, N. Kambe, M. Komatsu and N. Sonoda, *J. Org. Chem.*, 1997, **62**, 7550; M. A. Lucas and C. H. Schiesser, *J. Org. Chem.*, 1998, **63**, 3032; C. H. Schiesser and M. A. Skidmore, *J. Organomet. Chem.*, 1998, **552**, 145; C. H. Schiesser and L. M. Wild, *J. Org. Chem.*, 1999, **64**, 1131; L. Engman, M. J. Laws, J. Malmström, C. H. Schiesser and L. M. Zugaro, *J. Org. Chem.*, 1999, **64**, 6764; M. A. Lucas, O. T. K. Nguyen, C. H. Schiesser and S.-L. Zheng, *Tetrahedron*, 2000, **56**, 3995; S. Kim, S. M. Hovat and C. H. Schiesser, *Aust. J. Chem.*, 2002, **55**, 753; S. M. Hovat, S. Kim and C. H. Schiesser, *Chem. Commun.*, 2003, 1182; A. Studer, S. Amrein, H. Matsubara, C. H. Schiesser, T. Doi, T. Kawamura, T. Fukuyama and I. Ryu, *Chem. Commun.*, 2003, 1190.

7 C. H. Schiesser and L. M. Wild, *J. Org. Chem.*, 1998, **63**, 670.

8 C. H. Schiesser, B. A. Smart and T.-A. Tran, *Tetrahedron*, 1995, **51**, 3327.

9 C. H. Schiesser and L. M. Wild, *Aust. J. Chem.*, 1995, **48**, 175; C. H. Schiesser, M. L. Styles and L. M. Wild, *J. Chem. Soc., Perkin Trans. 2*, 1996, 2257; C. H. Schiesser and M. L. Styles, *J. Chem. Soc., Perkin Trans. 2*, 1997, 2335; S. M. Horvat and C. H. Schiesser, *J. Chem. Soc., Perkin Trans. 2*, 2001, 939; S. M. Horvat, C. H. Schiesser and L. M. Wild, *Organometallics*, 2000, **19**, 1239; H. Matsubara, S. M. Horvat and C. H. Schiesser, *Org. Biomol. Chem.*, 2003, **1**, 1190; H. Matsubara and C. H. Schiesser, *J. Org. Chem.*, 2003, **68**, 9299.

10 H. Matsubara and C. H. Schiesser, *Org. Biomol. Chem.*, 2003, **1**, 4335.

11 For computational studies on acyl radicals, see: M. Guerra, *Theor. Chem. Acc.*, 2000, **104**, 455; S. Yamago, H. Miyazoe, R. Goto, M. Hashidume, T. Sawazaki and J. Yoshida, *J. Am. Chem. Soc.*, 2001, **123**, 3697; H. Matsubara, I. Ryu and C. H. Schiesser, *J. Org. Chem.*, 2005, **70**, 3610; C. H. Schiesser, H. Matsubara, I. Ritsner and U. Wille, *Chem. Commun.*, 2006, 1067; H. Matsubara, C. T. Falzon, I. Ryu and C. H. Schiesser, *Org. Biomol. Chem.*, 2006, **4**, 1920; I. Ryu, Y. Uenoyama and H. Matsubara, *Bull. Chem. Soc. Jpn.*, 2006, **79**, 1476; C. H. Schiesser, U. Wille, H. Matsubara and I. Ryu, *Acc. Chem. Res.*, 2007, **40**, 303.

12 For a comprehensive review on acyl radicals, see: C. Chatgilialoglu, D. Crich, M. Komatsu and I. Ryu, *Chem. Rev.*, 1999, **99**, 1991.

13 T. Morihovitis, C. H. Schiesser and M. A. Skidmore, *J. Chem. Soc., Perkin Trans. 2*, 1999, 2041; C. T. Falzon, I. Ryu and C. H. Schiesser, *Chem. Commun.*, 2002, 2338.

14 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, V. G. Zakrzewski, J. A. Montgomery, Jr., R. E. Stratmann, J. C. Burant, S. Dapprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, A. G. Baboul, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. G. Johnson, W. Chen, M. W. Wong, J. L. Andres, M. Head-Gordon, E. S. Replogle and J. A. Pople, *GAUSSIAN 98 (Revision A.9)*, Gaussian, Inc., Pittsburgh, PA, 1998.

15 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery, Jr., T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. G. Johnson, W. Chen, M. W. Wong, C. Gonzalez and J. A. Pople, *GAUSSIAN 03 (Revision B.04)*, Gaussian, Inc., Wallingford, CT, 2004.

16 W. J. Hehre, L. Radom, P. v. R. Schleyer and P. A. Pople, *Ab Initio Molecular Orbital Theory*, Wiley, New York, 1986.

17 W. R. Wadt and P. J. Hay, *J. Chem. Phys.*, 1985, **82**, 284; P. J. Hay and W. R. Wadt, *J. Chem. Phys.*, 1985, **82**, 270; P. J. Hay and W. R. Wadt, *J. Chem. Phys.*, 1985, **82**, 299.

18 A. Höllwarth, M. Böhme, S. Dapprich, A. W. Ehlers, A. Gobbi, V. Jonas, K. F. Köhler, R. Stegmann, A. Veldkamp and G. Frenking, *Chem. Phys. Lett.*, 1993, **208**, 237.

19 T. H. Dunning and P. J. Hay, *Modern Theoretical Chemistry*, Plenum, New York, 1976, ch. 1, pp. 1–28.

20 We are aware of a very recent experimental and DFT study on the radical carbonylation mechanism (O. Itsenko, D. Norberg, T. Rasmussen, B. Langstrom and C. Chatgilialoglu, *J. Am. Chem. Soc.*, 2007, **129**, 9020), in which the energy barrier for the iodine transfer reaction from ethyl iodide to *n*-propanoyl radical and the reaction energy of the reaction were calculated to be 6.1 kcal mol^{-1} (34.7 kJ mol^{-1}) and 8.3 kcal mol^{-1} (17.6 kJ mol^{-1}) respectively at the CCSD(T)/6-311+G**/LanL2DZdp//MPKWCIS1K/6-31+G*/LanL2DZdp level of theory; these values are good agreement with the results from our study listed in Table 3.