Water-Soluble Organometallic Compounds. 9.[1] Catalytic Hydrogenation and Selective Isomerization of Olefins by Water-Soluble Analogues of Vaska's Complex

József Kovács,[†] Tara Decuir Todd,[‡,§] Joseph H. Reibenspies,[‡] Ferenc Joó,*[,†] and Donald J. Darensbourg*[,‡]

Research Group on Homogeneous Catalysis of the Hungarian Academy of Sciences at the Institute of Physical Chemistry, University of Debrecen, Debrecen, Hungary, and Department of Chemistry, Texas A&M University, P.O. Box 30012, College Station, Texas 77842-3012

Received May 4, 2000

Water-soluble analogues of Vaska's complex, *trans*-[IrCl(CO)(PPh_3)$_2$], have been prepared using the water-soluble phosphine ligands TPPMS and (1,3,5-triaza-7-phosphaadamantane) PTA. The structural parameters in *trans*-[IrCl(CO)(TPPMS)], where the sodium cations are encapsulated with kryptofix-221, closely resemble those found in the parent complex, as revealed by X-ray crystallography. ^{13}C and ^{31}P NMR of the PTA derivative demonstrate the *trans* arrangement for phosphine ligands in this derivative as well. The oxygen adduct [(O_2)-IrCl(CO)(TPPMS)$_2$] has been isolated and identified by infrared spectroscopy (ν_{CO} = 2012 cm^{-1} and ν_{O2} = 854 cm^{-1}) and ^{31}P NMR (δ 12.8 ppm). The solution behavior of *trans*-[IrCl-(CO)(TPPMS)$_2$] (**1**) in water is markedly different from that of Vaska's complex in organic solvent; that is, reactions with O_2 and H_2 are irreversible due to formation of the strongly hydrated proton and chloride ions produced during these processes. Importantly, complex **1** has been shown to be an active catalyst for the hydrogenation of olefinic double bonds in short-chain unsaturated acids in aqueous solution. Included in these studies were crotonic, maleic, fumaric, and α-acetamidocinnamic acids. The turnover frequency for the hydrogenation of maleic acid in water was significantly greater employing **1** as a catalyst than the comparable process involving Vaska's complex in dimethylacetamide at a much higher temperature. In addition complex **1** was demonstrated to be an effective catalyst for both hydrogenation and isomerization of unsaturated fatty acids in soybean lecithin. More significantly was the observation that *cis*−*trans* isomerization was selective over hydrogenation in these liposomes; for example, oleic acid was isomerized to elaidic acid with little hydrogenation.

Introduction

The discovery of Vaska's complex has elicited a great deal of research activity.[2−5] A particularly interesting observation was that in benzene solutions *trans*-[IrCl-(CO)(PPh_3)$_2$] formed [(O_2)IrCl(CO)(PPh_3)$_2$] reversibly,[6] serving as one of the first structurally well-characterized synthetic oxygen carriers.[7] Because of the important *bioinorganic* implications[8] of this property, it seemed logical to prepare a water-soluble variant of Vaska's compound. Indeed, *trans*-[IrCl(CO)(TPPMS)$_2$], **1**, and [(O_2)IrCl(CO)(TPPMS)$_2$], **2**, where TPPMS = the sodium salt of (*m*-sulfonatophenyl)diphenylphosphine, were prepared and their infrared properties reported in 1980,[9] although details of the synthesis were not published until 1990.[10] Later we synthesized the complex in a less cumbersome manner[11] by replacing the PPh_3 ligands in *trans*-[IrCl(CO)(PPh_3)$_2$] by TPPMS in tetrahydrofuran,[12] a procedure that has been successfully used for the synthesis of a number of Ir(I)−TPPMS and Ir(I)−TPPTS complexes by Atwood and co-workers (TPPTS = the sodium salt of tris(*m*-sulfonatophenyl)-phosphine).[13]

Vaska's complex has also been studied as a catalyst for a large variety of reactions, including the hydrogenation and isomerization of olefins and acetylenes,[14] hydrogenation of ketones,[15] the knall gas reaction(H_2/O_2 → H_2O),[16] oxidation,[14a,17] and deoxygenation[18] processes. With reference to the potentially great practical advantages of conducting organometallic catalysis in

* To whom correspondence should be addressed. E-mail: Jooferenc@tigris.kite.hu and djdarens@mail.chem.tamu.edu. Fax: (979) 845−0158.

[†] University of Debrecen.

[‡] Texas A&M University.

[§] Present address: Department of Chemistry, King College, 1350 King College Rd., Bristol, TN 37620.

(1) Darensbourg, D. J.; Beckford, F. A.; Reibenspies, J. H. *J. Cluster Sci.* **2000**, *11*, 95.

(2) Vaska, L.; DiLuzio, J. W. *J. Am. Chem. Soc.* **1961**, *83*, 2784.

(3) Dickson, R. S. *Organometallic Chemistry of Rhodium and Iridium*; Academic Press: New York, 1983.

(4) Vaska, L. *Science* **1963**, *140*, 809.

(5) Vaska, L.; Werneke, M. F. *Trans. N. Y. Acad. Sci.* **1971**, *33*, 70.

(6) Vaska, L.; Chen, L. S.; Senoff, C. V. *Science* **1971**, *174*, 587.

(7) La Placa, S. J.; Ibers, J. A. *J. Am. Chem. Soc.* **1965**, *87*, 2581.

(8) Griffith, J. S. *Proc. R. Soc. (London)* **1956**, *A235*, 23.

(9) Joó, F.; Tóth, Z. *J. Mol. Catal.* **1980**, *8*, 369.

(10) Bényei, A.; Joó, F. *J. Mol. Catal.* **1990**, *58*, 151.

(11) Chock, P. B.; Halpern, J. *J. Am. Chem. Soc.* **1966**, *88*, 3511.

(12) Sertchook, H.; Avnir, D.; Blum, J.; Joó, F.; Kathó, A.; Schumann, H.; Weimann, R.; Wernik, S. *J. Mol. Catal.* **1996**, *108*, 153.

(13) Paterniti, D. P.; Roman, P. J., Jr.; Atwood, J. D. *J. Chem. Soc., Chem. Commun.* **1996**, 2659. (b) Roman, P. J., Jr.; Paterniti, D. P.; See, R. F.; Churchill, M. R.; Atwood, J. D. *Organometallics* **1997**, *16*, 1484. (c) Paterniti, D. P.; Roman, P. J., Jr.; Atwood, J. D. *Organometallics* **1997**, *16*, 3371. (d) Paterniti, D.; Atwood, J. D. *Polyhedron* **1998**, *17*, 1177. (e) Paterniti, D.; Francisco, L. W.; Atwood, J. D. *Organometallics* **1999**, *18*, 123.

(14) Vaska, L.; Rhodes, R. E. *J. Am. Chem. Soc.* **1965**, *87*, 4970. (b) James, B. R.; Memon, N. A. *Can. J. Chem.* **1968**, *46*, 217.

10.1021/om000380x CCC: $19.00
Publication on Web 08/23/2000

water[9,19−24] or in aqueous/organic biphasic systems, it seemed to us of utmost interest to study the catalytic properties of **1** in water and the influence of the aqueous environment on reversible oxygenation and hydrogenation of the water-soluble analogue of Vaska's compound. Recent studies revealed a great deal of information on the properties of *trans*-[IrCl(CO)(TPPMS)$_2$], especially that which concerns the activation of H_2 in DMSO and in aqueous solutions.[13] However, only limited references can be found in the literature to the catalytic use[10] of water-soluble iridium(I)−tertiary phosphine complexes, namely, in the isomerization of allylbenzene to propenylbenzene in aqueous/organic biphasic systems.[12,20] Similarly, the compounds, studied so far, were based on a limited variety of sulfonated triphenylphosphine ligands, such as TPPMS (Na^+ and K^+ salts) and tris(*m*-sulfonatophenyl)phosphine,[13c,21] TPPTS (Na^+ salt). It also seemed conceivable to extend these studies to the use of a structurally rather different phosphine ligand, 1,3,5-triaza-7-phosphaadamantane (PTA), complexes of which with ruthenium,[22] rhodium,[23] palladium,[24,25] platinum,[24,25] and nickel[24,25] central ions had been extensively studied by us in aqueous solutions.

Catalytic hydrogenation is an important methodology in biochemistry to adjust the saturated/unsaturated lipid ratio within the cell membranes.[26] Reduction of the C═C double bonds in the polar lipids results in the straightening of the acyl chains and, consequently, in increased membrane rigidity.[26,27] In principle, the same effect can be achieved by isomerization of the unsaturated fatty acyl residues from their *cis* configuration (most abundant in living systems) to the *trans* geometry. Since the iridium(I) complexes, related to Vaska's compound, are known to display rather low catalytic activity in hydrogenation of simple, unactivated olefins, we report here our attempts at selective *isomerization* of polar lipids (represented by soybean lecithin) in aqueous dispersions (liposomes) catalyzed by **1**.

In this article we describe our recent results on the preparation and properties of water-soluble iridium(I) complexes analogous to Vaska's compound, focusing attention on the new complexes [(O$_2$)IrCl(CO)(TPPMS)$_2$], **2**, and *trans*-[IrCl(CO)(PTA)$_2$], **3**, and the catalytic behavior of *trans*-[IrCl(CO)(TPPMS)$_2$] in hydrogenation of simple olefinic carboxylic acids and unsaturated lipids.

Experimental Section

All manipulations were carried out under an inert atmosphere, either argon or nitrogen, unless otherwise indicated.

Reagents. [Ir(COD)Cl]$_2$ and *trans*-[IrCl(CO)(PPh$_3$)$_2$] were purchased from Strem Chemicals and used as received. *trans*-[IrCl(CO)(TPPMS)$_2$], **1**, was synthesized from *trans*-[IrCl(CO)(PPh$_3$)$_2$] and TPPMS by ligand exchange in THF, as described previously.[12,19e] TPPMS[19e,28] and PTA[19f,29] were prepared and purified by known methods, and their purity was checked by ^{1}H, ^{31}P NMR or HPLC methods. Water was doubly distilled and had been purged with argon or nitrogen for at least 30 min prior to use. Deuterated solvents were purchased from Cambridge Isotope Laboratories and used as received; D_2O was stored in an airtight flask under argon at all times. Tetrahydrofuran, methylene chloride, and hexane were freshly distilled before each use, THF and hexane were stored over Na/benzophenone, and CH_2Cl_2 was dried and stored over CaH_2. Dimethyl sulfoxide (Aldrich) was used as received. Carbon monoxide was purchased from Matheson Gas Products, Inc. and ^{13}CO from Cambridge Isotope Laboratories; these were used without further purification.

Instrumentation. NMR spectra were recorded on a Varian 200XL broad-band, a Varian Unity-300, or a Bruker 360 WY spectrometer. The ^{31}P NMR data were recorded against an external reference of 85% H_3PO_4, δ 0.0 ppm. Infrared spectra were obtained using a Mattson 6021 Galaxy Series or a Perkin-Elmer Paragon 1000 PC FT-IR spectrometer, in a 0.01 mm CaF_2 cell for aqueous samples or a 0.1 mm NaCl cell for other solution samples or KBr disks for solid samples. UV−visible spectra were recorded on a Hewlett-Packard 8452A diode array spectrophotometer.

Preparation of [Na-kryptofix-221]$_2$[IrCl(CO)(Ph$_2$PC$_6$H$_4$-*m*-SO$_3$)$_2$], 1a. A 50 mg sample of **1** was suspended in THF, followed by slow addition of 2-methoxyethanol (4 mL) until the solid was dissolved completely. A 2 equiv amount of solid kryptofix-221 was added, and the solution was allowed to stir for 22 h. The resultant solution was filtered into a large Schlenk tube containing an open test tube of diethyl ether. Slow diffusion of the solvents resulted in the formation of very small yellow needles over a 2 week period. Anal. Calcd for **1** [$C_{37}H_{28}O_7ClNa_2IrP_2S_2$]: C, 45.15; H, 2.87. Found: C, 45.10; H, 3.30. Anal. Calcd for **1a** [$C_{69}H_{92}O_{17}N_4ClNa_2IrP_2S_2$]: C, 50.25; H, 5.62; N, 3.40. Found: C, 50.07; H, 5.43; N, 3.30.

Preparation of [(O$_2$)IrCl(CO)(TPPMS)$_2$], 2. A solution of 100 mg of **1** and 10 mL 2-methoxyethanol was bubbled with air until the complete disappearance of the 376 nm absorption in the UV−vis spectrum. The colorless solution was then added drop by drop to 40 mL of diethyl ether. The resulting precipitate was collected on a sintered glass filter, washed with diethyl ether, and dried in air. Yield: 51 mg (50%) of an off-white solid. Ir (KBr): ν_{CO} 2012 cm^{-1}, ν_{O2} 854 cm^{-1}. ^{31}P NMR (2-methoxyethanol:D_2O = 10:1): δ 12.8 ppm (s). Anal. Calcd for **2** [$C_{37}H_{28}O_9ClNa_2IrP_2S_2$]: C, 43.73; H, 2.78. Found: C, 43.98; H, 3.00.

(15) Strohmeier, W.; Michel, M.; Wiegelt, L. *Z. Naturforsch.* **1980**, *35b*, 648
(16) Vaska, L.; Tadros, M. E. *J. Am. Chem. Soc.* **1971**, *93*, 7099.
(17) Lyons, J. E. in *Aspects of Homogeneous Catalysis*, Vol. 2; Ugo, R., Ed.; Reidel: Dordrecht, 1997; p 1.
(18) Zahalka, H. A.; Alper, H. *Organometallics* **1986**, *5*, 2497.
(19) Horváth, I. T., Joó, F., Eds. *Aqueous Organometallic Chemistry and Catalysis*; NATO ASI Series 3/5; Kluwer: Dordrecht, 1995. (b) Cornils, B., Herrmann, W. A., Eds. *Applied Homogeneous Catalysis by Organometallic Complexes*; VCH: Weinheim, 1996. (c) Horváth, I. T., Ed. Catalysis in Water, special issue of *J. Mol. Catal.* **1997**, *116 (1−2)*. (d) Herrmann, W. A.; Kohlpaintner, C. W. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1524. (e) Joó, F.; Kathó, Á.; Bényei, A. C.; Decuir, T.; Darensbourg, D. J. *Inorg. Synth.* **1998**, *32*, 1. (f) Daigle, D. J. *Inorg. Synth.* **1998**, *32*, 40. (g) Cornils, B., Herrmann, W. A., Eds. *Aqueous-Phase Organometallic Catalysis*; Wiley-VCH: Weinheim, 1998. (h) Joó, F.; Kathó, Á. *J. Mol. Catal. A* **1997**, *116*, 3. (i) Joó F.; Kovács, J.; Bényei, A.; Kathó Á. *Catal. Today* **1998**, *42*, 441.
(20) Kathó, A.; Kovács, J.; Joó, F. *Abs. ISHC-10 (Princeton, 1996)*, PP-A29. (b) Joó, F.; Papp, É.; Kathó, Á. *Top. Catal.* **1998**, *5*, 113.
(21) Herrmann, W. A.; Kellner, J.; Riepl, H. *J. Organomet. Chem.* **1990**, *389*, 103.
(22) Darensbourg, D. J.; Joó, F.; Kannisto, M.; Kathó, A.; Reibenspies, J. H. *Organometallics* **1992**, *11*, 1990. (b) Darensbourg, D. J.; Joó, F.; Kannisto, M.; Kathó, A.; Reibenspies, J. H.; Daigle, D. J. *Inorg. Chem.* **1994**, *33*, 200.
(23) Darensbourg, D. J.; Stafford, N. W.; Joó, F.; Reibenspies, J. H. *J. Organomet. Chem.* **1995**, *488*, 99. (b) Joó, F.; Nádasdi, L.; Bényei, A. Cs.; Darensbourg, D. J. *J. Organomet. Chem.* **1996**, *512*, 45.
(24) Darensbourg, D. J.; Decuir, T. J.; Stafford, N. W.; Robertson, J. B.; Draper, J. D.; Reibenspies, J. H.; Kathó, A.; Joó, F. *Inorg. Chem.* **1997**, *36*, 4218.
(25) Darensbourg, D. J.; Robertson, J. B.; Larkins, D. L.; Reibenspies, J. H. *Inorg. Chem.* **1999**, *38*, 2473.
(26) Quinn, P. J.; Joó, F.; Vígh, L. *Prog. Biophys. Mol. Biol.* **1989**, *53*, 71. (b) Vígh, L.; Joó, F. In *Aqueous Organometallic Chemistry and Catalysis*; Horváth, I. T., Joó, F., Eds.; NATO ASI Series 3/5; Kluwer: Dordrecht, 1995; p 281. (c) Joó, F.; Balogh, N.; Horváth, L. I.; Filep, Gy.; Horváth, I.; Vígh, L. *Anal. Biochem.* **1991**, *194*, 34.
(27) Vígh, L.; Gombos, Z.; Joó, F. *FEBS Lett.* **1985**, *191*, 200.
(28) Ahrland, S.; Chatt, J.; Davies, N. R.; Williams. A. A. *J. Chem. Soc.* **1958**, 276.
(29) Daigle, D. J.; Pepperman, A. B., Jr.; Vail, S. L. *J. Heterocycl. Chem.* **1974**, *11*, 407.

Preparation of *trans*-[IrCl(CO)(PTA)$_2$], 3. The procedure follows that described by Burke and Crabtree[30] for a general synthesis of analogues of Vaska's compound. A 50 mL Schlenk flask was charged with 100 mg (0.15 mmol) of [Ir(COD)Cl]$_2$ and 94 mg (0.60 mmol) of PTA. A 20 mL solvent mixture of hexane/CH_2Cl_2 (50:50 v/v) was added, which resulted in an orange solution with some undissolved PTA (white solid). The mixture was stirred under argon for 10 min, and subsequently the atmosphere was changed to CO. After further stirring for 1 h a pale yellow precipitate formed. The solution was concentrated to one-half the original volume under vacuum, followed by filtration through a sintered glass frit. The product was washed three times with hexanes and dried in vacuo. IR ν(CO) (KBr): 1946 cm^{-1}, 1938 cm^{-1} (split, $\Delta = 8$ cm^{-1}); (H_2O) 1985 cm^{-1}. ^{31}P NMR (D_2O): δ −53.7 ppm (s). Anal. Calcd for **3** [$C_{13}H_{24}OClIrN_6P_2$]: C, 27.39; H, 4.24; N, 14.74. Found: C, 29.24; H, 4.65; N, 15.27. This elemental analysis is consistent with the presence of ∼10% excess PTA.

Preparation of *trans*-[IrCl(^{13}CO)(PTA)$_2$], 3a. The carbon-13-labeled complex was synthesized by the same procedure as for **3**, substituting a ^{13}CO atmosphere for ^{12}CO. The infrared spectrum displayed a broad ν_{CO} (KBr) at 1901 and 1892 cm^{-1} (split, $\Delta = 9$ cm^{-1}). ^{31}P NMR (D_2O): δ −53.7 ppm (d) with $J(^{13}C-P) = 11$ Hz.

pH-Metric Measurements. A Radiometer ABU 91 autoburet was used for pH measurements and control (pH-meter or pH-stat function); the equipment and procedure are described in more detail elsewhere.[19i] Software for the control PC was developed by Dr. Attila Cs. Bényei of Debrecen University. The complexes were dissolved under argon in a thermostated reaction vessel equipped with a Radelkis OP-08080 combined glass electrode and with a capillary inlet (and outlet) for gases (Ar or H_2) and for a base solution, delivered by the autoburet, if necessary in order to keep the pH constant. In the pH-static measurements a carbonate-free 0.2 M KOH solution was used, standardized against 0.05 M potassium hydrogen phthalate. The extent of proton production upon dissolution (hydrolysis) or upon hydrogenation of **1** was calculated from the volume readings of KOH recorded by the PC.

Catalytic Experiments. Hydrogenation of water-soluble unsaturated carboxylic acids was studied at 60 °C using a constant-pressure hydrogenation apparatus as described elsewhere.[31] Large unilamellar liposomes of soybean lecithin were prepared by sonication in water using a Branson Sonifier 250 apparatus, followed by several freeze/thaw cycles and finally filtering through a LiposoFast membrane filtration equipment as described in the literature.[32] A solution of **1** was added to the liposomes under H_2, and the hydrogenation was followed in time by gas chromatography (Hewlett-Packard 5890 Series II chromatograph, 30 m SP 2330 column, 190 °C isothermal separation, FID) of the methyl esters, resulting from extraction and transmethylation of the samples according to standard protocols.[33]

X-ray Crystal Structure Determination. A small needle of **1a** (0.02 × 0.02 × 0.20 mm) was mounted on a glass fiber. The crystal was cooled to 163 K, and data collection was undertaken on a Rigaku AFC5R rotating anode X-ray diffractometer. Omega scans of 25 randomly chosen reflections indicated that the crystal was of poor quality. A total of 12 673 reflections were collected; however, most of these reflections were of poor quality. After much effort a solution was found and all atoms were located. Unfortunately, refinement proved impossible on the unconstrained model. Various restraints were added to the carbon−carbon, carbon−sulfur, and sulfur−oxygen bonds and nonbonding distances. After several refinement cycles the *R* factor dropped to about 28%. Examination of the model and the resulting Fourier maps indicated that the cryptate cations were heavily disordered. Several attempts to model the disorder failed. Finally, the cryptate cations were removed and the program SQUEEZE (PLATON, 1997) was employed to remove their contribution to the crystallographic data. The resulting model was then refined to $R = 14\%$ with all atoms isotropic.

(30) Burke, M. J.; Crabtree, R. H. *Inorg. Chem.* **1986**, *25*, 931.
(31) Tóth, Z.; Joó, F.; Beck, M. T. *Inorg. Chim. Acta* **1986**, *42*, 153.
(32) MacDonald, R. C.; MacDonald, R. I.; Menco, B. P. M.; Takeshita. K.; Subbarao, N. K.; Hu, L. *Biochim. Biophys. A* **1991**, *1061*, 297.
(33) Vígh, L.; Joó, F.; Droppa, M.; Horváth, L. I.; Horváth, G. *Eur. J. Biochem.* **1985**, *147*, 477.
(34) Churchill, M. R.; Fettinger, J. C.; Buttery, L. A.; Barkan, M. D.; Thompson, J. S. *J. Organomet. Chem.* **1988**, *340*, 257.

Results and Discussion

Complexes of the general formula *trans*-[IrCl(CO)L$_2$], where L is a water-soluble phosphine such as TPPMS, TPPTS or PTA, can each be prepared by either of the three procedures depicted in eqs 1−3:

$$2H_2IrCl_6 + 5CO + 4TPPMS + 3H_2O \rightarrow 2[IrCl(CO)(TPPMS)_2] + 3CO_2 + 10HCl \quad (1)$$

$$[IrCl(CO)(PPh_3)_2] + 2TPPTS \rightarrow [IrCl(CO)(TPPTS)_2] + 2PPh_3 \quad (2)$$

$$[IrCl(COD)]_2 + 2CO + 4PTA \rightarrow 2[IrCl(CO)(PTA)_2] + 2COD \quad (3)$$

It is of interest to note that *trans*-[IrCl(CO)(TPPTS)$_2$] could not be obtained by extraction of a toluene solution of [IrCl(CO)]$_n$ with an aqueous solution of TPPTS; although the iridium moved to the aqueous phase, the compound was best formulated as [IrCl(CO)(TPPTS)$_3$].[21] For the ligand exchange reactions 2 and 3, the solvents (THF or hexane/CH_2Cl_2) should be carefully dried. When **1** is prepared by *refluxing* a THF solution of *trans*-[IrCl(CO)(PPh$_3$)$_2$] in the presence of TPPMS, some *trans*-[Ir(OH)(CO)(TPPMS)$_2$] and [HIr(CO)(TPPMS)$_3$] may form as impurities, as shown by the ^{31}P NMR resonances at $\delta = 27.7$ ppm and $\delta = 15.7$ ppm, respectively, in D_2O.

Although our attempts to grow crystals of *trans*-[IrCl(CO)(TPPMS)$_2$] failed, we were able to obtain small bright yellow crystals of its kryptofix-221-encapsulated sodium derivative from a THF/2-methoxyethanol/diethyl ether solution. Unfortunately, the two complexed sodium cations were highly disordered, and we were not able to model the disorder and precisely define the solid-state structure. The disorder of the chloride and CO ligands about the iridium center has previously been modeled by Churchill and co-workers[34] in the parent triphenylphosphine analogue. Nevertheless, the connectivity within the metal dianion was well defined, with its structural parameters closely resembling those of its nonsulfonated triphenylphosphine analogue (Figure 1). For example, the Ir−P, Ir−C, and Ir−Cl bond distances computed at 2.309(5), 1.750(1), and 2.429(9) Å respectively are quite similar to those found (2.330(1), 1.791(13), and 2.382(9) Å) in Vaska's complex.[34] Figure 2 presents a superposition of stick drawings of the dianion of complex **1a** and *trans*-[IrCl(CO)(PPh$_3$)$_2$].

The water-soluble 1,3,5-triaza-7-phosphaadamantane (PTA) analogue of Vaska's complex, *trans*-[IrCl(CO)(PTA)$_2$], **3**, was prepared from [Ir(COD)Cl]$_2$ and excess PTA in a hexane/CH_2Cl_2 solvent mixture under an atmosphere of carbon monoxide. The singlet ^{31}P NMR resonance observed in water at −53.7 ppm for complex

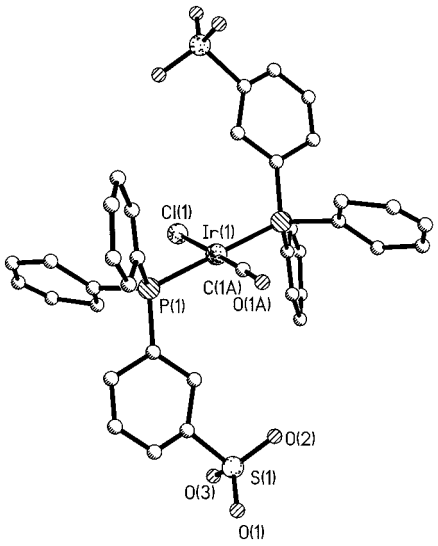

Figure 1. Ball-and-stick representation of the dianion of complex **1a**.

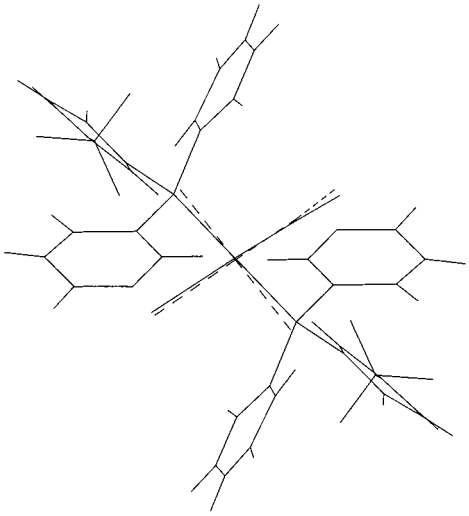

Figure 2. Superposition of stick drawings of the dianion of complex **1a** and Vaska's complex, *trans*-[IrCl(CO)-$(PPh_3)_2$].

3, which split into a doublet (J_{C-P} = 11 Hz) upon replacing ^{12}CO with ^{13}CO, is consistent with a *trans* configuration for the PTA derivative as well.[35]

$[(O_2)IrCl(CO)(TPPMS)_2]$, **2**, was obtained from a direct reaction of **1** with dioxygen in 2-methoxyethanol solution and isolated as a white powder upon precipitation with diethyl ether. Its UV−vis spectrum in water or in 2-methoxyethanol shows no characteristic absorbances. Infrared spectral properties, such as ν_{CO} at 2012 cm^{-1} and ν_{O2} at 854 cm^{-1}, are in good agreement with those of $[(O_2)IrCl(CO)(PPh_3)_2]$. Attempts to isolate suitable crystals of complex **2** for X-ray analysis were unsuccessful. However, these spectral data, together with the singlet ^{31}P NMR resonance at 12.8 ppm, are consistent with the trigonal bipyramidal structure established[7] by LaPlaca and Ibers for $[(O_2)IrCl(CO)(PPh_3)_2]$. That is, complex **2** can be viewed as containing a side-on-bonded dioxygen molecule in the equatorial plane with two TPPMS ligands in axial positions.

(35) Krogstad, D. A.; Terry, T. J.; Young, V. G., Jr. *218th National ACS Meeting*, New Orleans, LA, August 1999, INOR 86.
(36) Al-Jibori, S. A. *J. Organomet. Chem.* **1996**, *506*, 119.

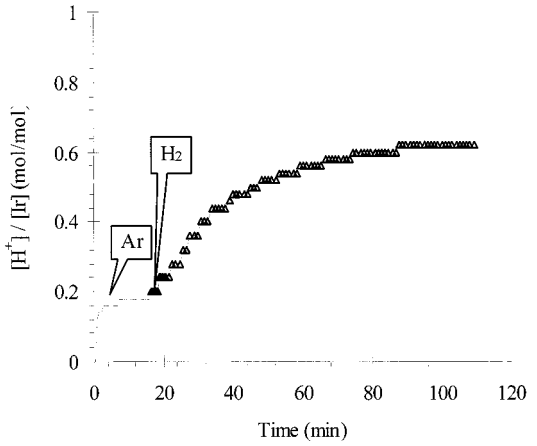

Figure 3. Time course of proton production on dissolution and on subsequent hydrogenation of *trans*-[IrCl(CO)-$(m$TPPMS$)_2$] at a preset pH: 7.20 mg of *trans*-[IrCl(CO)-$(m$TPPMS$)_2$], 0.2 mol dm^{-3} KCl, V = 10 mL, T = 25 °C.

Solution Behavior of *trans*-[IrCl(CO(TPPMS)$_2$]. In contrast with the $TPPMS^-K^+$ derivative,[13] the sodium salt of TPPMS renders complex **1** sufficiently soluble in D_2O for NMR studies. ^{31}P NMR measurements revealed, depending on the equilibrium chloride concentration (i.e., on the total concentration of **1** and the presence/absence of external Cl^-), that extensive loss of Cl^- from the complex can take place. For example, when 50 mL of water was thoroughly purged with argon in the reaction vessel of the titration apparatus (see Experimental Section) until a pH 7 was attained, **1** (25 mg, 4.8×10^{-4} M) was dissolved in this water under argon, and the pH dropped to 4.7, indicating that the extent of proton production (eq 4) was about 4%. When

$$[IrCl(CO)(TPPMS)_2] + H_2O \rightleftharpoons [Ir(OH)(CO)(TPPMS)_2] + H^+ + Cl^- \quad (4)$$

the gas purge was changed from argon to H_2, a further pH drop occurred to 3.4 (*vide infra*). Separate experiments, using the titration apparatus in the pH-stat mode, were undertaken to determine the extent of proton production upon dissolution under more defined conditions. That is, these experiments were performed in the presence of a supporting electrolyte (0.2 M $NaClO_4$) and 3 equiv of TPPMS per Ir. Proton production was calculated from the amount of 0.2 M KOH solution delivered by the autoburet to keep the pH constant with time (Figure 3). The results are illustrated in Figure 4.

It can be seen from Figure 4 that under such conditions, proton production is negligible below pH 7, but rapidly increases with increasing pH and reaches the stoichiometric value of one H^+ for one Ir in strongly basic solutions. This is consistent with the formation of the known[13b] hydroxo-iridium complex [Ir(OH)(CO)-$(TPPMS)_2$]. $[Ir(OH)(CO)(PPh_3)_3]$ can be easily synthesized in high yields in the direct reaction of [IrCl(CO)-$(PPh_3)_3$] and aqueous alkali.[36] At the temperature of 35 °C these pH equilibria are established in a few minutes, and the solutions remain stable. However, at elevated temperatures, secondary processes take place especially at pH >10; Atwood and co-workers have also noted that the attack of OH^- on the coordinated CO results in the formation of unidentified products in H_2O.[13b]

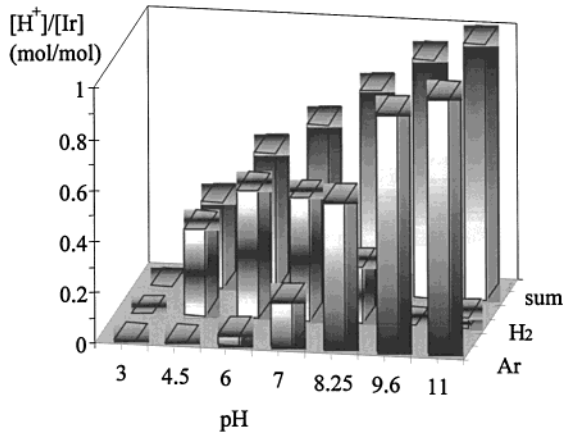

Figure 4. Equilibrium proton production on dissolution and on subsequent hydrogenation of *trans*-[IrCl(CO)-(*m*TPPMS)$_2$] in water in the pH range 3−11: 20 mg of *trans*-[IrCl(CO)(*m*TPPMS)$_2$], 0.2 mol dm^{-3} KCl, $V = 10$ mL, $T = 25$ °C.

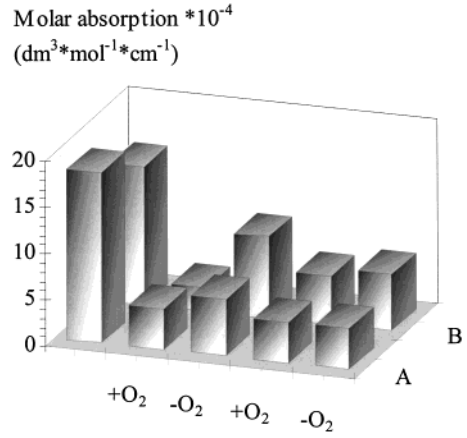

Figure 5. Oxygenation/deoxygenation of **1** in water and in 2-methoxyethanol solutions: 1.14×10^{-3} mol dm^{-3} *trans*-[IrCl(CO)(*m*TPPMS)$_2$], $T = 25$ °C, (A) 378 nm, water; (B) 386 nm, 2-methoxyethanol.

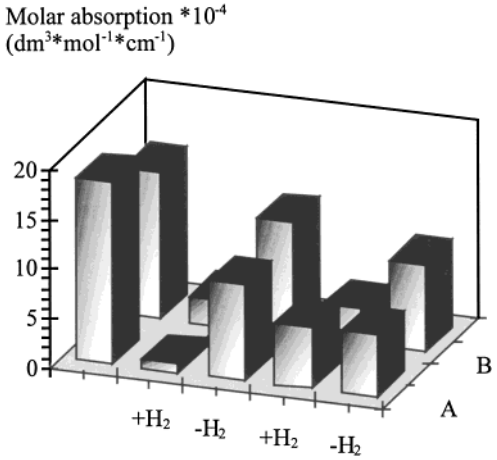

Figure 6. Hydrogenation/dehydrogenation of **1** in water and in 2-methoxyethanol solutions: 1.14×10^{-3} mol dm^{-3} *trans*-[IrCl(CO)(*m*TPPMS)$_2$], $T = 25$ °C, (A) 378 nm, water; (B) 386 nm, 2-methoxyethanol.

It is further evident from Figure 4 that the extent of *further* proton production upon hydrogenation of aqueous solutions of **1** strongly depends on the actual pH; in fact, it displays a maximum value at pH = 6. The total amount of protons formed per moles of iridium is close to zero in the acidity range pH < 3 and approaches, but does not exceed, $[H^+]/[Ir] = 1$ at pH = 11. This behavior can be interpreted by assuming formation in rather acidic solutions (pH = 3) of [$(H)_2$Ir(CO)Cl-$(TPPMS)_2$], the straightforward product of oxidative addition of dihydrogen, or [$(H)_2$Ir(CO)$(TPPMS)_3]^+$, formed by subsequent chloride dissociation, in agreement with Atwood's results.[13] Proton production in less acidic and in basic solutions signals the formation of hydrido-iridium complexes with heterolytic splitting of dihydrogen, as depicted in eqs 5 and 6.

$$[IrCl(CO)(TPPMS)_2] + H_2 + TPPMS \rightleftharpoons [HIr(CO)(TPPMS)_3] + H^+ + Cl^- \quad (5)$$

$$[IrCl(CO)(TPPMS)_2] + 2H_2 \rightleftharpoons [(H)_3Ir(CO)(TPPMS)_2] + H^+ + Cl^- \quad (6)$$

Although it is not possible to establish the products from solely the pH-potentiometric results, in an excess of TPPMS (as in our pH-static experiments) the presence of the monohydrido derivative is highly probable.

It has been demonstrated earlier[13c] that the rate of the hydrogenation of **1** in aqueous solutions decreased with increasing pH, showing a sharp drop around pH 6, and this pH dependence was attributed to protonation/hydrogen-bonding interactions of **1** in water. Protonation of the iridium(I) center would lead to the formation of [HIrCl(CO)$(TPPMS)_2]^+$; however, this compound was not directly observed. Nor is its existence at pH > 3 supported by our pH-potentiometric data, according to which the midpoint of proton formation upon dissolution is at pH 8.3 (Figure 3). This is considerably higher than the midpoint of the pH dependence of the **1** + H_2 reaction (approximately pH 6).[13c] Since pH-potentiometry refers to the final (equilibrium) state of the reaction, we can only conclude that hydrogen-bonding interactions are more likely to produce the observed pH dependence.

Because a significant feature of *trans*-[IrCl(CO)-$(PPh_3)_2$] is its capacity to reversibly bind[4−6] dioxygen and dihydrogen, we have attempted these reactions with complex **1** in both water and 2-methoxyethanol as solvents. The reactions were followed by UV−vis spectrophotometry at one of the characteristic absorptions of complex **1**, $\lambda = 378$ nm (water) or $\lambda = 386$ nm (2-methoxyethanol). The oxygenated and the hydrogenated complexes exhibited negligible absorption at these wavelengths in the respective solvents. The solutions were purged at room temperature with O_2 or H_2 until the disappearance of the absorption peak(generally carried out for 10−15 min) and then with argon until constant spectra were obtained (generally required 30−40 min); following that, the cycle was repeated. The results are presented in Figures 5 and 6.

It is seen that both oxygenation and hydrogenation are far from being reversible. The reaction of **1** with O_2 can be only slightly reversed even in the first cycle upon bubbling Ar through the solutions, irrespective of the solvent. Furthermore, this small reappearance of the peak in the spectrum could not be observed in the second cycle. With H_2 the first cycles are 50−70% reversible in water and in 2-methoxyethanol, respectively, but while in the organic solvent some reversibility

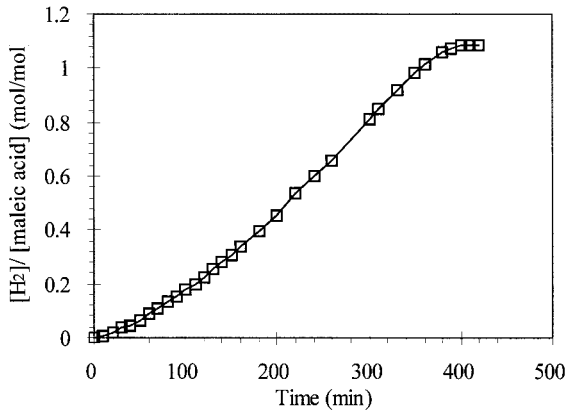

Figure 7. Hydrogenation of maleic acid in aqueous solution catalyzed by **1:** 0.5 mmol maleic acid, 0.01 mmol *trans*-[IrCl(CO)(*m*TPPMS)$_2$], V = 10 mL, T = 60 °C.

is seen in the second cycle, too, the aqueous solutions display the same constant spectra under both hydrogen and argon. Of the four possible hydrides [$(H)_2$IrCl(CO)-(TPPMS)$_2$], [$(H)_2$Ir(CO)(TPPMS)$_3$]$^+$, [HIr(CO)(TPPMS)$_3$], and [$(H)_3$Ir(CO)(TPPMS)$_2$], the latter two are formed with concomitant proton and chloride production (eqs 5 and 6). It is probably the very strong hydration of H^+ and to a lesser extent that of Cl^- that makes these reactions irreversible in water. Solvation energies of the same charged species are probably lower in 2-methoxyethanol, which accounts for the somewhat more expressed reversibility of oxygenation and hydrogenation of *trans*-[IrCl(CO)(TPPMS)$_2$] in that medium.

Catalytic Hydrogenation and Isomerization of Water-Soluble Olefins and Unsaturated Lipids. In aqueous solutions under mild conditions (total pressure 1 bar, temperature 60 °C) **1** is a moderately effective catalyst for hydrogenation of unsaturated short-chain fatty acids at the pH established according to the proton dissociation of these substrates (pH 2.4−2.9). The hydrogenation starts with an induction period, characteristic of reactions catalyzed by Vaska's compound in polar organic solvents such as dimethylacetamide[14b] and dimethylformamide.[37] A typical hydrogen uptake plot is shown in Figure 7 for reduction of maleic acid. Crotonic, maleic (MA), fumaric (FA), and α-acetamidocinnamic acids were used as substrates with initial turnover frequencies (calculated from data for the first 30 min) of 25.7, 11.3, 7.8, and 3.6 (mol H_2)(mol catalyst)$^{-1}$ h^{-1}, respectively. Despite the lower temperature, this catalytic activity compares favorably with that observed in reduction of MA in dimethylacetamide at 80 °C with *trans*-[IrCl(CO)(PPh_3)$_2$] as catalyst (TOF = 1−5 h^{-1} depending on the substrate concentration).[14b] It is noteworthy that the reactions went to completion with no side reactions of the catalyst to diminish its activity. In line with the generally faster hydrogenation of *cis*-olefins compared with their *trans*-isomers,[38] MA is reduced faster than FA. On the other hand, this is in contrast with the case of hydrogenation of the same substrates in water with the [RhCl(TPPMS)$_3$] catalyst.[39] When the reaction mixture of maleic acid hydrogenation was monitored with time by high-performance liquid chromatography, a slow buildup of fumaric acid was detected until reaching a steady-state concentration of 0.55 mol % of the initial concentration of MA. The appearance of FA shows that **1** also catalyses the slow *cis*−*trans* isomerization of MA to FA and is consistent with the lower reactivity of fumaric acid.

Table 1. Distribution of Fatty Acids in Soybean Lecithin Catalytically Hydrogenated with *trans*-[IrCl(CO)(*m*TPPMS)$_2$][a]

	distribution of fatty acids		
	reaction time (min)		
fatty acids	0	30	60
18:0	4.9	5.6	6.0
18:1	8.6	19.9	23.3
18:2	56.9	45.4	43.0
18:3	7.8	7.0	6.7
conversion of double bonds (%)	0	9.7	11.2

[a] 0.010 mmol *trans*-[IrCl(CO)(*m*TPPMS)$_2$], 10 mg soybean lecithin in 10 mL of phosphate buffer, pH = 7.0, T = 60 °C, p_{total} = 1 bar. 18:0, stearic acid; *cis*-18:1, oleic acid; *trans*-18:1, elaidic acid; 18:2, linoleic acid; 18:3, linolenic acid. The other fatty acid present in 21.8% is palmitic acid (16:0), which is saturated.

Unsaturated lipids form vesicles when dispersed in an aqueous medium (e.g., by ultrasonication), and the liposomes obtained serve as models for biological membranes.[40] The low hydrogenation activity together with the *cis*−*trans* isomerization capability of **1** holds promise for selective isomerization of unsaturated lipids in membranes, which would be a valuable technique for membrane modification in addition to hydrogenation.[26] We have therefore undertaken a study of hydrogenation of soybean lecithin liposomes at 60 °C and 1 bar total pressure using complex **1** as catalyst. The distribution of fatty acids in the soybean lecithin studied was

- 4.9% stearic acid ($CH_3(CH_2)_{16}COOH$), 18:0
- 8.6% oleic/elaidic acids ($cis/trans$-$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$), 18:1
- 56.9% linoleic acid ($CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$, *cis-cis* isomer), 18:2
- 7.8% linolenic acid ($CH_3CH_2CH{=}CHCH_2CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$, *cis-cis-cis* isomer), 18:3

The other fatty acid present in 21.8% is palmitic acid (16:0), which is saturated and unaffected under the conditions of hydrogenation. The results from the hydrogenation studies of 18:1, 18:2, and 18:3 are found in Table 1, whereas, the isomerization reaction involving 18:1 is provided in Table 2.

The pattern of hydrogenation follows the usual trend observed in modification of biomembranes by catalytic reduction.[26] Accordingly, the reaction of highly unsaturated acyl moieties (18:2 and 18:3) of the lipid takes preference over the 18:1 to 18:0 reduction. It is interesting to note that there is only a small further hydrogena-

(37) Burnett, M. G.; Morrison, R. J.; Strugnell, C. J. *J. Chem. Soc., Dalton Trans.* **1973**, 701.
(38) Chaloner, P. A.; Esteruelas, M. A.; Joó, F.; Oro. L. A. *Homogeneous Hydrogenation (Catalysis by Metal Complexes, Vol. 15)*; Kluwer: Dordrecht, 1994.
(39) Joó, F.; Csiba, P.; Bényei, A. *J. Chem. Soc., Chem. Commun.* **1993**, 1602.
(40) Joó, F.; Vígh, L. In *Handbook of Nonmedical Applications of Liposomes Vol. III*; Barenholz, Y., Lasic, D. D., Eds.; CRC Press: Boca Raton, 1996; p 257.

Table 2. Relative Abundance of *cis*-18:1 (Oleic Acid) and *trans*-18:1 (Elaidic Acid) in Soybean Lecithin, Unmodified or Catalytically Hydrogenated with *trans*-[IrCl(CO)(*m*TPPMS)$_2$][a]

	distribution of fatty acids (%)		
	reaction time (min)		
fatty acids	0	30	60
cis-18:1	93.2	58.1	52.1
trans-18:1	6.7	41.9	47.9

[a] 0.010 mmol *trans*-[IrCl(CO)(*m*TPPMS)$_2$], 10 mg of soybean lecithin in 10 mL of phosphate buffer, pH = 7.0, T = 60 °C, p_{total} = 1 bar. *cis*-18:1, oleic acid; *trans*-18:1, elaidic acid.

tion of the membrane after 30 min of reaction. In general, the gradual rigidification of the membrane caused by saturation of its lipids decreases the accessibility of the C═C double bonds inside the lipid bilayer, and therefore the reaction slows down. However, in this particular case there can be another explanation for the phenomenon. According to the data of Table 2, in the first 30 min of the reaction the distribution of isomeric 18:1 fatty acids is changed dramatically and the *trans*-isomer (elaidic acid) comprises already more than 40% of all 18:1. It can be reasonably assumed that, similar to the maleic acid/fumaric acid pair, *trans*-unsaturated lipids react less readily than their *cis*-isomers, and this can decisively contribute to slowing down the overall reaction. We could not quantify the isomeric distribution of the higher unsaturated fatty acyl chains in the lipids, but it is conceivable that they are subject to a similar catalytic conversion. In fact, gas chromatography of the reaction mixture after 60 min of hydrogenation showed (Figure 8) very extensive isomerization of the lipid around all the C═C bonds with only 11.2% of these bonds removed by hydrogenation.

This is the first example of extensive *cis*−*trans* isomerization of lipids in model or biomembranes with a pronounced selectivity over hydrogenation. Although the high reaction temperature used in this study is not acceptable for work with samples of biological origin, there is ample possibility to make the conditions biocompatible. We would like to stress that removal of approximately 5−10% of all double bonds in lipids of biomembranes by hydrogenation is more than enough to produce meaningful "answers" of the cells in order to maintain their so-called homeoviscous state; in fact, a larger extent of membrane saturation seriously decreases viability of the cells.[26] *Cis*−*trans* isomerization is expected to have an effect on membrane fluidity comparable to hydrogenation, so the extent of isomerization achieved in our studies is actually too large for application in biological studies. However, further detailed studies are required to establish the usefulness of **1** as a catalyst of biomembrane modification with respect to its activity and selectivity at lower temperatures, toxicity for cells, and compatibility with components of cell culture media.

Concluding Remarks

The work presented in this paper has shown by X-ray structural and/or spectroscopic studies that the general molecular skeletal arrangements in *water-soluble* analogues of Vaska's complex, i.e., *trans*-[IrCl(CO)(TPPMS)$_2$], *trans*-[IrCl(CO)(PTA)$_2$], and [(O_2)IrCl(CO)(TPPMS)$_2$], closely resemble those of the PPh_3 derivative. On the other hand, solution behavior of *trans*-[IrCl(CO)(TPPMS)$_2$] in water is markedly different in that its reactions with O_2 and H_2 are not reversible due to formation of strongly hydrated H^+, Cl^-, and cationic complexes in the reactions. Finally, *trans*-[IrCl(CO)(TPPMS)$_2$] was shown to be a moderately active catalyst for hydrogenation of olefinic double bonds both in short-chain unsaturated fatty acids and in unsaturated lipid vesicles. Due to its high isomerization activity, this water-soluble derivative can be used for modification of lipid membranes by catalytic isomerization rather than hydrogenation.

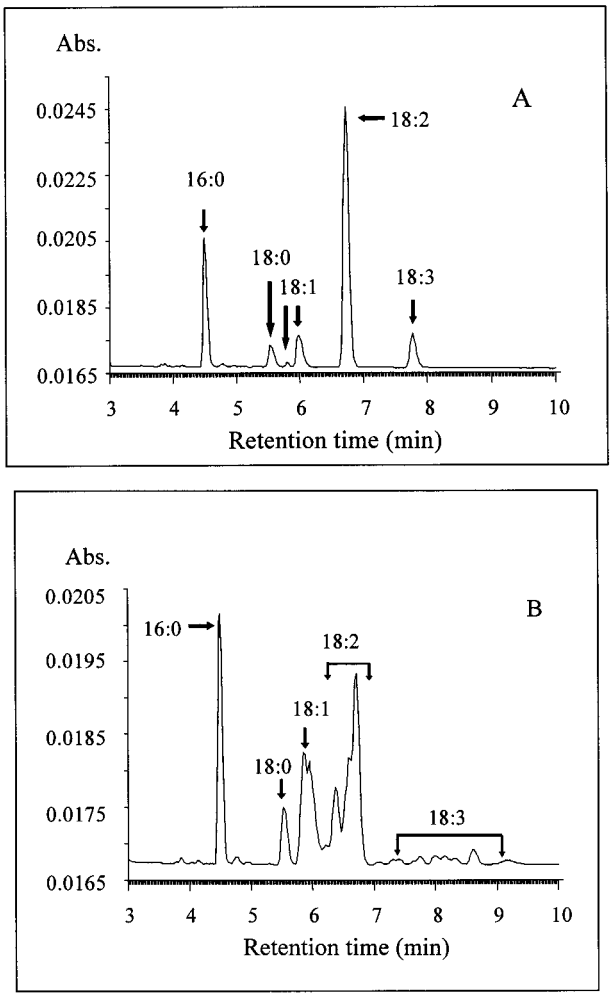

Figure 8. Gas chromatograms of fatty acid methyl esters obtained by transeseterification of soybean lecithin, unmodified (A) or catalytically hydrogenated (B) with *trans*-[IrCl(CO)(*m*TPPMS)$_2$].

Acknowledgment. The support of this work by the National Science Foundation (Grant CHE96-15866 and INT93-13951), the Robert A. Welch Foundation, and the National Science and Research Foundation of Hungary (OTKA; Grant T029934) is gratefully acknowledged.

OM000380X