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Resonant acoustic mixing (RAM) for efficient mechanoredox catalysis without grinding or impact media†

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Resonant acoustic mixing (RAM) enables mechanoredox catalysis with BaTiO₃ as the piezoelectric catalyst on model diazonium coupling reactions. RAM proceeds without formal grinding or impact media, is faster than the analogous ball-milling strategy, and is readily scalable. X-ray diffraction and spectroscopy indicate that reusability of BaTiO₃ as a mechanoredox catalyst under ball-milling or RAM might be limited by boration.

Mechanochemical reactions by impact, stress or shear have emerged as powerful approaches for synthesis without bulk solvents.^{1,2} Mechanochemistry also offers unexpected benefits, such as enhanced control over reaction selectivity, stoichiometry, as well as reactions or products that are difficult to achieve in solution.³ An exciting opportunity in mechanosynthesis, introduced by the Ito group, is the use of a piezoelectric material, such as BaTiO₃, to catalyse electron-transfer reactions.⁴ In such mechanoredox catalysis,⁵ the mechanical impact from the grinding media (*e.g.*, milling balls) triggers the piezoelectric effect on the catalyst, enabling reaction progress. Grinding media, however, are generally found to complicate mechanochemical reaction design because of unwanted leaching, abrasion, and/or chipping.⁶ Moreover, the complex motion of such media renders scaling-up difficult, requiring changes to instrument design and/or further trial-and-error screening of reaction parameters such as filling ratios, milling frequency, choice and number of milling balls.⁷

Resonant Acoustic Mixing (RAM, Fig. 1), a technology developed for media-free mixing and blending of sensitive materials,

such as explosives,⁸ can enable mechanosynthesis without either bulk solvent or milling media. So far, RAM has been used for synthesis of cocrystals,^{8,9} metal–organic frameworks, and for metal-catalysed coupling reactions.^{10,11} In contrast to ball-milling, RAM reaction design is simplified by the absence of grinding media, and reactions are readily scalable.¹¹

Here we show that, despite the lack of mechanical impact from milling media, RAM is amenable to piezoelectric catalysis. By using commercial cubic BaTiO₃ as catalyst, we establish single electron transfer (SET) borylation and arylation of diazonium salts,[‡] scalable from *ca.* 0.1 gram to at least gram amounts (Fig. 1). When the catalyst is reused, a loss of activity is observed, but is smaller than under ball-milling. We tentatively attribute this activity loss to *in situ* BaTiO₃ boration.

Cubic BaTiO₃ was obtained from Sigma-Aldrich, with declared particle size < 100 nm (BET, ≥ 99% purity trace metals basis), and was used as-is. As a model reaction we chose the borylation of aryldiazonium salts, with *p*-chlorobenzenediazonium tetrafluoroborate (**1a**) and bis(pinacolato)boron (**bpb**) as test substrates. Because this reaction pioneered mechanoredox catalysis,⁴ it offers an opportunity to compare RAM and ball-milling protocols. Acoustic mixing was performed using a Resodyn LabRAM II instrument, with samples placed in glass vials mounted on in-house designed holders (Fig. 1A and B).¹¹ RAM of an equimolar mixture (0.3 mmol each) of **1a** and **bpb** at an acceleration of 90g ($g = 9.81 \text{ m s}^{-2}$) led to no reaction, as revealed by ¹H-NMR analysis in DMSO-*d*₆. Addition of 300 mg (4.3 equivalents) of BaTiO₃, however, led to *ca.* 10% conversion to the anticipated product **2a** after 3 h. Similar results were seen when RAM was performed with a small amount of a non-polar liquid additive (ratio of the liquid volume to weight of solid reaction mixture $\eta = 0.25 \text{ } \mu\text{L mg}^{-1}$) such as hexanes (17%) or toluene (13%). Acetonitrile (MeCN) as the liquid additive at $\eta = 0.10 \text{ } \mu\text{L mg}^{-1}$ led to 92% NMR conversion to **2a** in 3 h, comparable to a 3 hour ball-milling protocol.⁶

Screening¹³ of reaction times at $\eta = 0.25 \text{ } \mu\text{L mg}^{-1}$ indicated that reaction conversion increases for up to 2 h of RAM and

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Fig. 1 (A) Resodyn LabRAM II instrument and (B) different views of the in-house designed RAM sample holder used in this work; (C) the mechanoredox diazonium borylation studied in this work; (D) η -dependent conversion for the borylation of *p*-chlorophenyldiazonium tetrafluoroborate (**1a**, R = *p*-Cl) with **bpb** after 1 hour RAM, and (E) time-dependent conversion for the reaction conducted at $\eta = 0.10$ and $0.25 \mu\text{L mg}^{-1}$. All reactions were performed in triplicate, at 90g, using 0.3 mmol of **1a** and 0.3 mmol of **bpb** in the presence of BaTiO₃ (300 mg, 4.3 eq. with respect to **1a**) and MeCN liquid additive. The ¹H NMR yields were obtained upon dissolution of the crude product in DMSO-*d*₆.

then levels off, which is noticeably shorter compared to 3 h reported for ball-milling (Fig. 1E). Attempts to further optimize the reaction through screening η -values between 0 and $1.5 \mu\text{L mg}^{-1}$ revealed maximum conversion (η_{max})¹⁴ at $\eta = 0.25 \mu\text{L mg}^{-1}$ (Fig. 1D). Conversion fell at lower accelerations, and at lower amounts of BaTiO₃. Consequently, all work was performed at 90g, using 4.3 equivalents of BaTiO₃ (see ESI†). The relevance of BaTiO₃ for the reaction was verified by conducting RAM with the same weight amount of Celite, sand, or NaCl. In each case, only trace of reaction was observed by ¹H NMR (below 5%).

The established RAM conditions were applicable to a range of aryldiazonium salts, with diverse positioning and nature of the aromatic ring substituent. In almost all cases, reactions proceeded with high (>80%) to excellent (>95%) yields within 2 h (Scheme 1). For substrates with unexceptional conversions after 2 h (e.g., **1c**, **1d**), the yield of product increased significantly upon extending the reaction time to 3 h, e.g., from 69% to 90% for **2d**. For substrates **1a–1g**, the NMR yields (70–99%) are significantly higher than reported by ball-milling (52–86%, see also ESI†).⁴

From the examples in Scheme 1, there is no clear trend between the electronic properties of arene and the yield of **2**. For example, diazonium salts bearing two meta-substituents,

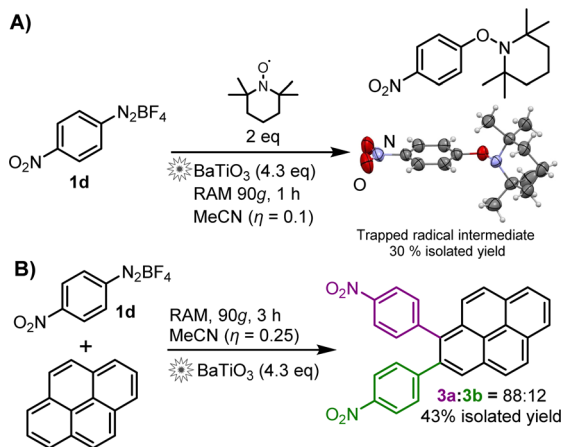
Scheme 1 NMR yields of products **2a–2j** bearing different substituents, with isolated yields in parentheses. Reaction conditions: 0.3 mmol **1a–1j**, 0.3 mmol **bpb** (0.63 mmol for **1j**), 1.29 mmol (4.3 equivalents) of BaTiO₃, MeCN ($\eta = 0.25 \mu\text{L mg}^{-1}$) at RAM acceleration of 90g for 2 or 3 h. *Isolated yields after column chromatography.

1h and **1i**, both provide more than 90% NMR yields after 2 h of RAM, despite electronically very different groups (–OMe in **1h**, –CF₃ in **1i**). Overall, RAM-based mechanoredox catalysis provides access to a broad range of products with excellent yields, faster than previously reported for ball-milling. Efficiency of RAM opens access to ditopic substrates such as **1j**, when using 2.1 equivalents of **bpb**. Here, **2j** was obtained in 92% after 3 h, i.e., 96% yield per each pinacolato boron function (67% isolated yield).

We hypothesize that the RAM reaction mechanism is much the same as *via* ball-milling, i.e., follows a radical SET mechanism. This is supported by the reaction of **2d** in the presence of BaTiO₃ and two equivalents of TEMPO radical scavenger (Scheme 2A). After 1 h, the expected⁴ TEMPO-trapped radical intermediate was obtained in 30% yield, characterised by ¹H and ¹³C NMR, as well as X-ray single-crystal diffraction.

Application of RAM to mechanoredox catalysis is not limited to borylation, as demonstrated by a successful pyrene arylation (Scheme 2B). RAM of pyrene and **1d** proceeded readily over 3 h in the presence of MeCN ($\eta = 0.25 \mu\text{L mg}^{-1}$) and BaTiO₃ (4.3 equivalents) to produce a 88:12 mixture of 1- and 2-(4-nitrophenyl)pyrenes (**3a**, **3b**) in 43% overall isolated yield.

Because BaTiO₃ is present in super-stoichiometric amounts, we also explored the possibility of re-using it. In a typical procedure, with **1a** as the model reactant, RAM was conducted over 1 h, and BaTiO₃ was separated from the crude reaction mixture by extracting the organic materials with ethyl acetate (EtOAc), followed by centrifugation and drying, before being used in the next reaction cycle. Mass loss of BaTiO₃ between cycles ranged between 5 and 10%. Upon several such reactions, the yield of **2a** per cycle steadily decreased, from 68% when using pristine BaTiO₃ to 11% after the fourth cycle (Table 1).



Scheme 2 (A) Radical-trapping reaction by RAM mechanoredox catalysis, using TEMPO as the radical scavenger. A molecule of the TEMPO-trapped reaction intermediate is shown using a thermal ellipsoid plot (50% probability) based on single crystal X-ray crystal structure analysis (CCDC deposition number 2205247†). (B) Pyrene arylation via BaTiO₃-catalysed RAM mechanoredox reaction; the **3a** : **3b** ratio was determined by ¹H-NMR spectroscopy in CDCl₃ solution.

Table 1 NMR yields of **2a** for 1 hour mechanoredox borylation of **1a** with **bpb** using recycled BaTiO₃, conducted by ball-milling or RAM^a

Cycle	Ball-milling NMR yield (%)	RAM NMR yield (%)
1	43	68
2	32	42
3	10	21
4	8	11

^a Reactions were performed for 1 h in the presence of MeCN as liquid additive (ball-milling at 30 Hz in a 10 mL zirconia jar and ball; RAM at 90g). ¹H NMR yields were obtained by dissolving the crude product in DMSO-d₆.

Loss of BaTiO₃ activity was also seen in ball-milling reactions (Table 1). A potential cause for the higher yields and improved retention of BaTiO₃ activity in RAM might be the gentler nature of acoustic mixing, evident from scanning electron microscopy (SEM) images of BaTiO₃ before and after reactions by RAM and by ball milling (Fig. 2A). Commercial BaTiO₃ was found to consist of spherical particles, tens of micrometers in size, that were significantly disrupted by ball-milling. By contrast, RAM led to little morphological change, but for a layer of finer material on the larger particles.

Further analysis of BaTiO₃ across multiple reaction cycles was carried out by powder X-ray diffraction (PXRD) and Fourier-transform infrared attenuated total reflectance spectroscopy (FTIR-ATR) (Fig. 2B and C, also ESI†).^{§15} Analysis by PXRD revealed very little broadening of BaTiO₃ Bragg reflections after four runs under either RAM or ball-milling conditions, indicating that the loss of reactivity in either protocol is not due to crystal structure disruption. PXRD analysis of materials after the 3rd and 4th cycles revealed the appearance of new, low-intensity X-ray reflections distinct from those of BaTiO₃, suggesting the formation of a yet unidentified phase.

Surprisingly, FTIR-ATR spectra revealed the appearance of a new absorption band at 1050 cm⁻¹ immediately after the first

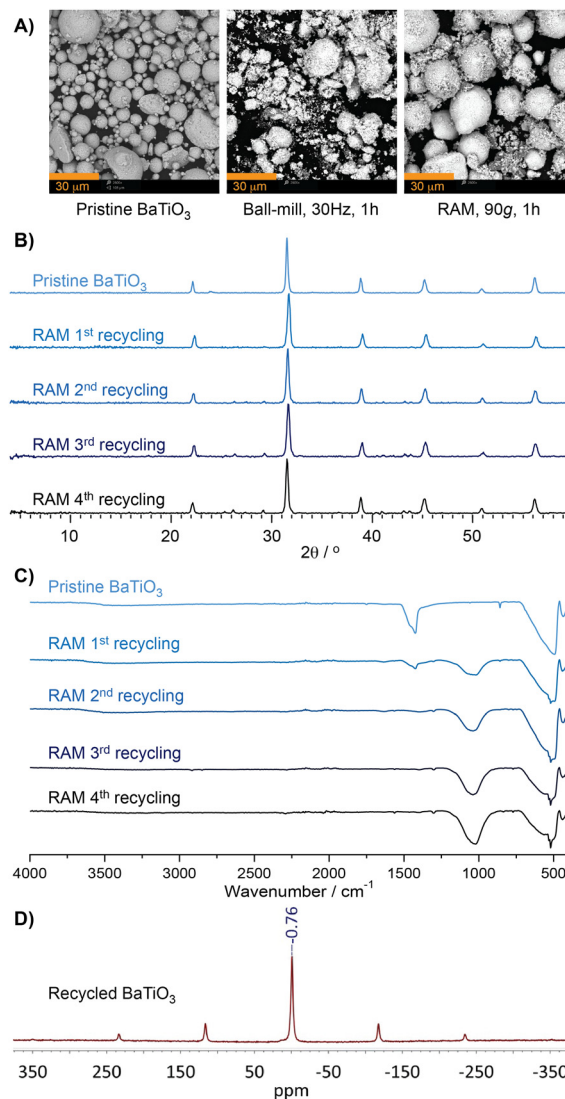


Fig. 2 Investigation of recyclability of BaTiO₃ in mechanoredox catalysis by RAM and by ball-milling. (A) SEM images of BaTiO₃ particles: pristine, recycled from a ball-milling, and from a RAM process. (B) PXRD patterns for BaTiO₃ pristine and recycled from RAM reactions. (C) Comparison of FTIR-ATR spectra for BaTiO₃ pristine and recycled from RAM reactions. (D) ¹¹B ssNMR spectrum of BaTiO₃ recycled from a RAM mechanoredox reaction.

cycle. This new band, not seen for pristine BaTiO₃, is retained upon extensive washing with EtOAc, suggesting a strongly bound and/or inorganic species arising from the reaction mixture.

Moreover, thermogravimetric analysis (TGA) of recycled BaTiO₃, conducted in air up to 900 °C, did not reveal any loss of weight that would have been expected from adsorbed organic materials. Consequently, we speculate that the feature at 1050 cm⁻¹ would be related to a boron species, as the infrared B–O and B–F stretching bands are found around 900–1100 cm⁻¹, depending on the chemical environment.¹⁶ In order to verify the presence of boron, a washed sample of the BaTiO₃ after one cycle was analysed by ¹¹B solid-state NMR (ssNMR) spectroscopy, which revealed a signal centered at –0.76 ppm with respect to F₃B–O(C₂H₅)₂ (Fig. 2D). The ¹¹B signal exhibited symmetry

consistent with a tetrahedral boron species, such as BO_4 or BF_4 .¹⁷ No boron signal was detected in pristine BaTiO_3 initially used for this reaction (see ESI†). BaTiO_3 analysis by X-ray photoelectron spectroscopy (XPS) was largely inconclusive due to the overlap of the B 1s and Ba 4p_{1/2} regions, but the growth of the peak around 193 eV suggests incorporation of boron (see ESI†).¹⁸ Based on spectroscopy, we suggest that the loss of BaTiO_3 activity might be due to the incorporation and/or surface adsorption of boron species.¶¹⁹

Finally, we explored the potential to scale-up RAM-based mechanoredox reactions. Previous reports indicate that scaling-up RAM conditions can be simple and straightforward.¹⁰ Here, the BaTiO_3 -catalysed reaction between **1a** and **bpb** was immediately adapted from the initial scale of 150 mg reactants to 2 grams, while retaining the same relative amounts of BaTiO_3 and MeCN (see ESI†). Such linear scaling-up led to 80% conversion to **1b** within 2 h and >99% conversion after 3 h.

In summary, combining mechanoredox catalysis and RAM provides an attractive protocol that simultaneously avoids milling media, enables reactivity driven by the piezoelectric effect, and achieves excellent yields faster than a ball-milling process. While the effectiveness of BaTiO_3 as a catalyst drops upon repeated use, the loss of activity is smaller than under ball-milling. This loss appears to be due to inadvertent boration of BaTiO_3 by mechanochemical reaction components, which purports the need to develop more robust mechanoredox catalysts.

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Conflicts of interest

There are no conflicts to declare.

Notes and references

‡ Diazonium salts should always be handled with care and reactions performed behind a glass shield.

§ The FTIR-ATR spectrum of pristine BaTiO_3 reveals a band at 1425 cm^{-1} , ascribed to small amounts of carbonate.¹⁵ Upon mechanoredox catalysis, this band vanishes, and can also be removed by calcination in N_2 (see ESI†).

¶ Deactivation of BaTiO_3 by boron species would be consistent with a slower loss of catalyst activity reported for mechanoredox arylation reactions with furan.⁴

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