MECHANOCHEMISTRY

Redox reactions of small organic molecules using ball milling and piezoelectric materials

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Over the past decade, photoredox catalysis has harnessed light energy to accelerate bond-forming reactions. We postulated that a complementary method for the redox-activation of small organic molecules in response to applied mechanical energy could be developed through the piezoelectric effect. Here, we report that agitation of piezoelectric materials via ball milling reduces aryl diazonium salts. This mechanoredox system can be applied to arylation and borylation reactions under mechanochemical conditions.

isible light photoredox catalysis represents a recent key development in contemporary organic synthesis (1–5). In these transformations, the photoexcited catalyst can act as a potent single-electron oxidant, transferring an electron to an acceptor, after which single-electron oxidation of a donor affords the product under concomitant regeneration of the ground-state catalyst (Fig. 1A). The broad success of photoredox catalysis hinges on the susceptibility of the coupling partners to redox activation and ensuing bond-forming reactions with high levels of efficiency and selectivity.

There has also been substantial parallel progress in mechanochemical organic transformations using ball milling (6-18). Since the term mechanochemistry was introduced by Ostwald in 1887, mechanochemical synthesis has been extensively exploited in materials science (6-8), polymer chemistry (9), and inorganic synthesis (8), but its application to organic synthesis is more recent (10-18). Advantages of mechanochemical synthesis using ball milling include the avoidance of potentially harmful organic solvents and external heating, shorter reaction times, and simpler operational handling. Additionally, mechanochemical reactions are particularly useful for substrates that are poorly soluble in common organic solvents.

Inspired by the unique profile of photoredox systems based on light irradiation and the utility of ball milling in mechanochemistry, we hypothesized that redox activation of small organic molecules could be achieved through a mechanistically distinct approach using mechanical energy (19-22). Specifically, we envisioned that the agitation of piezoelectric materials (23-35) via ball milling could generate temporarily highly polarized particles. These particles might act as strong reductants to transfer electrons to small organic molecules, followed by oxidative quenching of a donor, thereby inducing the selective formation of bonds in a manner analogous to photoredox catalysis (Fig. 1B). Such a mechanoredox approach could potentially represent a powerful and attractive strategy to reduce the environmental impact of chemical processes; photoredox approaches, similarly to other conventional organic reactions, often require complicated reaction setups, substantial amounts of dry and degassed organic solvents, and an inert gas atmosphere (1-5).

For a proof-of-concept study, we selected commercially available, inexpensive, and easyto-handle BaTiO₃ nanoparticles as the piezoelectric material (Fig. 1B). This choice was motivated by pioneering studies, in which ultrasonic agitation of BaTiO₃ produces a suitable electrochemical potential to overcome the water splitting potential (1.23 V) (28, 29) and reduce a N,N,N',N',N'',N''-hexamethyl[tris(aminoethyl) amine] (Me₆TREN)-ligated CuBr₂ complex, which has a reduction potential of -0.30 V [versus saturated calomel electrode (SCE)] (29, 36). These studies suggested that mechanical agitation of BaTiO₃ in a ball mill could generate an electrochemical potential suitable for



Fig. 1. Working hypothesis for a mechanoredox system for the activation of small organic molecules in organic synthesis. (**A**) A commonly employed photoredox catalyst and a generic photoredox oxidative quenching cycle. A, acceptor; D, donor. (**B**) Proposed mechanoredox paradigm using a ball mill and a piezoelectric material. (**C**) Proposed mechanism for the mechanoredox arylation and borylation using BaTiO₃ and ball milling. *t*Bu, tertiary butyl; ppy, (2-pyridinyl)phenyl; dtbpy, 4.4'-di-tert-butyl-2,2'-bipyridine; pin, pinacolato; R, substituent.

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the activation of redox-active, small organic molecules in organic synthesis.

The photoredox systems that activate aryl diazonium salts for coupling with heteroarenes (37) or borylation (38) have been reported by König and Yan, respectively. The key step in these transformations is the photochemical reduction of aryl diazonium salts to aryl radical species. Andrieux and Pinson have reported a reduction potential of -0.16 V (versus SCE) for phenyl diazonium tetrafluoroborate (39), which was within range for feasible redox activation using BaTiO₃. In our postulated mechanism (Fig. 1C), the agitation of BaTiO₃ via ball milling generates a temporary electrochemical potential in response to mechanical impact. According to the aforementioned inorganic studies (28, 29), the temporary polarization should be sufficiently persistent to reduce an aryl diazonium salt (1) via a single-electron transfer (SET) mechanism analogous to the photoredox reaction, to furnish the corresponding aryl radical I. The addition of I to heteroarene 2 would afford radical addition intermediate II, which would be subsequently oxidized by the hole in the agitated BaTiO₃ to form carbocation intermediate III (37). Finally, deprotonation of III would lead to arylation product **3**. In the borylation (38), the generated radical I reacts with bis(pinacolate) diboron (4), to cleave the B-B bond, resulting in the formation of the boryl substitution product 5 as well as radical anion intermediate IV. Subsequently, oxidation of IV by the agitated BaTiO₃ could form F-B(pin) (V) as a by-product.

To explore this mechanistic hypothesis, we first attempted the proposed mechanoredox C-H arylation with 1a and furan (2a) in the presence of commercially available BaTiO₃, using a Retch MM400 mixer mill (1.5-ml stainless steel milling jar with 5-mm diameter stainless steel ball) (Fig. 2A). The corresponding arylation product (3a) was obtained in 40% yield after milling at 20 Hz for 1 hour under air. The reaction did not proceed in the absence of BaTiO₃, suggesting that the mechanical energy provided by ball milling generated the piezoelectric potential to reduce 1a. In contrast, even when ultrasound irradiation was applied to the mixture with BaTiO₃ in dimethyl sulfoxide (DMSO) under a nitrogen atmosphere, the formation of the product was not observed. A small amount of 3a was obtained when the reaction was carried out in the presence of SrTiO₃, which exhibits piezoelectric properties upon applying in-plain strain (40). When using non-piezoelectric ceramic materials, such as TiO₂, BaCO₃, or Al₂O₃, the reaction did not proceed, which suggests that piezoelectric materials are essential for this arylation reaction. We found that conducting the reaction at higher ball-milling frequency (30 Hz) substantially improved the yield (81%).



Optimization for mechanoredox arylation

catalyst	milling frequency (Hz)	NMR yield of 3a (%)
BaTiO ₃	20	40
none	20	<1
BaTiO ₃	-	<1*
SrTiO ₃	20	3
TiO ₂	20	<1
BaCO ₃	20	<1
Al ₂ O ₃	20	<1
BaTiO ₃	30	81
LiNbO ₃	30	24
ZnO	30	15

1 none MeCN 1 54 DMF 1 37

Optimization for mechanoredox borylation

time (h)

LAG

NMR yield

of 5a (%)

21

DMSO	1	13
toluene	1	11
hexane	1	15
MeCN	1.5	62
MeCN	3	89
MeCN	3	<1*
*Reaction was	carried out v	vithout BaTiO ₃ .

В



Fig. 2. Mechanoredox arviation and borvlation using mechanical force. (A) Optimization of the mechanoredox arylation and borylation reactions. (B) Reaction mixture of the mechanoredox arylation of 2a after grinding in a ball mill. A stainless steel milling jar (1.5 ml) and a stainless steel ball (diameter, 5 mm) were used. See supplementary materials for details. equiv, equivalent; h, hour.

This result is consistent with our hypothesis that the required piezoelectric potential is generated by mechanical force provided by the ball milling of BaTiO₃. Using other piezoelectric materials, such as LiNbO₃ and ZnO, also afforded 3a, albeit in lower yield (24% and 15%, respectively). Using a bigger jar (5.0 ml) and ball (7.5 mm) provided 3a in high yield (82%, table S2). Product **3a** was isolated by filtration of the obtained crude solid mixture (Fig. 2B), followed by column chromatography on silica gel.

We then investigated the possibility of mechanoredox borylation using the same setup (Fig. 2A). We found that the borylation of 1a with $\mathbf{4}$ in the presence of BaTiO₃ afforded the desired arylboronate (5a) in 21% yield. Next, we attempted to improve the reactivity by using liquid-assisted grinding (LAG), in which a substoichiometric amount of liquid is added (41). In all LAG reactions, the ratio of liquid additive (microliters) to reactant (milligrams) was 0.12. Use of acetonitrile (MeCN) as the LAG additive improved the yield of 5a, whereas other common solvents, such as N.N-dimethylformamide (DMF), DMSO, toluene, or hexane, led to little or no improvement. We also found that prolonging the reaction time led to a higher yield of 3a (89%) when MeCN was used as the LAG additive. Using a bigger jar (5.0 ml) and ball (7.5 mm) did not substantially affect the transformation (86%, table S3). The reaction without $BaTiO_3$ did not proceed, supporting our mechanistic hypothesis. Compared with the analogous photoredox reaction, the present mechanoredox borylation exhibited much faster reaction kinetics and a better product yield (38).

Subsequently, we explored the scope of the mechanoredox arvlation reaction with various aryl diazonium salts using a 5-ml stainless steel milling jar with a 7.5-mm diameter stainless steel ball (Fig. 3A). Electron-deficient aryl diazonium salts (1a to 1h) were converted into the desired products (3a to 3h) in good yield under the optimized conditions. Simple aromatic substrates (1i to 1k) also reacted to give the corresponding products (3i to 3k) in good

Fig. 3. Scope of the mechanoredox arylation and borylation reactions using aryl diazonium

salts. Data for each entry (in bold) are reported as isolated yield percentages. Proton NMR integrated yields are shown in parentheses. (A) Substrate scope of the mechanoredox arylation of heteroaromatic compounds. (B) Substrate scope of the mechanoredox borylation of aryl diazonium salts. Reactions were performed at 0.3 mmol scale using a stainless steel milling jar (5 ml) and stainless steel ball (diameter, 7.5 mm). Arylation conditions: 1 (0.3 mmol), 2 (4.5 mmol), and BaTiO₃ (1.5 mmol). Borylation conditions: 1 (0.3 mmol), 4 (0.3 mmol), BaTiO₃ (1.5 mmol), and MeCN (0.12 µL/mg). See supplementary materials for details. Me, methyl; Boc, tertiary butoxycarbonyl.



yield. However, in the case of an electron-rich, methoxy-substituted diazonium salt (11), the product (31) was obtained in relatively low yield. This was probably due to the relatively high reduction potential of 11. Other heteroarenes, namely, thiophene and pyrrole, successfully reacted to form the desired products (3m and 3n). Arylation reactions using thienyl diazonium salts afforded the corresponding heterobiaryls (3o and 3p), which are typical structural motifs for organic semiconductors (42). Minor regioisomers (3mb and 3pb) were observed as competing products in the reac-

tions with thiophene, whereas the photoredox system developed by König and co-workers, using eosin Y, produced **3ma** and **3pa** as single isomers (*37*). We also confirmed that the developed mechanoredox borylation conditions were applicable to a variety of aryl diazonium salts (Fig. 3B).

To demonstrate the practical utility of this protocol, we investigated a gram-scale synthesis of heterobiaryls under the developed mechanoredox conditions, as well as the recycling of $BaTiO_3$ (Fig. 4, A and B). The mechanoredox C–H arylation of furan (**2a**) with **10** was car-

ried out on an 8-mmol scale in a 25-ml stainless steel ball-milling jar with one 15-mm diameter stainless steel ball, affording **30** in 71% yield (Fig. 4A). After separation from the crude reaction mixture and washing, BaTiO₃ could be reused for the mechanoredox arylation of furan (**2a**) under the same reaction conditions at least three times before the yield of **3k** declined substantially (Fig. 4B).

Direct C–H arylation of polycyclic aromatic hydrocarbons (PAHs) has attracted considerable interest (43, 44) on account of their role in organic light-emitting diodes, organic photovoltaics,

A Gram-scale synthesis



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Fig. 4. Exploration of a

gram-scale synthesis, catalyst recycling, and the arylation of polyaromatic

hydrocarbon compounds.

(A) Mechanoredox arylation

of 2a with 1o on the gram

milling jar (pictured on the right). (**B**) BaTiO₃ recycling experiments using **1k** and

2a. (C) Mechanoredox aryl-

ation of the polyaromatic

hydrocarbons 6 with 1f.

See supplementary

materials for details.

rt. room temperature.

scale using a 25-ml ball-

organic semiconductors, and organic thinfilm transistors. With this in mind, we conducted a preliminary investigation of the feasibility of the C-H arylation of PAHs using our mechanoredox approach (Fig. 4C). The reaction of 1f with pyrene (6a) in the presence of BaTiO₃ and a small amount of MeCN as the LAG additive afforded the desired C-H arylation product (7aa) in good vield with high regioselectivity (7aa:7ab = 92:8). Furthermore, coronene (6b) was also arylated in moderate vield under the mechanoredox conditions. When the arylation of coronene (6b) was attempted via König's photoredox procedure using eosin Y, no reaction occurred (37). This was probably due to the low solubility of coronene (6b) in the polar solvents required for such photoredox reactions. These results demonstrate the promising potential of the mechanoredox arylation as an operationally simple and mild route to synthesize functionalized PAHs from poorly soluble substrates that are incompatible with photoredox conditions.

We postulated that the mechanoredox C–H arylation and borylation were proceeding via SET events, in which an aryl radical is generated through piezoelectric reduction (Fig. 1C); this assumption is supported by the results of preliminary mechanistic investigations (Fig. 5). When 2,2,6,6-tetramethylpiperidinoxyl (TEMPO) (**8**) was treated with aryl diazonium salt **1a** in the absence of furan (**2a**), the TEMPO-trapped intermediate **9** was obtained (Fig. 5A). Furthermore, the addition of TEMPO (**8**) to a reaction mixture containing **1a**, furan (**2a**), and BaTiO₃ halted the arylation process, and the TEMPO-trapped intermediates **9** and **10** were detected (Fig. 5A). Compound **10** might have been formed through the reaction of TEMPO (**8**) with the intermediate **II** (Fig. 1C), followed by oxidative aromatization by BaTiO₃ or atmospheric oxygen. Overall, the identified compounds suggest that the mechanoredox activation with BaTiO₃ proceeds via a radical pathway.

We used a scanning electron microscopy (SEM) analysis to confirm that the mechanical stimulus provided by ball milling is transferred onto the BaTiO₃ particles under the applied conditions (Fig. 5B) (24). The SEM image of commercially available BaTiO₃ powder shows



Fig. 5. Mechanistic studies. (A) Radical scavenger experiments. (B) SEM images of BaTiO₃ particles (i) before and (ii) after ball milling (30 Hz; 60 min). (C) Thermographic image of the milling jar after the mechanoredox arylation of **2a** with **1a**. See supplementary materials for details. GC-MS, gas chromatography–mass spectrometry.

a regular shape of the BaTiO₃ particles before the reaction (approximate size, $<75 \,\mu$ m) [Fig. 5B (i)]. Subsequently, the powder was subjected for 60 min to ball milling at 30 Hz and then analyzed by SEM. The resulting image clearly shows a pronounced distortion of the shape and a decrease in the size of the BaTiO₃ particles [Fig. 5B (ii)]. These results suggest that the mechanical stimulus provided by ball milling is efficiently transferred onto the BaTiO₃ particles, which would result in the generation of localized electrochemical potentials on the surface of the BaTiO₃ particles that can be used for the activation of the aryl diazonium salts.

To investigate whether the friction during ball milling generates a thermal effect, the temperature inside the milling jar during the mechanoredox arylation of **2a** with **1a** was measured using thermography immediately after opening the jar (Fig. 5C). The crude mixtures were prepared under optimized conditions. The obtained image showed that the temperature after arylation in the ball mill was around 30°C, which discounts the possibility of thermal activation of the aryldiazonium salts generating aryl radical species by the heat provided from ball milling.

To demonstrate the robustness of the mechanoredox transformations, we conducted the borylation of **1k** with $BaTiO_3$ in air using a hammer (fig. S8 and movie S1). First, the reaction mixture was prepared by gentle grinding in a mortar. Subsequently, the mixture was wrapped in a piece of a weighing paper and placed in a zipper-locking plastic bag, followed by striking with a hammer over 200 times. Even under these crude conditions, the mechanoredox borylation product **5i** was obtained in 43% yield, as assessed by nuclear magnetic resonance (NMR) integration.

The present mechanoredox reactions can be carried out on gram scale without the use of large amounts of dry and degassed organic solvents in air, and the reactions do not require special operating conditions. This operational simplicity suggests that the present approach may complement existing photoredox transformations in a practical and environmentally friendly manner. Beyond the immediate benefits of this protocol, our strategy could be applicable to light-sensitive or light-absorbing substrates that cannot be subjected to conventional photoredox systems.

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ACKNOWLEDGMENTS

Funding: This work was supported by the Japan Society for the Promotion of Science (JSPS) through KAKENHI grants 18H03907, 17H06370, and 19K15547; by the JST CREST grant number JPMJCR19R1; and by the Institute for Chemical Reaction Design and Discovery (ICReDD), which was established by the World Premier International Research Initiative (WPI), MEXT, Japan. Y.P. thanks the Otsuka Toshimi Scholarship Foundation for a scholarship. We thank D. F. Toste and T. Shimada for advice on the preparation of this manuscript. We thank Nippon Chemical Industrial Co., Ltd. for the gift of piezoelectric materials. Author contributions: H.I. came up with the original idea; K.K. and H.I. directed the project; K.K. and H.I. designed the experiments; K.K. and Y.P. performed the experiments; A.M. prepared ceramic materials used in this study; and K.K. and H.I. wrote the manuscript with feedback from the other authors. Competing interests: H.I. and K.K. are inventors on patent application JP, 2019-163323 submitted by Hokkaido University that covers mechanoredox reactions using piezoelectric materials and manufacturing methods using the reaction setup with the ball mill. The authors declare no other competing interests. Data and materials availability: All data are available in the supplementary materials.

SUPPLEMENTARY MATERIALS

10.1126/science.aav8224

science.sciencemag.org/content/366/6472/1500/suppl/DC1 Materials and Methods Figs. S1 to S9 Tables S1 to S5 NMR Spectra References (45–58) Movie S1 22 July 2019; accepted 30 October 2019



Redox reactions of small organic molecules using ball milling and piezoelectric materials

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Science **366** (6472), 1500-1504. DOI: 10.1126/science.aay8224

Redox catalysis in a ball mill

Mixing solid reactants in a ball mill is a promising means of avoiding the copious solvent waste associated with most chemical syntheses. Kubota *et al.* now report that adding a piezoelectric catalyst to the mix can promote bond formation through apparent electron transfer cycles (see the Perspective by Xia and Wang). Specifically, barium titanate activates aryl diazonium salts toward borylation and coupling with heterocycles in a manner reminiscent of solutionphase photoredox catalysis. The reactions are insensitive to air and were demonstrated up to gram scale. *Science*, this issue p. 1500; see also p. 1451

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