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Atomically precise palladium nanocluster catalyzed tandem oxidation processes of alcohols and phosphorous ylides: Facile access to α,β-unsaturated esters

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A B S T R A C T

The mesoporous silica nanosphere supported palladium nanocluster was synthesized through a simple impregnation method and well characterized. The as prepared catalyst shows excellent catalytic performance in tandem oxidation process (TOP) of alcohol and phosphorous ylide, which provides an efficient access to α,β-unsaturated esters with high yields utilizes 1 atmosphere of molecular oxygen as sole oxidant. This work represents the first example of atomically precise palladium nanocluster catalyzed tandem oxidation process of alcohol and phosphorous ylide and is expected to open new horizons for nanoclusters in the tandem reactions.

Introduction

Atomically precise nanoclusters (APNCs) [1], as a new family of nanomaterials, have emerged as one of the most important branches of nanoscience and nanotechnology during the past decade and attracted significant attentions due to its applications in catalysis [2], biology [3] and sensing [4]. Owing to its high surface-to-volume ratio and the unique geometric structure and electronic structure, nanocluster show distinct catalytic activity in selective oxidation [5], reduction [6] and carbon–carbon coupling [7] reactions. Nanocluster with determined crystal structure and compositions make it possible to reveal the relationship between catalytic performance and their atomic level structure, which enable it have huge advantages over the uncertain surface structure of traditional metal nanoparticles [8]. Therefore, the development of new chemical processes promoted by atomically precise nanoclusters is a high desirable, yet challenging task.

One-pot tandem reactions [9], in which two or more transformation processes are combined into one synthetic operation, are great importance for efficient and practical organic synthesis and for green and sustainable chemistry, which avoid the isolation and purification of the intermediate. Thus allowing a reduction in time, labor and yield losses associated with the isolation and purification of intermediates. The tandem oxidation processes initiated by alcohol oxidation to the corresponding more reactive aldehydes, which can be easily trapped *in situ* by many nucleophilic agent leading to a variety of synthetically useful compounds such as esters, imines, amides and heterocycles [10].

The tandem oxidation-Wittig reaction, when the nucleophilie is stable phosphorous ylide, is an important reaction in organic synthesis because it provides a facile method to α,β-unsaturated ester, which is a very important 1,4-addition synthon in many organic reactions. Conventionally, various oxidants such as MnO_2 [11], Dess-Martin agent [12], IBX [13], PCC [14] were studied for the one-pot tandem oxidation-Wittig reaction. However, these protocols require the use of stoichiometric or even large excess amounts of oxidant, which generated many unpredictable by-products and much effort is needed to remove the oxidant (Scheme 1(a)). Moreover, some of this oxidant themselves are highly toxic and hard to handle. To avoid the use of hazardous oxidants, a great deal of effort has been devoted to design of new catalysts with green oxidants (Scheme 1(b)). For example, Williams and co-works [15] reported the tetra-*n*-propylammonium perruthenate (TPAP) catalyzed tandem oxidation-process of alcohols with stable ylides to give the α,β-unsaturated esters using O_2 as oxidant and *N,N,N′,N′*-Tetramethylethylenediamine dioxide ($TMEDAO_2$) as co-oxidant. Park and co-works [16] reported porous aluminum oxyhydroxide embedded ruthenium nanoparticles catalyzed alcohol oxidation-Wittig reaction in toluene with O_2 as oxygen source. However, this

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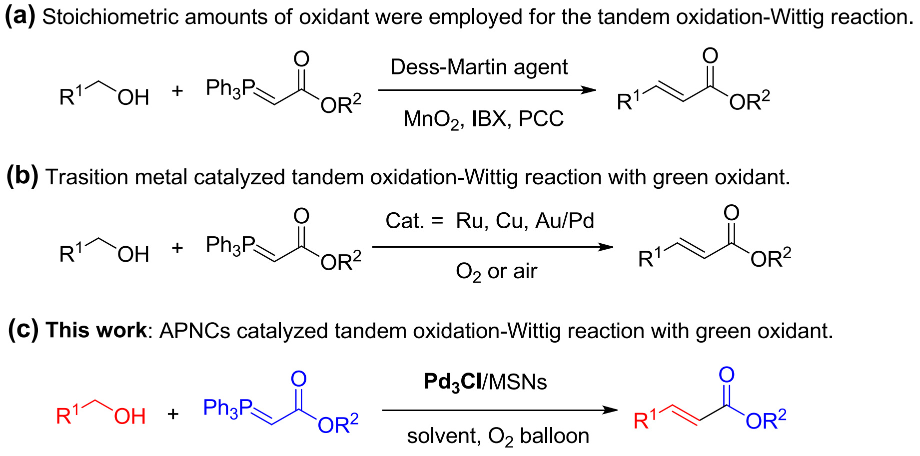


Scheme 1. Tandem oxidation-wittig reaction of alcohol and phosphorous ylide.

system suffers from high temperature and the poor recyclability of the catalysts. The Au/Pd bimetallic nanoparticles were also explored by Kobayashi and co-works to promote the tandem process of alcohol oxidation and Horner–Wadsworth–Emmons reaction [17]. Recently, using CuI/TEMPO as co-catalyst and air as the oxidant, Yu and co-works reported an efficient method to synthesis of α,β-unsaturated esters [18]. Despite this advances, the novel catalyst with excellent catalytic activity, easy recyclability and green oxidant are still highly demanding. So we developed and herein report the first mesoporous silica nanoparticles (MSNs) supported atomically precise palladium nanocluster $[Pd_3Cl(PPh_3)_3(PPh_2)_2]^+Cl^-$ (abbreviated **Pd_3Cl**) catalyzed tandem oxidation-Wittig reaction of alcohol and phosphorous ylide with 1 atmosphere O_2 (O_2 balloon) as oxidant (Scheme 1(c)).

Results and discussions

The **Pd_3Cl** nanocluster was synthesized following the previously reported method [19]. The as-prepared Pd_3Cl nanocluster shows distinct peak at 418 nm and a weak absorption band at 485 nm in UV–vis absorption spectra (Fig. 1(A)), which is consistent with the literature. MALDI-MS analysis of the as-prepared Pd_3Cl cluster with positive model in Fig. 1(B) shows mass peak at m/z = 1511.9 (assigned to molecular ion peak of $[Pd_3Cl(PPh_3)_3(PPh_2)_2]^+$, theoretical molecular weight: 1511.9). There are two fragment peaks at 1249.9 and 986.6, assigned to $[Pd_3Cl(PPh_3)_2(PPh_2)_2]$ and $[Pd_3ClPPh_3(PPh_2)_2]$ respectively, after lost one or two PPh_3 from the **Pd_3Cl** clusters, caused by the high energy of MALDI-MS method (The fragment is inevitable in MALDI-MS analysis because of the hard ionization method (high laser intensity)). No other peaks are found in the wide range of MALDI-MS spectrum indicating the purity of the as-obtained **Pd_3Cl** clusters. The ^1H and ^{31}P NMR spectra of **Pd_3Cl** demonstrated that there is phenyl and P in the nanocluster, which is well consistent with the result of MALDI-MS analysis. The uniform spherical morphology with average particle size ~100 nm of MSNs can be easily observed from the TEM image (Fig. 2(A) and (B)). The as-prepared **Pd_3Cl** cluster was loaded onto MSNs by impregnation of MSNs powder in a DCM solution of cluster. As expected, the Pd_3Cl nanoclusters are absorbed into the pore of the MSNs. After the **Pd_3Cl** loading, the structure and morphology of MSNs are well maintained (Fig. 2(C) and (D)). To conform the Pd nanoclusters after loaded on the MSNs are well dispersed, the energy dispersive X-ray spectroscopy (EDX) mapping analysis of Si, O, and Pd was conducted and shown in Fig. 3. The results demonstrate that the Pd element is distributed

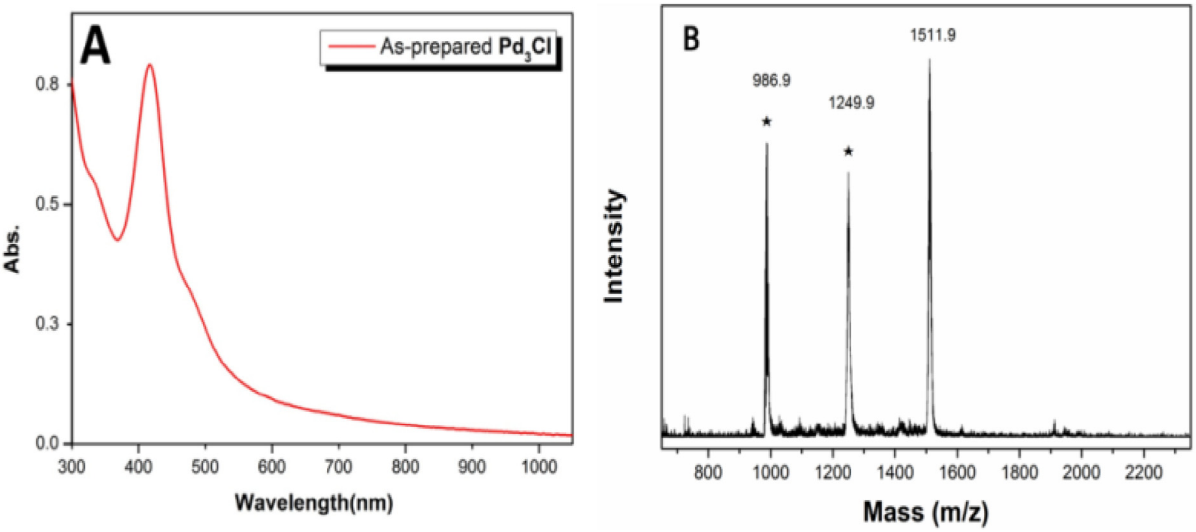


Fig. 1. (A) UV–vis spectrum and (B) positive mode MALDI mass spectrum of Pd_3Cl nanoclusters. The peak marked with an asterisk (*) in (B) is a fragment caused by the MALDI method.

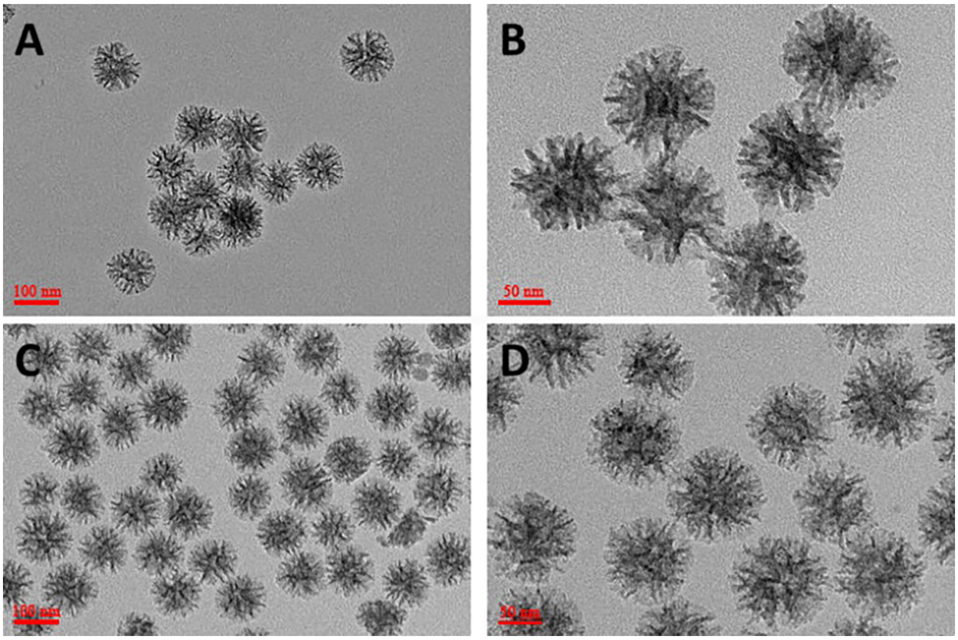


Fig. 2. (A) and (B) TEM image of MSNs. (C) and (D) TEM image of Pd_3Cl/MSNs catalyst.

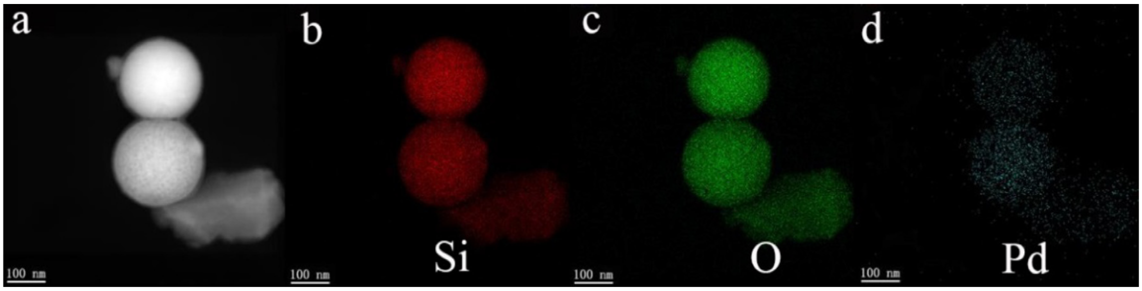


Fig. 3. TEM image of Pd_3Cl/MSNs (a), EDX mapping analysis of Si (b), O (c) and Pd (d).

homogenously throughout the whole MSNs. In addition, ICP-MS analysis shows that the Pd content of the **Pd_3Cl/MSNs** catalyst is 1.1 wt%.

The free Pd_3Cl, MSNs and Pd_3Cl/MSNs were analyzed by FT-IR and the results are shown in Fig. 4A. A strong absorption at 1439 cm^{-1} was observed in **Pd_3Cl** owing to the stretching vibration of Ph—P bond, which is the characteristic absorption peak of triphenylphosphine group. After loading on the MSNs, the absorption peak was still observed (Fig. 4A, red line). The peaks at 2940 cm^{-1} and 693 cm^{-1} assigned to stretching vibration and bending vibration of C—H bond, respectively. To gain insight into the oxidation state of palladium nanocluster, the free **Pd_3Cl** and

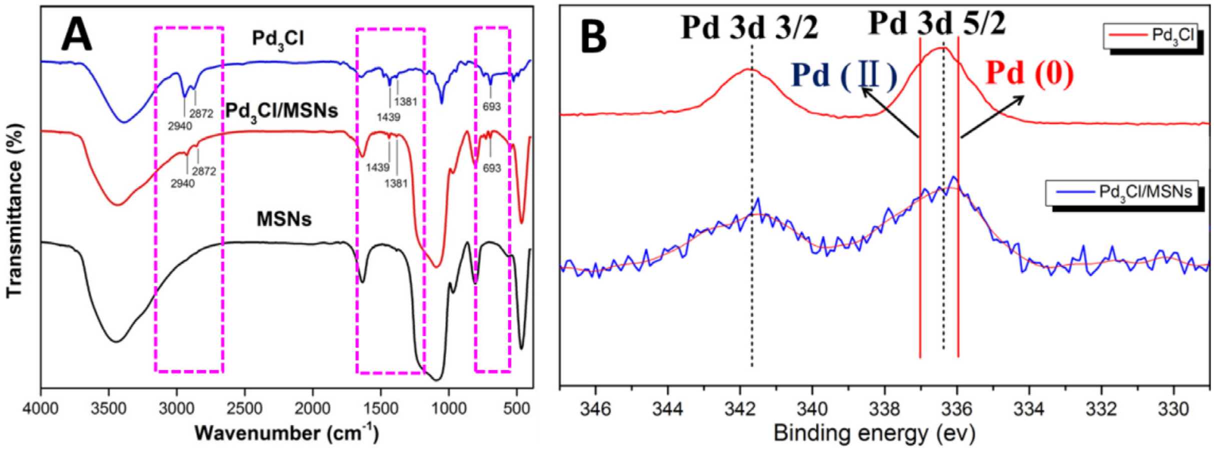
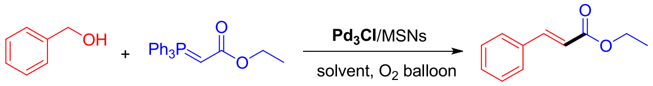


Fig. 4. FT-IR spectra of free Pd_3Cl, MSNs and Pd_3Cl/MSNs (A), XPS spectra in Pd 3d of free Pd_3Cl and Pd_3Cl/MSNs (B).

Table 1
Palladium nanocluster catalyzed one-pot tandem oxidation-wittig reaction of benzyl alcohol and phosphorous ylide[a].

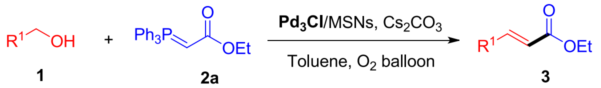


1a **2a** **3a**

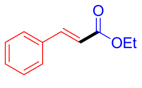
Entry	Solvent	Additive	Yield[b] (%)
1	Toluene	–	–
2[c]	Toluene	–	–
3	Toluene	Na_2CO_3	46
4	Toluene	NEt_3	19
5	Toluene	Cs_2CO_3	52
6	CH_3CN	Cs_2CO_3	26
7	DMSO	Cs_2CO_3	33
8	Dioxane	Cs_2CO_3	48
9	THF	Cs_2CO_3	trace
10[d]	Toluene	Cs_2CO_3	71
11[c]	Toluene	Cs_2CO_3	89
12[c,e]	Toluene	Cs_2CO_3	27.
13[c,f]	Toluene	Cs_2CO_3	n.r.
14[c,g]	Toluene	Cs_2CO_3	n.r.
15[c,h]	Toluene	Cs_2CO_3	n.r.

[a]Reaction conditions: benzyl alcohol (0.2 mmol), ylide (0.24 mmol), additive (0.24 mmol), solvent (1 ml), catalyst (20 mg) at rt. [b] Isolated yield. [c] The reaction was carried out at 50 °C. [d] The reaction was carried out at 30 °C. [e] The reaction was carried out under air atmosphere. [f] The reaction was carried out at N_2 atmosphere. [g] The reaction was catalyzed with bare MSNs. [h] The reaction was carried out without catalyst.

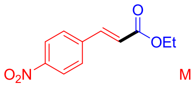
Table 2
Substrate scope of the tandem oxidation-Wittig reaction.[a,b]



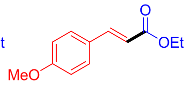
1 **2a** **3**



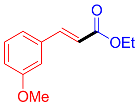
3a, 89% [23:1]



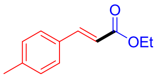
3b, 96% [17:1]



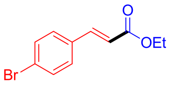
3c, 85% [30:1]



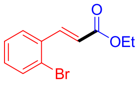
3d, 79% [20:1]



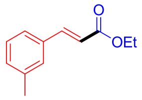
3e, 87% [14:1]



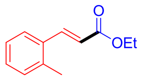
3f, 94% [25:1]



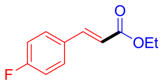
3g, 82% [21:1]



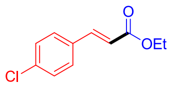
3h, 81% [23:1]



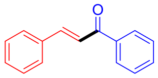
3i, 71% [24:1]



3j, 87% [25:1]



3k, 90% [14:1]



3l, 68% [16:1]

[a] Reaction conditions: alcohol (0.2 mmol), ylide (0.24 mmol), Cs_2CO_3 (0.24 mmol), toluene (1 ml), catalyst (20 mg) at 50 °C. [b] Isolated yield. Values in [ ] represent *E*:*Z* isomer ratios determined by ^1H NMR.

Pd_3Cl/MSNs were analyzed by X-ray photoelectron spectra (XPS). As shown in Fig. 4**B**, there are two observable peaks centred at 336.4 and 341.7 eV, which are assigned to Pd 3d5/2 and Pd 3d3/2, respectively. In comparison of the standard binding energy of Pd(0) 3d5/2 (~335.9 eV) and Pd(Ⅱ) 3d5/2 (~337.0 eV), we can conclude that the oxidation state of Pd in **Pd_3Cl** nanocluster is between zero and two. The distinctive oxidation state of Pd in palladium nanocluster may play an important role in the tandem reactions. After immobilized on the MSNs, the binding energy of Pd 3d has no obvious change (Fig. 4B blue line).

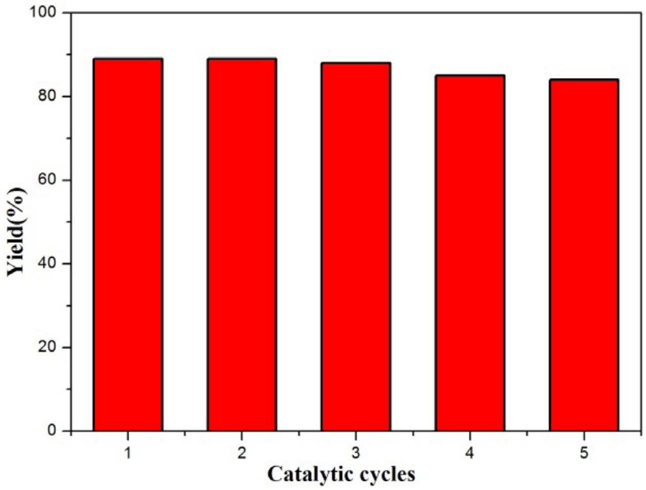


Fig. 5. Recyclability of the Pd_3Cl/MSNs.

Then, the tandem oxidation-Wittig reaction of benzyl alcohol **1a** and phosphorous yilde **2a** was chosen as a model reaction to test the catalytic activity of **Pd_3Cl**/MSNs and optimize the reaction parameters (Table 1). Unfortunately, no reaction occurred in the solvent of toluene under the O_2 balloon, even the reaction temperature was increased to 50 °C (Table 1, entries 1 and 2). To our delighted, when 1.2 equiv. of Na_2CO_3 was added, the desired one-pot tandem oxidation-Wittig reaction took place smoothly with moderate yield (Table 1, entry 3). Further investigation showed that, compared with Na_2CO_3 and NEt_3, Cs_2CO_3 was the promising additive (Table 1, entries 4 and 5). Screening of solvents revealed that toluene was the best one among CH_3CN, DMSO, Dioxane and THF, although the yields are still unsatisfied (Table 1, entries 6–9). Gratifyingly, significant improvement of yield was obtained when the reaction was carried out at 50 °C (Table 1, entries 10 and 11). The results of control and blank experiment clearly suggest that palladium nanocluster is the true catalytic species and O_2 is the oxidant (Table 1, entries 12–15).

With the reaction conditions optimized, the generality of the tandem oxidation-Wittig reaction was then tested and the results are summarized in Table 2. Generally, the reaction proceeded smoothly to give the corresponding α,β-unsaturated esters in good to excellent E/Z selectivity and yields (68–96%). It was found that the substituents electronic effect has slightly impact in the yield of the tandem reaction. Benzyl alcohol with electron-withdraw substituents (4-NO_2, 4-Br, 4-Cl, 4-F) and electron-donating substituents (4-Me, 4-OMe, 3-OMe) all reacted efficiently and give the desired products with good yields. In addition, the more hindered *ortho*-substitute alcohols such as 2-bromobenzyl alcohol and 2-methyl benzyl alcohol could also be tolerated in this tandem oxidation-Wittig reaction, which generated the corresponding α,β-unsaturated esters with 82% and 71% yield, respectively (Table 2, **3g and 3i**). The semi-stabilized phosphorous ylide was also examined under the optimized reaction conditions and the desired α,β-unsaturated ketone was obtained in good yield (Table 2, **3 l**).

The recyclability of the as-prepared **Pd_3Cl**/MSNs was then tested. When the reaction completed, the catalyst was collected simply by centrifugation, washed with water and ethanol three times, and dried at 50 °C. A new catalytic cycle was run under the same conditions using the recycled catalyst. To our surprise, the recycled catalyst showed almost as the same activity as the fresh catalyst after 5 cycles (Fig. 5). So we can conclude that **Pd_3Cl/MSNs** is a good recyclable catalyst.

Conclusions

In summary, we have disclosed a novel, efficient and recyclable catalyst for the one-pot tandem oxidation-Wittig reaction of alcohol and phosphorous ylide. With this protocol, a wide range of α,β-unsaturated esters were produced in good to excellent yields. This also represents the first tandem reaction catalyzed by atomically precise nanocluster. This work is expected to open up a new frontier for atomically precise nanocluster in tandem reactions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tetlet.2020.152385.

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