



Cite this: *Catal. Sci. Technol.*, 2024, 14, 1279

A hybrid Au/Ru catalyst for sequential alkyne hydration/asymmetric transfer hydrogenation reactions†

Bengi Ozgun Ozturk, ^{*,a} Burcu Durmuş Ağlamaz,^a Mina Aşkun,^a Zeynep Tunalı,^a Halenur Özer,^a Kutay Sagdic^{bc} and Fatih Inci ^{bc}

The utilization of organic/inorganic core/shell support materials by compartmentalizing of Au(II)/Ru(II) catalysts has led to the formation of chiral alcohol derivatives from alkynes *via* sequential alkyne hydration and asymmetric transfer hydrogenation reactions. A Ru(II) complex was supported on chiral ligand end-capped amphiphilic ROP polymers. The micellar Ru(II) catalyst was coated with a mesoporous silica shell to produce a secondary compartment where an IPuAuCl complex was confined in mesopores of silica gel through post-pore size reduction. A variety of alkynes were converted to chiral alcohol derivatives in quantitative yields with high enantioselectivity in a MeOH/H₂O mixture using sequential alkyne hydration/asymmetric transfer hydrogenation reactions.

Received 29th December 2023,
Accepted 19th January 2024

DOI: 10.1039/d3cy01795h

rsc.li/catalysis

Introduction

One-pot multistep reactions offer great advantages such as minimalization of solvent usage and elimination of any purification/isolation protocols, making the overall process more efficient and cost-effective.^{1,2} Combining different catalytic reactions in a tandem/sequential fashion is usually preferred to synthesize more sophisticated molecular structures in a selective and efficient manner.^{3,4} However, the incompatibility of different catalytic reaction conditions is the main obstacle when adapting catalytic reactions in a one-pot procedure. Hence, the compartmentalization of each catalyst in pre-defined regions emerged as a solution for the current challenge in the last decade.⁵ The synthesis of alcohols from alkynes using a one-pot procedure requires specific synthesis approaches involving sequential addition of the reactions or compartmentalization of reactions in spatial confinements.⁶ A variety of functionalized alkyne derivatives are commercially available in the market or can be synthesized on the lab scale using well-defined protocols.⁷ Alkynes therefore emerged as perfect starting materials to synthesize chiral or non-chiral alcohol derivatives using alkyne hydration (AH) and transfer

hydrogenation (TH)/asymmetric transfer hydrogenation (ATH) reactions. However, the AH and ATH reaction conditions are incompatible, which is the main issue with combining these two reactions. To tackle this challenge, earlier studies utilized binary catalyst systems. For instance, in 2013, Xiao *et al.* reported a sequential protocol where an alkyne hydration reaction proceeded in the presence of excess formic acid, followed by iridium-catalyzed transfer hydrogenation reactions.⁸ The presence of excess formic acid limited the catalyst's reactivity, thereby giving corresponding alcohols in moderate yields. In a similar approach, a sequential AH/ATH reaction was proceeded by employing trifluoromethanesulfonic acid as the AH catalyst and a fluorinated chiral ruthenium(II) complex as the ATH catalyst in 2,2,2-trifluoroethane.⁹ The catalyst system denoted a positive fluorine effect on the selectivity and performance of the sequential reaction. In another study, in 2020, Luo and colleagues used a Tang catalyst based on formic acid/iridium to catalyze sequential reactions of alkyne hydration/transfer hydrogenation.¹⁰ Regarding the earlier study demonstrated by Xiao *et al.*,⁸ only a five-fold excess of formic acid relative to alkyne was used at 80 °C to obtain the hydration product. In addition to acid-based sequential AH/ATH reactions, binary homogeneous catalyst systems including Au/Ru, Au/Rh, and Co/Ru were employed to produce alcohols from alkynes. Even though these systems showed high performance and selectivity in AH/ATH reactions, the catalyst systems are not reusable.^{11–13}

Contrary to the homogeneous binary catalyst systems, the compartmentalization approach was developed using polymersomes and inorganic support materials to reduce

^a Hacettepe University, Faculty of Science, Chemistry Department, Çankaya, Ankara, Turkey. E-mail: bengi04@hacettepe.edu.tr

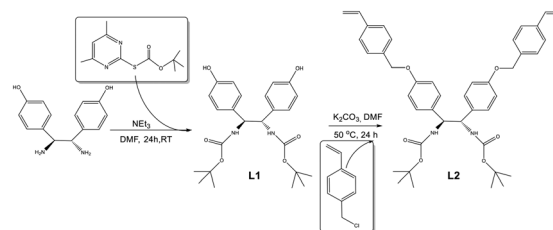
^b Institute of Materials Science and Nanotechnology, Bilkent Üniversitesi, Çankaya, Ankara, Turkey

^c UNAM—National Nanotechnology Research Center, Bilkent University, Çankaya, Ankara, Turkey

† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d3cy01795h>

metal leaching and improve the reusability of the catalyst system.^{14,15} In 2012, Rh(I) complex-bearing siloxane functionalized phosphine ligands were incorporated into periodic mesoporous silica gel and used along with FeCl₃ to catalyze sequential AH/ATH reactions of phenylacetylene.¹⁶ Although the corresponding chiral alcohols were obtained in moderate yield and high enantioselectivity, FeCl₃ was used equitably to the introduced alkyne. Xia *et al.* developed a heterogeneous catalyst system in which the ruthenium catalyst was covalently immobilized on ultra-large pore FDU-12 silica gel through chiral diamine ligands, whereas an AH catalyst, IPrAuBF₄, was supported on FDU-12 through non-covalent interactions. Tandem AH/ATH reactions were conducted in dichloroethane using an FDU-12 based Ru/Au catalyst system in the presence of HCOOH/NEt₃/H₂O (5/2/0.1; mol/mol/mol), resulting in high quantitative yields of halochiral alcohols.¹⁷ Amphiphilic triblock copolymers of poly(2-oxazoline)s were used to confine the Co-porphyrin complex within the hydrophobic core while Rh(I) was compartmentalized in the outer hydrophilic shell in the micelle structure.¹⁸ In a recent study, Liu developed a homogeneous incorporated cobaloxime and mesoporous silica-supported ruthenium/diamine catalyst for ATH reactions.⁶ A variety of arylacetylene derivatives were converted to corresponding alcohols in high yields with high enantioselectivity, however only supported catalysts showed high reusability. As reported in the literature,^{14–18} the compartmentalization of different catalysts using inorganic support materials or amphiphilic polymers emerged as a unique solution to isolate incompatible catalysts. This compartmentalization can be achieved by combining homogeneous and heterogeneous catalyst systems or using a micellar system to confine AH/ATH catalysts in hydrophobic and hydrophilic compartments. In this context, ring-opening metathesis polymerization (ROMP) has emerged as an efficient method for synthesizing amphiphilic random or block polymers for various applications including the development of novel polymersomes and micellar systems for drug delivery, nano-reactors and sensor applications.^{19–25} In addition, a variety of different hydrophobic/hydrophilic monomers and chain-transfer agents can be applied to ROMP reactions to obtain novel amphiphilic macromolecular structures.^{26–29} The amphiphilic ROMP polymers can be used as efficient support materials to conduct catalytic organic reactions within micelle structures.^{20,21,28,29}

In this study, we have designed a hybrid catalyst system through the compartmentalization of chiral Ru(II) and Au(I) catalysts within amphiphilic ROMP polymer/mesoporous SiO₂ as the core/shell structure. The coating of the amphiphilic polymer supported micellar Ru(II) catalyst with a mesoporous SiO₂ shell structure led to the unique core/shell material. We have confined the 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene)gold(I) chloride (IPrAuCl) (**Au-1**) complex within the mesopores of silica gel through post-pore size reduction. The performance of the catalytic system was tested on alkyne hydration, asymmetric transfer hydrogenation and



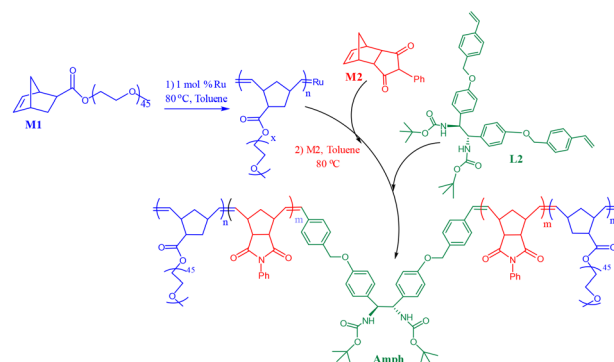
Scheme 1 Synthesis of the chiral ligand precursor.

sequential alkyne hydration/asymmetric transfer hydrogenation using various aryl and alkylacetylene derivatives in MeOH/H₂O.

To the best of our knowledge, this study is the first example in the literature to combine micellar catalysts and inorganic support materials to confine AH/ATH catalysts in individual domains using a hybrid catalyst system for sequential alkyne hydration/asymmetric transfer hydrogenation reactions of alkynes.

Results and discussion

The combination of AH and ATH reactions in a one-pot procedure requires the presence of confined individual domains to conduct each reaction separately to prevent the inhibition of the catalyst and improve the reaction's selectivity. For this purpose, we tried to form two different compartments using ruthenium-tagged amphiphilic ring-opening metathesis polymers (ROMP) as the micellar core for ATH reactions and mesoporous silica gel as the shell and outer compartment for Au(I)-catalyzed alkyne hydration reactions. An amphiphilic polymer-based ruthenium catalyst was synthesized by integrating a chiral diamine ligand on amphiphilic ROMP copolymers. Initially, (1*S*,2*S*)-1,2-bis(4-hydroxyphenyl)ethylenediamine was reacted with *S*-Boc-2-mercapto-4,6-dimethylpyrimidine in dimethylformamide (DMF) at room temperature to integrate *t*-Boc as a protecting group for amine groups (Scheme 1). This protection step is necessary to prevent the inhibition of the ruthenium metathesis catalyst by free amine groups during ROMP reactions. After 24 h, **L1** was isolated as an off-white solid in



Scheme 2 Synthesis of the ROMP polymer (Amph).

Table 1 ROMP reactions in the presence of varying monomer/CTA (**L2**) ratios

Entry ^a	M2/M1/L2/Ru	Time (h)	Conv. %	Cat. (Ru)	M_n^b (kDa)	D^c	T_g^d (°C)
1	100/10/1/1	12	97	HG2	14	1.2	63
2	100/10/2/1	12	95	HG2	11	1.1	61
3	100/10/5/1	12	96	HG2	9	1.1	60
4	100/10/10/1	12	99	HG2	5.5	1.2	57
5	100/10/1/1	18	99	G3	15	1.3	65
6	100/10/2/1	18	99	G3	12	1.3	63
7	100/10/5/1	18	99	G3	6.8	1.2	60
8	100/10/10/1	18	98	G3	4.6	1.2	48
9	500/10/10/1	24	70	G3	24	1.1	68

^a Reaction conditions: HG3 or G3 (0.015 mmol), **M1** (0.15 mmol), **M2** (1.50 mmol) and chain-transfer agent (**L2**) (0.030 mmol) in dry toluene, reaction temperature is 80 °C. ^b Determined by size exclusion chromatography using linear PMMA standards in THF (1 mL min⁻¹) at 30 °C. For more details please see the ESI.† ^c M_w/M_n . ^d Determined by differential scanning calorimetry (DSC) measurements under a nitrogen atmosphere with a heating rate of 10 °C min⁻¹.

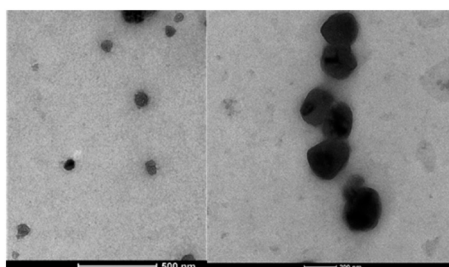
60% yield. The ¹H NMR spectrum of **L1** in d₆-DMSO showed the presence of an -OH group at 9.54 (s, -OH, 2H) ppm as a singlet peak (ESI,† Fig. S1). The aromatic proton signals have appeared between 7.01 and 7.06 (d, *J* = 8.4 Hz, Ar-H, 4H) and 6.70 and 6.59 (d, *J* = 8.4 Hz, Ar-H, 4H) ppm as doublets in the ¹H NMR spectrum of **L1**. The singlet peak appearing at 5.38 ppm (s, 2H) was assigned as the CH-Ar- proton peak. The *tert*-butyl group was observed at 1.29 ppm as a singlet peak (s, 18H). The ¹³C NMR spectrum of **L1** showed carbonyl peaks at 155.59 and 154.06 ppm (ESI,† Fig. S2). Aromatic group carbon peaks appeared at 129.24, 127.76, 119.04 and 114.44 ppm. The -CH-NH- carbon peak was observed at 77.79 ppm. The carbon peaks for the *tert*-butyl group appeared at 53.14 (-C(CH₃)) and 28.60 (-C(CH₃)₃). The ESI-MS spectrum of **L1** showed the corresponding [M-H]⁺ peak at *m/z*: 443.2201 Da (ESI,† Fig. S3). **L2** was synthesized through the reaction of hydroxy groups of **L1** with 1-vinyl chlorobenzene in the presence of potassium carbonate in DMF at room temperature. The integration of vinyl groups is required to use **L2** as a chain-transfer agent (CTA) in ROMP reactions for end-functionalization of polymers.

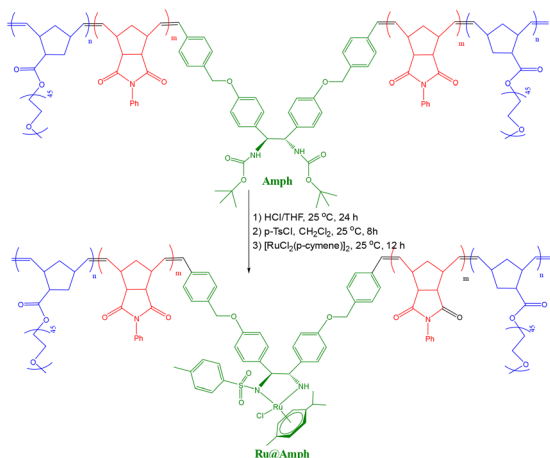
The ¹H NMR spectrum of **L2** in d₆-DMSO showed the presence of the phenyl groups between 6.79 and 7.46 ppm as multiplets along with the olefinic proton of the H₂C=CH-C₆H₄- group (ESI,† Fig. S4). The other olefinic proton signal was observed at 5.85 ppm as a doublet (2 H, d, *J* = 17.0 Hz). The -HN-CH- proton signal appeared as a doublet at 5.28 ppm (*J* = 10.2 Hz, 2H) while the -CH₂ group of the attached

vinyl benzene group appeared at 4.96 as a singlet peak. The carbonyl group (-C=O-) of **L2** was observed at 156.22 ppm in the ¹³C NMR spectrum (ESI,† Fig. S5). Olefinic carbon signals appeared at 136.60 and 111.79 ppm and phenyl carbons appeared between 128.88 and 113.87 ppm. *tert*-Butyl carbon peaks were observed at 78.80 (-C(CH₃)₃) and the MALDI-ToF mass spectrum of **L2** which was recorded in the presence of silver(i) trifluoroacetate showed a signal at *m/z* 783.253 Da for [M + Ag]⁺ (ESI,† Fig. S6). The structure was also confirmed by ESI-MS analysis in positive mode (ESI,† Fig. S7).

Ring-opening metathesis polymerization (ROMP) reactions were carried out using a hydrophilic monomer (**M1**) and a hydrophobic monomer (**M2**) in the presence of **L2**. For this purpose, a Schlenk reactor was loaded with the hydrophilic monomer (**M1**) in toluene and the ROMP reaction was initiated with the introduction of the Hoveyda-Grubbs 2nd generation catalyst (HG2) or Grubbs 3rd generation catalyst (G3) under a nitrogen atmosphere at 80 °C (Scheme 2) (ESI,† Fig. S8–S11). After 30 minutes of reaction time, the hydrophobic monomer (**M2**) was introduced into the reaction media to form the hydrophobic compartment, followed by the addition of CTA (**L2**) to terminate the reaction. To control the efficiency of **L2** as the chain-transfer agent, ROMP reactions were carried out using different **M2/M1/L2/Ru** mol ratios (Table 1). The M_n values of ROMP polymers were systematically decreased with an increase in **M2/M1/L2** ratio, indicating efficient polymer chain termination.^{30–32} The end-capped amphiphilic ROMP polymers are denoted as Amph. The ¹H NMR spectrum of Amph confirmed the integration of the chiral ligand precursor on the polymer structure according to the small peaks appearing at 5.23 and 5.79 ppm (ESI,† Fig. S12–S14). Aromatic proton signals were overlapped at 7.03–7.37 ppm as multiplets. In addition, the MALDI ToF-MS spectrum of the Amph confirmed the termination of the amphiphilic block polymer formation with CTA (**L2**) (ESI,† Fig. S15).

Moreover, the amphiphilic nature of the Amph was investigated using dynamic light scattering (DLS) and high contrast transmission electron microscopy (TEM). The average particle size of the amphiphilic polymer (Amph, M_n :

**Fig. 1** High contrast TEM images of Amph.



Scheme 3 Synthesis of Ru@Amph.

12 kDa) was found as $140 \text{ nm} \pm 30 \text{ nm}$ as confirmed by TEM analysis (Table 1 entry 6, Fig. 1, S16 and S17). Sphere-like nanoparticles were formed in aqueous medium. DLS results confirmed the presence of nanosized structures with an average particle size of $170 \text{ nm} \pm 23 \text{ nm}$ (ESI,† Fig. S18).

The ruthenium complex was synthesized using a one-pot procedure. The protecting group (*t*-Boc) was removed from the amphiphilic polymer (Amph) through the treatment with HCl/THF and followed by modification of free-amine groups with *para*-toluenesulfonyl chloride. $[\text{RuCl}_2(\textit{p}\text{-cymene})]_2$ was added to the polymeric material to obtain the corresponding ruthenium complex which is denoted as Ru@amph (Scheme 3). The ^1H NMR spectrum of Ru@amph is given in Fig. 2 (ESI,† Fig. S19). The peaks appearing between 5.70 and 5.78 ppm as doublets confirmed the presence of the *p*-cymene group. The aromatic proton signals of the tosylate group appeared at 6.77 ppm as multiplets. To further evaluate the structure of Ru@amph, X-ray photoelectron spectroscopy (XPS) analysis was performed for both Ru@amph and the starting complex $[\text{RuCl}_2(\textit{p}\text{-cymene})]_2$ and detailed comparison is given in Fig. 3 and 4. The Ru $3d_{5/2}$ signal of $[\text{RuCl}_2(\textit{p}\text{-cymene})]_2$ was slightly shifted from 281.2

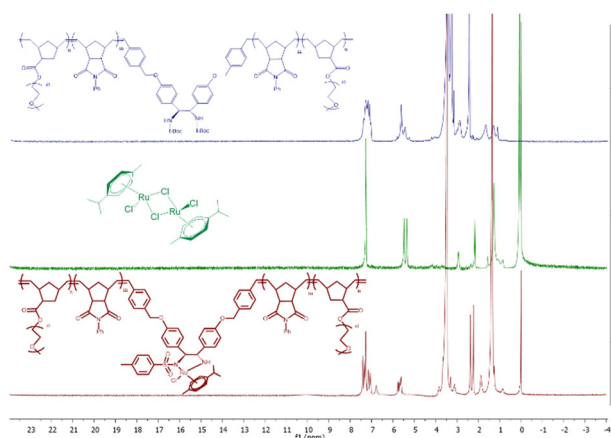
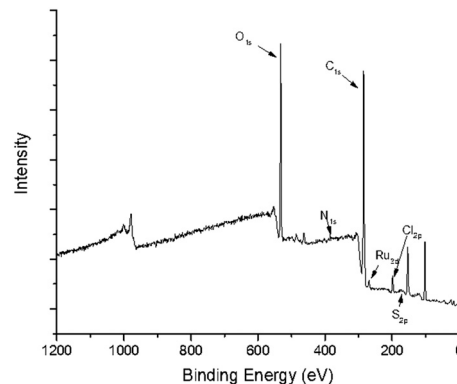
Fig. 2 ^1H NMR spectrum comparison of Ru@amph in CDCl_3 .

Fig. 3 XPS survey scan of Ru@amph.

eV to 281.8 eV indicating the coordination of ruthenium to the Amph structure through amine groups. Similarly, the Cl 2p signal was shifted to 198.69 eV.

Once Ru@amph was characterized by means of ^1H NMR, TEM and XPS methods, Ru@amph in the water/ethanol mixture was coated with a SiO_2 shell using the Stöber method to isolate the micellar catalyst forming a secondary compartment through mesopores of the silica shell (Scheme 4). For this purpose, Ru@amph was dispersed in an ethanol/water mixture (v/v: 9/1), and the non-ionic surfactant Synperonic® F108 was added to prevent the coagulation of silica particles. The cationic surfactant cetyltrimethylammonium bromide (CTAB) was added to form the mesopores of silica gel. Tetraethoxysilane (TEOS) and concentrated ammonia (aq.) were added to the reaction media to initiate the reaction and the mixture was stirred mechanically for 24 h. After 24 h, the silica gel was isolated through centrifugation and the isolated silica gel was dispersed in ethanol and stirred for 12 h at room temperature in order to remove the surfactants and open the pores of the silica shell. The material was denoted as

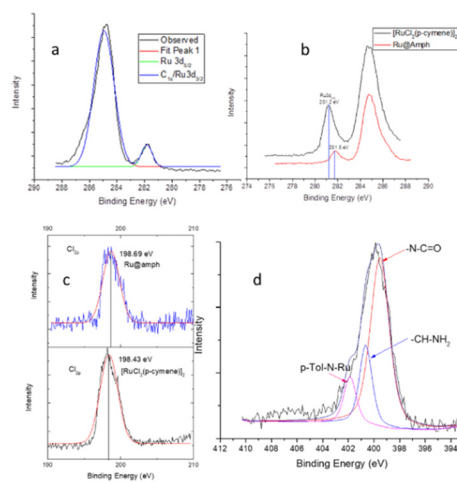
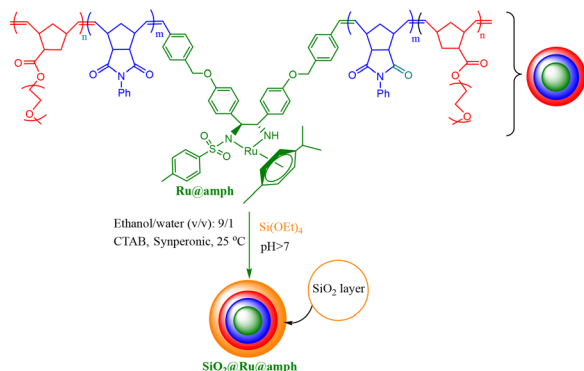
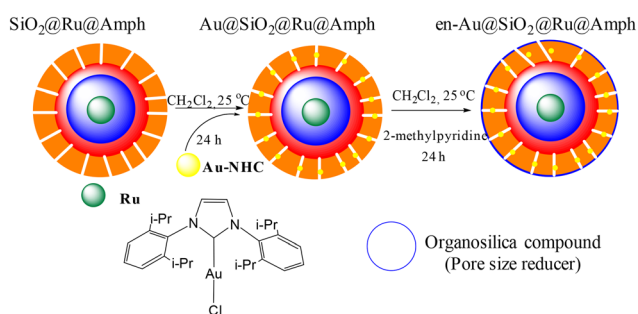


Fig. 4 The detailed XPS spectrum of Ru@amph: a) Ru 3d; b) the comparison of Ru 3d signals; c) Cl 2p and d) N 1s.



Scheme 4 Coating of Ru@amph using the Stober method.



Scheme 5 Post-pore size reduction of Au@SiO₂@Ru@amph through silylation.

SiO₂@Ru@amph. High resolution TEM-EDX-line analyses are given in the ESI† (Fig. S20–S22).

Ruthenium free core/shell particle SiO₂@Amph (amph) was also synthesized and characterized using various techniques including FTIR, TGA, DLS, XPS, TEM, and N₂ adsorption/desorption isotherms and results are given in the ESI† (Fig. S23–S32). Post pore-size reduction using organosilane derivatives emerged as an efficient method to minimize metal leaching during catalytic reactions.^{33,34} **Au-1** (1,3-bis(2,6-diisopropylphenyl-imidazol-2-ylidene)gold(i) chloride, IPrAuCl) was impregnated on SiO₂@Ru@amph in dichloromethane at room temperature for 24 h. After that,

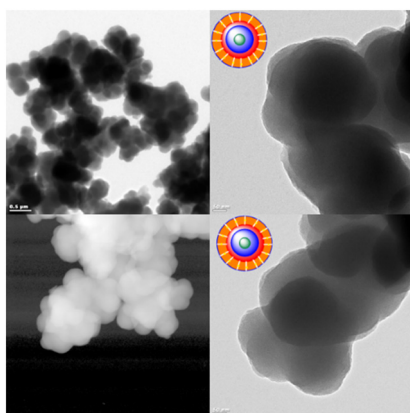


Fig. 5 High-resolution TEM images of en-Au@SiO₂@Ru@amph.

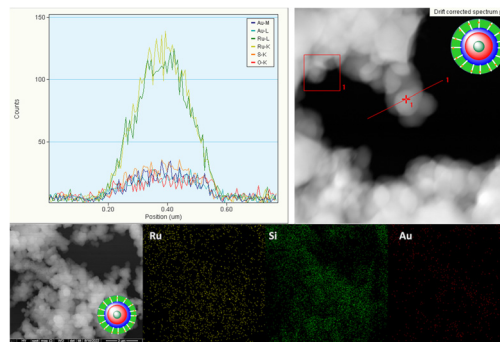


Fig. 6 TEM-EDX analysis of en-Au@SiO₂@Ru@amph.

various organosilica derivatives including dichlorodiphenylsilane, dichloromethylphenylsilane and dichlorodimethylsilane were introduced into the solution along with 2-methylpyridine to reduce the pore size and to form a bulky layer on the silica surface (Scheme 5). After 24 h of intense stirring at room temperature, the solvent was evaporated and the resulting solid was washed with dichloromethane. Encapsulated catalysts were denoted as en-Au@SiO₂@Ru@amph. TEM images confirmed the formation of a uniform outer shell of mesoporous silica (Fig. 5). The core/shell particles have a spherical morphology and the average particle size was found to be 374 nm (±67 nm).

EDX-line and EDX-mapping analysis of encapsulated catalysts showed the compartmentalization of Au and Ru complexes on the silica gel structure (Fig. 6). The detailed EDX-map analysis showed that Au particles were confined in a sphere-like orientation which indicates the presence of Au on the outer silica gel structure.

XPS analysis of Au@SiO₂@Ru@amph showed that the oxidation state of the gold complex was Au(+1) and no sign of reduction was observed (Fig. 7). The surface area of SiO₂@Ru@amph was found to be 170 m² g^{−1} as confirmed by N₂ adsorption/desorption isotherms. The pore size and volume for SiO₂@Ru@amph were found to be 0.10 cm³ g^{−1} and 2.70 nm. A type IV adsorption/desorption isotherm was observed with an H2-type hysteresis loop, indicating the presence of a mesoporous structure³⁵ (ESI† Fig. S33 and S34).

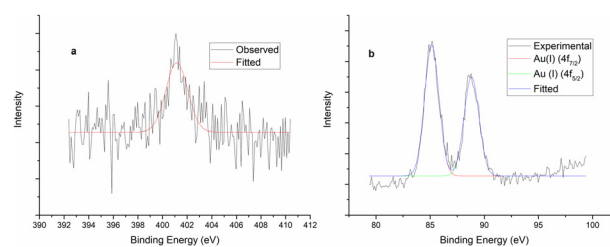


Fig. 7 XPS analysis for Au(I) (Au@SiO₂@Ru@amph (SiCl₂Ph₂)): a) N 1s (left side) b) Au_{4f} (right side).

Table 2 Surface properties of core/shell materials

	Surface area ^a (m ² g ⁻¹)	Pore volume (cm ³ g ⁻¹)	Pore size (nm)
SiO ₂ @Ru@amph	170	0.10	2.70
en-Au@SiO ₂ @Ru@amph (SiCl ₂ (CH ₃) ₂)	140	0.10	2.65
en-Au@SiO ₂ @Ru@amph (SiCl ₂ PhCH ₃)	110	0.080	2.50
en-Au@SiO ₂ @Ru@amph (SiCl ₂ Ph ₂)	45	0.055	2.12

^a Determined by N₂ adsorption/desorption isotherms using the BET method.

Following the addition of **Au-1** (IPrAuCl), a post-pore size reduction protocol was applied to Au@SiO₂@Ru@amph to prevent catalyst leaching and obtain a size-selective catalyst system on sequential alkyne hydration/ATH reactions. As expected, following the post-pore size reduction, the surface area and pore volume were significantly decreased (Table 2). The surface area was reduced to 45 m² g⁻¹ using dichlorodiphenylsilane as the silylating agent.

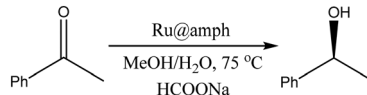
Asymmetric transfer hydrogenation (ATH) reactions using Ru@Amph, SiO₂@Ru@Amph and en-Au@SiO₂@Ru@amph

Asymmetric transfer hydrogenation reactions were carried out using the micellar catalyst Ru@amph and the silica-coated core/shell catalyst SiO₂@Ru@Amph. In the first trials, ATH reactions were performed in the MeOH/H₂O mixture at 80 °C using Ru@amph as the catalyst in the presence of different hydride sources such as HCOONa, HCOOK, HCOOH/KOH, HCOOH/NaOH and HCOOH/NEt₃ (Table 3). The reaction proceeded smoothly with a catalytic loading of 1% mol Ru (Ru@amph), reaching complete conversion within one hour in the presence of sodium formate. Binary mixtures of HCOOH/NaOH and HCOOH/KOH showed similar performance. On the other hand, the performance of the

catalyst decreased in the presence of formic acid (HCOOH) and the binary mixture of formic acid (HCOOH/NEt₃). As reported in the literature, the performance of the asymmetric transfer hydrogenation reactions can be tuned by varying the molar ratio of the azeotropic mixture of formic acid and triethylamine.³⁶ However, the reaction proceeded solely in formic acid/NEt₃ acting as both the solvent and hydride source. In our case, the reaction proceeded in MeOH/H₂O due to the optimum alkyne hydration reaction conditions. Therefore, the performance of the ATH reactions is limited when using the formic acid/triethylamine mixture.

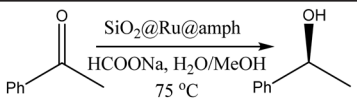
The effect of the SiO₂ shell on the activity of SiO₂@Ru@amph was tested using optimized reaction conditions and the performance of both the micellar catalyst Ru@amph and the hybrid catalyst (SiO₂@Ru@amph) was compared in ATH reactions of acetophenone. As a result of diffusion limitations exerted by the SiO₂ shell, the ATH reaction reached complete conversion within 6 h with a catalytic loading of 1 mol% Ru. As can be seen in Table 4, the ATH reaction slowed down when Ru@amph was coated with an outer layer of SiO₂. This diffusion effect is more dominant when the substrate/Ru ratio is further increased up to 500/1 (mol/mol). The mesoporous shell acted as a diffusion barrier. Although the conversion rate of the ATH

Table 3 Asymmetric transfer hydrogenation of acetophenone using Ru@amph

						
Entry ^a	Additive	Ru/Subst./Add. (mol/mol/mol)	Time (h)	Conv. ^b %	TON (TOF)	ee% ^c
1	HCOONa	1/100/200	1	99	99 (99)	90
2	HCOOK	1/100/200	1	95	95 (95)	90
3	HCOOH/NaOH	1/100/200	2	99	99 (49.5)	88
4	HCOOH/KOH	1/100/200	2	96	96 (48)	91
5	HCOOH	1/100/200	24	20	n.d.	n.d.
6	HCOOH	1/100/500	24	40	n.d.	n.d.
7	HCOOH/NEt ₃	1/100/200	24	5	n.d.	n.d.
8	HCOOH/NEt ₃	1/100/500	24	8	n.d.	n.d.
9	HCOONa	1/1000/2000	24	70	700 (29)	90
10	HCOONa	1/500/1000	9	80	400 (44)	90
11	HCOONa	1/200/400	2	95	190 (5)	88

^a Reaction conditions: Ru@amph (80 mg, 0.016 mmol Ru per g), acetophenone (1.6 mmol, 190.0 μL) in the MeOH/H₂O mixture (v/v: 1 mL/1 mL). The reaction temperature is 75 °C. ^b Determined by GC-MS using *n*-tetradecane as an internal standard. ^c Determined by GC using a chiral column.

Table 4 ATH reactions of the silica-coated Ru catalyst ($\text{SiO}_2\text{@Ru@amph}$)

						
Entry ^a	Catalyst	Ru %	Time (h)	Conv. ^b %	TON ^c (TOF)	% ee ^d
1	Ru@amph ^e	1	1	99	99 (99)	90
2	$\text{SiO}_2\text{@Ru@amph}$ ^f	1	4	85	85 (21.3)	88
3	$\text{SiO}_2\text{@Ru@amph}$	1	6	99	99 (16.5)	90
4	Ru@amph	0.5	2	95	190 (95)	90
5	$\text{SiO}_2\text{@Ru@amph}$	0.5	12	80	160 (13)	91
6	Ru@amph	0.2	24	80	400 (17)	89
7	$\text{SiO}_2\text{@Ru@amph}$	0.2	24	50	250 (10)	90

^a Reaction conditions: Ru-amph (100 mg, 0.016 mmol Ru per g), acetophenone (0.16 mmol, 19.0 μL) in the MeOH/ H_2O mixture (v/v: 1 mL/1 mL). The reaction temperature is 75 °C. ^b Determined by GC-MS using *n*-tetradecane as an internal standard. ^c Turn-over number (TON), turn-over frequency (h^{-1}). ^d Determined by GC using a chiral column. ^e 0.016 mmol Ru per g. ^f 0.118 mmol Ru per g.

reaction was slowed down, the enantiomeric selectivity of the catalyst did not get affected. The kinetic graphs for the conversion of acetophenone using Ru@Amph and $\text{SiO}_2\text{@Ru@amph}$ are given in the ESI† (Fig. S35).

On the next trial, ATH reactions were performed with Au(I) encapsulated catalysts bearing different organosilica derivatives as post-pore size reducers (Table 5). The impregnation of Au(I) on the mesopores of the silica gel did not significantly affect the performance of the ATH reactions using the non-encapsulated catalyst Au@ $\text{SiO}_2\text{@Ru@amph}$. The steric effect of the silylating agent became predominant in ATH reactions when the en-Au@ $\text{SiO}_2\text{@Ru@amph}$ catalyst bearing a bulkier silylating agent $\text{SiCl}_2\text{CH}_3\text{Ph}$ was used.

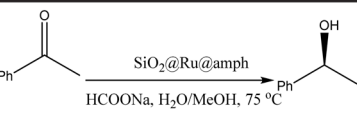
Alkyne hydration reactions catalyzed by Au@ $\text{SiO}_2\text{@Ru@amph}$ and en-Au@ $\text{SiO}_2\text{@Ru@amph}$

The optimum reaction conditions for hydration of phenylacetylene were determined using Au@ $\text{SiO}_2\text{@Ru@Amph}$ as the model catalyst. Ru@amphRu@amph alkyne hydration

reactions were optimized by varying MeOH/ H_2O (v/v) ratios (v/v: 4/1; 2/1 and 1/1) and silver(I) salts (5 mol% AgX equiv.: AgBF_4 , AgNO_3 , AgOTf and AgSbF_6) or mineral acids (5 mol% equivalent H_2SO_4 , HNO_3 and H_3PO_4) (Table 6) using Au@ $\text{SiO}_2\text{@Ru@Amph}$. In the first trials, the MeOH/ H_2O volume/volume ratio and the effect of added silver(I) salts and acids were investigated in detail. For this purpose, the reaction was initiated using 1 mol% Au loading and 5 mol% corresponding silver salts or acids (as 4 M solution). In the absence of silver(I) salts or mineral acids (H_2SO_4 or H_3PO_4) the reaction did not proceed. A conversion value of 99% was obtained in the case of AgOTf and AgSbF_6 within one hour of reaction time. The reaction showed poor performance in the presence of AgBF_4 and AgNO_3 . The optimum solvent mixture ratio was found to be 1/1 (v/v: MeOH/ H_2O) (Table 6).

The effect of post-pore size reduction on the performance of gold-catalyzed alkyne hydration reactions was investigated using optimum reaction conditions (MeOH/ H_2O (v/v: 1/1) at 80 °C under a nitrogen atmosphere with a catalytic loading

Table 5 ATH reactions using encapsulated catalysts

					
Catalyst	Ru % (mol%)	Time (h)	Reusability ^{a,b} (Conv. %)		
			Run 1	Run 2	Run 3
Au@ $\text{SiO}_2\text{@Ru@amph}$	1	6	99	98	95
	0.5	12	80	78	75
en-Au@ $\text{SiO}_2\text{@Ru@amph}$	1	6	99	99	95
($\text{SiCl}_2(\text{CH}_3)_2$)	0.5	18	78	75	75
en-Au@ $\text{SiO}_2\text{@Ru@amph}$	1	8	99	99	99
($\text{SiCl}_2\text{CH}_3\text{Ph}$)	0.5	24	78	72	70
en-Au@ $\text{SiO}_2\text{@Ru@amph}^c$	1	12	98	98	97
($\text{SiCl}_2(\text{Ph})_2$)	0.5	24	75	65	55

^a Reaction conditions: Ru-amph (100 mg 0.016 mmol Ru per g) acetophenone (0.16 mmol, 19.0 μL) in the MeOH/ H_2O mixture (v/v: 1/1 mL). The reaction temperature is 75 °C. ^b Determined by GC-MS using *n*-tetradecane as an internal standard. ^c 0.0120 mmol Au per g, 0.118 mmol Ru per g.

Table 6 Alkyne hydration reactions using Au@SiO₂@Ru@Amph

$\text{Ph-C}\equiv\text{C-C}\equiv\text{C} \xrightarrow[\text{MeOH/H}_2\text{O}, 80^\circ\text{C}]{\begin{matrix} 0.1 \text{ mol \% Au} \\ 5 \% \text{ mol H}_2\text{SO}_4 \end{matrix}} \text{Ph-C(=O)-CH}_2\text{-C}\equiv\text{C}$				
Catalyst	Time (h)	Reusability (conversion %)		
		Run 1	Run 2	Run 3
Au@SiO ₂ @Ru@amph	0.5	99	60	0
en-Au@SiO ₂ @Ru@amph (SiCl ₂ (CH ₃) ₂)	1	99	61	10
en-Au@SiO ₂ @Ru@amph (SiCl ₂ CH ₃ Ph)	2.5	99	70	40
en-Au@SiO ₂ @Ru@amph (SiCl ₂ (Ph) ₂)	6	99	99	99

Reaction conditions: Au@SiO₂@Ru@Amph (0.077 mmol Au per g, 100 mg, 7.7 μmol), phenylacetylene (7.7 mmol, 85.0 μL) and sulfuric acid (5% mol equiv., 4 M acid solution, 10 μL) in the MeOH/H₂O mixture (v/v: 1 mL/1 mL). The reaction temperature is 80 °C.

of 1 mol% Au.) (Table 7 and ESI† Fig. S36). As previously reported by several research groups, the counterion effect on gold–NHC complexes play a predominant role in the activity of the catalyst in hydration reactions.^{37–39} Silver(i) salts form cationic gold complexes with corresponding anions of silver(i) salts, thus increasing the performance as a result of the interaction between anions and the *in situ* formed cationic gold(i)-alkyne intermediates.⁴⁰ A similar counterion effect was also observed in gold(i) catalyzed alkyne hydration reactions using mineral acids.⁴¹

As shown in Table 7, the non-capsulated catalyst Au@SiO₂@Ru@amph showed high performance in hydration reactions, reaching quantitative yields within 30 minutes of reaction time. The recycled catalyst can be used only twice and in the third run no conversion to the desired product was observed. Silylation of silica gel using dichlorodimethylsilane has no significant effect on both the performance and recyclability of the catalyst. The substitution of methyl groups with relatively bulky phenyl groups has increased the performance of the recycled

Table 7 AH reactions in the presence of encapsulated catalysts

$\text{Ph-C}\equiv\text{C-C}\equiv\text{C} \xrightarrow[\text{MeOH/H}_2\text{O}, 80^\circ\text{C}]{\begin{matrix} 0.1 \% \text{ mol Au} \\ 5 \% \text{ mol AgX} \\ \text{or } 5 \% \text{ mol mineral acid} \end{matrix}} \text{Ph-C(=O)-CH}_2\text{-C}\equiv\text{C}$						
Entry ^a	MeOH/H ₂ O (v/v)	T (°C)	Additive	Time (h)	Conv. ^b (%)	Yield ^c (%)
1	1/1	80	—	24	—	—
2	1/1	80	AgBF ₄	24	35	30
3	1/1	80	AgOTf	1	99	97
4		50		4	65	60
5	1/1	80	AgSbF ₆	1	99	97
6		50		4	68	65
7	1/1	80	AgNO ₃	48	10	n.d.
8	1/2	80	AgOTf	2	90	88
9	1/3	80	AgOTf	4	88	85
10	1/4	80	AgOTf	9	85	82
11	—/1	80	AgOTf	24	—	—
12	1/—	80	AgOTf	24	5	n.d.
13	1/1	80	H ₂ SO ₄	0.5	99	97
14		50		5	55	50
15 ^d	1/1	80	H ₂ SO ₄	12	8	n.d.
16	1/1	80	HNO ₃	8	55	52
17	1/1	80	H ₃ PO ₄	8	20	n.d.
18	1/2	80	H ₂ SO ₄	1	99	96
19	1/3	80	H ₂ SO ₄	4	95	94
20	1/4	80	H ₂ SO ₄	8	92	90
21	—/1	80	H ₂ SO ₄	24	—	—
22	1/—	80	H ₂ SO ₄	24	—	—

^a Reaction conditions: Au@SiO₂@Ru@Amph (0.077 mmol Au per g, 100 mg, 7.7 μmol), phenylacetylene (7.7 mmol, 85.0 μL), silver(i) salts (5% mol equiv., AgOTf (0.0385 mmol), 10 mg) or mineral acid (5% mol equiv., 4 M acid solution, 10 μL) in the MeOH/H₂O mixture (v/v: 1 mL/1 mL). The reaction temperature is 80 °C. ^b Determined by GC-MS using *n*-tetradecane as an internal standard. ^c Isolated yield. ^d The reaction proceeded in the absence of the gold catalyst.

Table 8 Sequential AH/ATH reactions

Time (h)	Method ^a	1a ^d (%)	2a (%)	3a (%)
1	A ^b	80	20	—
2	A	57	42	1
4	A	48	50	2
6	A	33	65	2
24	A	30	68	2
1	B ^c	69	31	—
2	B	37	63	—
6	B	0	99	—
8	B	—	70	29
12	B	—	32	67
20	B	—	5	95

^a Reaction conditions: en-Au@SiO₂@Ru@amph (–SiCl₂Ph₂) (100 mg, 0.0120 mmol Au per g, 0.118 mmol Ru per g), phenylacetylene (12.0 mmol, 1.3 mL) and in MeOH/H₂O (1 mL/1 mL). AgOTf (5% mol equiv., 0.60 mmol, 15.0 mg) was added for AH reactions and sodium formate (24.0 mmol, 1.63 g) was added for ATH reactions. The reaction temperature is 80 °C for alkyne hydration and 75 °C for asymmetric transfer hydrogenation reactions. ^b For method A, all compounds were added to the Schlenk reactor at once and the reaction mixture was stirred at 80 °C. ^c The compounds were added sequentially. ^d Determined by GC-MS.

catalyst. However, due to the diffusion limitations exerted by phenyl groups, the reaction proceeded more slowly and reached quantitative yields within 2.5 h. Post-pore size reduction using dichlorodiphenylsilane has significantly improved the recyclability of the catalyst and minimized Au leaching.

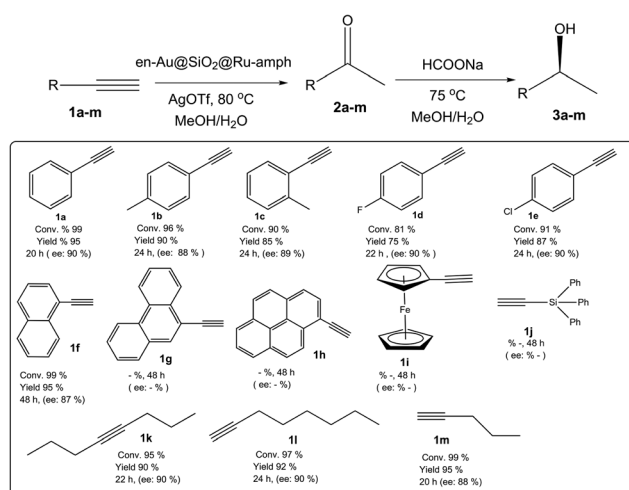
Sequential alkyne hydration/asymmetric transfer hydrogenation reactions

Encapsulated catalysts were used for sequential alkyne hydration and asymmetric transfer hydrogenation reactions in a one-pot procedure to produce chiral alcohol derivatives from alkynes. AH/ATH reactions were tested using two different protocols. In protocol A, AH/ATH reactions proceeded in a one-pot procedure through the addition of both silver(I) salts and hydride sources (HCOONa) to the Schlenk reactor. In protocol B, a representative alkyne was first transformed into corresponding ketone derivatives using silver(I) salts and then the introduction of sodium formate to the reaction media initiated the ATH reactions of ketone derivatives. In protocol A, the reaction did not proceed selectively (Table 8).

The alkyne hydration reaction proceeded very slowly in a tandem one-pot procedure and only traces of the ATH product were observed even after 24 h of reaction time. In sequential protocol (B), phenylacetylene was first converted to the hydration product acetophenone and then sodium formate was introduced into the reaction mixture to initiate the ATH reactions through a one-pot procedure. At the early stages of the reaction, acetophenone (2a) was formed in 31% yield within one hour of reaction time. After 6 h of reaction time, phenylacetylene (1a) was completely consumed and sodium formate was introduced into the solution to initiate

the ATH reactions. The ATH reaction proceeded smoothly following the addition of sodium formate and the corresponding chiral alcohol 1-phenylethanol was formed in 95% yield after 20 h of reaction time with a catalytic loading of 1% mol Ru and 0.1% mol Au. It is possible that a small portion of ruthenium may be deactivated before the ATH reactions, due to the presence of additives in AH reactions such as silver(I) salts; as a result, the reaction proceeded relatively slower in a sequential fashion.

Arylacetylene derivatives bearing different polyaromatic hydrocarbon substituents were tested in sequential AH/ATH reactions to demonstrate the substrate selectivity of the encapsulated catalyst system. en-Au@SiO₂@Ru@amph (SiCl₂-Ph₂) with sterically hindered diphenyl substituted silica groups on pore surfaces was chosen as the model catalyst



Scheme 6 AH/ATH reactions of various alkynes.

Table 9 Reusability of en-Au@SiO₂@Ru@amph in AH/ATH reactions

Reaction scheme: Phenylacetylene (**1a**) reacts with AgOTf (5% mol equiv.) in MeOH/H₂O at 80 °C to form phenylacetone (**2a**). **2a** then reacts with sodium formate (HCOONa) in MeOH/H₂O at 75 °C to form (S)-1-phenylethanol (**3a**). The catalyst en-Au@SiO₂@Ru@amph is recycled.

Run ^a	Conv. ^b % (1a)	Yield %		Time (h)	TON (AH)	TON (ATH)	ee % (3a)
		2a	3a				
1	99	—	95	20	990	95	90
2	99	5	90	24	990	85	90
3	99	10	85	24	990	80	88
4	99	16	78	24	990	78	88
5	95	25	65	36	950	65	85
6	95	35	50	36	900	50	80
7	92	70	20	48	880	20	80
8 ^c	92	85	5	48	80	5	—

^a A Schlenk reactor was charged with en-Au@SiO₂@Ru@amph (–SiCl₂Ph₂) (100 mg, 0.0120 mmol Au per g, 0.118 mmol Ru per g) and dispersed in MeOH/H₂O (1 mL/1 mL) using a sonicator. Phenylacetylene (12.0 mmol, 1.3 mL) and AgOTf (5% mol equiv., 0.60 mmol, 15.0 mg) were added to the reaction medium and the mixture was stirred at 80 °C under a nitrogen atmosphere. The progress of the reaction was monitored by GC-MS. Once the conversion of phenylacetylene has reached a plateau, sodium formate (24.0 mmol, 1.63 g) was added and the reaction mixture was stirred at 75 °C under a nitrogen atmosphere. Once the conversion reached a plateau, the reaction mixture was centrifuged and the organic phase was extracted with diethyl ether while the solid catalyst remained within the tube. The remaining solid was washed with diethyl ether and then re-used in the next cycle. ^b Determined by GC-MS.

owing to the minimal catalyst leaching. Aryl/alkyl acetylene derivatives bearing relatively smaller substituents were converted to the corresponding ketone derivatives and then transformed into chiral alcohol derivatives. Acetylene derivatives with bulky and relatively larger substituents 9-ethynylphenanthrene (**1g**), 1-ethynylpyrene (**1h**), ethynyl ferrocene (**1i**) and ethynyl triphenylsilane (**1j**) didn't undergo alkyne hydration reactions due to the diffusion limitations exerted by diphenylsilane groups on the silica shell (Scheme 6). The halogen substituted arylacetylenes (**1d** and **1e**) converted to the desired chiral alcohols. The methyl group in the *ortho* position in 1-ethynyl toluene has no steric effect on the performance of the catalyst in both AH and ATH reactions.

The reusability of the catalyst (en-Au@SiO₂@Ru@amph) was tested on AH/ATH reactions using optimum reaction conditions. The performance of the sequential reaction was tested for both AH and ATH reactions (Table 9). At the first run, **1a** was completely transformed into **2a** and then **2a** immediately underwent ATH reactions to produce **3a** in 95% yield. The performance of the catalyst started to decrease after the 1st run, although **1a** was completely consumed in the first 4th run, the yield of the ATH reaction decreased to 78%. Although the performance of the AH didn't significantly change at the 8th run, the performance of the micellar Ru catalyst in ATH reactions drastically decreased until the 8th run and only 5% yield of the desired product was obtained at the 8th run. ICP-MS analysis showed that ruthenium wasn't leached during the reactions as a result of efficient shielding by the SiO₂ shell and therefore the decrease in performance of the ATH reaction was related to catalyst decomposition.

As summarized in Table 10, different homogeneous and heterogeneous binary catalytic systems were developed for

sequential AH/ATH(TH) reactions in the literature. The homogeneous salen-Co³⁺/Ru-TSDPEN binary catalytic system showed high enantioselectivity up to 97% with a yield of 92% for AT/ATH reactions of phenylacetylene.¹² For the same reaction in *i*PrOH, the binary homogeneous catalyst system IPrAuCl/Shvo (Ru) exhibited 85% yield forming a racemic mixture.¹³ The combination of CF₃SO₃H and a fluorinated chiral diamine Ru(II) complex in aqueous CF₃CH₂OH has led to the formation of 97% enantioselective (*S*)-1-phenylethanol in 95% yield. Although these systems are efficient in sequential AH/ATH (TH) reactions, the catalytic systems don't show any reusability. On the other hand, mesoporous silica-based catalytic systems bearing supported chiral Rh (ref. 16) and Ru (ref. 17) complexes are reusable in AH/ATH reactions of alkynes. The catalytic performance of our compartmentalized system is compatible with other reported mesoporous silica-based heterogeneous systems (Table 10).^{16,17} In addition, our catalytic system catalyzed the sequential AH/ATH reactions with relatively lower amounts of Au (0.1% mol) and Ru (1% mol) loadings.

Experimental section

Otherwise noted all chemicals were purchased from Sigma-Aldrich and used as received. [RuCl₂(*p*-cymene)]₂ was purchased from Strem and used as received. ((1*S*,2*S*)-1,2-Bis(4-hydroxyphenyl)ethylenediamine) was purchased from Sigma-Aldrich. Dimethylformamide (DMF) was dried over molecular sieves 4 Å overnight and the drying agent was removed through decantation, followed by vacuum distillation. THF was pre-dried over CaH₂ and distilled over Na-wire/benzophenone under a nitrogen atmosphere. N₂

Table 10 Literature comparison for catalytic sequential AH/TH(ATH) reactions of phenylacetylene

AH cat. (mol%) solvent	TH or ATH cat. (% mol)	Yield% (time)	Catalyst system (reusability, ±)	Ref.
FeCl ₃ (100%) H ₂ O	[RhCl(TsDPEN)(Cp)] (1%)	86 (24 h)	Heterogeneous-mesoporous silica gel (+)	16
IPrAuCl/AgSbF ₆ (1%) i-PrOH	Shvo catalyst (Ru) (1%)	85 (48 h)	Homogeneous (–)	13
Co-salen (2%) CH ₃ OH/H ₂ O	[RuCl(<i>R,R</i> -TsDPEN)(<i>p</i> -cymene)] (% 0.5)	92 (24 h)	Homogeneous (–)	12
Co-porphyrin (0.17%) CH ₃ OH/H ₂ O	[RhCl(TsDPEN)(Cp)] (%0.07) (micellar)	74 (36 h)	Micellar catalyst (–)	18
CF ₃ SO ₃ H (% 20) CF ₃ CH ₂ OH	[RuCl(<i>S,S</i> -TsDPEN)(<i>p</i> -cymene)] ^b (0.5%)	95 (24 h)	Homogeneous (–)	9
IPrAuBF ₄ (% 2) dichloroethane	Mesitylene RuTsDPEN (% 2.4)	93 (20 h)	Heterogeneous-mesoporous silica gel (+)	17 ^a
IPrAuCl (0.1%) CH ₃ OH/H ₂ O	[(<i>R,R</i> -TsDPEN)Ru(<i>p</i> -cymene)] (1%)	95 (20 h)	Heterogeneous-mesoporous silica gel-micellar catalyst (+)	This study

^a Haloalkynes are used instead of phenylacetylene. ^b –C₆F₅ substituent is used instead of –C₆H₅CH₃ in the sulfonyl group of the ruthenium catalyst.

physical adsorption/desorption tests were performed on a Quantachrome Corporation Autosorb-6 adsorption analyzer (samples were degassed at 160 °C for 8 h before the measurements). The BET surface areas were evaluated from data in the relative pressure range from 0.05 to 0.25. The total pore volume was estimated from the amount adsorbed at the highest P/P_0 (above 0.99). The surface chemistry of the functionalized particles was analyzed with X-ray photoelectron spectroscopy (XPS) (K-Alpha XPS, ThermoFisher Scientific, U.S.A). Environmental scanning electron microscope (SEM) images were recorded using an FEI Quanta 200 FEG ESEM device. Gas chromatography-mass spectrometry (GC-MS) analyses were performed with a Shimadzu GC-MS 2010 Plus using a Restek Rxi-5Sil column (30 m × 0.25 mm × 0.25 μm) and a temperature range of 50–320 °C with a constant helium flow rate of 1 mL min^{–1}. The enantioselectivity of chiral alcohols was determined by GC-MS analysis using a Trajan™ SGE-Cydex-B column (25 m × 0.22 mm × 0.25 μm) with a constant helium flow rate of 0.8–1 mL min^{–1}. Dynamic light scattering (DLS) analysis was carried out using a Malvern Seta-Sizer Nano-ZS90 with a fixed scattering angle of 90°. High contrast transmission electron microscopy (TEM) images were recorded at METU Central Lab (Ankara) with an FEI Tecnai G2 Spirit Bio(TWIN) 600 TEM at 120 kV using carbon film-coated copper grids by dropping 1 μL of samples into the grids from EtOH diluted samples.

Synthesis of L1

A 100 mL two-necked glass flask (100 mL) was charged with (1*S*,2*S*)-1,2-bis(4-hydroxyphenyl)ethylenediamine (1.0 g, 4.1 mmol) and *S*-Boc-2-mercapto-4,6-dimethylpyrimidine (3.97 g, 16.5 mmol) in 10 mL of dry DMF. The reaction mixture was stirred at room temperature for 24 h under a nitrogen atmosphere. The solvent was evaporated under vacuum resulting in a dark yellow solid. The flask was charged with dichloromethane (20 mL) to dissolve the unreacted starting materials and side products. The resulting suspension was filtered and the remaining solid was washed with hexane (10 mL × 2) and dried under high vacuum, resulting in a light yellow/off-white solid (yield: 60%). ¹H NMR (400 MHz, d₆-DMSO) δ 9.54 (s, 2H), 7.04 (d, *J* = 21.1 Hz, 2H), 6.64 (d, *J* =

45.7 Hz, 2H), 5.38 (s, 2H), 1.29 (s, 18H). ¹³C NMR (100 MHz, d₆-DMSO) δ 155.99, 154.06, 129.24, 127.76, 119.04, 114.44, 77.79, 28.60; ESI-MS (*m/z*): 443.2201 [M–H]⁺.

Synthesis of L2

L1 (0.30 g, 0.7 mmol) was dissolved in 5 mL of dry DMF at room temperature in a 50 mL glass flask. K₂CO₃ (0.6 g, 4.34 mmol) was added to the reaction flask in small portions over one hour. *p*-Vinylbenzyl chloride (0.45 g, 2.95 mmol) was added to the reaction flask and stirred at room temperature for 24 h. The reaction mixture was filtered over a small pad of silica gel and solvent and excess *p*-vinylbenzyl chloride was removed using a rotary evaporator under vacuum. The resulting yellow solid was washed with diethyl ether (10 mL × 2) and dried under high vacuum (yield%: 46%). ¹H NMR (400 MHz, CDCl₃) δ 7.46–7.05 (m, 12H), 6.91–6.79 (m, 6H), 5.83 (d, *J* = 17.8 Hz, 4H), 5.68 (d, *J* = 2.4 Hz, 2H), 5.29 (d, *J* = 11.3 Hz, 2H), 4.96 (s, 4H), 1.29 (s, 18H). ¹³C NMR (100 MHz, CDCl₃) δ 156.22, 136.60, 128.88, 128.27, 127.47, 126.62, 126.40, 120.49, 113.87, 111.79, 78.80, 69.64, 56.63, 46.14, 28.49. MALDI-ToF MS (*m/z*): 783.253 [M + Ag]⁺.

Synthesis of Amph

A Schlenk reactor was charged with the **M1** monomer (0.64 g, 0.15 mmol) in 10 mL of dry toluene. The Hoveyda–Grubbs 2nd generation catalyst (HG2, 0.010 g, 0.015 mmol) was added to the reactor and stirred at 80 °C under a nitrogen atmosphere. After 30 minutes, the **M1** monomer (0.40 36 g, 1.70 50 mmol) and **L2** (0.02 g, 0.03 mmol) as the chain-transfer agent were added to the reactor and stirred at 80 °C for 12 h. After 12 h, the reaction mixture was cooled down to room temperature and poured into cold diethyl ether and the precipitated polymer was isolated by simple filtration. The off-white polymer was dissolved in THF and precipitated in cold diethyl ether to remove the unreacted monomers and residual catalysts. The amphiphilic polymer was characterized using ¹H NMR, SEC, DLS and high contrast TEM analysis.

Synthesis of Ru@Amph

The amphiphilic polymer (Amph, 0.10 g) was dissolved in dry THF (5 mL) at room temperature. Following this protocol,

aqueous 4 M HCl (400 μ L) was added to the solution to remove the protecting *t*-Boc groups to obtain free amine groups on the polymer backbone. The reaction mixture was washed with saturated NaHCO₃ solution to remove the excess acid and then extracted with deionized water. The organic phase was separated and the polymer was precipitated in cold diethyl ether. The polymer was dried under high vacuum overnight. The polymer (Amph) was taken to a Schlenk reactor and the polymer was dissolved in dry dichloromethane (10 mL). After the dissolution of Amph, triethylamine (1.6 mol equivalent) and *p*-toluenesulfonyl chloride (1.2 mol equivalent) were added to the reactor and stirred at room temperature for 4 h under a nitrogen atmosphere. Following this protocol, [RuCl₂(*p*-cymene)]₂ (0.5 mol equivalent) was added to the reactor and stirred for 12 h at room temperature. After 12 h, the reaction mixture was filtered over a pad of silica gel and precipitated in cold diethyl ether.

The coating of Ru@Amph with SiO₂ (SiO₂@Ru@Amph)

0.20 g of Ru@Amph was dispersed in 10 mL of pure water and diluted with 90 mL of ethanol using a mechanical stirrer. 0.10 g Synperonic® F108 and 0.10 g centrimonium bromide (CTAB) were added to the reaction mixture and stirred for one hour to ensure the complete dissolution of the added surfactants. After one hour, concentrated ammonia (1 mL) was added to the reaction mixture and stirred for five minutes. Tetraethyl orthosilicate (TEOS) (1.50 g) was added dropwise to the solution under mechanical stirring at 280 rpm. Following the addition of TEOS, the reaction mixture was stirred for 24 h at room temperature. Silica-coated particles were isolated by centrifugation of the reaction mixture at 6000 rpm. The isolated silica particles were washed with ethanol (10 mL $\times$ 2) and dried under high vacuum overnight.

Immobilization of [IPrAuCl] (Au-1) on SiO₂@Ru@Amph (Au@SiO₂@Ru@Amph)

SiO₂@Ru@Amph (0.50 g) was taken to a Schlenk reactor and dispersed in 10 mL of dry dichloromethane. IPrAuCl (0.025 g, 0.040 mmol) in dichloromethane (1 mL) was added to the reaction medium and stirred magnetically at 800 rpm at room temperature under a nitrogen atmosphere. After 24 h, dichloromethane was removed under high vacuum. The resulting solid was washed with ethanol (2 mL $\times$ 2). 90 wt% of the added gold complex was immobilized on the support material as confirmed by ICP-MS analysis (0.077 mmol Au per g).

Post-pore size reduction of Au@SiO₂@Ru@Amph through silylation reactions (en-Au@SiO₂@Ru@Amph)

A 100 mL three-necked Schlenk flask was charged with SiO₂@Ru@Amph (1.0 g, 0.118 mmol Ru per g) and dispersed in dry dichloromethane through ultrasonication for five minutes. After that, IPrAuCl (10 mg, 0.0161 mmol) was added

to the reaction medium and stirred for 12 h at room temperature under a nitrogen atmosphere. To reduce the pore size, dichlorodiphenylsilane (SiCl₂Ph₂, 20 μ L, 0.096 mmol) and 2-methylpyridine (0.20 mmol, 20 μ L) were added to the reaction media and stirred for 12 h at room temperature. The solvent was evaporated under high vacuum. The resulting orange/yellow solid was washed with dichloromethane (2 mL $\times$ 2) and dried under vacuum at 30 °C.

Representative procedure for alkyne hydration (AH) reactions

A Schlenk reactor was charged with Au@SiO₂@Ru@Amph (100 mg, 0.077 mmol Au per g) or en-Au@SiO₂@Ru@Amph (encapsulated, 100 mg, 0.012 mmol Au per g) and dispersed in MeOH/H₂O (1 mL/1 mL) using sonication. Phenylacetylene (0.77 mmol, 85 μ L or 0.12 mmol, 13 μ L) was added to the reactor and the silver(i) salt (1 mol% equivalent, AgOTf or AgSbF₆) was added. When the conversion of the substrate has reached a plateau the reaction was cooled to room temperature and the product was extracted with diethyl ether.

Representative procedure for asymmetric transfer hydrogenation (ATH) reactions of ketones

A Schlenk reactor was charged with Ru@Amph (0.016 mmol Ru per g) or en-Au@SiO₂@Ru@Amph and dispersed in the MeOH/H₂O (1 mL/1 mL) mixture at room temperature under a nitrogen atmosphere. Acetophenone (1.6 mmol, 190 μ L) and sodium formate (HCOONa, 3.2 mmol, 0.22 g) was added to the reaction media to initiate the reaction. The reaction was monitored by taking aliquots (10 μ L) from the reaction mixture and analyzed by GC-MS. Once the conversion of acetophenone had reached a plateau, the reaction mixture was cooled down to room temperature and extracted with diethyl ether.

Representative procedure for sequential alkyne hydration (AH)/asymmetric transfer hydrogenation (ATH) reactions

A Schlenk reactor was charged with en-Au@SiO₂@Ru@Amph (100 mg, 0.0120 mmol Au per g, 0.118 mmol Ru per g) and dispersed in MeOH/H₂O (2 mL). Phenylacetylene (1000 mol equivalent to Au and 100 mol equivalent to ruthenium) was added to the reaction media and the alkyne hydration reaction was initiated by addition of AgOTf (1 mol%, 0.0120 mmol, 3.0 mg) and the reaction mixture was stirred at 80 °C under a nitrogen atmosphere. Once all the phenylacetylene was converted to the desired hydration product acetophenone, sodium formate (2.4 mmol, 0.163 g) was added to the reaction media to initiate the asymmetric transfer hydrogenation reactions. After the conversion of acetophenone reached a plateau, the catalyst was separated by centrifugation at 5000 rpm for two minutes and the solution phase was taken to a separation funnel and extracted with diethyl ether.

Conclusions

A chiral Ru(II) catalyst and a NHC-Au(I) catalyst were successfully confined in different compartments of a core/shell hybrid support consisting of amphiphilic polymers and mesoporous silica gel. This study demonstrates an alternative approach to confine incompatible catalysts within organic micellar and inorganic porous systems. The core/shell isolation approach also prevents the leaching of the core Ru(II) complex. The leaching of the outer confined Au(I) catalyst was prevented through post-pore size reduction. The hybrid catalyst system allowed us to conduct AH/ATH reactions sequentially. Our future research will be focused on the development of novel support materials with multiple spatial confinements for more complex transformation reactions.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Dr. B. Ö. Öztürk would like to thank The Scientific and Technological Research Council of TÜRKİYE (TUBITAK) for the financial support through the TUBITAK-1001 program (Project No: 120Z204). This work was supported by the BAGEP Award of the Science Academy with funding supplied by the 2023 BAGEP program. We would like to thank Prof. Dr. B. Salih and Assoc. Prof. Dr. M. Atakay for their help with MALDI-ToF-MS analyses.

Notes and references

- Y. Hayashi, *Chem. Sci.*, 2016, **7**, 866–880.
- M. J. Climent, A. Corma, S. Iborra and M. J. Sabater, *ACS Catal.*, 2014, **4**, 870–891.
- M. Zhao, J. Xu, S. Song and H. Zhang, *Chin. J. Catal.*, 2023, **50**, 83–108.
- P. S. G. Nunes, H. D. A. Vidal and A. G. Corrêa, *Org. Biomol. Chem.*, 2020, **18**, 7751–7773.
- (a) P. Qu, M. Kupfert, S. Jockush and M. Weck, *ACS Catal.*, 2019, **9**, 2701–2706; (b) J. Shi, Y. Wu, S. Zhang, D. Yang and Z. Jiang, *Chem. Soc. Rev.*, 2018, **47**, 4295–4313; (c) P. Qu, J. W. Cleveland, E. Ahmed, F. Liu, S. Dubrawski, C. W. Jones and M. Weck, *Chem. Soc. Rev.*, 2022, **51**, 57–70.
- Z. Liu, Y. Wang, K. Liu, S. Wang, H. Liao, Y. Zhu, B. Hou, C. Tan and G. Liu, *Front. Chem.*, 2021, **9**, 732542.
- J. Lei, L. Su, K. Zeng, T. Chen, R. Qiu, Y. Zhou, C.-T. Au and S.-F. Yin, *Chem. Eng. Sci.*, 2017, **171**, 404–425.
- J. Li, C. Wang, D. Xue, Y. Wei and J. Xiao, *Green Chem.*, 2013, **15**, 2685–2689.
- H. Liu, S. Liu, H. Zhou, Q. Liu and C. Wang, *RSC Adv.*, 2018, **8**, 14829–14832.
- N. Luo, Y. Zhong, J.-T. Liu, L. Ouyang and R. Luo, *Synthesis*, 2020, **52**, 3439–3445.
- F. Li, N. Wang, L. Lu and G. Zhu, *J. Org. Chem.*, 2015, **80**, 3538–3546.
- S. Wang, C. Miao, W. Wang, Z. Lei and W. Sun, *ChemCatChem*, 2014, **6**, 1612–1616.
- L. Li and S. B. Herzon, *J. Am. Chem. Soc.*, 2012, **134**, 17376–17379.
- R. J. R. W. Peters, M. Marguet, S. Marais, M. W. Fraaije, J. C. M. van Hest and S. Lecommandoux, *Angew. Chem., Int. Ed.*, 2014, **53**, 146–150.
- G. Xie, J. Zhang and X. Ma, *ACS Catal.*, 2019, **9**, 9081–9086.
- J. Huang, F. Zhang and H. Li, *Appl. Catal., A*, 2012, **431–432**, 95–103.
- X. Xia, J. Meng, H. Wu, T. Cheng and G. Liu, *Chem. Commun.*, 2017, **53**, 1638–1641.
- J. Lu, J. Dimroth and M. Weck, *J. Am. Chem. Soc.*, 2015, **137**, 12984–12989.
- S. Varlas, S. B. Lawrenson, L. A. Arkinstall, R. K. O'Reilly and J. C. Foster, *Prog. Polym. Sci.*, 2020, **107**, 101278–101319.
- Y. Liu, V. Piñón III and M. Weck, *Polym. Chem.*, 2011, **2**, 1964–1975.
- B. Ö. Öztürk, B. Durmuş and S. Karabulut Şehitoğlu, *Catal. Sci. Technol.*, 2018, **8**, 5807–5815.
- V. Heroguez, Y. Gnanou and M. Fontanille, *Macromolecules*, 1997, **30**, 4791–4798.
- S. Sutthasupa, M. Shiotsuki and F. Sanda, *Polym. J.*, 2010, **42**, 905–915.
- A. E. Madkour, A. Koch, K. Lienkamp and G. N. Tew, *Macromolecules*, 2010, **43**, 4557–4561.
- B. Ö. Öztürk and S. Karabulut Şehitoğlu, *Polymer*, 2019, **183**, 121868.
- K. Nomura and M. M. Abdellatif, *Polymer*, 2010, **51**, 1861–1881.
- E. Ahmed, C. T. Womble, J. Cho, K. Dancel-Manning, W. J. Rice, S. S. Jang and M. Weck, *Polym. Chem.*, 2021, **12**, 1967–1974.
- E. Ahmed, J. Cho, S. S. Jang and M. Weck, *Chem. – Eur. J.*, 2023, **29**, e202301231.
- (a) E. Ahmed, J. Cho, L. Friedmann, S. S. Jang and M. Weck, *JACS Au*, 2022, **2**, 2316–2326; (b) M. T. Zarka, O. Nuyken and R. Weberskirch, *Macromol. Rapid Commun.*, 2004, **25**, 858–862.
- B. Ö. Öztürk, G. Çalışgan, H. Özer and S. Karabulut Şehitoğlu, *React. Funct. Polym.*, 2018, **126**, 63–73.
- I. Mandal, A. Mandal, A. Rahman and A. F. M. Kilbinger, *Chem. Sci.*, 2022, **13**, 12469–12478.
- W. E. Crowe, J. P. Mitchell, V. C. Gibson and R. R. Schrock, *Macromolecules*, 1990, **23**, 3534–3536.
- Q. Li, T. Zhou and H. Yang, *ACS Catal.*, 2015, **5**, 2225–2231.
- M. Aşkun, K. Sagdic, F. Inci and B. Ö. Öztürk, *Catal. Sci. Technol.*, 2022, **12**, 6174–6183.
- J. E. Shields, S. Lowell, M. A. Thomas and M. Thommes, *Characterization of Porous Solids and Powders: Surface Area, Pore Size and Density*, Kluwer Academic Publisher, Boston, MA, USA, 2004, pp. 43–45.
- X. Zhou, X. Wu, B. Yang and J. Xiao, *J. Mol. Catal. A: Chem.*, 2012, **357**, 133–140.

- 37 M. Jia and M. Bandini, *ACS Catal.*, 2015, **5**(3), 1638–1652.
- 38 Z. Lu, T. Li, S. R. Mudshinge, B. Xu and G. B. Hammond, *Chem. Rev.*, 2021, **121**, 8452–8477.
- 39 D. Zuccaccia, A. Del Zotto and W. Baratta, *Coord. Chem. Rev.*, 2019, **396**, 103–116.
- 40 J. Schießl, J. Schulmeister, A. Doppiu, E. Wörner, M. Rudolph, R. Karch and A. S. K. Hashmi, *Adv. Synth. Catal.*, 2018, **360**, 2493–2502.
- 41 M. Brill, F. Nahra, A. Gómez-Herrera, C. Zinser, D. B. Cordes, A. M. Z. Swalin and S. P. Nolan, *ChemCatChem*, 2017, **9**, 117–120.