β-Deuterium Isotope Effects for the Solvolysis of 2-Methyl-d_3-*exo*-2-norbornyl *p*-Nitrobenzoate and 2-Methyl-d_3-*endo*-2-norbornyl *p*-Nitrobenzoate

René J. Muller, Charles Winternitz, and B. L. Murr*

Department of Chemistry, The Johns Hopkins University, Baltimore, Maryland 21218

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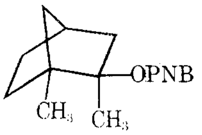
Kinetic isotope effects for the solvolysis of 2-methyl-d_3-*exo*-2-norbornyl *p*-nitrobenzoate and 2-methyl-d_3-*endo*-2-norbornyl *p*-nitrobenzoate were determined in 70% aqueous ethanol. Within experimental error, k_H/k_D for both epimers are similar—exo *p*-nitrobenzoate (1.22 ± 0.02 at 75.0°), endo *p*-nitrobenzoate (1.26 ± 0.04 at 130.0°; 1.31 ± 0.05 corrected to 75.0°)—where k_H/k_D is calculated for three deuteriums for fully deuterated substrate. The similarity of the kinetic isotope effects for the exo and endo epimers argues against the supposition of extensive bridging in the intermediate for the solvolysis of the exo *p*-nitrobenzoate. These results are in good agreement with kinetic isotope effect measurements for other deuterated tertiary norbornyl substrates already in the literature.

There is extensive experimental evidence that carbonium ions derived from solvolysis of esters of exo tertiary norbornanols are classical and do not involve significant bridging.

Goering and Humski, on observing that most of the activity remained in the products of solvolysis (alcohol + olefin) of optically active 1,2-dimethyl-*exo*-2-norbornyl *p*-nitrobenzoate (**1**) in 90% aqueous acetone, concluded that ionization proceeded predominantly through the asymmetric classical ion **2**.[1]



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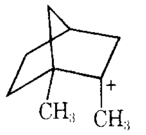

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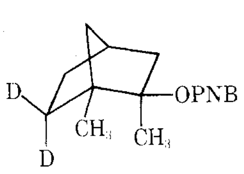
The same workers,[2] in trying to establish experimentally that the large γ-deuterium isotope effect (1.10) reported for the solvolysis of the secondary 6,6-dideuterio-*exo*-2-norbornyl brosylate[3] was a manifestation of assisted ionization, measured the rate of solvolysis of the tertiary 6,6-dideuterio-1,2-dimethyl-*exo*-2-norbornyl *p*-nitrobenzoate (**3**) in 90% aqueous acetone (78.47°). They observed a negligible kinetic isotope effect (k_H/k_D was 1.02 ± 0.01), a result consistent with the expectation of a classical intermediate.



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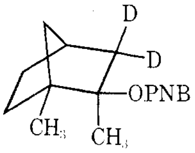

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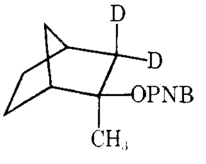
Humski[4] measured k_H/k_D for 1,2-dimethyl-*exo*-2-norbornyl-*3,3*-d_2 *p*-nitrobenzoate (**4**) in mixtures of 50–70% dioxane–water (69.30°). Although the observed kinetic isotope effects varied from 1.278 ± 0.010 for 50% dioxane–water to 1.351 ± 0.079 for 70% dioxane–water, the k_H/k_D calculated for ionization after correction for elimination was remarkably constant (1.22) over the entire range of solvent composition.[5a] Humski concluded that a k_H/k_D of 1.22 indicated that solvolysis proceeded through a classical intermediate.

Borčić and Sunko[6] measured k_H/k_D for both 2-methyl-*exo*-2-norbornyl-*3,3*-d_2 *p*-nitrobenzoate (**5**) and its endo epimer (**6**) in 70% aqueous acetone.[7] They observed a k_H/k_D of 1.334 ± 0.018 (95.0°) for **5** and 1.306 ± 0.060 (120.7°) for **6**. Even with the larger uncertainty in the value for **6**, there does not seem to be a significant difference in kinetic isotope effects between the exo and endo *p*-nitrobenzoates. It should also be noted that the k_H/k_D for **5** falls within the range of the *observed* k_H/k_D for **4** measured by Humski in 70% dioxane–water (1.351 ± 0.079).[4]



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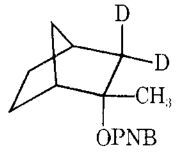

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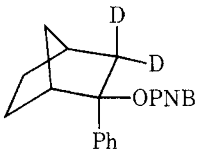
Schaefer[8] examined 2-phenyl-*exo*-2-norbornyl-*3,3*-d_2 *p*-nitrobenzoate (**7**) and the endo epimer (**8**) in 60% aqueous dioxane. The observed k_H/k_D for **7** was 1.18 ± 0.02 (39.50°) and that for **8** was 1.15 ± 0.02 (62.50°). After correction to full deuteration[5b] (the *p*-nitrobenzoates contained 1.87 atoms of deuterium per molecule), k_H/k_D per D was 1.09 ± 0.01 for **7** and 1.08 ± 0.01 for **8**. Within the certainty of the measurements, the kinetic isotope effects for the exo and endo *p*-nitrobenzoates are indistinguishable and it was concluded that in both cases solvolysis involved a classical intermediate.



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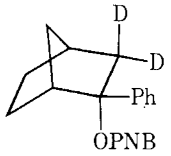

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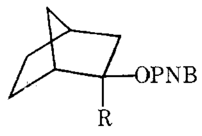
To complete the series of kinetic isotope effect measurements on tertiary norbornyl substrates, we prepared 2-methyl-d_3-*exo*-2-norbornyl *p*-nitrobenzoate (**9b**) and the endo epimer (**10b**)[9] and determined k_H/k_D in 70% aqueous ethanol at 75.0 and 130.0°, respectively. Rate constants for the solvolyses and the kinetic isotope effects (observed, corrected for full deuteration per D, corrected for full deuteration for three deuteriums, and, for **10**, corrected to 75.0°) are given in Table I. Within experimental error, $k_H/$



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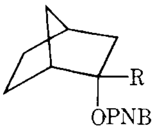

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a, R = CH_3
b, R = CD_3

Table I
Rate Constants and Kinetic Isotope Effects for the Solvolysis of 9a, 9b, 10a, and 10b in 70% Aqueous Ethanol[a]

Compd[b]	Temp, °C	$10k$, hr^{-1}	$(k_H/k_D)_{obsd}$	$(k_H/k_D)_{corr/D}$[c]	$(k_H/k_D)_{corr/3D}$[d]
9a	75.0	2.51 ± 0.03	1.19 ± 0.02	1.07 ± 0.01	1.22 ± 0.02
9b		2.11 ± 0.03			
10a	130.0	2.63 ± 0.05	1.25 ± 0.04	1.08 ± 0.01	1.26 ± 0.04
10b		2.11 ± 0.05		(correction to 75.0° negligible)	(1.31 ± 0.05 corrected to 75.0°)[e]

[a] Rate constants and standard deviations were calculated by computer as described in the Experimental Section and are the averages of two determinations. Errors for k_H/k_D were calculated from the formula given in W. J. Blaedel and V. W. Meloche, "Elementary Quantitative Analysis," 2nd ed, Harper and Row, New York, N.Y., 1963, p 642. [b] Deuterium analysis showed 2.59 atoms of D/molecule (86.3%) for **9b** and 2.74 atoms of D/molecule (91.3%) for **10b**.[12] [c] Isotope effect per D for fully deuterated substrate.[5b] [d] $[(k_H/k_D)_{corr/D}]^3$. [e] $(k_H/k_D)_{T_2} = (k_H/k_D)_{T1}{}^{T1/T2}$.

k_D for the exo and endo deuterated p-nitrobenzoates are virtually the same. For closer comparison, since neither ester was fully deuterated, the observed kinetic isotope effects were corrected for full deuteration for three deuteriums, giving 1.22 ± 0.02 for **9b** and, after further correction to 75.0°, 1.31 ± 0.05 for **10b**.[10]

It is interesting to compare these results with those of Humski and Schaefer cited earlier. (Because our p-nitrobenzoates are trideuterated and the others dideuterated, k_H/k_D values corrected per D for full deuteration[5b] will be used for this comparison.) The k_H/k_D for **9b** (1.07 ± 0.01) is in fair agreement with Humski's number (1.11) for the solvolysis of 4 in aqueous dioxane; the k_H/k_D values for Schaefer's exo and endo p-nitrobenzoates 7 (1.09 ± 0.01) and 8 (1.08 ± 0.01) are, within experimental error, identical with k_H/k_D for **9b** (1.07 ± 0.01) and **10b** (1.08 ± 0.01).[11] The near identity of k_H/k_D for 9 and 10 argues against significant participation for the solvolysis of **9b**, as the results quoted earlier argued against it for the solvolyses of the exo tertiary substrates in 1–8.

Experimental Section[12]

Synthesis. Methyl iodide-d_3 was prepared according to the procedure of Kuhn and Trischmann.[13]

2-Methyl-d_3-*endo*-2-norbornanol was prepared by adaptation of the procedure of Sauers.[14] A solution of Grignard reagent prepared from 51.64 g (0.3636 mol) of methyl iodide-d_3 and 8.8 g (0.36 mol) of magnesium in 110 ml of anhydrous ether was added to 20.0 g (0.182 mol) of norcamphor (Aldrich) in 150 ml of anhydrous ether. The reaction mixture was stirred at room temperature for 16 hr, allowed to stand overnight, and hydrolyzed by addition to a mixture of 200 g of ice, 26 g of ammonium chloride, and 50 ml of water. The layers were separated and the aqueous layer was extracted with ether (2 × 100 ml). The combined ether extracts were dried over magnesium sulfate and most of the solvent was removed by distillation through a Vigreux column. The crude product was distilled under aspirator pressure (~15 mm) to give 16 g (70%) of the deuterated norbornanol, bp 73.5–74.5°. The product solidified on standing, mp 30–31° (lit.[15] mp 31–32°).

2-Methyl-d_3-*endo*-2-norbornyl p-nitrobenzoate (10b) was prepared from the alcohol by the method of Brown.[15] To a stirred solution of 1 g (0.0079 mol) of the deuterated norbornanol in 30 ml of hexane, 2.72 ml (0.0079 mol) of n-butyllithium in hexane (Alfa Inorganics) was added with a syringe. Under nitrogen, 1.466 g (0.0079 mol) of p-nitrobenzoyl chloride (Aldrich, recrystallized from ligroin, mp 71–72°) was added to the stirred solution through a 15-cm tube attached to the flask. A fine, white precipitate appeared almost immediately and the suspension was stirred overnight.

The solid was removed by filtration and the hexane was removed on a rotary evaporator. Two recrystallizations from hot pentane afforded 0.5 g of **10b** mp 100–101° (lit.[15] mp 100.5°) after vacuum pumping. Deuterium analysis indicated the presence of 2.74 deuterium atoms/molecule (91.3%).

2-Methyl-d_3-*exo*-2-chloronorbornane was prepared by adaptation of the procedure of Bartlett and Sargent.[16] A mixture of 12.6 g of 2-methyl-d_3-*endo*-2-norbornanol and 75 ml of concentrated hydrochloric acid was stirred vigorously at room temperature for 2 hr. Petroleum ether was added and the organic layer was separated, washed with saturated calcium chloride, and dried over calcium chloride. The solvent was removed on a rotary evaporator, affording about 14 g of a colorless oil. The ir spectrum showed no hydroxyl absorption.

2-Methyl-d_3-*exo*-2-norbornanol was prepared by adaptation of a procedure of Bartlett and Sargent.[16] Ice-cold aqueous 1 N sodium hydroxide (175 ml) was added to the flask containing the crude norbornyl chloride from the preparation above. The mixture was heated at 95° for 45 min and then stirred vigorously at room temperature for 16 hr. Ether was added and the organic layer was separated, washed with water, and dried over magnesium sulfate. The solvent was removed by careful evaporation, yielding a white, fluffy solid. The alcohol was recrystallized four times from pentane and sublimed, affording 6 g (57%) of fine, needle-like crystals, mp 84.8–85.4° (lit.[16] mp 84–85°).

2-Methyl-d_3-*exo*-2-norbornyl p-nitrobenzoate (9b) was prepared from the alcohol by the method of Brown[15] as described previously for the endo epimer. The ester crystallized as white, shimmering plates, mp 113.5–114.5° (lit.[15] mp 114.5°). Deuterium analysis indicated the presence of 2.59 deuterium atoms/molecule (86.3%).

2-Methyl-*endo*-2-norbornyl p-nitrobenzoate (10a) and **2-methyl-*exo*-2-norbornyl p-nitrobenzoate (9a)** were prepared by the same procedures described above except that methyl iodide was used instead of methyl iodide-d_3.

Kinetic Procedure. The rates of solvolysis in 70% aqueous ethanol for **9a, 9b, 10a,** and **10b** were measured with a Cary 14 ultraviolet spectrophotometer equipped with a thermostated cell holder, by following the absorbance [λ_{max} 2610 Å (ϵ 9330)] as a function of time. Because p-nitrobenzoic acid [λ_{max} 2710 Å (ϵ 10,037)] had a component of absorption at the λ_{max} of the ester, it was necessary to subtract the A_∞ value of the ester from each A_t value in the kinetic plot. In all cases, plots of $A_t - A_\infty$ *vs.* time were linear. As a check on the sampling technique, the undeuterated ester was solvolyzed at the same time as the deuterated ester for each determination of k_H/k_D.

The solvolyses were carried out in 10-ml Pyrex break seal ampoules. About 3 ml of approximately 1.3 × 10^{-4} M ester solution was dispensed into the ampoule, which was then fitted with a drying tube, cooled in Dry Ice–acetone, and sealed. Typically, seven or eight ampoules of both deuterated and undeuterated ester were prepared for each run. Solvolyses of the exo p-nitrobenzoate esters were carried out at 75.0° and those of the endo p-nitrobenzoates were carried out at 130.0°. After equilibration for about 1 hr, tubes were withdrawn every 0.5 hr, cooled in Dry Ice–acetone, and stored in the freezer (−20°) until analysis. The infinity samples were solvolyzed for at least 10 half-lives.

To check the analytical method, a run with **9a** was made where the unconverted **9a** and the liberated acid (as the anion) were separated by extraction and analyzed separately. Plots of ln (A_t − A_∞) *vs.* time for the disappearance of the ester and ln (A_∞ − A_t) for the appearance of the acid were both linear and gave, within experimental error, the same rate constants as observed for solvolysis of **9a** measured by analyzing the ester–acid mixture.

The extraction procedure was carried out as follows. The aliquot to be analyzed (2 ml) was pipetted into a 50-ml separatory funnel (Teflon stopcock) containing 10 ml of spectral grade hexane and 1 ml of 5% sodium hydroxide. The separatory funnel was shaken vigorously for about 1 min. After the layers had separated, approximately 3 ml of the hexane solution was withdrawn with a Pasteur pipet and stored in a vial. The first few drops of the aqueous layer were discarded and the remainder of the solution was stored in a vial until analysis.

To prepare samples for the reference beam for the spectrophotometric analysis of both the hexane and the aqueous layers, an extraction was carried out exactly as described above except that 2 ml of 70% aqueous ethanol was used in place of the ester solution.

The 70% aqueous ethanol solution was prepared by weight, employing the appropriate corrections for buoyancy.[17] Reagent absolute ethanol (Pharmco) and distilled water were used without further purification. The solvent was stored in a sealed 2-l. erlenmeyer flask, equipped with a siphoning device.

Kinetic runs were carried out in 3-ml quartz uv cells (Pyrocell Manufacturing Company) which had a 1-cm path length. The cells had ground-glass stoppers, which were tightly sealed during the kinetic runs to minimize evaporation.

Beers' law plots of absorbance at 2610 Å *vs.* concentration were linear for both the exo and endo *p*-nitrobenzoate esters over the range of concentration through which the solvolysis kinetics were followed. Similar plots for *p*-nitrobenzoic acid both at 2710 Å (λ_{max} of the acid) and at 2610 Å (λ_{max} of the ester) were linear.

Rate constants were calculated from a sub-routine for plotting ln ($A_t - A_\infty$) *vs.* time of a computer program devised by York,[18] modified by Dr. Michael Marron and used previously by Dr. John Conkling for calculating the rates of solvolysis of deuterated norbornyl brosylates.[19] An IBM 7094 computer was used for the calculations, giving the first-order rate constant and standard deviation for each run.

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Registry No.—**9a**, 22467-58-9; **9a** free alcohol, 3212-15-5; **9b**, 53432-35-2; **9b** free alcohol, 53432-36-3; **10a**, 13351-30-9; **10a** free alcohol, 3212-16-6; **10b**, 53432-37-4; **10b** free alcohol, 53466-51-6; norcamphor, 497-38-1; methyl iodide-d_3, 865-50-9; *p*-nitrobenzoyl chloride, 122-04-3; methyl iodide, 74-88-4.

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(5) (a) When the correction is made for full deuteration, k_H/k_D per D is 1.11. (b) For full deuteration, k_H/k_D per D is given by $[k_H/k_D]_{obsd}^{1/X}$, where X = the number of atoms of deuterium per molecule [J. P. Schaefer, M. J. Dagani, and D. S. Weinberg, *J. Amer. Chem. Soc.*, **89**, 6938 (1967)].
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(9) The synthesis of the alcohol precursors of **10b** and **9b** was modeled after undeuterated analogs. See the Experimental Section.
(10) For the solvolysis of 1,2-dimethyl-*exo*-2-norbornyl *p*-nitrobenzoate (**4**) cited previously,[4] Humski observed that the k_H/k_D varied somewhat with the amount of elimination products as the solvent was changed from 50 to 70% dioxane-water. It should be pointed out that different amounts of elimination into the methyl groups of the undeuterated and deuterated *p*-nitrobenzoate esters could influence the k_H/k_D for **9** and **10**.
(11) Correction to 75° does not effect these numbers significantly.
(12) Melting points were determined in glass capillary tubes with a Thomas-Hoover apparatus and are corrected. Deuterium analyses (combustion-falling drop method) were performed by Mr. Joseph Nemeth, Urbana, Ill.
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Bicyclo[3.2.0]hept-6-en-2-yl Carbonium Ion. 2-Methyl Substituent Effects[1]

Kazuyuki Yano

Department of Chemistry, Saitama Medical School, Moroyama-cho, Iruma-gun, Saitama 350-04, Japan

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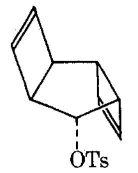
The methyl substituent effects on the rates and products of the solvolysis reactions of *exo*- and *endo*-2-methylbicyclo[3.2.0]hept-6-en-2-yl *p*-nitrobenzoates (**6-OPNB** and **5-OPNB**, respectively) were investigated by comparing those of the demethylated analogs (**7-OTs** and **2-OTs**, respectively) to elucidate the nature of the bicyclo[3.2.0]hept-6-en-2-yl carbonium ion **3**. The acetolysis rate of **7-OTs** indicates a rate enhancement of 3500 (25°) when compared to that of **2-OTs**, while **6-OPNB** undergoes solvolysis at a rate only 2.8 times as fast as **5-OPNB** at 25°. The acetolysis of **7-OTs** gives exclusively *anti*-7-norbornenyl acetate **14**, while **2-OTs** undergoes acetolysis to a 35:65 mixture of **7-OAc** and **14**. On the other hand, **5-OPNB** and **6-OPNB** yield exclusively **6-OH** through one common classical carbonium ion **15**. The above results suggest that **3** is mainly stabilized by a homoallylic interaction to lead to the initial carbonium ion **12**, which rearranges to the stable bishomocyclopropenyl carbonium ion **13**.

Although there is no straightforward demonstration of the existence of homoallylic carbonium ion intermediates, the unusual reactivities and stereospecific products of the solvolysis reactions of some rigid polycyclic ring compounds have been interpreted by homoallylic interactions between electron-deficient carbinyl carbon and electron-rich double bond.[2] In our recent study of *anti*-tricyclo[5.2.0.0^{2,5}]nona-3,8-dien-6-yl tosylate (**1-OTs**)[3] we observed that the rate of acetolysis of **1-OTs** is enhanced by a factor of 7.3 × 10^4 when compared to that of *endo*-bicyclo[3.2.0]hept-6-en-2-yl tosylate (**2-OTs**) which is in the partially similar ring system. In connection with this result, it seems to be of some interest to further investigate the nature of the bicyclo[3.2.0]hept-6-en-2-yl carbonium ion **3**.[2-4] Thus, *exo*- and *endo*-2-methylbicyclo[3.2.0]hept-6-en-2-yl *p*-nitrobenzoates (**6-OPNB** and **5-OPNB**, respectively) and



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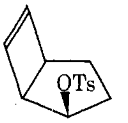

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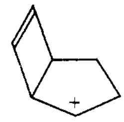

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