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Supporting Information

The Hydrovinylation Reaction: A New Highly Selective Protocol Amenable to Asymmetric Catalysis

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General Methods. All hydrovinylation catalysts were synthesized under an inert atmosphere of nitrogen in a Vacuum Atmospheres drybox, and hydrovinylations were carried out by Schlenk techniques. Ethylene (99.5 %) was purchased from Matheson Inc. and passed through Drierite before use. Methylene chloride was distilled from calcium hydride under nitrogen. Tetrahydrofuran (THF) and diethyl ether were distilled under nitrogen from sodium/benzophenone ketyl. Styrene was purchased from Aldrich, vacuum transferred, and stored at -30°C. Isobutylstyrene and 6-methoxy-2-vinylnaphthalene were prepared by the procedure of Nugent and McKinney¹ by Ni(0)-catalyzed cross-coupling of the corresponding bromoarene and a Grignard reagent. Other substrates for hydrovinylation were available from Aldrich and were purified by passing through a short pad of silica gel. $[\text{Ni}(\text{allyl})\text{Br}]_2$ was synthesized according to the procedure of Corey and Semmelhack.² Literature procedures were used to synthesize (*R*)-MOP-OMe³, (*R*)-MOP-OBn³ and $[(3,5)\text{-(CF}_3)_2\text{C}_6\text{H}_3]_4\text{B}^-[\text{Na}^+]$.⁴ Analytical TLC was done on E. Merck precoated (0.25 mm) silica gel 60 F254 plates. Column chromatography was conducted by using silica gel 40 (Scientific Adsorbents Incorporated, Microns Flash). Yields refer to isolated yields of compounds with greater than 97% purity analyzed by GC. ¹H NMR spectra (250 MHz) were recorded on a Bruker AM-250 spectrometer in CDCl₃ with CHCl₃ (δ 7.26) as an internal standard. Gas chromatographic analyses were performed on a Hewlett-Packard 5890 equipped with an HP-ultra-1 crosslinked methyl silicone capillary column (25 m length x 0.2 mm i.d.) and an FID detector connected to an HP 3396 integrator with helium as the carrier gas. Chiral gas chromatographic separations were accomplished using Chirasil-Val on WCOT fused silica (25m X 0.25 mm, 0.12 μm film thickness)

capillary GC column purchased from Chrompack (1130 Route 202 South Raritan, New Jersey 08869). Chiral HPLC separations were accomplished using a Chiracel OJ column (Daicel). Elemental analyses were done by Atlantic Microlab, Inc., Norcross, GA.

Typical examples of hydrovinylations.

(a). Hydrovinylation of 4-bromostyrene: Synthesis of 3-(4-bromophenyl)-1-butene.

The following procedure is typical. In a dry box, $[\text{Ni}(\text{allyl})\text{Br}]_2$ (2.6 mg, 0.0072 mmol), triphenylphosphine (4.0 mg, 0.015 mmol), and silver triflate (4.9 mg, 0.019 mmol) were weighed into three different vials. To a red solution of $[\text{Ni}(\text{allyl})\text{Br}]_2$ in CH_2Cl_2 (1.5 mL) was added a solution of triphenyl phosphine in CH_2Cl_2 (1.5 mL). The solution turned immediately to orange-yellow and was added to a suspension of silver triflate in CH_2Cl_2 (1.0 mL). After 1.5h stirring at room temperature, the resulting brownish suspension was filtered through a plug of celite in a micropipet and the celite pad was washed with CH_2Cl_2 (1.5 mL). The yellow filtrate collected in a Schlenk flask was removed from the drybox and cooled to -55°C . Oxygen-free ethylene (~ 1 atm) was then introduced into the yellow catalyst solution, and 4-bromostyrene (366 mg, 2.0 mmol) was slowly added through a rubber septum with a syringe. After 2 hr stirring at -55°C under an ethylene atmosphere (~ 1 atm), the reaction mixture was quenched with a half-saturated ammonium chloride solution, warmed up to room temperature allowing evaporation of all the volatile materials, and extracted with ether. The organic layer was dried over magnesium sulfate and then concentrated *in vacuo* to afford 410 mg (97 % yield) of a colorless liquid. GC analysis of the crude product showed that the minor components amount to 2.1 % (4-bromostyrene, 1.3 %; 2-(4-bromophenyl)-2-butene, 0.8 %). The regioselectivity of 3-(4-bromophenyl)-1-butene over 2-(4-bromophenyl)-2-butene is 99%. The ^1H NMR spectra of the product did not detect peaks for the starting material or 2-(4-bromophenyl)-2-butene. Anal. Found (calcd): C, 57.00 (56.90); H, 5.30 (5.25); Br, 37.72 (37.85). ^1H NMR (250 MHz, CDCl_3) δ 7.42 (m, aromatic, 2H), 7.09 (m, aromatic, 2H), 5.96 (ddd, $J_{\text{trans}} = 18$ Hz, $J_{\text{cis}} = 10$ Hz, $J = 6$ Hz, 1H), 5.05 (dt, $J_{\text{trans}} = 18$ Hz, $J = 2$ Hz, 1H), 5.04 (dt, $J_{\text{cis}} = 10$ Hz, $J = 2$ Hz, 1H), 3.43 (m, 1H), 1.35 (d, $J = 7$ Hz, 3H).

(b). Asymmetric hydrovinylation of 4-isobutylstyrene: Synthesis of 3-(4-Isobutylphenyl)-1-butene.

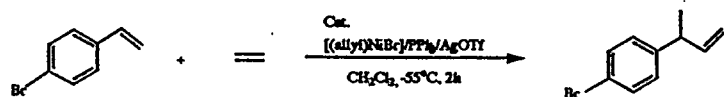
To the red solution of $[\text{Ni}(\text{allyl})\text{Br}]_2$ (2.6 mg, 0.0072 mmol) in

CH₂Cl₂ (1.5 mL) was added a solution of (*R*)-**MOP-OMe** (**8a**, 6.8 mg, 0.014 mmol) in CH₂Cl₂ (1.5 mL) in a drybox. The resulting orange mixture was combined with [Na]⁺[[3,5]-(CF₃)₂C₆H₃]₄B]⁻ (17.5 mg, 0.020mmol) in CH₂Cl₂ (1.0 mL), stirred for 1.5 h at room temperature, filtered through a plug of celite in a micropipet into a Schlenk flask, and then taken out of the drybox. Oxygen-free ethylene (~1 atm) was introduced into the orange catalyst solution at -55°C, and 4-isobutylstyrene (161 mg, 1.0 mmol) was added dropwise via a syringe. The resulting solution immediately became dark red and then gradually changed to orange during the stirring period of 2h at -55°C under an ethylene atmosphere (~1 atm). After quenching with a half-saturated ammonium chloride solution, the reaction mixture was extracted with ether, and the organic layer was dried over magnesium sulfate and concentrated *in vacuo* to yield 173 mg (93 % yield) of the crude product. The ¹H NMR spectra of the crude product did not detect the starting material, but 2.5% of the starting material was detected in the crude product by GC analysis. Chiral HPLC on Chiralcel-OJ column (hexane, 0.3 mL/min flow) gave baseline separation of the two enantiomers with an ee of 40 % for the slow-moving enantiomer (retention times: *R*-isomer 17.4 min., *S*-isomer 19.2 min.). To determine the absolute configuration and to verify the enantioselectivity, the crude product was converted into the corresponding ibuprofen (-)-menthyl esters by the following sequence: (a) ozonolysis of the butene to an aldehyde, (b) oxidation of the aldehyde with potassium permanganate to give ibuprofen, (c) preparation of the (-)-menthyl ester by reaction with (-)-menthol and dicyclohexylcarbodiimide. The diastereomeric menthyl esters were analyzed by GC on a Chirasil-*L*-Val column (conditions: 150°C isothermal, 1.5 mL helium/min. Retention times: *R*-acid ester 33.7 min.; *S*-acid ester 34.7 min.). The major acid isomer was identified as *R*-ibuprofen (38 % ee) by comparison of retention times with that of authentic samples. Correspondingly, the olefin product, 3-(4-isobutylphenyl)-1-butene was established as having the *S* configuration (38 % ee). Anal. Found (calcd): C, 89.22 (89.30); H, 10.64 (10.70). ¹H NMR (250 MHz, CDCl₃) δ 7.09 (m, aromatic, 4H), 6.01 (ddd, *J*_{trans} = 17 Hz, *J*_{cis} = 10 Hz, *J* = 7 Hz, 1H), 5.04 (dt, *J*_{trans} = 17 Hz, *J* = 2 Hz, 1H), 5.01 (dt, *J*_{cis} = 10 Hz, *J* = 2 Hz, 1H), 3.44 (m, 1H), 2.44 (d, *J* = 7 Hz, 2H), 1.85 (sept., *J* = 7 Hz, 1H), 1.35 (d, *J* = 7 Hz, 3H) 0.91 (d, *J* = 7 Hz, 6H).

(c). Asymmetric hydrovinylation of 2-methoxy-6-vinylnaphthalene (MVN): Synthesis of 3-(6-methoxy-2-naphthyl)-1-butene. To a solution of [(allyl)NiBr]₂ (2.6 mg, 7.2 mmol) of CH₂Cl₂ (0.5 mL) under nitrogen at room temperature was added a solution of (*R*)-MOP-OBn (**8b**, 7.8 mg, 14.4 mmol) in CH₂Cl₂ (1.5 mL). The resulting brown solution was added to a solution of [Na]⁺[[3,5]-(CF₃)₂C₆H₃]₄B]⁻ (15.3 mg, 17.3 mmol) in CH₂Cl₂ (2 mL). After stirring for 1.5 h at rt, the mixture was filtered through a small plug of Celite, and the precipitate was rinsed with CH₂Cl₂ (1 mL). The filtrate was collected in a Schlenk flask, and was taken out of the drybox. The catalyst solution was cooled to -55 °C. Under one atmosphere of ethylene, a solution of 2-methoxy-6-vinylnaphthalene¹ (0.184 g, 1.00 mmol) in CH₂Cl₂ (1 mL) was added dropwise to the catalyst solution. After stirring at -55 °C for 2 h, the mixture was quenched with saturated aqueous NH₄Cl solution and extracted three times with 10 mL portions of CH₂Cl₂. The combined organic layers were dried over MgSO₄ and concentrated *in vacuo*. The crude product was analyzed by GC which indicated that the alkene product was produced in 99+% yield with no starting material left. The crude product was purified by flash chromatography on silica gel, eluting with hexanes/ethyl acetate (19:1) gave a clear oil (206 mg, 97%). ¹H NMR (250 MHz, CDCl₃) δ 7.10-7.75 (m, 6 H), 6.09 (ddd, *J* = 6, 10, 17 Hz, 1 H), 5.09 (dt, *J* = 1, 17 Hz, 1 H), 5.07 (dt, *J* = 1, 10 Hz, 1 H), 3.92 (s, 3 H), 3.61 (m, 1 H), 1.45 (d, *J* = 7 Hz, 3 H). The enantiomeric excess of product alkene was determined by HPLC on Chiracel OJ column (Daicel) (hexane/*i*-PrOH = 95/5, 0.5 mL/min) as 73%, enriched in the (*S*)- isomer. The same reaction carried out at -70 °C for 7 h gave an yield of 93 % and enantiomeric excess of 80 %.

References

1. Nugent, W. A., McKinney, R. J. *J. Org. Chem.*, **50**, 5370-5372 (1985).
2. Corey, E. J., Semmelhack, M. F. *J. Am. Chem. Soc.* **89**, 2755-2756 (1967).
3. Uozumi, Y., Tanahashi, A., Lee, S.-Y., Hayashi, T. *J. Org. Chem.* **58**, 1945-1948 (1993).
4. Brookhart, M., Grant, B., Volpe, A. *Organometallics* **11**, 3920-3922 (1992).

Reaction**GC Test Condition**

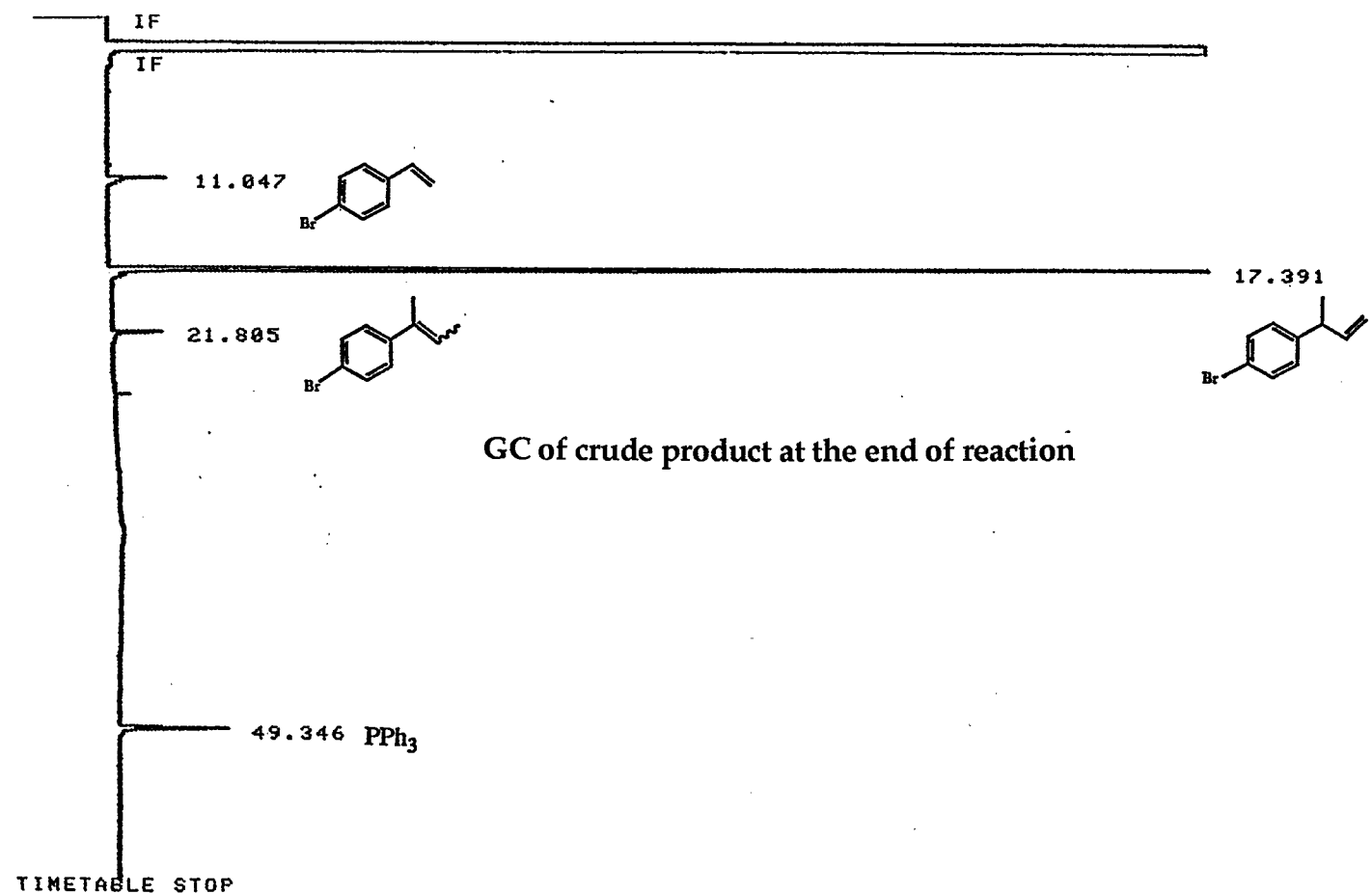
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* RUN # 233 MAR 14, 1981 18:44:18

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TIMETABLE STOP

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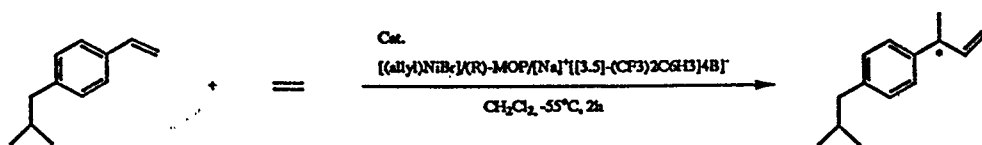
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AREA%

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MUL FACTOR=1.0000E+00

Reaction.**GC Test Condition**

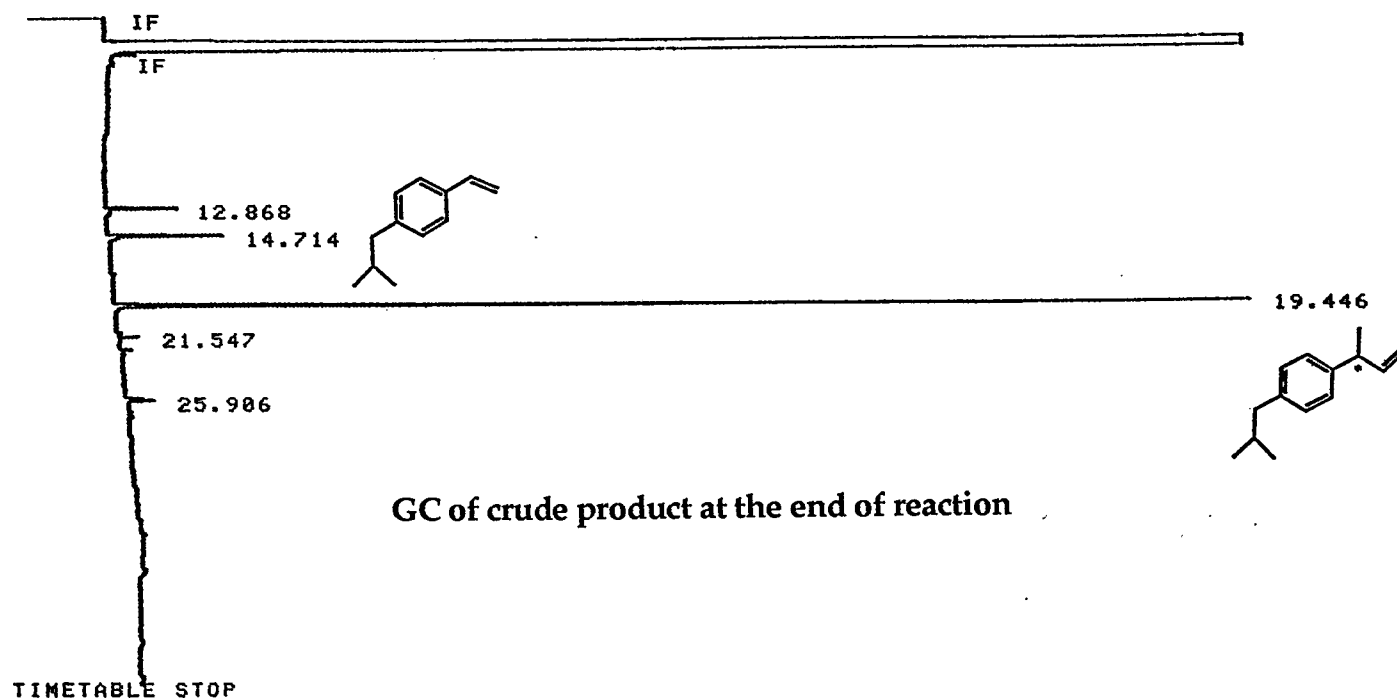
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	Temp	Time	($^\circ\text{C}/\text{min}$)	Temp	Time	Time
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* RUN # 403 MAR 28, 1997 20:46:56

START



GC of crude product at the end of reaction

TIMETABLE STOP

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RUN# 403 MAR 28, 1997 20:46:56

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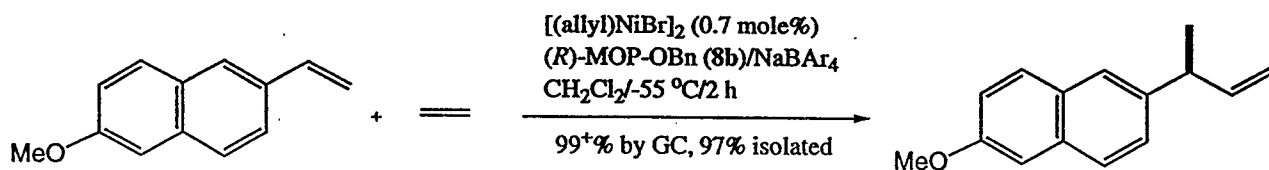
AREA%

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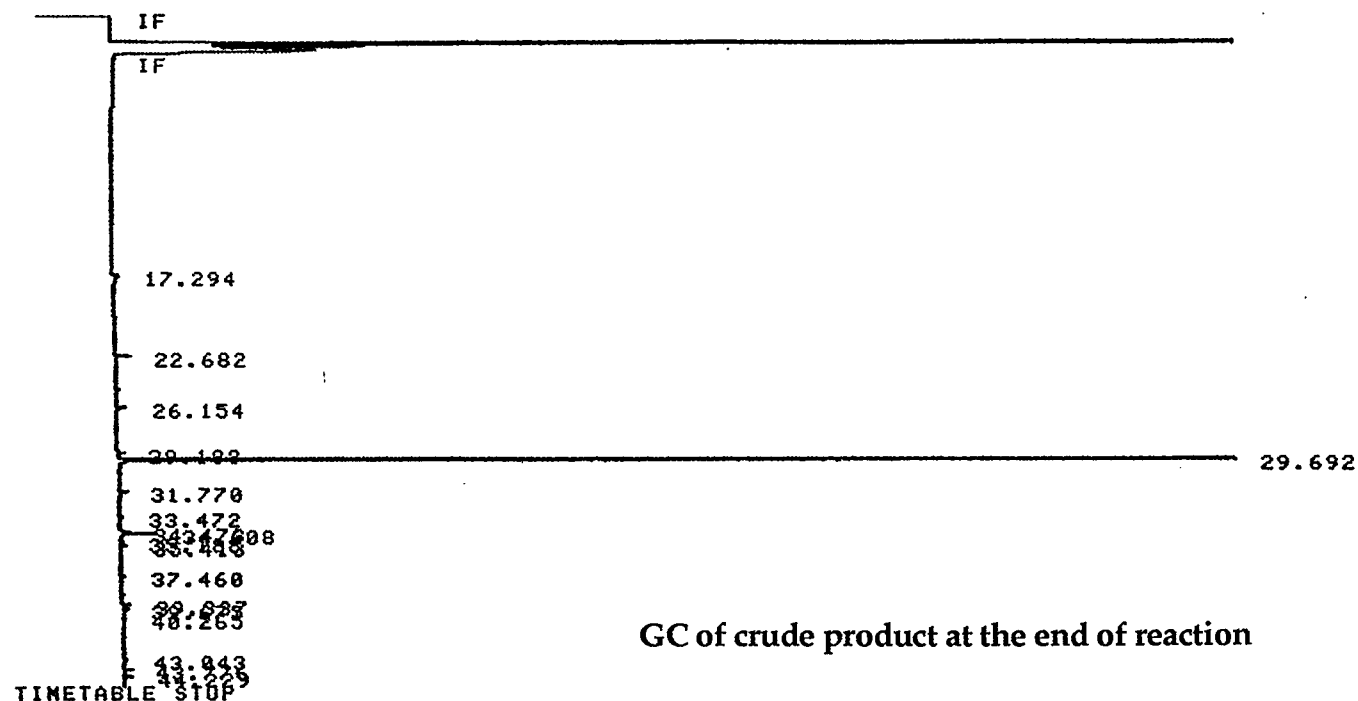


Crude GC spectrum:

GC condition: Initial Temp. 120 °C; Initial Time 10 min; rate 4 °C/min; Final Time 250 °C.

* RUN # 504 APR 28, 1997 15:24:13

START



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RUN# 504 APR 28, 1997 15:24:13

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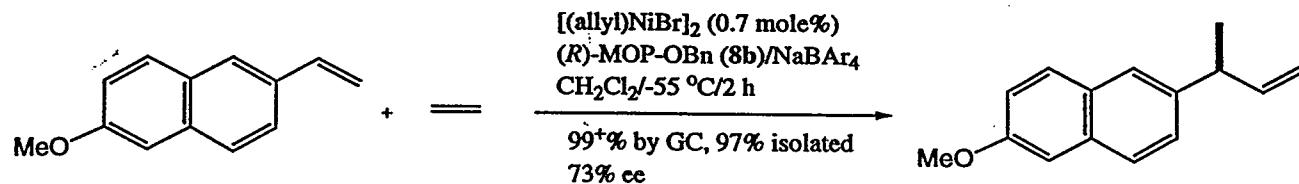
AREA%

RT	AREA	TYPE	WIDTH	AREA%
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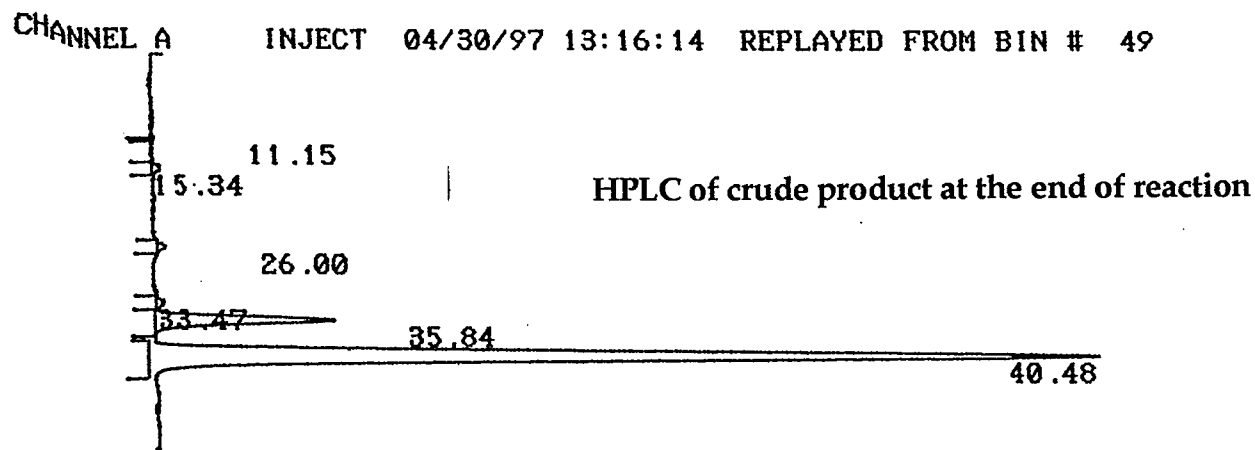
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MUL FACTOR=1.0000E+00

*



HPLC condition:
 CHIRACEL OJ column (Daicel); solvent hexane/*i*-PrOH = 95/5; rate 0.5 ml/min.



04/30/97 13:16:14 CH= "A" PS= 1.

FILE 1. METHOD 0. RUN 360 INDEX 358 BIN 49

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5	13.174	35.84	571309 03	73% ee
6	85.394	40.48	3703083 01	

TOTAL 100. 4336485