Cent. Eur. J. Chem. • 8(6) • 2010 • 1147-1171
DOI: 10.2478/s11532-010-0114-z

VERSITA

Central European Journal of **Chemistry**

P-Acylphosphonium salts and their vinyloges - application in synthesis

Review Article

Beata Kolesinska

Institute of Organic Chemistry,
Technical University of Lodz, 90-924 Lodz, Poland

Received 26 March 2010; Accepted 3 September 2010

Abstract: Review with 101 refs. of progress in synthetic applications and properties of *P*-acylphosphonium salts including acylation *via* *P*-acylphosphonium salts, enantioselective acylation using chiral phosphine ligands, nucleophilic (β)-oniovinylation, and reaction involving vinyloges of *P*-acylphosphonium salts formed by treatment conjugated alkenoates or alkynoates with phosphines.

Keywords: *Phosphine* • *Acylation* • *Enantioselective acylation* • *Isomerization of conjugated alkynes* • *Cycloaddition* • *Vinylphosphonium salts*

1. Introduction

There are several organophosphorus compounds which are widely used as reagents in synthetic organic chemistry. The most common applications include the use of phosphorus ylides in the Wittig [1] and/or Horner-Wadsword-Emmons olefination [2], the use of phosphines in the Staudinger [3], Mitsunobu [4], Rauhut–Currier [5], Morita-Baylis-Hillman [6] reactions and the use of phosphines as ligands in transition metal-catalyzed processes [7]. All these applications have been thoroughly reported and numerous reviews have appeared in the literature [8]. Synthetic applications of *P*-acylphosphonium salts remain less explored. *P*-acylphosphonium salts, crucial to several important chemical transformations, are usually generated *in situ* in reactions involving phosphines; only in a few cases *P*-acylphosphinium salts were isolated and thoroughly studied as individual species. However, in the last two decades the number of reports of phosphines being used as nucleophilic catalysts have grown significantly, showing that phosphines are to as effective as 4-(*N,N*-disubstituted amino)pyridines as a nucleophilic catalysts in acylation of nucleophiles. Moreover, the latest results of studies on donation of electron pair by phosphines to electron deficient counterparts strongly suggest the broad scope of the new and diversified synthetic applications of vinylated analogues and complexes with a “frustrated electron pair” [9] or their analogues with a quasielastic P-P bond [10].

2. Nucleophilicity of Phosphines

The nucleophilicity index N, introduced by Mayr and co-workers [11], enables quantitative measurement of nucleophilicity of phosphines. This empirical parameter is not universal, but it is a measure specific to every interacting pair of an electrophile and a nucleophile, since the uniform scale of nucleophilicity does not exist. The index is based on frontier molecular orbital interactions between a nucleophile and its electrophilic partner. Assuming that A is the nucleophile and B is the electrophile, the empirical nucleophilicity index was defined by Jaramillo *et al*. [12] as follows

$$\omega^{-} = \frac{1}{2}\frac{(\mu_A - \mu_B)^2}{(\eta_A + \eta_B)^2}\eta_A \qquad (1)$$

where μ_A and μ_B are the corresponding chemical potentials, and η_A and η_B represent the respective hardness. Eq. 1 was derived considering that the electronic charge transferred between species A and B is defined by the Eq. 2

$$N = \frac{\mu_A - \mu_B}{\eta_A + \eta_B} \qquad (2)$$

---

* E-mail: beata.kolesinska@p.lodz.pl

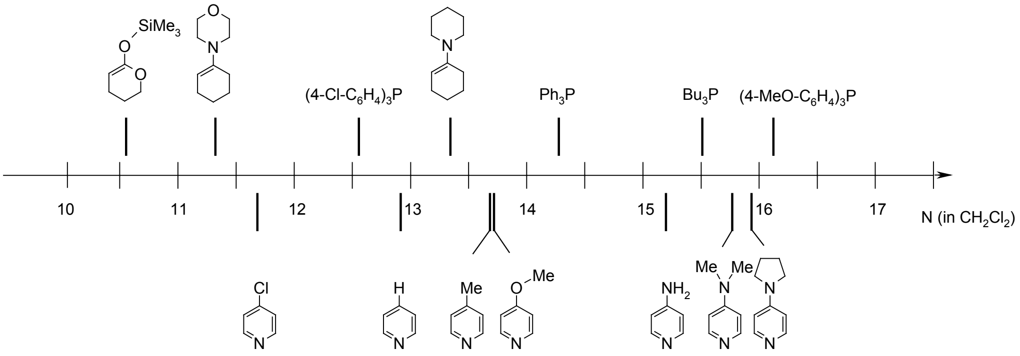


Figure 1. Nucleophilicity index N of phosphines, pyridines, and other related nucleophiles, according to Mayr and co-workers [6].

Table 1. Experimental rate constant (logk) [13] and calculated properties for phosphanes and phosphites using tricarbonylcyclohexadienyliron cation as electrophile.

	logk	η (au)	μ (au)	N	ω (eV)
Nucleophiles					
$P(2\text{-}OMeC_6H_4)_3$	5.833	0.177	-0.112	-0.695	1.164
PBu_3	5.526	0.225	-0.110	-0.593	1.074
PAn_3	4.808	0.179	-0.119	-0.663	1.070
$PTol_3$	4.452	0.185	-0.119	-0.646	1.050
PPh_2Tol	3.908	0.186	-0.125	-0.625	0.988
PPh_3	3.873	0.187	-0.127	-0.612	0.954
$P(OBu)_3$	2.004	0.252	-0.120	-0.513	0.903
$P(OEt)_3$	1.662	0.251	-0.122	-0.509	0.885
$P(OMe)_3$	1.473	0.252	-0.126	-0.495	0.839
$P(OPh)_3$	-1.384	0.218	-0.135	-0.521	0.807
Electrophile					
$(CO)_3(C_6H_7)Fe+$		0.079	-0.290		

All calculations were performed at B3LYP/6-31+G(d,p) level of theory.

The N values of tributylphosphine and tri(p-methoxyphenyl)phosphine exceed these of DMAP or 4-(pyrrolidin-1-yl)pyridine, see Fig. 1.

As mentioned above, the value of index N vary from one electophile to another. The value of hardness, chemical potential, charge transfer, and the nucleophilicity index of phosphanes and phosphites are shown in Table 1.

The empirical nucleophilicity index used to test the nucleophilic trend within a family of phosphorous nucleophiles, validated against the kinetic data of phosphanes and phosphites interacting with the corresponding electrophilic partners, showed good correlations with the experimental rate constants in the studied systems. Thus, the nucleophilicity index N, tested on several phosphane and phosphate species [12], has a predictive character and can be used as a unified measure of nucleophilicity of-phosphorus compounds in comparison with nitrogen nucleophiles.

The chemistry of phosphines is related to the non-bonding pair of electrons which may be used to form a new bond between phosphorus and a variety of electrophilic species. The increase in use of phosphines as nucleophilic catalysts has been related to the introduction of several convenient procedures transforming these air-sensitive compounds into relatively stable derivatives. These derivatives can either be used as phosphines substitutes or be easily converted into phosphines either *in situ* or by application of an expedient transformation procedure. All trialkylphosphines, which are air-sensitive reagents and must be handled with care, can be protected as their air-stable conjugate acids, and then converted back, *in situ,* by treatment with an appropriate base. Another approach to stabilize phosphines, reported by Fu [14], has been to form a stable $[HPBu_3]BF_4$ complex of phosphine; the complex can be stored for several months, exposed to air, without showing any detectable signs of deterioration. Furthermore, the complex was shown to be as effective as the free phosphine in catalyzing the Morita–Baylis–Hillman reaction.

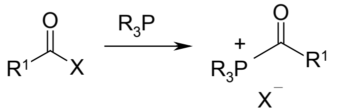
3. Synthesis and properties of *P*-acylphosphonium salts

There is strong evidence that the primary products of acylation of tertiary phosphines are *P*-acylphosphonium salts.

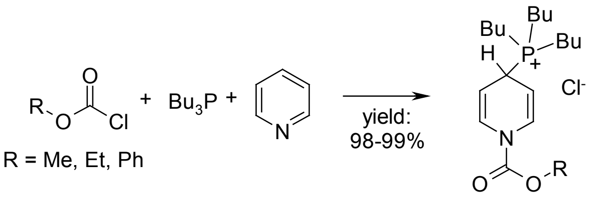
The first reports indicating the formation of appropriate *P*-acylphosphonium chlorides in reaction of triethylphosphine with chloroformates were presented by Jensen [14] in 1937. Reactions of acyl halides with phosphines were also described by Yashkin and Sokalskaya [15]. Acylation proceeded smoothly, at -22°C - 0°C in inert solvent, with a broad range of acid chlorides of aliphatic carboxylic acids as well as with benzoyl chloride [16]. The salts were highly hygroscopic, but relatively stable in the absence of moisture. The IR C=O absorptions of these compounds showed frequencies lower than those observed in aliphatic ketones, despite the inductive effect of the phosphonium group; the UV spectra also showed a bathochromic shift for the n -> π* band from interaction between C=O and atom of phosphorus. Analogous reaction with carbamoyl chlorides proceeded less readily, although the expected *P*-carbamoylated tributylphosphonium chloride was obtained in good yield [17]. Only in the presence of pyridine a different reaction path was documented (see Scheme 2); an almost quantitative yield of dihydropyridine derivative, formed by 1,4-addition of appropriate tributylphosphonium salt to the pyridine ring, was reported [18].

Also anhydrides of carboxylic acids yielded appropriate *P*-acylphosphonium salts. There is, however, a report suggesting a more complex reaction between phosphine and the acetylating reagent leading to different products (see Scheme 3). In this case acetic anhydride reacted with excess of phosphine and initially formed *P*-acetylphosphonium acetate underwent subsequent rearrangements as shown below.

The rearrangement involved the enolization of the *P*-acetyl fragment giving the acetylated bisfophosphinylated product which, after elimination of acetic acid, yielded bisphosphonylated alkene as shown in Scheme 3. The structure of the product was unambiguously confirmed by crystallographic studies [19].



Scheme 1. Reaction of phosphines with acylating reagents yielding *P*-acylphosphonium salts



Scheme 2. Synthesis of tributyl(1-alkoxycarbonyl-1,4-dihydropyridin-4-yl)phosphonium chloride by treatment of pyridine with alkylchloroformate and tributylphosphine

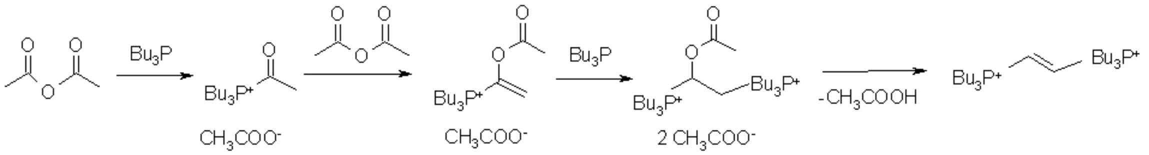
The formation of bisphosphonylated products by addition of nucleophilic phosphine to the carbon-carbon double bond was confirmed in experiments carried out with acyl chlorides and bromides prepared from unsaturated carboxylic acids [20]. Under strictly anhydrous conditions, acylation of tetraphosphacubane with $MeCO^+SbCl_6^-$ at room temperature gave monoacetylated phosphonium salt in 75% yield after 3 days. The ^{31}P NMR spectrum showed two resonances at 194.5 (3P) and 84.2 (IP), appearing as a doublet and a quartet, respectively (J = 18 Hz), due to the P-P coupling. The MeCO gave a singlet at 2.13 ppm in the ^1H NMR spectrum and the C=O group appeared as a multiplet at 191.3 ppm in the ^{13}C NMR spectrum [21].

4. Acylation in the Presence of Phosphines

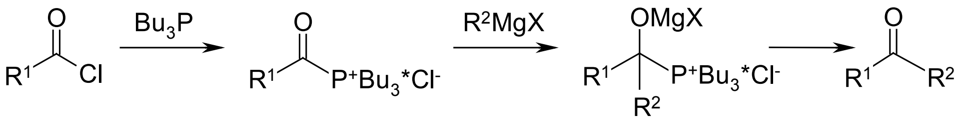
Acylation of nucleophiles by several acylating agents, including alcoholysis of anhydrides, cyclic anhydrides [22], diketene, pyridylthioesters, benzoylcyanide, and imidoyl esters derived from carbodiimides, has been found to be accelerated in the presence of tributylphosphine. This is not the case with less reactive acylating species such as p-nitrophenylesters, vinyl acetate or acyl azides.

However, in the case of azide-based acylating species more complex transformations were observed. Benzoyl azide treated with tributylphosphine gave *N*-benzoyl-tributylphosphinimin with liberation of nitrogen [23]. Analogous reactions leading to phosphinimin were reported for sulfonylazide [24]. In the presence of tributylphosphine mixed anhydrides, prepared by activation of carboxylic acids with chloroformates, easily underwent transformation into appropriate alkylcarboxylates with loss of CO_2 [24].

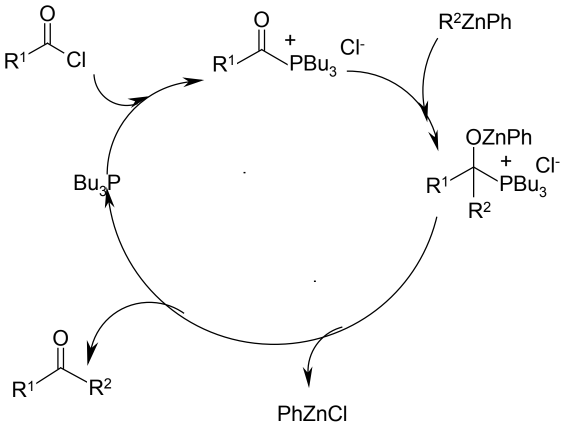
The reaction of *in situ* formed *P*-acylphosphonium chlorides with Grignard reagents or organolithium reagents gave appropriate ketones in high yield [25].



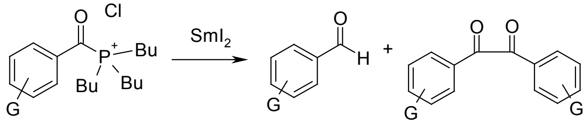
Scheme 3. Structures of products formed during reaction of excess of tributylphosphine with acetic anhydride



Scheme 4. Acylation of Grignard reagents by *P*-acylphosphonium chlorides



Scheme 5. A possible catalytic role of n-Bu_3P in n-Bu_3P-catalyzed acylation of n-alkyl phenylzincs



Scheme 6. Reduction of *P*-benzoylated tributylphosphonium chloride with SmI_2

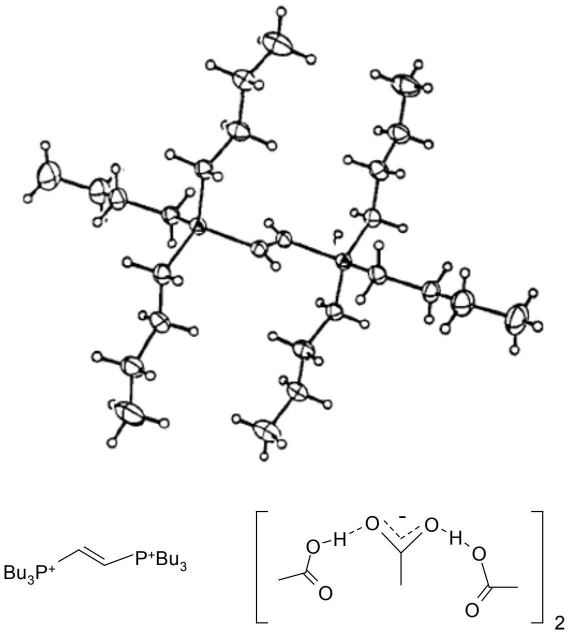


Figure 2. Crystallographic structure of vinylenebis(phosphonium)

This procedure was found useful in the case of dicarboxylic acid dichlorides and alkoxycarbonyl alkanoyl chlorides yielding appropriate diketones or ketoesters respectively *via* bis- or mono-phosphonium ions generated *in situ* by treatment with n-Bu_3P [26]. The acylation of Grignard reagents has been found generally useful and fairly good yields were obtained even in reaction of *N,N*-dialkylcarbamoyl chlorides with alkyl or aryl Grignard reagents *via* appropriate *P*-phosphonium carbamates.

An alternative approach involved organozinc reagents. To avoid ambiguity during acylation, a symmetrical organozinc or unsymmetrical reagents with one alkyl and one aryl group or one alkyl and one unreactive *tert*-butyl group were used [27].

Acylation with acyl chlorides carried out in the presence of catalytic amounts of tributylphosphine gave appropriate ketones in 38-90% yield (see Table 2).

In the presence of samarium diiodide a change in the reaction pathway was observed, and reaction of *P*-benzoylphosphonium chlorides gave 4-benzoylbenzaldehyde. This process is based on the reduction of potentials of alkanoyl and benzoyltributylphosphonium ions which are much more positive than those of the corresponding acid chlorides. This facilitates conversion into aldehydes without over-reduction to alcohols [16c]. Only in the case of substituted benzoyl derivatives appropriate 1,2-diketones are formed as byproducts or even as major products in the case of 4-substituted benzoic acid [17].

In the past several years the use of samarium(0) as a reducing agent in organic synthesis has attracted much attention. This is due to the fact that metallic samarium is stable in air and has a strong reducing potential ($Sm^{3+}/Sm = -2.41$ V). It is also cheap and easy to handle. The reduction of acyl chlorides with samarium(0), either without any additives or with the usual additives such as iodine, TMSCl and allylic bromide used to activate metallic samarium, gave only the coupling products; no formation of aldehydes was observed under various temperatures, solvents, and proton sources. However, in the presence of tributylphosphine, used as acylation catalyst, a facile and efficient reduction of aromatic and aliphatic acyl chlorides to their corresponding aldehydes took place *via in situ* formation of the *P*-acylphosphonium ion. The procedure, based on Sm(0)/Bu_3P, has been found to have a broad scope of application as an efficient conversion of both aromatic and aliphatic acyl chlorides to their corresponding aldehydes in 87-95% yield without over-reduction to alcohols [28].

The one-step transformation of carboxylic acids into aldehydes has also been achieved by the electrochemical oxidation of Ph_3P in a one-compartment cell equipped with a graphite anode and a graphite cathode under a nitrogen atmosphere and in conditions strongly facilitating formation of appropriate *P*-acylphosphonium salts [29]. *P*-acyltrialkylphosphonium salt by itself can act as a hydride donor promoting the reduction of the appropriate reactive intermediate. The reductive coupling of acyl cyanides promoted by trimethylphosphine or tributylphosphine, under mild reaction conditions, at room temperature, in various solvents, within 6 h gave the corresponding products in good yields. The possible mechanism involved in the reaction, proposed on the basis of deuterium labeling and control experiments, indicated that a hydride transfer took place from alkyl phosphine to *O*-acyl cyanohydrin (see Scheme 7).

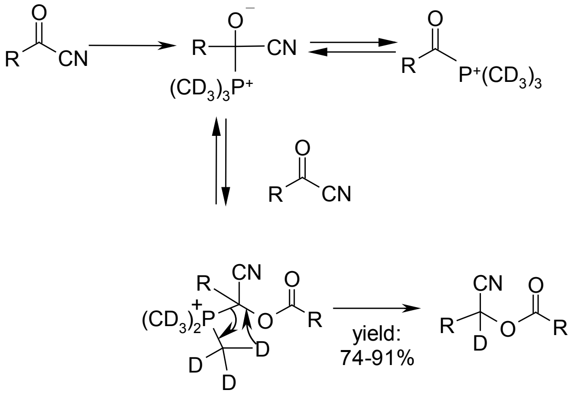
The high efficiency of acylation catalyzed by phosphines, proceeding *via* *P*-acylphosphonium salts, has been shown in the synthesis of rotaxanes using appropriate acyl chlorides or anhydrides [30].

P-acylphosphonium salts were found useful as catalysts of polymerization of cyclic acetals [31], cationic polymerization of β-propiolactone or ε-caprolactone [32], and polyaddition of terminal acetylenes bearing electron-withdrawing groups [33].

5. Enantioselective Acylation Using Phosphines as Catalysts

Development of enantiomerically pure compounds (EPC) is one of the most important goals of today's organic chemistry. Numerous applications of enantioselective syntheses in the pharmaceutical industry as well as in the production of chiral fragrances and agrochemicals indicate the importance of EPC in the chemical industry [34]. Over the past two decades enormous success has been achieved in stereoselective organic transformations catalyzed with complexes of transition metals with the C2-symmetric atropisomeric diphosphine ligands. With regard to stereochemical control, many structurally diverse phosphine ligands, especially the chelating C2-symmetric atropisomeric diphosphines (*e.g.* BINAP, BIPHEMP, and MeO-BIPHEP) have been proved to be highly effective for countless asymmetric transformations. High enantioselectivity and productivity of the catalyst are of great importance. Unfortunately, theory has thus far offered scant help as to which substituents on the trivalent phosphorus atom give rise to the desired catalytic properties. This uncertainty has hitherto challenged the creativity of the catalyst chemists. Meanwhile the palette of phosphorus ligands ranges from electron-rich alkylphosphines [35] through phosphinites [36] and phosphonites [37], to electron-deficient phosphites [38]. Several chiral phosphines, with a stereogenic center on P atom as well as *P*-substituted with chiral groups, have been described in the literature. Comprehensive reviews have been available since the groundbreaking work of Pietrusiewicz [39]; most of them deal with new synthetic methodology [40]. However, this synthetic potential, although well documented in the literature, still remains incompletely explored. Recently, a substantial progress has been done increasing the scope and improving efficiency of procedures based on kinetic resolution [41] to survey nucleophilic properties of chiral phosphines catalysts in enantioselective acylation.

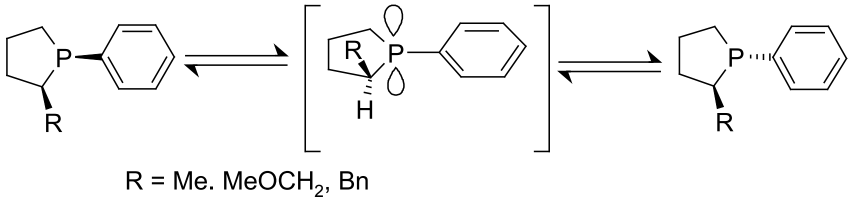
In comparison to tertiary amines, which found



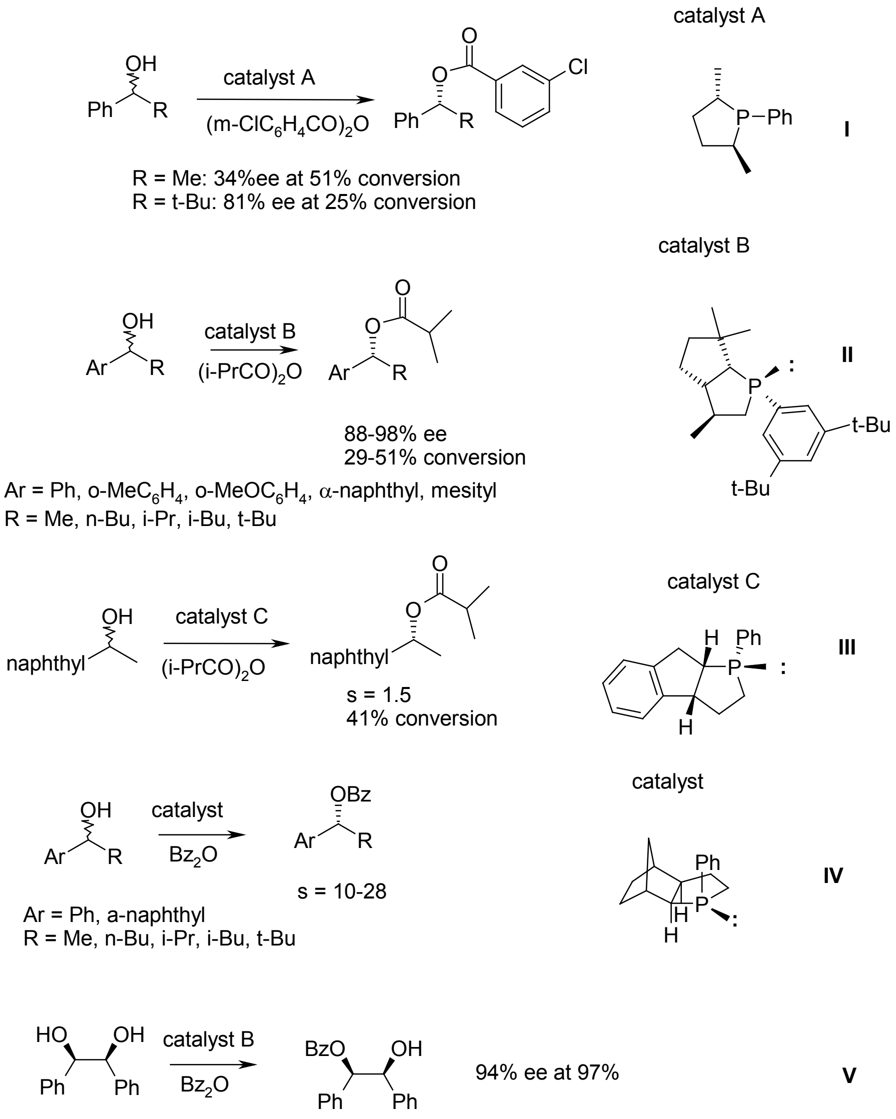
Scheme 7. A proposed reaction mechanism studied by isotopic labeling experiment strongly suggests intermolecular reductive coupling reaction of acyl cyanide by a hydride transfer from alkyl phosphine to the carbonyl group

Table 2. $n\text{-}Bu_3P$-catalyzed acylation of mixed n-alkyl phenylzincs with acyl chlorides in THF

Entry	R¹	R²	Yield (%)
1	n-Bu	Ph	77
2	n-heptyl	Ph	80
3	n-decyl	Ph	90
4	Np	Ph	-
5	$PhZn(CH_2)_6$	Ph	67
6	$MeCOO(CH_2)_4$	Ph	54
7	n-Bu	$4\text{-}MeC_6H_4$	83
8	n-Bu	Me_3C	38



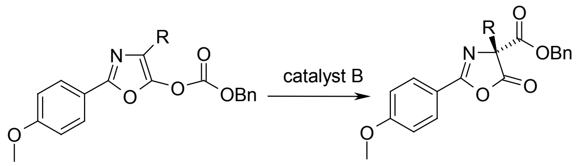
Scheme 8. Phosphines with stereogenic centre located on phosphorous atom are relatively stable. Epimerization of cis-phospholane to the thermodynamically more stable trans-isomer proceeds slowly after heating to 190°C for 8 h



Scheme 9. Chiral phosphines as enantioselective acylating agents

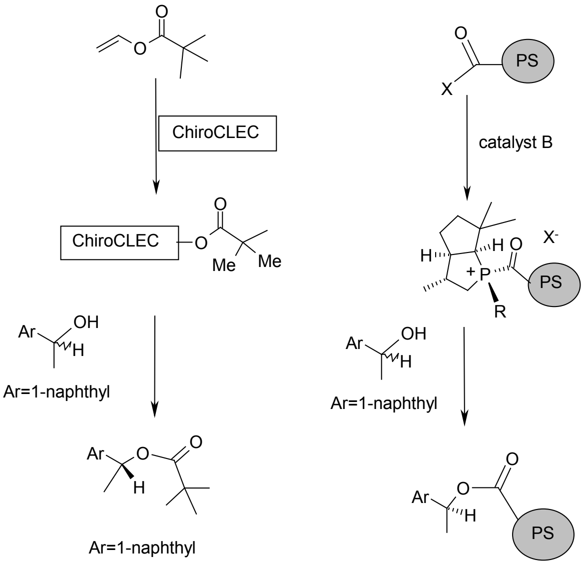
broad applications as organocatalysts, phosphines are also widely used as catalyst and they have several advantages which give them superiority over tertiary amines.

In the case of phosphines, only after prolonged heating a slow inversion of configuration the chiral phosphorus atom of phosphine was observed. *P*-Chirogenic phospholanes with *cis*- relationship between the α-substituent and the *P*-substituent can be selectively epimerized to the thermodynamically more stable *trans*- isomers after heating to 190°C for 8 h [42] or even under more vigorous conditions. It is very likely that the mechanism of epimerization by pyramidal inversion involves the planar transition state featuring



R = Me, Bn, allyl, i-Bu (89-92% ee), Ph (20% ee)

Scheme 10. Acyl transfer reaction catalyzed by phosphine B



Scheme 11. Catalytic parallel kinetic resolution

a sp^2 phosphorus atom, that is, in equilibrium with each form of the phospholanes (Scheme 8).

The first application of chiral phosphines for kinetic resolution of racemic secondary alcohols (Scheme 9, Eq. **I**) was reported in 1996 by Vedejs. He reported the application *tran*s-2,5-dimethyl-1-phenylphospholane (catalyst A) to kinetic resolution of secondary alcohols [43]. Higher enantiomeric excess was achieved in the presence of more reactive second generation 2-phosphabicyclo[3.3.0]octane (PBO) (catalyst B) [44]. For most aryl alkyl carbinols, acylation with $(i\text{-PrCO})_2O$ and 3-5 mol% chiral phosphine gave enantiomeric purity of the isopropyl ester product ranging from 88% to 98% ee (Scheme 9, Eq. **II**). The new catalysts C and D were compared with the PBO catalyst B in a kinetic resolution of 1-(1-naphthyl)ethanol. It was found that catalyst C proved to have modest reactivity (5-6-fold lower compared to catalyst of B) and poor enantioselectivity in isobutyroylation (Scheme 9, Eq. **III**). In contrast, the reactivity of catalyst D was comparable to catalyst B if the relative rates were adjusted for the difference in catalyst loading. However, the enantioselectivity observed with D was somewhat lower, and little improvement in selectivity was observed at lower temperatures [45]. More promising results were obtained when the more reactive catalyst D was used for the activation of benzoic anhydride (Scheme 9, Eq. **IV**).

It was found that the same catalyst was very efficient in desymmetrization of *meso*-diols giving acylated products in moderate enantiomeric excess [46]. The desymmetrization of *meso*-hydrobenzoin with benzoic anhydride (Scheme 9, Eq. **V**) gave a remarkable 94% ee at 97% conversion [47].

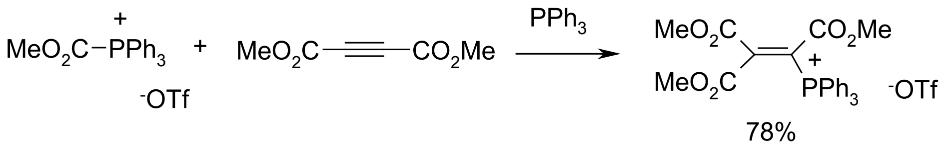
Recently, Vedejs and co-workers reported an application of their bicyclic chiral phosphine catalyst for the synthesis of quaternary carbon centers by an acyl transfer reaction of an oxazole enol carbonate giving an azlactone (Scheme 10) in good enantioselectivity [48].

A general problem in kinetic resolution is how to obtain high enantiomeric purity in both the product and the unreacted starting material when selectivity is not very high. As the reaction progresses, the relative concentration of the faster reacting enantiomer *versus* the slower reacting enantiomer decreases, resulting in a drop in the relative rates of the intrinsically faster *versus* the intrinsically slower acylation reactions. One way to avoid this change in the relative concentrations of the enantiomers is to run two simultaneous derivatization reactions, a method named as parallel kinetic resolution. Vedejs first reported this technique in 1997 using a chiral DMAP catalyst [49]. If the rates and enantioselectivities are similar and complementary, the enantiomer ratio of the substrate remains 1 : 1 throughout the reaction. Vedejs and co-workers [50] selected an insoluble cross-linked lipase (ChiroCLEC-PC) as an acyl transfer catalyst to complement the nucleophilic chiral phosphine catalyst (Scheme 11).

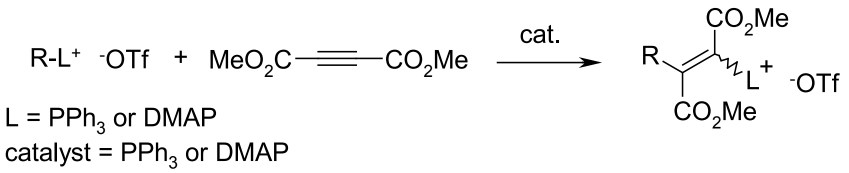
The anhydride intended for phosphine activation was attached to an insoluble resin as a mixed anhydride so phosphine activation at the less-hindered carbonyl would generate *P*-acylphosphonium attached to solid support. In this manner, the (S)-enantiomer of the alcohol became resin-bound as an ester, while the (R)-enantiomer remained in the solution as an ester. From racemic 1-naphthyl methyl carbinol, excellent (92 –96% ee) resolution was achieved with both reactions benefiting in terms of product ee *versus* simple resolution to 50% conversion.

6. Nucleophilic (β)-Oniovinylation (NOV)

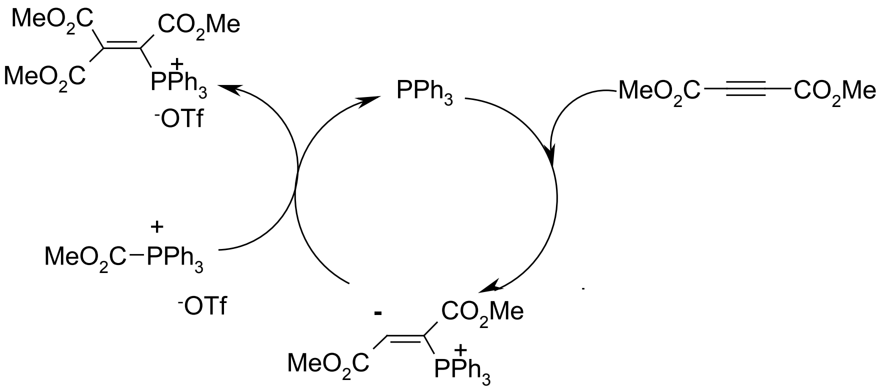
In 2008 Weiss and Huber [51] described the reaction of presynthesized acyl-onio salts with alkynes activated by phosphine which provide vinylogous acyl-onio compounds. In the reaction of (methoxycarbonyl)-triphenylphosphonium triflate with dimethyl acetylenedicarboxylate (DMAD) in the presence of a catalytic amount (2%) of PPh_3, a *β*-oniosubstituted



Scheme 12. Synthesis of vinylogous acyl-onio compounds



Scheme 13. General reaction of nucleophilic (β)-oniovinylation (NOV)



Scheme 14. Proposed catalytic cycle of formation of vinylogous acyl-onio compounds

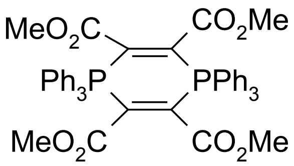


Figure 3. Structure of a stable 2:1 compound obtained from DMAD and PPh$_3$

Michael system was obtained as a sole reaction product. It was found that in the absence of PPh$_3$, the product did not form (Scheme 12).

The reported reaction can be considered as a novel synthetically useful type of nucleophilic substitution that amounts for an insertion of an electron-deficient alkyne into the C-L bond of a highly electrophilic R-C(O)-L$^+$ system under the mediating influence of nucleophile L. The reaction was referred to as nucleophilic (*β*)-oniovinylation (NOV).

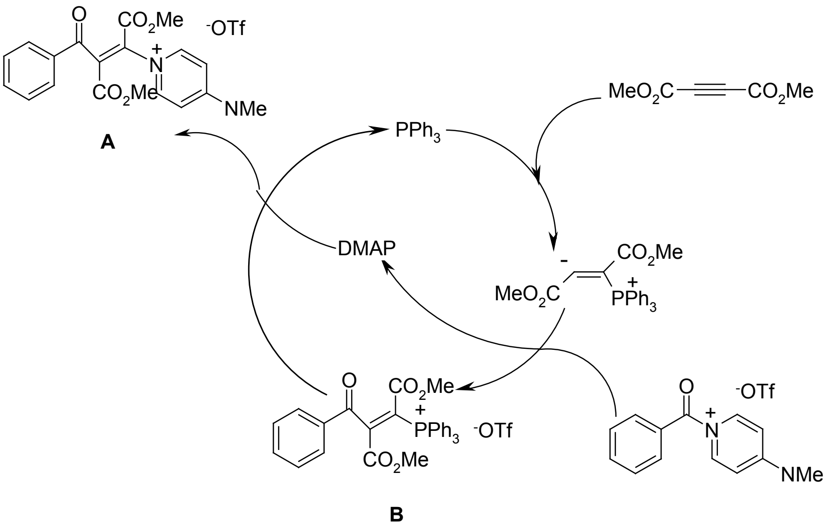
The authors successfully applied the NOV methodology to a number of onio-activated electrophiles. A general reaction equation is shown in Scheme 13.

It was found that there was possible to use either L tertiary phosphine (PPh$_3$) or tertiary amine (DMAP) as ligands or catalysts. The proposed mechanism for the reaction showed in Scheme 12 is presented in Scheme 14. The initial step is the attack of the primary nucleophile, PPh$_3$, on the acetylene, generating the intermediate, which reacts fast, attacking the electrophilic carbonyl center of the acyl-phosphonio salt. In a proposed addition-elimination process, the product is formed and the catalyst PPh$_3$ is liberated.

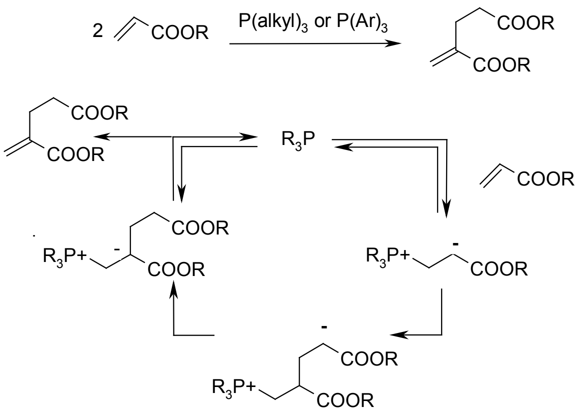
This reaction is significantly faster than the possible side reaction of the intermediate, obtained from DMAD with PPh$_3$, with another PPh$_3$ molecule, forming a stable 2:1 compound presented in Fig. 3, previously described by Shaw [52].

A different proposition has to be made for the reaction sequence and especially for the role of the catalyst PPh$_3$ in the case of DMAP as an onio ligand. The reaction sequence is similar to the one presented above, up to the formation of a vinylphosphonio intermediate and liberation of the initial onio ligand DMAP. In the next step replacement of phosphonium fragment from n product B into amonium fragment in product A is observed. The C-N bond is lower in energy compared to the C-P bond, thus the substitution fits expectations. Consequently, the final product **A** instead of **B** is formed. The catalyst is regenerated for further catalytic cycles (Scheme 15).

There is some evidence that the initial product of the catalytic cycle shown in Scheme 15 is the *syn* addition



Scheme 15. Catalytic cycle of formation of product A



Scheme 16. The Rauhut-Currier dimerization of activated alkenes

product **A**. This could be due to a S_N2-type phosphine/pyridine substitution reaction (instead of addition-elimination process). Studies by Rappoport [53] suggest that substitutions at Michael position are very fast and thus S^N2-like. For this reason, inversion at the reaction center has to be expected.

X-ray structures were obtained for a number of such β-oniovinylation products. A mechanism for this novel insertion reaction, which accounts for the topology of the products and rationalizes the observed stereochemistry, is presented. The β-onio-activated Michael systems generated this way represent a virtually unexplored class of compounds. The onio substituent in such compounds can be selectively replaced by a number of nucleophiles. Thus a series of Michael systems with donor functions in the β-position can be easily synthesized. These compounds represent a source of useful further transformations, for example, cyclizations to quinolones, thiochromones, and pyrazoles.

7. Vinyloges of *P*-Acylphosphonium Salts

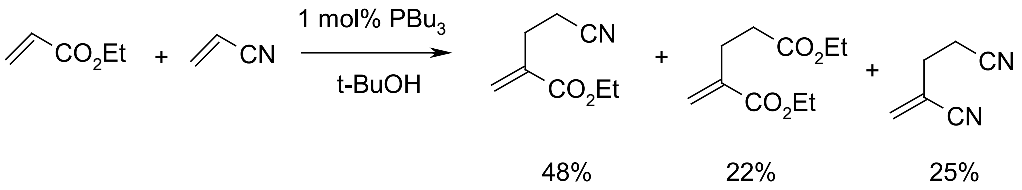
Vinyloges of *P*-acylphosphonium salts were formed by insertion of a broad range of electron-deficient alkynes into *P*-acylphosphonium salts. Insertion of other unsaturated system into *P*-acylphosphonium salts can lead to many useful synthetic pathways. In many cases, the participation of vinyloges of *P*-acylphosphonium salt were well documented, however in some cases the participation of *P*-acylphosphonium salts is only postulated, without any experimental evidence.

7.1. The Rauhut–Currier and Morita–Baylis–Hillman reactions

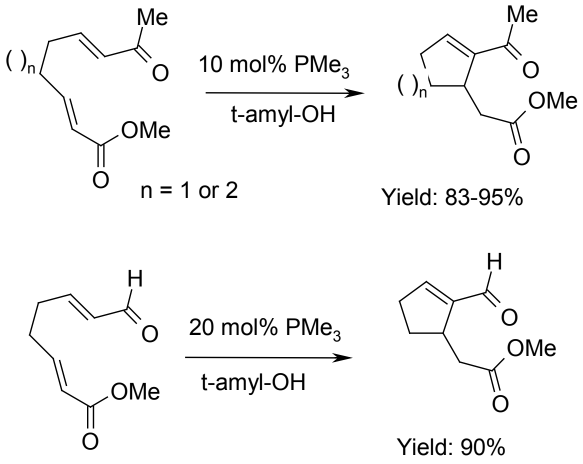
In 1963 Rauhut and Currier [54] described a phosphine-catalyzed dimerization of activated alkenes (Scheme 16). This transformation was independently investigated by McClure [55] and Baizer and Anderson [56], and was suggested that it involved a reversible conjugate addition of phosphine to an activated alkene, followed by a Michael reaction of the enolate with the second molecule of the activated alkene. A prototropic shift, followed by an elimination process, formed the dimer and released the phosphine.

The first cross-coupling reaction between ethyl acrylate and acrylonitrile was reported by McClure [57] (Scheme 17). A single cross-coupled product, 2-ethoxycarbonyl-4-cyano-1-butene, was isolated in 48% yield, but the final product was contaminated by the products of dimerization of both reactants.

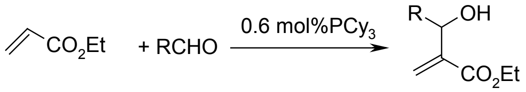
Recently, the groups of Krische and Roush [58] applied this procedure to transformation of an intramolecular process, in which the activated alkenes



Scheme 17. Cross-coupling in Rauhut-Currier reaction



Scheme 18. Intramolecular Rauhut-Currier reaction



R = Me, Et, n-Pr, i-Pr, Ph, p-Cl-C_6H_4, p-Me-C_6H_4

Scheme 19. Phosphine-catalyzed Morita-Baylis-Hillman reaction

are tethered by a 2- or 3-atom connecting chain (Scheme 18). Symmetric enone-enoate and enal-enoate combinations cyclized with high chemoselectivity, with the more electrophilic α,β-unsaturated system serving as the "initiator" of the cyclization.

It is noteworthy that phosphines are far superior to amine nucleophiles, such as DABCO, DBU, Et_2NH and DMAP, in the intramolecular Rauhut–Currier reaction. Perhaps due to their softer character they are better suited to the soft activated alkene substrate [59]. However, it needs to be noted that the addition of triphenylphosphine was ineffective, while tricyclohexylphosphine generally gave low conversion. The smaller phosphines, such as tributylphosphine and particularly trimethylphosphine, proved to be optimal. The self-condensation of reactive enal-enoate substrates could be suppressed by lowering the concentration from 0.1 M to 0.01 M.

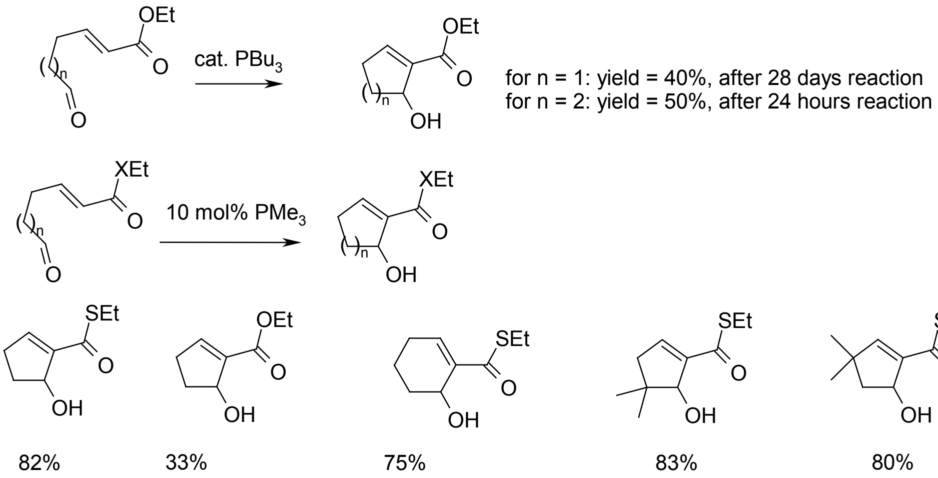
The zwitterionic phosphonium Michael adducts can be trapped with other electrophiles such as *e.g.* aldehydes. The Morita–Baylis–Hillman reaction is a coupling of an activated alkene and an aldehyde in the presence of a nucleophilic catalyst (Scheme 19).

The reaction was first reported by Morita and co-workers [60] in 1968 and by Baylis and Hillman [61] in 1972. Morita employed tricyclohexylphosphine as a nucleophilic catalyst, while Baylis and Hillman used tertiary amines such as DABCO. Activated alkenes, used in the experiments, included acrylic esters, acrylonitrile, vinyl ketones, phenyl vinyl sulfone, phenyl vinyl sulfonate ester, vinyl phosphonate, and acrolein. β-Substituted alkenes added slowly to the phosphine catalyst and therefore required stronger reaction conditions. A variety of coupling partners, such as aliphatic, aromatic and α,β-unsaturated aldehydes, have been successfully employed. Unfortunately, the applications of the Morita–Baylis–Hillman reaction in complex synthetic problems are limited by low rates and low conversions, as well as by highly substrate-dependent yields. Unfortunately, due slow reaction rates, low conversions, and high dependency of reaction yield on the structure of the substrate the Morita–Baylis–Hillman reaction has limited use in complex synthetic transformations. The rate-determining step is typically the bimolecular coupling of the zwitterionic intermediate and the aldehyde [62]. The intramolecular variant of the Morita–Baylis–Hillman reaction was reported first by Frater [63] in 1992 and investigated further by Murphy [64], who described enone cyclization onto an aldehyde to give five- and six-membered rings (Scheme 20). While tributylphosphine proved to be the optimal catalyst for six-membered ring formation, only low yields were obtained for five-membered ring formation.

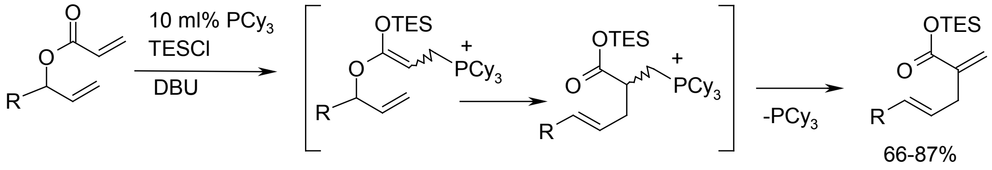
Keck [65] observed slow cyclization of unsaturated esters using trimethylphosphine (Scheme 20), however unsaturated thiol esters cyclized efficiently giving both cyclopentene and cyclohexene derivatives. Enolizable aldehydes were more prone to side reactions, such as bimolecular condensation, and cyclizations were sensitive to even small variations in experimental conditions.

In 1978, Evans and co-workers reported the phosphoniosilylation of α,β-unsaturated carbonyl compounds by treatment with triphenylphosphine in the presence of silylating agents [66]. Based on this precedent, Inanga proposed synthesis of a phosphonium silyl ketene acetal from an allylic acrylates, which could then undergo the Ireland rearrangement after deprotonation by a base (Scheme 21).

The process occurred efficiently and was catalyzed by tricyclohexylphosphine, giving α-methylene-γ,δ-



Scheme 20. Intramolecular Morita-Baylis-Hillman reaction catalyzed by phosphine



Scheme 21. Synthesis of α-methylene-γ,δ-unsaturated carboxylic acids from allylic acrylates

unsaturated carboxylic acids [67]. It was found that silylation of the intermediate phosphonium enolate was necessary.

7.2. Michael addition reactions of activated alkenes and alkynes

The Michael addition of CH-acids to activated alkenes is usually catalyzed by strong bases such as hydroxide or alkoxide ions. The mechanism generally includes deprotonation of the carbon acid by the base, followed by addition of the stabilized carbanion to the activated alkene. In 1973 White and Baizer [68] reported a phosphine-catalyzed Michael addition of 2-nitropropane to ethyl acrylate (Scheme 22).

The weak basicity of the phosphine catalysts, PBu_3, PPh_3, $PPhMe_2$ and PPh_2Me, suggests a mechanism in which the phosphines act as nucleophiles rather than as bases. It is reasonable to infer that the zwitterionic phosphine-alkene adduct (Scheme 22, Eq. **I**) participates in the process as the general base, deprotonating the carbon acid (Scheme 22, Eq. **II**) which then undergoes Michael addition to another molecule of the activated alkene (Scheme 22, Eq. **III**).

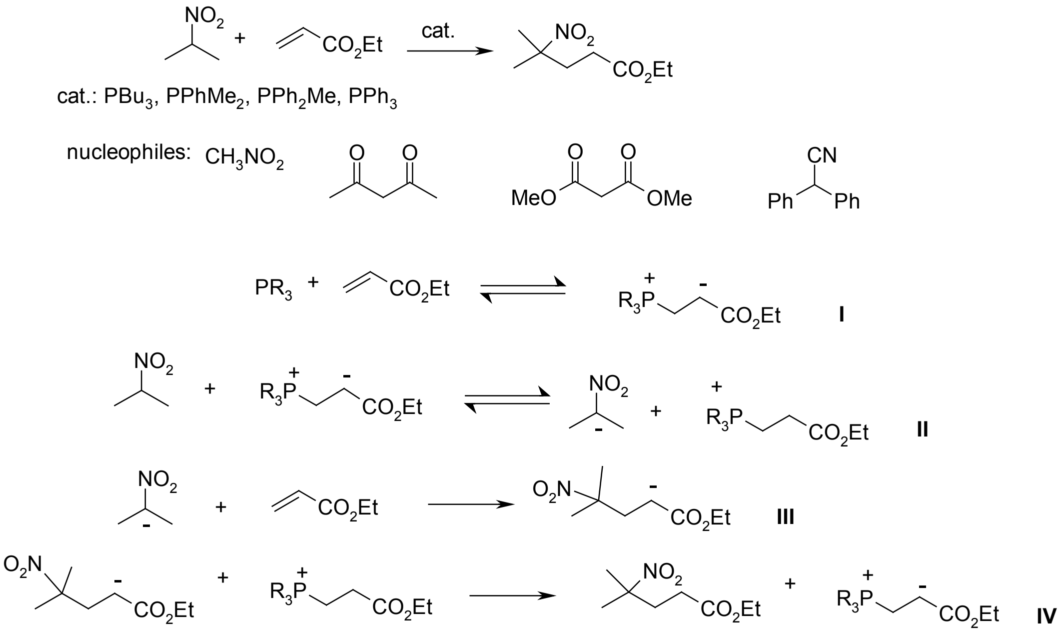
Recently, Toste and Bergman [69] reported a phosphine-catalyzed Michael addition of alcohols and water to activated alkenes (Scheme 23).

The mechanism likely involves again the zwitterionic phosphonium Michael adduct (Scheme 22, Eq. **I**) behaving as a general base to deprotonate the alcohol or water; the alkoxide or hydroxide then undergoes Michael addition to the activated alkene. It is noteworthy that trialkylphosphines catalyze the transformation while tertiary amines, such as DABCO and triethylamine, do not; this is consistent with phosphines behaving as strong nucleophiles, but not as strong bases. Phosphines also catalyze the Michael addition of alcohols to activated alkynes, although through a different mechanism. In 1993 Inanaga and co-workers reported that tributylphosphine catalyzed the addition of primary and secondary alcohols to α,β-unsaturated alkynoates [70] in good to excellent yield (Scheme 24).

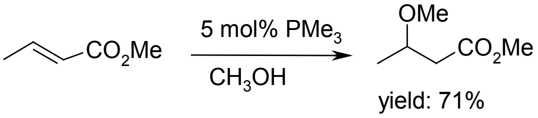
Again the phosphine adds to the alkynoate and the intermediate zwitterion deprotonates the alcohol (Scheme 24, Eq. **I**), however the alkoxide then adds in a Michael fashion into the same phosphonium salt (Scheme 24, Eq. **II**) regenerating the phosphine. Tributylphosphine generally rendered exclusive *(E)*-stereoselectivity, while with triphenylphosphine the *(E)/(Z)*-selectivity was only 5 : 1. This process has become quite valuable in synthetic studies of the polycyclic ether family of natural products [71].

7.3. Isomerization of conjugated alkynes to conjugated dienes

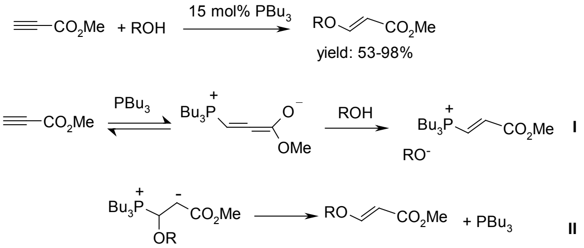
In 1988, Lu, Trost, and Inoue independently reported the isomerization of alkynones to dienones by ruthenium and palladium complexes [72]. Further study showed that the addition of excess of phosphine, used as the



Scheme 22. Phosphine-catalyzed Michael addition



Scheme 23. Phosphine-catalyzed Michael addition of alcohols to activated alkenes



Scheme 24. Conjugate addition of alcohols to methyl propynoate

ligand, improved efficiency of the reaction. In 1992 Trost [73] reported that triphenylphosphine alone could catalyze the transformation at elevated temperature (Scheme 25). In the first step of these reactions a nucleophilic tertiary phosphine adds to the triple bond of an electron-deficient alkyne forming a phosphonium salt, which is later eliminated from the reaction product after a series of transformations. Thus, the tertiary phosphine plays the role of a catalyst. Inactivated alkynes were unreactive and the reaction did not occur under tertiary amine catalysis. The relative rate of the isomerization depends on the structure and electron-deficiency of the alkyne, *i.e.*, acetylenic ketones react faster than esters, which in turn isomerize faster than amides. Acetic acid can be added as a cocatalyst to accelerate slow-reacting substrates. Alternatively, Rychnovsky and co-workers [74] suggested the use of phenol as a cocatalyst for sensitive substrates.

Trost suggests that the internal redox reaction proceeds through a series of prototropic shifts via an allenic intermediate. Attempts to detect the intermediates, shown in Scheme 25, were unsuccessful, however, Trost demonstrated that allenic esters isomerize to the corresponding dienoates much faster than alanyl esters, and therefore are viable reaction intermediates. The general mechanism of the process [75] is shown in Scheme 25. The reaction involves the formation of an allene intermediate which then undergoes nucleophilic addition of triphenylphoshine (Scheme 25, Eq. **II**). Two prototropic shifts (Scheme 25, Eq. **III**), followed by elimination, gave the diene. The high selectivity of this simple procedure makes it a practical approach to the synthesis of conjugated diene systems.

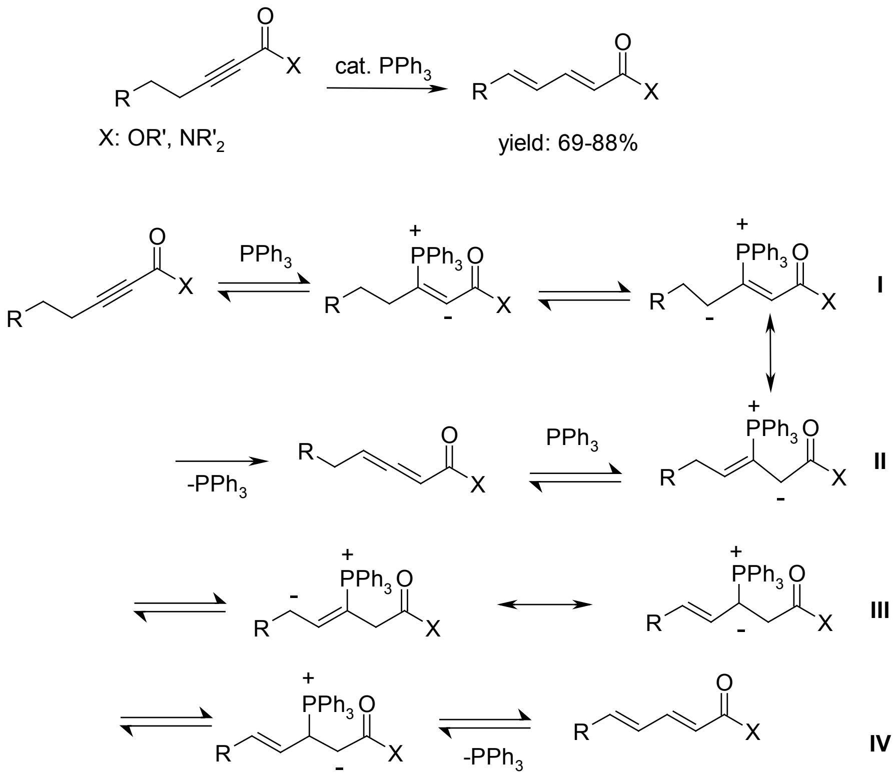
The isomerization of ethyl 4-hydroxyoct-2-ynoate by using Ph_3P as the catalyst surprisingly gave ethyl octa-2,4-dienoate as the major product and ethyl 4-oxo-oct-2-enoate as the minor one (Scheme 26). It was found [76] that the yield of ethyl octa-2,4-dienoate depended on the amount of triphenylphosphine added as "the ligand".

When one equivalent of triphenylphosphine was used, ethyl octa-2,4-dienoate was isolated in 86% yield as the sole product; triphenylphosphine oxide was also isolated in nearly quantitative yield, indicating that triphenylphosphine, initially added as the ligand, participated in the reaction with the alkyne. The proposed reaction mechanism, outlined in Scheme 27, is based on the nucleophilicity and deoxygenation of the phosphine. The IR spectra of the reaction mixture, recorded halfway through the deoxygenation-isomerization reaction of ethyl 4-hydroxyoct-2-ynoate, showed absorption at 1965 cm^{-1}, confirming the existence of an allene intermediate in this reaction.

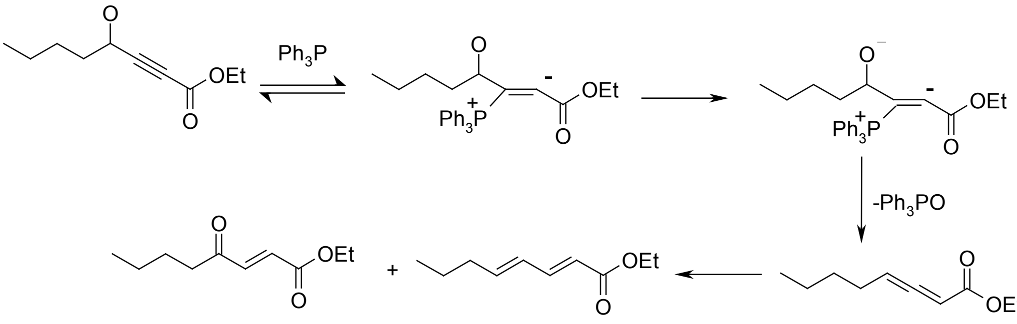
In further experiments, it was shown that the isomerization reaction could also occur smoothly in the presence of only catalytic amounts of triphenylphosphine and an alcohol. Moreover, ynones could also isomerize to dienones in the presence of only a catalytic amount of triphenylphosphine, without the addition of an alcohol [77].

7.4. Umpolung γ- and α-addition of nucleophiles to vinylphosphonium salts

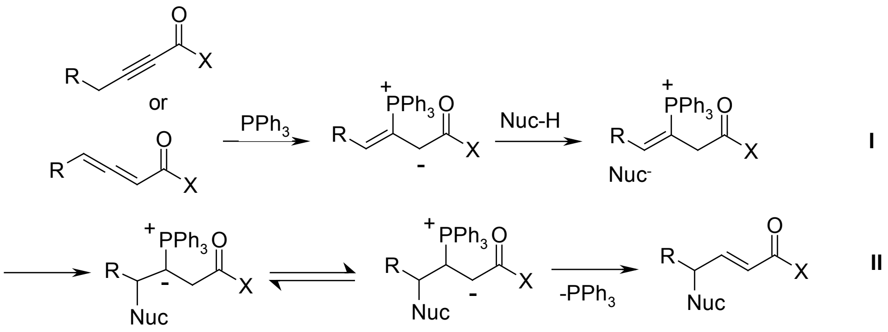
The mechanism proposed for the isomerization of conjugated alkynes to conjugated dienes, outlined in Scheme 22, suggests the potential for the interception of vinylphosphonium intermediates by appropriate nucleophiles. Scheme 27 details a γ-addition sequence, which formally constitutes an umpolung of this process (normally the γ-position of an enone, when deprotonated, reacts with electrophiles). Phosphine addition to an alkynyl or allenyl carbonyl compound generates a vinylphosphonium salt, which may then deprotonate a pronucleophile (Nuc-H) (Scheme 27, Eq. **I**). Subsequent nucleophilic addition of the conjugate base occurs at the



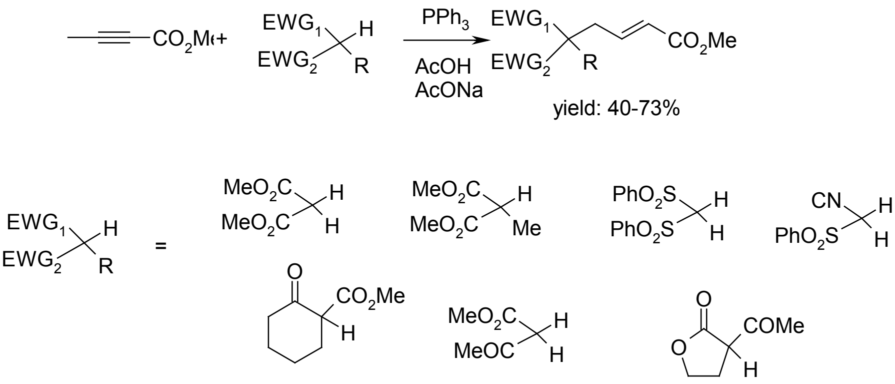
Scheme 25. Isomerization of conjugated alkynes to conjugate dienes



Scheme 26. The isomerization of ethyl 4-hydroxyoct-2-ynoate to ethyl octa-2,4-dienoate (the major product) and ethyl 4-oxo-oct-2-enoate (the minor product)



Scheme 27. The proposed mechanism of γ-addition of a nucleophile to vinylphosphonium salt



Scheme 28. Umpolung γ-addition of pronucleophiles to an ynoate

γ-position to give an ylide. A prototropic shift allows for elimination and recycling of the phosphine (Scheme 27, Eq. **II**).

A variety of carbon acids with pKa <16 were treated with alkynyl esters and amides using triphenylphosphine as the catalyst to give γ-alkylated products (Scheme 28).

An acetic acid and sodium acetate buffer has a double function during the process: it assists with proton shuffling and maintaining a pH range in which carbon acids can behave as nucleophiles.

Oxygen nucleophiles have also been utilized in the γ-addition reaction. Generally, alcohols [78] are much poorer Michael donors than carbon nucleophiles, however in this phosphine-catalyzed isomerization-addition reaction they are in fact superior (Scheme 29, Eq. **I**).

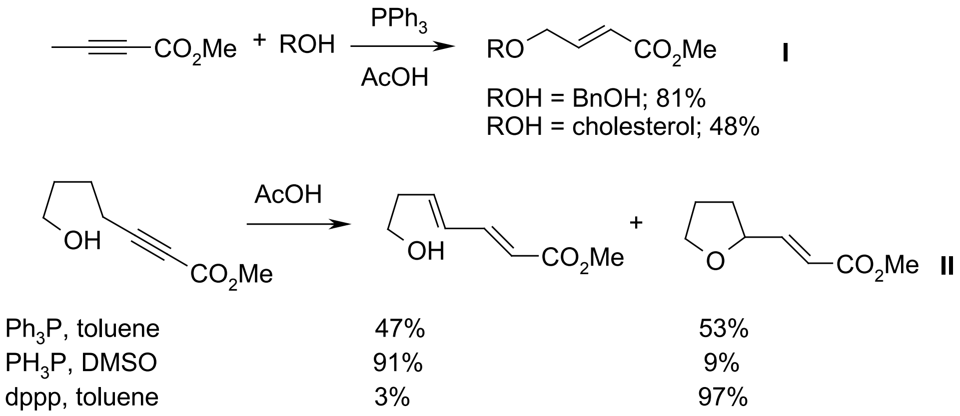
Trost and co-workers established that if an alcohol is tethered to the phosphonium intermediate, derived from the alkynoate, faster than isomerization to the diene occurs, then the intramolecular γ-addition should be the favored reaction (Scheme 29, Eq. **II**). On the other hand, it has been found that the application of the more polar DMSO as a solvent strongly favored diene formation in comparison to experiment using toluene as a solvent, while catalysis with 1,3-bis(diphenylphosphine)propane (dppp) again strongly favored isomerization-addition. It was also found that the use of a polar solvent, like DMSO, favors diene formation to a greater extent than the use of less polar toluene, and that catalysis with 1,3-bis(diphenylphosphine)propane (dppp strongly favored isomerization-addition. The advantage of using bidentate phosphine may be due to the ability of the second phosphine to function as a general base catalyst.

The successful use of oxygen nucleophiles turned scientists' [79] attention to nitrogen nucleophiles. It has been found that acidic nitrogen pronucleophiles, such as *p*-toluenesulfonamide, phthalimide and tetrahydrophthalimide, undergo γ-addition to alkynyl esters in good yield (Scheme 30, Eq. **I**).

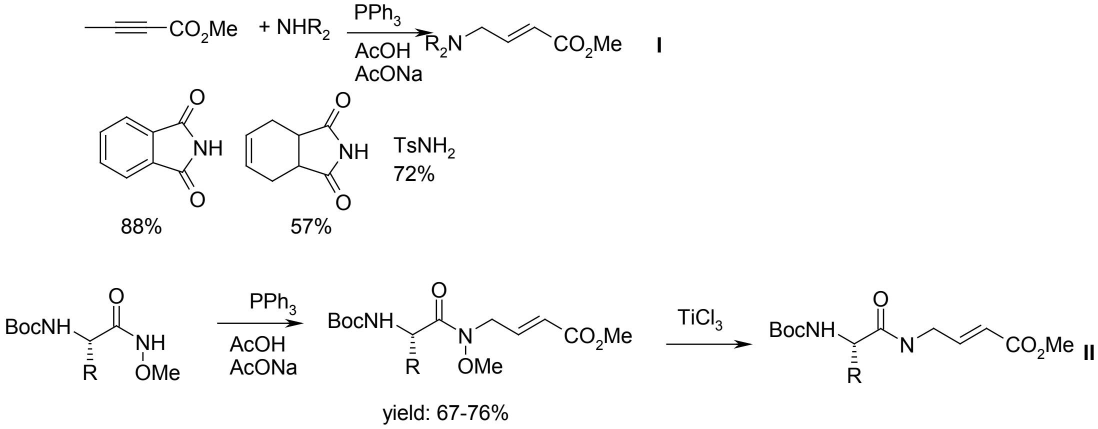
Alanine, valine, and tryptophan-derived hydroxamic acids also underwent smooth reaction with methyl 2-butynoate (Scheme 30, Eq. **II**), and the subsequent cleavage of the N-O bond by $TiCl_3$ provided an entry into vinylogous amino acid derivatives.

Alvarez-Ibarra [80] reported the use of carboxylates as pronucleophiles in a similar phosphine-catalyzed γ-addition to alkynyl esters with both aliphatic and aromatic carboxylic acids (Scheme 31).

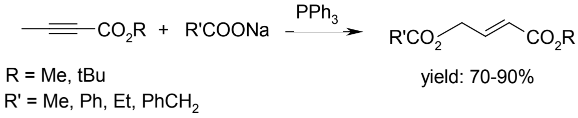
Recently, Zhang and co-workers [81] reported the application of phosphabicyclo[2.2.1]heptane as a chiral catalyst in the γ-addition reaction in asymmetric synthesis (Scheme 32).



Scheme 29. γ-Addition reaction of oxygen nucleophiles



Scheme 30. γ-Addition of nitrogen pronucleophiles to activated alkynes



Scheme 31. γ-Addition of carboxylates as pronucleophiles to activated alkynes

Treatment of ethyl 2,3-butadienoate and a variety of carbon acids with 10 mol% of *P*-chiral phosphine and a sodium acetate-acetic acid buffer gave γ-addition products in 41-75% ee. Although the NaOAc/HOAc buffer slows the reaction rate, it was found that these additives considerably enhance enantioselectivity. Several other examined acetates (*e.g.* Li, K, Cs, NH_4) gave comparable results.

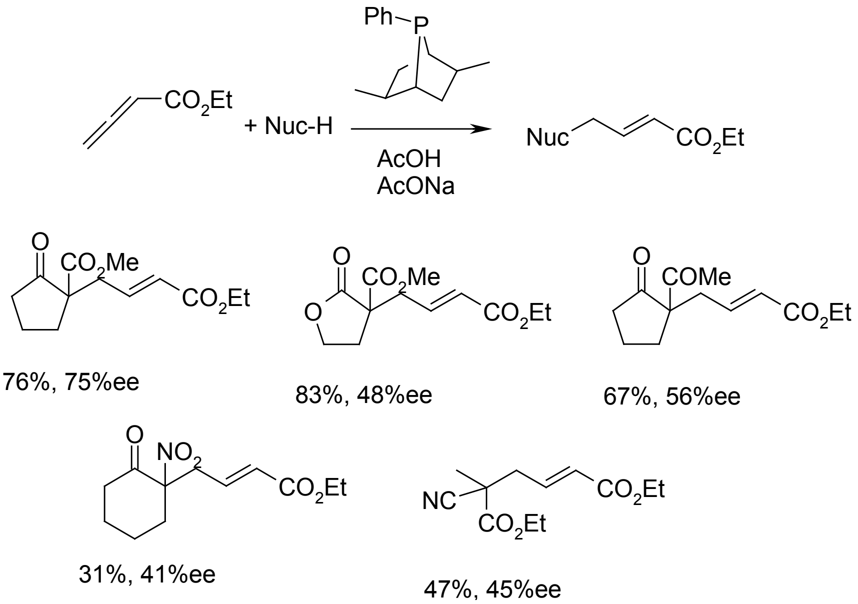
When acidic hydrogen is present at the γ-position of the activated alkyne, treatment with a phosphine at elevated temperatures leads to allene formation (Scheme 25). However, in the absence of methine hydrogen, the intermediate phosphonium ion could be trapped by a nucleophile at the α-position (Scheme 33). The zwitterionic adduct deprotonates a weak acid, and then the conjugate base acts as a nucleophile.

Trost and co-workers discovered that the addition of nitrogen pronucleophiles does indeed occur at the α-position of propynoate esters (Scheme 34).

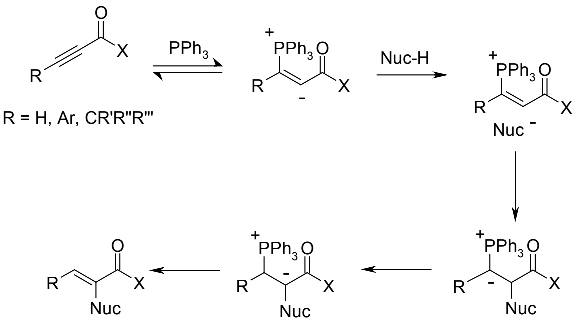
Related experiments with methyl 2-heptynoate gave the expected products of α-addition, γ-addition, and isomerization to the corresponding diene. The ability to redirect the selectivity from classic β-addition to α-addition through the influence of phosphine catalysis is quite remarkable.

It has been found that α-addition of carbon nucleophiles to alkynes activated by phosphines occurred in appropriate conditions [82]. A carbon–carbon coupling reaction allows to link 1,3-diketones, malonates, β-ketoesters, and β-ketophosphonates to unsaturated systems through a PPh_3-catalyzed α-C-addition of these activated methylenes to alkynoates (Scheme 35).

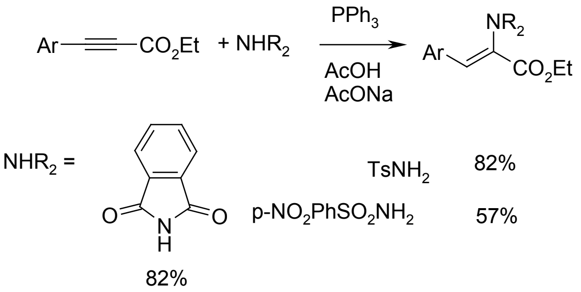
The first step of the process involves a Michael addition of PPh_3 to alkynoate generating an active phosphonium intermediate. This intermediate, after proton exchange with the 1,3-dicarbonyl compound, undergoes nucleophilic α-C-addition of the enolate, followed by a HC-transfer and elimination of PPh_3 giving the final product. No O- adducts or Michael-



Scheme 32. The γ-addition reaction in asymmetric synthesis



Scheme 33. Nucleophilic addition in the α-position of activated alkynes



Scheme 34. Nucleophilic α-addition to propynoates

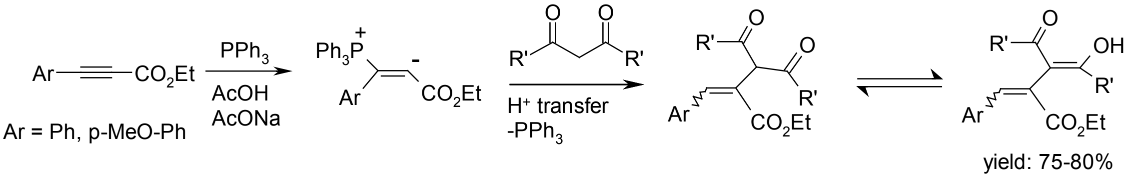
type adducts were observed demonstrating the ability of the phosphine to redirect the regio- and chemo-selectivity from the classic β-addition mode. Since the first step of the mechanism involves a Michael addition of the catalyst to the alkyne, the nucleophilic and steric characteristics of the catalyst are very important to the efficiency of the process. A comparative study was performed of reaction of electron-deficient alkynes with a variety of 1,3-dicarbonyl compounds in the presence of 19 different P, N, and As acting as nucleophiles, and with acetic acid/sodium acetate buffer as a cocatalyst.

The best results were obtained for Ph$_2$PH and Bu$_3$P; the reaction did not take place when amine catalysts, DABCO,–DMAP, PPY, NMI, were used. A bifunctional nucleophile can also be used as a starting material in complex reactions, including γ- or α-addition and intramolecular β-addition First, the γ- or α-addition to an activated alkyne or allene would produce an activated alkene and an intermediate with a nucleophilic center, which would undergo the intramolecular β-addition during the second step (Scheme 36). Lu and Lu [83] demonstrated this tandem reaction to construct various oxygen and nitrogen-containing heterocycles.

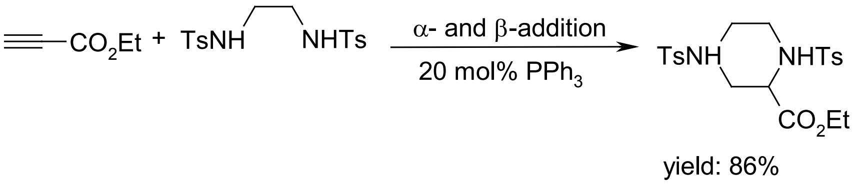
Bis(*N*-tosyl)ethylenediamine provided piperazine derivatives. Available data suggest that the second β-addition is catalyzed by phosphine, since lower catalyst loadings (*e.g.* 5 mol% PPh$_3$) yielded substantial quantities of the intermediate acyclic products of monoaddition.

7.5. Cycloaddition reactions of activated alkynes and allenes

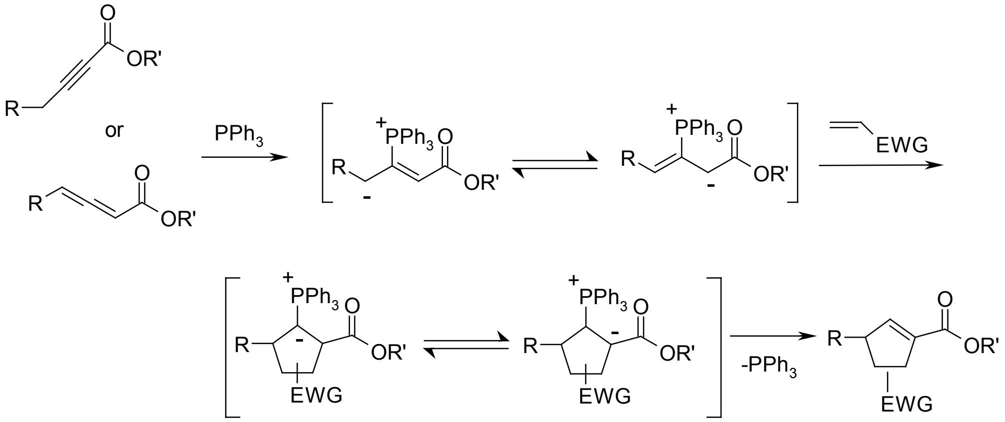
If a proposed four-electron, three-carbon zwitterionic intermediate were formed during the phosphine-catalyzed isomerization of activated alkynes and allenes (Scheme 25) it would be possible to intercept it in a [3+2] cycloaddition reaction (Scheme 37). After formation of a new bond construction a prototropic shift would allow for elimination of the phosphine to give the final cyclic products.



Scheme 35. Addition of 1,3-dicarbonyl pronucleophiles to alkynoates



Scheme 36. Tandem α- and Michael addition



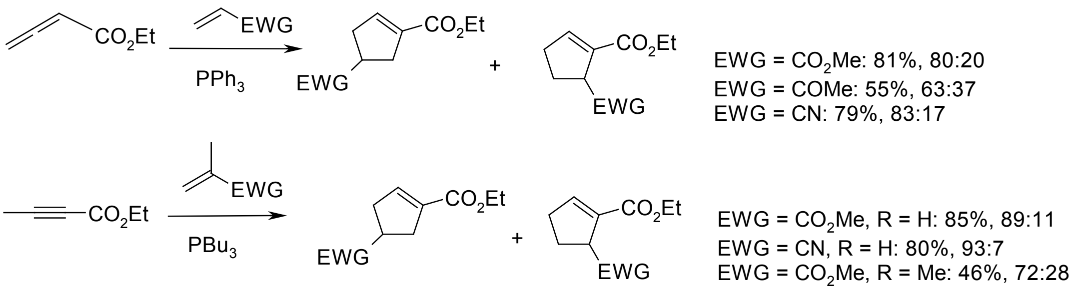
Scheme 37. Mechanism of [3+2] cycloaddition in the presence of phosphine as a catalyst

In 1995 Lu and co-workers [84] reported that these allylic anions could be trapped with ethyl acrylate (Scheme 38). The reaction of allenyl esters with triphenylphosphine or tributylphosphine and an activated alkene gave [3+2] cycloadducts with good regioselectivity (4 : 1). Cycloaddition using less active alkenes, such as methyl (*E* or *Z*)-crotonate or methyl methacrylate, failed due to competing homodimerization of the allenyl ester. Reaction of alkynyl esters used as the precursor failed with triphenylphosphine, but provided good yields of [3+2] adducts when tributylphosphine was used. No reaction of allenyl or alkynyl esters occurred when triethylamine was used instead of a phosphine.

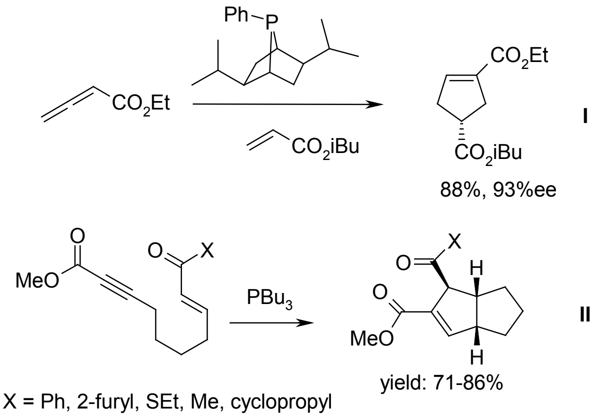
Zhang and co-workers [85] investigated an asymmetric variant of [3 + 2] cycloaddition in presence of chiral mono- and bisphosphines. A screening of chiral phosphines showed that the application of phosphabicyclo[2.2.1]heptane as a catalyst (Scheme 39, Eq. **I**) gave the best enantioselectivity (93% ee) in the [3+2] reaction of ethyl 2,3-butadienoate with isobutyl acrylate, giving a single regioisomer in 88% yield.

Intramolecular cycloadditions enable an expeditious entry into complex polycyclic ring systems from simple acyclic starting materials; they can be more diastereoselective and regioselective than intermolecular cycloadditions. Potential isomerization of 2-alkynoates and alkynones to conjugated dienes is a major concern in the development of an intramolecular variant of the phosphine-catalyzed [3+2] cycloaddition. Recently Krische [86] reported the tributylphosphine-catalyzed cycloisomerization of electron-deficient 1,7-enynes providing access to diquinane structures in >95 : 5 de. Included in the array of examined substrates are cyclopropyl enones, which are generally incompatible with transition metal catalysis, but which react smoothly under nucleophilic organocatalysis. Krische [87] has applied the intramolecular [3+2] cycloaddition to the total synthesis of hirsutene, in which a quaternary center is generated as a single diastereomer. Lu and co-workers [88] also reported a highly regioselective synthesis of spirocycles *via* triphenylphosphine-catalyzed [3+2] cycloaddition of α-methylene cyclic ketones with alkynyl and allenyl esters (Scheme 40).

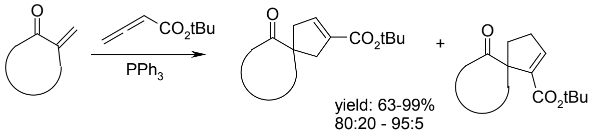
The use of *tert*-butyl 2,3-butadienoate gave significant improvement in regioselectivity over reaction



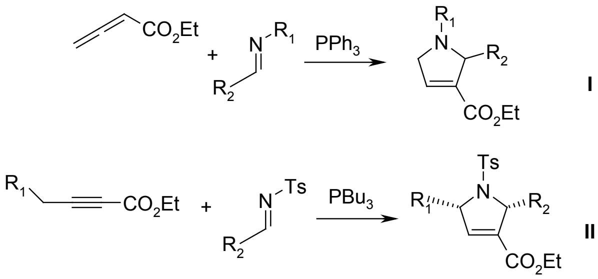
Scheme 38. [3 + 2] Cycloaddition of allenyl and alkynyl esters



Scheme 39. Asymmetric and intramolecular [3 + 2] cycloadditions



Scheme 40. Synthesis of spirocycles *via* triphenylphosphine-catalyzed [3+2] cycloaddition



Scheme 41. [3 + 2] Cycloaddition of activated alkynes and allenes with imines

using smaller esters, supporting a steric argument for the observed regioselectivity. The success of the phosphine-catalyzed [3+2] reaction with activated alkenes led Lu and co-workers to consider other dipolarophiles such as *N*-tosylimines. It has been found [89] that triphenylphosphine catalyzed a highly regioselective cycloaddition of 2,3-butadienoates with a variety of *N*-tosylimines to afford pyrrolines in very good yield (Scheme 41, Eq. **I**). Unfortunately, application of aliphatic imines limited the scope of the reaction. Similarly, DABCO or DMAP failed to catalyze the cycloaddition. The observed regioselectivity indicates that the zwitterionic phosphonium intermediate undergoes electrophilic addition to the imine at the α-position.

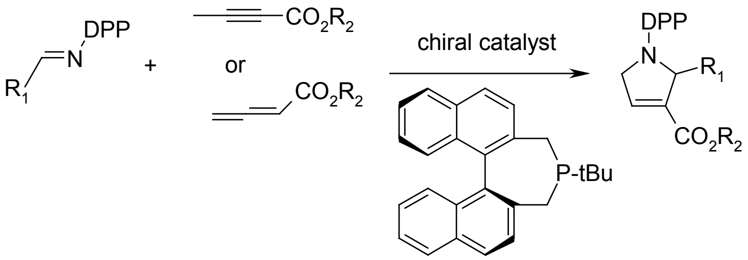
Lu [90] also investigated *N*-(β-trimethylsilylethanesulfonyl)imines to afford products with a β-trimethylsilylethanesulfonyl (SES) protective group, expecting it to be more easily removed after the reaction. Conveniently, ethyl 2-heptynoate and *N*-tosylbenzaldimine combine in the presence of tributylphosphine giving a single *syn*-diastereomeric pyrroline cycloadduct (Scheme 41, Eq. **II**). *N*-Tosylpyrrolines can be oxidized to *N*-tosylpyrroles upon treatment with DDQ and the tosyl group can be subsequently removed under mild sodium methoxide/methanol conditions, whereas SES-group can be converted directly into deprotected pyrroles with TBAF. Recently, the application of binaphthophosphepine as a catalyst for the [3+2] cyclization between allenoates or 2-butynoates and *N*-protected imines was investigated by Marinetti *et al.* [91]. In comparative studies of the effects of the imine protecting group on both the catalytic activity and enantioselectivity, it was found that *N*-diphenylphosphinoyl(DPP)-imines displayed lower reactivity, but afforded the desired pyrrolines in higher enantiomeric excess in comparison to *N*-tosylimines (Scheme 42, Table 3).

He and co-workers [92] described the application of the dipolarophile imines, with an easily removable activating group O,O-diethyl(thio)phosphoryl, as starting materials in the nucleophilic phosphine-catalyzed [3+2] cycloaddition of electron-deficient allenes (Scheme 43).

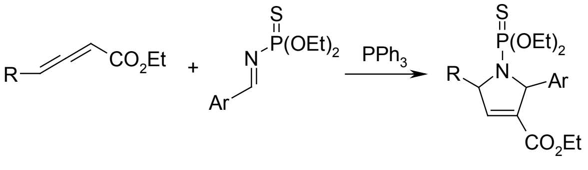
Under the catalysis of a tertiary phosphine, *N*-(thio)phosphorylimines readily undergo [3+2] cycloaddition with ethyl 2,3-butadienoate or ethyl 2,3-pentadienoate, yielding the corresponding *N*-(thio)phosphoryl 3-pyrrolines in moderate to high yields. Removal of the (thio)phosphoryl group from the adducts has been successfully achieved *via* the acidic methanolysis of the P–N bond, giving free amine 3-pyrrolines in fair to good

Table 3. Enantioselective [3+2] cyclizations of N-DPP-imines with 2-butynoates promoted by binaphthophosphepine

	N-DPP-Pyrroline				**N-Ts-Pyrroline**	
R_1	R_2	Solvent	Yield [%]	Ee [%]	Yield [%]	Ee [%]
Ph	Et	toluene	<20	75	-	-
Ph	Et	CH_2Cl_2	50	85	64	71
Ph	C_6H_{11}	CH_2Cl_2	45	88	86	62
1-Naph	Et	CH_2Cl_2	36	84	70	54
1-Naph	C_6H_{11}	CH_2Cl_2	74	85	88	41
o-(CH_2=CH)C_6H_4	Et	CH_2Cl_2	40	77		
p-$NO_2C_6H_4$	Et	CH_2Cl_2	25	73		



Scheme 42. [3 + 2] annulation reaction of N-DPP-imines and allenoates (or 2-butynoates)



yield: 41-76%

Scheme 43. Phosphine-catalyzed [3 + 2] cycloaddition of allenes with N-(thio)phosphoryloimines

yields without aromatization.

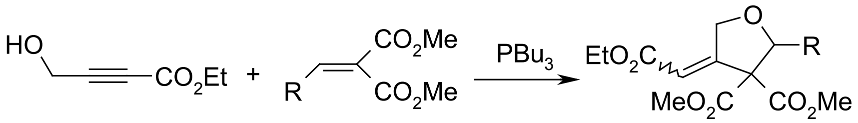
Bifunctional substrates [93] bearing activated alkyne fragments and alcohol groups have been used in organocatalytic processes during which the alcohol function behaves as a pronucleophilic group. Recently, Williamson [94] used this strategy (Scheme 44) in synthesis of methylenetetrahydrofurans. In this case, an alcoholate function is generated by addition of a nucleophilic phosphine to ethyl γ-hydroxy-2-butynoate and subsequent proton exchange reaction. The alcoholate adds then to highly activated electrophilic olefins to afford methylenetetrahydrofurans, *via* formal [3+2] annulations.

The scope of the reaction was explored with a range of alkylidene-, arylidene-, and heteroarylidene malonate/Meldrum's acid based alkene derivatives [95].

In analogous reaction of methyl γ-hydroxy-2-butynoate with *N*-tosylbenzaldimine and PBu_3 as a catalyst 4-methylene-1,3-oxazolidine was obtained [96] as the unique reaction product (Scheme 45).

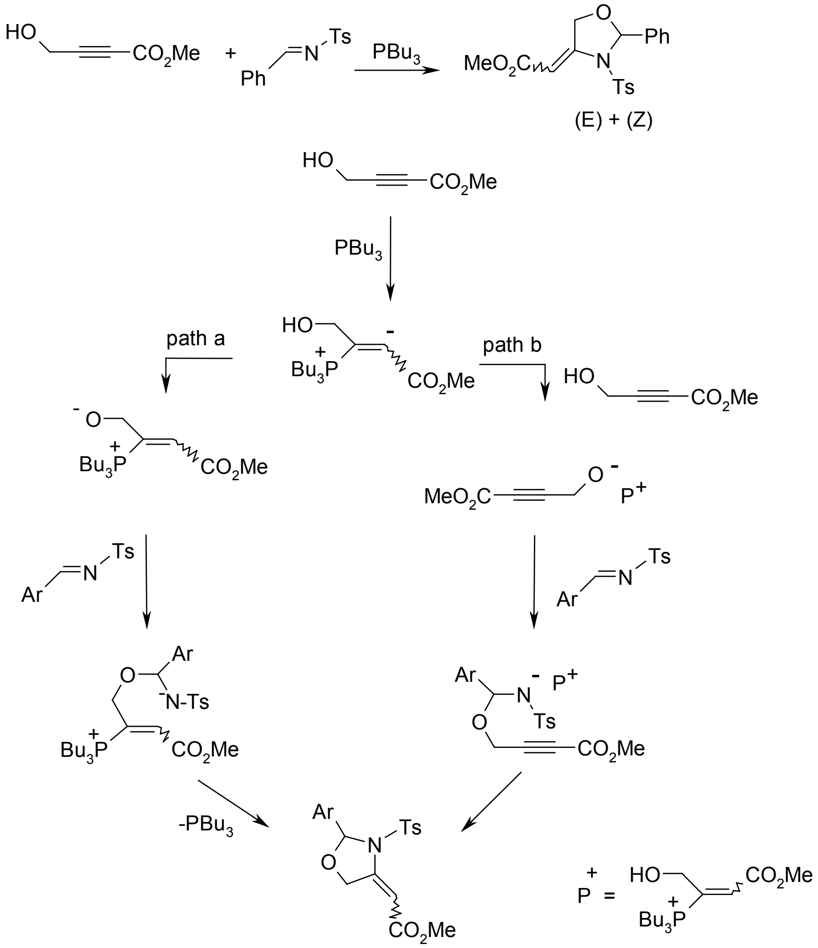
Two possible mechanisms of the cyclization reaction are shown in Scheme 46. As the first step, both pathways involve addition of PBu_3 to γ-hydroxybutanoate to give the vinyloges of *P*-acylphosphonium salt. It is followed by a proton exchange between the carbanionic moiety and a hydroxyl function in either an intramolecular (path a) or an intermolecular process (path b). The alcoholate adds then to the imine and, finally, an intramolecular Michael reaction gives final oxazolidine. Phosphines such as PPh_3 or $P(iBu)_3$ are inactive, which likely relates to their lower nucleophilic character, compared to PBu_3. The [3+2] cycloaddition of imines with 2-allyl substituted 2,3-butadienoates in the presence of a phosphine catalyst [97] is triggered by α-addition of the zwitterionic intermediate to the imine leading to pyrroline formation. Kwon and co-workers [98] envisioned that the substitution of hydrogen at the α-position of the 2,3-butadienoate with an alkyl group might block α-attack of the phosphonium intermediate and lead to a reaction manifold initiated by γ-addition. Remarkably, mixing 2-alkyl-2,3-butadienoate derivatives with imines in the presence of 20 mol% PBu_3 (Scheme 46) resulted in the diastereoselective formation of tetrahydropyridine derivatives instead of pyrrolines.

It seems that 2-alkyl-2,3-butadienoates act as 1,4-dipole synthons, not as 1,3-dipole synthons, giving the products of [4+2] cycloaddition in good to excellent yields with a variety of aromatic imines. It has been found that alkyl and vinyl *N*-tosylimines fail to give the desired cycloadducts. A γ-addition to the imine by the zwitterionic phosphonium adduct, followed by two consecutive proton-transfer steps an *N*-tosyl Michael addition lead to tetrahydropyridine system. Preliminary experiments with a chiral phosphine, (S,S)-DIPAMP, gave an encouraging 34% ee, confirming phosphine involvement in the carbon-carbon bond forming step.



R = Me, nPr, iPr, iBu, nHept, $PhCH_2CH_2$-, p-MeO-C_6H_4-, o,m-$(MeO)_2$-C_6H_3-, m-Br-C_6H_4, tiophen

Scheme 44. Synthesis of methylenetetrahydrofurans catalyzed by PBu_3



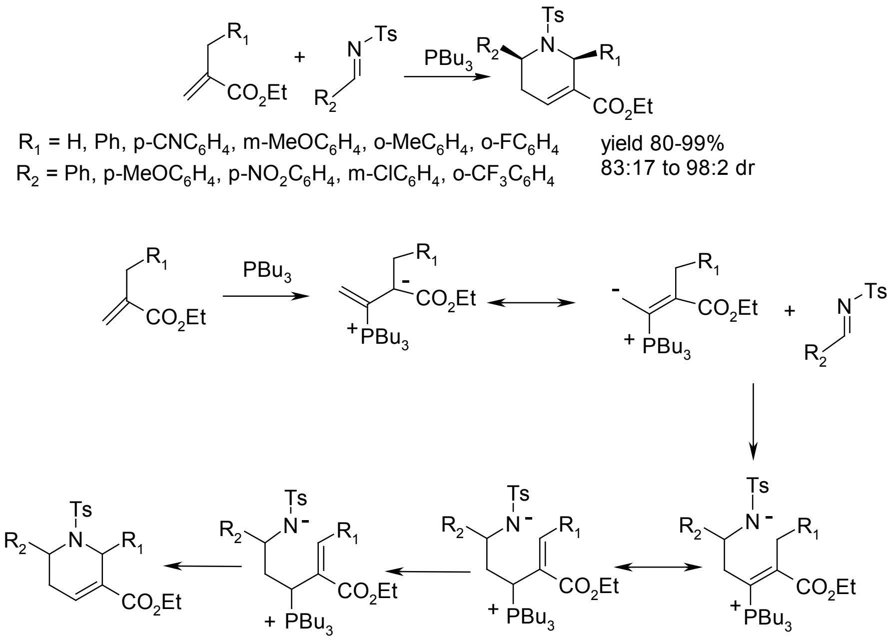
Scheme 45. Phosphine-promoted cyclization between γ-hydroxybutanoate and N-tosylbenzaldimine

7.6. Differences between trialkylamine and trialkylphosphine as a catalyst in addition of alcohols to alkyl propiolates

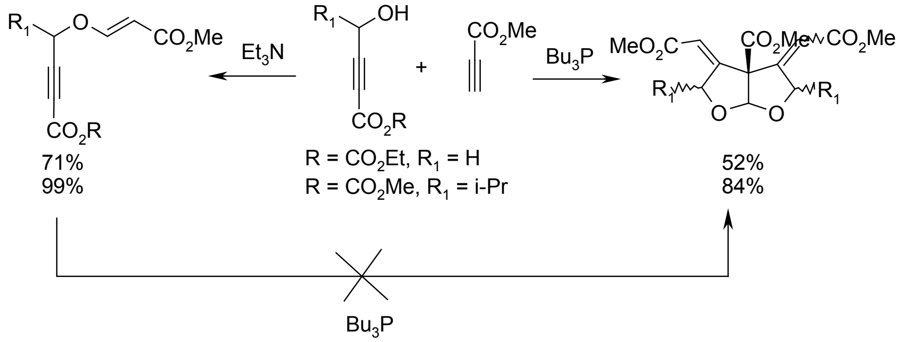
Tejedor and García-Tellado [99] showed that conjugate addition of activated propargylic alcohols to alkyl propynoates is a catalyst-dependent reaction. In the case of reaction catalyzed by trilakylamines 1,4-addition of the alcohol yielded a β-alkoxyacrylate derivative. In a trialkylphosphine-catalyzed reaction densely functionalized bicyclic hexahydrofuro[2,3-*b*]furan derivatives (Scheme 47) were obtained.

In a parallel experiment, it was observed that an enol ether (product of reaction catalyzed by Et_3N) could not be transformed into a bicyclic hexahydrofuro[2,3-*b*]furan derivative. The postulated mechanisms for the addition of alcohols to methyl propiolate depending on the nature of the catalyst are shown in Scheme 48.

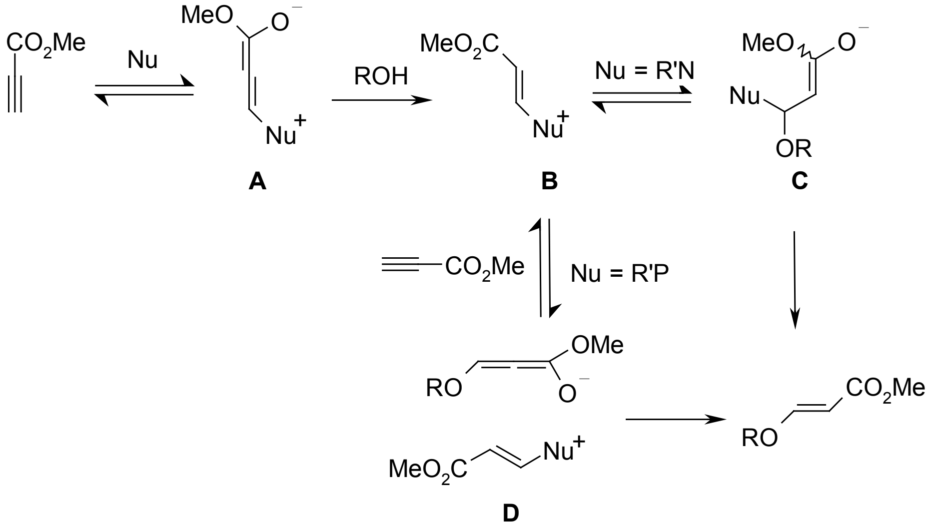
Intermediate **B** is common to both processes, but since *N*-acylvinylammonium and *P*-acylvinylphosphonium salts behave differently when the catalyst is a tertiary phosphine, the alkoxide ion is not capable of reacting with the corresponding vinylphosphonium. Instead, it reacts with another propiolate molecule to form the intermediate **D** which leads to the final enol ether.



Scheme 46. A phosphine catalysed [4 + 2] cycloaddition



Scheme 47. Addition of activated propargylic alcohol catalyzed by Et_3N and Bu_3P



Scheme 48. Postulated addition of alcohols to methyl propiolate depending on the nature of catalyst

8. Conclusions

The rich organic chemistry exhibited by phosphines and discovered over the past decade is remarkable. The unique properties of weakly basic and strongly nucleophilic phosphines paved the way for several synthetic pathways. The well known catalysis of acyl group transfer, from a broad range of acylating species to heteroorganic nucleophiles such as alcohols and amines, was mastered into a highly enantioselective catalytic process. In favorable conditions efficiency was high enough for preparation of enantiomerically pure products from racemic substrates in the process of kinetic resolution proceeding in the presence of chiral phosphines. Expedient results were obtained in the transfer of the acyl group onto hydrogen or carbon nucleophiles affording appropriate aldehydes and ketones, respectively. Moreover, the most thriving seems the reaction involving the interaction of phosphines with vinyl (ethynyl) carbonyl derivatives bearing vinylcarbonyl or ethynylcarbonyl fragments. Appropriate intermediate *P*-acylphosphonium salts showed several unprecedented synthetic transformations. The combination of strong electron withdrawing effects of the carbonyl group and the phosphonium group with ability of phosphine to participate in rearrangement as the leaving group gave a plethora of new valuable preparative transformations. The conjugation of phosphonium and carbonyl group, isomerization of unsaturated fragments of reactive intermediates, and umpolung effects have led to the discovery of several novel reactions of carbonyl activated alkenes and alkynes. The potential of the Rauhut–Currier, Morita–Baylis–Hillman, and cycloaddition reactions is still being systematically developed. Still, the new reactions exploring the synthetic versatility of interactions of the acyl group conjugated to the phosphonium group are introduced into the arsenal of modern chemical transformations. Configurationally stable chiral phosphine with a stereogenic centre at the phosphorus atom suits well the idea of organocatalysis, strongly demanding stereoselective transformations. All of this has made acyl phosphonium salts and their vinyl analogues a “hot spot” in many rapidly expanding areas of modern organic synthesis.

Acknowledgements

This work was supported by MSHE Grant **N N204 228734.**

References

[1] (a) X.-L. Sun, J.-C. Zheng, Y. Tang, Pure App. Chem. 82, 625 (2010); (b) S.P. Marsden, Nature Chem. 1, 685 (2009); (c) F. Palacios, C. Alonso, D. Aparicio, G. Rubiales, J. de los Santos, Tetrahedron 63, 523 (2006); (d) R. Mazurkiewicz, B. Fryczkowska, R. Gabanski, Wiadomosci Chemiczne 59, 249 (2005)

[2] (a) S. Sano, J. Pharm. Soc. Jap. 120, 432 (2000); (b) J. Motoyoshiya, Trends Org. Chem. 7, 63 (1998)

[3] (a) F.P. Cossio, A. Arrieta, M.A. Sierra, Acc. Chem. Res. 41, 925 (2008); (b) M. Koehn, R. Breinbauer, Angew. Chem., Int. Ed. 43, 3106 (2004); (c) R. Hartung, L. Paquette, Chemtracts 17, 72 (2004)

[4] (a) S.K.C. Kumara, K.N.N. Bhuvan, E. Balaraman, K.V.P.P. Kumar, Chem. Rev. 109, 2551 (2009); (b) A.J. Reynolds, M. Kassiou, Curr. Org. Chem. 13, 1610 (2009); (c) N.E. Golantsov, A.V. Karchava, M.A. Yurovskaya, Chem. Heterocyc. Comp. 44, 263 (2008); (d) R. Dembinski, Eur. J. Org. Chem. 13, 2763 (2004)

[5] (a) M. Schuler, D. Duvvuru, P. Retailleau, J.-F. Betzer, A. Marinetti, Org. Lett. 11, 4406, (2009); (b) C.E. Aroyan, A. Dermenci, S.J. Miller, Tetrahedron 65, 4069 (2009); (c) W. Yao, W. Yihua, G. Wang, Y., Zhang, C. Ma, Angew. Chem., Int. Ed. 48, 9713 (2009); (d) Y. Qiao, S. Kumar, W.P. Malachowski, Tetrahedron Lett. 51, 2636 (2010); (e) E. Marques-Lopez, R.P. Herrera, T. Marks, W.C. Jacobs, D. Konning, R.M. de Figueiredo, M. Christmann, Org. Lett. 11, 4116 (2009); (f) F.O. Seidel, J.A. Gladysz, Adv. Synth.Catal. 350, 2443 (2008)

[6] (a) Y. Wei, M. Shi, Acc. Chem. Res. 43, 1005 (2010); (b) V. Carrasco-Sanchez, M.J. Simirgiotis, L.S. Santos, Molecules 14, 3989 (2009); (c) G. Masson, C. Housseman, J. Zhu, Angew. Chem., Int. Ed. 46, 4614 (2007)

[7] Y.-M. Li, F.-Y. Kwong, W.-Y. Yu, A.S.C. Chan, Coord. Chem. Rev. 251, 2119 (2007)

[8] (a) V. Nair, R.S. Menon, A.R. Sreekanth, N. Abhilash, A.T. Biju, Acc. Chem. Res. 39, 520 (2006); (b) J.L. Methot, W.R. Roush, Adv. Synth. Catal. 346, 1035 (2004); for representative and recent examples, see: (c) J.-C. Wang, S.-S. Ng, M.J. Krische, J. Am. Chem. Soc. 125, 3682 (2003); (d) J.-C. Wang, M.J. Krische, Angew. Chem., Int. Ed. 42, 5855 (2003); (e) J.E. Wilson, G.C. Fu, Angew. Chem., Int. Ed. 45, 1426 (2006);

(f) B.J. Cowen, S.J. Miller, J. Am. Chem. Soc. 129, 10988 (2007); (g) D.J. Wallace, R.L. Sidda, R.A. Reamer, J. Org. Chem. 72, 1051 (2007); (h) Y.S. Tran, O. Kwon, J. Am. Chem. Soc. 129, 12632 (2007); (i) Y. Du, J. Feng, X. Lu, Org. Lett. 7, 1987 (2005); (j) J. Feng, X. Lu, A. Kong, X. Han, Tetrahedron 63, 6035 (2007); (k) D. Gonzalez-Cruz, D. Tejedor, P. de Armas, F.Garcia-Tellado, Chem. Eur. J. 13, 4823 (2007); (l) V. Sriramurthy, G.A. Barcan, O. Kwon, J. Am. Chem. Soc. 129, 12928 (2007); (m) C.E. Henry, O.Kwon, Org. Lett. 9, 3069 (2007); (n) L.-W. Ye, X.-L. Sun, Q.-G. Wang, Y. Tang, Angew. Chem., Int. Ed. 46, 5951 (2007); (o) G.S. Creech, O. Kwon, Org. Lett. 10, 429 (2008)

[9] (a) D.W. Stephan, Org. Biomol. Chem. 6, 1535 (2008); (b) D.W. Stephan, Dalton Trans. 3129 (2009); (c) E. Otten, R.C. Neu, D.W. Stephan, J. Am. Chem. Soc. 131, 9918 (2009); (d) T.A. Rokob, A. Hamza, I. Papai, J. Am. Chem. Soc. 131, 10701 (2009); (e) C.M. Mömming, E. Otten, G. Kehr, R. Fröhlich, S. Grimme, D.W. Stephan, G. Erker, Angew. Chem. Int. Ed. 48, 6643 (2009)

[10] S. Burck, K. Götz, M. Kaupp, M. Nieger, J. Weber, J. Schmedt auf der Günne, D. Gudat, J. Am. Chem. Soc. 131, 10763 (2009).

[11] (a) H. Mayr, B. Kempf, A.R. Ofial, Acc. Chem. Res. 36, 66 (2003); (b) F. Brotzel, B. Kempf, T. Singer, H. Zipse, H. Mayr, Chem. Eur. J. 13, 336 (2007); (c) R. Lucius, R. Loos, H. Mayr, Angew. Chem. Int. Ed. 41, 91 (2002); (d) S. Minegishi, H. Mayr, J. Am. Chem. Soc. 125, 286 (2003); (e) T. Bug, H. Mayr, J. Am. Chem. Soc. 125, 12980 (2003); (f) B. Kempf, H. Mayr, Chem. Eur. J. 11, 917 (2005); (g) T.B. Phan, H. Mayr, Can. J. Chem. 83, 1554 (2005); (h) S. Minegishi, S. Kobayashi, H. Mayr, J. Am. Chem. Soc. 126, 5174 (2004)

[12] P. Jaramillo, P. Fuentealba, P. Perez, Chem. Phys. Lett. 427, 421 (2006)

[13] H. Mayr, M. Patz, Angew. Chem. Int. Ed. 33, 938 (1994)

[14] K.A. Jensen, J. Prakt. Chem. 148, 101 (1937)

[15] (a) A.I. Razumov, E.A. Krasilnikova, N.A. Moskva, T.V. Zykova, R.A. Salakhutdinov, J. Gen. Chem. USSR (Engl. Transl.) 41, 1502 (1971); (b) V.V. Yakshin, L.I. Sokalskaya, J. Gen. Chem. USSR (Engl. Transl.) 43, 438 (1973); (c) H. Maeda, T. Maki, H. Ohmori, Tetrahedron Lett. 36, 2247 (1995)

[16] H. Maeda, Y. Huang, N. Hino, Y. Yamauchi, H. Ohmori, Chem. Commun. 23, 2307 (2000)

[17] L. Lemoucheux, J. Rouden, M.-C. Lasne, Tetrahedron Lett. 41, 9997 (2000)

[18] P.H. Lee, K. Lee, J.H. Shim, S.G. Lee, S. Kim, Heterocycles, 67, 777 (2006)

[19] E. Vedejs, S.T. Diver, J. Am. Chem. Soc. 115, 3358 (1993)

[20] H.-J. Cristau, G. Duc, H. Christol, Synthesis 5, 374 (1983)

[21] K.K. Laali, B. Geissler, M. Regitz, J.J. Houser, J. Org. Chem. 60, 47 (1995)

[22] E. Vedejs, N.S. Bennett, L.M. Conn, S.T. Diver, M. Gingras, S. Lin, P.A. Oliver, M.J. Peterson, J. Org. Chem. 58, 7286 (1993)

[23] W. Wiegraebe, H. Bock, Chem. Berich. 101, 1414 (1968)

[24] C.A. Obafemi, Phosph. Sulf. Silic. Relat. Elem. 8, 197 (1980)

[25] H. Maeda, K. Takahashi, H. Ohmori, Tetrahedron 54, 12233 (1998)

[26] H. Maeda, N. Hino, Y. Yamauchi, H. Ohmori, Chem. Pharm. Bull., Japan. 48, 1196 (2000)

[27] E. Erdik, Ö.Ö. Pekel, Tetrahedron Lett. 50, 1501 (2009)

[28] X. Jia, X. Liu, J. Li, P. Zhaoa, Y. Zhang, Tetrahedron Lett. 48, 971 (2007)

[29] H. Maeda, T. Maki, H. Ohmori, Chem. Pharm. Bull. Japan. 42, 1041 (1994)

[30] Y. Tachibana, H. Kawasaki, N. Kihara, T. Takata, J. Org. Chem. 71, 5093 (2006)

[31] P. Kubisa, K. Matyjaszewski, R. Szymanski, K. Brzezinska, W. Chwialkowska, S. Penczek, Polimery 24, 270 (1979)

[32] A. Hofman, R. Szymanski, S. Somkowski, S. Penczek, Makromol. Chem. 185, 655 (2003)

[33] H. Kuroda, I. Tomita, T. Endo, Polymer, 38, 6049 (1997)

[34] (a) J.-P. Genet, Acc. Chem. Res. 36, 908 (2003); (b) H.U. Blaser, E. Schmidt, Asymmetric Catalysis on Industrial Scale (Wiley-VCH, Weinheim, 2004)

[35] (a) K.V.L. Crepy, T. Imamoto, Tetrahedron Lett. 43, 7735 (2002); (b) G. Hoge, H.-P. Wu, W.S. Kissel, D.A. Pflum, D.J. Greene, J. Bao, J. Am. Chem. Soc. 126, 5966 (2004)

[36] M. Clochard, E. Mattmann, F. Mercier, L. Ricard, F.Mathey, Org. Lett. 5, 3093 (2003)

[37] M.T. Reetz, A. Gosberg, R. Goddard, S.-H. Kyung, Chem. Commun. 2077 (1998)

[38] (a) M. Dieguez, A. Ruiz, C. Claver, Dalton Trans. 2957 (2003); (b) Z. Hua, V.C. Vassar, I. Ojima, Org. Lett. 5, 3831 (2003); (c) H. Huang, Z. Zheng, H. Luo, C. Bai, X. Hu, H. Chen, Org. Lett. 5, 4137 (2003); (d) I. Gergely, C. Hegedues, H. Gulyas, A. Szellesy, A. Monsees, T. Riermeier, J. Bakos, Tetrahedron: Asymm. 14, 1087 (2003);

(e) A. Korostylev, A. Monsees, C. Fischer, A. Boerner, Tetrahedron: Asymm. 15, 1001 (2004)
[39] K.M. Pietrusiewicz, M. Zablocka, Chem. Rev. 94, 1375 (1994)
[40] (a) T.P. Clark, Clark R. Landis, Tetrahedron: Asymm. 15, 2123 (2004); (b) A. Marinetti, J.-P. Genêt, (Compte Rendeus) C. R. Chimie 6, 507 (2003)
[41] E. Vedejs, M. Jure, Angew. Chem. Int. Ed. 44, 3974 (2005)
[42] G. Hoge, J. Am. Chem. Soc. 126, 9920 (2004)
[43] E. Vedejs, O. Daugulis, S.T. Diver, J. Org. Chem. 61, 430 (1996)
[44] (a) E. Vedejs, O. Daugulis, J. Am. Chem. Soc. 121, 5813 (1999); (b) E. Vedejs, O. Daugulis, Latv. Kim. Z. 1, 31 (1999); (c) E. Vedejs, O. Daugulis, J.A. MacKay, E. Rozners, Synlett 1499 (2001); (d) E. Vedejs, O. Daugulis, J. Am. Chem. Soc. 125, 4166 (2003); (e) E. Vedejs, O. Daugulis, L.A. Harper, J.A. MacKay, D.R. Powell, J. Org. Chem. 68, 5020 (2003).; (f) J.A. MacKay, E. Vedejs, J. Org. Chem. 69, 6934 (2004)
[45] J.A. MacKay, E. Vedejs, J. Org. Chem. 71, 498 (2006)
[46] E. Vedejs, J.A. MacKayd, Org. Lett. 3, 535 (2001)
[47] E. Vedejs, O. Daugulis, N. Tuttle, J. Org. Chem. 69, 1389 (2004)
[48] S. Shaw, P. Aleman, E. Vedejs, J. Am. Chem. Soc. 125, 13368 (2003)
[49] E. Vedejs, X. Chen, J. Am. Chem. Soc. 119, 2584 (1997)
[50] E. Vedejs, E. Rozners, J. Am. Chem. Soc. 123, 2428 (2001)
[51] R. Weiss, M. Bess, S. M. Huber, F. W. Heinemann, J. Am. Chem. Soc. 130, 4610 (2008)
[52] M.A. Shaw, J.C. Tebby, J. Ronayne, D.H. Williams, J. Chem. Soc. C 10, 944 (1967)
[53] (a) Z. Rappoport, Acc. Chem. Res. 14, 7 (1981); (b) Z. Rappoport, Acc.Chem. Res. 25, 474 (1992)
[54] M. Rauhut, H. Currier, U. S. Patent 3,074,999, (1963); Chem. Abstr. 58, 11224a (1963)
[55] J.D. McClure, U. S. Patent 3,225,083, (1965)
[56] M.M. Baizer, J.D. Anderson, J. Org. Chem. 30, 1357 (1965)
[57] J.D. McClure, J. Org. Chem. 35, 3045 (1970)
[58] (a) L.-C. Wang, A.L. Luis, K. Agapiou, H.-Y. Jang, M.J. Krische, J. Am. Chem. Soc. 124, 2402 (2002); (b) S.A. Frank, D.J. Mergott, W.R. Roush, J. Am. Chem. Soc. 124, 2404 (2002)
[59] (a) J.L. Methot, W.R. Roush, Adv. Synth. Catal. 346, 1035 (2004); (b) L.-W. Ye, J. Zhou, Y. Tang, Chem. Soc. Rev. 37, 1140 (2008)
[60] K. Morita, Z. Suzuki, H. Hirose, Bull. Chem. Soc. Japan 41, 2815 (1968)
[61] A.B. Baylis, M.E.D. Hillman, German Patent 2,155,113 (1972); Chem. Abstr. 77, 34174q (1972)
[62] M.L. Bode, P.T. Kaye, Tetrahedron Lett. 32, 5611 (1991)
[63] F. Roth, P. Gygax, G. Frater, Tetrahedron Lett. 33, 1045 (1992)
[64] (a) F. Dinon, E. Richards, P.J. Murphy, D.E. Hibbs, M.B. Hursthouse, K.M.A. Malik, Tetrahedron Lett. 40, 3279 (1999); (b) E. Richards, P.J. Murphy, F. Dinon, S. Fratucello, P.M. Brown, T. Gelbrich, M. B. Hursthouse, Tetrahedron 57, 7771 (2001); (c) P.M. Brown, N. Kappel, P.J. Murphy, Tetrahedron Lett. 43, 8707 (2002)
[65] G.E. Keck, D.S. Welch, Org. Lett. 4, 3687 (2002)
[66] (a) D.A. Evans, K.M. Hurst, J.M. Takacs, J. Am. Chem. Soc. 100, 3467 (1978); (b) A.P. Kozilowski, S.H. Jung, J.Org. Chem. 51, 3400 (1986)
[67] T. Hanamoto, Y. Baba, J. Inanaga, J. Org. Chem. 58, 299 (1993)
[68] D.A. White, M.M. Baizer, Tetrahedron Lett. 14, 3597 (1973)
[69] I.C. Stewart, R.G. Bergman, F.D. Toste, J. Am. Chem.Soc. 125, 8696 (2003)
[70] J. Inanaga, Y. Baba, T. Hanamoto, Chemistry Lett. 241 (1993)
[71] L.-W. Ye, S.-B. Wang, Q.-G. Wang, X.-L. Sun, Y. Tang, Y.-G. Zhou, Chem. Commun. 3092 (2009)
[72] (a) D. Ma, Y. Lin, X. Lu, Y. Yu, Tetraderon Lett. 29, 1045 (1988); (b) B.M. Trost, T.A. Schmidt, J. Am. Chem. Soc. 110, 2301 (1988); (c) Y. Inoue, S. Imaizumi, J. Mol. Catal. 49, L19 (1988); (d) X. Lu, C. Zhang, Z. Xu, Acc. Chem. Res. 34, 535 (2001)
[73] (a) B.M. Trost, U. Kazmaier, J. Am. Chem. Soc. 114, 7933 (1992); (b) C. Guo, X. Lu, Chem. Commun. 394 (1993); (c) C. Guo, X. Lu, Perkin Trans. 1 1921 (1993)
[74] S.D. Rychnovsky, J. Kim, J. Org. Chem. 59, 2659 (1994)
[75] X. Lu, C. Zhang, Z. Xu, Acc. Chem. Res. 34, 535 (2001)
[76] C. Guo, X.A Lu, J. Chem.Soc., Chem. Commun. 394 (1993)
[77] C. Guo, X. Lu, J. Chem. Soc., Perkin Trans. 1 1921 (1993)
[78] B.M. Trost, C.-J. Li, J. Am. Chem. Soc. 116, 10819 (1994)
[79] B.M. Trost, G.R. Drake, J. Am. Chem. Soc. 119, 5670 (1997)

[80] C. Alvarez-Ibarra, A.G. Csaky, C. Gomez de la Oliva, Tetrahedron Lett. 40, 8465 (1999)
[81] Z. Chen, G. Zhu, Q. Jiang, D. Xiao, P. Cao, X. Zhang, J. Org. Chem. 63, 5631 (1998)
[82] M. Hanédanian, O. Loreau, F. Taran, C. Mioskowski, Tetrahedron Lett. 45, 7035 (2004)
[83] C. Lu, X. Lu, Org. Lett. 4, 4677 (2002)
[84] C. Zhang, X. Lu, J. Org. Chem. 60, 2906 (1995)
[85] G. Zhu, Z. Chen, Q. Jiang, D. Xiao, P. Cao, X. Zhang, J. Am. Chem. Soc. 119, 3836 (1997)
[86] J.-C. Wang, S.-S. Ng, M. J. Krische, J. Am. Chem. Soc. 125, 3682 (2003)
[87] J.-C. Wang, M. J. Krische, Angew. Chem. Int. Ed. 42, 5855 (2003)
[88] Y. Du, X. Lu, Y. Yu, J. Org. Chem. 67, 8901 (2002)
[89] (a) Z. Xu, X. Lu, Tetrahedron Lett. 38, 3461 (1997); (b) Z. Xu, X. Lu, J. Org. Chem. 62, 5031 (1997)
[90] Z. Xu, X. Lu, Tetrahedron Lett. 40, 549 (1999)
[91] N. Pinto, N. Fleury-Brégeot, A. Marinetti, Eur. J. Org. Chem. 146 (2009)
[92] B. Zhang, Z. He, S. Xu, G. Wu, Z. He, Tetrahedron 64, 9471 (2008)
[93] (a) B.M. Trost, C.-J. Li, J. Am. Chem. Soc. 116, 10819 (1994); (b) H. Kuroda, I. Tomita, T. Endo, Org. Lett. 5, 129 (2003); (c) F. Silva, M. Sawicki, V. Gouverneur, Org. Lett. 8, 5417 (2006); (d) Y.K. Chung, G.C. Fu, Angew. Chem., Int. Ed. 48, 2225 (2009)
[94] Y. Pedduri, J.S. Williamson, Tetrahedron Lett. 49, 6009 (2008)
[95] (a) H. Guo, Q. Xu, O. Kwon, J. Am. Chem. Soc. 131, 6318 (2009); (b) D. Tejedor, D. González-Cruz, A. Santos-Expósito, J.J. Marrero-Tellado, P. de Armas, F. García-Tellado, Chem. Eur. J. 11, 3502 (2005); (c) R.K. Thalji, W.R. Roush, J. Am. Chem. Soc. 127, 16778 (2005)
[96] N. Fleury-Brégeot, A. Voituriez, P. Retailleau, A. Marinetti,Tetrahedron Lett. 50, 4700 (2009)
[97] Z. Xu, X. Lu, J. Org. Chem. 63, 5031 (1998)
[98] X.-F. Zhu, J. Lan, O. Kwon, J. Am. Chem. Soc. 125, 4716 (2003)
[99] D. Tejador, A. Santos-Expósito, G. Méndez-Abt, C. Ruiz-Pérez, F. García-Tellado, Synlett, 8, 1223 (2009)