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Reactivity of mixed organozinc and mixed organocopper reagents: 10 Comparison of the transferability of the same group in acylation of mixed and homo halozinc diorganocuprates with benzoyl chloride. A kinetic study

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ABSTRACT

A detailed kinetic study has been carried out for the acylation of iodozinc *n*-butyl (substituted phenyl) cuprates, *n*-Bu(FG-C_6H_4)CuZnI and iodozinc di*n*-butylcuprate, *n*-Bu_2CuZnI with benzoyl chloride in THF at 15–(−15)°C. Third order reaction was found which is first order in benzoyl chloride and second order in cuprate. We offered a reaction mechanism for the acylation of halozinc diorganocuprates depending on the kinetic data and activation parameters. Lower reaction rate of transferable group, *n*-Bu in mixed cuprate, n-Bu(PhCuZnI than that of homocuprate, *n*-Bu_2CuZnI and Hammett correlation of the reaction rate of transferable group, *n*-Bu in *n*-Bu(FG-C_6H_4)CuZnI reagents with the substituent constants of residual group, FG-C_6H_4 with a positive reaction constant (relative reactivity of FG: 4-Br > 3-MeO > H > 3-Me > 4-Me > 4-MeO) are in accordance with the proposed mechanism. These findings support our hypothesis that the reaction rate of transferable group, R_T changes depending on the residual group, R_R in mixed cuprates. R_RR_TCuM (M = Li, MgX, ZnX) and also provide a kinetic explanation for the commonly accepted hypothesis regarding the dependence of the R_T group transfer ability on the strength of the R_R–Cu bond in mixed cuprates, R_RR_TCuLi.

1. Introduction

Diorganocuprates R_2CuM (M = Li, MgX, ZnX; X = Br, Cl) are one of the most useful organometallic reagents [1,2,3]. Mixed cuprates, R_RR_TCuM (M = Li, MgX) composed of one transferable group R_T together with a residual (dummy) group R_R have been developed to solve the problem of using two organyl groups to transfer only one of them in homocuprates, R_2CuM. As residual groups R_R, both organyl groups, such as cyano [4], 2-thienyl [5,6], 1-alkynyl [6], trimethylsilylmethyl [7] and nonorganyl groups, such as RS [8], R_2N [9,10] and R_3P [9,10,11] have been frequently used. In the mixed cuprates of R^1R^2CuM type, one of the R^1 and R^2 groups has a higher transfer rate than the other.

Mixed lithium cuprates, both R_RR_TCuLi type [4,5,6,8,9,10,11,12,13] and R^1R^2CuLi type [5,7,14,15,16,17,18] have found application in organic synthesis. The successful use of mixed bromomagnesium cuprates, both R_RR_TCuMgBr type [19,20] and R^1R^2CuMgBr type [19,21,22] have been also reported.

Whitesides [5], House [14], Posner [15] and Lipshutz [16] investigated the group selectivity in the reactions of mixed lithium cuprates, R^1R^2CuLi in detail and found the group selectivity in the order of *n*-Bu ∼ s-Bu > *t*-Bu >> Ph > alkynyl and alkenyl > Me in their substitution reactions [5,14,15], but Me > alkenyl >> alkynyl in their 1,4-addition reactions [16].

The group selectivity in the reaction of mixed diorganocuprates, R^1R^2CuM in the reaction with an electrophile $E^{\oplus}$ arises in the process of reductive elimination of a Cu(III) intermediate R^1R^2CuM, which is formed in the oxidative addition (Scheme 1) [2,3,23].

The long accepted hypothesis in the group selectivity of R(X)CuLi reagents (X = alkynyl, CN, RS, R_2N, R_3P) in their substitution and 1,4-addition reactions has been that the group forming a stronger Cu–C bond acts as the group of lower selectivity or as a better residual group, R_R. However, theoretical studies of Nakamura on the allylic substitution [24] and 1,4-addition reactions [25] of R(X)CuLi reagents (X = *t*-Bu, alkynyl, CN, RS) indicated that the group of lower selectivity is determined by thermodynamic stability and kinetic reactivity of Cu(III) intermediates and the group which simultaneously binds to Cu and Li atoms acts as an effective residual group, R_R. Recently, Bertz observed peculiar properties of

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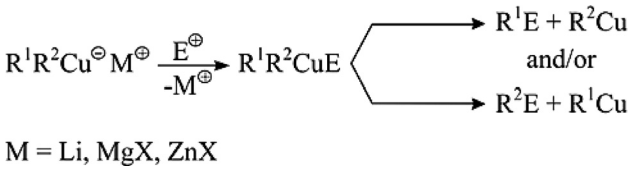


Scheme 1. Group selectivity in the reaction of mixed diorganocuprates with an electrophile.

R_R groups in π-complexes of R_RR_TCuLi reagents formed in their 1,4-addition reactions [26].

Our interest in the reactivity of mixed diorganocuprates, diorganozincs and triorganozincates prompted us to carry out systematic studies with the aim of (i) to find the dependence of the group selectivity on the reaction parameters, both continuous and discrete [27], (ii) to develop new atom-economic synthetic procedures by controlling the group selectivity, and (iii) to probe the origin of group selectivity. In our continuing studies on the reactions of mixed bromomagnesium cuprates, R^1R^2CuMgBr [28,29], diorganozincs, R^1R^2Zn [30,31,32,33,34] and Cu(I) catalyzed triorganozincates, $R^1R^2{}_2$ZnMgBr [35], we observed that the group selectivity depends on the reaction parameters, such as solvent [30] and temperature [35] and we developed new procedures for C-acyl [31], C-alkyl [33] C–N coupling [32] using mixed arylzinc reagents.

We also think that in the reactions of mixed diorganocuprates, R^1R^2CuM, not only group transfer ability, but also transfer rate of R^1 group to an electrophile, $E^{\oplus}$ should depend on the strength of R^2-Cu bond. So, we hypothesized that residual R^2 group can change the transfer rate of transferable R^1 group leading to different reaction rate of mixed cuprates, R^1R^2CuM from that of homocuprates, $R^1{}_2$CuM.

In other words, kinetics of mixed diorganocuprates would possibly provide another support for the commonly accepted hypothesis. For this purpose, we investigated the reaction of mixed diorganocuprates, *n*-Bu(FG-C_6H_4)CuMgBr and homocuprate, *n*-Bu_2CuMgBr with *n*-alkyl bromides in THF at 25 °C using competitive kinetics [28] and recently, direct kinetic study [29]. We found that in the second order reaction, the *n*-Bu group transfer rate to *n*-pentyl bromide in THF at 25 °C, is much lower in the mixed cuprate *n*-BuPhCuMgBr [36] than that in the homocuprates, *n*-Bu_2CuMgBr. In addition, *n*-Bu group transfer rate is well correlated with Hammett substituent constants of residual FG-C_6H_4 groups (FG = 3-Me, 4-Me, 3-MeO, 4-MeO, 4-Br) and we evaluated the unexpected positive sign of the Hammett reaction constant depending on the reaction mechanism.

However, in the reactions of catalytic mixed diorganocuprate *n*-BuPhCuMgBr derived *in situ* from CuI catalyzed reaction of mixed zincate, *n*-$BuPh_2$ZnMgBr with *n*-pentyl bromide in THF at 65 °C, Ph group is the transferable group [35] and its transfer rate to *n*-pentyl bromide is higher in the mixed catalytic cuprate, *n*-BuPhCuMgBr than that in the catalytic homocuprates Ph_2CuMgBr.

As seen group selectivity in the mixed *n*-BuPhCuMgBr reagents also depends on the organometallic reagent to be transmetallated, i.e. Grignard reagent or bromomagnesium zincate and/or temperature. Then we thought that it would be of interest to carry out similar kinetic studies using mixed halozinc diorganocuprates, R_RR_TCuZnCl with the aims of (i) determining the kinetic order and finding the difference between the reaction rate of transferable group R_T in mixed and homocuprates, R_RR_TCuZnCl and $(R_T)_2$CuZnCl, respectively, (ii) offering a reaction pathway and also (iii) evaluating the dependence of the reaction rate of transferable group, R_T on the residual group, R_R. Due to the unreactivity of halozinc cuprates toward *n*-alkyl electrophiles, we used acylation as model reaction. To the best of our knowledge, mechanistic studies on the reaction of Grignard, organolithium organocopper and organozinc reagents are very scarce in the literature. A study on acylation of Grignard reagents under CuCl catalysis using competitive kinetics was reported by Dubois et al. [37]. Recently, Nakamura, et al. reported an experimental and computational study on the mechanism of acyl electrophiles with lithium diorganocuprates [38].

In this work, we describe the kinetics of acylation of mixed and homo halozinc diorganocuprates, R_RR_TCuZnX and $(R_T)_2$ZnX, to obtain additional proof for our hypothesis regarding the dependence of the R_T group transfer rate on the R_R group.

2. Results and discussion

For acylation reactions of mixed halozinc diorganocuprates we used iodozinc *n*-BuPhCuZnI as a model halozinc mixed cuprate aiming a comparison with our previous results on the group selectivity of *n*-BuPhCu^{0} nucleophiles.

On our recent work [39], optimal conditions showed that the acylation of *n*-BuPhCuZnI **1ab** with benzoyl chloride **2** can take place at room temperature with an acylation yield of 78% and *n*-Bu group:Ph group transfer ration of 76:24–64:36 (Scheme 2).

2.1. Kinetics of the acylation of *n*-BuPhCuZnI and *n*-Bu_2CuZnI with benzoyl chloride

For the kinetic and mechanistic study of *n*-butyl selective acylation of mixed cuprate *n*-BuPhCuZnI **1ab** and acylation of homocuprate *n*-Bu_2CuZnI **1a₂** with benzoyl chloride **2** in THF, we focused on the determining of

(i) the reaction order and rate constant of acylation of mixed cuprate **1ab**
(ii) the reaction order and rate constant of acylation of homocuprate **1a₂** and
(iii) activation parameters for acylation of **1ab.**

In the evaluation of the rate data, we used the method that we already developed and successfully used for the evaluation of the rate data in the alkylation of stoichiometric mixed cuprates, R^1R^2CuMgBr [29], catalytic mixed cuprates derived from mixed zincates, $R^1(R^2)_2$ZnMgBr [35] and also in the allylation of mixed diorganozincs, R^1R^2Zn [34].

In the coupling with homocuprate **1a₂**, benzoyl chloride **2** gives only **3a** as product whereas **3a** and **3b** are formed in the case of coupling with mixed cuprate **1ab**. While applying this method, we used calculated value for c = [benzoyl chloride]$_t$, i.e. the concentration of benzoyl chloride **2** at time *t* rather than directly measured value due to the hydrolysis of **2** during the work-up of aliquots. *c* can be calculated as

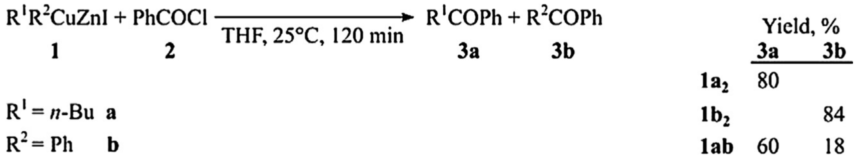
$$c = [\text{Benzoyl chloride}]_0 - [n - \text{BuCOPh}]_t \tag{1a}$$

for the acylation of **1a₂** (Method A) and

$$c = [\text{Benzoyl chloride}]_0 - [n - \text{BuCOPh}]_t + [\text{PhCOPh}]_t)\mathbf{1b} \tag{1b}$$

for the acylation of **1ab** (Method B). The disappearance of the benzoyl chloride **2** and the formation of the products **3a** and **3b** were monitored relative to an internal standard using gas chromatographic analysis of quenched aliquots.

The preparation method for halozinc diorganocuprates seemed important to collect the reproducible kinetic data. So, for the

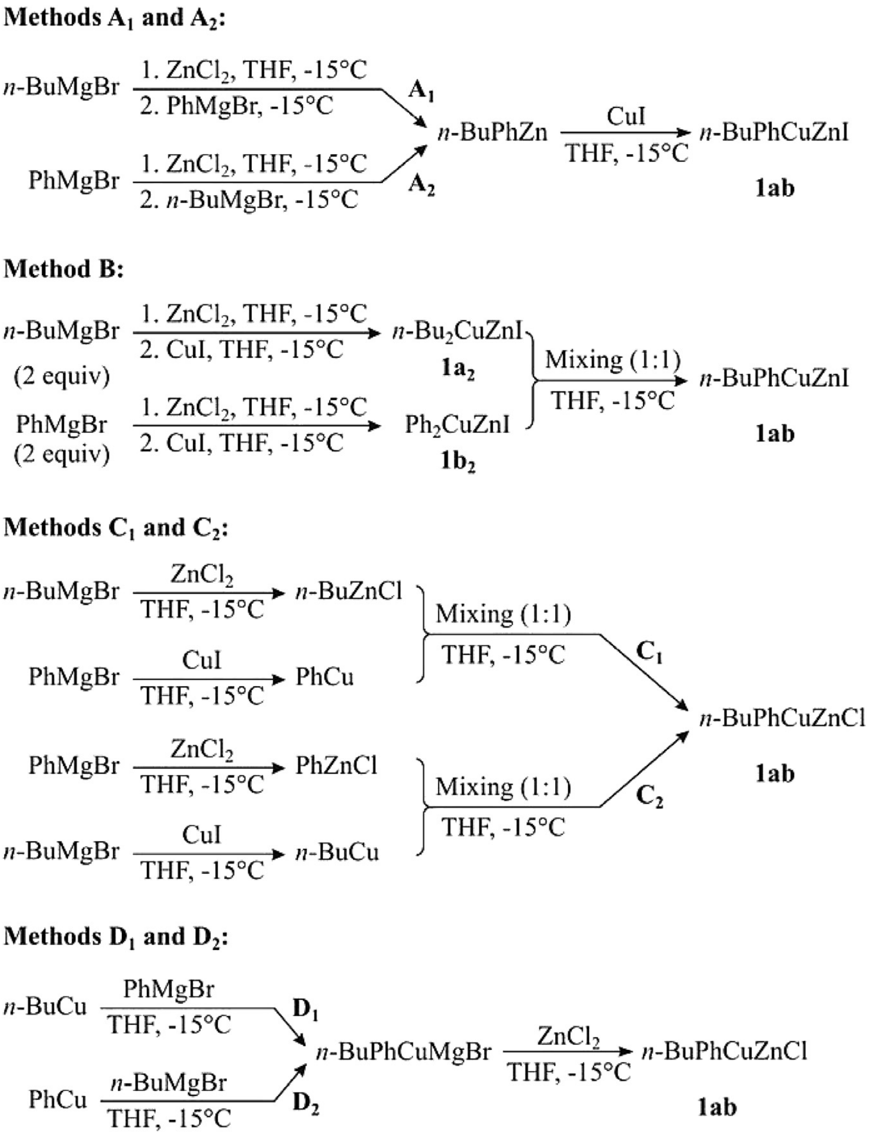


Scheme 2. Acylation reactions of mixed cuprate *n*-BuPhCuZnI **1ab** with benzoyl chloride **2**.

preparation of halozinc *n*-butyl phenyl cuprate, *n*-BuPhCuZnX **1ab** (X = I, Cl) we used four different methods A, B, C and D starting from Grignard reagents. As outlined in Scheme 3, we carried out first Mg → Zn transmetallation [30,40,41] and then Zn → Cu transmetallation in Methods A–C. We carried out Mg → Zn transmetallation of bromomagnesium *n*-butylphenylcuprate *n*-BuPhCuMgBr in Method D.

In the *in situ* Methods A_1 and A_2, *n*-BuZnCl prepared by transmetallation of *n*-BuMgBr was allowed to react with PhMgBr and then with CuI (Method A_1) or similarly, PhZnCl prepared by transmetallation of *n*-BuMgBr was allowed to react with *n*-BuMgBr and then with CuI (Method A_2). Mg → Zn transmetallation gives *n*-BuPhZn and Zn → Cu transmetallation gives *n*-BuPhCuZnI. Mixing equimolar amounts of homocuprates *n*-Bu_2CuZnI **1a₂** and Ph_2CuZnI **1b₂** also leads to formation of *n*-BuPhCuZnI (Method B). In Methods C_1 and C_2, we mixed equimolar amounts of *n*-BuZnCl and PhCu or PhZnCl and *n*-BuCu, respectively to give *n*-BuPhCuZnCl.

For evaluating the effect of preparation method of *n*-BuPhCuZnI **1ab** on the group selectivity in its coupling with benzoyl chloride, total acylation yield and **3a**:**3b** product ratios were found in a reaction carried out with equimolar amounts of coupling partners in THF at 25 °C in 2 h.



Scheme 3. Preparation methods for mixed halozinc diorganocuprates, *n*-BuPhCuZnX (X = I, Cl) **1ab**.

First, we tested Method A_1 and Method A_2 to see if the organyl group originally bonded to Zn could make a change in the total yield and in the relative transfer ability of *n*-Bu or Ph groups. As expected, Methods A_1 and A_2 gave almost equal total yields (71–78%) and **3a**:**3b** product ratios (58:42–76:24) and the original bonding of *n*-Bu or Ph group to Zn was found not to be important. We tried Method B to see if the organyl group transfer ability would be affected by the possible equilibrium between homocuprates *n*-Bu_2CuZnI **1a₂** and Ph_2CuZnI **1b₂** to form mixed cuprate *n*-BuPhCuZnI **1ab** the total yield of 76% and **3a**:**3b** product ratio of 56:44 showed that Methods A_1 and A_2 and Method B give possibly the same reagents. Methods C_1 and C_2 also resulted in similar total yields (76–84%) and not much different **3a**:**3b** product ratios (59:41–69:31). The use of Methods D_1 and D_2 gave erratic values in the products yields. Comparison of the yields and **3a**:**3b** product yields obtained in Methods A and Methods C reveals that either *in situ* transmetallation of R^1R^2Zn reagents with CuI (Method A) or transmetallation of R^1ZnX reagent with prepared R^2Cu reagent (Method C) lead to the same mixed diorganozinc cuprate R^1R^2CuZnX. However, we found one pot successive Mg → Zn and Zn → Cu transmetallation reactions (Methods A_1 and A_2) more practical for the preparation of halozinc mixed diorganocuprates and in addition, we wanted to avoid the equilibrium on the formation of the mixed diorganocuprate (Method B). So, we prepared the mixed cuprate **1ab** according to Method A_2 for kinetic experiments.

For the acylation of mixed cuprate **1ab** and homocuprate **1a₂**, we collected the rate data under pseudo-first order conditions, i.e. in the presence of excess and varied concentration of diorganocuprate **1ab** or **1a₂** reagent to find the reaction order in benzoyl chloride **2** and in diorganocuprate **1ab** or **1a₂**. The initial concentration of benzoyl chloride **2** was kept constant and concentration of mixed cuprate **1ab** or homocuprate **1a₂** was changed between 6 and 12 times than that of **2**. We obtained pseudo-first order plots which are linear up to 70–90% completion of the reaction for both mixed cuprate **1ab** and homocuprate **1a₂**.

Pseudo-first order rate constants, k' were calculated by linear regression analysis ($r^2 \geq 0.980$).

(i) In the first set of experiments, we found the pseudo-first order rate constant, k' of mixed cuprate **1ab** and we chose acylation at 0 °C in a model kinetic run. As an example, a pseudo-first order plot is given in Fig. 1. Pseudo-first order rate constants, k' in the presence of excess concentration of mixed cuprate **1ab** are listed in Table 1. The plot of log k' values versus log [mixed cuprate] gave a slope of 1.997 ($r^2 = 0.973$) (Fig. 2) confirming the second order reaction in mixed cuprate **1ab.**

Table 1
Effect of *n*-butylphenylcuprate **1ab** concentration on the pseudo-first order rate constants, k' of benzoylation of **1ab** with benzoyl chloride **2** in THF at 0 °C and third order rate constants, *k*.

$$\underset{\textbf{1ab}}{n\text{-BuPhCuZnI}} + \underset{\textbf{2}}{\text{PhCOCl}} \xrightarrow[\text{THF, 0°C}]{} n\text{-BuCOPh} + \text{PhCOPh}$$

[*n*-BuPhCuZnI], (M)	k', min^{-1} [a]	*k*, M^{-2} min^{-1} [b]
0.095	0.027	3.0
0.110	0.035	2.9
0.126	0.042	2.6
0.142	0.057	2.8
0.158	0.064	2.6
0.173	0.087	2.9
0.189	0.111	3.1

[a] [PhCOCl] = 0.0158 M.
[b] $k = k'/[n\text{-BuPhCuZnI}]^2$.

Thus, the total rate law for the benzoylation of mixed cuprate **1ab** in THF can be written as:

$$\text{Rate} = -\frac{d[\text{PhCOCl}]}{dt} = k[n-\text{BuPhCuZnCl}]^2[\text{PhCOCl}] = k'[\text{PhCOCl}] \qquad (2)$$

The third order rate constants were calculated as $k = k'/[n\text{-Bu(PhCuZnI]}^2$ for acylation of mixed cuprate **1ab** and taking the average led to rate constant of $k = 2.9 \pm 0.1$ M^{-2} min^{-1} in THF at 0 °C with the uncertainty of max. 7% which is in the error limit of GC analysis (Table 1).

(ii) In the second set of experiments, we found the pseudo-first rate constants, k' of homocuprate **1a₂** in a similar way used in the pseudo-first order rate experiments of mixed cuprate **1ab.** Due to the instantaneous reaction at 0 °C, we could collect the rate data only for the reaction at −15 °C.

As an example, a pseudo-first order plot is given in Fig. 3. Then, we determined the pseudo-first order rate constants, k' in the presence of excess concentration of homocuprate **1a₂** (Table 2).

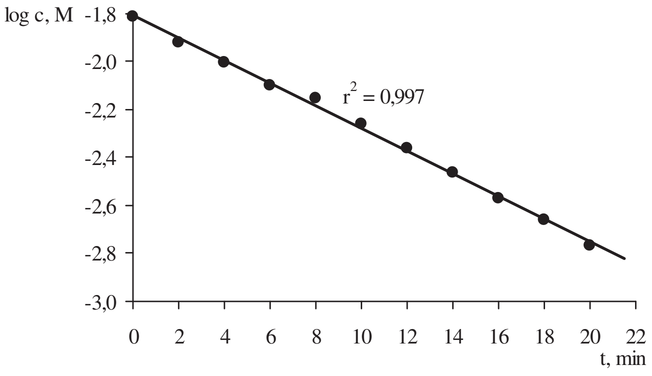


Fig. 1. Typical first-order plot for the reaction of *n*-butylphenylcuprate **1ab** with benzoyl chloride **2** in THF at 0 °C; $[n\text{-Butylphenylcuprate}]_0 = 0.189$ M, $[\text{PhCOCl}]_0 = 0.0158$ M, $c = [\text{PhCOCl}]_0 - ([n\text{-BuCOPh}]_t + [\text{PhCDPh}]_t)$.

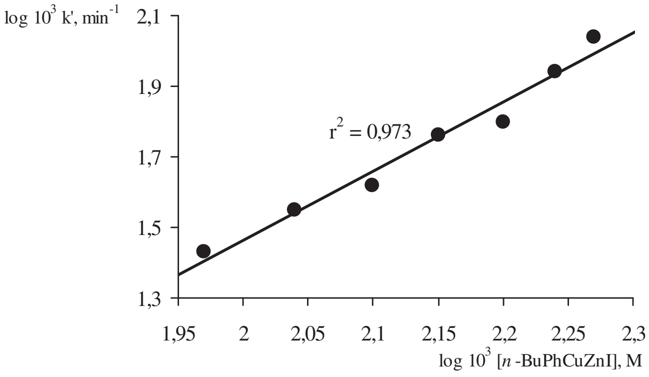


Fig. 2. Effect of *n*-butylphenylcuprate **1ab** concentration on the pseudo-first order rate constant k' for the reaction of **1ab** with benzoyl chloride **2** in THF at 0 °C. Data are from Table 1.

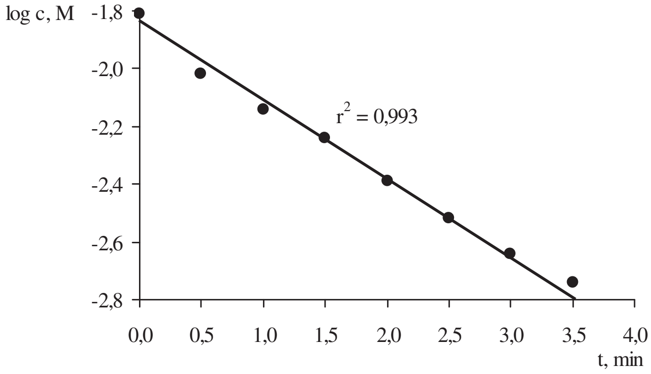


Fig. 3. Typical first-order plot for the reaction of di-*n*-butylcuprate $\mathbf{1a_2}$ with benzoyl chloride **2** in THF at −15 °C; $[\text{di-}n\text{-Butylcuprate}]_0 = 0.142$ M, $[\mathrm{PhCOCl}]_0 = 0.0158$ M, $c = [\mathrm{PhCOCl}]_0 - [n\text{-BuCOPh}]_t$.

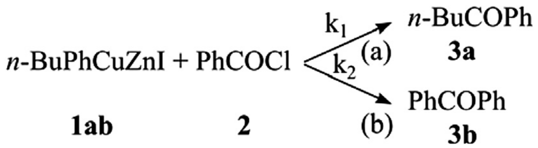
Plotting of log k' values versus log [homocuprate] gave a slope of 1.940 ($r^2 = 0.980$) confirming again the second order reaction in the homocuprate (Fig. 4). The total rate law for the acylation of homocuprate $\mathbf{1a_2}$ is also expressed using Eq. (3).

$$\begin{aligned}\text{Rate} &= -\frac{\mathrm{d[PhCOCl]}}{\mathrm{dt}} = \mathrm{k}[n-\mathrm{Bu_2CuZnCl}]^2[\mathrm{PhCOCl}] \\ &= \mathrm{k'[PhCOCl]}\end{aligned} \tag{3}$$

The third order rate constants for acylation of homocuprate $\mathbf{1a_2}$ were calculated as above for the acylation of mixed cuprate **1ab** and taking the average led to rate constant of $k = 33.7 \pm 2.1$ $\mathrm{M^{-2}\ min^{-1}}$ in THF at −15 °C (Table 2).

The first order reaction for acyl halide in the acylation reactions of homocuprate $\mathbf{1a_2}$ and mixed cuprate **1ab** is an expected result. However, the second order reaction for the cuprate seemed surprising.

The problem in the acylation kinetics of mixed *n*-BuPhCuZnI **1ab** seemed that the coupling yield of residual group, i.e. Ph group, is not low enough to be ignored and more important, it does not remain constant, i.e. increases during a kinetic run. Then we thought that evaluating the acylation reaction of mixed cuprate *n*-BuPhCuZnI **1ab** as two parallel reactions, i.e. acylation of *n*-Bu group and acylation of Ph group rather than selective acylation of *n*-Bu group would be better Eq. (4).



(4)

As we could determine the concentrations of the products of both reactions, it seemed possible to separate values of reaction rate constants k_1 and i_2 for the benzoylation of *n*-Bu and Ph groups, respectively. In this evaluation, we used the valid relationships to measure the time dependence of concentration of **3a** and **3b** [42]. Under the pseudo-first order rate conditions, i.e. in the excess of mixed cuprate these equations can be written as follows to find the k'_1 and k'_2 constants:

$$[n-\mathrm{BuCOPh}]_t = [n-\mathrm{BuCOPh}]_0 + \frac{k'_1[\mathrm{PhCOCl}]_0}{k'}\left(1 - e^{-k't}\right) \tag{4a}$$

Table 2
Effect of din-butylcuprate $\mathbf{1a_2}$ concentration on the pseudo-first order rate constants, k' of benzoylation of $\mathbf{1a_2}$ with benzoyl chloride **2** in THF at −15 °C and third order rate constants, *k*.

$$\underset{\mathbf{1a_2}}{n\text{-Bu}_2\text{CuZnI}} + \underset{\mathbf{2}}{\text{PhCOCl}} \xrightarrow[\text{THF, -15°C}]{} n\text{-BuCOPh}$$

$[n\text{-Bu}_2\text{CuZnI}]$, (M)	k', min^{-1}[a]	k, $\mathrm{M^{-2}\ min^{-1}}$[b]
0.095	0.29	32.1
0.110	0.39	32.2
0.126	0.59	37.1
0.142	0.65	32.2
0.158	0.90	36.1
0.173	0.96	32.1

[a] [PhCOCl] = 0.0158 M.
[b] $k = k'/[n\text{-Bu}_2\text{CuZnI}]^2$.

$$[\mathrm{PhCOPh}]_t = [\mathrm{PhCOPh}]_0 + \frac{k'_2[\mathrm{PhCOCl}]_0}{k'}\left(1 - e^{-k't}\right) \tag{4b}$$

For the model pseudo-first order reaction given above (Fig. 1), we plotted $[n\text{-BuCOPh}]_t$ versus $(1 - e^{-k't})$ and also $[\mathrm{PhCOPh}]_t$ versus $(1 - e^{-k't})$ (Fig. 5). As $[\mathrm{PhCOCl}]_0 = 0.0158$ M and pseudo-first order total rate constant, $k' = 0.111\ \mathrm{min}^{-1}$ are known, separate pseudo-first order rate constants k'_1 and k'_2 rate constants, can be calculated. We determined that $k'_1 = 0.091\ \mathrm{min}^{-1}$ and $k'_2 = 0.020\ \mathrm{min}^{-1}$ and the sum of the separate rate constants, $k' = \mathrm{k'}_1 + k'_2 = 0.111\ \mathrm{min}^{-1}$ were found not to be different from the total pseudo-first order rate constant.

To see the dependence of separate pseudo-first order rate constants, k'₁ and k'₂ on the excess concentration of mixed cuprate, we first determined these values for all total k' values listed in Table 1. However, as the initial concentration of products equals zero, i.e. $[n\text{-BuCOPh}]_0 = 0$ and $[\mathrm{PhCOPh}]_0 = 0$, we also used another possibility for determining k'_1 and k'_2 values [42] and we found the ratio of $[n\text{-BuCOPh}]_t/[\mathrm{PhCOPh}]_t$ after a chosen time interval:

$$[n-\mathrm{BuCOPh}]_t/[\mathrm{PhCOPh}]_t = k'_1/k'_2 \tag{5}$$

Finding this ratio in at least seven cases, taking the average of similar values and using the total rate constant, k', we listed the calculated separate k'_1 and k'_2 values in Table 3.

It was pleasant that plotting of log k'_1 values and log k'_2 values versus log [*n*-BuPhCuZnI] gave again slopes of 2.3 ($r^2 = 0.868$) and 1.71 ($r^2 = 0.983$), respectively and confirmed the second order

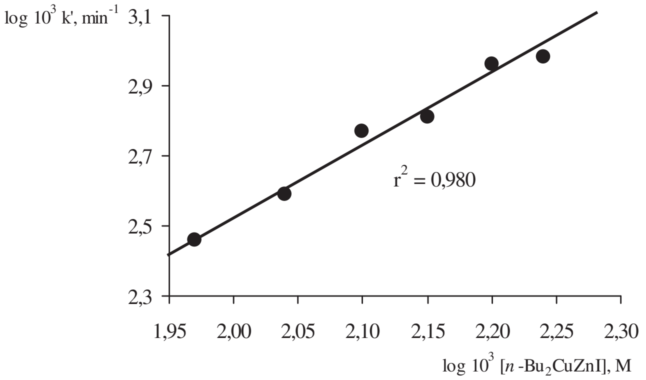


Fig. 4. Effect of di-*n*-butylcuprate $\mathbf{1a_2}$ concentration on the pseudo-first order rate constant k' for the reaction of $\mathbf{1a_2}$ with benzoyl chloride **2** in THF at −15 °C. Data are from Table 2.

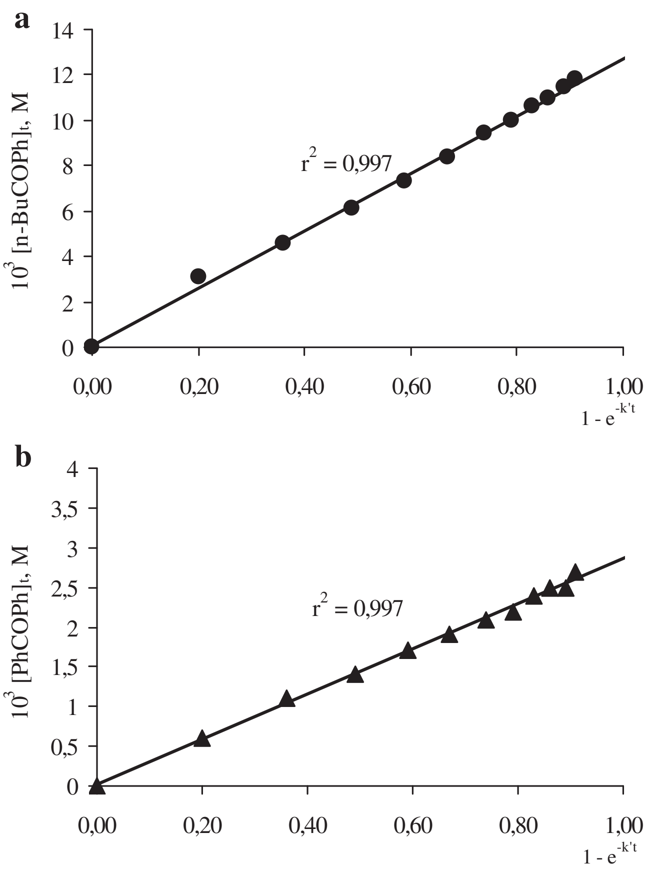


Fig. 5. Plots of [n-BuCOPh]$_t$ (●) and [PhCOPh] (▲) versus $1 - e^{-k't}$ in the reaction of n-butylphenylcuprate **1ab** with benzoyl chloride **2** in THF at 0 °C; [n-Butylphenylcuprate] = 0.189 M, [PhCOCl] = 0.0158 M, $k' = 0.111$ min^{-1}.

reaction both in the n-Bu group transfer and Ph group transfer of n-BuPhCuZnI reagent in acylation with benzoyl chloride (Fig. 6).

In evaluating the rate data, we can consider either total rate constants, k which depend on benzoyl chloride **2** disappearance rate or separate rate constants k_1 and k_2, which depend on product formation rate for n-BuCOPh **3a** and PhCOPh **3b**, respectively. However, we could simply note that there is little difference between the k_1/k ratios for the transfer of n-Bu group acylation of n-BuPhCuZnI, i.e. $k_1/k = 0.79–0.80$. So, due to a lower error, we preferred to use the total rate constants, k for the comparison of the transfer rate of n-Bu group in the mixed cuprate, n-BuPhCuZnCl **1ab** and homocuprate, n-Bu$_2$CuZnCl **1a$_2$**. In THF, at −15 °C, we determined that the reaction rates of mixed cuprate **1ab** and homocuprate **1a$_2$** are 1.8 M^{-2} min^{-1} and 33.7 M^{-2} min^{-1}, respectively. As seen, acylation rate of mixed cuprate, n-BuPhCuZnCl is much lower than that of homocuprate, n-Bu$_2$CuZnCl being similar to the lower alkylation rate of n-BuPhCuMgBr than that of n-Bu$_2$CuMgBr (in THF, 0.77 M^{-1} min^{-1} for mixed cuprate at 25 °C, 0.83 M^{-1} min^{-1} for homocuprate at 0 °C) [36].

Table 3
Pseudo-first order rate constants, k'_1 and k'_2 of n-Bu group and Ph group transfer rate in the acylation of n-BuPhCuZnCl **1ab** with benzoyl chloride **2a** in THF at 0 °C in the presence of excess **1ab**.

[n-BuPhCuZnI], (M)	k'_1, min^{-1}[a]	k'_2, min^{-1}[a]	k_1, M^{-2} min^{-1}[b]	k_2, M^{-2} min^{-1}[c]
0.095	0.021	0.006	2.22	0.77
0.110	0.025	0.008	2.07	0.70
0.126	0.036	0.009	2.28	0.60
0.142	0.045	0.012	2.23	0.60
0.158	0.049	0.015	1.96	0.60
0.173	0.070	0.017	2.34	0.57
0.189	0.091	0.020	2.55	0.56

[a] [PhCOCl] = 0.0158 M.
[b] $k_1 = k'_1/[n\text{-BuPhCuZnI}]^2$.
[c] $k_2 = k'_2/[n\text{-BuPhCuZnI}]^2$.

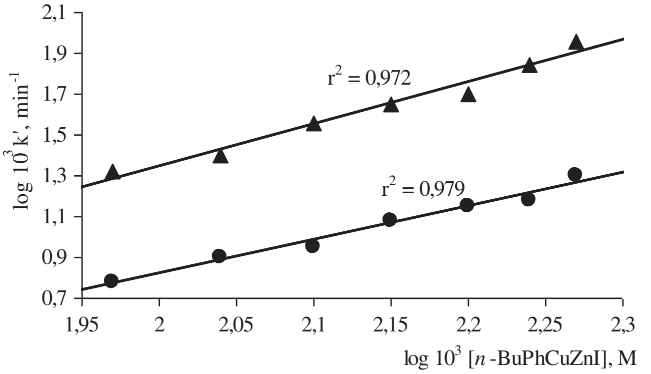


Fig. 6. Effect of n-butylphenylzinc cuprate **1ab** concentration on the pseudo-first order rate constants k'_1 (●) and k'_2 (▲) for the product formation n-BuCOPh **3a** and PhCOPh **3b**, respectively in the reaction of **1ab** with benzoyl chloride in THF at 0 °C.

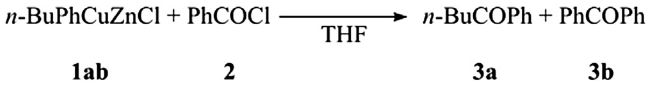
(iii) To calculate the activation parameters, the acylation reaction of mixed cuprate **1ab** was studied at 15–(−15)°C temperatures. The third order rate constants are given in Table 4. Eyring plot of ln (k/T) versus $1/T$ was found linear ($r^2 = 0.942$) and activation parameters, $\Delta H^{\neq} = 38.7 \pm 8.4$ kJ mol^{-1} and $\Delta S^{\neq} = -93.3 \pm 16.0$ Jmol^{-1} K^{-1} were determined.

Low value of $\Delta H^{\neq}$ and relatively low negative value of $\Delta S^{\neq}$ is consistent with an associative process involving the development of charge separation in the transition state. As the activation entropy is relatively small, the reaction rate is mainly controlled by enthalpy factor. This result, together with the significant exothermic character of the reaction might possibly point to a transition state occurring rather early in the reaction profile.

2.2. Reaction pathway for the acylation reaction of halozinc diorganocuprates in THF

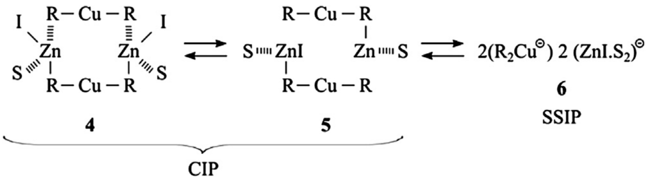
In order to propose a reaction pathway for the reaction of halozinc diorganocuprates with acyl halides which appears to be consistent with the kinetic data, we assumed a contact ion pair such as a homodimer **4** or a heteroaggregate **5** (CIP) in equilibrium with solvent-separated ion pair (SSIP) **6** for their structure similar to lithium homo and mixed diorganocuprates

Table 4
Temperature dependence of the third order rate constants for the acylation of mixed cuprate, n-BuPhCuZnI **1ab** with benzoyl chloride **2** in THF.



$$\underset{\mathbf{1ab}}{n\text{-BuPhCuZnCl}} + \underset{\mathbf{2}}{\text{PhCOCl}} \xrightarrow[\text{THF}]{} \underset{\mathbf{3a}}{n\text{-BuCOPh}} + \underset{\mathbf{3b}}{\text{PhCOPh}}$$

T, K	288	283	278	273	268	258
k, M^{-2} min^{-1}	7.4	6.7	3.5	2.9	2.3	1.8



Scheme 4. Plausible equilibria for CIP and SSIP structures for halozinc diorganocuprates in solution.

[2,3,23,43–47] and Grignard reagent derived homocuprates [23,45,47] (Scheme 4).

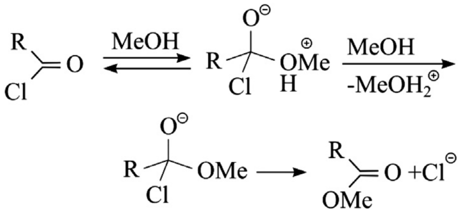
It is known that it is essentially only CIP structures of a cuprate which undergoes the reaction and the reactions proceed with a small equilibrium concentration of CIP in solution and SSIP is the much less or even unreactive species [3,23,44,48–54].

Nakamura et al. recently suggested a mechanism for the reaction of lithium organocuprates with acyl halides depending on theoretical calculations and experimental studies [38]. First, the diorganocuprate dimer forms a complex A through the Li–O interaction and charge transfer from the diorganocuprate dimer to the C═O bond leads to the formation of a π-complex **B**. Rearrangement of the complex gives a more stable oxidative addition transition state **C**. Li assisted C–Cl bond cleavage and C–C bond formation occur simultaneously in the reductive elimination step to give the ketone (Scheme 5).

For the reactions of acyl chlorides with Grignard reagent derived catalytic organocuprates, six-centered transition state in which chloride is displaced without addition to the carbonyl group by catalytic cuprate RCu(Cl)MgX (X = Br, Cl) was already offered [37] (Scheme 6).

Six-centered transition states [55–57] and formation of ketone-dimeric Grignard reagent complexes [58] have been also reported for the mechanism of Grignard reagent addition to ketones.

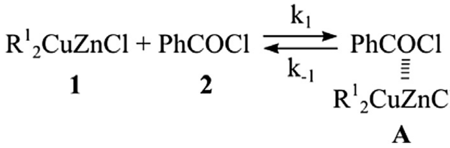
In fact, the literature on the acylation reactions of alcohols [59,60] and amines [61] in aprotic solvents also show a third order kinetic term. In the alcoholysis Eq. (6), methanol first gives a tetrahedral intermediate (nucleophilic catalysis), this intermediate reverts to reactants or it is deprotonated with a second molecule of methanol to give a new tetrahedral intermediate which collapses to product [59,60].



(6)

For the acylation of diorganocuprates with acyl halides we propose the pathway given in Scheme 7, which is similar to the mechanism reported by Nakamura et al. (Scheme 5) [38]. We think that, first, the diorganocuprate can form similarly a complex through the Zn–O interaction and complexation between Cu atom and C═O bond gives the oxidative addition transition state **D**. Zn–O complexation is expected to affect the simultaneous formation of C═O bond and C–Cl bond cleavage. In the R-acyl coupling reaction of $R^1R^2CuZnCl$ reagent, both R^1 and R^2 groups are expected to react in the same pathway. The discussion that follows is expected to relate the kinetic data in our work to the acylation reaction of homo or mixed diorganocuprates.

A pathway for the formation of the acylation product by reacting two molecules of zinc cuprate with one molecule of acyl halide could involve first formation of acyl halide – zinc cuprate complex **A** by Zn–O interaction Eq. (7a) and then reaction of **A** with acyl halide Eq. (7b).

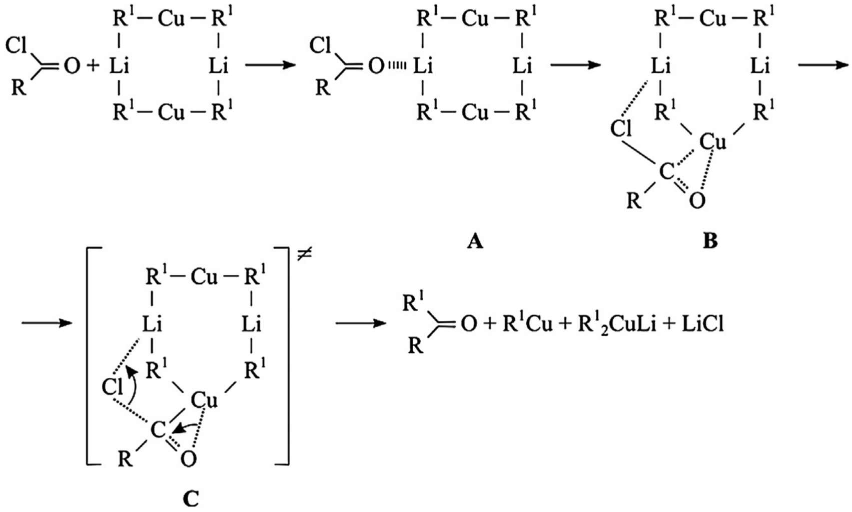


$$\underset{\mathbf{1}}{R^1{}_2CuZnCl} + \underset{\mathbf{2}}{PhCOCl} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \underset{\mathbf{A}}{\overset{PhCOCl}{\underset{R^1{}_2CuZnCl}{\vdots}}} \quad (7a)$$

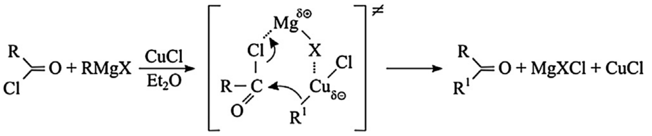
$$A + \underset{\mathbf{1}}{R^1{}_2CuZnCl} \xrightarrow{k_2} \underset{\mathbf{3}}{PhCOR^1} + R^1Cu + ZnCl_2 \quad (7b)$$

We think that steady-state kinetics provide a straightforward explanation for the rate laws expressed by Eqs. (1) and (2).

We assume that the concentration of halide-cuprate complex **A** does not change with time as an intermediate since it is used up as



Scheme 5. Mechanism for the acylation of lithium diorganocuprates with acyl halides.



Scheme 6. Six-centered mechanism for acylation of catalytic organocuprate reagents *in situ* derived from RMgX and CuCl.

fast as is formed, giving either cuprate **1** and PhCOCl **2** in step a or ketone **3** in step b.

$$O = \frac{d[A]}{dt} = k_1[\text{cuprate}][\text{PhCOCl}] - k_{-1}[A] - k_2[A][\text{cuprate}] \quad (8)$$

The value for [**A**] is inserted into the original rate expression depending on the benzoyl halide disappearance and

$$\text{Rate} = -\frac{d[\text{PhCOCl}]}{dt} = k_2[\mathbf{A}][\text{cuprate}] = \frac{k_1k_2[\text{cuprate}]^2[\text{PhCOCl}]}{k_{-1}+k_2[\text{cuprate}]} \quad (9)$$

is obtained.

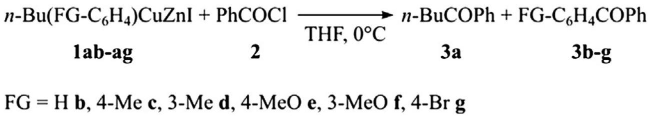
If we consider the first step as a rapid attainment of equilibrium followed by rate determining acylation step, we can write

$$\text{Rate} = \frac{k_1k_2}{k_{-1}}[\text{cuprate}]^2[\text{PhCOCl}] \quad (10)$$

as the rate expression which shows the first order reaction in acyl halide **2** and second order reaction in cuprate **1**.

2.3. Dependence of the *n*-Bu transfer rate on the FG-C_6H_4 group in the acylation reaction of *n*-Bu(FG-C_6H_4)CuZnI with benzoyl chloride

In order to evaluate the dependence of the reaction rate of transferable *n*-Bu group on the residual group we screened a series of FG-C_6H_4 (FG = 4-Me **c**, 3-Me **d**, 4-MeO **e**, 3-MeO **f**, 4-Br **g**) groups as residual groups (Scheme 8). We determined the reaction rate of all mixed halozinc cuprates *n*-Bu(FG-C_6H_4)CuZnI in THF at 0 °C. The third order reaction rates, *k* were determined depending on benzoyl halide **2** disappearance under pseudo-first order conditions and they were listed in Table 5.



$$\underset{\mathbf{1ab\text{-}ag}}{n\text{-Bu(FG-}C_6H_4\text{)CuZnI}} + \underset{\mathbf{2}}{\text{PhCOCl}} \xrightarrow[\text{THF, 0°C}]{} \underset{\mathbf{3a}}{n\text{-BuCOPh}} + \underset{\mathbf{3b\text{-}g}}{\text{FG-}C_6H_4\text{COPh}}$$

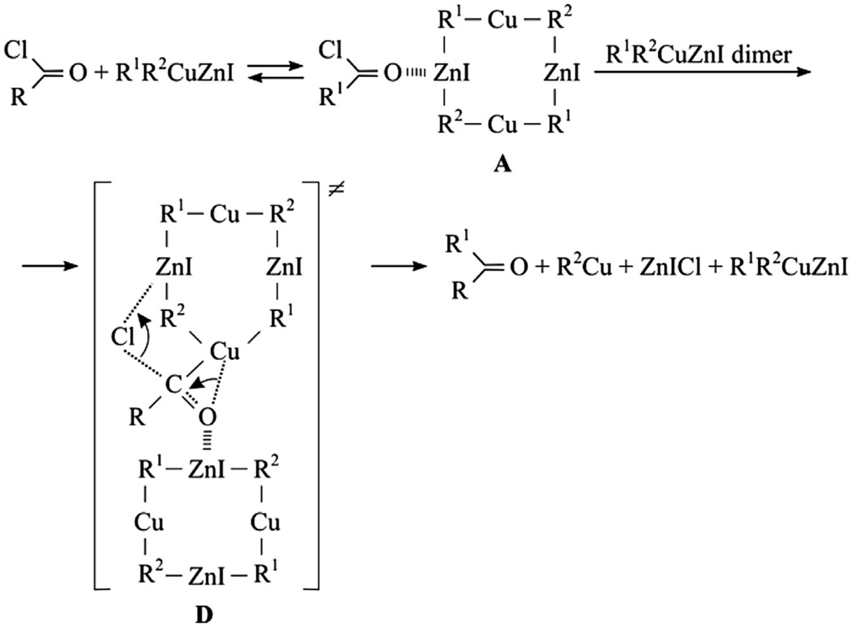
FG = H **b**, 4-Me **c**, 3-Me **d**, 4-MeO **e**, 3-MeO **f**, 4-Br **g**

Scheme 8. Acylation reactions of mixed halozinc cuprates *n*-Bu(FG-C_6H_4)CuZnI **1ab**–**ag** with benzoyl chloride **2**.

In the alkylation of *n*-Bu selective *n*-BuPhCuMgBr with *n*-pentyl bromide in THF at 25 °C, we already correlated [29] *n*-Bu group transfer rate to electronic affects of substituents on the FG-C_6H_4 group using Hammett σ values [62–65]. We evaluated the positive reaction constant as a quite important support for our hypothesis that the residual group R_R affects the reaction rate of transferable group, R_T in mixed cuprates, R_RR_TCuM (M = Li, MgX, ZnX).

Expecting a similar substituent effect of residual FG-C_6H_4 group on the acylation rate of *n*-Bu group, we plotted the rate constants of *n*-Bu(FG-C_6H_4)CuZnI **1ab**–**ag** in THF at 0 °C against Hammett σ values (Fig. 7). It is clear that there is a good linear correlation with a positive reaction constant $\rho = 1.95$ ($r^2 = 0.946$). The deviations for 3-MeO may be attributed to the inadequacy of applying the standard σ constants of the H-bond accepting substituents for the reactions carried in a polar aprotic solvents and these deviations related to the reactions of Grignard reagents and cuprates were already reported [66–69]. The finding of correlation between the reaction rate of transferable *n*-Bu group and electronic effects of substituents on the residual seemed us another important support for our hypothesis.

For the interpretation of the result of Hammett study, we checked the consistency of the correlation with our proposed mechanism for acylation reaction of halozinc cuprates (Scheme 6). We concentrated on the effect of the strength of FG-C_6H_4–Cu bond for the formation of transition state **D** in the reaction of benzoyl chloride – cuprate complex **A** with cuprate,



Scheme 7. Reaction pathway for the acylation of halozinc diorganocuprates, $R^1 = R^2$ or $R^1 \neq R^2$.

Table 5
Rate constants of acylation of iodozinc *n*-butyl (substituted phenyl) cuprates **1ab**–**ag** with benzoyl chloride **2** in THF at 0 °C.

$$\underset{\textbf{1ab-ag}}{n\text{-Bu(FG-C}_6\text{H}_4\text{)CuZnI}} + \underset{\textbf{2}}{\text{PhCOCl}} \xrightarrow[\text{THF, 0°C}]{} \underset{\textbf{3a}}{n\text{-BuCOPh}} + \underset{\textbf{3b-g}}{\text{FG-C}_6\text{H}_4\text{COPh}}$$

FG	*H*, **b**	4-Me, **c**	3-Me, **d**	4-MeO, **e**	3-MeO, **f**	4-Br, **g**
k, M^{-2} min^{-1}	2.9	1.1	2.0	0.8	1.8	4.6

which is rate determining step. An electrostatic interaction between R^2 = FG-C_6H_4 group and Zn atom might cause a stronger coordination and increase the stability of the transition state. Inductive and resonance effects of FG groups are expected to affect this interaction leading to a lower activation energy and easier transfer of R^1 = *n*-Bu group to carbonyl group. However, the electronic charge of R^2 = FG-C_6H_4 group is expected to increase not only the strength of R^2—Zn bond, but also the strength of R^2—Cu bond due to similar electronegativities of Zn and Cu. If this is true, simultaneous formation of C═O bond and C—Cl bond cleavage in the transition state will be easier resulting in a higher coupling rate of R^1 = *n*-Bu group with C═O group. This result allows us to conclude that our proposed reaction mechanism for the acylation of halozinc diorganocuprates, R_2CuZnI is also supported by the Hammett study of reaction rates of transferable alkyl groups to correlate with the substituent effect of residual substituted phenyl groups, *n*-Bu(FG-C_6H_4)CuZnI. Of course, a detailed mechanism which explains both the acylation of cuprates and the dependence of transferable group rate on the residual group are not clear at this time.

3. Conclusions

We introduced this work to confirm our hypothesis that the reaction rate of transferable group, R_T changes depending on the residual group, R_R in mixed cuprates, R_RR_TCuM (M = Li, MgX, ZnX).

For this purpose, we have reported a detailed kinetic study of the acylation of *n*-Bu(FG-C_6H_4)CuZnCl with benzoyl chloride in THF at 15 − (−15)°C. We have determined the kinetic law to be rate = *k* [acyl halide] [cuprate]^2. We offered a reaction mechanism for the acylation of halozinc diorganocuprates depending on the kinetic data and activation parameters. Correlation of the reaction rate of transferable group, *n*-Bu to the Hammett substituent constants of residual group, FG-C_6H_4 gave a positive reaction constant which is in accordance with the proposed mechanism and also shows the dependence of *n*-Bu group transfer ability on the electron withdrawing ability of the FG substituents of residual FG-C_6H_4 groups resulting in a lower reaction rate of mixed cuprates *n*-Bu (FG-C_6H_4)CuZnCl than that of homocuprate, *n*-$Bu_2CuZnCl$.

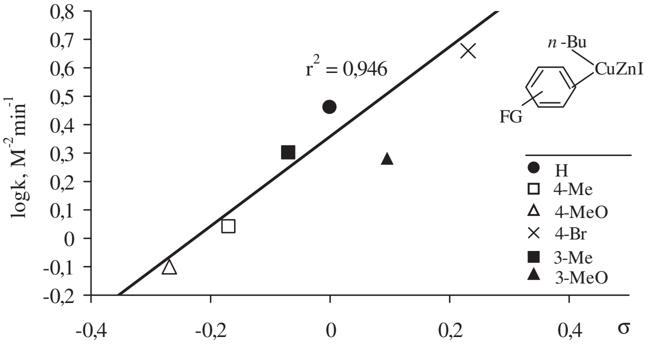


Fig. 7. Hammett study showing correlation of reaction rate of transferable *n*-Bu group with σ values of the residual FG-C_6H_4 group substituents in the acylation reaction of *n*-Bu(FG-C_6H_4)CuZnI in THF at 0 °C. Substituent constants are taken from Ref. [71].

In summary, these findings support our hypothesis and also provide a kinetic explanation for the commonly accepted hypothesis regarding the dependence of the R_T group transfer ability on the strength of R_R—Cu bond in mixed cuprates, R_RR_TCuLi.

4. Experimental

All reactions were carried out under dry nitrogen atmosphere using oven dried glassware. Reagents and solvents were handled by using standard syringe-septum cap techniques [70]. Quantitative GLC analysis were performed on a Thermo Finnigan gas chromatograph equipped with a ZB-5 capillary column packed with phenylpolysiloxane using internal standard technique. THF was distilled from sodium benzophenone dianion. *n*-Butyl bromide, bromobenzene, and 4-methyl-, 3-methyl-, 4-methoxy-, 3-methoxy-, 4-bromo- and 3-bromobenzenes were obtained commercially and purified. Mg turnings for Grignar reagents was used without further purification. $ZnCl_2$ (Aldrich) was dried under reduced pressure at 100 °C for 2 h and used as a THF solution. CuI was purified according to the literature procedure, dried under reduced pressure at 60–90 °C for at least 1 h and kept under nitrogen [71]. Benzoyl chloride was obtained commercially and purified. Grignard reagents *n*-BuMgBr and FG-C_6H_4MgBr (FG = H **b**, 4-Me **c**, 3-Me **d**, 4-MeO **e**, 3-MeO **f**, 4-Br **g**, 3-Br **h**) were prepared in THF by standard methods and their concentration were found by titration prior to use [72].

Typical procedure for the preparation of mixed diorganozinc cuprate, *n*-BuPhCuZnI **1ab** using Method A_2 is given below: To 1 mol equiv of $ZnCl_2$ in THF at −15 °C, first, 1 mol equiv of PhMgBr in THF and after stirring for 20 min at that temperature, 1 mol equiv of *n*-BuMgBr in THF was added. The gray-colored heterogenous solution of *n*-BuPhZn was stirred at −15 °C for 20 min and a suspension of 1 mol equiv of CUI in THF at −15 °C and dark yellow heterogeneous solution of *n*-BuPhCuZnI was stirred at that temperature for another 20 min.

Homo di-*n*-butylzinc cuprate *n*-Bu_2CuZnI **1a₂** reagent was prepared by addition of 2 mol equiv of *n*-BuMgBr reagent in THF to a solution of 1 mol equiv of $ZnCl_2$ in THF at −15 °C, stirring at that temperature for 20 min and adding 1 mol equiv of CuI in THF to Ph_2Zn and then stirring again at −15 °C for 30 min.

A typical kinetic procedure for reaction of *n*-BuPhCuZnI **1ab** with benzoyl chloride **2** in THF at 15 − (−15)°C under pseudo-first order conditions in the presence of excess 1ab is given below:

In a flame-dried, two-necked flasks with septum caps and stirring bars, n-BuPhCuZnI **1ab** (10 mmol) was prepared using THF solution of $ZnCl_2$ (10 mmol), PhMgBr (10 mmol) in THF, *n*-BuMgBr (10 mmol) in THF and CuI (10 mmol) at −15 °C as explained above. To the stirred mixture, internal standard nonane (1 mmol) and PhCOCl **2** (1 mmol) was added. While carrying out the pseudo-first order kinetic experiments, the volume of the reaction mixture was kept constant in order to keep the concentration of benzoyl chloride **2** constant. The mixture was quickly thermostated by immersing the flask cooling bath at constant temperature on a magnetic stirrer. Aliquots (10–16) were withdrawn from the mixture by syringe under nitrogen atmosphere at 5 or 5 min intervals and were hydrolyzed in a vial containing saturated NH_4Cl solution containing 20% NH_3. The aqueous phase was extracted with ether and the ethereal phase was analyzed by GC. The rate data were collected by measuring the concentration of coupling products **3a** and **3b** in each sample. Self consistent data could be obtained for two-four half lives. Reproducibility of the rate constants was generally ±5–10% which is in the error limit of GC analysis.

Acknowledgments

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References

[1] R.J.K. Taylor, Organocopper Reagents: a Practical Approach, Oxford University Press, Oxford, 1994.
[2] N. Krause, Modern Organocopper Chemistry, Wiley-VCH, Weinheim, 2000.
[3] Z. Rappoport, I. Marek (Eds.), Patai's the Chemistry of Organocopper Compounds, Wiley, Chichester, 2009.
[4] H.O. House, M.J. Umen, J. Org. Chem. 38 (1973) 3893.
[5] W.H. Mandeville, G.M. Whitesides, J. Org. Chem. 39 (1974) 400.
[6] B.H. Lipshutz, J.A. Kozlowski, D.A. Parker, S.L. Nguyen, K.E. McCarthy, J. Organomet. Chem. 285 (1985) 437.
[7] P. Knochel, C. Plazza, Angew. Chem. Int. Ed. 41 (2002) 3263.
[8] S.H. Bertz, G. Dabbagh, J. Chem. Soc. Chem. Commun. (1982) 1030.
[9] S.H. Bertz, G. Dabbagh, G.M. Villacorta, J. Am. Chem. Soc. 104 (1982) 5824.
[10] S.H. Bertz, G. Dabbagh, J. Org. Chem. 49 (1984) 1119.
[11] S.F. Martin, J.R. Fishpaugh, J.M. Power, D.M. Giulando, R.A. Jones, C.M. Nunn, A.H. Cowley, J. Am. Chem. Soc. 110 (1988) 7226.
[12] S.H. Bertz, G. Miao, M. Eriksson, Chem. Commun. (1996) 815.
[13] S.H. Bertz, M. Eriksson, G. Miao, P.S. Synder, J. Am. Chem. Soc. 118 (1996) 10906.
[14] H.O. House, C.-Y. Chou, J.M. Wilkins, M.J. Umen, J. Org. Chem. 40 (1975) 1460.
[15] G.H. Posner, C.E. Whitten, J.J. Sterling, D.J. Brunelle, Tetrahedron Lett. 30 (1974) 2591.
[16] B.H. Lipshutz, R.S. Wilhelm, J.A. Kozlowski, Tetrahedron 40 (1984) 5005.
[17] B.H. Lipshutz, Synthesis (1987) 325.
[18] N. Yoshikai, E.-i. Nakamura, Bull. Soc. Chim. Jpn. 77 (2004) 1.
[19] D.E. Bergbreiter, G.M. Whitesides, J. Org. Chem. 40 (1975) 779.
[20] F. Leyendecker, F. Jesser, Tetrahedron Lett. 21 (1980) 1311.
[21] D.E. Bergbreiter, J.M. Killough, 41, 1976, 2750.
[22] S.M.H. Kabir, M.T. Rahman, J. Organomet. Chem. 619 (2001) 31.
[23] N. Yoshikai, E.-i. Nakamura, Chem. Rev. 112 (2012) 2339.
[24] M. Yamanaka, E.-i. Nakamura, J. Am. Chem. Soc. 127 (2005) 4697.
[25] M. Yamanaka, E.-i. Nakamura, J. Am. Chem. Soc. 123 (2001) 5675.
[26] S.H. Bertz, R.A. Hardin, M.D. Murphy, C.A. Ogle, J.D. Richter, E.A. Thomas, Angew. Chemie. Int. Ed. 51 (2012) 2681.
[27] P.M. Murray, S.N.G. Tyler, J.D. Moseley, Org. Process Res. Dev. 117 (2013) 40.
[28] E. Erdik, D. Özkan, J. Phys. Org. Chem. 12 (2009) 1148.
[29] E. Erdik, D. Özkan, React. Kinet. Mech. Catal. 108 (2013) 293.
[30] E. Erdik, Ö.Ö. Pekel, J. Organomet. Chem. 693 (2008) 338.
[31] E. Erdik, Ö.Ö. Pekel, Tetrahedron Lett. 50 (2009) 1501.
[32] E. Erdik, Ö.Ö. Pekel, M. Kalkan, Appl. Organomet. Chem. 23 (2009) 245.
[33] Ö.Ö. Pekel, E. Erdik, Tetrahedron Lett. 52 (2011) 7087.
[34] E. Erdik, M. Kalkan, J. Phys. Org. Chem. 26 (2013) 256.
[35] E. Erdik, E.Z. Serdar, J. Organomet. Chem. 703 (2012) 1.
[36] D. Özkan, E. Erdik, React. Kinet. Cat. Mech. 108 (2013) 293.
[37] J.A. Mac Phee, M. Boussu, J.-E. Dubois, J. Chem. Soc. Perkin. Trans. 2 (1974) 1525.
[38] N. Yoshikai, R. Iida, E. Nakamura, Adv. Synth. Catal. 350 (2008) 1063.
[39] Ö.Ö. Pekel, Ph.D. Thesis, Ankara University, 2011.
[40] J.G. Kim, P.J. Walsh, Angew. Chem. Int. Ed. 45 (2006) 4175.
[41] C. Lutz, P. Jones, P. Knochel, Synthesis (1999) 312.
[42] D.F. Shriver, P.W. Atkins, C.H. Langford, Inorganic Chemistry, Oxford University Press, London, 1992, p. 80.
[43] E. Nakamura, N. Yoshikai, Bull. Chem. Soc. Jpn. 77 (2004) 1.
[44] T. Gartner, R.M. Henze, J. Gschwind, J. Am. Chem. Soc. 129 (2007) 11362.
[45] R. Bamparola, R.P. Davies, S. Hornaver, A.J.P. White, Angew. Chem. Int. Ed. 47 (2008) 5812.
[46] M. Ito, D. Hashiuzeme, T. Fukunaga, T. Matsuo, K. Tamao, J. Am. Chem. Soc. 131 (2009) 18024.
[47] R. Davies, Coord. Chem. Rev. 255 (2011) 1226.
[48] M. John, C. Auel, C. Behrens, M. Marsch, K. Harms, F. Basold, R.M. Gschwind, P.R. Rajamohanan, G. Boche, Chem. Eur. J. 6 (2000) 3059.
[49] E. Nakamura, S. Mori, Angew. Chem. Int. Ed. 39 (2000) 3750.
[50] S. Mori, E. Nakamura, K. Morokuma, J. Am. Chem. Soc. 122 (2000) 7294.
[51] S.H. Bertz, S. Cope, D. Donna, M. Murphy, C.A. Ogle, Angew. Chem. Int. Ed. 46 (2007) 7082.
[52] R.I. Yousef, B. Walfort, T. Rüffert, C. Wagner, H. Schmidt, R. Herzog, D. Steinborn, J. Organomet. Chem. 690 (2005) 1178.
[53] D.R. Armstrong, C. Dougan, D.V. Graham, E. Hevia, A.R. Kennedy, Organometallics 27 (2008) 6063.
[54] S. Mori, A. Hirai, M. Nakamura, E. Nakamura, Tetrahedron 56 (2000) 2805.
[55] E.C. Ashby, Pure Appl. Chem. 52 (1980) 545.
[56] H.G. Richey Jr., Grignard Reagents: New Developments, Wiley, Chichester, 2000.
[57] G.S. Silverman, P.E. Rakita, Handbook of Grignard Reagents, Marcel Dekker, New York, 1996.
[58] S. Yamazaki, S. Yamabe, J. Org. Chem. 67 (2000) 9346.
[59] D.N. Kevill, F.D. Foss, J. Am. Chem. Soc. 91 (1969) 5054.
[60] D.N. Kevill, W.F.K. Wang, J. Chem. Soc. Perkin Trans. 2 (1998) 2631.
[61] M. Jedrzejczak, R.E. Motie, D.P.N. Satchell, J. Chem. Soc. Perkin Trans. 2 (1993) 599.
[62] P. Zuman, R.C. Patel, Techniques in Organic Reaction Kinetics, Wiley, New York, 1984.
[63] N.S. Isaacs, Physical Organic Chemistry, Longman, Harlow, 1987.
[64] J.H. Espenson, Chemical Kinetics and Reaction Mechanisms, Mc-Graw Hill, Toronto, 1995.
[65] C. Hanisch, A. Leo, R. Taft, Chem. Rev. 91 (1991) 165.
[66] H. Yamataka, T. Matsuyuma, T. Hanofusa, J. Am. Chem. Soc. 111 (1989) 4912.
[67] N.H. Yamataka, Miyano, T. Hanafusa, J. Org. Chem. 56 (1991) 2573.
[68] E. Erdik, F. Eroğlu, D. Kâhya, J. Phys. Org. Chem. 18 (2005) 950.
[69] E. Erdik, Ö. Ömür, App. Organomet. Chem. 19 (2005) 887.
[70] J. Leonard, B. Lygo, G. Procter, Advanced Practical Organic Chemistry, Blackie, London, 1995.
[71] R.N. Keller, H.D. Wyncoff, Inorg. Synth. 2 (1946) 1.
[72] J.H. Watson, J.F. Eastham, J. Organomet. Chem. 9 (1967) 1.