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# Notes

## Intermolecular Metallo-ene Reaction Catalyzed by Palladium

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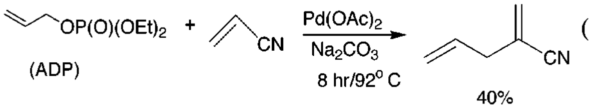
The metallo-ene reaction is a known chemical process, whereby two double bonds interact to form a new C−C bond. The resulting product is a 1,4-diene as per general Scheme 1. Mechanistically, in the presence of Pd(0), it is most probably an insertion reaction of the terminal double bond into a Pd-$\pi$-allyl system that has originated from the allyl acetate (Scheme 1) and a Pd(0) species; it is followed by a $\beta$-elimination reaction. Several such reactions are known[1,2,3] but they are of an *intramolecular* nature, as shown in general Scheme 1. To the best of our knowledge, no *intermolecular* metallo-ene type reaction, except with norbornene,[4] has been previously recorded. A related Pd catalyzed reaction was developed by Stille,[5] whereby allyl halides were coupled with vinyl tin compounds to give 1,4-dienes. Of course, an intermolecular metallo-ene reaction between two isolated olefins is of significance, since it gives rise to the formation of a C−C bond generating an acyclic 1,4- diene system.

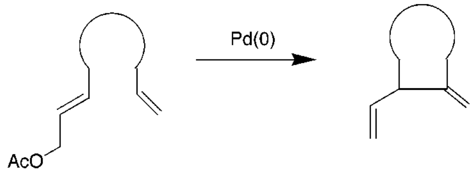
We have examined the above idea by reacting allyl acetate with 1-octene, as well as with acrylonitrile, in the presence of $Pd(OAc)_2$ (with and without added $PPh_3$), and $K_2CO_3$. In all cases the reaction failed. Our recent positive experience with the reactivity of allyl diethyl phosphate (ADP) in a new selective Pd catalyzed dehydrogenation reaction of carbonyl compounds,[6] as well as in the oxidation of alcohols,[7] prompted us to examine the reactivity of ADP as the allyl component in a possible intermolecular metallo-ene reaction (eq 1).



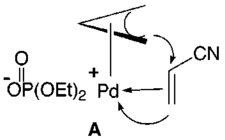
(1)

Indeed, an intermolecular insertion product, 2-methylene-4-pentenenitrile, was isolated in 40% yield (eq 1). The reaction was carried out in excess acrylonitrile as solvent, (stabilized with hydroquinone). $Pd_2dba_3{\cdot}CHCl_3$ was found to be as reactive as $Pd(OAc)_2$, indicating that Pd(0) is a reactive catalytic species. The reaction was unaffected by the presence of $PPh_3$, and gave the same results with $NaHCO_3$ or $K_2CO_3$. The product was purified by low-pressure distillation and characterized by MS, IR, $^1H$ NMR, $^{13}C$ NMR, and DEPT NMR. The $^1H$ NMR spectral results were in agreement with those reported in the lit.[8] for 2-methylene-4-pentenenitrile. Although the yield was moderate (40% after distillation), it is a *one* step coupling reaction from readily available and simple starting materials and therefore is useful from the synthetic point of view.

**Scheme 1**



The new C−C bond formation was selective toward the $\alpha$ position of the acrylonitrile, implying addition of the Pd atom to the $\beta$ position of the acrylonitrile, a fact that may justify the following reaction intermediate (**A**):



**A**

The favorable reactivity of allyl diethyl phosphate in the above reaction, in variance with that of allyl acetate (vide supra), may be due to a more favorable equilibrium, leading to the above Pd-$\pi$-allyl diethyl phosphate intermediate (**A**). Being a weaker base (nucleophile) than an acetate anion, the diethyl phosphate anion may account for such an equilibrium shift toward the Pd-$\pi$-allyl intermediate. A small quantity of methanol was added to the reaction mixture to promote reduction of the precatalyst to Pd(0), the metal precursor for the above Pd-$\pi$-allyl intermediate. No reaction took place when ADP was replaced with allyl methyl carbonate.

The reaction is general with respect to the allyl phosphate component, as the following reactions (eqs 2 and 3) could be readily carried out. In both reactions the selectivity toward the $\alpha$ position of the acrylonitrile has been maintained. The opposite regioselectivity would have generated isomeric linear products, lacking the $sp^2$-$CH_2$ group, which was verified by DEPT NMR.

The allyl systems, resulting from the allyl phosphates depicted in eqs 2 and 3 reacted at the least substituted end of the double bond. This was also verified by DEPT NMR measurement of the products.

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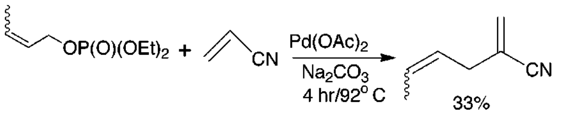
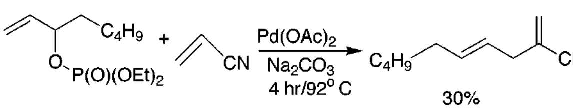
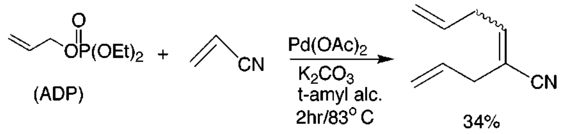


(2)



(3)

Surprisingly, when the reaction described in eq 1 was carried out in the presence of *tert*-amyl alcohol as solvent and $K_2CO_3$ as base, a triene product of double allylation (verified by MS and $^{13}$C NMR) was obtained (eq 4).



(4)

DEPT NMR indicated the presence of two sp$^2$ and two sp$^3$ $CH_2$ groups as well as three sp$^2$-CH groups, in accordance with the above structure of 2-(2-propenyl)-2,5-hexadienenitrile. Significantly, the regiochemistry of the two allylation steps (eq 4) are different, i.e., both the $\alpha$ and $\beta$ positions of the acrylonitrile reacted. The sequence of the two-allylation reactions is not known. Furthermore, the reason for the above reaction in response to the added *tert*-amyl alcohol is presently not clear. The products from eqs 2−4 were not previously reported; they were characterized by spectral methods (see Experimental Section). Presently it was not possible to identify the stereochemistry around the conjugated double bond.

Unfortunately, under our present experimental conditions, the reaction is not general with respect to the alkene component. Thus, when the acrylonitrile in eq 1 was replaced with 1-octene or methyl acrylate, no allylation products with ADP could be observed. Thus, at the present stage, the intermolecular metallo-ene reaction described herein is known to proceed only with acrylonitrile, perhaps due to its known better ligating power. Nevertheless, our present finding has demonstrated the feasibility of an intermolecular metallo-ene reaction that may also be useful in synthetic organic chemistry. This reaction certainly deserves a further study.

## Experimental Section

All NMR spectra were measured in $CDCl_3$.

**2-Methylene-4-pentenenitrile (General Procedure).** A mixture of allyl diethyl phosphate[9] (0.97 g; 5 mmol), Pd(OAc)$_2$ (0.045 g; 0.2 mmol) sodium carbonate (0.64 g; 6 mmol), acrylonitrile (4 mL), 2 drops of methanol, and 10 mg of hydroquinone were heated in an oil bath (92 °C) with magnetic stirring under Argon for 8 h. After cooling to room temp, methylene chloride (20 mL) was added. The mixture was washed with water (2 × 20 mL) and dried over $MgSO_4$, then evaporated under vacuum. The residue was distilled, bp 27°/0.9 mm, to give a clear liquid (0.19 g; 40%) of 2-methylene-4-pentenenitrile.[8] MS: $m/z$ M$^+$ (93). IR $\nu(CH_2Cl_2)$: 2226 cm$^{-1}$. $^1$H NMR ($\delta$): 5.91(s, 1H); 5.8(m, 1H); 5.71(s, 1H), 5.20(d, $J = 17$ Hz, 1H), 5.23 (d, $J = 10$ Hz, 1H); 3.00(d, $J = 6.6$ Hz, 2H). $^{13}$C NMR ($\delta$): 131.9, 130.8, 121.2, 118.9, 118.3, 38.3. DEPT NMR: 3CH$_2$ (130.8, 118.9, 38.3) CH (131.9).

**2-Methylene-4-hexenenitrile.** A mixture of 2-butenyl diethyl phosphate[10] (1.04 g; 5 mmol), $Na_2CO_3$ (0.64 g; 6 mmol), acrylonitrile (4 mL), Pd(OAc)$_2$ (0.045 g; 0.2 mmol), 2 drops of methanol and 10 mg of hydroquinone was heated under Argon for 4 h at 92 °C (oil bath temp). After workup (described above), a liquid, 2-methylene-4-hexenenitrile, bp 30°/0.9 mm, 0.18 g (33%) was obtained. MS: $m/z$ M$^+$ (107). IR $\nu(CCl_4)$ 2225 cm$^{-1}$. $^1$H NMR ($\delta$): 5.86(s, 1H); 5.73(s, 1H); 5.45−5.62(m, 2H); 2.92(d, $J = 8$ Hz, 2H); 1.72 (dd, $J = 6.2$, 1.2 Hz, 3H). $^{13}$C NMR ($\delta$): 130.3, 130.1, 124.6, 122.4, 118.7, 37.5, 17.9. DEPT NMR: CH$_3$ (17.9), 2CH$_2$ (130.1, 37.5), 2CH (130.3, 124.6).

**2-Methylene-4-decenenitrile.** A mixture of 1-vinyl hexyl diethyl phosphate[11] (1.32 g; 5 mmol), $Na_2CO_3$ (0.64 g; 6 mmol), acrylonitrile (4 mL), Pd(OAc)$_2$ (0.045 g; 0.2 mmol), 2 drops of methanol and 10 mg of hydroquinone, was heated under Argon for 4 h at 92 °C (oil bath temp). After workup (described above), the crude product was purified by column chromatography (silica) with methylene chloride. A liquid, 2-methylene-4-decenenitrile, 0.24 g (30%) was obtained. MS: $m/z$ M$^+$ (163). IR $\nu(CCl_4)$: 2226 cm$^{-1}$. $^1$H NMR ($\delta$): 5.87(s, 1H); 5.73(s, 1H); 5.65−5.54(m, 1H); 5.45−5.10(m, 1H); 2.93(d, $J = 6$ Hz, 2H); 2.04(m, 2H); 1.36(m, 6H); 0.89(t, $J = 6.7$ Hz, 3H). $^{13}$C NMR ($\delta$): 135.4, 129.9, 123.0, 120.2, 118.5, 37.2, 32.2, 31.0, 28.6, 22.2, 13.7. DEPT NMR: CH$_3$ (13.7), 6CH$_2$ (129.9, 37.2, 32.2, 31.0, 28.6, 22.2), 2CH (135.4, 123.0).

**2-(2-Propenyl)-2,5-hexadienenitrile.** A mixture of ADP (0.97 g; 5 mmol), Pd(OAc)$_2$ (0.045 g; 0.2 mmol), potassium carbonate (0.83 g; 6 mmol), acrylonitrile (2 mL), *tert*-amyl alcohol (4 mL), 2 drops of methanol, and 10 mg of hydroquinone was heated under Argon in an oil bath (83° C) for 2 h. The crude product after workup (see general procedure) was purified by column chromatography (silica). A liquid, 2-(2-propenyl)-2,5-hexadienenitrile, emerged with methylene chloride−pet. ether 30:70, 0.111 g (34%). MS: $m/z$ M$^+$ (133). Anal. Calc. for $C_9H_{11}N$: C, 81.20; H, 8.27; N, 10.52. Found: C, 81.01; H, 8.35; N, 10.76. IR $\nu(CCl_4)$: 2214 cm$^{-1}$. $^1$H NMR ($\delta$): 6.57−6.85(m, 2H, C=CH); 5.8(m, 1H, NCC=CH); 5.50(dd, $J = 10$, 15 Hz, 2H, C=CH2); 5.07(dd, $J = 10$, 18 Hz, 2H, C=CH2); 2.28−2.40(br, 4H). $^{13}$C NMR ($\delta$): 144.5, 135.9, 132.8, 124.1, 117.2, 116.3, 113.7, 33.4, 31.9. DEPT NMR: 4CH$_2$ (124.1, 116.3, 33.4, 31.9), 3CH (144.5, 135.9, 132.8).

**Supporting Information Available:** Four $^1$H NMR spectra (numbered S1−4) of all the products obtained in this study are presented to support characterization and purity of the products. This material is available free of charge via the Internet at http://pubs.acs.org.

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