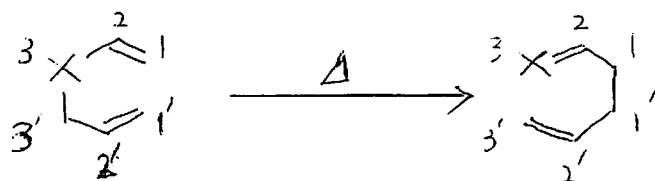


Catalyzed [3,3]-Sigmatropic Rearrangements

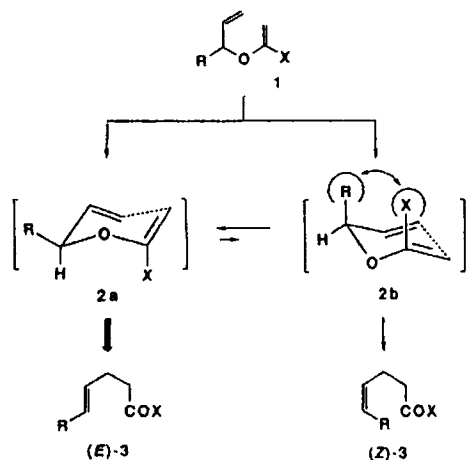
[Introduction]

⊙ Thermal [3,3]-Sigmatropic Rearrangement



X = C : Cope rearrangement
X = O : Claisen rearrangement

irreversible due to the thermodynamic stability of the product



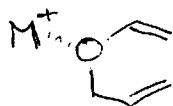
The reactions take place by a concerted mechanism through a cyclic six-membered chairlike transition state. When X is larger than H, the E/Z ratio can be greater than 99:1.

High temperatures are generally required.

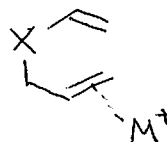
⊙ Catalyzed [3,3]-Sigmatropic Rearrangement

(1) Hard Lewis Acid

(2) Soft Lewis Acid



Coordination to Oxygen Atom



Coordination to π -Bond

Milder Conditions

[Contents]

(1) Hard Lewis Acid (Coordination to the Oxygen Atom)

(1-1) Organoaluminum-Promoted Claisen Rearrangement

(2) Soft Lewis Acid (Coordination to the π -Bonds)

(2-1) Mercury(II)- and Palladium(II)-Catalyzed [3,3]-Sigmatropic Rearrangements

(2-2) Gold(I)-Catalyzed Propargyl Claisen Rearrangement

(3) A Combined C-H activation/Cope Rearrangement

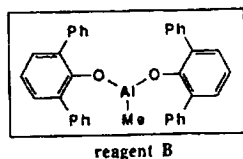
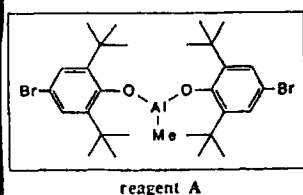
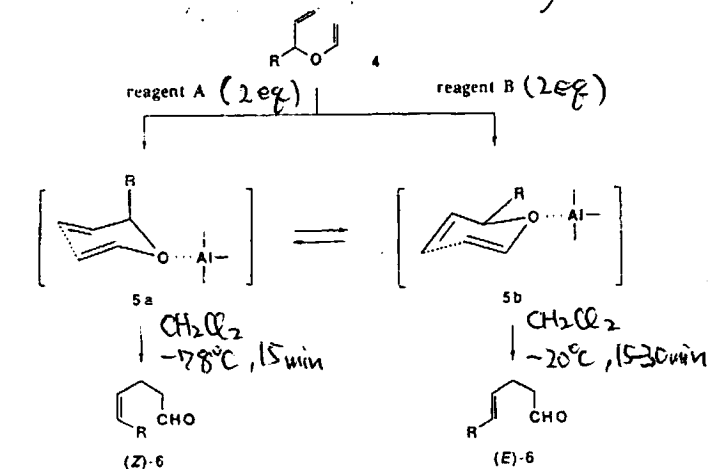
(1-1)

J. Am. Chem. Soc. 1990, 112, 316-322

Organoaluminum-Promoted Claisen Rearrangement of Allyl Vinyl Ethers

Katsumasa Nonoshita, Hiroshi Banno, Keiji Maruoka, and Hisashi Yamamoto*

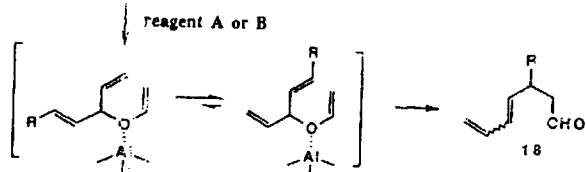
(i) Control of the E/Z selectivity



5a is favored over 5b.
(1,2 steric interaction between R and the cat.)

The Claisen rearrangement proceeds under very mild conditions.

(ii) Control of the regiochemistry



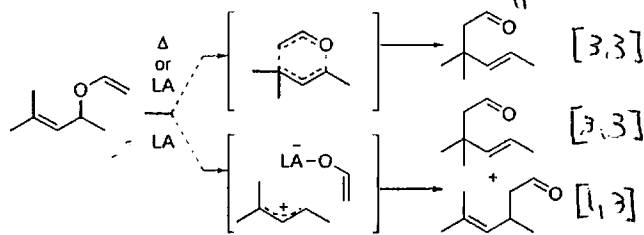
minimization of steric repulsions.

Table I. Organoaluminum-Promoted Claisen Rearrangement

entry	reagent ^a	product ^b	yield, %	ratio ^{d,e} (E/Z)
2	A	X = CHO	64	7:93
3	B	X = CH ₂ OH	85	(97:3) (92:8)
4	E	X = CH ₂ OH	55	87:13
6	A	X = CHO	41	9:91
7	B	X = CH ₂ OH	86	97:3
8	A	X = CHO	72	16:84
9	A ^f	X = CHO	70	12:88
10	B	X = CH ₂ OH	94	(99:1) (92:8)
11	A	X = CHO	58	61:39
12	B	X = CH ₂ OH	94	(95:5) (83:17)
21	A	X = CHO	40	7:93
22	B	X = CH ₂ OH	97	95:5
23	B ^g	X = CH ₂ OH	84	(97:3) (93:7)

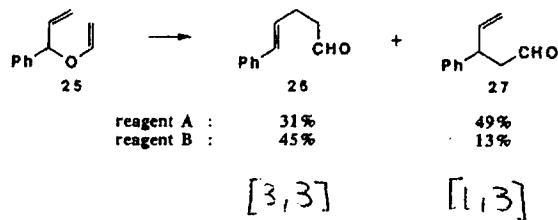
^a Reagent E: Diisobutylaluminum 4-bromo-2,6-di-*tert*-butylphenoxide. For structures of reagents A, B, and MAD, see text. ^b When aluminum reagent B was utilized, olefinic aldehydes were generally reduced to the corresponding alcohols with NaBH₄ in view of the easy product separation from 2,6-diphenylphenol. ^c Isolated yield by column chromatography. ^d Determined by GLC after conversion to the corresponding trimethylsilyl ethers. For details, see the Experimental Section. ^e The E/Z ratios in parentheses refer to those in the thermal rearrangement (250 °C). ^f At -95 °C. ^g At -78 °C.

(iii) [3,3] vs [1,3] rearrangement



ionic intermediate

(allyl cation and metallo-enolate ion pair)



(iv) Remote transfer of vinyloxy moiety by [3,5]-rearrangement

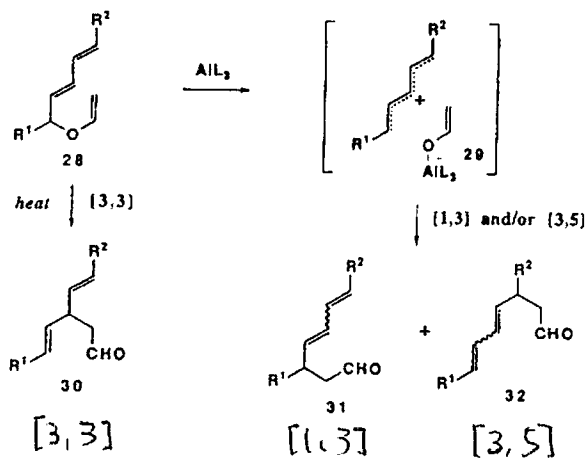


Table II. Organoaluminum-Promoted Rearrangement of Dienyl Vinyl Ethers

entry	reagent ^a	solvent ^b	conditions, °C h	yield, ^c %	ratio ^d
1	A	DME/CH ₂ Cl ₂	-78, 0.5	57	55:34:11
2	A	ether/CH ₂ Cl ₂	-78, 1	57	58:31:11
3	A	(CH ₂ Cl) ₂	-20, 0.3	57	49:35:16
4	A	CH ₂ Cl ₂	-78, 0.3	91	44:34:22
5	A	CH ₂ Cl ₂	0, 0.3	69	31:31:38
6	A	toluene	-78, 0.3	82	6:5:89
7	B	toluene	-20, 0.3	89	0:0:100
8	MAD	CH ₂ Cl ₂	-78, 0.3	92	4:3:93
9	heat	decane	200, 0.5	95	0:0:100

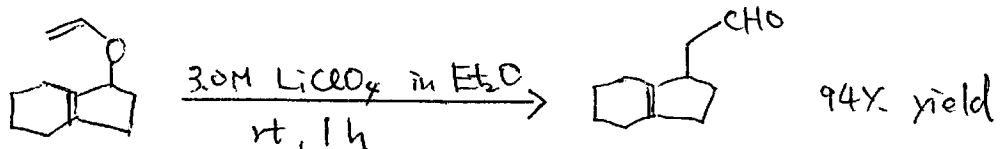
* Remarkable solvent effect

The use of reagent A in the polar solvent stabilized the ionic intermediate 29.

J. Am. Chem. Soc. 1991, 113, 5488-5489

[1,3] Sigmatropic Rearrangement of Allyl Vinyl Ethers at Ambient Temperature in 3.0 M Lithium Perchlorate-Diethyl Ether

Paul A. Grieco,* Jerry D. Clark, and Christopher T. Jagoe



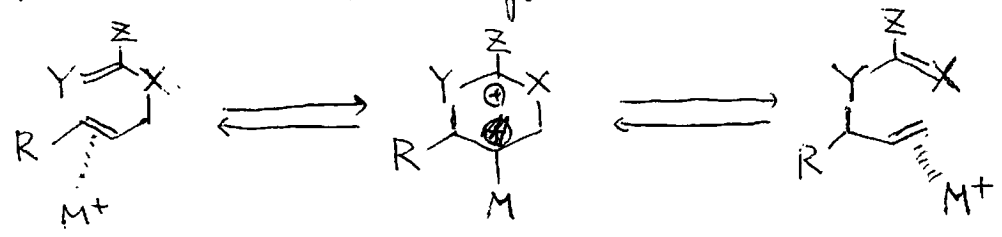
(sterically hindered allyl vinyl ethers.)

strongly ionizing conditions

(2) Soft Lewis Acid

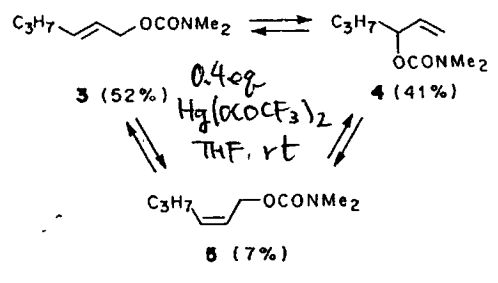
(2-1) Hg(II)- and Pd(II)- Catalyzed [3,3]-Sigmatropic Rearrangements

⊙ Cyclization-induced rearrangement mechanism



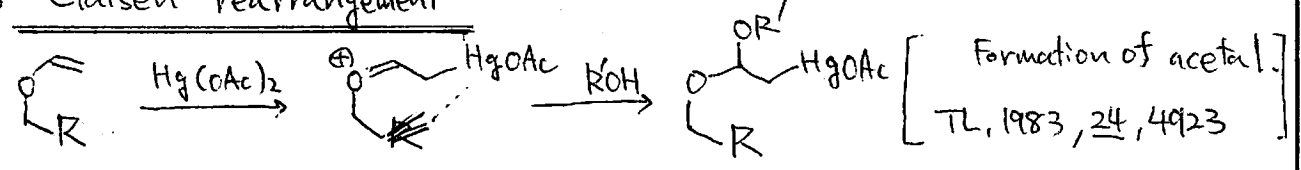
review: L.E. Overman, *Angew. Chem. Int. Ed. Engl.*, 1984, 23, 519

[3,3]-sigmatropic rearrangement of allylic carbamates (Overman et al. *JOC*, 1976, 41, 3339.)



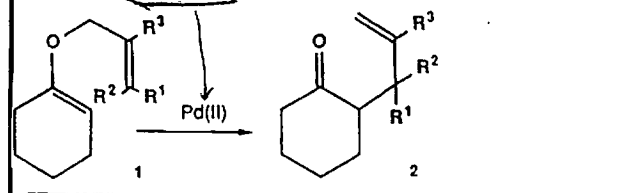
cf. *N*-arylbenzimidate
 ↓ chiral Pd(II) complex
 chiral *N*-arylbenzamides

Claisen rearrangement



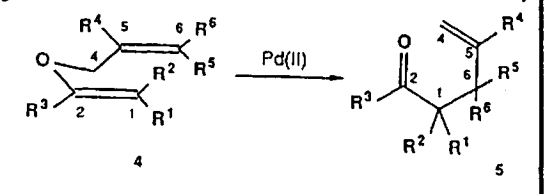
The irreversible binding of the electrophilic metal catalyst at the strongly nucleophilic vinyl ether function prevents its binding at the allylic double bond.

Table 1: $PdCl_2(CH_3CN)_2$ catalyzed Claisen rearrangement of allyl vinyl ethers



Rearrangement	Conditions ^a solvent, time	Yield ^b of Claisen product
1 → 2		
a : R ¹ =CH ₃ ; R ² =R ³ =H	C ₆ H ₆ , 2 h	65%
	CH ₂ Cl ₂ , 2 h	54%
	THF, 2 h	71%
b : R ¹ =R ² =R ³ =H	C ₆ H ₆ , 2 h	65%
	CH ₂ Cl ₂ , 2 h	56%
	THF, 2 h	45%
c : R ¹ =R ² =H; R ³ =Me	C ₆ H ₆ , 24 h	<2%
d : R ¹ =R ² =Me; R ³ =H	C ₆ H ₆ , 24 h	<5%

(Bickelhaupt et al. *TL*, 1986, 27, 6267.)



a : R ¹ =R ² =R ³ =R ⁴ =R ⁵ =H; R ⁶ =Me	C ₆ H ₆ , 24 h	<2%
b : R ¹ =R ² =R ³ =R ⁴ =H; R ⁵ =R ⁶ =Me	C ₆ H ₆ , 24 h	<5%
c : R ¹ =R ² =H; R ³ =Me; R ⁴ =R ⁵ =R ⁶ =H	C ₆ H ₆ , 24 h	<2%
d : R ¹ =R ² =Me; R ³ =R ⁴ =R ⁵ =R ⁶ =H	C ₆ H ₆ , 18 h	19%
e : R ¹ =H; R ² =Me; R ³ =R ⁴ =R ⁵ =H; R ⁶ =Me	C ₆ H ₆ , 4 h	18%
f : R ¹ =H; R ² =Me; R ³ =Et; R ⁴ =R ⁵ =R ⁶ =H	THF, 2 h	71%
g : R ¹ =H; R ² =Me; R ³ =Et; R ⁴ =R ⁵ =H; R ⁶ =Me	THF, 2 h	93%

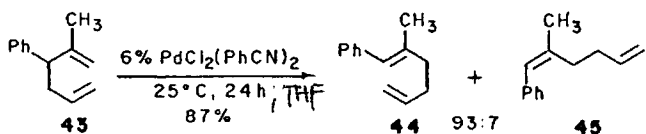
steric hindrance at allylic double bond
 Substitution at C1 is crucial.

^a All rearrangement were performed by stirring a 0.2 M solution of 1 or 4 in the dry solvent indicated with 0.05 equiv. of $PdCl_2(CH_3CN)_2$ at room temperature. ^b determined by GLC analysis.

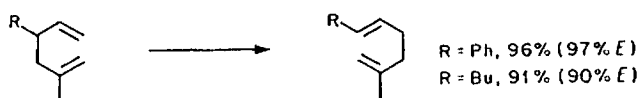
This catalysis does not have general synthetic utility.

Cope rearrangement

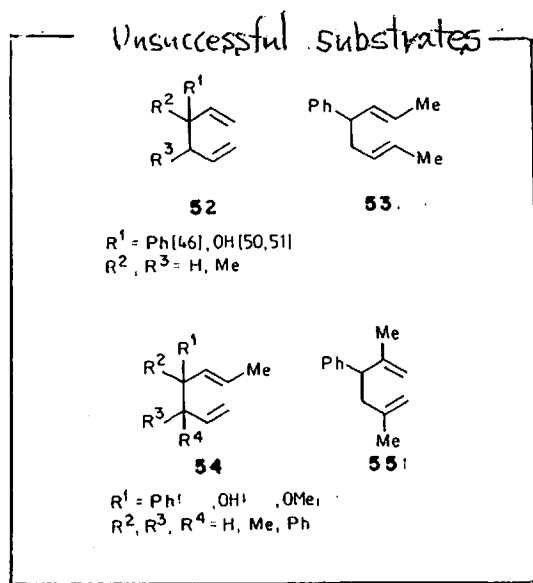
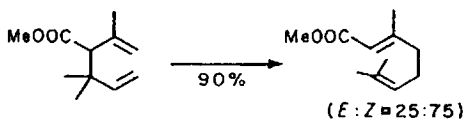
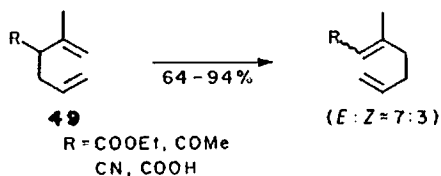
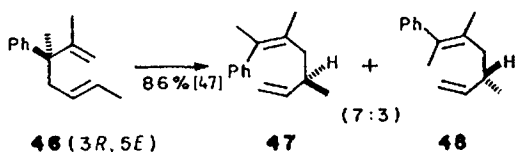
Overman et al. (JACS, 1980, 102, 865.
 JACS, 1982, 104, 1225.
 TL, 1983, 24, 3757.)



cf. Thermal Cope rearrangement of 43
 $t_{1/2} = 13 \text{ h at } 177^\circ\text{C}$
 $44 : 45 = 3 : 1$



equilibrium conversion at 25°C



* Significant limitations

The Pd(II) catalysis appears to require that the C2 and C5 of the substrate have one hydrogen and one "non-hydrogen" substituent.

* Advantage

- mild conditions

Scheme 13. Representative examples of palladium(II) chloride-catalyzed Cope rearrangements [a] (at 25-40°C, molar ratio allylic ester : PdCl₂(RCN)₂ = 1:0.1).

J. AM. CHEM. SOC. 2004, 126, 15978-15979

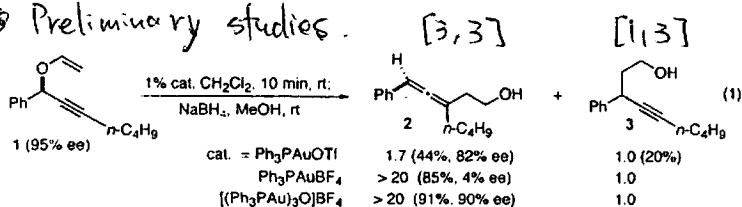
Gold(I)-Catalyzed Propargyl Claisen Rearrangement

Benjamin D. Sherry and F. Dean Toste*

Hg(II) and Pd(II)-catalyzed reaction is often limited.

Recent reports of Au(I)-catalyzed additions to alkynes, suggest that this limitation might be absent in a Au(I) catalyzed acetylenic Claisen rearrangement.

Preliminary studies.



* The intermediate aldehyde is unstable.

Poor chirality transfer is most likely a result of rapid (5min) racemization of the allene.

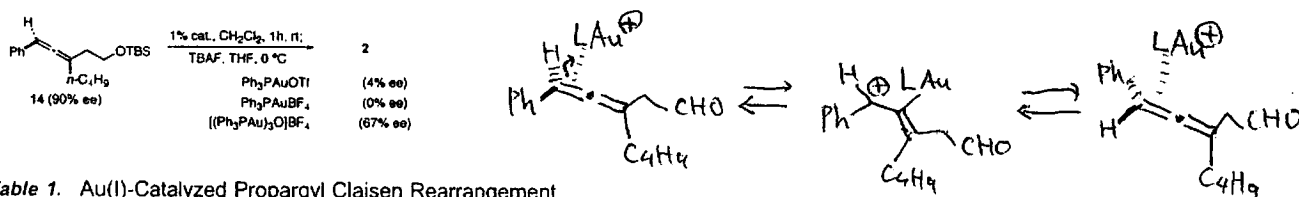
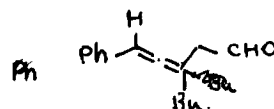
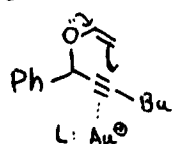


Table 1. Au(I)-Catalyzed Propargyl Claisen Rearrangement

entry	compd	R ¹	R ²	R ³	time	yield ^a
1	a	Ph	H	H	5 h	78%
2	b	Ph	H	OTBS	0.5 h	89%
3	c	Ph	H	OPiv	25 h	81%
4	d	p-MeO-C ₆ H ₄	H	n-C ₄ H ₉	12 h	89%
5	e	p-F ₃ C-C ₆ H ₄	H	Me	19 h	86%
6 ^b	f	o-Br-C ₆ H ₄	H	n-C ₄ H ₉	6.5 h	96%
7 ^b	g	n-C ₃ H ₇	H	Ph	5 h	93%
8 ^b	h	i-Pr	H	Ph	6 h	87%
9	i	TBSO	H	n-C ₄ H ₉	23 h	76%
10	j	Me	H	Ph	12 h	84%
11 ^c	k	n-C ₃ H ₇	H	Ph	6 h	90%
12 ^c	l	Ph	Me	Me	1 h	91%
13 ^c	m	-(CH ₂) ₆ -	H	Ph	1 h	61%

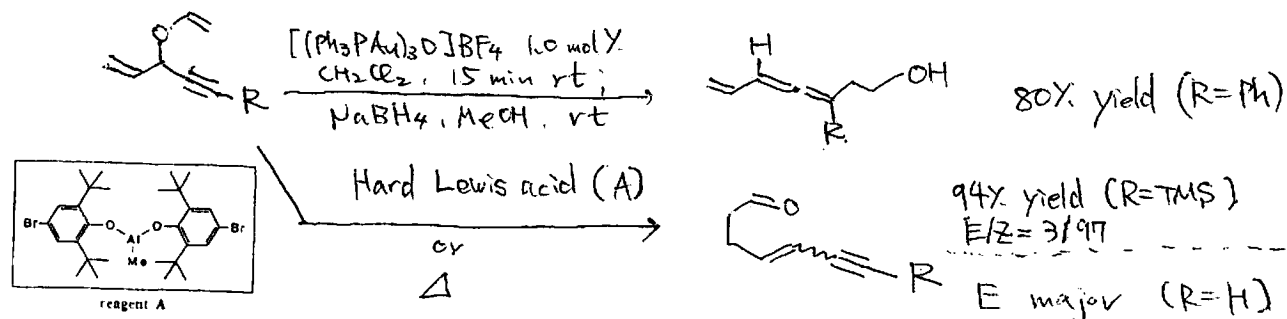
chirality transfer

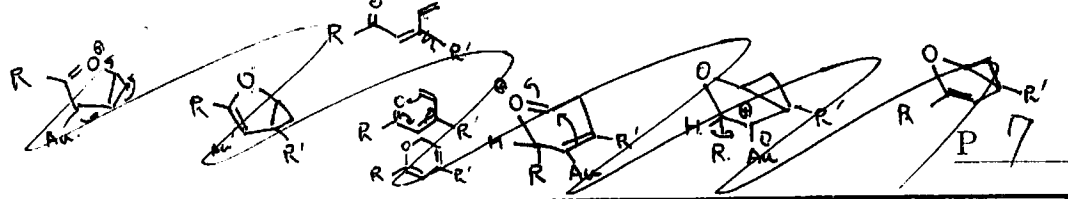
72% ee → 88% ee



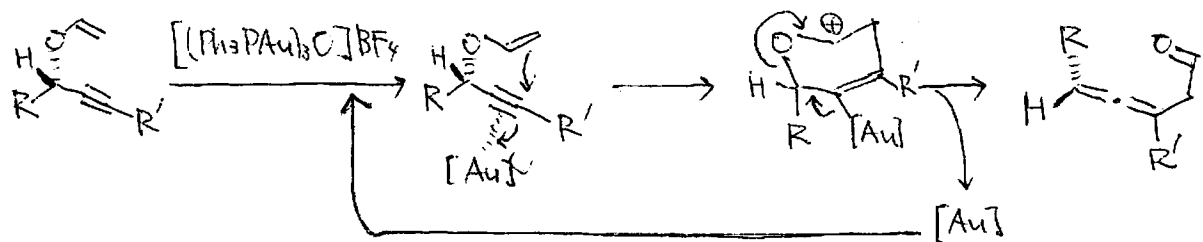
79% ee → 77% ee

^a Isolated yield after column chromatography. ^b Run with 0.1 mol % [(Ph₃PAu)₃O]BF₄. ^c Run at 75 °C in 1,2-dichloroethane.



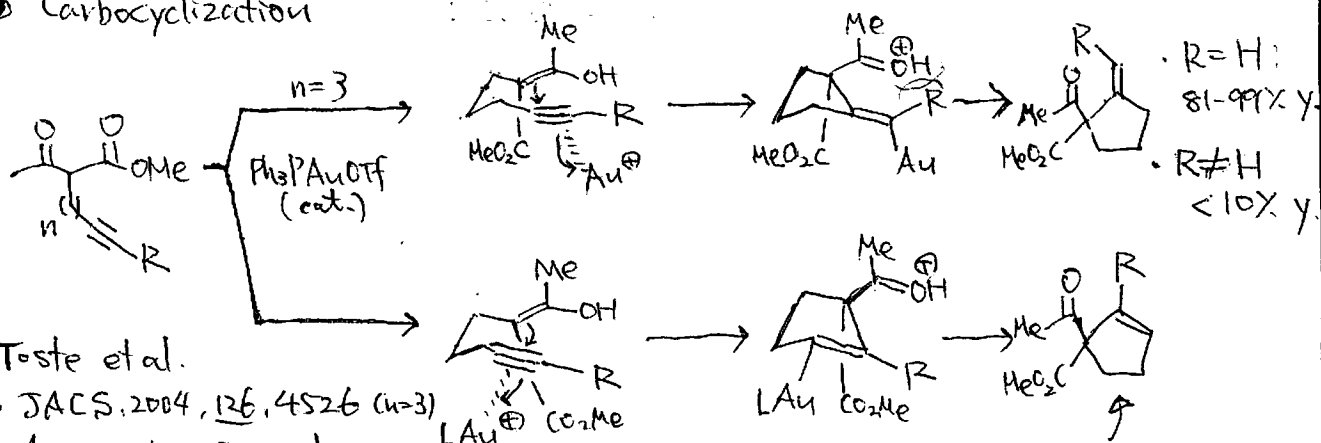


③ Proposed Mechanism based on a cyclization-induced rearrangement



④ Cf. other Au(I)-catalyzed reactions.

● Carbocyclization

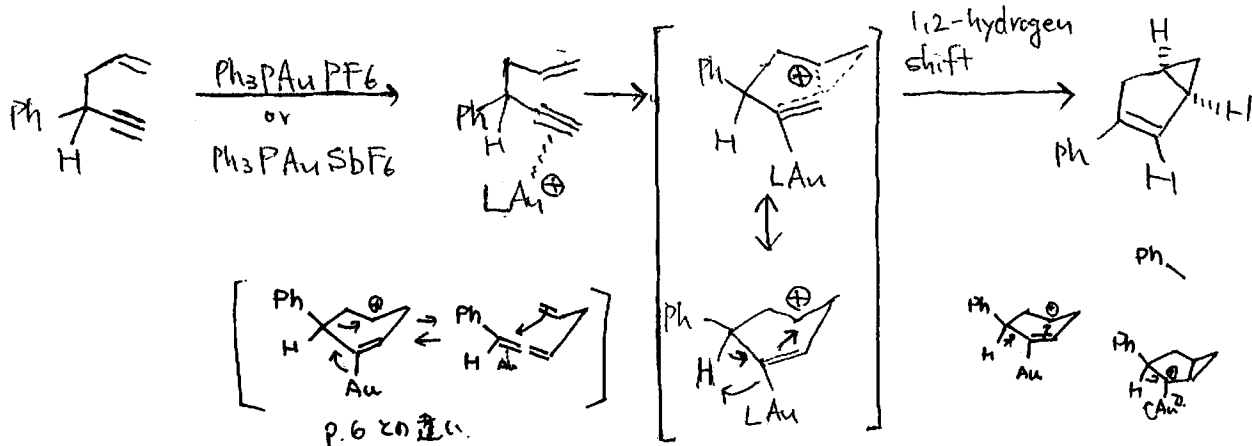


Toste et al.

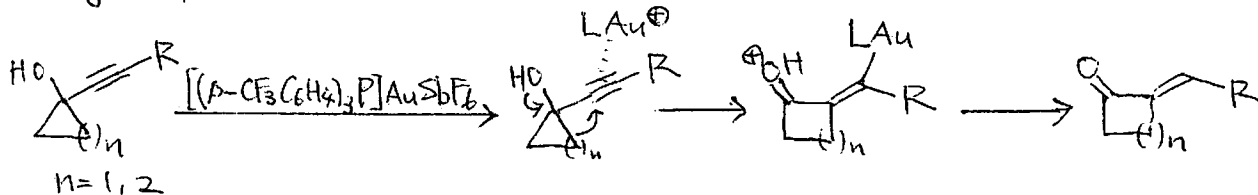
- JACS, 2004, 126, 4526 (n=3)
- Angew. Chem. Int. Ed. 2004, 43, 5350 (n=2)

Non-terminal alkynes are OK.

⑤ Isomerization of 1,5-enynes (Toste et al. JACS, 2004, 126, 10858.)



⑥ Ring expansion (Toste et al. JACS, 2005, 127, ASAP)



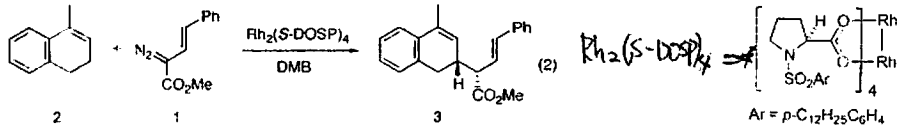
Highly Diastereoselective and Enantioselective C-H Functionalization of 1,2-Dihydronaphthalenes: A Combined C-H Activation/Cope Rearrangement Followed by a Retro-Cope Rearrangement

Huw M. L. Davies* and Qihui Jin

Department of Chemistry, University at Buffalo, The State University of New York, Buffalo, New York 14260-3000

Received May 13, 2004; E-mail: hdavies@buffalo.edu

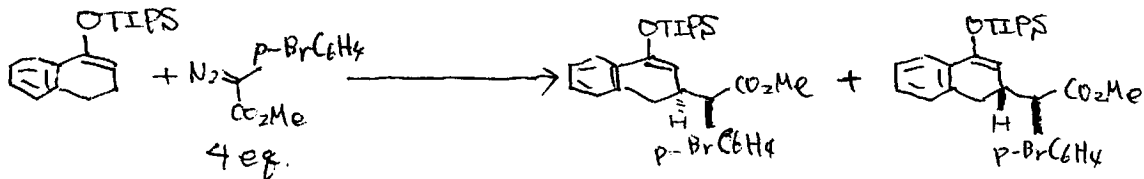
© The formation of formal C-H activation product



The highly stereoselective nature was unexpected.

1:2	Rh ₂ (S-DOSP) ₄	temp. °C	yield, %	de, %	ee, %
1:2	1 mole%	23	92	> 98	98.9
1:1.2	0.1 mole%	23	82	> 98	98.3
1:1.1	0.5 mole%	0	95	> 98	99.5

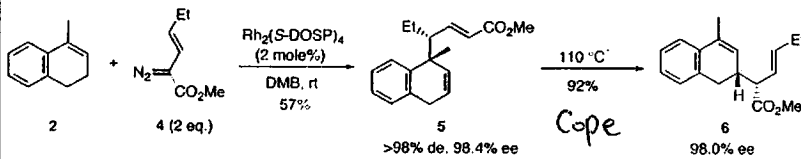
DMB = 2,2-dimethylbutane



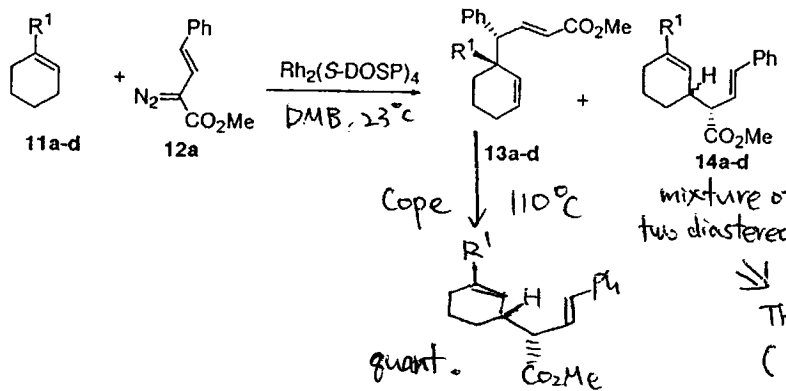
{ 68% yield (total)
74:26 dr
90% ee (major diastereomer)

JACS, 2001, 123, 2070

Earlier studies on the reaction with aryl diazoacetate displayed only modest diastereoselectivity.



~~6~~ → ~~5~~
Most obvious but impossible



R¹ = Me
{ 40% yield (13)
1:6 = 1 (13:14)
> 98% de (13)
99% ee (13), 97% ee (14)

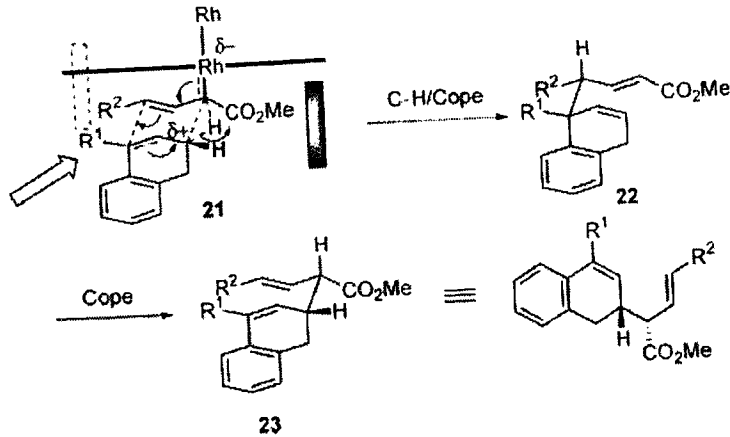
∴ The direct C-H activation product (low diastereoselectivity)

A possible explanation for the high diastereoselectivity is the involvement of a more elaborate reaction mechanism than a direct C-H activation.



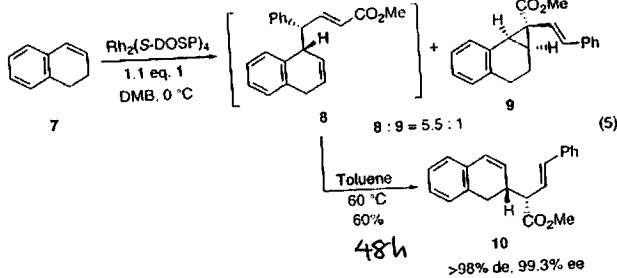
A combined C-H activation / Cope rearrangement

Scheme 1. Predictive Model

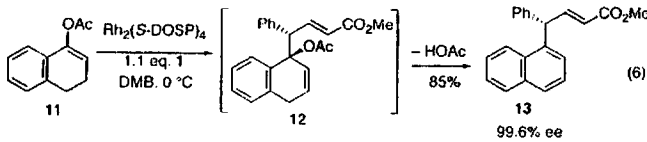


The high diastereoselectivity is an indication that very little direct C-H activation is occurring.

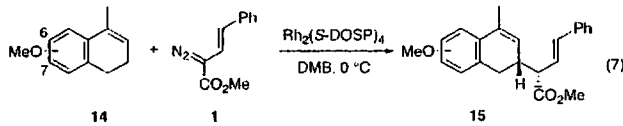
Other substrates



8 + 9 = 77% yield

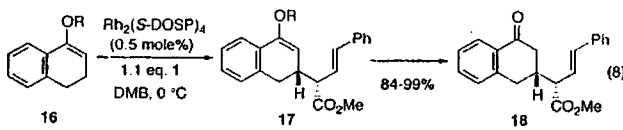


Aromatization occurs faster than the retro-Cope rearrangement.



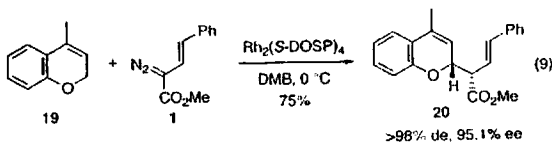
With 14b, competing benzylic C-H activation occurs to a minor extent.

Entry (Comp.)	yield, %	de, %	ee, %
a (14a, 7-methoxy)	90	> 98	98.9
b (14b, 6-methoxy)	77	> 98	99.3

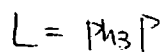
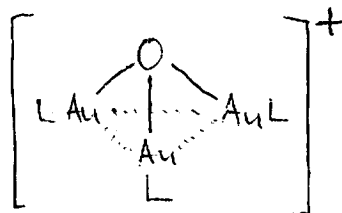
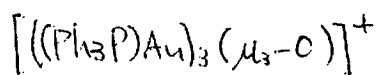
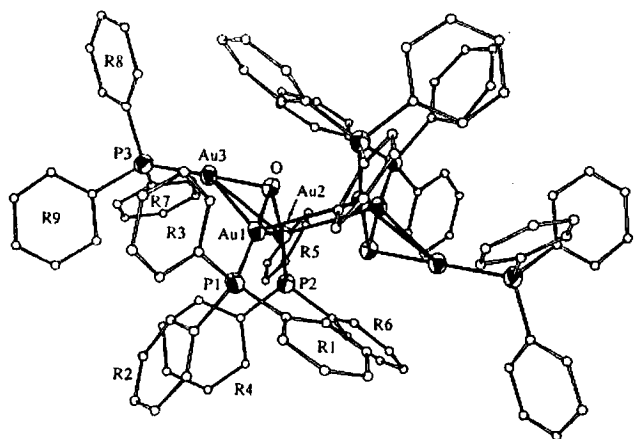


17 can be formally considered to be equivalent to Michael adduct.

Entry	R	yield, %	de, %	ee, %
a	TMS	55	>98	97.5
b	TBS	78	>98	95.2
c	TIPS	53	>98	91.3



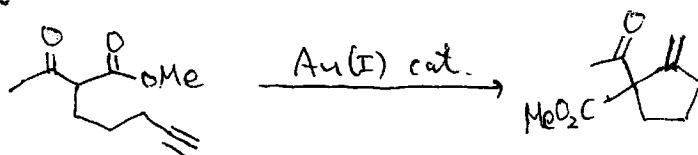
Appendix



(The two cations are related by an inversion center)

Inorg. Chem.
1993, 32, 1946.

Cf.



10 mol% Ph_3PAuOTf , DCE, rt < 15 min, > 95% conv.
 1 mol% $[(\text{Ph}_3\text{PAu})_3\text{O}]\text{BF}_4$, DCE, 60°C 1 h, 0% conv.
 1 mol% $[(\text{Ph}_3\text{PAu})_3\text{O}]\text{BF}_4$, 5 mol% HOTf, DCE, rt, < 15 min, > 95% conv.

cationic triphenylphosphine gold(I) complex is the active catalyst.

Relative stabilities for complexes between $[\text{Me}_3\text{PAu(I)}]^+$ and several neutral ligands (Ab initio calculation)

$\text{CH}_2\text{Cl}_2 (+63) < \text{H}_2\text{O} (+44) < \text{acetylene} (+38) < \text{MeOH} \approx 1,4\text{-dioxane} (+24)$
 $< \text{propyne} (+18) < \text{THF} (+2) < 2\text{-butyne} (0) < \text{Me}_2\text{S} (-18) < \text{Ph}_3\text{P} (-114)$

• Teles et al. Angew. Chem. Int. Ed. 1998, 37, 1415 (kJ mol⁻¹)