第 50 卷第 11 期 中国科学技术大学学报 Vol. 50, No. 11
2020 年 11 月 JOURNAL OF UNIVERSITY OF SCIENCE AND TECHNOLOGY OF CHINA Nov. 2020
Received：2020-11-09；Revised：2020-11-23 doi:10.3969/j.issn.0253-2778.2020.11.004

Visible light induced Barton decarboxylation free of radical initiators

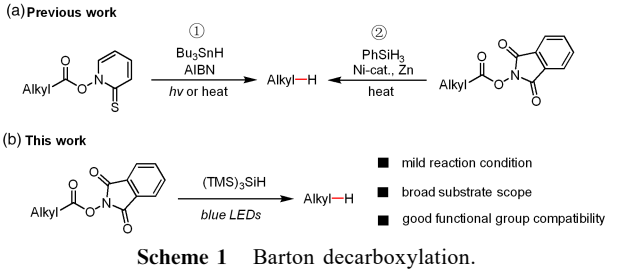
WANG Jiaxin, FU Mingchen*
Department of Chemistry, University of Science and Technology of China, Hefei 230026, China
*Corresponding author：fumingchen@ustc.edu.cn

Abstract：Herein, a novel protocol for visible light induced decarboxylation was reported. The method avoids the addition of radical initiators. A series of primary, secondary, and tertiary redox-active esters underwent decarboxylation efficiently, as well as amino acid and peptide derivatives. Many natural products and drug molecules containing carboxyl groups can also be transformed well. The method has mild reaction conditions, wide substrate scope, satisfactory functional group compatibility with good to excellent yields. The preliminary mechanism studies suggested that tris(trimethylsilyl)silane($(TMS)_3SiH$) acts not only as a hydrogen source, but also as an electron donor to form electron donor-acceptor (EDA) complex with redox-active esters, and the reaction involves the radical process.

Keywords：visible light induced; electron donor-acceptor complex; decarboxylation; radical; tris (trimethylsilyl)silane
CLC number：O621.2 **Document code**：A

1 Introduction

The unit of carboxylic acid is an important class of organic synthons, and commonly found in natural products and drug molecules[1-3]. Due to its intrinsic properties of being readily available, inexpensive, bench-stable, non-toxic and easy to store, they have been widely used in organic synthetic chemistry. The named reaction of Barton decarboxylation is an effective protocol for the decarboxylation of alkyl carboxylic acids into alkanes, which involves the radical process[4-7]. Barton esters (thiohydroxamic esters) can liberate carbon dioxide under light irradiation or heat conditions in the presence of tributyltin hydride and 2, 2'-azobis (2-methylpropionitrile) (AIBN) as the radical initiator, deliver a variety of alkanes (Scheme 1, (a) ①). Considering the toxicity of the reductant, other alternatives such as tris (trimethylsilyl) silane ($(TMS)_3SiH$)[8] or chloroform[9] have been introduced for Barton decarboxylation. However, these methods still inevitably use the low stability thiohydroxamic esters which are photo- and thermal sensitive, and the radical initiators. Therefore, it is still highly desirable to develop a much greener and more efficient method for Barton decarboxylation. For this, Okada and Oda's group developed a novel N-hydroxyphthalimide redox-active ester, which can be easily obtained from alkyl carboxylic acids and N-hydroxyphthalimide[10]. Using 1, 6-bis (dimethylamino) pyrene (BDMAP) as the photosensitizer and *tert*-butyl mercaptan as the hydrogen source, a series of alkyl carboxylic acid derivatives can proceed decarboxylation smoothly under the irradiation of 400 W Hg lamp. Recently, Baran et al. reported a nickel-catalyzed decarboxy-lative protocol using $PhSiH_3$ as a hydrogen atom source. Various functionalized N-hydroxyphthalimide redox-active esters successfully delivered the reductive decarboxylation products (Scheme 1,(a) ②)[11].



Scheme 1 Barton decarboxylation.

In recent years, the strategy of visible-light catalysis has received much attention in organic synthetic area, due to its ability to prompt chemists to discover new reactivity of traditional catalysts, and realize many important transformations that cannot be achieved by traditional methods[12-17]. Our laboratory made progress in this area[18,19], especially for visible light-induced general catalytic radical generation from electron donor-acceptor complex (EDA complex)[20-22]. The single electron donor or electron acceptor substrate

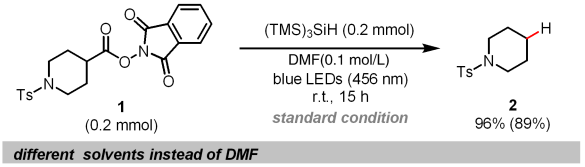
Citation：WANG Jiaxin, FU Mingchen. Visible light induced Barton decarboxylation free of radical initiators. J. Univ. Sci. Tech. China, 2020, 50(11): 1403-1410.

has no obvious absorption in visible light range but the resulting EDA complex does, and subsequently induces electron transfer to achieve free radical type conversion under visible light irradiation[23,24]. Based on continuous research in this field, we found that associating the redox-active esters of N-acyloxyphthali-mide as the electron acceptor with $(TMS)_3SiH$[25] as the electron donor can form the EDA complex, which can successfully undergo Barton decarboxylation process under the irradiation of 456 nm blue light-emitting diodes. The method has mild reaction conditions, wide substrate scope, good functional group compatibility. Primary, secondary, tertiary alkyl carboxylic acids, as well as amino acid and peptide derivatives smoothly underwent decarboxylation with good to excellent yields. The simple operation and high yields of this practical protocol will be a welcome advance for Barton decarboxylation.

2 Results and discussion

2.1 Screening of reaction conditions

Tab. 1 Key reaction-controlling parameters of decarboxylation.

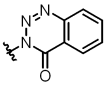
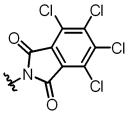


different solvents instead of DMF							
DMA	MeCN	THF	$PhCF_3$	CH_2Cl_2	EtOAc	dioxane	acetone
90	50	trace	trace	trace	trace	56	52

different silanes instead of $(TMS)_3SiH$					
$PhSiH_3$	Ph_2SiH_2	Et_2SiH_2	Ph_3SiH	Et_3SiH	$(EtO)_3SiH$
0	0	0	0	0	0

different wavelength of visible light			
467 nm	440 nm	427 nm	390 nm
40	95	96	93

control experiments		
w/o light, 60 °C	$(TMS)_3SiH$ (0.1 mmol)	$(TMS)_3SiH$ (0 mmol)
0	44	0

other redox-activation groups instead of -NPhth		
		
trace	55	94[a]

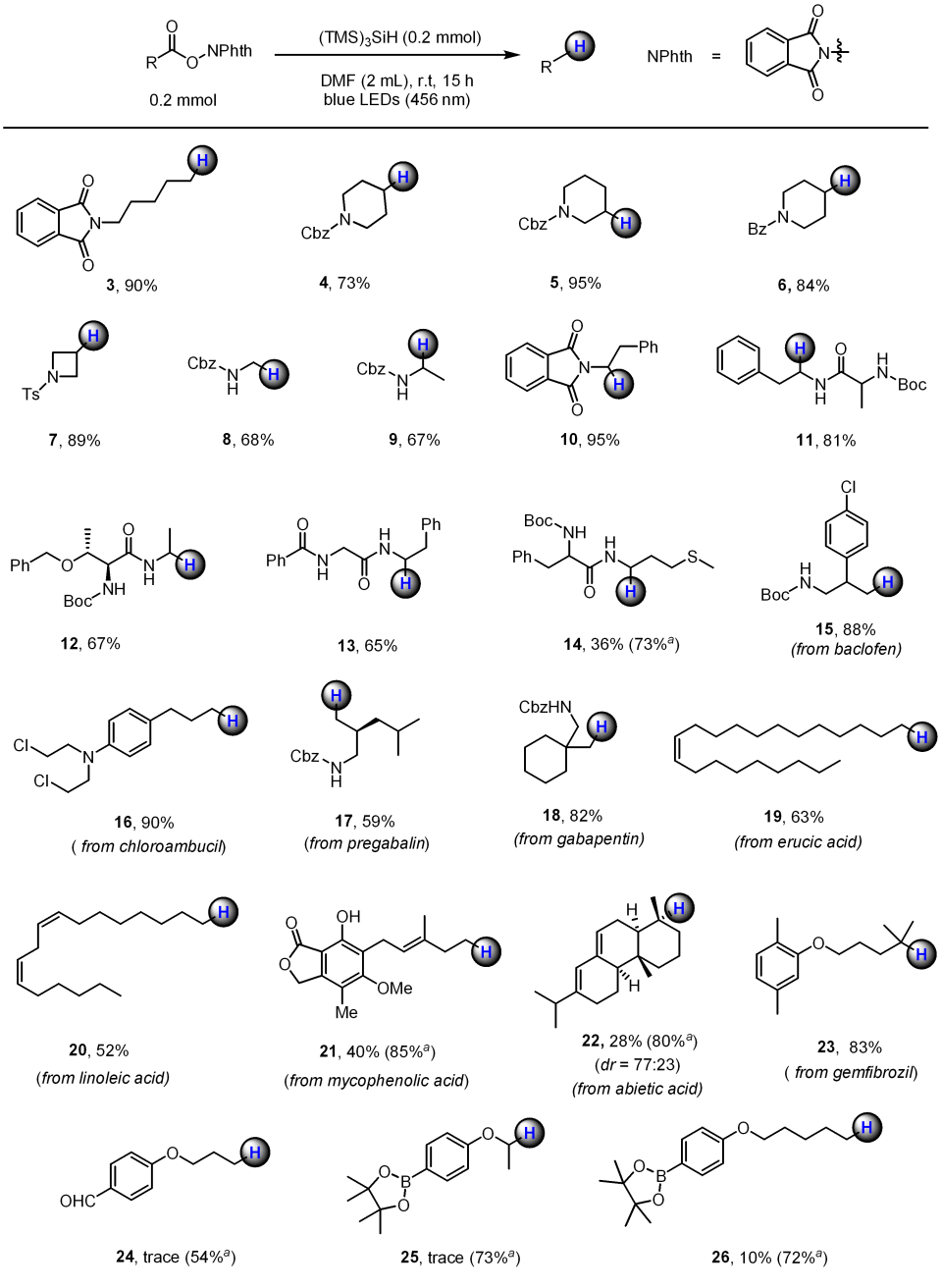
Reaction conditions: **1** (0.2 mmol), $(TMS)_3SiH$ (0.2 mmol), DMF (2.0 mL), room temperature (r.t.), 15 h, blue LEDs (456 nm). The yield was determined by ^1H NMR using diphenylmethane as internal standard. Isolated yield in parentheses.[a] Reaction time: 15 min.

Our investigation into the key reaction-controlling parameters of decarboxylation is shown in Tab. 1. At the beginning, **1** was chosen as the model substrate. After careful optimization of all reaction parameters, the desired product **2** was obtained in 96% yield using $(TMS)_3SiH$ (0.2 mmol) as hydrogen source in DMF (*N*, N-dimethylformamide) under 456 nm blue LEDs irradiation at room temperature. Solvation has a significant influence on the assembly of electron donor-acceptor complex and an effect on the reaction outcome (row 1). When using DMA (*N*,*N*-dimethylacetamide) as the solvent, 90% yield of the product was obtained. When using CH_3CN, dioxane or acetone instead of DMF, the reaction proceeded in lower yields. The reaction was totally suppressed when using THF (tetrahydrofuran), $PhCF_3$, CH_2Cl_2 or EtOAc as the solvent. To our surprise, other silanes, such as $PhSiH_3$, Ph_2SiH_2, Et_2SiH_2, Ph_3SiH, Et_2SiH_2 and $(EtO)_3SiH$ failed to afford the desired product with the raw materials remaining intact (row 2), which indicated that $(TMS)_3SiH$ acts not only as a hydrogen source, but also as the electron donor to form electron donor-acceptor (EDA) complex with **1**. Next, the wavelength of the irradiation source was investigated (row 3). The reaction performed smoothly under the wavelength of 390 nm to 456 nm, whereas the efficiency dramatically dropped when the wavelength was increased to 467 nm, only 40% yield of **2** was obtained. Control experiments showed that both irradiation and $(TMS)_3SiH$ were essential for the success of this new Barton decarboxylation protocol. The yield of the desired product **2** was decreased to 44% when the amount of $(TMS)_3SiH$ was reduced to 0.5 equivalent. In addition, we also investigated other types redox-active esters in this protocol (row 4). Using 3-hydroxy-1, 2, 3-benzotriazin-4 (3*H*)-one as the active group was ineffective, but 1-hydroxybenzo-triazole gave **2** in 55% yield. It was worth noting that when using tetrachloro-N-hydroxyphthalimide-derived redox-active esters, the desired product could be obtained equivalently within 15 min. Considering the issue of atom economy, we still chose N-hydroxyphthalimide types of redox-active esters in the following investigation.

2.2 Scope of the decarboxylation

With the optimized conditions in hand, we next explored the reaction scope for this hydrodecarboxylation. As shown in Tab. 2, primary, secondary and third redox-active esters of N-acyloxyphthalimide were readily converted to the corresponding alkanes in good to excellent yields. This protocol has good functional group tolerance, such as phthalimide (**3**), benzyloxycarbonyl (**4**, **5**), benzoyl (**6**) and p-toluenesulfonyl (**7**), all well-tolerated. Both six-membered ring and four-membered ring carboxylic acid-derivatives transformed smoothly (**4-7**). In addition, this protocol was also successfully applied to amino acid and peptide derivatives (**8**-**13**). Redox-active esters of amino acids or dipeptides with different protecting groups, such

Tab. 2 Scope of substrates



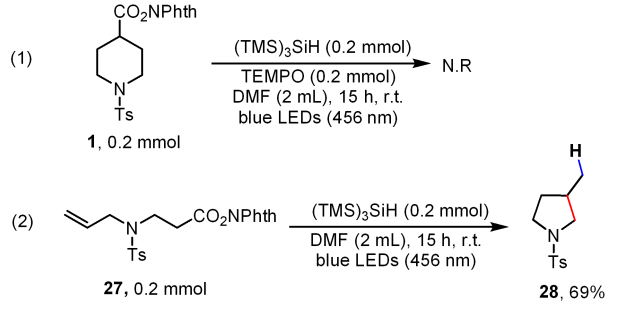
Reaction conditions:redox-active esters (0.2mmol, 1.0 eqiuiv.), $(TMS)_3SiH$ (0.2 mmol), DMF (2 mL), 15 h, r.t., blue LEDs (456 nm). Isolated yield.
[a] NaI (10 mol%), PPh_3(10 mol%).

as benzyloxycar-bonyl, phthalimide, and tert-butoxycarbonyl group, were amenable substrates, delivered 65% ～ 95% isolated yield of the desired product. Decarboxylative hydrogenation product **14** was obtained only in 36% isolated yield using this method. To our delight, we found the yield can be increased to 73% by adding a catalytic amount of sodium iodide and triphenylphosphine[18].

To further test the practicability of this method, we investigated a series of natural products and drug molecules containing carboxylic acid groups (**15**-**23**). The drug molecules derivatives, such as baclofen, chloroambucil, pregabalin, gabapentin, mycophenolic acid and gemfibrozil also underwent decarboxylation smoothly to the corresponding alkanes. Additionally, various carbonyl functional groups, including aryl chloride (**15**), alkyl chloride (**16**), N,N-dialkyl arylamine (**16**), ester (**21**) and aryl ether (**23**), were all tolerated under this condition. It was worth noting that the unprotected acidic phenolic hydroxyl group in

mycophenolic acid-derived Barton ester (**21**) also remained intact, and the yield could be successfully increased to 85% by adding a catalytic amount of sodium iodide and triphenylphosphine. Natural products, such as erucic acid, linoleic acid and abietic acid could be transformed smoothly, and the alkene group susceptived to free radicals also remained intact. All these results highlight the high chemoselectivity and functional group tolerance of the method. It should be noted that the activity of the reaction was totally suppressed when using the substrates containing aromatic aldehydes (**24**) and aromatic boronic esters (**25**, **26**). It is possible that these functional groups affect the formation of EDA complexes. Gratifyingly, by adding a catalytic amount of sodium iodide and triphenylphosphine, these types of substrates could smoothly undergo decarboxylation.

2.3 Mechanistic investigation



To further shed light on the mechanism of this method, the radical inhibitor 2, 2, 6, 6-tetramethylpiperidinyloxy (TEMPO) was added to the model reaction system (Eq. (1)), and the formation of product **2** was totally suppressed. Furthermore, the radical-clock experiment was conducted using **27** as the substrate, giving ring-closing pyrrolidine product **28** as exclusive product. These results all support the involvement of a free radical mechanism in this reaction[26].

A large number of literatures have been reported about the reaction with $(TMS)_3SiH$ participating as a radical-based reducing agent, with heating condition or with additional radical initiators (e. g. AIBN)[25]. However, the radical initiator was not necessary in this method. We speculated that $(TMS)_3SiH$ could act as the electron donor to form the chromophore (EDA complex) with *N*-acyloxyphthalimide redox-active ester as the electron acceptor through weak interaction. Under visible light irradiation, intermolecular electron transfer could occur between $(TMS)_3SiH$ and *N*-acyloxyphthalimide redox-active ester, subsequently generating alkyl radicals with liberating carbon dioxide, and then reacting with the reducing agent $(TMS)_3SiH$ to form the decarboxylated product.

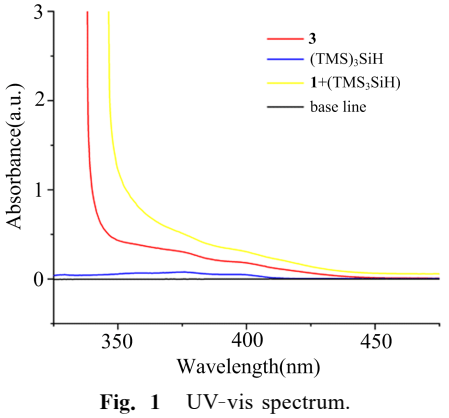


Fig. 1 UV-vis spectrum.

In order to further verify the above speculation,the ultraviolet-visible spectrophotometric experiment was carried out under the condition of maintaining the original concentration of the model reaction (Fig. 1). The experimental results showed that $(TMS)_3SiH$ has almost no absorption above the wavelength of 400 nm. However, an obvious redshift absorption of the mixed solution of $(TMS)_3SiH$ with compound **1** was observed compared to pure **1** solution, which confirmed that the chromophore was formed between $(TMS)_3SiH$ and **1** in DMF.

3 Conclusions

In summary, an efficient visible light induced Barton decarboxylation has been developed without using a radical initiator. The reaction proceeds under mild conditions with excellent functional group compatibility and broad substrate scope. Primary, secondary, and tertiary alkyl acid-derivatives underwent decarboxylation efficiently, as well as amino acid and peptide derivatives. Preliminary mechanism studies suggested that $(TMS)_3SiH$ acts not only as a radical-based reducing agent, but also as the electron donor to form electron donor-acceptor (EDA) complex with redox-active esters .

4 Experimental section

4.1 General procedure

General procedure A: Redox active ester (1.0 eq., 0.2 mmol) was placed in a 10 mL transparent Schlenk tube equipped with a stirring bar. The tube was evacuated and filled with argon (three times). To these solids, anhydrous DMF (2.0 mL) and $(TMS)_3SiH$ (1.0 eq., 0.2 mmol) were added via a gastight syringe under argon atmosphere. The reaction mixture was stirred under irradiation with blue LEDs (456 nm, distance app. 3.0 cm from the bulb), maintained at approximately room temperature in the air-conditioned room of 25°C. After 15 h, the mixture was quenched with 5 mL water, then extracted with ethyl acetate (3 x 10 mL). The organic layers were combined and concentrated under vacuo. The product was purified via flash column

chromatography on silica gel (petroleum ether/ethyl acetate=50:1～2:1).

General procedure B: Redox active ester (1.0 eq., 0.2 mmol), NaI (20 mol%), PPh_3(20 mol%) were placed in a 10 mL transparent Schlenk tube equipped with a stirring bar. The tube was evacuated and filled with argon (three times). To these solids, anhydrous DMF (2.0 mL) and $(TMS)_3SiH$ (1.0 eq., 0.2 mmol) were added via a gastight syringe under argon atmosphere. The reaction mixture was stirred under irradiation with blue LEDs (456 nm, distance app. 3.0 cm from the bulb), maintained at approximately room temperature in the air-conditioned room of 25 °C. After 15 h, the mixture was quenched with 5 mL water, then extracted with ethyl acetate (3 x 10 mL). The organic layers were combined and concentrated under vacuo. The product was purified *via* flash column chromatography on silica gel (petroleum ether/ethyl acetate=50:1～2:1).

4.2 Characterization data for products

1-tosylpiperidine (**2**)[11]: obtained following the procedure A, 95% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64 (d, J=8.2 Hz, 2H), 7.32 (d, J=8.1 Hz, 2H), 3.01－2.92 (m, 4H), 2.43 (s, 3H), 1.64 (dt, J=11.3, 5.8 Hz, 4H), 1.46－1.35 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.3, 133.2, 129.6, 127.7, 46.9, 25.2, 23.5, 21.5.

2-pentylisoindoline-1, 3-dione (**3**)[27]: obtained following the procedure A, 45.4 mg, 90% yield, white solid. The compound data was in agreement with the literature (Ref: *J. Am. Chem. Soc.* 2016, 138, 696－702). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69－7.60 (m, 2H), 7.56－7.49 (m, 2H), 3.51－3.45 (m, 2H), 1.58－1.37 (m, 2H), 1.23－1.04 (m, 4H), 0.70 (t, J=6.9 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 168.5, 133.8, 132.2, 123.1, 38.0, 29.0, 28.3, 22.3, 13.9.

benzyl piperidine-1-carboxylate (**4**)[6]: obtained following the procedure A, 32.0 mg, 73% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72－7.00 (m, 5H), 5.12 (s, 2H), 3.63－3.19 (m, 4H), 1.78－1.42 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.3, 137.0, 128.4, 127.9, 127.8, 66.9, 44.9, 25.7, 24.4.

phenyl(piperidin-1-yl)methanone (**6**)[28]: obtained following the procedure A, 31.8 mg, 83% yield, colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42－7.36 (m, 5H), 3.71 (s, 2H), 3.34 (s, 2H), 1.75－1.46 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 170.4, 136.4, 129.4, 128.4, 126.8, 48.8, 43.1, 26.4, 25.9, 24.6.

1-tosylazetidine (**7**)[29]: obtained following the procedure A, 37.6 mg, 89% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.73 (d, J=8.3 Hz, 2H), 7.38 (d, J=8.4 Hz, 2H), 3.87－3.71 (m, 4H), 2.47 (s, 3H), 2.18－1.94 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.0, 131.5, 129.7, 128.4, 50.9, 21.6, 15.3.

benzyl methylcarbamate (**8**)[30]: obtained following the procedure A, 22.5 mg, 68% yield, colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61－7.26 (m, 5H), 5.10 (s, 2H), 4.76 (br s, 1H), 2.79 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.0, 136.6, 128.5, 128.1, 66.7, 27.6.

benzyl ethylcarbamate (**9**)[31]: obtained following the procedure A, 24.0 mg, 67% yield, colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49－7.28 (m, 5H), 5.09 (s, 2H), 4.78 (br, 1H), 3.23 (br, 2H), 1.13 (t, J=7.2 Hz, 3H).^{13}C NMR (101 MHz, $CDCl_3$) δ 156.3, 136.7, 128.5, 128.1, 128.1, 66.6, 35.9, 15.3.

2-phenethyl-1H-indene-1,3(2H)-dione (**10**): obtained following the procedure A, 44.7 mg, 95% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82 (m, 2H), 7.74－7.67 (m, 2H), 7.33－7.17 (m, 5H), 3.92 (m, 2H), 3.04－2.84 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 168.2, 138.0, 133.9, 132.1, 128.9, 128.6, 126.7, 123.2, 39.3, 34.6. HRMS (ESI) *calcd*. for $C_{16}H_{13}NO_2Na^+$: $[M+Na]^+$: 274.0844, *found*: 274.0832

***tert*-butyl (1-oxo-1-(phenethylamino) propan-2-yl) carbamate** (**11**)[32]: obtained following the procedure A, 47.4 mg, 81% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34－7.15 (m, 5H), 6.33 (br s, 1H), 5.08 (br s, 1H), 4.11 (s, 1H), 3.62－3.41 (m, 2H), 2.81 (t, J=7.1 Hz, 2H), 1.43 (s, 9H), 1.31 (d, J=7.1 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 172.7, 155.5, 138.7, 128.7, 128.6, 126.5, 80.0, 50.1, 40.7, 35.7, 28.3, 18.6.

***tert*-butyl ((2S, 3R)-3-(benzyloxy)-1-(ethylamino)-1-oxobutan-2-yl) carbamate** (**12**): obtained following the procedure A, 45.1 mg, 67% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38－7.27 (m, 5H), 6.47 (br, 1H), 5.50 (d, J=6.2 Hz, 1H), 4.58 (q, J=11.4 Hz, 2H), 4.28－4.12 (m, 2H), 3.36－3.22 (m, 2H), 1.45 (s, 9H), 1.16 (d, J=6.3 Hz, 3H), 1.11 (t, J=7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 168.3, 154.6, 136.8, 127.2, 126.5, 126.4, 78.8, 73.6, 70.3, 56.3, 33.1, 27.0, 14.2, 13.5. HRMS (ESI) *calcd*. for $C_{18}H_{28}N_2O_4Na^+$: $[M+Na]^+$: 359.1947, *found*: 359.1939.

N-(2-oxo-2-(phenethylamino) ethyl) benzamide (**13**)[33]: obtained following the procedure A, 36.7 mg, 65% yield, white solid. ^{1}H NMR (400 MHz, CDCl3) δ 7.85－7.81 (m, 2H), 7.57－7.37 (m, 4H), 7.26－7.13 (m, 5H), 6.86 (brs, 1H), 4.08 (d, J=5.0 Hz, 2H), 3.54 (q, J=7.1 Hz, 2H), 2.82 (t, J=7.1 Hz, 2H). ^{13}C NMR (101 MHz, CDCl3) δ 169.3, 168.0, 138.6, 133.3, 132.0, 128.7, 128.6, 127.2, 126.6, 43.9, 40.9, 35.6.

tert-butyl(1-((3-(methylthio)propyl)amino)-1-oxo-3-phenylpropan-2-yl)carbamate (**14**): obtained following the procedure B, 51.5 mg, 73% yield, yellow liquid.^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33－7.13 (m, 5H), 6.04 (br s, 1H), 5.12 (br s, 1H), 4.28 (d, J=6.9 Hz, 1H), 3.26 (qt, J=13.3, 6.6 Hz, 2H), 3.03 (qd, J=13.5, 7.4 Hz, 2H), 2.52－2.31 (m, 2H), 2.03 (s, 3H), 1.66 (dd, J=13.1, 6.4 Hz, 2H), 1.40 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 171.2, 155.4, 136.8, 129.3, 128.7, 127.0, 80.2, 56.1, 38.7, 38.5, 31.4, 28.3,

28.3, 15.4. HRMS (ESI) *calcd*. for $C_{18}H_{28}N_2OSNa^+$: [M+Na]$^+$: 375.1718, *found*: 375.1707.

tert-butyl (2-(4-chlorophenyl) propyl) carbamate (15): obtained following the procedure A, 47.4 mg, 88% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31—7.23 (m, 2H), 7.13 (d, *J* = 8.3 Hz, 2H), 4.48 (br s, 1H), 3.35 (dd, *J* = 13.0, 6.4 Hz, 1H), 3.15 (ddd, *J* = 13.6, 8.2, 5.4 Hz, 1H), 2.91 (dd, J = 13.6, 6.7 Hz, 1H), 1.41 (s, 9H), δ 1.23 (dd, *J* = 7.0, 1.0 Hz, 3H). 13C NMR (101 MHz, CDCl3) δ 155.9, 142.7, 132.2, 128.7, 128.6, 79.2, 47.3, 39.6, 28. 4, 19. 0. HRMS (ESI) *calcd*. for $C_{14}H_{20}ClNO_2Na^+$: [M+Na]$^+$: 292.1080, *found*: 292.1073

N, N-bis (2-chloroethyl)-4-propylaniline (16): obtained following the procedure A, 46.8 mg, 90% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.08 (d, *J* = 8.7 Hz, 2H), 6.64 (d, *J* = 8.7 Hz, 2H), 3.76—3.57 (m, 8H), 2.53—2.46 (t, *J* = 14.5 Hz, 2H), 1.59 (dq, *J* = 14.8, 7.4 Hz, 2H), 0.93 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.9, 132.3, 129.7, 112.3, 53.8, 40.5, 36.9, 24.8, 13.9. HRMS (ESI) *calcd*. for $C_{13}H_{20}Cl_2N^+$: [M + H]$^+$: 260.0973, *found*: 260.0963.

benzyl (S)-(2,4-dimethylpentyl)carbamate (17): obtained following the procedure A, 38.2 mg, 77% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.51—7.27 (m, 5H), 5.30—4.99 (m, 2H), 4.83 (s, 1H), 3.13 (dt, *J* = 12.1, 5.9 Hz, 1H), 2.96 (dt, *J* = 13.4, 6.7 Hz, 1H), 1.88—1.49 (m, 2H), 1.13 (ddd, *J* = 13.8, 8.4, 5.7 Hz, 1H), 1.07—0.95 (m, 1H), 0.98—0.71 (m, 9H).^{13}C NMR (101 MHz, $CDCl_3$) δ 156.6, 136.7, 128.5, 128.1, 128.1, 66.6, 47.4, 43.7, 31.2, 25.2, 23. 4, 22. 1, 17. 6. HRMS (ESI) *calcd*. for $C_{15}H_{23}NO_2Na^+$:[M+Na]$^+$: 272.2626, *found*: 272.1616

benzyl ((1-methylcyclohexyl)methyl)carbamate (18): obtained following the procedure A, 42.7 mg, 82% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41—7.27 (m, 5H), 5.12 (d, *J* = 19.0 Hz, 2H), 4.81 (br s, 1H), 3.02 (dd, *J* = 18.0, 6.2 Hz, 2H), 1.59—1.34 (m, 5H), 1.36—1.11 (m, 5H), 0.87 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.81, 136.70, 128.54, 128.17, 128.12, 66.68, 51.34, 35.21, 34.29, 26.29, 23.00, 21.75. HRMS (ESI) *calcd*. for $C_{15}H_{24}NO_{2+}$: [M + H]$^+$: 262.1807, *found*: 262.1802.

(*Z*)-heptadec-8-ene (19)[9]: obtained following the procedure A, 27.2 mg, 67% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.44—5.28 (m, 2H), 2.06—1.99 (m, 4H), 1.37—1.24 (m, 22H), 0.89 (t, J = 6.8 Hz, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 128.1, 30.1(two singals), 28.0, 27.8, 27.6, 27.5(two singals), 25.4, 20.9, 12.3.

(6*Z*, 9*Z*)-heptadeca-6, 9-diene (20)[34]: obtained following the procedure A, 24.6 mg, 52% yield, white solid. ^{1}H NMR (400 MHz, CDCl3) δ 5.35—5.01 (m, 4H), 2.58 (t, J = 6.4 Hz, 2H), 1.86 (q, J = 6.8 Hz, 4H), 1.23—0.98 (m, 18H), 0.69 (m, J = 6.9, 3.3 Hz, 6H). ^{13}C NMR (101 MHz, CDCl3) δ 128.4, 126.2, 126.1, 30.1, 29.7, 27.9, 27.6, 27.5, 27.4, 25.5, 25.4, 23.8, 20.9, 20.8, 12.3, 12.3.

(*E*)-7-hydroxy-5-methoxy-4-methyl-6-(3-methylpent-2-en-1-yl) isobenzofuran-1(3*H*)-one (21): obtained following the procedure A, 47.0 mg, 85% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.67 (s, 1H), 5.20 (s, 1H), 5.19—5.16 (m, 1H), 3.77 (s, 3H), 3.40 (d, *J* = 6.9 Hz, 2H), 2.15 (s, 3H), 1.99 (q, *J* = 7.7 Hz, 2H), 1.79 (s, 3H), 0.97 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 173.0, 163.7, 153.7, 143.9, 137.7, 122.6, 120.4, 116.7, 106.4, 70.0, 61.0, 32.4, 22.6, 16.1, 12.6, 11.6. HRMS (ESI) *calcd*. for $C_{16}H_{20}O_4Na^+$: [M + Na]$^+$: 299.1259, *found*: 299.1250.

(1S/R,4aS)-7-isopropyl-1,4a-dimethyl-1,2,3,4,4a,4b,5,6,10,10a-decahydrophenanthrene (22)[35]: obtained following the procedure A, 36.2 mg, 80% yield, colorless liquid (d: r = 77: 23). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.78 (s, 1H, vinyl H), 5.52—5.37 (m, 1H, vinyl H), 2.30—2.03 (m, 4H), 1.82 (tq, *J* = 10.6, 3.6 Hz, 5H), 1.66—1.39 (m, 6H), 1.06—0.96 (m, 10H), 0.78 (s, 2.3H, major diastereoisomer), 0. 72 (s, 0. 7H, minor diastereoisomer).

1,4-dimethyl-2-((4-methylpentyl)oxy)benzene (23): obtained following the procedure A, 34.3 mg, 83% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.00 (d, *J* = 7.4 Hz, 1H), 6.65 (d, *J* = 7.6 Hz, 1H), 6.62 (s, 1H), 3.92 (t, *J* = 6.5 Hz, 2H), 2.30 (s, 3H), 2.18 (s, 3H), 1.84—1.75 (m, 2H), 1.62 (dp, *J* = 13.3, 6.7 Hz, 1H), 1.39—1.32 (m, 2H), 0.92 (d, *J* = 6.6 Hz, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.1, 136.4, 130.3, 123.6, 120.5, 112.0, 68.1, 35.3, 27.8, 27.3, 22.6, 21.4, 15.8. HRMS (ESI) *calcd*. for $C_{14}H_{23}O^+$ [M+H]$^+$:207.1749, *found*: 207.1739.

4-propoxybenzaldehyde (24)[36]: obtained following the procedure B, 32.0 mg, 73% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.88 (s, 1H), 8.37—7.54 (m, 2H), 7.15—6.80 (m, 2H), 4.01 (t, *J* = 6.6 Hz, 2H), 2.11—1.77 (m, 2H), 1.06 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 190.9, 164.3, 132.0, 129.7, 114.8, 69.9, 22.4, 10.5.

2-(4-ethoxyphenyl)-4, 4, 5, 5-tetramethyl-1, 3, 2-dioxaborolane (25)[37]: obtained following the procedure B, 36.2 mg, 90% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.74 (d, *J* = 8.6 Hz, 2H), 6.88 (d, *J* = 8.7 Hz, 2H), 4.05 (q, *J* = 7.0 Hz, 2H), 1.41 (t, *J* = 7.0 Hz, 3H), 1.33 (s, 12H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 161.5, 136.5, 113.8, 83.5, 63.2, 24.9, 14.8.

4,4,5,5-tetramethyl-2-(4-(pentyloxy)phenyl)-1,3,2-dioxaborolane (26): obtained following the procedure B, 41.6 mg, 72% yield, white solid. ^{1}H NMR (400 MHz, CDCl3) δ 7.77 (d, J = 8.5 Hz, 2H), 6.92 (d, J = 8.5 Hz, 2H), 4.00 (t, J = 6.6 Hz, 2H), 2.01—1.69 (m, 2H), 1.61—1.10 (m, 16H), 0.96 (t, J = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 162.34, 137.08, 136.22, 114.45, 84.11, 68.36, 29.51, 28.78, 25.45, 23.06, 14.63. ^{1}HRMS (ESI) *calcd*. for $C_{17}H_{27}BO_{3+}$: [M+H]$^+$: 291.2132, *found*: 291.2117.

3-methyl-1-tosylpyrrolidine (28)[38]: obtained following

the procedure A, 33.0 mg, 69% yield, white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69 (d, J = 8.2 Hz, 2H), 7.30 (d, J = 8.0 Hz, 2H), 3.40 (dd, J = 9.7, 7.2 Hz, 1H), 3.36－3.29 (m, 1H), 3.23－3.16 (m, 1H), 2.73 (dd, J = 9.7, 7.8 Hz, 1H), 2.42 (s, 3H), 2.10 (td, J = 14.7, 7.1 Hz, 1H), 1.93－1.84 (m, 1H), 1.33 (dq, J = 12.3, 8.3 Hz, 1H), 0.90 (d, J = 6.7 Hz, 3H).^{13}C NMR (101 MHz, $CDCl_3$) δ 143.25, 134.02, 129.60, 127.53, 54.77, 47.62, 33.32, 33.26, 21.55, 17.65.

Acknowledgements

This work was supported by the USTC Research Funds of the Double First-Class Initiative (YD2060002003).

Conflict of interest

The authors declare no conflict of interest.

Author information

WANG Jiaxin is currently a Master student in the Lab of Anhui Province Key Laboratory of Biomass Clean Energy under the supervision of Associate Prof. Shi Jing at University of Science and Technology of China. Her current research mainly focuses on visible light driven radical synthetic chemistry.

FU Mingchen (corresponding author) received his Ph.D. degree in Organic Chemistry from University of Science and Technology of China (USTC). He is currently an associate researcher at USTC. His research interests include photochemistry in organic synthesis and carbonylation reaction using formic acid as the carbon source.

References

[1] Shang R, Liu L. Transition metal-catalyzed decarboxylative cross-coupling reactions. Sci. China. Chem., 2011, 54: 1670-1687.

[2] Johanna S, Burkhaed K. Decarboxylative reactions with and without light-a comparison. Green Chem., 2018, 20: 323-361.

[3] Patrick J M, Rylan J L. Metal-catalyzed ionic decarboxylative cross-coupling reactions of C(sp^3) acids: reaction development, mechanisms, and application. ACS. Catal., 2020, 10: 1742-1753.

[4] Barton D H R, Crich D, Motherwell W B. New and improved methods for the radical decarboxylation of acids. J. Chem. Soc. Chem. Commun., 1983, 939-941.

[5] Barton D H R, Crich D, Motherwell W B. The invention of new radical chain reactions. Part VIII. Radical chemistry of thiohydroxamic esters; A new method for the generation of carbon radicals from carboxylic acids. Tetrahedron, 1985, 41: 3901-3924.

[6] Li Z, Wang K F, X Z, et al. Manganese-mediated reductive functionalization of activated aliphatic acids and primary amines. Nat. Commun., 2020, 11:5036.

[7] Bosque I, Bach T. 3-Acetoxyquinuclidine as catalyst in electron donor-acceptor complex-mediated reactions triggered by visible light. ACS Catal. 2019, 9: 9103-9109.

[8] Kazuya Y, Yuji K, Hiroshi A, et al. Construction of a cis-cyclopropane via reductive radical decarboxylation. Enantioselective synthesis of cis- and trans-1-Arylpiperazyl-2-phenylcyclopropanes designed as antidopaminergic agents. J. Org. Chem., 2003, 68: 9255-9262.

[9] Ko E J, Savage G P, Williams C M, et al. Reducing the cost, smell, and toxicity of the barton reductive decarboxylation: chloroform as the hydrogen atom source. Org. Lett., 2011, 13: 1944-1947.

[10] Okada K, Okamoto K., Oda M. A new and practical method of decarboxylation: photosensitized decarboxylation of N-acyloxyphthalimides via electron-transfer mechanism. J. Am. Chem. Soc., 1988, 110: 8736-8738.

[11] Qin T, Malins L R, Edwards J T, et al. Nickel-catalyzed barton decarboxylation and giese reactions: A practical take on classic transforms. Angew. Chem. Int. Ed., 2017, 56: 260-265.

[12] Prier C K, Rankic D A, Macmillan D W C. Visible light photoredox catalysis with transition metal complexes: Applications in organic synthesis. Chem. Rev., 2013, 113: 5322-5363.

[13] Marzo L, Pagire S K, Reiser O, et al. Visible-light photocatalysis: Does it make a difference in organic synthesis? Angew. Chem. Int. Ed., 2018, 57: 10034- 10072.

[14] Fawcett A, Pradeilles J, Wang Y H, et al. Photoinduced decarboxylative borylation of carboxylic acids. Science, 2017, 357: 283-286.

[15] Liang, Y, Zhang X, Macmillan D W C. Decarboxylative sp3 C-N coupling via dual copper and photoredox catalysis. Nature, 2018, 559: 83-88.

[16] Mao R, Frey A, Balon J, et al. Decarboxylative sp^3 C-N coupling via dual copper and photoredox catalysis. Nat. Catal., 2018, 1: 120-126.

[17] Hu A H, Guo J J, Pan H, et al. Selective functionalization of methane, ethane, and higher alkanes by cerium photocatalysis. Science, 2018, 361: 668.

[18] Wang G Z, Shang R, Cheng W M, et al. Irradiation-induced heck reaction of unactivated alkyl halides at room temperature. J. Am. Chem. Soc., 2017, 139: 18307-18312.

[19] Cheng W M, Shang R, Fu Y. Irradiation-induced palladium-catalyzed decarboxylative desaturation enabled by a dual ligand system. Nat. Commun., 2018, 9: 5215-5224.

[20] Fu M C, Shang R, Zhao B, et al. Photocatalytic decarboxylative alkylations mediated by triphenylphosphine and sodium iodide. Science, 2019, 363: 1429.

[21] Fu M C, Wang J X, Shang R. Triphenylphosphine-catalyzed alkylative iododecarboxylation with Lithium Iodide under Visible Light. Org. Lett., 2020, 22: 8572-8577.

[22] Wang Y T, Fu M C, Zhao B, et al. Photocatalytic decarboxylative alkenylation of α-amino and α-hydroxy acid-derived redox active esters by NaI/PPh_3 catalysis. Chem. Commun., 2020, 56: 2495-2498.

[23] Crisenza G E M, Mazzarella D, Melchioorre P. Synthetic methods driven by the photoactivity of electron-donor acceptor complexes. J. Am. Chem. Soc., 2020, 142: 5461-5476.

[24] Mcclain E J., Monos T M, Mori M, Beatty J W, Stephenson C R J. Design and implementation of a catalytic electron donor-acceptor complex platform for radical trifluoromethylation and alkylation. ACS. Catal., 2020, 10: 12636-12641.

[25] Chatgilialoglu C. $(Me_3Si)_3SiH$: twenty years after its discovery as a radical-based reducing agent. Chem. Eur. J., 2008, 14: 2310-2320.

[26] Zhang L, Wu Z Q, Jiao L. Photoinduced radical borylation of alkyl bromides catalyzed by 4-Phenylpyridine. Angew. Chem. Int. Ed., 2020, 59: 2095-2099.

[27] Quinn R K, Könst Z A, Michalak S E, et al. Site-selective aliphatic C-H chlorination using N-chloroamides enables a

synthesis of chlorolissoclimide. J. Am. Chem. Soc., 2016, 138: 696-702.
[28] Balaboina R, Thirukovela S N, Vadde R, et al. Amide bond synthesis via silver(I) N-heterocyclic carbene-catalyzed and tert-butyl hydroperoxide-mediated oxidative coupling of alcohols with amines under base free conditions. Tetrahedron Lett., 2019, 60: 847-851.
[29] Li Zhou, Ebule R, Kostyo J, et al. HBr-DMPU: The first aprotic organic solution of hydrogen bromide. Chem. Eur. J., 2017, 23: 12739-12743.
[30] Peixoto S, Nguyen T M, Crich D, et al. One-pot formation of piperidine- and pyrrolidine-substituted pyridinium salts via addition of 5-alkylaminopenta-2, 4-dienals to N-acyliminium ions: Application to the synthesis of (±)-Nicotine and analogs. Org. Lett., 2010, 12: 4760-4763.
[31] Artuso E, Degani I, Fochi R, et al. One-pot, three-step preparation of alkyl and aryl alkylcarbamates from S-methyl N-alkylthiocarbamates. Synthesis, 2008, 10: 1612-1618.
[32] Zhao H, Huang Z, Chen W. Total synthesis of tricladins A and B and identification of their absolute configuration. J. Org. Chem., 2014, 79: 11290-11294.
[33] Cassani C, Bergonzini G, Wallentin C J. Photocatalytic decarboxylative reduction of carboxylic acids and its application in asymmetric Synthesis. Org. Lett., 2014, 16: 4228-4231.
[34] Hutzinger M W, Oehlschlager A C, Stereoselective synthesis of 1, 4-dienes. Application to the preparation of insect pheromones (3Z,6Z)-dodeca-3,6-dien-1-ol and (4E,7Z)-trideca-4,7-dienyl acetate. J. Org. Chem., 1995, 60: 4595-4601.
[35] Barton D H R, Crich D, Motherwell W B. The invention of new radical chain reactions. Part VIII. Radical chemistry of thiohydroxamic esters; A new method for the generation of carbon radicals from carboxylic acids. Tetrahedron, 1985, 41: 3901-3924,
[36] Feng Q, Song Q. Aldehydes and ketones formation: Copper-catalyzed aerobic oxidative decarboxylation of phenylacetic acids and α-hydroxyphenylacetic acids. J. Org. Chem., 2014, 79: 1867-1871.
[37] Dong J, Guo H, Hu Q S. Room temperature Ni^0/PCy3 -catalyzed coupling reactions of aryl arenesulfonates with bis (pinacolato)diboron. Eur. J. Org. Chem., 2017, 47: 7087-7090.
[38] Pan X, Lacôte E, Lalevée J, et al. Polarity reversal catalysis in radical reductions of halides by N-heterocyclic carbene boranes. J. Am. Chem. Soc., 2012, 134:5669-5674.

无需自由基引发剂参与实现可见光诱导 Barton 脱羧

王佳鑫，付明臣*
中国科学技术大学化学系，安徽合肥 230026

摘要：报道了一种可见光诱导 Barton 脱羧的新方法.在不需要外加自由基引发剂的条件下，可以实现一系列一级、二级、三级以及氨基酸、多肽类氧化还原性羧酸酯脱羧，而且许多含有羧基的天然产物及药物分子也可以很好地发生转化，反应条件温和、底物范围广，具有良好的收率和官能团兼容性.初步机理实验研究表明，三(三甲基硅基)硅烷在该反应体系中不仅作为氢源，同时也作为电子给体和氧化还原性羧酸作用形成电子供体-受体复合物，反应经历自由基历程.

关键词：可见光诱导；电子供体-受体复合物；脱羧；自由基；三(三甲基硅基)硅烷