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Deracemization of Atropisomeric Biaryls Enabled by Copper Catalysis

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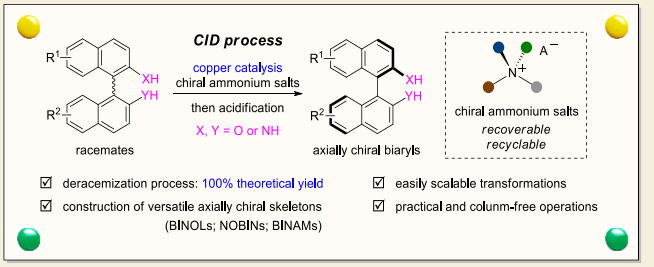
ABSTRACT: Atropisomeric biaryls have found crucial applications in versatile chiral catalysts as well as in ligands for transition metals. Herein, we have developed an efficient crystallization-induced deracemization (CID) method to access chiral biaryls from their racemates with a chiral ammonium salt under copper catalysis including BINOL, NOBIN, and BINAM derivatives. After being significantly accelerated by its bidentate diamine ligand, the copper catalyst exhibits high efficiency and selectivity in racemizing biaryl skeletons, and the cocrystal complex would be enantioselectively formed together with chiral ammonium salt, which on acid-quenching would directly deliver chiral biaryl without further chromatographic purification. This CID process is easily scalable, and the chiral ammonium salt was nicely recoverable. Ligand effect studies showed that bulky alkyl substitution was an indispensable element to ensure efficient racemization, which probably proceeds via a radical-cation intermediate and further allows axial rotation by forming a delocalized radical.



KEYWORDS: *deracemization, racemization, copper, atropisomeric biaryls, crystallization*

INTRODUCTION

Crystallization-based chiral resolution processes are industrially widespread, given the fact that they are practically scalable, easy to handle, and generally column-free to give high enantioselectivity.[1] Consequently, in the resolution process, one enantiomer was crystallized with an appropriate chiral auxiliary through selective host−guest molecular recognition, while the other remains in the mother liquid, thus, resulting in a theoretical yield limited to 50%. In combination with the resolution process, crystallization-induced deracemization (CID)[2] relies on the chirality inversion, under which one enantiomer of the substrate is able to undergo the continuous isomerization to the other enantiomer in the solution.[3] Therefore, CID would directly produce the corresponding single enantiomer through molecular complexation from its racemate, with a theoretical yield of 100%. The key solution is to find an efficient and compatible catalyst to efficiently racemize chiral substrates for CID development. Currently, the CID strategy has been successfully used to access chiral carbonyl compounds and amines, in which stereochemical center of α-carbonyls was inversed via base-promoted racemization, and α-amine chirality was flipped via a Schiff base intermediate (Scheme 1a,b).[2]

On the other hand, axially chiral biaryls, featuring the hindered axial rotation around the aryl−aryl bond, are highly important structural motifs in natural products,[4] pharmaceuticals,[5] privileged chiral ligands,[6] and organocatalysts[7] (Scheme 1c). Mastigophorenes A and B, a class of active natural products isolated from the Boruneo liverwort *Mastigophora diclados*, contain unique axially chiral herbertane-type sesquiterpene dimers.[8] These compounds have shown potential application prospects for the treatment of neurodegenerative diseases such as Alzheimer's and Parkinson's disease.[9] (+)−Isokotanin A, isolated from the sclerotia of *Aspergillus alliaceus*, also includes the unit of axially chiral 2,2′-dihydroxy-1,1′-biaryl.[10] Standing as the most representative structure with axial chirality, 2,2′-binaphthol (BINOL) and its derivatives,[11] as well as NOBINs and BINAMs, have attracted particular interest due to their wide applications in asymmetric catalysis.[12] From these basic axially chiral skeletons, diversified chiral organocatalysts and metal ligands could be easily accessible.[13] Up to today, many protocols have been developed to access the enantiopure form of axially chiral biaryls including chiral resolution,[14] asymmetric coupling reactions,[15] enzymatic hydrolysis/esterification,[16] and central-to-axial chirality transformations.[17] Among these methods, crystallization-based chiral resolution can be achieved to produce chiral BINOLs in a practical and scalable way (Scheme 1b).[18] Targeting the CID of atropisomeric biaryls, the key solution

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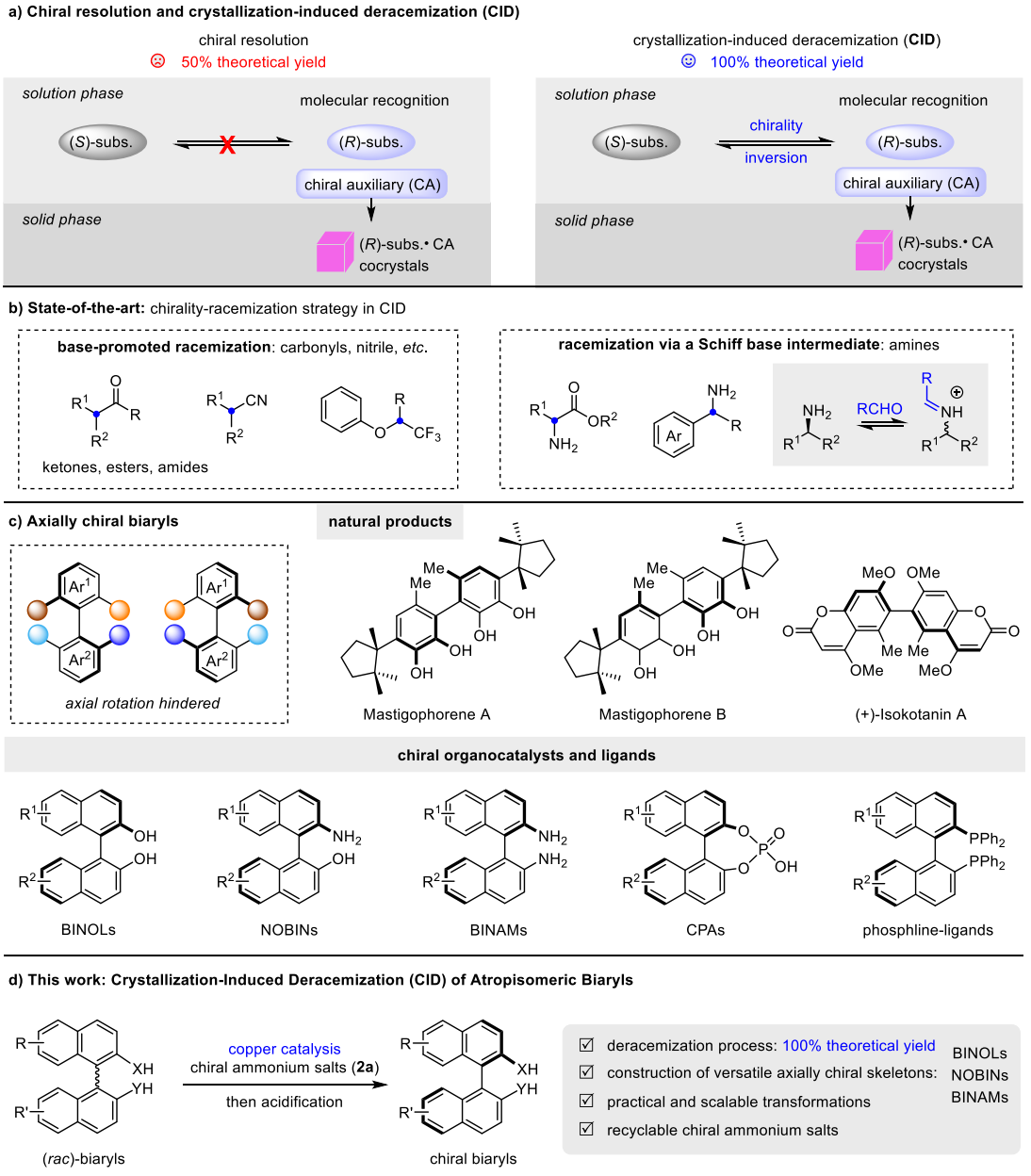
Scheme 1. CID of Atropisomeric Biaryls. X, Y = O or NH



would be the development of efficient and compatible racemization catalysis. To the best of our knowledge, CID of atropisomeric biaryls, including BINOL, NOBIN, and BINAM derivatives, is still unexplored. Herein, we report the first example of efficient CID of BINOLs under the catalysis of copper in the presence of a chiral ammonium salt (Scheme 1d). With these combined protocols, a one-pot approach to chiral BINOLs from their 2-naphthol analogues was equally realized.

RESULTS

Although previous work has shown that, in the presence of stoichiometric amounts of copper and chiral amine, one enantiomer of BINOL can be eventually transformed to the other via axial rotation by forming a ternary complex,[19,20] catalytic racemization for CID system is still undeveloped, and is greatly challenging due to the potential formation of a stable complex with BINOL substrate, which exterminates its catalytic activity.[20] Based on the concept of catalytic racemization of BINOLs, we started to investigate the activity of complexes based on 3d transition metals, given the fact they are generally earth-abundant, inexpensive, and of low toxicity (Scheme 2a).[21] When the reaction was performed with (*R*)-BINOL (>99% *ee*) under the catalysis of metal chloride in toluene at 40 °C, racemization of chiral BINOL was ultimately observed only in the presence of $FeCl_3$ or CuCl. Under the catalysis of $FeCl_3$, BINOL was recovered with 51% *ee*. In contrast, slower racemization was accomplished with CuCl, as shown by the detected enantiomeric excess of 96%. Surprisingly, $FeCl_2$ and $CuCl_2$ showed no activity toward chiral BINOL.

With these results in hand, we turned to introducing ligands to accelerate the racemization step, given the fact that a suitable ligand can significantly change the electronic property of the central metal (Scheme 2b). A collection of nitrogen-containing bidentate ligands was studied together with the

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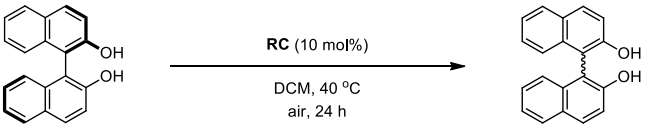
Scheme 2. Optimization of Racemization Catalysts using (*R*)-BINOL

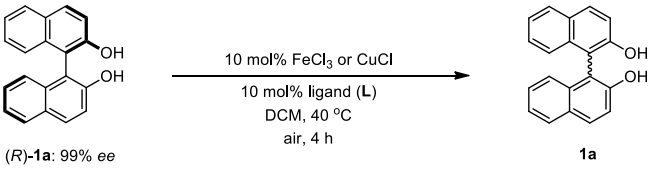
a) Evaluation of racemization catalysts based on 3d transition metals[a]



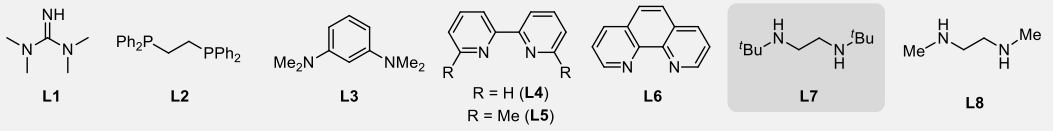
(*R*)-**1a**: >99% *ee* — **1a**

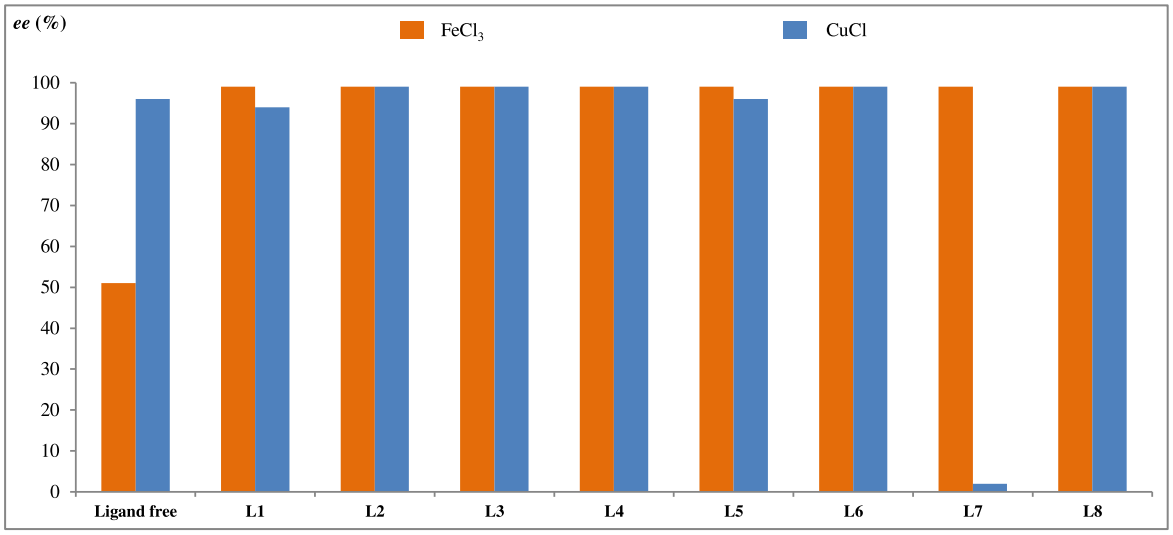
RC based on 3d metals	$CrCl_3$	$MnCl_2$	$FeCl_2$	$FeCl_3$	$CoCl_2$	$NiCl_2{\cdot}6H_2O$	CuCl	$CuCl_2$	$ZnCl_2$
ee of recoverd **1a**[b]	>99%	>99%	>99%	51%	>99%	>99%	96%	>99%	>99%

b) Ligand effect in the racemization of (*R*)-BINOL[c]



(*R*)-**1a**: 99% *ee* — **1a**





[a]The reaction was carried out using (*R*)-**1a** (*c* = 0.1 M), metal chloride (10 mol%) at 40 °C in DCM for 24 h under an air atmosphere. [b]The *ee* values were determined by chiral high-performance liquid chromatography (HPLC). [c]The reaction was carried out using (*R*)-**1a** (*c* = 0.1 M), CuCl (10 mol%) or $FeCl_3$ (10 mol%), and ligand (10 mol%) at 40 °C in DCM for 4 h under an air atmosphere. **RC** = racemization catalyst. DCM = Dichloromethane.

catalyst of $FeCl_3$ or CuCl. Interestingly, the coordination of a *N,N*-bidentate ligand to $FeCl_3$ tends to block its activity, as a retarded racemization process is observed in all tested cases. In the system of copper chloride, many ligands performed with negative influence as well, e.g., guanidine derivatives (**L1** and **L2**), 1,3-phenylenediamine (**L3**), bipyridines (**L4** and **L5**), and 1,10-phen (**L6**). We further turned to aliphatic diamines as the ligand in copper catalysis to enhance its reactivity. To our surprise, complete racemization was achieved from chiral BINOL in 50 min with CuCl and the ligand **L7**, which bears two ^{t}Bu groups, revealing the high efficiency of the catalytic system. It is noteworthy to mention that diamine ligand **L8**, where two methyl groups replace the two ^{t}Bu groups in **L7**, shows completely no activity in racemizing chiral BINOL. These observations indicate the necessity of bulky substituents in the diamine ligand. Therefore, **L7** was defined as the optimal ligand for further study.

Compatibility of racemization catalysis with chiral resolution is a great test for CID development. Crystallization-based chiral resolution can be achieved to produce chiral BINOLs via selective supramolecular recognition with chiral ammonium salts. Therefore, we turned to investigating the compatibility of this copper catalysis with chiral resolution triggered by chiral ammonium salt. First, we started to evaluate the performance

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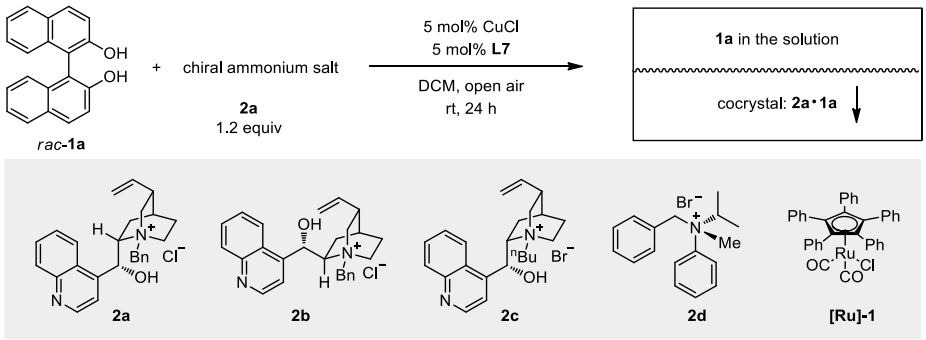
Table 1. Screening of the Reaction Conditions[a]



entry	deviations	yield of the cocrystal (%)[b]	*ee* of **1a** from the cocrystal (%)[c,d]	*ee* of **1a** in the solution (%)[c]
1	no CuCl, no **L7**	47	98, (*R*)	94, (*S*)
2	none	75	98, (*R*)	<1
3	no CuCl	45	99, (*R*)	95, (*S*)
4	no **L7**	43	99, (*R*)	94, (*S*)
5[e]	[Cu(OH)Cl•TMEDA]$_2$	74	97, (*R*)	66, (*S*)
6[f]	[**Ru**]-**1** instead of CuCl/**L7**	52	99, (*R*)	95, (*S*)
7	**2b** instead of **2a**	N. P.	-	-
8	**2c** instead of **2a**	N. P.	-	-
9	**2d** instead of **2a**	N. P.	-	-
10	MeCN:DCM = 1:1	73	94, (*R*)	<1
11	DCE	37	92, (*R*)	<1
12	MeOH	67	86, (*R*)	30, (*S*)
13	0.5 mmol scale	88	98, (*R*)	<1

[a]The reaction was conducted at room temperature (rt) in solvent (1 mL) with *rac*-**1a** (0.1 mmol), **2a** (1.2 equiv) in the presence of CuCl (5 mol %), and ligand (**L7**) (5 mol %). [b]Isolated yield. [c]Enantiomeric excess (*ee*) was determined by chiral HPLC. [d]The *ee* value of (*R*)-**1a** was tested after quenching the cocrystal of **2a**•(*R*)-**1a** with HCl (aq., 1 M). [e][Cu(OH)Cl•TMEDA]$_2$ (2.5 mol %) was used. [f]KO^{t}Bu (10 mol %) was added. N. P. = no precipitation.

of the chiral ammonium salt. In the presence of *N*-benzylcinchonidinium chloride (**2a**), cocrystal **2a**•(*R*)-**1a** was kinetically precipitated in 47% yield, and 98% *ee* of (*R*)-**1a** was obtained after quenching the cocrystal with HCl. Meanwhile the residual (*S*)-**1a** with 94% *ee* remains in the solution (Table 1, Entry 1). In combination with the chiral resolution process, racemization catalysis was then utilized based on the studies in Scheme 2b. We are delighted to see that the cooperative system works nicely in one pot, leading to cocrystal **2a**•(*R*)-**1a** in 75% yield with CuCl and **L7**, which further delivers 98% *ee* of (*R*)-**1a** via acid quenching (Table 1, Entry 2). Neither CuCl nor the ligand (**L7**) could be absent from the reaction (Table 1, Entries 3,4). The reaction led to a lower yield by replacing CuCl/**L7** with [Cu(OH)Cl•TMEDA]$_2$, where the detected (*S*)-**1a** with 66% *ee* in the solution suggests that the racemization step is still not fast enough with [Cu(OH)-Cl•TMEDA]$_2$ (Table 1, Entry 5). Previous report by Akai et al. has shown catalytic activity of Bäckvall's Ru complex [**Ru**]-**1** toward the racemization of BINOLs,[16g] however, [**Ru**]-**1** failed to promote such CID together with chiral ammonium salt **2a** (Table 1, Entry 6). Other chiral ammonium salts were also investigated, and no precipitate could be formed with **2b**−**d** (Table 1, Entries 7−9). Finally, a further detailed survey of solvents suggested that DCM was the best for the CID system (Table 1, Entries 10−12). Inspiringly, the isolated yield of the cocrystal **2a**•(*R*)-**1a** was further improved to 88% by scaling up the reaction to 0.5 mmol level (Table 1, Entry 13). Therefore, CuCl (5 mol %) and **L7** (5 mol %), together with the chiral ammonium salts **2a** (1.2 equiv) at room temperature under open air, were defined as the optimized reaction conditions for additional study.

Cocrystal of **2a**•(*R*)-**1a** could be easily decomposed through acidification to release (*R*)-**1a** in 86% yield from *rac*-**1a**. Under the optimized CID conditions, C_2-symmetric 2,2′-binaphthols bearing two methyl, ethyl, chloro, bromo, or methoxyl substituents at 6- and 6′-positions were successfully deracemized in the presence of **2a** under copper catalysis, thus optically active products (*R*)-**1b**, (*R*)-**1c**, (*R*)-**1d**, (*R*)-**1e**, and (*R*)-**1f** in 81−99% yields and excellent *ees* (95−99%) (Scheme 3). The applicability of this method to C_1-symmetric 2,2′-binaphthols has been demonstrated, although racemization became slightly slower with functional groups, such as bromo or methoxy groups at 7-positions, probably due to the increase of steric hindrance during axial rotation. (*R*)-**1g** and (*R*)-**1h** were produced with excellent enantioselectivity after HCl-quenching without further chromatography purification. Substituents at 6-position on one naphthene ring were found to be nicely tolerated, e.g., (*R*)-**1i** and (*R*)-**1j** could also be obtained in 93% and 83% yield, with 97% and 99% *ee*, respectively. Functional groups in monosubstituted BINOLs could be extended to Cl, Br, CO_2Me, CHO, and OMe. Introducing a bromo group at one 3-position led to a decrease of enantioselectivity in (*R*)-**1p**, due to the fact that crystallization of *rac*-BINOL **1p** with ammonium salt **2a** was not efficient via molecular recognition; therefore, relatively lower yield and selectivity were obtained simultaneously. To our delight, *rac*-BINOL **1q** with two different groups at 6- and 6′-positions also reacted smoothly. Substitution of bromo at the 4-position failed to undergo CID, which is inactive in the

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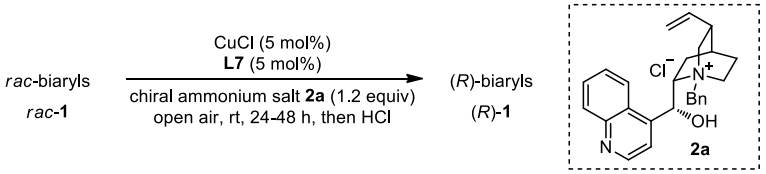
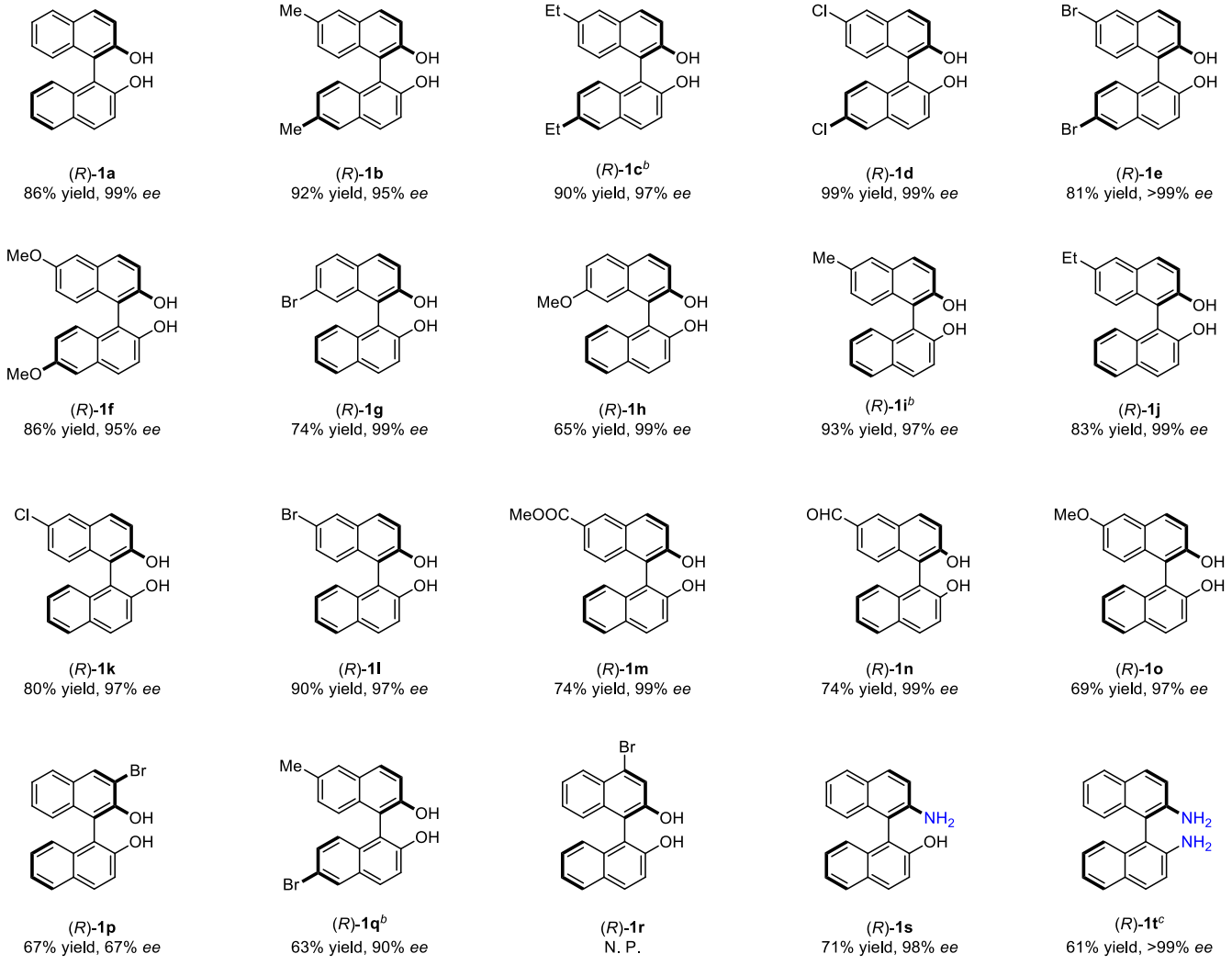
Scheme 3. Substrate Scope[a]





[a]The reaction was conducted at room temperature with *rac*-**1a** (0.5 mmol), **2a** (1.2 equiv) in the presence of CuCl (5 mol%) and **L7** (5 mol%). [b][Cu(OH)Cl·TMEDA]$_2$ (2.5 mol%) was used instead of CuCl and **L7**. [c]CuCl (10 mol%) and **L7** (10 mol%) were used.

cocrystallization process with **2a**. It is noteworthy to mention that CID is not only applicable to BINOL derivatives but also works for NOBIN and BINAM, where (*R*)-**1s** and (*R*)-**1t** were, respectively, released from cocrystals in 71% and 61% yield, with excellent *ee*s (≥98%). Finally, by using ammonium salt **2d**, the CID of *rac*-**1a** was successfully realized to provide the other enantiomer, (*S*)-**1a**, in 72% yield, with 97% *ee* (for details, see the Supporting Information).

The preparation of chiral products on a large scale with convenient operations is the focus of industrial production. Based on this concern, CID of *rac*-**1e** on a 5-g scale was conducted to deliver chiral (*R*)-**1e** in 84% yield, with 97% *ee* without any chromatography purification, with chiral ammonium salt **2a** recovered in 92% yield via simple extraction, which could be reused in a new CID process (Scheme 4a; for details, see the Supporting Information). Moreover, since racemic BINOL was also obtained via the oxidative coupling of 2-naphthol under copper catalysis, this catalytic procedure might be extended with 2-naphthol as the starting material. Under the standard conditions, (*R*)-**1a** and (*R*)-**1e** could be easily generated in 71% yield from 2-naphthol **3a**, and 68% yield from 2-naphthol **3e** respectively, with excellent enantioselectivity in both reactions. Copper catalyst not only works for the oxidative coupling to deliver racemic BINOLs, but also takes responsibility for the dynamic racemization in CID transformations (Scheme 4b). Furthermore, it is encouraging to achieve the axial chirality inversion with this CID procedure, thus, (*R*)-**1a** was obtained in 82% yield with

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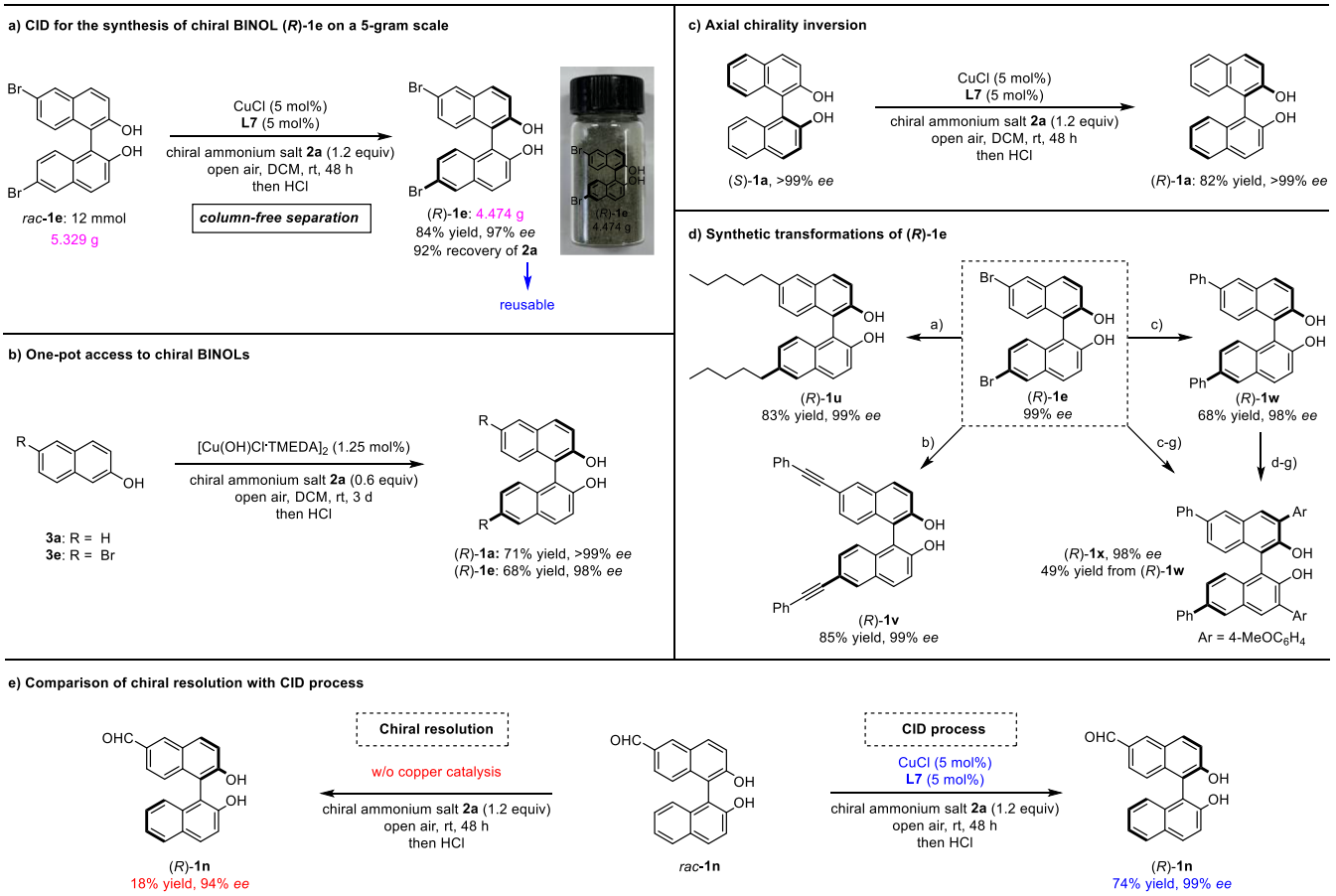
Scheme 4. Synthetic Transformations



a) *n*-$C_5H_{11}MgBr$, $Pd(dppf)Cl_2{\cdot}CH_2Cl_2$, THF, reflux, 12 h; b) Phenylacetylene, $Pd(PPh_3)_4$, CuI, NEt_3/DMSO, 80 °C, 5 h; c) $PhB(OH)_2$, $Pd(PPh_3)_4$, K_2CO_3, THF/H_2O, 85 °C, 18 h; d) NaH, bromomethyl methyl ether, THF, 0 °C to rt, 12 h; e) *n*-BuLi, I_2, THF, -78 °C to rt, 6 h; f) $ArB(OH)_2$, $Pd(PPh_3)_4$, K_2CO_3, THF/H_2O, 85 °C, 12 h; g) HCl (aq. 6 M), dioxane, 85 °C, 6 h.

>99% *ee* from (*S*)-**1a** of >99% *ee* (Scheme 4c). Finally, diverse transformations of (*R*)-**1e** were set up to exhibit potential applications of this method in asymmetric catalysis (Scheme 4d). Efficient alkylation, alkynylation, and arylation were successfully realized to conveniently deliver chiral BINOL derivatives. Two aryl substituents could also be installed onto BINOL skeleton at 3,3′-positions after diphenylation of (*R*)-**1e** at 6,6′-positions. To further evaluate the performance of this CID method, two parallel experiments were conducted under chiral resolution conditions in the absence of copper catalyst (CuCl/**L7**), and the standard CID conditions respectively (Scheme 4e). To our surprise, only an 18% yield of (*R*)-**1n** with 94% *ee* was obtained through chiral resolution, while a remarkably improved yield of 74% was obtained with 99% *ee* in the CID process. These outcomes indicate that the significant yield improvement in CID process is not only simply due to the push of the theoretical yield limit from 50% in chiral resolution to 100% by inversing the (*S*)-BINOL to (*R*)-enantiomer, but also contributed by the acceleration of cocrystal formation by increasing the concentration of cocomplex [(*R*)-BINOL•**2a**] in the solution. Moreover, the enantioselectivity in CID was also improved. It is noteworthy to mention that, in chiral resolution of *rac*-**1n**, attempts to increase the cocomplex concentration by simply decreasing the use of solvent lead to the precipitation of racemic substrate, thus, dramatically lowers enantioselectivity in the products.

DISCUSSION

Initial ligand screening outcomes in Scheme 2b have shown the significance of substituents in the diamine ligand toward BINOL racemization (**L7** vs **L8**). Bulky groups endow the ligand with high catalytic efficiency, while bis-methyl substituents fail to promote the racemization process. Based on these observations, we next evaluated two more diamine ligands bearing two ethyl (**L9**) and *iso*propyl (**L10**) groups, respectively, in the racemization of (*R*)-BINOL, and their steric hindrance should be located between methyl (**L8**) and *tert*-butyl (**L7**) groups, in principle. As shown in Scheme 5a, ligand **L9** bearing two ethyl groups also exhibits no catalytic activity, while BINOL racemization could be detected with **L10** to 83% *ee* in 60 min, by increasing the steric hindrance of the alkyl substituents from two ethyl to *iso*propyl groups. Obviously, the catalytic activity trends could be concluded to be strongly dependent on the steric hindrance of the bisalkyl substituents in ligands, and **L7** gave the best performance at the current stage. Bis-hydroxylamine **L11** was also investigated, which fails to promote racemization activity as shown by the formation of (*R*)-**1a** with >99% *ee* in the presence/absence of Na_2CO_3, excluding its intermediacy in BINOL racemization.[22]

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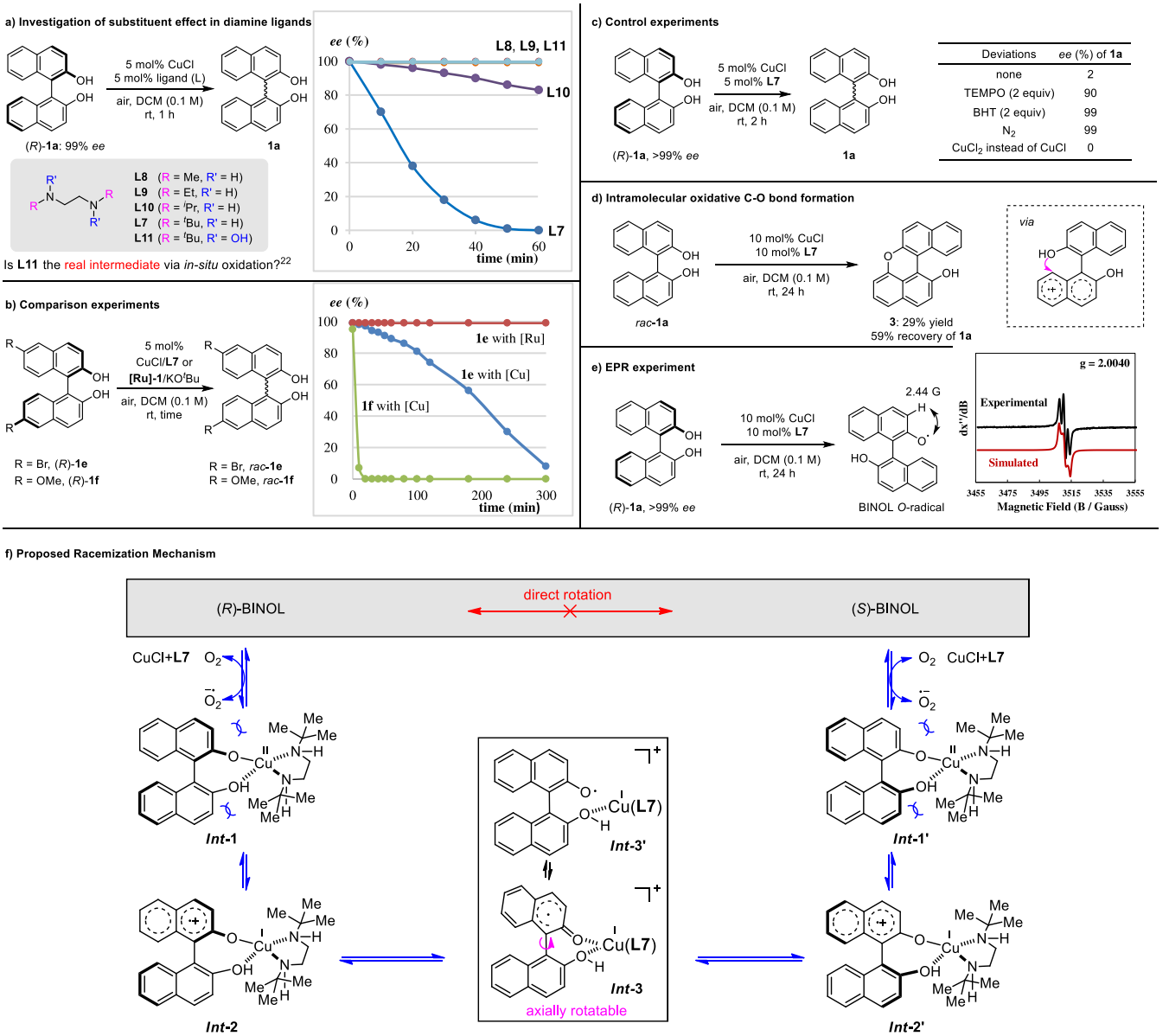
Scheme 5. Reaction Mechanism



Further studies on the substituent effect on racemization activity were carried out with BINOL (*R*)-**1e** with two bromo groups and (*R*)-**1f** with two methoxyl groups at 6,6′-positions, respectively, as shown in Scheme 5b, electron-rich BINOLs were racemized much faster, thus are more reactive under copper catalysis. These results imply a pathway of electron transfer from the BINOL moiety during racemization. The catalyst of [**Ru**]-**1** activated by KO^{t}Bu shows complete no activity in the racemization of (*R*)-**1e** under current conditions. The dynamic process was almost completely suppressed by (2,2,6,6-tetramethylpiperidin-1-yl)oxyl (TEMPO) or butylated hydroxytoluene (BHT), suggesting a possible radical pathway for BINOL racemization (Scheme 5c). The axial structure stops flipping when removed from an air atmosphere, making clear that oxygen plays an indispensable role to initiate the copper catalysis. $CuCl_2$ exhibits equal activity on BINOL racemization together with **L7**, implying the intermediacy of the Cu^{II} species. Moreover, oxidized product **3** was produced in 29% yield, forming an intramolecular C−O bond under the catalysis of CuCl/**L7** with 59% recovery of *rac*-**1a**, pointing to the intermediacy of radical-cation species, forming the C−O bond via an intramolecular *O*-nucleophilic attack (Scheme 5d). Electron paramagnetic resonance (EPR) experiment of (*R*)-**1a** was subsequently conducted with CuCl and **L7** to give a characteristic signal of BINOL *O*-radical, validating the generation of the oxy radical during racemization (Scheme 5e).

Based on the reaction outcomes and mechanistic studies, a possible radical mechanism[23] for the dynamic racemization of BINOL is proposed in Scheme 5f. After being oxidized to Cu^{II} under an air atmosphere in the presence of bidentate ligand **L7**, binuclear coordination of (*R*)- or (*S*)-BINOL to the Cu^{II} center leads to the formation of tetrahedral copper(II) complexes, ***Int*-1** and ***Int*-1′**, respectively. Single-electron oxidation[7,24] of BINOL moiety by copper(II) would generate radical-cation species ***Int*-2** or ***Int*-2′**, in which rotation barrier can be significantly decreased by calculations. Alternative description is that bond isomerization subsequently produces copper(I)-radical species *Int*-**3**, which is a delocalized radical

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allowing the axial rotation.[25] Compared with the coordination effect in ***Int*-1** or ***Int*-1′**, oxygen from the carbonyl group in ***Int*-3** becomes weakly bonded to the copper center, resulting in a substantial decrease of the rotation barrier and the consequent inversion of the axial element of chirality. Isomerization of ***Int*-3** to ***Int*-3′** occurs simultaneously, which further releases a BINOL radical as determined by EPR experiments. Ligand has been demonstrated as a crucial factor for the efficient racemization of BINOL, as shown in Scheme 5a, and the two ^{t}Bu groups in **L7** enhanced its steric hindrance to ensure the reversible coordination of the copper complex with BINOL substrate, other than forming a stable ternary copper complex.[20c]

CONCLUSIONS

In summary, an efficient crystallization-induced deracemization (CID) of various biaryls has been developed with a chiral ammonium salt under copper catalysis, including BINOL, NOBIN, and BINAM derivatives. The bidentate diamine ligand plays a crucial role in racemizing biaryl skeletons, and bulky alkyl substitution (^{t}Bu) in the ligand was an indispensable element to endow the racemization with high efficiency and selectivity. In contrast with chiral resolution, CID not only significantly improved the reaction yield but also enhanced the enantioselectivity in the product. The CID process is easily scalable and exhibits an abroad substrate scope without chromatographic purification, with chiral ammonium salt nicely recoverable. Moreover, this CID method could also be extended with 2-naphthol as the starting material.[26] At this stage, copper catalysis promotes oxidative coupling reactions of 2-naphthol to produce racemic BINOLs. Besides, it performs as the racemization catalyst for the CID of axially chiral skeletons. Mechanistic studies show that racemization of biaryls probably proceeds via a radical-cation intermediate, further allowing axial rotation by forming a delocalized radical. The key BINOL *O*-radical was detected by EPR analysis under CuCl/**L7**. Further studies of the mechanism and its synthetic applications are currently ongoing in our laboratory.

METHODS

Representative Procedure for the CID of *rac*-1

Under an air atmosphere, to a 10 mL reaction tube charged with a magnetic stirring bar were added *rac*-**1** (0.5 mmol) and the indicated solvent. A solution of *N*-benzylcinchonidinium chloride (**2a**, 0.6 mmol) in the indicated solvent was dropwise added with rapid stirring. Then, CuCl (0.025 mmol) and *N*,*N*′-di-*tert*-butylethane-1,2-diamine (0.025 mmol) were sequentially added to the reaction mixture. After that, the reaction tube was sealed with a rubber septum, and the reaction mixture was stirred at room temperature for 24 h. The resulting precipitate was isolated through filter paper by using a Buchner funnel and washed with cold CH_3CN. The precipitated complex was fully dissolved in a mixture of HCl (aq., 1 M, 20 mL) and EtOAc (20 mL). The organic phase was separated, and the aqueous phase was further extracted with EtOAc (20 mL × 2). The combined organic phases were dried in anhydrous Na_2SO_4 and concentrated under reduced pressure to afford (*R*)-**1**.

ASSOCIATED CONTENT

Data Availability Statement

All data generated or analyzed during this study are included in this article and the Supporting Information. All other data are available from the corresponding author upon request.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/jacsau.3c00623.

Experimental procedures, mechanistic studies, characterization data, NMR and HPLC spectra (PDF)

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Author Contributions

[§]These authors contributed equally: J.Z., K.W., and C.Z. conceived the project, performed the initial experiments, analyzed the data, and wrote the manuscript. J.Z. and K.W. performed most of the experiments. All authors discussed the results and commented on the manuscript. CRediT: **Jie Zhang** data curation, formal analysis, methodology, writing-review & editing; **Kun Wang** data curation, formal analysis; **Can Zhu** conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing-original draft, writing-review & editing.

Notes

The authors declare the following competing financial interest(s): C. Z. and J. Z. are inventors on a Chinese patent application (Application No. CN202310648405.5). The remaining authors declare no competing interests.

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