New Convenient One-Pot Methods of Conversion of Alkynes to Cyclobutenediones or α,β-Unsaturated Carboxylic Acids Using Novel Reactive Iron Carbonyl Reagents

Mariappan Periasamy,*,† Chellappan Rameshkumar,†
Ukkiramapandian Radhakrishnan,† and Jean-Jacques Brunet‡

School of Chemistry, University of Hyderabad, Central University P.O., Hyderabad 500 046, India, and Labratoire de Chimie de Coordination du CNRS, Unite No. 8241, 205 Route de Narbonne, 31077 Toulouse Cedex, France

Reactions of $NaHFe(CO)_4$/RX or $[HFe_3(CO)_{11}]^-$ reagents with alkynes lead to the formation of the corresponding α,β-unsaturated carboxylic acids and/or the cyclobutenediones. The reagent generated in situ using the $NaHFe(CO)_4$/CH_3I combination in THF, on reaction with alkynes followed by $CuCl_2·2H_2O$ oxidation, gives the corresponding cyclobutenediones (27−42%) and α,β-unsaturated carboxylic acids (10−22%), whereas the reagent generated using CH_2Cl_2 in place of CH_3I leads to α,β-unsaturated carboxylic acids (37−60%) and their derivatives (35−55%) at 25 °C. The same reagent system in the presence of acetic acid (4 equiv) yields the corresponding cyclobutenedione (33%). The reaction using Me_3SiCl gives the corresponding α,β-unsaturated carboxylic acids (45−54%) at 25 °C and the corresponding cyclobutenediones (51−63%) at 60 °C. Interestingly, the reaction of the $[HFe_3(CO)_{11}]^-$ species generated using $Fe(CO)_5$/$NaBH_4$/CH_3COOH, with alkynes at 25 °C, followed by $CuCl_2·2H_2O$ oxidation gives the corresponding cyclobutenediones (60−73%). The possible intermediates and pathways for the formation of α,β-unsaturated carboxylic acids and cyclobutenediones are discussed.

Introduction

There has been immense interest in the use of iron carbonyl reagents in recent years.[1] The readily accessible $HFe(CO)_4^-$ is a versatile reagent used in many organic transformations.[1a] It has been reported that the reaction of $[Et_4N]HFe(CO)_4$ with CH_3I in CH_3CN leads to the formation of $Fe(CO)_4(CH_3CN)$ and CH_4.[2] It appeared that this method of generation of "$Fe(CO)_4$" in situ would serve as a simple alternate method for synthetic applications of these species.[3] In continuation of our efforts on the synthesis and utilization of reactive iron carbonyls,[4] we became interested in examining the reactivity pattern of "$Fe(CO)_4$" species generated using the $NaHFe(CO)_4$/RX system with alkynes.

Preliminary experiments using the $NaHFe(CO)_4$/CH_3I reagent combination revealed that the reaction of the species generated in this way with alkynes at 60 °C

followed by $CuCl_2·2H_2O$ oxidation gives the corresponding cyclobutenediones (27−42%) and the α,β-unsaturated carboxylic acids (10−22%) (eq 1).[5]
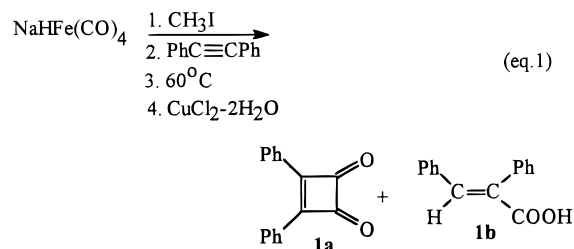
The transformation has been found to be general. Several substituted alkynes, propargyl alcohol derivatives, and enynes were converted to the corresponding cyclobutenediones and α,β-unsaturated carboxylic acids. We have investigated these transformations further to standardize conditions to obtain the cyclobutenediones or α,β-unsaturated carboxylic acids from alkynes in acceptable yields. The results are described here.

Results and Discussion

Reaction of $NaHFe(CO)_4$/CH_2Cl_2 System with Alkynes. It has been reported by Whitmire et. al. that $HFe(CO)_4^-$ slowly decomposes to $[HFe_3(CO)_{11}]^-$ in CH_2Cl_2 through the "$Fe(CO)_4$" intermediate (eq 2).[6]

We have carried out experiments using CH_2Cl_2 in place of CH_3I to examine the difference in reactivity, if any. It was observed that the species generated in situ by

† University of Hyderabad.
‡ Labratoire de Chimie de Coordination du CNRS.
(1) (a) Brunet, J. J. *Chem. Rev.* **1990,** *90,* 1041. (b) Khumtaveeporn, K.; Alper, H. *Acc. Chem. Res.* **1995,** *28,* 414. (c) Liebeskind, L. S.; Baysdon, S. L.; South, M. S.; Iyer, S.; Leeds, J. P. *Tetrahedron* **1985,** *41,* 5839. (d) Fatiadi, A. J. *J. Res. Natl. Inst. Stand. Technol.* **1991,** *96,* 1.
(2) Whitmire, K. H.; Lee, T. R.; Lewis, E. S. *Organometallics* **1986,** *5,* 987.
(3) (a) Poliakoff, M.; Turner, J. J. *J. Chem. Soc., Dalton Trans.* **1974,** 2276. (b) Black, J. D.; Braterman, P. S, *J. Organomet. Chem.* **1975,** *85,* C7. (c) Kane, V. V.; Light, J. R. C.; Whiting, M. C. *Polyhedron* **1985,** *4,* 533. (d) Pearson, A. J.; Dubbert, R. A. *Organometallics* **1994,** *13,* 1656. (e) Pearson, A. J.; Perosa, A. *Organometallics* **1995,** *14,* 5178. (f) Elzinga, J.; Hogeveen, H. *J. Chem. Soc., Chem. Commun.* **1997,** 705. (g) Narasaka, K.; Shibata, T. *Chem. Lett.* **1994,** 315.
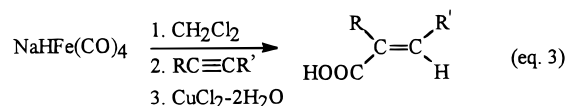(4) (a) Devasagayaraj, A.; Periasamy, M. *Trans. Met. Chem.* **1991,** *16,* 503. (b) Periasamy, M.; Devasagayaraj, A.; Radhakrishnan, U. *Organometallics* **1993,** *12,* 1424. (c) Periasamy, M.; Reddy, M. R.; Radhakrishnan, U.; Devasagayaraj, A. *J. Org. Chem.* **1993,** *58,* 4997. (d) Radhakrishnan, U.; Periasamy, M. *Organometallics* **1997,** *16,* 1800.

(5) Periasamy, M.; Radhakrishnan, U.; Brunet, J. J.; Chauvin, R.; El-Zaizi, A. W. *J. Chem. Soc., Chem. Commun.* **1996,** 1499.
(6) Whitmire, K. H.; Lee, T. R. *J. Organomet. Chem.* **1985,** *282,* 95.

$$2HFe(CO)_4^- \longrightarrow 2 \text{ "}Fe(CO)_4\text{"}$$

$$\xrightarrow{HFe(CO)_4^-} HFe_3(CO)_{11}^-$$

(eq. 2)
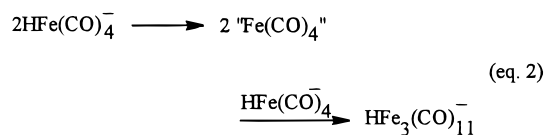
treating $NaHFe(CO)_4$ (1 equiv) with CH_2Cl_2 (13 equiv) in THF on reaction with terminal and internal alkynes gave the hydrocarboxylated products in a regio- and stereocontrolled fashion after $CuCl_2 \cdot 2H_2O$ oxidation (eq 3).[7] The reaction proceeds satisfactorily under mild conditions at 25 °C. The results obtained using representative terminal and internal alkynes are summarized in Table 1.
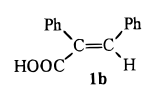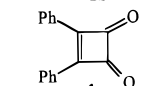
$$NaHFe(CO)_4 \xrightarrow[\substack{2.\ RC\equiv CR' \\ 3.\ CuCl_2\text{-}2H_2O}]{1.\ CH_2Cl_2} \quad \underset{HOOC}{\overset{R}{\diagdown}}C=C\underset{H}{\overset{R'}{\diagup}} \quad \text{(eq. 3)}$$
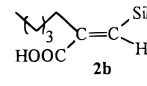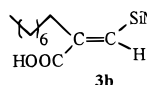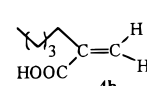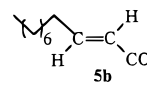
In the case of diphenylacetylene (entry 1, Table 1), the cyclobutenedione **1a** was isolated as a side product (21%). However, with other alkynes (entries **2**−**4**, Table 1), the reaction proceeds well at 25 °C to give β-(E)-alkenoic acids, and only a trace of cylobutenedione (<2%) was isolated. 1-Decyne undergoes α-carbonylation (i.e., at the terminal position), but the reaction with 1-heptyne leads to β-carbonylation (entries 4 and 5, Table 1). The regioselective carbonylation is interesting since only one of the isomers is formed out of the four regio- and stereoisomers possible for the transformation. It is also of interest to note the difference in the regioselectivities in the case of 1-heptyne and 1-decyne. Previously, it has been reported by Alper et al. that regio- and stereoselectivity of certain Pd-catalyzed hydrocarboxylations is dependent on the steric bulk of substitutents.[8] The β-silyl-(E)-α,β-unsaturated carboxylic acids of the type **2b** and **3b** are potential intermediates in many reactions as they contain silyl and carbonyl moieties in the adjacent carbon atoms. Many efforts have been directed previously toward the synthesis of such compounds.[9]

The presence of CH_2Cl_2 as coreactant is required for this transformation. It was observed that the reaction leads to a low yield of carboxylic acid (<10%) without CH_2Cl_2. As mentioned earlier, it has been observed by Whitmire et al.[2] that the reaction of $[Et_4N]HFe(CO)_4$ with CH_2Cl_2 affords $[HFe_3(CO)_{11}]^-$. Presumably, the reactive species responsible for the formation of both cyclobutenediones and carboxylic acids may be derived from these species.
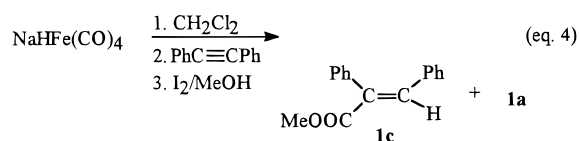
It is well-known that acylferrate anion $[RCOFe(CO)_4]^-$ reacts with I_2 in the presence of nucleophiles such as CH_3OH and R_2NH to give the corresponding carboxylic acid derivatives.[10] A similar type of reactivity may be anticipated for the intermediate formed here. Regio- and stereoselective synthesis of α,β-unsaturated carboxylic acid derivatives could be achieved if such generalizations could be made. Indeed, this has been observed (eq 4).

The intermediate generated in situ (eq 4) upon I_2 treatment in the presence of methanol gives the methyl

(7) Periasamy, M.; Radhakrishnan, U.; Rameshkumar, C.; Brunet, J. J. *Tetrahedron Lett.* **1997**, *38*, 1623.

(8) (a) Amer, I.; Alper, H. *J. Organomet. Chem.* **1990**, *383*, 573. (b) Zargarian, D.; Alper, H. *Organometallics* **1993**, *12*, 712.

(9) Takeuchi, R.; Sugiuchi, M.; Ishii, N.; Sato, N. *J. Chem. Soc., Chem. Commun.* **1992**, 1358 and references therein.

(10) Collman, J. P, *Acc. Chem. Res.* **1975**, *8*, 342.

Table 1. Reaction of $NaHFe(CO)_4/CH_2Cl_2$ with $RC\equiv CR'$ in THF

S.No	Substrate	Temp	Product[a]	Yield[b]
1	$Ph-C\equiv C-Ph$	50 °C	**1b** / **1a**	60 / 21
2	(CH$_2$)$_2$—C≡C—SiMe$_3$	25 °C	**2b**	41
3	(CH$_2$)$_5$—C≡C—SiMe$_3$	25 °C	**3b**	37
4	(CH$_2$)$_2$—C≡CH	25 °C	**4b**	50
5	(CH$_2$)$_5$—C≡CH	25 °C	**5b**	42

[a] The regio- and stereoselectivity of the product **1b** were confirmed by analysis of spectral data and comparison with the reported data.[11] The regio- and stereoselectivity of the products **2b** and **3b** were confirmed by comparison of the spectral data obtained for the corresponding methyl ester,[12a] which is prepared following a reported procedure.[12b] The regio- and stereochemistry of products **4b** and **5b** were confirmed by the analysis of spectral data and comparisons with the reported data.[8] [b] Yields are of products isolated by column chromatography and based on the amount of alkynes used.

$$NaHFe(CO)_4 \xrightarrow[\substack{2.\ PhC\equiv CPh \\ 3.\ I_2/MeOH}]{1.\ CH_2Cl_2} \quad \underset{MeOOC}{\overset{Ph}{\diagdown}}C=C\underset{H}{\overset{Ph}{\diagup}} + \textbf{1a} \quad \text{(eq. 4)}$$
1c

ester **1c** in addition to the corresponding cyclobutenedione **1a**. The corresponding amide **1d** was obtained when diethylamine was used instead of CH_3OH. A similar transformation was also observed with 1-heptyne (Table 2).

Reaction of $NaHFe(CO)_4/Me_3SiCl$ System with Alkynes. We have also examined the reactivity of the species generated using the $NaHFe(CO)_4/Me_3SiCl$ combination to compare the results obtained using the alkyl halides. It was observed that the intermediate complex, generated in situ by treating $NaHFe(CO)_4$ (3 equiv) with Me_3SiCl (3 equiv), reacts with terminal and internal alkynes (1 equiv) at 25 °C to yield α,β-unsaturated carboxylic acids with excellent regio- and stereoselectivities (eq 5).

$$NaHFe(CO)_4 \xrightarrow[\substack{2.\ PhC\equiv CPh \\ 3.\ 25\,°C}]{1.\ Me_3SiCl} [\quad] \xrightarrow{CuCl_2\cdot 2H_2O} \textbf{1b} \quad \text{(eq. 5)}$$

The reaction was found to be general, and various alkynes were converted to (E)-alkenoic acids (Table 3). This reactivity pattern is similar to that realized using $NaHFe(CO)_4/CH_2Cl_2$ reagent system. In all these cases,
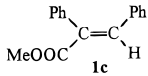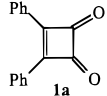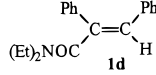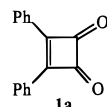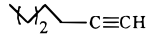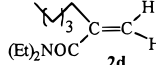
Table 2. Reaction of NaHFe(CO)$_4$/CH$_2$Cl$_2$/RC≡CR′ with I$_2$/ROH or R$_2$NH

S.No	Substrate	Temp	Product[a]	Yield(%)[b]
1	Ph—C≡C—Ph	50°C	Ph, Ph / C=C / MeOOC, H **1c**	55
			Ph, O / Ph, O (cyclobutenedione) **1a**	20
2	Ph—C≡C—Ph	50°C	Ph, Ph / C=C / (Et)$_2$NOC, H **1d**	50
			Ph, O / Ph, O (cyclobutenedione) **1a**	20
3	⋀⋀—C≡CH (CH$_2$)$_2$	25°C	⋀⋀(CH$_2$)$_3$—C=C / H, H / (Et)$_2$NOC **2d**	35

^{a} Products were identified by analysis of spectral data (IR, ^{1}H NMR, ^{13}C NMR, and MS). The amide **2d** was identified by comparing the spectral data with that of the reported data.[11] ^{b} Yields are of products isolated by column chromatography and based on the amount of alkynes used.

Table 3. Reaction of NaHFe(CO)$_4$/Me$_3$SiCl with RC≡CR′ at 25 °C

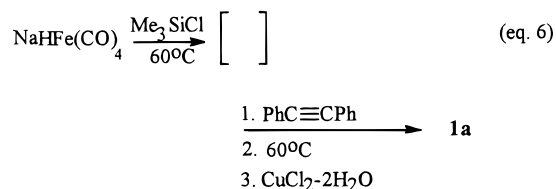| S.No	Substrate	Temp	Product[a]	Yield(%)[b]
1	Ph—C≡C—Ph	25°C	Ph, Ph / C=C / HOOC, H **1b**	54[c]
2	⋀⋀—C≡C—SiMe$_3$ (CH$_2$)$_2$	25°C	⋀⋀(CH$_2$)$_3$—C=C / SiMe$_3$, H / HOOC **2b**	50[d]
3	⋀⋀—C≡CH (CH$_2$)$_2$	25°C	⋀⋀(CH$_2$)$_3$—C=C / H, H / HOOC **4b**	49[e]
4	⋀⋀—C≡CH (CH$_2$)$_5$	25°C	⋀⋀(CH$_2$)$_6$—C=C / H, H / COOH **5b**	45[e]

^{a} Products were identified by analysis of the spectral data. ^{b} Yields are of products isolated by column chromatography using hexane/ethyl acetate (97:3) as eluent and based on the amount of alkynes used. ^{c} The compound **1b** was identified by comparison of the spectral data with the reported data.[11] ^{d} The regio- and stereoselectivity of the product **2b** was confirmed by comparison with the spectral data obtained for the methyl ester with the data reported.[12a] ^{e} The regio- and stereoselectivity of the products **4b** and **5b** were confirmed by analysis of spectral data and comparison with the reported data.[8]

the corresponding cyclobutenediones were obtained in very low yields (<5%). Even in the case of diphenylacetylene, the α,β-unsaturated carboxylic acid **1b** was isolated as the major product (53%) in addition to only traces (<5%) of the corresponding cyclobutenedione **1a**.

The stereochemistry of the (E)-alkenoic acids was confirmed by comparison of ^{13}C and ^{1}H NMR spectral data with that of the reported compounds.[8,11,12] Again, in the case of 1-decyne (entry 4, Table 3), α-carbonylation (i.e., at the terminal position) rather than β-carbonylation

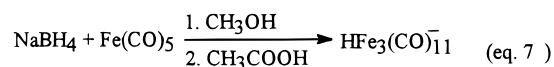was observed. The yields (45−54%) of the α,β-unsaturated carboxylic acids realized using NaHFe(CO)$_4$/Me$_3$SiCl (Table 3) are slightly better in some cases than the yields obtained with the NaHFe(CO)$_4$/CH$_2$Cl$_2$ system (Table 1). However, the latter system has the advantage that it requires the use of the inexpensive CH$_2$Cl$_2$.

We have observed an interesting temperature effect for this reaction. It was found that the reagent, prepared using NaHFe(CO)$_4$/Me$_3$SiCl at 60 °C, on reaction with diphenylacetylene followed by CuCl$_2$·2H$_2$O oxidation produced cyclobutenedione **1a** (63%) as the only product (eq 6).

$$\text{NaHFe(CO)}_4 \xrightarrow[60°C]{\text{Me}_3\text{SiCl}} [\quad] \qquad (\text{eq. 6})$$

$$\xrightarrow[\substack{1.\ \text{PhC≡CPh} \\ 2.\ 60°C \\ 3.\ \text{CuCl}_2\text{-}2\text{H}_2\text{O}}]{} \quad \textbf{1a}$$

The reaction was found to be general. The corresponding cyclobutenediones were obtained in relatively good yields using representative terminal, internal, and substituted alkynes (Table 4). It may be of interest to note that Graham et al. reported that the R$_3$Si(H)Fe(CO)$_4$ on heating gives an Fe(CO)$_4$ species that readily undergoes trimerization to Fe$_3$(CO)$_{12}$.[13−15]

Reaction of the [HFe$_3$(CO)$_{11}$]$^-$ Reagent Prepared Using Fe(CO)$_5$/NaBH$_4$/CH$_3$COOH with Alkynes. To further examine the possibility of whether an [HFe$_3$(CO)$_{11}$]$^-$ related species is responsible for the formation of cyclobutenedione, we decided to prepare the [HFe$_3$(CO)$_{11}$]$^-$ species to examine its reactivities. The [HFe$_3$(CO)$_{11}$]$^-$ species has been previously prepared using Fe(CO)$_5$/NaBH$_4$/CH$_3$OH/CH$_3$COOH in THF and isolated as the PPN salt in 73% yield (eq 7).[18]

$$\text{NaBH}_4 + \text{Fe(CO)}_5 \xrightarrow[2.\ \text{CH}_3\text{COOH}]{1.\ \text{CH}_3\text{OH}} \text{HFe}_3\text{(CO)}_{11}^- \quad (\text{eq. 7})$$

We have observed that the [HFe$_3$(CO)$_{11}$]$^-$ species, prepared in situ using Fe(CO)$_5$/NaBH$_4$/CH$_3$COOH, reacts with alkynes to give the corresponding cyclobutenediones in good yields (60−73%) after CuCl$_2$·2H$_2$O oxidation (eq 8).[19] Several alkynes were converted to the corresponding cyclobutenediones. The results are summarized in the Table 5.

Evidently, the reagent system can tolerate unmasked functional groups such as hydroxy group (entries 5a and 6a, Table 5). The formation of cyclobutenedione from an enyne shows that the reagent reacts with alkynes with-

(11) *Handbook of Proton NMR Spectra and Data*; Asahi Research Center Co., Ltd., Ed.; Academic Press: Tokyo, 1986; Vols. 1−9.

(12) (a) Takeuchi, R.; Sugiura, M. *J. Chem. Soc., Perkin Trans. 1* **1993**, 1031. (b) Ono, N.; Yamada, T.; Saito, T.; Tanaka, K.; Kaji, A. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 2401.

(13) Nasta, M. N.; MacDiarmid, A. G. *J. Am. Chem. Soc.* **1971**, *93*, 2813.

(14) Jetz, W.; Graham, W. A. G. *J. Am. Chem. Soc.* **1969**, *91*, 3375.

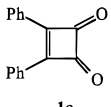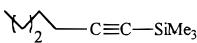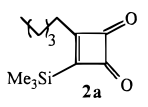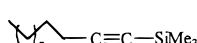(15) Jetz, W.; Graham, W. A. G. *Inorg. Chem.* **1971**, *10*, 4.
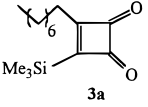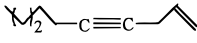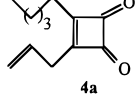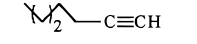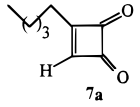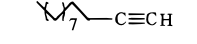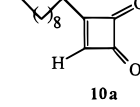
(16) (a) Hoberg, H.; Herrera, A. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 927. (b) Herrera, A.; Hoberg, H. *Synthesis* **1981**, 831.

(17) (a) Parker, M. S. A.; Rizzo, C. J. *Synth. Commun.* **1995**, *25*, 2781. (b) Ried, W.; Schmidt, A. H. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 997.

(18) Hodali, H. A.; Arcus, C.; Shriver, D. F. *Inorg. Synth.* **1980**, *20*, 218.

(19) Preliminary communication: Periasamy, M.; Rameshkumar, C.; Radhakrishnan, U. *Tetrahedron Lett.* **1997**, *38*, 7229.

Table 4. Reaction of NaHFe(CO)$_4$/Me$_3$SiCl with Alkynes at 60 °C
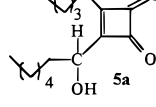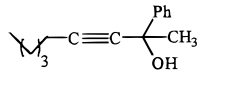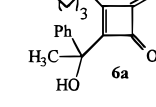
S.No	Substrate	Product[a]	Yield[b]
1	Ph—C≡C—Ph	**1a**	63[c]
2	(substrate) C≡C—SiMe$_3$	**2a**	51[d]
3	(substrate) C≡C—SiMe$_3$	**3a**	53
4	(substrate) C≡C (allyl)	**4a**	60
5	(substrate) C≡CH	**7a**	56[e]
6	(substrate) C≡CH	**10a**	57[e]

[a] Products were identified by analyzing the spectral data (IR, ^{1}H NMR, ^{13}C NMR, and MS). *[b]* Yields are of products isolated by column chromatography using hexane/ethyl acetate (98:2) as eluent and based on the amount of alkynes used. *[c]* The cyclobutenedione **1a** was identified by analysis of spectral data and comparisons with the reported data.[16] *[d]* For the cyclobutenedione **2a**, HRMS data were also obtained. *[e]* The spectral data of product **7a** (IR, NMR) were identical to the data reported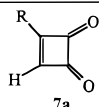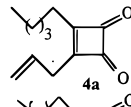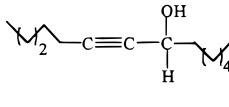 for this compound.[17a] The spectral data of product **10a** are comparable to the spectral data reported for the cyclobutenedione **7a**.

out affecting the olefin moiety (entry 4a). The yields of the cyclobutenediones obtained following this method are somewhat better than that realized using the NaH-Fe(CO)$_4$/Me$_3$SiCl system (Table 4). Moreover, whereas the NaHFe(CO)$_4$ preparation requires Na$_2$Fe(CO)$_4$, which in turn is prepared from Fe(CO)$_5$/Na/naphthalene, the preparation of the reactive species from the Fe(CO)$_5$/NaBH$_4$/CH$_3$COOH combination is relatively less complicated. Further, in the latter method the reaction is carried out at ambient conditions and hence should be more convenient for synthetic applications.

The UV spectra recorded for the reaction mixture in all reagent combinations described above exhibit characteristic absorptions reported for [HFe$_3$(CO)$_{11}$]$^-$ in solution.[20] If the reactive species is derived from this reagent, then the reactivity difference between the species generated using Fe(CO)$_5$/NaBH$_4$/CH$_3$COOH in THF and the reagent prepared using NaHFe(CO)$_4$/CH$_2$Cl$_2$ in THF is difficult to rationalize. The reaction of the former combination with alkynes leads to cyclobutenediones (eq 9), and the latter results in the α,β-unsaturated carboxylic acids (eq 3). Probably, the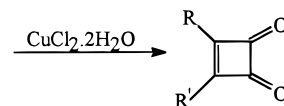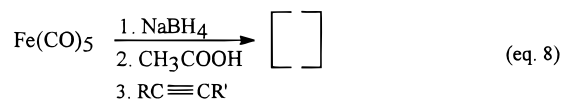 CH$_3$COOH used to destroy the excess NaBH$_4$ may play a role in the formation of the reactive species from [HFe$_3$(CO)$_{11}$]$^-$. If this is the
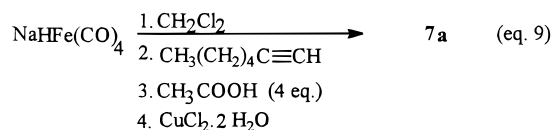
(20) Case, J. R.; Whiting, M. C. *J. Chem. Soc.* **1960**, 4632.

Table 5. Reaction of Fe(CO)$_5$/NaBH$_4$/CH$_3$COOH with Alkynes

S.No	Substrate	Product[a]	Yield[b]
	R-C≡C-H		
1	R = C$_5$H$_{11}$	**7a**	73[c]
2	R = C$_6$H$_{13}$	**8a**	69[c]
3	R = C$_8$H$_{17}$	**9a**	70[c]
4	R = C$_{10}$H$_{21}$	**10a**	68[c]
5	R = C$_6$H$_5$	**11a**	65[d]
6	(substrate) C≡C (allyl)	**4a**	60
7	(substrate) C≡C—CH(OH)...	**5a**	61
8	(substrate) C≡C—C(Ph)(OH)CH$_3$	**6a**	63[e]

[a] Products were identified by the spectral data. *[b]* Yields are of products isolated by column chromatography and based on the amount of alkynes used. *[c]* The spectral data of products **8a**, **9a**, and **10a** are comparable to the spectral data reported for the product **7a**.[16a] *[d]* The cyclobutenedione **11a** was identified by analysis of spectral data and comparison with the reported data.[16b] *[e]* For the cyclobutenedione **6a**, HRMS data were also obtained.

$$\text{Fe(CO)}_5 \quad \xrightarrow[\substack{\text{2. CH}_3\text{COOH} \\ \text{3. RC}\equiv\text{CR'}}]{\text{1. NaBH}_4} \quad \square \qquad \text{(eq. 8)}$$

$$\xrightarrow{\text{CuCl}_2.2\text{H}_2\text{O}} \text{(cyclobutenedione product)}$$

case, the use of an additional amount of CH$_3$COOH in the reaction using NaHFe(CO)$_4$/CH$_2$Cl$_2$ should also give similar results. Indeed, this was observed. The corresponding cyclobutenedione was obtained in 33% yield, and the α,β-unsaturated carboxylic acid was not formed under these conditions (eq 9).

$$\text{NaHFe(CO)}_4 \quad \xrightarrow[\substack{\text{2. CH}_3(\text{CH}_2)_4\text{C}\equiv\text{CH} \\ \text{3. CH}_3\text{COOH (4 eq.)} \\ \text{4. CuCl}_2.2\text{H}_2\text{O}}]{\text{1. CH}_2\text{Cl}_2} \quad \textbf{7a} \qquad \text{(eq. 9)}$$

Although the nature of the reactive species is not clearly understood, it may be of interest to compare the results with previous reports on the reaction of iron carbonyls with alkynes so as to provide a working hypothesis to rationalize the transformations. It has been reported that Fe(CO)$_5$ reacts with alkynes to give the corresponding cyclobutadiene−Fe(CO)$_3$ complexes or cyclopentadienone−Fe(CO)$_3$ complexes under different conditions.[21] Whereas di-*tert*-butylacetylene on reaction with Fe$_2$(CO)$_9$ or Fe$_3$(CO)$_{12}$ gives the $(t\text{-Bu}_2\text{C}_2)\text{Fe}_2(\text{CO})_6$

Scheme 1

Scheme 2
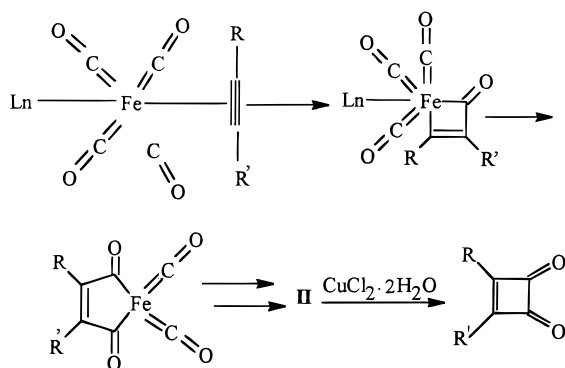
or $(t\text{-Bu}_2C_2)_2Fe_2(CO)_4$ complexes,[22] acetylene and mono-substituted acetylenes have been reported to give the corresponding tropone derivatives.[23] A mixture of 2,5- and 2,6-disubstituted quinones is obtained in the photochemical reaction of $Fe(CO)_5$ with some monosubstituted alkynes. The quinones have been also obtained in 30% yield in the reaction of alkynes with $Fe(CO)_5$ in aqueous alkali at 80–90 °C.[24] However, acetylene gives the dienol complex **I** at room temperature, which after $FeCl_3$ oxidation in ether yields cyclobutenedione.[25] It has been reported that the yields of the dienol complexes **I** were poor for higher alkynes even after a long reaction time (3 days). More recent studies reveal that the complex **I** is formed as one among more than 10 products.[26] We have observed that the use of $FeCl_3$ in the place of $CuCl_2\cdot 2H_2O$ (eq 8) leads a complex mixture of products. However, the possibility of the intermediates of the type **I** or **II** cannot be ruled out for the transformation reported here.
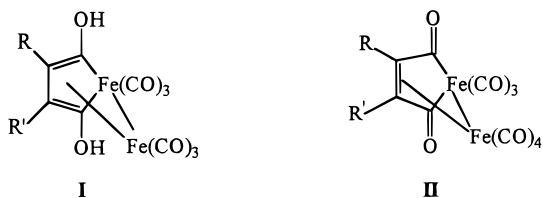

A tentative mechanistic pathway for the formation of cyclobutenediones can be visualized as shown in Scheme 1. The species of the type **II** could result from coordination of the alkyne moiety to the iron carbonyl species followed by carbon monoxide insertion.

The formation of α,β-unsaturated carboxylic acids may take place through hydrometalation of the alkynes by $[HFe_3(CO)_{11}]^-$ produced under the reaction conditions (Scheme 2).
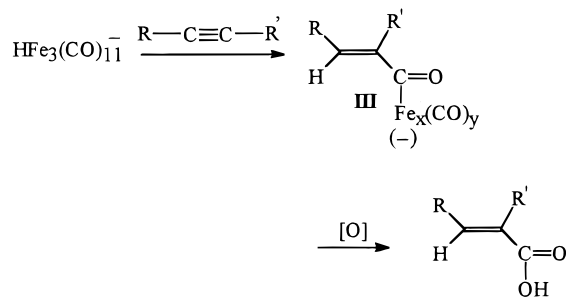
Presumably, heating of the reaction mixture after addition of Me_3SiCl (eq 6) and decomposition of the iron carbonyl species formed using $Fe(CO)_5/NaBH_4$ with acetic acid (eq 8) may give another reactive iron carbonyl species, which on reaction with alkyne followed by $CuCl_2\cdot 2H_2O$ oxidation results in the formation of cyclobutenediones. However, the mechanistic proposals and intermediates suggested can be only tentative.

Conclusions

The reaction of the reagent generated using NaH-$Fe(CO)_4$ and CH_2Cl_2 with alkynes gave α,β-unsaturated carboxylic acids [(*E*)-isomer] (37–60% yields) in a regio- and stereoselective manner after $CuCl_2\cdot 2H_2O$ oxidation. This reagent system was also demonstrated to be useful in the synthesis of certain α,β-unsaturated carboxylic esters and amides, albeit in moderate yields. The reaction of $NaHFe(CO)_4/Me_3SiCl$ and alkynes at 25 °C, followed by $CuCl_2\cdot 2H_2O$ oxidation, gave the corresponding α,β-unsaturated carboxylic acids (45–54% yields) with good regio- and stereoselectivity. The yields are slightly better than that obtained using the $NaHFe(CO)_4/$$CH_2Cl_2$ system in some cases. However, the latter method requires the use of the inexpensive CH_2Cl_2 and hence is advantageous for synthetic applications. It was also observed that addition of alkynes to the species generated in the reaction of $NaHFe(CO)_4/Me_3SiCl$ at 60 °C followed by $CuCl_2\cdot 2H_2O$ oxidation led to the corresponding cyclobutenediones. The cyclobutenediones have been also obtained in 60–73% yields in the reaction of alkynes with the $Fe(CO)_5/NaBH_4/CH_3COOH$ system. The method is more convenient for application than the method using $NaHFe(CO)_4/Me_3SiCl$ system, and the yields are also better in some cases.

It is well-known that cyclobutenediones and their adducts are highly versatile starting materials for the synthesis of substituted naphthalenes, phenols, catechols, heterocycles, and polycyclic aromatics.[27] It has been also reported that cyclobutenediones might show some biological activity.[28] For instance, it was suggested that cyclobutenedione derivatives might show interesting antitumor properties.[29] Accordingly, the methods described here for the synthesis of cyclobutenediones should be useful for further synthetic applications.

(21) (a) Hubel, W.; Braye, E. H. *J. Inorg. Nucl. Chem.* **1959**, *10*, 250. (b) Weiss, E.; Hubel, W. *Chem. Ber.* **1962**, *95*, 1179. (c) Braye, E. H.; Hubel, W. *J. Organomet. Chem.* **1965**, *3*, 25.

(22) (a) Cotton, F. A.; Jamerson, J. D.; Stults, B. R. *J. Am. Chem. Soc.* **1976**, *98*, 1774. (b) Nicholas, K.; Bray, L. S.; Davis, R. E.; Pettit, R. *J. Chem. Soc., Chem. Commun.* **1971**, 608.

(23) (a) Braye, E. H.; Hubel, W. *J. Organomet. Chem.* **1965**, *3*, 25. (b) Smith, D. L.; Dahl, L. F. *J. Am. Chem. Soc.* **1962**, *84*, 1743. (c) Wiss, E.; Merenyi, R. G.; Hubel, W. *Chem. Ind. (London)* **1960**, 407.

(24) (a) Reppe, W.; Vetter, H. *Justus Liebigs Ann. Chem.* **1953**, *582*, 133. (b) Victor, R.; Shoshan, R. B.; Sarel, S, *Tetrahedron. Lett.* **1973**, 4211.

(25) Whiting, M. C. *Chem. Weekblad.* **1963**, *59*, 119.

(26) (a) Sternberg, H. W.; Friedel, R. A.; Markby, R.; Wender, I. *J. Am. Chem. Soc.* **1956**, *78*, 3621. (b) Aime, S.; Milone, L.; Sappa, E.; Tiripicchio, A.; Lanfredi, A. M. M. *J. Chem. Soc., Dalton Trans.* **1979**, 1664.

(27) (a) Lee, K.; Turnbull, P.; Moore, H. W. *J. Org. Chem.* **1995**, *60*, 461. (b) Sun, L.; Liebeskind, L. S. *J. Org. Chem.* **1995**, *60*, 8194. (b) Sun, L.; Liebeskind, L. S. *Tetrahedron Lett.* **1997**, *38*, 3663. (c) Paquette, L. A..; Tae, J. *Tetrahedron Lett.* **1997**, *38*, 3151. (d) Pacquette, L. A.; Doyon, J. *J. Org. Chem.* **1997**, *62*, 1723. (e) Zhang, D.; Llorente, I.; Liebeskind, L. S. *J. Org. Chem.* **1997**, *62*, 4330.

(28) (a) Kraus, J. L. *Tetrahedron Lett.* **1987**, *28*, 1765. (b) Cole, R. J.; Kirksey, J. W.; Cutler, H. G.; Doupnik, B. L.; Peckham, J. C. *Science* **1973**, *179*, 1324.

(29) Kraus, J. L. *Tetrhedron Lett.* **1985**, *26*, 1867.

Experimental Section

General Methods. ^{1}H (200 MHz) and ^{13}C NMR (50 MHz) spectra were taken in CDCl$_3$ unless otherwise stated with TMS as reference ($\delta = 0$ ppm). The chemical shifts are reported in ppm on the δ scale relative to CDCl$_3$ (77.0 ppm), and coupling constants are reported in hertz. Melting points are uncorrected. Chromatographic purification was conducted by column chromatography using 100–200 mesh silica gel obtained from Acme Synthetic Chemicals, India. The alkynes used in the reactions (except 1-heptyne) were prepared by following a reported procedure.[30] THF supplied by E-Merck, India, was distilled over sodium–benzophenone ketyl before use. Iron pentacarbonyl samples supplied by Fluka and Aldrich were used. Naphthalene supplied by LOBA-Chemie, India, was sublimed before use. All reactions and manipulations were conducted under a dry nitrogen atmosphere. All yields reported are isolated yields of materials judged homogeneous by TLC, IR, and NMR spectroscopy.

Reaction of NaHFe(CO)$_4$ with Diphenylacetylene in the Presence of CH$_2$Cl$_2$. The NaHFe(CO)$_4$ (6 mmol) in THF (30 mL) [generated by acidification of Na$_2$Fe(CO)$_4$ (6 mmol) with CH$_3$COOH (6 mmol, 0.39 g)] was treated with 5 mL of CH$_2$Cl$_2$ under nitrogen atmosphere. After 1 h, diphenylacetylene (2.5 mmol, 0.45 g) was added, and the contents were heated to 50 °C and stirred for 8 h. The metal carbonyl complex was decomposed using CuCl$_2$·2H$_2$O (20 mmol, 3.4 g) in acetone (15 mL). Saturated aqueous NaCl was added, and the resulting solution was extracted with ether, washed with brine, dried over anhydrous MgSO$_4$, and concentrated. The residue was subjected to column chromatography. Ethyl acetate (1%) in hexane eluted the cyclobutenedione **1a** (21%, 0.25 g), and α,β-unsaturated carboxylic acid **1b** (60%, 0.387) was isolated using ethyl acetate (2%) in hexane.[11]

1a: mp 95–96 °C (lit.[16a] mp 97 °C); IR (KBr) 1780 cm^{-1}; ^{1}H NMR δ 7.45–7.68 (m, 6H), 8.14 (m, 4H); ^{13}C NMR δ 128.7, 129.7, 131.2, 134.6, 187.4, 196.1; MS(EI) m/z 235 (M + 1), 179 (B).

1b: mp 171.5 °C (lit.[31] mp 172–173 °C); IR (KBr) 1678 cm^{-1}; ^{1}H NMR δ 7.1–7.4 (m, 10H), 7.9 (s, 1H); ^{13}C NMR δ 128.1, 128.3, 128.7, 129.5, 129.8, 130.9, 131.7, 134.4, 135.4, 142.6, 173.5; MS(EI) m/z 224 (M), 179 (B). Anal. Calcd for C$_{15}$H$_{12}$O$_2$: C, 80.30; H, 5.35. Found: C, 80.04; H, 5.80.

The above procedure was followed for the conversion of other alkynes to the corresponding α,β-unsaturated carboxylic acids. The regio- and stereochemistry of the products **2b** and **3b** were confirmed by comparing the spectral data obtained for the methyl ester of **2b** with the reported data.[12] The stereo- and regiochemistry of the products **4b** and **5b** were confirmed by the analysis of spectral data and comparison with the reported data.[8]

Reaction of NaHFe(CO)$_4$/CH$_2$Cl$_2$ with Diphenylacetylene and I$_2$/MeOH. The NaHFe(CO)$_4$ (6 mmol) in THF (30 mL) [generated by acidification of Na$_2$Fe(CO)$_4$ (6 mmol)] with CH$_3$COOH (6 mmol, 0.39 g)] was treated with 5 mL of CH$_2$Cl$_2$ under nitrogen atmosphere. After 1 h, diphenylacetylene (2.5 mmol, 0.45 g) was added, and the contents were heated to 50 °C and stirred for 8 h. The contents were cooled to room temperature (25 °C) and then treated with MeOH (5 mL) and I$_2$ (5 mmol, 1.27 g) in THF. The metal carbonyl complex was decomposed using CuCl$_2$·2H$_2$O (20 mmol, 3.4 g) in acetone (15 mL). Saturated aqueous NaCl was added, and the resulting solution was extracted with ether, washed with brine, dried over anhydrous MgSO$_4$, and concentrated. The residue was subjected to column chromatography. The α,β-unsaturated carboxylic ester **1c** (55%, 0.325 g) and cyclobutenedione **1a** (20%, 0.117 g) were isolated.

1c: IR (neat) 1714 cm^{-1}; ^{1}H NMR δ 3.84 (s, 3H, –OCH$_3$), 6.93–7.98 (m, 11H); ^{13}C NMR δ 52.4, 127.9, 128.2, 128.7, 129.1, 129.8, 130.6, 131.5, 142.5, 168.3; MS (EI) m/z 238 (M), 178 (B).

The regio- and stereochemistry of the product **2d** were confirmed by the analysis of spectral data and comparison with the reported data.[11]

Reaction of NaHFe(CO)$_4$/Me$_3$SiCl with Diphenylacetylene at 25 °C. The NaHFe(CO)$_4$ (7.5 mmol) [generated by acidification of Na$_2$Fe(CO)$_4$ (7.5 mmol) with CH$_3$COOH (6 mmol, 0.39 g) in THF (30 mL)] was treated with Me$_3$SiCl (7.5 mmol, 0.81 g) under nitrogen atmosphere. After 1 h, diphenylacetylene (2.5 mmol, 0.45 g) was added, and the contents were stirred for 8 h at 25 °C. The metal carbonyl complex was decomposed using CuCl$_2$·2H$_2$O (20 mmol, 3.4 g) in acetone (15 mL). Saturated aqueous NaCl was added, and the resulting solution was extracted with ether, washed with brine, dried over anhydrous MgSO$_4$, and concentrated. The residue was subjected to column chromatography. A trace (<5%) of the corresponding cyclobutenedione **1a** was isolated using ethyl acetate (1%) in hexane. The α,β-unsaturated carboxylic acid **1b** (54%, 0.3 g) was isolated using ethyl acetate (2%) in hexane. The above procedure was followed for the conversion of other alkynes to the corresponding α,β-unsaturated carboxylic acids, and the results are summarized in Table 3. The spectral data were identical to those obtained for the samples previously isolated using the NaHFe(CO)$_4$/CH$_2$Cl$_2$ reagent system.

Reaction of NaHFe(CO)$_4$/Me$_3$SiCl with Diphenylacetylene at 60 °C. The NaHFe(CO)$_4$ (7.5 mmol) in THF (30 mL) [generated by acidification of Na$_2$Fe(CO)$_4$ (7.5 mmol) with CH$_3$COOH (6 mmol, 0.39 g)] was treated with Me$_3$SiCl (7.5 mmol, 0.81 g) under nitrogen atmosphere. The reaction mixture was stirred for 1 h at 50 °C; after the reaction mixture was cooled, diphenylacetylene (2.5 mmol, 0.45 g) was added, and the contents were stirred for 8 h at 60 °C. The metal carbonyl complex was decomposed using CuCl$_2$·2H$_2$O (20 mmol, 3.4 g) in acetone (15 mL). Saturated aqueous NaCl was added, and the resulting solution was extracted with ether. It was washed with brine, dried over anhydrous MgSO$_4$, and concentrated. The residue was subjected to column chromatography. The cyclobutenedione **1a** (63%, 0.383 g) was isolated using ethyl acetate (1%) in hexane.

Reaction of [HFe$_3$(CO)$_{11}$]$^-$ with Alkynes. The Fe(CO)$_5$ (2.9 g, 15 mmol) in THF (15 mL) was added dropwise for 1 h to NaBH$_4$ (0.567 g, 15 mmol) in THF (50 mL) and stirred for 8 h at 25 °C under nitrogen atmosphere. Acetic acid (2.7 g, 45 mmol) was added and the mixture stirred for 30 min. 1-Heptyne (0.24 g, 2.5 mmol) was added, and the contents were further stirred for 12 h. The metal carbonyl complex was decomposed using CuCl$_2$·2H$_2$O (6.8 g, 40 mmol) in acetone (25 mL). Saturated aqueous NaCl was added, and the contents were extracted with ether. The combined organic extract was washed with brine, dried, and concentrated. The residue was subjected to column chromatography (silica gel, hexane/ethyl acetate). Ethyl acetate (1%) in hexane eluted cyclobutenedione **7a** (73%, 0.275 g).[16a]

7a: yield 56% (0.21%); IR (neat): 1778 cm^{-1}; ^{1}H NMR δ 0.82 (t, $J = 7.3$, 3H), 1.27–1.40 (m, 4H), 1.70–1.83 (m, 2H), 2.81 (t, $J = 7.3$ Hz, 2H), 9.20 (s, 1H); ^{13}C NMR δ 13.7, 22.1, 25.6, 27.1, 31.2, 184.8, 196.6, 199.9, 208.3; MS(EI) m/z 152 (M), 81 (B).

Supporting Information Available: ^{13}C NMR spectra (50 MHz, CDCl$_3$) of all compounds and spectral data for all compounds (25 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

(30) (a) Dehmlow, E. V.; Lissel, M. *Tetrahedron* **1981**, *37*, 1653. (b) Brandsma, L.; Verkruijsse, H. D. *Synthesis of Acetylenes, Allenes and Cumulenes*; Elsevier: New York, 1981.

(31) Weast, R. C., Ed. *CRC Hand Book of Chemistry and Physics*; CRC Press: Boca Raton, 1974.