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September 2014: The paragraphs above replace the section "Handling and Disposal of Hazardous Chemicals" in the originally published version of this article. The statements above do not supersede any specific hazard caution notes and safety instructions included in the procedure.

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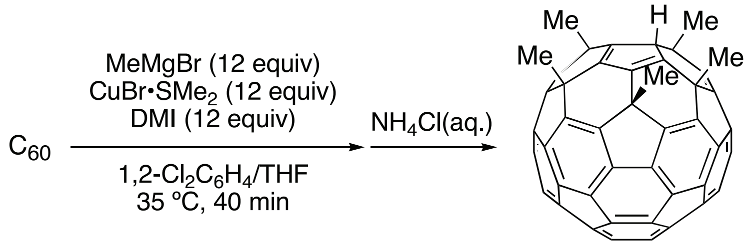
SYNTHESIS OF 6,9,12,15,18-PENTAMETHYL-1,6,9,12,15,18-HEXAHYDRO(C_{60}-I_h)[5,6]FULLERENE



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Checked by Peter Wipf and David L. Waller.[2]

1. Procedure

A 200-mL two-necked, round-bottomed flask (Note 1) connected to a vacuum/nitrogen manifold through a three-way stopcock is equipped with a Teflon-coated magnetic stirring bar, a vacuum/nitrogen inlet, and a glass stopper. A microcrystalline sample of [60]fullerene (2.00 g, 2.78 mmol) (Note 2) is placed in the 200-mL flask and the apparatus is flushed with nitrogen. The glass stopper is replaced with a rubber septum, and 1,2-dichlorobenzene (90 mL) (Note 3) is introduced into the flask via a syringe under nitrogen. The rubber septum is again replaced with a glass stopper. The reaction mixture is cooled with an ice/water bath and stirred under reduced pressure (1 mmHg) for 30 min to remove dissolved oxygen. Then the flask is flushed with nitrogen and warmed to room temperature (approximately 23 °C).

A 500-mL three-necked, round-bottomed flask (Note 1), connected to a vacuum/nitrogen manifold through a three-way stopcock, is equipped with a 3-cm Teflon-coated magnetic stir bar, a vacuum/nitrogen inlet, a 100-mL pressure-equalizing dropping funnel with a glass stopper, and a glass stopper. The flask is charged with copper(I) bromide-dimethyl sulfide complex (6.84 g, 33.3 mmol) (Note 4) and flushed with nitrogen (Note 5). The glass stopper on the top of the pressure-equalizing dropping funnel is replaced with a rubber septum, and the 1,2-dichlorobenzene solution of [60]fullerene is transferred to the dropping funnel via a Teflon cannula. The glass stopper on the 500-mL flask is replaced with a rubber septum and tetrahydrofuran (47 mL) (Note 6) is added to the copper complex via syringe. The resulting white suspension is stirred and the flask is placed into an oil bath (approximately 23 °C). A tetrahydrofuran solution of methylmagnesium bromide (3 M, 11.1 mL, 33.3 mmol) (Note 7) is added to this white suspension by syringe, followed by 1,3-dimethyl-2-imidazolidinone (DMI, 3.62 mL, 33.3 mmol) (Note 8). The organocopper reagent is quickly warmed in an oil bath to 35 °C within 5 min. The 1,2-dichlorobenzene solution of [60]fullerene in the dropping funnel is added at once to the organocopper reagent (Note 9). The color of the suspension changes to dark brown. The dropping funnel is replaced with a glass stopper.

After stirring for 40 min at 35 °C (Note 10), 3.0 mL of degassed saturated aqueous ammonium chloride solution is added quickly via syringe. The color of the mixture turns from dark brown to reddish brown. The septum is replaced with a glass stopper and the reaction mixture is stirred under reduced pressure (1 mmHg) at 23 °C to remove tetrahydrofuran and dimethyl sulfide until the volume is halved.

The concentrated mixture is diluted with degassed toluene (200 mL) and filtered through a pad of silica gel (Note 11) with toluene as eluent (Notes 12 and 13). The vermilion filtrate is collected into a 1-L, round-bottomed flask and concentrated on a rotary evaporator under reduced pressure (10 mmHg) at 40 °C. To remove 1,2-dichlorobenzene the bath temperature is raised to 80 °C until solid just begins to appear on the inside wall of the flask (Note 14). Nitrogen is added while the vacuum is broken, and the flask is removed from the rotary evaporator. Degassed methanol is added gently against the inside wall of the flask (Note 15). As methanol mixes with the product, the solution becomes cloudy and a precipitate forms. The addition is continued until precipitation is complete. The total amount of methanol required is approximately 400 mL. The precipitate is collected by filtration on a Buchner funnel (Note 16) and washed with methanol (5 x 10 mL) and hexane (3 x 10 mL). The product is dried under reduced pressure (1 mmHg) for 12 h at room temperature to obtain red microcrystals of the title compound (2.08 g, 2.61 mmol) in 94% overall yield and 91% purity (determined by HPLC analysis) (Note 17). The product can be used as is for further transformations, or it can be purified by preparative HPLC (Notes 18 and 19).

2. Notes

1. All glassware was dried in an oven (110 °C), assembled, and allowed to cool under nitrogen atmosphere. All solvents used for workup need to be degassed by N_2-bubbling since the final product as well as the intermediate are susceptible to air oxidation.

2. [60]Fullerene was provided by Frontier Carbon Corporation.

3. The checkers purchased 1,2-dichlorobenzene from Aldrich Inc. (99%) and used it without further purification. The submitters purchased 1,2-dichlorobenzene from Kanto Kagaku (>99.0%) and used it without further purification. The water content was checked with a Karl-Fischer Moisture Titrator (MK-210, Kyoto Electronics Company) to be less than 30 ppm.

4. Although the copper bromide dimethyl sulfide complex may be purchased from commercial suppliers and may work well, it is advisable to prepare it freshly because a successful reaction crucially depends on the purity of the copper complex. Copper bromide dimethyl sulfide complex, $CuBr•SMe_2$, was synthesized from commercially available CuBr (Aldrich Inc. (98%, checkers); Wako Pure Chemical Industries Ltd., (submitters)) according to the following literature procedures.[3,4] CuBr (25 g) is washed with methanol (4 x 50 mL) to remove colored impurities, and dried under reduced pressure for 1 h. The resulting green-tinged white powder of CuBr is dissolved in dimethyl sulfide (60 mL), and insoluble impurities are removed by filtration. The filtrate is diluted with hexane (200 mL) and the precipitate is collected by filtration under suction. After washing the colorless crystals five times with hexane, the light-sensitive white crystals are dried under a stream of nitrogen for 3 h. Drying under reduced pressure causes loss of the dimethyl sulfide ligand, which adversely affects the reaction. CAUTION: All procedures need to be performed in a well-ventilated hood because of the foul odor of dimethylsulfide.

5. The dimethyl sulfide complex $CuBr•SMe_2$ should not be kept under reduced pressure, as it will lose the sulfide ligand.[5]

6. Anhydrous tetrahydrofuran was purchased from EMD Chemicals Inc. (checkers) or Wako Pure Chemical Industries Ltd. (submitters) and used as received. The water content was checked with a Karl-Fischer Moisture Titrator (MK-210, Kyoto Electronics Company) to be less than 30 ppm.

7. A tetrahydrofuran solution of MeMgBr was purchased from

Aldrich Inc. (3 M, checkers) or Tokyo Kasei Kogyo Co., Ltd. (1 M, submitters) and used as received. Excess Grignard reagent is necessary to ensure completion of the reaction, since the copper reagent decomposes in competition with the desired reaction. The amount of excess Grignard reagent necessary is therefore reagent-dependent, and, for instance, the corresponding phenylation reaction under similar conditions may need about 8 equiv of PhMgBr and copper salt.

8. 1,3-Dimethyl-2-imidazolidinone (>98.0%) was purchased from Aldrich Inc. (checkers) or Tokyo Kasei Kogyo Co., Ltd. (submitters) and used without purification.

9. All operations from the addition of the solution of MeMgBr to the addition of the 1,2-dichlorobenzene solution of [60]fullerene are performed in about 15 min.

10. The flask is connected to a nitrogen-inlet/outlet during the reaction so that positive pressure due to ethane formation can be released.

11. Filtration is performed by silica gel flash chromatography (45 x 200 mm size) with the use of 90 g of silica gel (Sorbent Technologies Silica gel, particle size 230 – 450 mesh (checkers); Kanto Kagaku silica gel 60, spherical neutral, particle size 40 – 100 mm (submitters)).

12. The flask is washed with toluene three to ten times (the total amount is approximately 100 mL). The silica gel is repeatedly washed with toluene until the color of the filtrate turns to pale yellow.

13. The product gradually reacts with oxygen in air to afford $C_{60}Me_5O_nH$ (n = 2-3) in solution, therefore filtration needs to be performed as quickly as possible.

14. Care must be taken to stop evaporation when solid material just appears on the wall.

15. To minimize air oxidization of the product, methanol must be added immediately after the evaporation is complete.

16. If a part of the fine powder of the precipitate passes through the filter paper, the mother liquor can be filtered using the same filter paper.

17. HPLC analysis (flow rate: 1 mL/min) was performed on a Buckyprep column (Nacalai Tesque. Co. Ltd., 4.6 x 250 mm) with toluene/isopropanol (7/3) as eluent or an ODS column (4.6 x 250 mm) with toluene/isopropyl alcohol (3/7) as eluent.

18. The product shows the following spectroscopic properties: IR

(neat) cm^{-1}: 2973, 2912, 2858, 1572, 1546, 1518, 1459, 1370, 1324, 1286, 1265, 1234, 1169, 1145, 1128, 792, 747, 684; ^{1}H NMR (500 MHz, $CS_2/CD_3COCD_3(5\%)$) δ: 2.34 (s, 6 H), 2.35 (s, 6 H), 2.46 (s, 3 H), 4.50 (s, 1 H, C_{60}-*H*); ^{13}C NMR (100 MHz, $CS_2/CD_3COCD_3(5\%)$) δ: 27.23 (2C), 27.61 (2C), 33.14 (1C), 51.37 (1C), 51.45 (2C), 53.51 (2C), 59.75 (1C), 143.61 (2C), 144.12 (2C), 144.48 (2C), 144.53 (2C), 144.77 (2C), 144.89 (4C), 145.20 (2C), 145.42 (2C), 145.87 (2C), 145.96 (2C), 146.98 (1C), 147.14 (2C), 147.24 (2C), 148.03 (2C), 148.12 (2C), 148.29 (3C), 148.54 (2C), 148.60 (2C), 148.91 (4C), 149.10 (2C), 150.12 (2C), 154.27 (2C), 154.37 (2C), 154.62 (2C), 157.76 (2C).

19. The purity of the product in solution stored in the presence of air decreased to 80% in 24 h. Although the product is rather stable as a solid, its storage under air for several months may lead to a decrease of the purity.

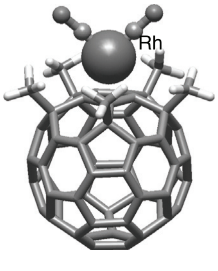
Safety and Waste Disposal Information

All hazardous materials should be handled and disposed of in accordance with "Prudent Practices in the Laboratory"; National Academy Press; Washington, DC, 1995.

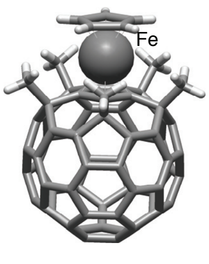
3. Discussion

Among numerous procedures to install organic residues into fullerenes, the procedure described here is unique for its selectivity and efficiency, as well as for the versatility of the product. The reaction can install five organic groups of considerable diversity into [60]fullerene in a single step in essentially quantitative yield.[6] The same reaction puts three organic groups onto [70]fullerenes.[7] This process represents one of the two reactions that are known for fullerenes to take place in nearly quantitative yield.[8] The examples are shown in Table 1. For the addition of arylmagnesium bromide/CuBr•SMe_2 reagents, the 1,3-dimethyl-2-imidazolidinone additive is not necessary. However, the additive is mandatory for the MeMgBr addition.

The penta-addition product has a cyclopentadienyl moiety surrounded by the five organic groups, and it can be derivatized to a number of interesting compounds. As in standard cyclopentadiene chemistry, the cyclopentadienyl moiety can be converted to metal complexes.[9] One striking application is the synthesis of a hybrid of ferrocene and the fullerene (bucky ferrocene).[8b,c] The penta-organo groups can serve to protect from oxidation low-valent metal atoms attached to the center cyclopentadienide group through steric and electronic protective effects.[8i] Crystal structures of some representative metal complexes are shown below.



$Rh(C_{60}Me_5)(CO)_2$



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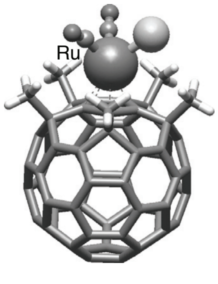

$Ru(C_{60}Me_5)Cl(CO)_2$

Table 1. Addition of Organocopper Reagent to Fullerenes

Fullerene	R	Product	RMgBr (equiv.)	$CuBr{\cdot}SMe_2$ (equiv.)	Yield (%)	reference
C_{60}	Me[a]	$C_{60}R_5H$	12	12	93	this work
C_{60}	Me[a]	$C_{60}R_5H$	30	30	92	6c
C_{60}	Ph	$C_{60}R_5H$	15	15	99.5	6b
C_{60}	4-$CF_3C_6H_4$	$C_{60}R_5H$	12	12	99	6b
C_{60}	4-$MeOC_6H_4$	$C_{60}R_5H$	16	16	99	6b
C_{60}	4-ClC_6H_4	$C_{60}R_5H$	15	15	99.6	6b
C_{60}	4-PhC_6H_4	$C_{60}R_5H$	15	15	99.8	6b
C_{60}	(*E*)-1-propenyl[b]	$C_{60}R_5H$	25	50	85	6d
C_{60}	(*Z*)-1-propenyl[b]	$C_{60}R_5H$	25	50	77	6d
C_{60}	(*E*)-2-phenylethenyl[b]	$C_{60}R_5H$	25	50	83	6d
C_{70}	Me[a]	$C_{70}R_3H$	30	30	90	7b
C_{70}	Ph	$C_{70}R_3H$	30	30	95	7b
C_{70}	4-PhC_6H_4	$C_{70}R_3H$	30	30	99	7b
C_{70}	4-$CF_3C_6H_4$	$C_{70}R_3H$	16	16	94	7b
C_{70}	4-ClC_6H_4	$C_{70}R_3H$	16	16	94	7b
C_{70}	1-naphthyl	$C_{70}R_3H$	16	16	95	7b

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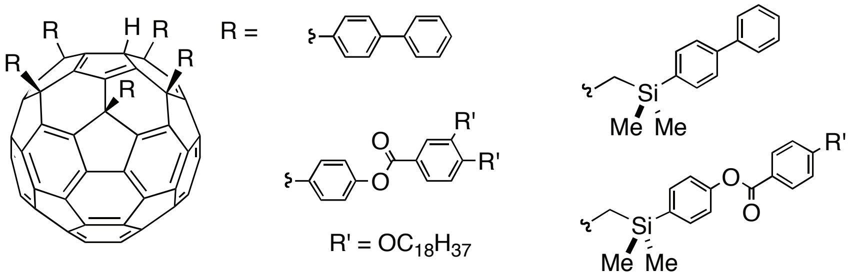
[a] 1,3-Dimethyl-2-imidazolidinone was used as an additive. [b] Substituted ethenyllithium reagents were used instead of Grignard reagents.

The fullerene compounds serve as useful building blocks in supramolecular chemistry.[10] Another application of the metal complexes is the formation of bilayer vesicles upon dissolution of a potassium salt in an aqueous solution.[9a] Upon installation of five suitable side chains, the shuttlecock-shaped penta-adduct exhibits a columnar liquid crystalline phase.[9d,e,f]



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2. Department of Chemistry, University of Pittsburgh, Pittsburgh, PA 15260, USA.
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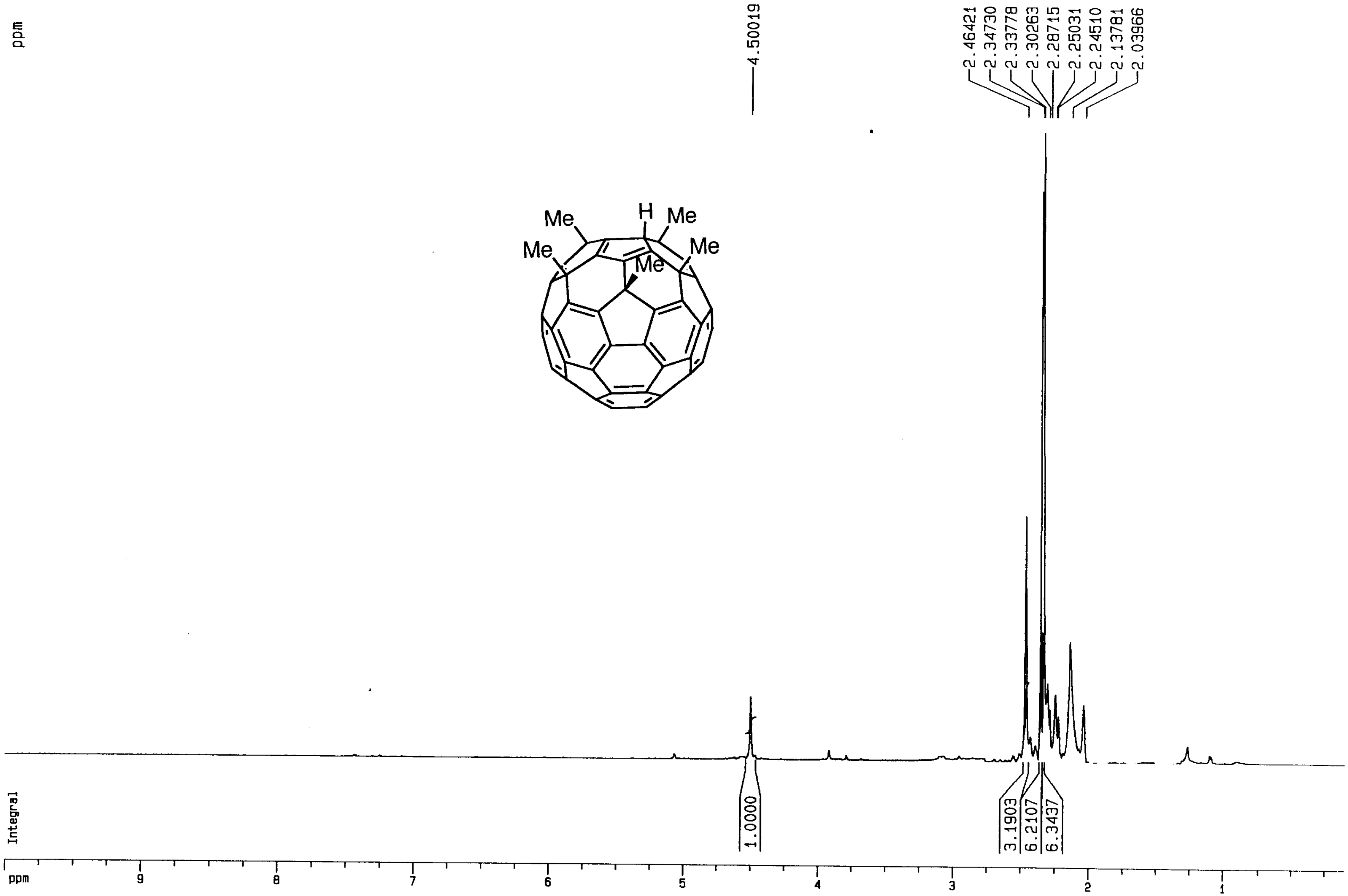
Appendix

Chemical Abstracts Nomenclature (Registry Number)

[60]Fullerene: [5,6]Fullerene-C60-Ih; (99685-96-8)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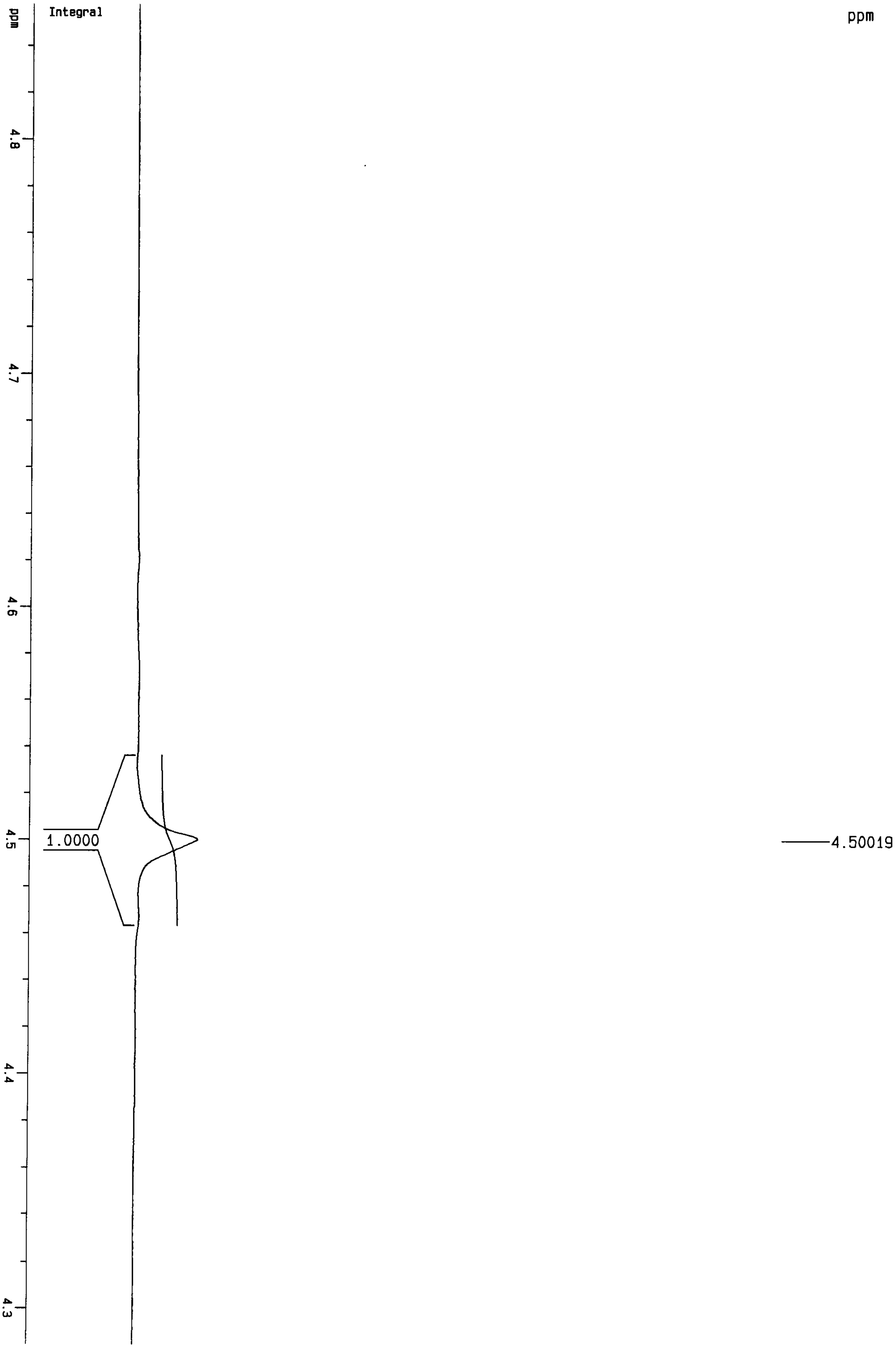
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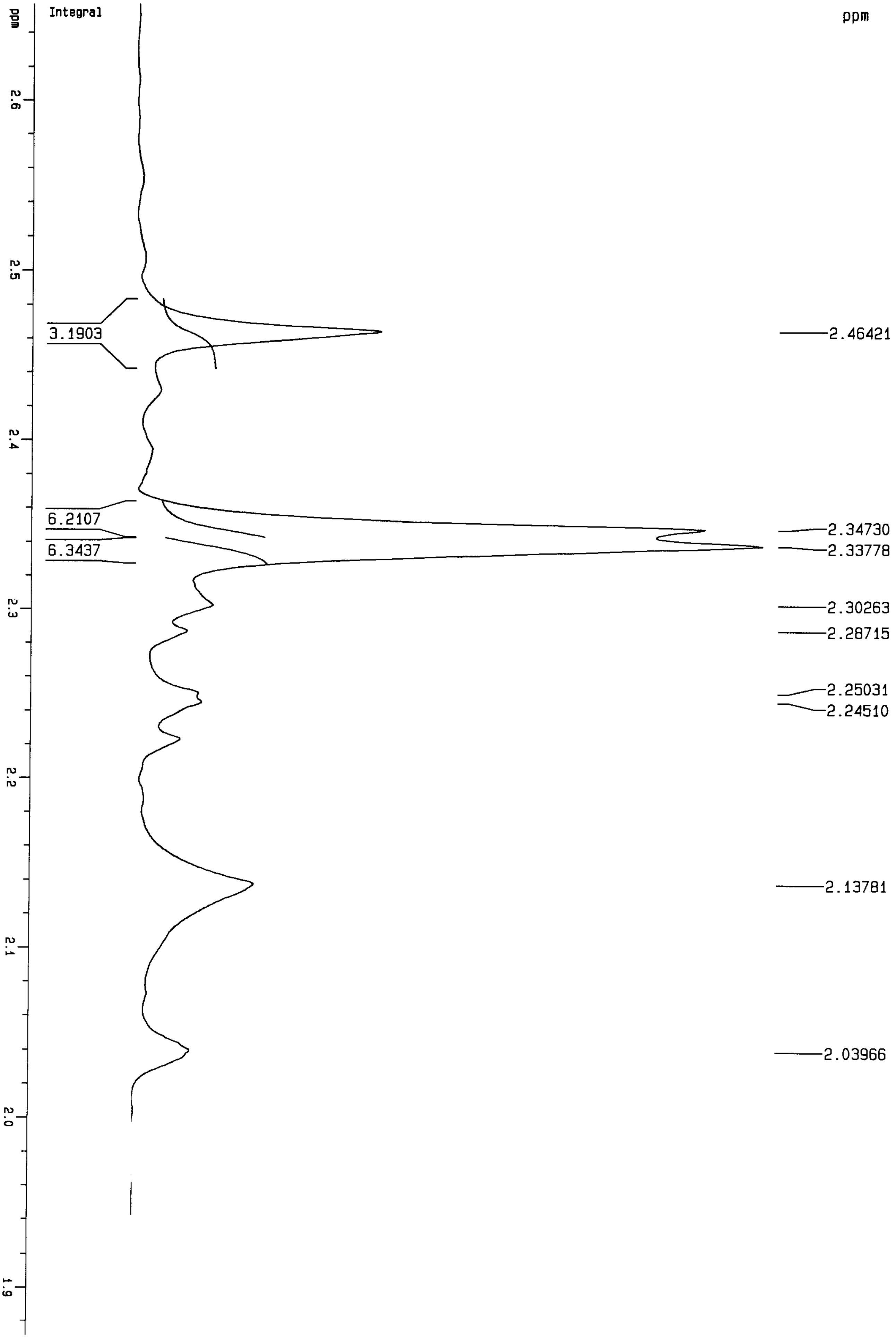
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