Carbon−Carbon Bond Formation by Electrochemical Catalysis in Conductive Microemulsions

Jianxin Gao, James F. Rusling,* and De-ling Zhou

Department of Chemistry, Box U-60, University of Connecticut, Storrs, Connecticut 06269-4060

Received May 8, 1996[⊗]

Bicontinuous microemulsions made from oil, water, and surfactants were examined as substitutes for organic solvents in carbon−carbon bond-forming reactions. Conjugated additions of primary alkyl iodides **3a**−**c** to 2-cyclohexen-1-one (**4**) to give 3-alkyl cyclohexanones **5a**−**c** and cyclization of 2-(4-bromobutyl)-2-cyclohexen-1-one (**9**) to 1-decalone (**10**) were mediated by the Co(I)L complex vitamin B_{12s} generated at carbon cloth electrodes under mild conditions. Reaction of the Co(I)L nucleophile with the alkyl halides gives a Co−alkyl complex. Cleavage of the Co−alkyl complexes by using an electrode potential of −0.85 V (all vs SCE) and irradiation with visible light, or a potential of −1.45 V in the dark, were compared. Addition of the resulting alkyl radicals to the activated double bonds gave comparable yields of 3-alkylcyclohexanone **5a**−**c** (70−80% using −0.85 V + light) and 1-decalone (90%, both cleavage modes) **10** in microemulsions and in DMF. Microemulsions containing hexadecyltrimethylammonium bromide (CTAB) gave remarkable stereoselectivity for the *trans* isomer of **10**, while homogeneous DMF and a sodium dodecylsulfate (SDS) microemulsion gave little stereoselectivity.

Introduction

Alternatives to organic solvents for synthesis are currently receiving attention because of environmental concerns. One alternative is microemulsions,[1,2] which we have been exploring for electrochemical catalysis.[3−8] Microemulsions are clear, thermodynamically stable fluids made from water, oil, and surfactants. They are less toxic and often less expensive than alternative organic solvents.[1−3]

Conductive fluids suitable for electrochemical synthesis include oil-in-water (o/w) microemulsions (μEs) featuring surfactant-coated oil droplets in a continuous water phase and bicontinuous microemulsions composed of dynamic intertwined microscopic networks of oil and water with surfactant at the interfaces.[1−3] Bicontinuous microemulsions have good solubility for polar and nonpolar compounds with faster mass transport for both types of solutes.[4b] Tuning reactivity by controlling microemulsion composition is also possible.[7] Reduction potential windows are extended by adsorption of surfactant on the electrode, which partly blocks the reduction of water.[9]

In electrochemical catalytic reductions, electrons are delivered from electrodes to reactants by a mediator. Kinetic studies of the electrochemically mediated formation of olefins from alkyl vicinal dibromides showed that rate enhancement can be achieved by reactant preconcentration at the electrode surface[4c] or by adjusting the formal potential of the mediator.[7] Benzyl radical coupling mediated by vitamin B_{12} was recently achieved in a microemulsion.[8]

Co(I)L forms of vitamin B_{12},[7,8,10−14] cobaloximes,[15a,16] Co(salen),[15a,17] Co(salophen),[15] and other cobalt complexes[18] react with alkyl halides to give alkylcobalt complexes. The carbon−cobalt bonds can be cleaved by visible light, electrolysis, or reducing agents to give carbon-centered radicals that can add *in-situ* to activated alkenes to form carbon−carbon bonds (eq 2).[10−18] Such cobalt-complex-mediated bond formation has been used for the syntheses of a variety of natural products.[10,11,19,20] Syntheses of

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* To whom correspondence should be addressed. Tel.: (860) 486-4909. Fax: (860) 486-2981. E-mail: Jrusling@nucleus.chem.uconn.edu.)

[⊗] Abstract published in *Advance ACS Abstracts,* August 1, 1996.

(1) Bourrel, M.; Schechter, R. S. *Microemulsions and Related Systems*; Marcel Dekker: New York, 1988.

(2) (a) Fendler, J. H. *Membrane Mimetic Chemistry*; Wiley: New York, 1982. (b) O'Connor, C. J.; Lomax, T. D.; Ramage, R. E. *Adv. Colloid Interface Sci.* **1984**, *20*, 21−97.

(3) (a) Rusling, J. F. In *Modern Aspects of Electrochemistry*; Conway, B. E., Bockris, J. O'M., Eds.; Plenum Press: New York, 1994; No. 26, pp 49−104. (b) Rusling, J. F. In *Electroanalytical Chemistry*; Bard, A. J., Ed.; Marcel Dekker: New York, 1994; Vol. 18, pp 1−88.

(4) (a) Owlia, A.; Wang, Z.; Rusling, J. F. *J. Am. Chem. Soc.* **1989**, *111*, 5091−5098. (b) Iwunze, M. O.; Sucheta, A.; Rusling, J. F. *Anal. Chem.* **1990**, *62*, 644−649. (c) Kamau, G. N.; Hu, N.; Rusling, J. F. *Langmuir* **1992**, *8*, 1042−1044.

(5) Iwunze, M. O.; Hu, N.; Rusling, J. F. *J. Electroanal. Chem.* **1992**, *333*, 353−361.

(6) (a) Zhang, S.; Rusling, J. F. *Environ. Sci. Technol.* **1993**, *27*, 1375−1380. (b) Schweizer, S.; Rusling, J. F.; Huang, Q. *Chemosphere* **1994**, 28, 961−970. (c) Huang, Q.; Rusling, J. F. *Environ. Sci. Technol.* **1995**, *29*, 98−103. (d) Zhang, S.; Rusling, J. F. *Environ. Sci. Technol.* **1995**, *29*, 1195−1199.

(7) Zhou, D.-L.; Gao, J.; Rusling, J. F. *J. Am. Chem. Soc.* **1995**, *117*, 1127−1134.

(8) Zhou, D.-L.; Carrero, H.; Rusling, J. F. *Langmuir* **1996**, *12*, 3067−3074.

(9) Texter, J. In *Electrochemistry in Colloids and Dispersions*; Mackay, R. A., Texter, J., Eds.; VCH Publishers: New York, 1992; pp 3−21.

(10) Scheffold, R.; Rytz, G.; Walder, L. In *Modern Synthetic Methods*; Scheffold, R., Ed.; Wiley: New York, 1983; Vol. 3, pp 355−439.

(11) Scheffold, R.; Abrecht, S.; Orlinski, R.; Ruf, H.-R.; Stamonli, P.; Tinembart, O.; Walder, L.; Weymuth, C. *Pure Appl. Chem.* **1987**, *59*, 363−372.

(12) (a) Dodd, D.; Johnson, M. D. *Organomet. Chem. Rev.* **1973**, *52*, 1−232. (b) Pratt, J. M.; Craig, P. J. *Adv. Organomet. Chem.* **1973**, *11*, 331.

(13) (a) Scheffold, R.; Dike, M.; Dike, S.; Herold, J.; Walder, L. *J. Am. Chem. Soc.* **1980**, *102*, 3642−3644. (b) Scheffold, R. *Chimia* **1985**, *39*, 203. (c) Scheffold, R.; Orlinski, R. *J. Am. Chem. Soc.* **1983**, *105*, 7202−7203. (d) Ruhe, A.; Walder, L.; Scheffold, R. *Helv. Chim. Acta* **1985**, *68*, 1301.

(14) (a) Zhou, D.-L.; Walder, P.; Scheffold, R.; Walder, L. *Helv. Chim. Acta* **1992**, *75*, 995. (b) Tinembart, O.; Walder, L.; Scheffold, R. *Ber. Bunsenges. Phys. Chem.* **1988**, *92*, 1225−1231.

(15) (a) Pattenden, G. *Chem. Soc. Rev.* **1988**, *17*, 361−382 and references cited therein. (b) Bhandal, H.; Howell, A. R.; Patel, V. F.; Pattenden, G. *J. Chem. Soc., Perkin Trans. 1* **1990**, 2709−2714.

(16) (a) Inokochi, T.; Tsuji, M.; Kawafuchi, H.; Torri, S. *J. Org. Chem.* **1991**, *56*, 5945−5948. (b) Torri, S.; Inokochi, T.; Yukama, T. *J. Org. Chem.* **1985**, *50*, 5875−5877.

(17) Fry, A. J.; Singh, A. H. *J. Org. Chem.* **1994**, *59*, 8172−8177.

(18) Ozaki, S.; Nakanishi, T.; Sugiyama, M.; Miyamoto, C.; Ohmori, H. *Chem. Pharm. Bull.* **1991**, *39*, 31−35.

(19) Auer, L.; Weymuth, C; Scheffold, R. *Helv. Chim. Acta* **1993**, *76*, 810−818.

Table 1. Reaction Media, Specific Conductivity, and Formal Potential of Co(II)L/Co(I)L Redox Couple of vitamin B_{12}

medium	composition	specific conductivity $\Omega^{-1}\cdot cm^{-1}$	$-E^{o\prime\, a}$
CTAB μE^{b}	CTAB:1-pentanol:tetradecane: H_2O = 17.5:35:12.5:35 (wt %)	2.0×10^{-3}	0.79
SDS μE	SDS:1-pentanol:tetradecane: brine[c] = 13.3:26.7:8:52 (wt %)	7.0×10^{-3}	0.73
DMF	0.2 M TBAB/DMF	3.5×10^{-3}	0.71[d]

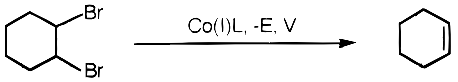
[a] Co(II)L/Co(I)L redox couple of vitamin B_{12}. [b] CTAB μE: cetyltrimethyl ammounium bromide microemulsion. [c] 0.1 M NaCl. [d] Data from ref 7.

olefins can be achieved directly *via* mediated reductive elimination of vicinal dihalides (eq 1).[11,21,22]

To our knowledge, dechlorinations of organic halides to hydrocarbons are thus far the only synthetic scale electrochemical catalytic reactions in microemulsions that have been reported.[6a,b,d,8] Microemulsions should be useful for reactions of more general synthetic utility. In this paper, we compare carbon−carbon bond-forming reactions in microemulsions and DMF. Comparable yields were obtained in DMF and microemulsions for all reactions. Remarkable stereoselectivity was obtained for an intramolecular cyclization in a microemulsion made with a quaternary alkylammonium salt surfactant.

Results

Microemulsions. While several microemulsions were originally explored, two fluids with high conductivities (Table 1) were found to be superior for a test reaction, reductive elimination of *trans*-1,2-dibromocyclohexane **1** (DBCH). For example, reductive elimination of DBCH to cyclohexene **2** at a carbon cloth electrode at −0.85 V vs SCE gave yields of 98% in the CTAB microemulsion and 97% in DMF/0.2 M tetrabutylammonium bromide (TBAB) with consumption of about 2 F/mol of electricity.



1 (*trans*) **2** (1)

Specific conductivities of the microemulsions are similar to that of 0.2 M TBAB in DMF, commonly used for electrochemical reactions. These microemulsions were previously characterized as bicontinuous.[23] Formal potentials of the Co(II)L/Co(I)L redox couple of vitamin B_{12} are also listed in Table 1.

Voltammetry. Cyclic voltammetry (CV) was used to choose appropriate electrode potentials for electrosynthesis. The vitamin B_{12} Co(II)L/Co(I)L redox couple gave a reversible CV at relatively low scan rates in all media (Figure 1a). A large increase in the reduction peak for Co(II)L after addition of DBCH was observed (Figure 1a), along with the disappearance of the oxidation peak. This is consistent with the catalytic debromination of DBCH.[7]

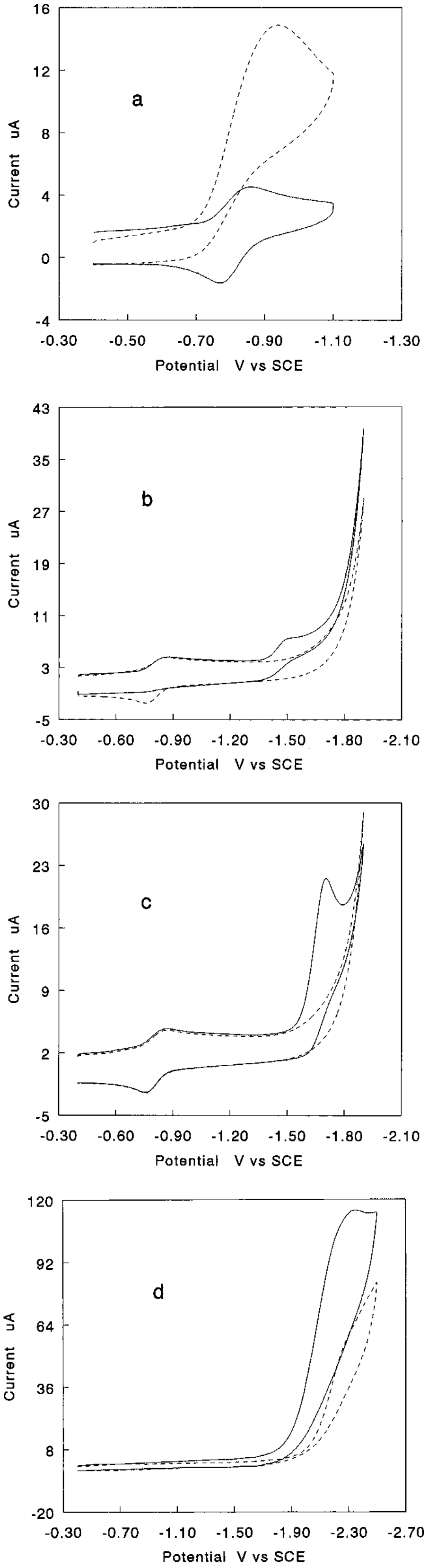


Figure 1. Cyclic voltammograms at 0.1 V s^{-1} on a glassy carbon electrode in CTAB microemulsions: (a) (---) 1 mM vitamin B_{12} + 1 mM DBCH, (—) 1 mM vitamin B_{12} alone; (b) (---) 1 mM vitamin B_{12} alone, (—) 1 mM vitamin B_{12} + 6 mM *n*-dodecyl iodide; (c) (---) 1 mM vitamin B_{12} alone, (—) 1 mM vitamin B_{12} + 1 mM 2-cyclohexen-1-one (**4**); (d) (---) background of CTAB microemulsion, (—) 6 mM *n*-dodecyl iodide.

Oxidative addition of the alkyl iodides **3a**−**c** to B_{12} Co(I)L gives an alkylcobalt complex that shows a new

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[20] Hemamalini, S.; Scheffold, R. *Helv. Chim. Acta* **1995**, *78*, 447−451.

[21] Lexa, D.; Saveant, J. M.; Schafer, H. J.; Su, K.-B.; Vering, B.; Wang, D. L. *J. Am. Chem. Soc.* **1990**, *112*, 6162−6177.

[22] Lexa, d.; Saveant, J. M.; Su, K.-B.; Wang, D. L. *J. Am. Chem. Soc.* **1987**, *109*, 6464−6470.

[23] (a) Ceglie, A.; Das, K. P.; Lindman, B. *Colloids Surf.* **1987**, *28*, 29−40. (b) Georges, J.; Chen, J. W. *Colloid Polym. Sci.* **1986**, *264*, 896−902.

Table 2. Reduction Potentials of Substrates and Alkylcobalt Complexes in Microemulsions and DMF

substrate	medium	E_p,[a] V	direct reduction potential,[b] V	concn of vit B_{12}, mM
3a	CTAB μE	−1.51	−2.37	1.0
3b	CTAB μE	−1.47	−2.31	0.9
3c	CTAB μE	−1.47	−2.40	0.6
3c	DMF	−1.42	*c*	1.0
3c	SDS μE	−1.48[d]	*c*	1.1
9	SDS μE	−1.45[d]	*c*	1.0
9	CTAB μE	−1.45	−1.82[e]	0.72
9	DMF	−1.40	−2.18[e]	1.0
4	CTAB μE		−1.71[e]	0.96

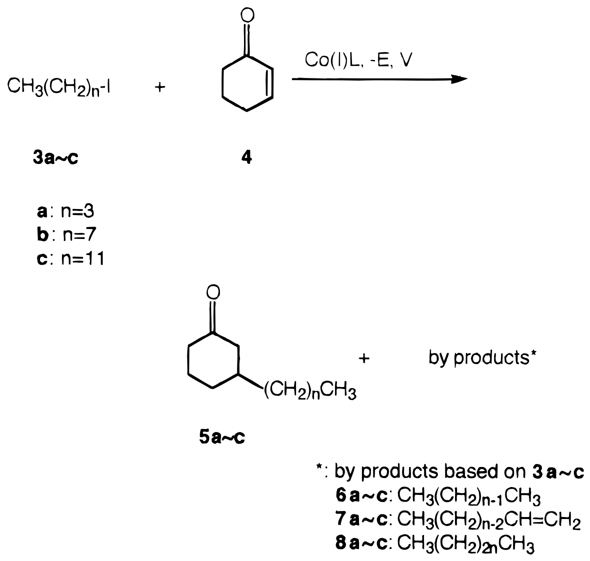
[a] Peak potential of reduction of Co−C bond measured by CV at scan rate 100 mV/s on glassy carbon electrode. [b] Measured by CV at scan rate 100 mV/s vs SCE on glassy carbon electrode. [c] The direct reduction potential is out of the potential window. [d] This reduction peak is overlapped with a background peak. [e] The reduction potential of the conjugated carbonyl group.

peak in the range −1.40 to −1.50 V, with disappearance of the oxidation peak for Co(I)L (Figure 1b). The new irreversible reduction peak represents cleavage of the alkyl−cobalt bond.

After activated alkene **4** was added to microemulsions containing only vitamin B_{12}, cathodic and anodic peaks of Co(II)L/Co(I)L were unchanged (Figure 1c). The irreversible peak at −1.71 V represents direct reduction of **4**. Peaks for direct, irreversible reduction of alkyl iodides in the CTAB microemulsion were at −2.3 to −2.4 V (Figure 1d and Table 2).

In the absence of vitamin B_{12} in the microemulsions, **9**, the starting material for the cyclization, gave an irreversible peak at −1.82 V from reduction of the conjugated carbonyl group (Table 2). In DMF, reduction potentials of alkyl−Co complexes were slightly more positive than in the microemulsion.

Intermolecular Addition. On the basis of the above results, photolytic cleavage of alkyl−Co complexes was done by using carbon cloth cathodes at an applied potential of −0.85 V, where formation of alkyl−Co complexes occurs following generation of Co(I)L. Direct electrochemical cleavage was done at −1.45 V. In the presence of vitamin B_{12} and **4**, alkyl iodides **3a**−**c** gave addition products **5a**−**c**, alkanes **6a**−**c** and **8a**−**c**, and alkenes **7a**−**c** (eq 2 and Table 3).



(2)

Photolytic cleavage after formation of the alkyl−Co complex gave much higher yields of addition products (Table 3, entries 1, 3, and 5). The number of electrons consumed per mole of iodide (*n*) was close to 1 in this mode. Yields of **5c** were similar in microemulsions and in DMF. In a control experiment with no catalyst (Table 3, entry 7), only a small amount of **5c** was formed by photolytic cleavage of the carbon−iodine bond of **3c** and subsequent radical addition to **4**.

A large mole ratio (*m*) of **4** to alkyl iodide was necessary to obtain good yields of coupling product **5** (Table 4). Alkene **7c** was the major product from mediated electrolysis of **3c** at $m = 1$, but the amount formed was small at $m = 300$. A mole ratio of $m = 40$ was sufficient for ≥70% yields of addition products in CTAB microemulsions. In 0.2 M TBAB/DMF with $m = 300$, a yield of **5c** similar to those in microemulsions was found using the photolytic cleavage mode (Table 3, entry 9).

Smaller yields of **5a**−**c** were obtained when electrochemical cleavage of the alkyl−Co complexes at −1.45 V was used (Table 3, entries 2, 4, and 6). The amount of **6c** and the *n* value increased compared to photolytic cleavage. This suggests that reductive dehalogenation competes with the addition reaction at the negative potentials required to cleave the alkyl−Co complex.

Table 3. Intermolecular Addition in Microemulsions and in DMF

						products[b] (mol %)			
entry	iodide	medium	−E, V vs SCE	F/mol **3a**−**c**[a] (*n*)	time (h)	**5a**−**c**	**6a**−**c**	**7a**−**c**	**8a**−**c**
1	**3a**	CTAB μE	0.85 with light	0.8	4	81 (**5a**)	*c*	*c*	*c*
2	**3a**	CTAB μE	1.45			45 (**5a**)	*c*	*c*	*c*
3	**3b**	CTAB μE	0.85 with light	1.0	3	68 (**5b**)	*c*	*c*	*c*
4	**3b**	CTAB μE	1.45			39 (**5b**)	*c*	*c*	*c*
5	**3c**	CTAB μE	0.85 with light	0.8	2	71 (**5c**)	19 (**6c**)	9 (**7c**)	2 (**8c**)
6	**3c**	CTAB μE	1.45	1.8	3	42 (**5c**)	42 (**6c**)	9 (**7c**)	3 (**8c**)
7[d]	**3c**	CTAB μE	0.85 with light no catalyst		4	14 (**5c**)	5 (**6c**)	1 (**7c**)	
8	**3c**	SDS μE	0.75 with light	0.9[e]	5.6	72 (**5c**)	14 (**6c**)	6 (**7c**)	≤1 (**8c**)
9	**3c**	0.2 M TBAB/DMF	0.85 with light	1.1[e]	1.5	69 (**5c**)	13 (**6c**)	15 (**7c**)	≤1 (**8c**)

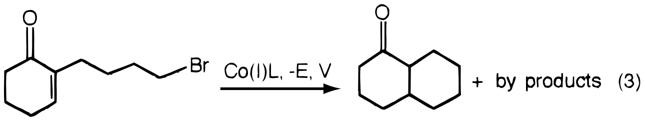
[a] After background current was substracted; mole ratio $m = 40$ unless otherwise noted. [b] GC yields based on **3a**−**c**. [c] Volatile byproducts not trapped for reactions of **3a,b**. [d] 80% of **3c** was recovered. [e] Mole ratio $m = 300$.

Table 4. Product Distributions of Intermolecular C−C Addition at Different Mole Ratios of 4/3c in CTAB Microemulsion[a]

entry	mole ratio of **4/3c**, *m*	F/mol of **3c**,[b] *n*	time (h)	products[c] (mol %)			
				5c	**6c**	**7c**	**8c**
1	1	0.8	4	14	24	61	1
2	5	0.9	5	44	23	29	2
3	10	0.8	4	50	20	26	1
4	40	1.0	2	71	19	9	2
5	300	1.1	4	74	13	4	0

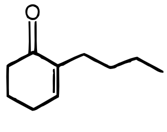
[a] At −0.85 V vs SCE under the irradiation of light. [b] Background current was subtracted. [c] GC yields based on **3c**.

Intramolecular Cyclization. Here, **9** was the starting material and photolytic and electrochemical alkyl−Co cleavage modes were tested in microemulsions and DMF. Both methods gave comparable results.



9 **10**(*trans* + *cis*)

by products:



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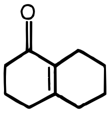

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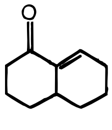

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The main products were *trans* and *cis* isomers of **10** (Table 5). Less than 2% of **11** was obtained. Two GC peaks had GC/MS ion peaks at $m/e = 150$, but no fragment ion peak at $m/e = 95$ that would be characteristic of a 2-alkyl-2-cyclohexen-1-one, such as **11**. These peaks may represent **12** and **13**.

Product distributions in the CTAB microemulsion were similar for both alkyl−Co bond cleavage modes, with a *trans:cis* ratio of 14 for **10** (Table 5). In DMF, this ratio was nearly one without acid, but increased to 2.5 when acetic acid was added. The ratio was 1.6 in the SDS microemulsion.

In DMF, the *n* value was doubled after acetic acid (Table 5, entry 4) was added. Without acid more **12** and **13** were formed (Table 5, entry 3). Similar results in DMF were reported by Scheffold *et al.*[13a] for the same reaction in DMF with 0.1 N $LiClO_4$, and 0.05 N NH_4Br at a Hg electrode at −1.54 V. In that work, 95% yields of **10** with a *trans:cis* ratio of unity were obtained. When CH_3OH was the solvent, the *trans* isomer predominated.

Discussion

Results demonstrate that microemulsions are suitable fluid media for synthetic applications using electrochemical catalysis. Yields of olefin from DBCH and of the more complex intermolecular carbon−carbon addition reactions were similar in microemulsions and DMF. The latter reaction gave higher yields by using electrochemical Co(I)L formation and photolytic alkyl−Co bond cleavage compared to the purely electrochemical approach.

For the intramolecular cyclization, remarkable stereoselectivity was obtained in the CTAB microemulsion compared to DMF or the SDS microemulsion. The *trans: cis* ratio of 14 for the formation of **10** in the CTAB microemulsion, obtained by both the electrochemical/photochemical or pure electrochemical method, was much larger than that in any other fluid. Results suggest that the stereoselectivity is related to a property of CTAB, as will be discussed below.

Reduction potentials of the radicals formed by cleavage of the Co−alkyl bond can be used to predict whether the reactions have radical or anionic pathways. Reduction potentials of primary alkyl radical $R^\bullet$ to carbanion R^- cannot be measured directly by voltammetry of the corresponding organic halide, which gives a single peak for two-electron reduction leading to the cabanion.[24] However, a standard potential of −1.3 to −1.42 V vs SCE was estimated for the primary butyl radical in DMF by Saveant *et al.*[25a] This is much more negative than potentials used in our experiments with photolytic cleavage. Comparing the direct reduction potentials for *n*-butyl iodide of −2.37 V (Table 2) in CTAB microemulsion and −2.33 V[25b] in DMF suggests that the difference in the redox potential of $R^\bullet/R^-$ in CTAB microemulsion and DMF may be small.

On the basis of the above and previous work,[17,25c] the photochemical cleavage mode with $E = -0.85$ V should cleave LCo(III)−R to give $R^\bullet$ radicals. First, nucleophile Co(I)L is produced by reducing vitamin B_{12a} at the electrode (Scheme 1). Oxidative addition then gives RCo(III)L. Photoactivated [RCo(III)L]* **A**, going through a transition state $[R^{\bullet\bullet}Co(II)L]$, leads to radical **B** (eq 7) or dehydrocobaltation (eq 6), as reported previously,[15] to form alkene. Alkyl radical **B** reacts rapidly with activated alkene **C** (Z = electron withdrawing group) to form a new radical **D**, which is an electrophile because a carbonyl group is attached to the radical center.[26] H-atom abstraction by **D** from some component in the medium yields the final addition products **5a**−**c**.

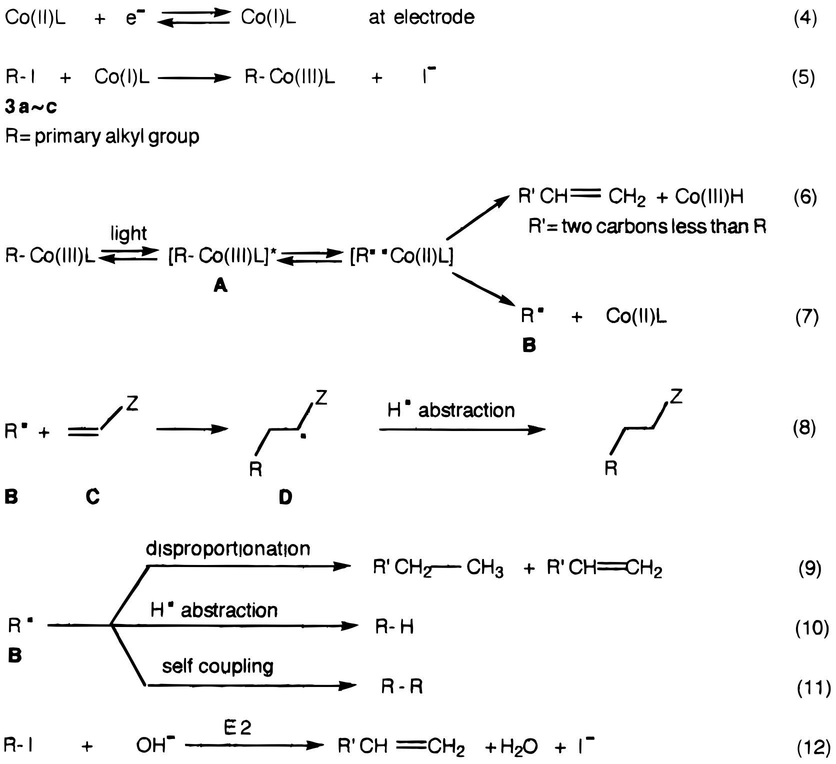
The reactive radical **B** also abstracts $H^\bullet$ from a donor in the fluid medium to form **6a**−**c** (eq 10). Radical **B** also can disproportionate to form **6a**−**c** and **7a**−**c** (eq 9)[24b] and dimerize to form **8a**−**c** (eq 11). An E2 elimination

Table 5. Intramolecular Cyclization in CTAB Microemulsion and DMF

entry	medium	F/mol of **9**,[a] *n*	time (h)	−*E*, V	products[b] (mol %)		
					10 (*trans:cis*)	**11**	**12** + **13**[c]
1	CTAB μE	2.1	3.4	1.45	90 (14:1)	2	5
2	CTAB μE	0.9	5	0.85 with light	89 (14:1)	2	4
3	DMF/0.2 M TBAB	0.9	1.5	0.85 with light	74 (2.5:1)	1	17
4	DMF/0.2 M TBAB/0.12 M acetic acid	1.8	2.6	0.85 with light	88 (1.0:1)	1	6
5	SDS μE	0.8	4.0	0.85 with light	75 (1.6:1)	0	17

[a] Background current was subtracted. [b] GC analysis results based on **9**. [c] Identities uncertain (see text), amounts estimated using the same GC response factor as **10**.

Scheme 1



involving the starting alkyl iodides (eq 12) may possibly contribute a small amount of **7a**−**c**.[24]

There may also be competition between eqs 6 and 7. If the mole ratio *m* is large, radical **B** can be trapped by **C** quickly, eq 7 may predominate, and more addition product **5c** may be formed (Table 4). Since the amount of **6c** and **8c** did not change much when the ratio *m* increases from 1 to 300, other radical followup reactions (eqs 9−11) are probably not much faster than the desired radical trapping (eq 8). If *m* is small, fewer radicals **B** may be trapped by **C**. Then dehydrocobaltation may yield more alkene (eq 6). Results in Table 3 (entries 1, 3, 5, 8, and 9) are also consistent with Scheme 1.

Radical cyclization is typically faster than intermolecular radical addition.[26] Thus, higher yields of intramolecular cyclization products were obtained. Other competitive radical and elimination reactions (eqs 6 and 9−11) were minimized in the CTAB microemulsion (Table 5, entry 2). Radical disproportionation, self-coupling, and E2 elimination products were not observed here. The *n* value of 0.9 is consistent with the one-electron pathway in Scheme 1.

The results of photolytic/electrochemical cyclizations in DMF and SDS microemulsions (Table 5, entries 3 and 5) are also consistent with Scheme 1. Lower yields of **10** may be caused by the lack of a good H-atom donor in the media. In the presence of acid in DMF (Table 5, entry 4), an 88% yield of **10** may indicate that acetic acid is a better H-atom donor. Consumption of more electrons than in entry 3 (Table 5) may involve protonation of a second intermediate complex.[14a] Similarly, Scheffold *et al.*[14b] reported that the radical $^{\bullet}CH_2COOMe$ was not reduced to the respective carbanion at −1.4 V in DMSO, and a one-electron pathway was favored during the cleavage of the C−Co bond. In the presence of acetic acid, a two-electron pathway was favored, leading to CH_3COOMe.

High stereoselectivity in the cyclization of **9** was found only in the CTAB microemulsion (Table 5). While the reasons are under further study, the results can be rationalized on the basis of kinetic control of addition of a H-atom to the intermediate radical **D** (Scheme 1). A similar rationale may be invoked in a two-electron pathway (Scheme 2, discussed below), where the key reaction is proton donation to an anion similar to **D**. In either case, a slower reaction would give a preference for the more stable *trans* isomer of **10**. If CTAB stabilizes the intermediate radical or anion, the *trans* isomer would be preferred. Very fast kinetics would lead to equal amounts of *cis* and *trans* isomers, as found in the other media. Also, specific interfacial influences may be involved in the CTAB microemulsion.

In the electrochemical cleavage mode (−1.45 V) in the CTAB microemulsion, the results (Table 3, entries 2, 4, and 6; Table 5, entry 1) are consistent with a two-electron pathway (Scheme 2).[11] At the potentials used, intermediate radicals derived from alkyl halide reactants are likely to be reduced to anions. Lower yields of **5a**−**c** are consistent with the formation of carbanion R^- and its subsequent fast protonation, which leads to more **6c** (Table 3, entry 6). The yield of **10** (Table 5, entry 1) may not be affected by formation of R^- because intramolecular cyclization is much faster.

In summary, the results reported here show that conductive microemulsions are synthetically useful media for carbon−carbon bond formation mediated by electrochemically generated Co(I)L from vitamin B_{12a}. Pho-

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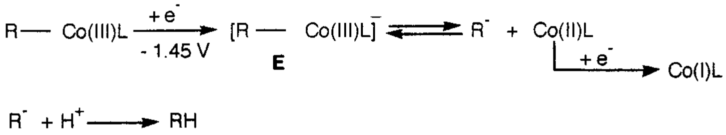
(24) (a) Cleary, J. A.; Mubarak, M. S.; Vieira, K. L.; Anderson, M. R.; Peters, D. G. *J. Electroanal. Chem.* **1986**, *198*, 107−124. (b) Vieira, K. L.; Peters, D. G. *J. Org. Chem.* **1986**, *51*, 1231−1239.

(25) (a) Andrieux, C. P.; Gallardo, I.; Saveant, J. M. *J. Am. Chem. Soc.* **1989**, *111*, 1620−1626. (b) Andrieux, C. P.; Gallardo, I.; Saveant, J. M.; Su, K.-B. *J. Am. Chem. Soc.* **1986**, *108*, 638−647. (c) Zhou, D.-L.; Tinembart, O.; Scheffold, R.; Walder, L. *Helv. Chim. Acta* **1990**, *73*, 2225−2241.

(26) Giese, B. *Radicals in Organic Synthesis: Formation of Carbon−Carbon Bonds*; Pergamon: Oxford, 1986.

Scheme 2



tolytic cleavage of C−Co bonds gave higher yields of intermolecular addition products than electrochemical bond cleavage. Cyclizations give excellent yields of **10** for both C−Co bond cleavage methods. The CTAB microemulsion provided excellent stereoselectivity for *trans* isomer of **10**. While products were not generally isolated, a workup involving treatment of the product mixture by passing twice through silica gel columns and evaporating the solvent (see the Experimental Section) gave 97% pure **5c**.

Experimental Section

Chemicals. Dimethylformamide (J. T. Baker) was purified by passing through a neutral activated alumina (Aldrich) column.[27] Tetrabutylammonium bromide (Aldrich) used for CV measurements was recrystallized from ethyl acetate (Aldrich). Other commercially available chemicals were used as received. Distilled water was purified with a Barnstead Nanopure system to a specific resistance >15 MΩ cm. A YSI Model 3400 cell and a YSI Model 35 Conductance Meter were used for conductance measurements. Cyclic voltammetry was done with a BAS-100B electrochemical analyzer (Bioanalytical Systems) as described previously.[6] All potentials are referred to aqueous saturated calomel electrode (SCE).

2-(4-Bromobutyl)-2-cyclohexen-1-one (**9**),[28] 2-butyl-2-cyclohexen-1-one (**11**),[28] and **5a**−**c**[29] were prepared according to the literature. **9** and **11** were purified by silica gel (EM Science, 70−230 mesh) chromatography with methylene chloride as eluent. **5a**−**c** were purified by silica gel chromatography with *n*-hexane/ethyl acetate (19:1, v/v) as eluent. Microemulsions were prepared by mixing the components in the desired ratios (Table 1), as described previously.[23] For the SDS microemulsion, tetradecane was used instead of dodecane.[23b]

Product Analysis. A Hewlett-Packard 5890 gas chromatograph (GC) with a thermal conductivity detector (TCD) was used for product analysis. The following operating conditions were employed: column, methyl silicone (10 m × 0.53 mm i.d.); carrier gas, helium.

For intermolecular addition products, t_R' of **5a** is 7.0 min, t_R' of **5b** is 10.7 min (temperature programmed from 50 to 250 °C at 15 °C/min), and t_R' of **5c** is 10.2 min (temperature programmed from 80 to 250 °C at 15 °C/min). For intramolecular cyclization products, t_R' of **10** is 5.4 min (*trans*) and 5.6 min (*cis*) (temperature programmed from 70 to 250 °C at 10 °C/min).

Products were identified by comparing their GC retention times and mass spectra with those of authentic samples. Mass spectra were recorded on a Hewlett-Packard GC/MS that had a 5970 quadrupole mass spectrometric detector attached to a HP 5890 GC operated at the same conditions as above for every product. The GC response factors of **1**, **2**, **3a**−**c**, **5a**−**c**, **6c**, **7c, 8c**, **9**, **10**, and **11** were measured for determining the mol % of these products.

Controlled Potential Electrolyses. A PARC Model 273 potentiostat and a H-type divided cell with water jacket were used for controlled potential electrolyses. Working and counter electrodes were 2 × 1 cm carbon cloth (National Electrical Carbon Corp.). The reference electrode was an SCE. A Kratos Xenon SS 1000 lamp was used as a light source, with the power supply set at 500 W. Electrolyses were done at 25 °C with magnetic stirring and a stream of argon passing through the cathode solution. When visible light was used, the lamp was positioned 20 cm away from the cell and filtered by a Schott glass filter (Melles Griot), with below 480 nm wavelength cutoff.

Reductive elimination of DBCH was done with 122.2 mg (0.5 mmol) of DBCH (99%), 34.57 mg (0.025 mmol) of vitamin B_{12a} (98%) in 10 mL of CTAB microemulsion, or 0.2 M TBAB/DMF at −0.85 V. Reaction mixtures were passed though a silica gel column with toluene as eluent. A volume of 100 mL was collected and analyzed by GC or GC/MS.

For intermolecular additions, **3c** is given as an example. The reaction was performed with 30.23 mg (0.1 mmol) of **3c** (98%), 28.22 mg (0.02 mmol) of vitamin B_{12a} at a variety of mole ratios **4**/**3c** in 10 mL microemulsions, or 10 mL of 0.2 M TBAB/DMF at −0.85 V with light or at −1.45 V without light. The reaction mixtures were passed through a silica gel column using *n*-hexane/ethyl acetate (19:1, v/v) as eluent. After concentration to 10 mL under vacuum, the eluent was analyzed by GC or GC/MS.

To isolate **5c**, the eluant from the first silica gel column was concentrated and then passed through a second silica gel column, and the solvent was removed completely from the second effluent under vacuum to yield a light yellow oil, which was 97% **5c** by GC/MS.[30]

Intramolecular additions were done with 23.81 mg (0.1 mmol) of **9** (97%) and 28.22 mg (0.02 mmol) of vitamin B_{12a} with the same conditions as for the intermolecular additions except ether was used as eluent.

Acknowledgment. This work was supported by Grant No. CTS-9306961 from NSF. The authors thank James M. Bobbitt for helpful discussions. **Registry nos. provided by the author:** **5a**, 113829-98-4; **5b**, 57242-85-0; **5c**, 138695-42-8; **11**, 34737-39-8; **9**, 74056-05-6.

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[27] Rusling, J. F.; Connors, T. F. *Anal. Chem.* **1983**, *55*, 776−781.

[28] Taber, D. F. *J. Org. Chem.* **1976**, *41*, 2649−2650.

[29] Whitmore, F. C.; Pedlow, G. W., Jr. *J. Am. Chem. Soc.* **1941**, *63*, 759−760.

[30] Surfactant, excess **4**, and vitamin B_{12} are retained on the silica columns.