Heteroatom Chemistry
Volume 7, Number 2, 1996

The Atherton-Todd Reaction of Hydridophosphoranes

Lunzu Liu,* Gouwei Li, Xingzhong Zeng, Lanbing Fu, and Ruzhen Cao

Institute of Elemento-Organic Chemistry, Nankai University, Tianjin 300071, People's Republic of China

Received 27 April 1995; Revised 24 October 1995.

ABSTRACT

Reaction of hydridophosphorane **1** *with nucleophilic reagents* **2** *and tetrachloromethane in the presence of triethylamine, according to the Atherton-Todd reaction methodology, leads ultimately to the formation of phosphoranes* **3** *in good yields. A probable mechanism has been suggested in terms of experimental observations.* © *1996 John Wiley & Sons, Inc.*

INTRODUCTION

The Atherton-Todd reaction is a synthetically valuable method for the preparation of tetracoordinated phosphorus compounds [1]. The versatility of the reaction results from the fact that the initial products in the reaction are the highly reactive dialkyl chlorophosphates, which, in the presence of amines or alcohols, are converted *in situ* into the corresponding dialkyl phosphoramides or trialkyl phosphates, respectively [2] (Equation 1).

$$(RO)_2P(O)H + CCl_4 \xrightarrow{B} (RO)_2P(O)Cl + CHCl_3$$

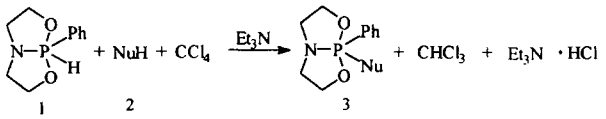
$$(RO)_2P(O)Cl + NuH \xrightarrow{B} (RO)_2P(O)Nu + B\cdot HCl \quad (1)$$

The reaction has recently been extended to some hydridophosphoranes by Houalla and co-workers [3]. Despite all this, there remain many interesting questions concerning the application of the Atherton-Todd reaction for hydridophosphoranes. One general question is whether or not the reaction is suitable for a variety of hydridophosphoranes. Another question is, what is the mechanism of the reaction for hydridophosphoranes?

It was the purpose of this work to provide some information or answers to the questions posed.

RESULTS AND DISCUSSION

Reaction of hydridophosphorane **1** with nucleophilic reagents **2** and tetrachloromethane in the presence of triethylamine, according to the Atherton-Todd reaction methodology, leads ultimately to the formation of phosphoranes **3** in good yields (Equation 2).



1 2 3 (2)

a: Nu = CH_3O; b: Nu = C_2H_5O; C: Nu = C_6H_5S;
d: Nu = n-C_3H_7S; e: Nu = $(CH_3)_2N$; f: Nu = $(C_2H_5)_2N$;
g: Nu = n-C_3H_7NH; h: Nu = i-C_3H_7NH; i: Nu = n-C_4H_9NH;
j: Nu = s-C_4H_9NH; k: Nu = i-C_4H_9NH; l: Nu = t-C_4H_9NH;
m: Nu = $C_5H_{10}N$(piperidyl); n: Nu = $C_6H_{11}NH$(cyclohexylamino)

The reaction was carried out under mild conditions in polar solvents, e.g., acetonitrile or dichloromethane. The yields of **3** were monitored quantitatively by ^{31}P NMR spectroscopy, with trimethyl

*To whom correspondence should be addressed.

CCC 1042-7163/96/020131-05

TABLE 1 ^{1}H and ^{31}P NMR Data of Compounds **3d–n**[a]

Compd.	^{1}H Chemical Shifts[b] Nu	Cyclic-NCH_2	Cyclic-OCH_2	C_6H_5P	^{31}P
	0.96 (t, S CH_2 CH_2 $\underline{CH_3}$)				
	1.36–1.88 (m, S CH_2 $\underline{CH_2}$ CH_3)				
3d	2.48–2.88 (dt, S $\underline{CH_2}$ CH_2 CH_3)	3.00–3.44	3.72–4.10	7.24–8.12	−27.73
3e	2.78 (d, $^{3}J_{HP}$ 9Hz, N $(\underline{CH_3})_2$	2.92–3.12	3.52–4.00	7.00–7.60	−43.07
	1.08 (t, N $(CH_2$ $\underline{CH_3})_2$)				
3f	2.84–3.40 (m, N $(\underline{CH_2}$ $CH_3)_2$)	2.84–3.40	3.60–3.92	7.12–7.60	−41.46
	0.92 (t, NH CH_2 CH_2 $\underline{CH_3}$)				
	1.24–1.76 (m, NH CH_2 $\underline{CH_2}$ CH_3)				
	2.66 (d, $^{2}J_{HP}$ 9.67 Hz, NH)				
3g	2.84–3.44 (m, NH $\underline{CH_2}$ CH_2 CH_3)	2.84–3.44	3.56–4.08	7.24–7.80	−46.71
	1.08 (dd, NH CH $(\underline{CH_3})_2$)				
	2.58 (d, $^{2}J_{HP}$ 9.72 Hz, NH)				
3h	3.36–4.00 (m, NH $\underline{CH}$ $(CH_3)_2$)	2.92–3.36	3.36–4.00	7.12–7.80	−47.25
	0.96 (t, NH CH_2 $(CH_2)_2$ $\underline{CH_3}$)				
	1.12–1.68 (m, NH CH_2 $(\underline{CH_2})_2$ CH_3)				
	2.68 (d, $^{2}J_{HP}$ 10.11Hz, NH)				
3i	2.84–3.50 (m, NH $\underline{CH_2}$ $(CH)_2)_2$ CH_3)	2.84–3.50	3.50–4.08	7.20–7.76	−46.30
	0.84 (t, NH CH (CH_3) CH_2 $\underline{CH_3}$)				
	1.04 (dd, NH CH $(\underline{CH_3})$ CH_2 CH_3)				
	1.16–1.56 (m, NH $CH(CH_3)$ $\underline{CH_2}$ CH_3)				
	2.56 (d, $^{2}J_{HP}$ 10.11Hz, NH)				
3j	2.90–3.40 (m, NH $\underline{CH}$ (CH_3) CH_2 CH_3)	2.90–3.40	3.40–4.00	7.12–7.76	−47.25
	1.06 (d, NH CH_2 CH $(\underline{CH_3})_2$)				
	1.48–2.08 (m, NH CH_2 $\underline{CH}$ $(CH_3)_2$)				
	2.78 (d, $^{2}J_{HP}$ 10.11Hz, NH)				
3k	2.88–3.12 (dd, NH $\underline{CH_2}$ CH $(CH_3)_2$)	3.12–3.60	3.60–4.20	7.20–7.92	−46.44
	1.20 (d, NH C $(\underline{CH_3})_3$)				
3l	2.60 (d, $^{2}J_{HP}$ 9.67Hz, NH)	2.84–3.10	3.44–4.04	7.16–7.80	−43.88
	1.52 (m, N CH_2 $(CH_2)_3$ CH_2)				
3m	2.72–3.44 (m, N $\underline{CH_2}$ $(CH_2)_3$ $\underline{CH_2}$)	2.72–3.44	3.44–3.92	7.08–7.60	−42.94
	0.80–2.16 (m, NH $\underline{CH}$ $(\underline{CH_2})_4$ $\underline{CH_2}$)				
	2.60 (d, $^{2}J_{HP}$ 10.11Hz, NH)				
3n	2.92–3.36 (m, NH $\underline{CH}$ $(CH_2)_4$ CH_2)	2.92–3.36	3.44–4.00	7.00–7.68	−47.25

[a]Solvent is $CDCl_3$.
[b]Unresolved multiplets.

phosphate added as an external standard (Table 4). Products 3 were easily isolable in pure form by distillation, and their structures were confirmed by spectroscopic criteria (Tables 1 through 3) and quantitative elemental analyses (Table 4).

We have reported previously that phosphoranes 3a and 3b are obtained in high yields from the reaction of 1 with alkyl benzenesulfinates [4]. Bentrude et al. have reported that the reaction of 1 with alkyl disulfides affords phosphoranes 3c [5]. However, no convenient synthetic routes to phosphoranes 3e–n have emerged. Hence, it appears that the reaction indicated in Equation 2 might be the most satisfactory method for the preparation of phosphoranes containing alkyl or dialkylamino groups.

The commonly accepted mechanism for the Atherton-Todd reaction is based on the investigation by Engel [6]. The initial step of this mechanism involves deprotonation of the dialkyl phosphonate by a base to give the dialkyl phosphite anion. The anion then

TABLE 2 ^{13}C NMR Data of Compounds **3d–n**[a,b]

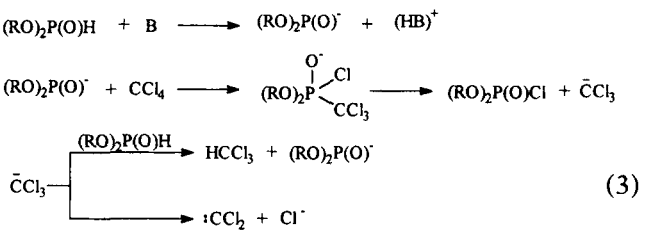
Compd.	*Cyclic-NCH_2*	*Cyclic-OCH_2*	*Nu*		*C_6H_5P*	
			S CH_2 CH_2 $\underline{CH_3}$	13.54	142.26(195.31)	ipso
			S CH_2 $\underline{CH_2}$ CH_3	24.21(7.32)	127.68(17.08)	o
3d	43.39(17.08)	59.26	S $\underline{CH_2}$ CH_2 CH_3	34.18(7.32)	128.93	p
					129.80(9.76)	m
			N $(\underline{CH_3})_2$	40.30(4.88)	143.23(224.60)	ipso
					127.14(12.20)	m
3e	43.39(17.08)	57.53			127.25(17.08)	o
					127.52(4.88)	p
			N $(CH_2$ $\underline{CH_3})_2$	15.49	143.67(224.23)	ipso
			N $(\underline{CH_2}$ $CH_3)_2$	43.55(4.8)	127.47(17.08)	o
3f	43.82(17.08)	58.07			127.68(9.76)	m
					128.01(7.32)	p
			NH CH_2 CH_2 $\underline{CH_3}$	11.37	142.63(217.28)	ipso
			NH CH_2 $\underline{CH_2}$ CH_3	25.51(7.32)	127.36(17.08)	o
3g	43.71(17.08)	57.96	NH $\underline{CH_2}$ CH_2 CH_3	44.85	127.74	p
					127.79(12.20)	m
			NH CH $(\underline{CH_3})_2$	26.27(7.32)	143.18(217.28)	ipso
			NH $\underline{CH}$ $(CH_3)_2$	43.55	127.57(17.08)	o
3h	44.26(7.32)	58.18			127.74	p
					128.01(12.21)	m
			NH CH_2 CH_2 CH_2 $\underline{CH_3}$	13.76	142.74(217.28)	ipso
			NH CH_2 CH_2 $\underline{CH_2}$ CH_3	20.04	127.47(17.08)	o
3i	43.06(17.08)	58.07	NH CH_2 $\underline{CH_2}$ CH_2 CH_3	34.61(7.32)	127.84	p
			NH $\underline{CH_2}$ CH_2 CH_2 CH_3	44.20	127.85(9.76)	m
			NH CH (CH_3) CH_2 $\underline{CH_3}$	10.61	143.18(222.16)	ipso
			NH CH $(\underline{CH_3})$ CH_2 CH_3	23.62(4.88)	127.22(17.08)	o
3j	43.85(17.08)	57.96	NH CH (CH_3) $\underline{CH_2}$ CH_3	32.34(7.32)	127.63	p
			NH $\underline{CH}$ (CH_3) CH_2 CH_3	49.29	127.90(12.20)	m
			NH CH_2 CH $(\underline{CH_3})_2$	20.15	142.80(219.72)	ipso
			NH CH_2 $\underline{CH}$ $(CH_3)_2$	30.28(7.32)	127.36(14.64)	o
3k	43.71(17.08)	57.96	NH $\underline{CH_2}$ CH $(CH_3)_2$	50.70	127.74	p
					127.90(9.77)	m
			NH C $(\underline{CH_3})_3$	32.39(4.88)	143.70(217.28)	ipso
			NH $\underline{C}$ $(CH_3)_3$	50.38	127.36(17.08)	o
3l	43.82(17.08)	57.96			127.90(7.33)	p
					128.28(9.76)	m
			N CH_2 CH_2 $\underline{CH_2}$ CH_2 CH_2	25.56	143.18(227.05)	ipso
3m	43.61(17.08)	57.64	N CH_2 $\underline{CH_2}$ CH_2 $\underline{CH_2}$ CH_2	27.52	127.14(17.08)	o
			N $\underline{CH_2}$ CH_2 CH_2 CH_2 $\underline{CH_2}$	48.53	127.36(7.32)	p
					127.96(9.77)	m
			NH CH CH_2 CH_2 $\underline{CH_2}$ CH_2 CH_2	25.56	143.23(219.72)	ipso
3n	43.93(17.08)	58.18	NH CH CH_2 $\underline{CH_2}$ CH_2 $\underline{CH_2}$ CH_2	25.78	127.47(17.08)	o
			NH CH $\underline{CH_2}$ CH_2 CH_2 CH_2 $\underline{CH_2}$	36.94(4.88)	127.74(4.88)	p
			NH $\underline{CH_2}$ CH_2 CH_2 CH_2 CH_2 CH_2	51.24	127.85(9.76)	m

[a]Solvent is $CDCl_3$.
[b]^{13}C–^{31}P coupling constants (Hz) in parenthesis.

TABLE 3 Mass Spectral Data of Compounds **3d–n**

Compd.	*m/e (rel intensity)*
3d	285(0.42, M^+), 284(1.23, M-1), 242(2.60, M-Pr), 210(1000, M-SP^r_n)
3e	254(50.27, M^+), 253(194.96, M-1), 210(10000, M-NMe_2)
3f	282(1.92, M^+), 281(3.37, M-1), 254(4.36, M-C_2H_4), 210(1000, M-NEt_2)
3g	268(24.59, M^+), 240(16.97, M-C_2H_4), 210(1000, M-NHP^r_n)
3h	268(17.55, M^+), 240(13.64, M-C_2H_4), 210(1000, M-NHP^r_i)
3i	282(1.40, M^+), 254(1.19, M-C_2H_4), 210(100, M-NHB^u_n)
3j	282(2.10, M^+), 254(1.12, M-C_2H_4), 239(2.11, M-C_3H_7), 210(100, M-NHB^u_s)
3k	282(1.62, M^+), 254(1.14, M-C_2H_4), 239(1.38, M-C_3H_7), 210(100, M-NHB^u_i)
3l	282(0.74, M^+), 267(0.72, M-CH_3), 252(1.29, M-$2CH_3$), 210(100, M-NHB^u_t)
3m	294(34.23, M^+), 266(25.80, M-C_2H_4), 240(21.18, M-C_4H_6), 210(10000, M-$C_5H_{10}N$)
3n	308(2.41, M^+), 278(1.02, M-C_2H_6), 240(0.96, M-C_5H_8), 210(100, M-$C_6H_{11}NH$)

reacts as a nucleophile toward tetrachloromethane, resulting in the sequence of reactions shown in Equation 3.



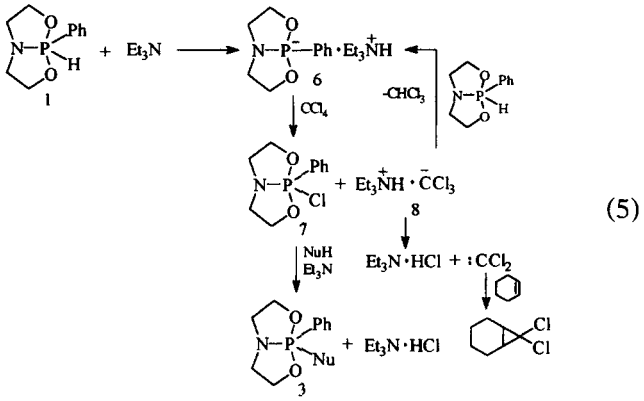
(3)

The validity of the first step for the case of the base being an amine is, however, questionable, since it has been established that amines are alkylated and not protonated at the nitrogen by dialkyl phosphonates [7] (Equation 4).

$$(RO)_2P(O)H + NR'_3 \rightarrow [(RO)P(O)HO]^- [RNR'_3]^+ \quad (4)$$

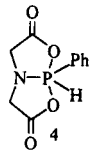
In the case of the reaction of the hydridophosphoranes with amines, the formation of the phosphoranide anion **6** has been reported [8], and we also similarly observed this result. Thus, for hydridophosphorane **1**, the initial step under the Atherton-Todd conditions involves a deprotonation of triethylamine instead of an alkylation. Otherwise, we have found that there are some valuable lines of evidence to support the reaction pathway proposed by us (Equation 5):

1. The formation of triethylamine hydrochloride and trichloromethane has been confirmed by NMR spectra, and the amount of these by-products is consistent with the stoichiometric calculation in Equation 5.
2. Dichlorocarbene that would result by decomposition of the trichloromethanide anion **8** has been trapped in the presence of cyclohexene to form 7,7-dichloronorcarane.
3. The active intermediate **7** was characterized by ^{31}P and ^{13}C NMR spectra.

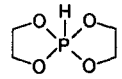


(5)

To further explore the scope of the reaction, we examined the Atherton-Todd reaction of hydridophosphoranes **4,5**. These compounds are similarly suitable for the reaction. These results will be reported in forthcoming publications.



4



5

EXPERIMENTAL SECTION

^1H, ^{31}P, and ^{13}C NMR spectra were taken on a JEOL FX-90Q spectrometer. ^1H and ^{13}C chemical shifts are reported in parts per million relative to internal tetramethylsilane. ^{31}P chemical shifts are reported in parts per million relative to 85% phosphoric acid (external). In all cases, the nuclei that are deshielded relative to their respective standards are assigned a positive chemical shift. ^{13}C and ^{31}P NMR spectra were obtained by using full proton decoupling. ^{31}P NMR spectra were acquired by using a 90° tip angle and a 2- to 4-second repetition rate with no pulse delay. Quantitative elemental analyses were run on

TABLE 4 Quantitative Elemental Analyses Data of Compounds **3a–n**

Compd.	Yield[a] (%)	Yield[b] (%)	B.P. (°C/mmHg)	Elemental Analyses (%) Calcd C	Calcd H	Calcd N	Found C	Found H	Found N
3a	99	54.2	114–114.5/0.025[c]	—	—	—	—	—	—
3b	89	47.0	119–121/0.025[d]	—	—	—	—	—	—
3c	67	32.1	thick liquid[e]	—	—	—	—	—	—
3d	65	31.6	113–114/0.003	54.72	7.06	4.91	54.22	7.00	4.67
3e	95	82.7	91–92/0.0045	56.68	7.53	11.02	56.17	7.74	11.17
3f	90	74.5	84–85/0.004	59.56	8.21	9.92	59.71	8.37	9.76
3g	92	55.1	117–118/0.0045	58.20	7.89	10.44	58.13	7.38	10.30
3h	93	71.3	109/0.0075[f]	58.20	7.89	10.44	58.05	7.85	10.51
3i	85	48.2	86–88/0.004	59.56	8.21	9.92	59.25	8.19	9.94
3j	96	85.7	104/0.006	59.56	8.21	9.92	59.57	8.32	10.07
3k	90	66.1	103/0.0045	59.56	8.21	9.92	59.48	7.94	10.02
3l	96	74.0	86–88/0.03[g]	59.56	8.21	9.92	59.57	8.45	9.80
3m	95	76.5	138–139/0.003	61.21	7.88	9.52	61.22	7.64	9.53
3n	100	64.9	132/0.0075	62.32	8.17	9.08	62.36	8.16	8.97

[a]Determined by ^{31}P NMR spectroscopy.
[b]Determined by isolation.
[c]$\delta^{31}P(CDCl_3)$: −37.02 (Ref. [4]: $\delta^{31}P$ ($CDCl_3$) −37.42, bp 116–117°C/0.05 mmHg).
[d]$\delta^{31}P(CDCl_3)$: −38.23 (Ref. [4]: $\delta^{31}P$ ($CDCl_3$) −38.23, bp 123.8–124°C/0.05 mmHg).
[e]$\delta^{31}P(CDCl_3)$: −29.21 (Ref. [5]: $\delta^{31}P$ ($CDCl_3$) −30.39).
[f]Mp 41–42.5°C.
[g]Mp 57–59°C.

a Yana MT-3 instrument. Mass spectra were recorded on a Hewlett-Packard 5988 instrument. All manipulations were carried out in a nitrogen atmosphere. All reagents and solvents were scrupulously dried and freshly distilled.

General Procedure for Preparation of Phosphoranes 3a-n

To a stirred solution of hydridophosphorane **1** [9] (20 mmol) in 10 mL acetonitrile or dichloromethane were added tetrachloromethane (40 mmol), triethylamine (60 mmol), and the selected nucleophilic reagent (40 mmol) (dimethylamine was passed in as a gas) at room temperature. The reaction mixture was stirred at ambient temperature for several hours until the ^{31}P NMR signal of hydridophosphorane **1** disappeared; then the mixture was filtered, and the filter cake was washed with ethyl ether. The filtrate was concentrated in vacuum at about 60°C by use of a rotary evaporator. The residue was mixed with 40 mL of ethyl ether and filtered, this being immediately followed by further concentration of the filtrate, which was then distilled under reduced pressure to give the desired compounds **3**.

Trapping of Dichlorocarbene

To a stirred solution of hydridophosphorane **1** (20 mmol) in dichloromethane (10 mL) were added tetrachloromethane (40 mmol), triethylamine (60 mmol), ethanol (40 mmol), and cyclohexene (10 mL) at room temperature. The reaction mixture was stirred at ambient temperature until the ^{31}P NMR signal of hydridophosphorane **1** disappeared, and the mixture was then filtered. The filtrate was immediately analyzed by GLC by using 7,7-dichloronorcarane as a standard. The result shows that both retention times were identical. The GLC analysis was carried out with a 25-m methyl silicone column.

Preparation and Characterization of Intermediate 7

To a stirred solution of hydridophosphorane **1** (20 mmol) in acetonitrile (10 mL) were added tetrachloromethane (40 mmol) and triethylamine (60 mmol) at room temperature. The reaction mixture was stirred at ambient temperature until the ^{31}P NMR signal of hydridophosphorane **1** disappeared; then the mixture was filtered, and the filtrate was concentrated in vacuum. The residue was dissolved in C_6D_6 for ^{31}P and ^{13}C NMR determinations. ^{31}P NMR (C_6D_6): −40.11; ^{13}C NMR(C_6D_6): 46.37(NCH_2), 58.50(OCH_2), 129.37 (d, ^2Jcp 17.08, ortho-C_6H_5P), 129.90(para-C_6H_5P), 130.78 (d, ^3Jcp 9.76, meta-C_6H_5P), 140.09 (d, ^1Jcp 229.49, ipso-C_6H_5P).

ACKNOWLEDGMENTS

This research has been supported by the National Natural Science Foundation of China and the National Laboratory of Elemento-Organic Chemistry.

REFERENCES

[1] F. R. Atherton, H. T. Openshaw, A. R. Todd, *J. Chem. Soc.*, 1945, **660**.
[2] F. R. Atherton, A. R. Todd, *J. Chem. Soc.*, 1947, 674.
[3] D. Houalla, Z. Bounja, S. Skouta, L. Riesel, D. Lindemann, *Tetrahedron Lett., 33(20),* 1992, 2817.
[4] L. Z. Liu, G. W. Li, Z. B. Zhang, R. Z. Cao, S. K. Zhang, *Phosphorus, Sulfur and Silicon, 84,* 1993, 1.
[5] W. G. Bentrude, T. Kawashima, B. A. Keys, M. Garroussian, W. Heide, D. A. Wedegaertner, *J. Am. Chem. Soc., 109,* 1987, 1227.
[6] A. Kong, R. Engel, *Bull. Chem. Soc. Jpn., 58,* 1985, 3671.
[7] K. Troev, E. M. G. Kirilov, D. M. Roundhill, *Bull. Chem. Soc. Jpn., 63,* 1990, 1284.
[8] B. Garrigues, D. Boyer, A. Munoz, *Can. J. Chem., 62,* 1984, 2170.
[9] D. Houalla, T. Mouheich, M. Sanchez, R. Wolf, *Phosphorus, 5,* 1975, 229.