

## Mechanochemistry

## Mechanochemical Gold(III)-Carbon Bond Formation

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**Abstract:** Starting from a [(<sup>MeO</sup>C<sup>^</sup>N<sup>^</sup>C)AuCl] complex as precursor, a direct substitution by C,H-activation from sp<sup>2</sup>- or sp<sup>3</sup>-C,H-bonds under basic conditions in a planetary ball mill was achieved. Because of the extraordinary photophysical properties of the target compounds, this protocol provides an easy access to a highly valued complex class. In contrast to existing protocols, no pre-functionalization of the starting materials is necessary and the use of expensive transition metal catalysts can be avoided, which makes this application appealing also for industrial purposes. In addition the methodology was not restricted to pincer complexes, which was demonstrated by the substitution of chelate type [(tpy)AuCl<sub>2</sub>] complexes.

A stronger focus on sustainability in a fast growing world is of great importance for mankind. The increasing demand for products is often tolerated at the expense of the environment. In order to improve sustainability and to protect the world from chemical waste or hazardous compounds the “12 principles of green chemistry” were introduced by Anastas and Warner.<sup>[1–3]</sup> In this context, mechanochemical applications allow an almost solvent-free synthesis of high value products. By grinding solids in a ball mill, chemical reactions take place which can, in an easy manner, lead to the desired products—simply driven by mechanical energy.<sup>[4–9]</sup> With this in hand, ball milling fulfills most of the principles of green chemistry. In this context, Pilarski et al. recently introduced mechanochemistry for the synthesis of arylated gold(I) complexes, which were obtained in good to excellent yields.<sup>[10]</sup> Because of the extraordinary photophysical properties of gold(III) compounds, especially of [(C<sup>^</sup>N<sup>^</sup>C)AuCl]

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complexes, we envisioned that the utilization of mechanochemistry towards these targets would be of significant interest.

Arylated or alkynylated [(C<sup>^</sup>N<sup>^</sup>C)AuCl] complexes were already applied in OLEDs,<sup>[11–16]</sup> PHOLEDs<sup>[17]</sup> and TADF, <sup>[18]</sup> respectively. In 2012, the group of Bochmann synthesized a [(<sup>tBu</sup>C<sup>^</sup>N<sup>^</sup>C<sup>tBu</sup>)AuOH] complex which served as key precursor for the isolation of different arylated and one alkynylated C<sup>^</sup>N<sup>^</sup>C-gold(III) compounds. While the arylation with different aryl boronic acids proceeded very well, a direct C,H-activation, avoiding the need for pre-functionalization, was limited to the reaction with pentafluorobenzene (Scheme 1 a).<sup>[19]</sup> In 2017, the group of Che used almost the same reaction conditions for the arylation of [(C<sup>^</sup>N<sup>^</sup>C)AuCl] complexes that showed good photoluminescence and solution-processed OLEDs made with these compounds showed high external quantum efficiencies.<sup>[14]</sup> Still one significant drawback for this reaction exists, namely the rather complex pre-preparation of the hydroxide complex. In addition, boronic acids also served as aryl precursors, these had to be synthesized before the reaction and are accompanied by the formation of stoichiometric amounts of waste salts.<sup>[14]</sup> A different approach was published by Yam et al. in 2017. A palladium-catalyzed Suzuki-like reaction enabled the direct arylation of [(C<sup>^</sup>N<sup>^</sup>C)AuCl] complexes in reasonable yields using aryl boronic acids as coupling partners (Scheme 1 b).<sup>[18,20]</sup> But the high catalyst and ligand loadings and the need for inert conditions make this protocol costly and circuitously. Very recently, our group exploited the reaction of [(C<sup>^</sup>N<sup>^</sup>C<sup>tBu</sup>)AuCl] with phenyl lithium to obtain the arylated [(C<sup>^</sup>N<sup>^</sup>C)Au] complex in 62 % yield (Scheme 1 c)<sup>[21]</sup> But the need of a moisture-sensitive organometallic reagent makes this entry laborious. Alternatively, the photochemical reaction of a diazonium salt with pentafluorophenylgold(I) dimethyl sulfide complex delivered the corresponding Au<sup>III</sup> complex. While this direct, mercury-free synthesis of the arylated gold(III) complex is attractive, the pre-preparation of the gold(I) compound is a disadvantage for this protocol. For this reason we were interested in a more sustainable, easy to handle and direct arylation of [(C<sup>^</sup>N<sup>^</sup>C)AuCl] complexes by ball milling (Scheme 1 d).

A 20 mL stainless steel container was charged with 50 stainless steel balls (5 mm in diameter), [(<sup>MeO</sup>C<sup>^</sup>N<sup>^</sup>C)AuCl] complex **1**, 4 equivalents of 1,5-dibromo-2,4-difluorobenzene and potassium *tert*-butoxide. The reaction was conducted in a planetary ball mill using 10 cycles (30 minutes each, interrupted by breaks of 15 minutes), which is comparable to the protocol of Pilarski et al.<sup>[10]</sup> To our delight, the corresponding arylated gold(III) complex **2a** was isolated in 42 % yield (Scheme 2). The connectivity of product **2a** was

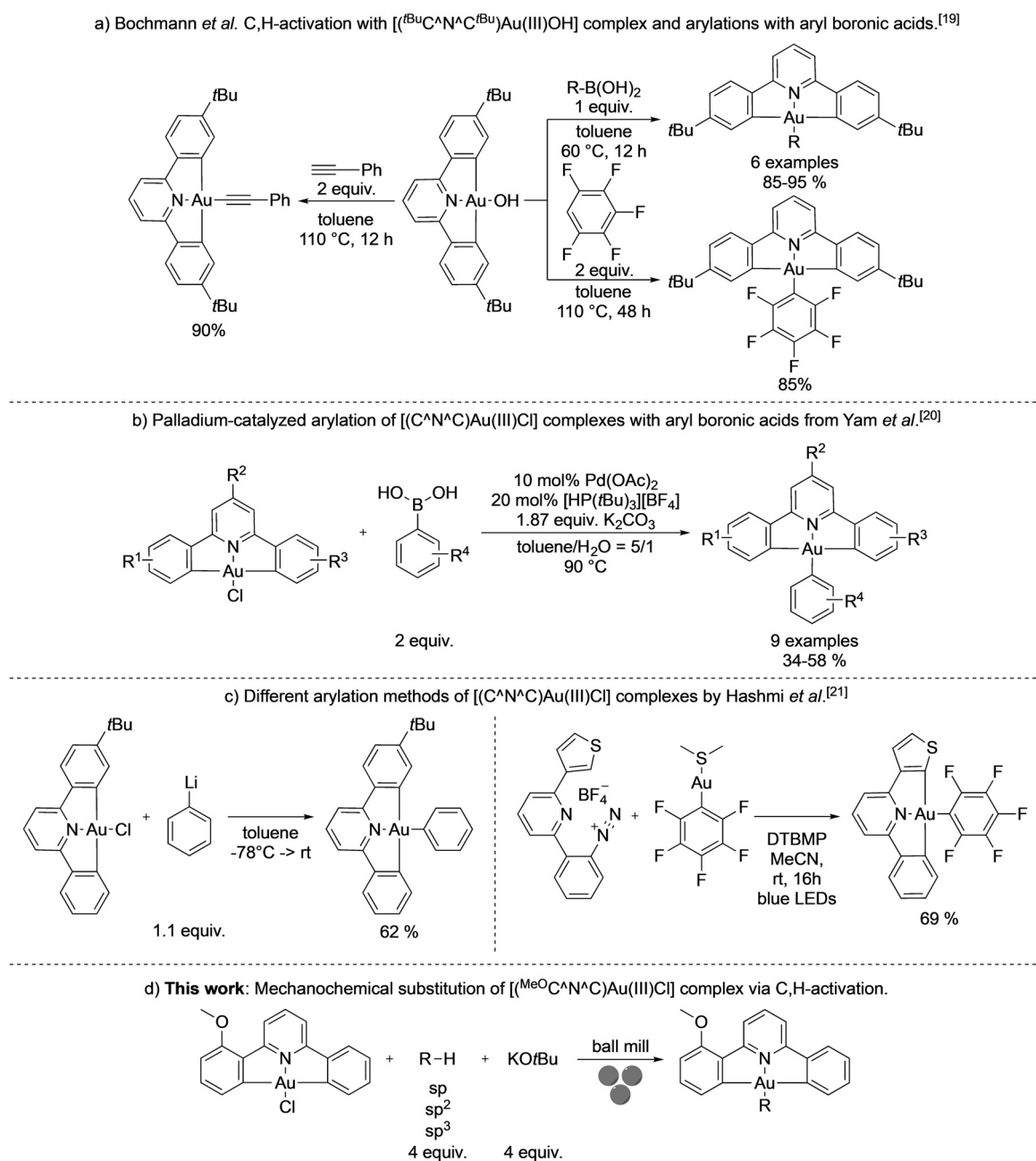
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**Scheme 1.** Overview of different arylation methods of  $[(\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{Au}]$  complexes.

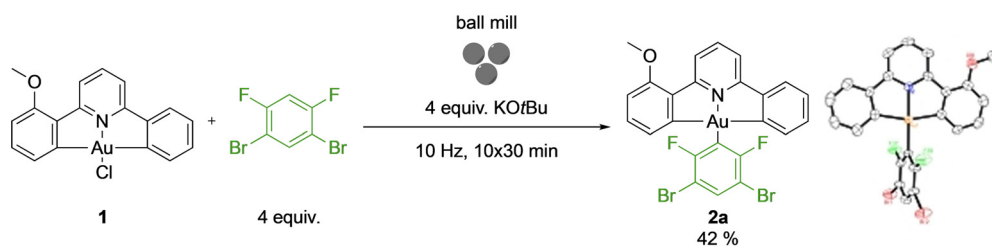
unambiguously confirmed by an X-ray single crystal structure analysis (Scheme 2, right side).

As partial decomposition was observed, we reduced the ball milling cycles to two, which enabled the isolation of  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{Au}(1,5\text{-dibromo-2,4-difluorobenzene})]$  complex **2a** in an excellent yield of 92% (Table 1). An upscaling, starting from 600 mg  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuCl}]$  complex **1**, resulted in 770 mg (1.06 mmol) of **2a** (86% yield).

Next, we cut the amount of base and the arylation compound in half, however, the yield of the arylated product dropped to 29%. So we confirmed the latter reaction conditions as optimal, under these reaction conditions various precursors were reacted with 50.0 mg  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuCl}]$  complex **1** in order to undergo a C,H-activation step

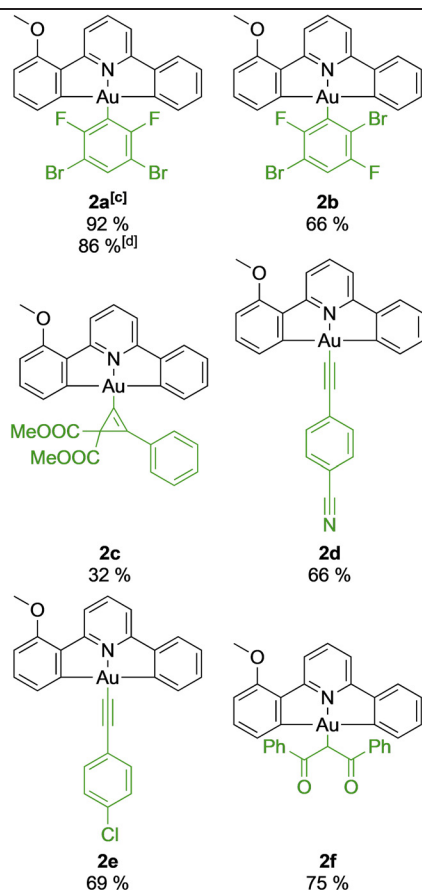
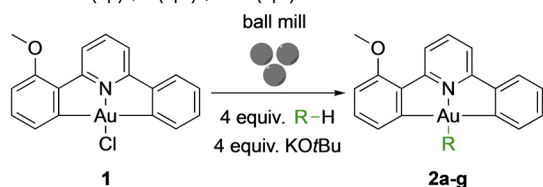
(Table 1). After milling, the synthesized complexes were transferred from the reaction vessel with a minimal amount of DCM to a round bottom flask and purified either by column chromatography or easy reprecipitation (depending on the solubility of the desired Au<sup>III</sup> complex).

The isomeric 1,4-dibromo-2,5-difluorobenzene, delivered the substituted gold(III) complex **2b** in 66% yield. A cyclopropene (dimethyl-2-phenylcycloprop-2-ene-1,1-dicarboxylate) with an  $pK_a$  value of about 30<sup>[23]</sup> was also a suitable substrate and the highly strained three-membered ring could be successfully aurated at the CH-position.<sup>[24]</sup> **2c** could be isolated in a moderate yield of 32%. Noteworthy, no ring-opening products were detected, despite the known reactivity of cyclopropenes as gold carbene precursors.<sup>[25]</sup> The structure



**Scheme 2.** First mechanochemical arylation of  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuCl}]$  complex **1** with 1,5-dibromo-2,4-difluorobenzene and solid state molecular structure of complex **2a**. Thermal ellipsoids set at 50% probability. Hydrogen atoms are omitted for a better overview.<sup>[22]</sup>

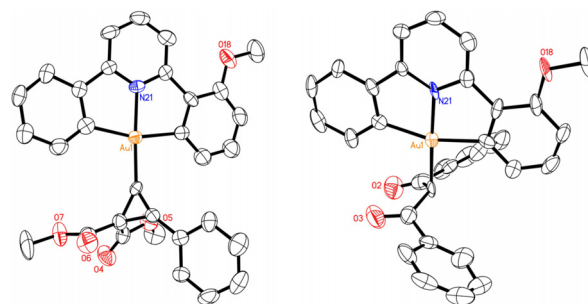
**Table 1:** Synthesis of substituted  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{Au}]$  complexes by C,H-activation of C(sp<sup>-</sup>), C(sp<sup>2</sup>-), or C(sp<sup>3</sup>)-H bonds.<sup>[a,b]</sup>



[a] Reaction conditions:  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuCl}]$  **1** (50.0 mg, 102  $\mu\text{mol}$ , 1 equiv), KOtBu (45. mg, 407  $\mu\text{mol}$ , 4 equiv) and the C(sp<sup>-</sup>),H-, C(sp<sup>2</sup>),H-, C(sp<sup>3</sup>),H-coupling partner (407  $\mu\text{mol}$ , 4 equiv) were milled in a stainless steel container with fifty 5 mm stainless steel balls for 2 cycles of 30 min at 600 rpm with 15 min break in a planetary ball mill; [b] Isolated yields; [c] 60 mg of  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuCl}]$  **1** (122  $\mu\text{mol}$ , 1 equiv) were used; [d] Scale-up experiment:  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuCl}]$  **1** (600 mg, 1.22 mmol, 1 equiv), KOtBu (548 mg, 4.88 mmol, 4 equiv) and the 1,5-dibromo-2,4-difluorobenzene (1.33 g, 1.22 mmol, 4 equiv) were milled in a stainless steel container with fifty 5 mm stainless steel balls for 2 cycles of 30 min at 600 rpm with 15 min break in a planetary ball mill.

of the metalated cyclopropene was verified by the results of an X-ray structure analysis (see Figure 1, left). Next, we turned our focus on C(sp<sup>-</sup>)-H activation. Both of the applied terminal alkynes as test substrates delivered the corresponding acetylide complexes **2d** and **2e**, in reasonable yields of 66 %

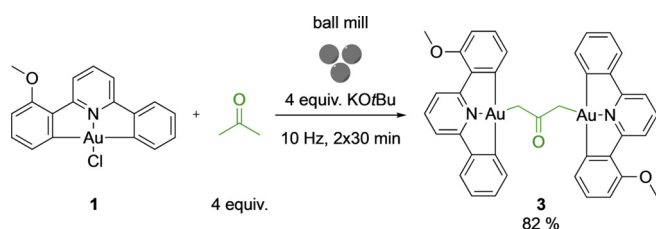
and 69 %, respectively. Finally, we were curious about the possible coupling of activated C(sp<sup>3</sup>)-H bonds. To our delight, the ball milling reaction of  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuCl}]$  complex **1** and 1,3-diphenylpropane-1,3-dione, delivered the desired compound **2f** in a good yield of 75 %. The solid state molecular structure of this compound also verifies the C,H-activation process.



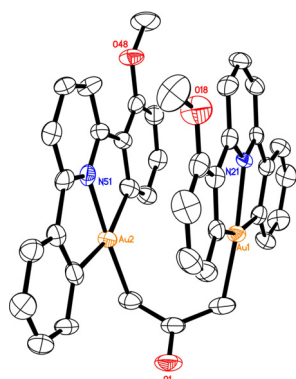
**Figure 1.** Solid state molecular structure of **2c** (left) and **2f** (right). Thermal ellipsoids set at 50% probability. Hydrogen atoms are omitted for clarity.<sup>[23]</sup>

As already mentioned, for **2c** and **2f** crystal structure determinations were possible. The structure of **2c** very nicely shows the pincer complex being connected to the cyclopropenyl unit, which represents the first example of a  $[(\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{Au}^{\text{III}}]$  compound with a highly strained three-membered ring (Figure 1—left side). Also the dione-segment in **2f** was characterized by X-ray crystallography (Figure 1, right side). This structure features the first example of a  $[(\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{Au}^{\text{III}}]$  complex including a gold(III)-C(sp<sup>3</sup>) bond which is formed starting from a gold(III) chloride.

Additionally, we tested the ball-milling reaction of  $[(^{\text{MeO}}\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuCl}]$  complex **1** with four equivalents of acetone in order to receive an unique Au-C-substituted digold(III) compound. The simple auration of acetone bearing a (C<sup>∧</sup>N<sup>∧</sup>C)-pincer complex with potassium carbonate as the base is already known from literature.<sup>[26]</sup> We envisioned that the stronger base and the initial activation with a gold complex formed a system that corresponds to a keto-enol system and is capable of a second gold incorporation. To our delight, the acetone-bridged digold(III) complex was isolated in a very good yield of 82 % (Scheme 3). The connectivity of this compound was unambiguously confirmed by an X-ray single crystal structure analysis (Figure 2).



**Scheme 3.** Synthesis of  $[(\text{MeOC}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuMeOMeAu}(\text{C}^{\wedge}\text{N}^{\wedge}\text{C}^{\text{OMe}})]$  complex **3** by ball mill reaction.

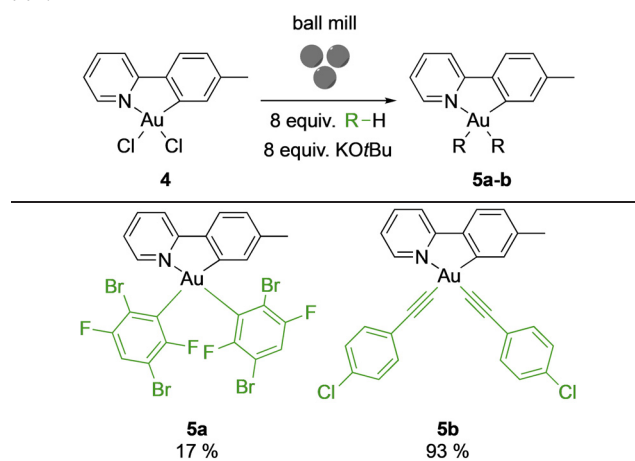


**Figure 2.** X-Ray structure of **3**. Thermal ellipsoids set at 50% probability. Hydrogen atoms are omitted for a clarity.<sup>[23]</sup>

After this success we questioned if the C,H-activation protocol was limited to pincer-type ligands or if chelate complexes with two chloride atoms can also undergo mechanochemical substitution. For the first experiment we started from  $[(\text{tpy})\text{AuCl}_2]$  for which we very recently published a protocol for mono- and dialkynylations *via* transmetalation from organolithium reagents.<sup>[27]</sup> In case of the arylation with 1,4-dibromo-2,5-difluorobenzene, the desired compound **5a** was obtained as an inseparable mixture of mono- and diarylated product in an overall yield of only 17%. To our delight, the two-fold alkynylated product **5b** was formed smoothly and could be isolated in an excellent yield of 93% (Table 2). For this type of reaction, no precautions like the exclusion of moisture were necessary and an easy-to-conduct entry to this compound class was achieved by solvent-free ball milling.

We herein report the easy and solvent-free access to differently substituted  $(\text{C}^{\wedge}\text{N}^{\wedge}\text{C})$ -gold(III) complexes. By simple mechanochemical reactions in a planetary ball mill of gold(III) chlorides, potassium *tert*-butoxide and different  $\text{C}(\text{sp})\text{H}$ -,  $\text{C}(\text{sp}^2)\text{H}$ - or  $\text{C}(\text{sp}^3)\text{H}$ -coupling partners, highly valued products could be isolated in good to excellent yields without the need for pre-functionalization. Overall this process represents a green and economically attractive protocol for the synthesis of materials suitable for the production of OLEDs, PHOLEDs and TADF, respectively. In combination with our already published mercury-free synthesis of  $[(\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{AuCl}]$  complexes, the C,H-activation under solvent-free conditions delivers highly regarded products with excellent photo-physical properties and results in a very green reaction process using only minimal amounts of solvents for the work-up. The relatively mild reaction

**Table 2:** Synthesis of substituted  $[(\text{tpy})\text{AuCl}_2]$  complexes by C,H-activation.<sup>[a,b]</sup>



[a] Reaction conditions:  $[(\text{tpy})\text{AuCl}_2]$  **3** (50.0 mg, 115  $\mu\text{mol}$ , 1 equiv), KOtBu (103 mg, 917  $\mu\text{mol}$ , 8 equiv) and desired R-H-compound (917  $\mu\text{mol}$ , 8 equiv) were milled in a stainless steel container with fifty 5 mm stainless steel balls for 2 cycles of 30 min at 600 rpm with 15 min break in a planetary ball mill; [b] Isolated yields.

conditions, short reaction times and broad substrate scope suggest that this method could be a useful synthetic tool for industrial application.

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## Conflict of interest

The authors declare no conflict of interest.

**Keywords:**  $[(\text{C}^{\wedge}\text{N}^{\wedge}\text{C})\text{Au}]$  complexes · ball mill · C,H-activation · mechanochemistry

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