Formal transfers of hydride from carbon–hydrogen bonds. Attempted generation of H_2 by intramolecular protonolyses of the activated carbon–hydrogen bonds of dihydrobenzimidazoles

Philippe Brunet and James D. Wuest

Abstract: Protonolyses of carbon–hydrogen bonds can occur under suitable conditions to produce carbocations and H_2. In an effort to accelerate these fundamental reactions, we have attempted to make them intramolecular by devising compounds in which carbon–hydrogen bonds designed to be particularly good formal donors of hydride are held in close proximity to acidic sites. Dihydrobenzimidazoles **4** and **11** are compounds of this type, since the carbon–hydrogen bonds at C2 are activated as formal donors of hydride by adjacent lone pairs in a dihydroaromatic ring, and acidic anilinium and carboxylic acid groups are held nearby. Unfortunately, this proximity does not lead to the formation of H_2 by protonolysis; instead, other reactions intervene when compounds **4** and **11** are subjected to pyrolysis.

Key words: intramolecular protonolysis of carbon–hydrogen bonds, formal donors of hydride, generation of H_2, dihydrobenzimidazoles.

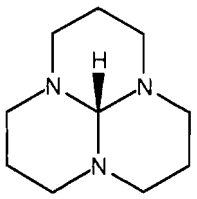
Résumé : La protonolyse des liaisons carbone–hydrogène peuvent se produire dans des conditions appropriées pour conduire à des carbocations et du H_2. Dans le but d'accélérer les vitesses de ces réactions fondamentales, on a essayé de faire des réactions intramoléculaires en construisant des composés dans lesquels des liaisons carbone–hydrogène comportant des donneurs formels d'hydrures particulièrement bons seront maintenues à faible distance des sites acides. Les dihydrobenzimidazoles **4** et **11** sont des composés de ce type puisque les liaisons carbone–hydrogène en C(2) sont activées comme donneurs formels d'hydrure par les paires non partagées adjacentes du noyau dihydroaromatique alors que les groupes acides anilinium et acide carboxylique sont maintenus à proximité. Malgré cette proximité, la protonolyse ne conduit malheureusement pas à la formation de H_2; quand les composés **4** et **11** sont soumis à une pyrolyse, il y a plutôt intervention d'autres réactions.

Mots clés : protonolyse intramoléculaire de liaisons carbone–hydrogène, donneurs formels d'hydrure, génération de H_2, dihydrobenzimidazoles.

[Traduit par la rédaction]

Introduction

Carbon–hydrogen bonds serve as formal donors of hydride in a variety of well-known redox reactions (1). Of particular practical importance are the formal transfers of hydride from carbon–hydrogen bonds that occur during catalytic cracking and reforming, as well as closely related reactions in which protonolyses of the carbon–hydrogen bonds of simple alkanes by strong acids produce carbocations and H_2 (2). To learn more about these fundamental processes, we have prepared compounds designed to be especially good formal donors of hydride, and we have studied their reactions with acids (3, 4). This work has shown that orthoformamide **1** and related compounds are remarkably reactive substrates for protonolyses, and their activated central carbon–hydrogen bonds react with acids to liberate H_2 and give the corresponding guanidinium ions under surprisingly mild conditions.[3] To further accelerate protonolyses of carbon–hydrogen bonds, we have attempted to make them intramolecular by devising a series of compounds in which similarly activated carbon–hydrogen bonds are held in close proximity to acidic groups (6). In this article, we describe the synthesis and reactions of two dihydrobenz-



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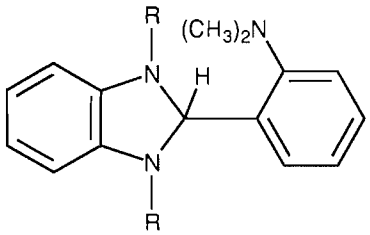
[3] Few other reactions are known in which protonolyses of carbon–hydrogen bonds generate H_2 (5).

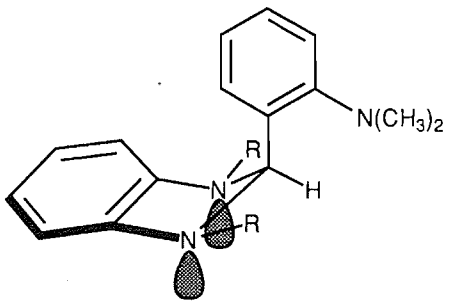
imidazoles that have been designed in this way to undergo intramolecular protonolyses of carbon–hydrogen bonds.

Results and discussion

Acid-catalyzed condensation of *N,N'*-dimethyl-1,2-benzenediamine (7) with 2-(dimethylamino)benzaldehyde (8) produced 2-[2-(dimethylamino)phenyl]-1,3-dimethyl-2,3-dihydro-1*H*-benzimidazole (**2**) in 75% yield. Dihydrobenzimidazole **2** incorporates a carbon–hydrogen bond at C2 able to serve as a



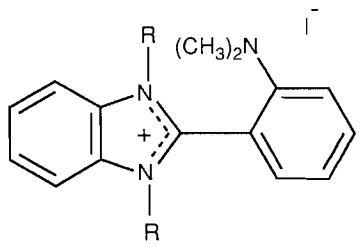
2 (R = CH_3)



2a (R = CH_3)

particularly effective formal donor of hydride for the following reasons : It is adjacent to two lone pairs in a dihydroaromatic ring, and loss of hydride would generate a stable benzimidazolium ion.[4] The conjugate acid of *N,N*-dimethylaniline is weaker (pK_a 5.1) than that of 1,2-benzenediamine (pK_a 4.5) (9), so protonation of compound **2** should produce a salt in which the hydridic carbon–hydrogen bond of the dihydrobenzimidazole unit is held in close proximity to an acidic dimethylanilinium group. We hoped that this juxtaposition would promote the formation of H_2 by intramolecular protonolysis.

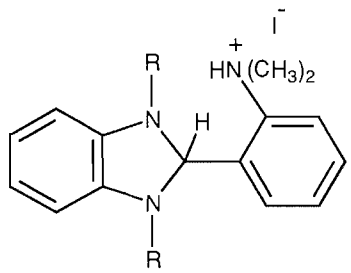
Examination of the IR spectrum of compound **2** in $CHCl_3$ revealed no Bohlmann bands in the region between 2750 and 2400 cm^{-1}, suggesting that the preferred conformation is structure **2a**, in which no lone pairs are antiperiplanar to the carbon–hydrogen bond at C2 (10).[5] Although this observation indicates that the carbon–hydrogen bond at C2 is not notably weakened and polarized by mixing of σ^*_{CH} with adjacent lone-pair orbitals, dihydrobenzimidazole **2** is nevertheless an effective reducing agent.[6] For example, treatment of com-



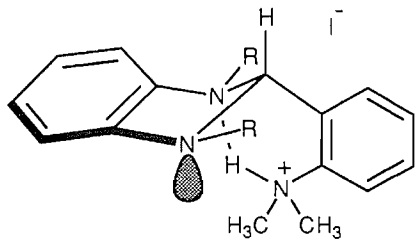
3 (R = CH_3)

pound **2** with methanolic I_2 at 25°C in the presence of K_2CO_3 rapidly produced benzimidazolium iodide **3** in 85% yield.

As expected, addition of aqueous HI to dihydrobenzimidazole **2** in deoxygenated ether provided salt **4** in high yield. Comparison of the ^1H NMR spectra of compounds **2** and **4** confirmed that the principal site of protonation is the nitrogen atom of the dimethylaniline group, since the hydrogens of this



4 (R = CH_3)



4a (R = CH_3)

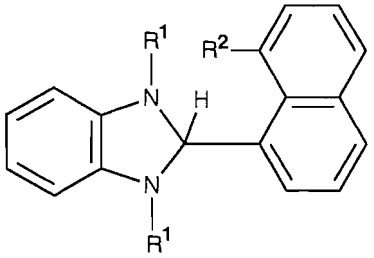
group showed important downfield shifts while those of the benzenediamine unit experienced only moderate shifts. Curiously, the hydrogen at C2 appears at δ 5.86 ($CDCl_3$) in dihydrobenzimidazole **2** but is shifted *upfield* to δ 4.83 ($CDCl_3$) in salt **4**. This unexpected shielding presumably arises in part because intramolecular hydrogen bonding now favors conformation **4a**, in which the carbon–hydrogen bond at C2 becomes antiperiplanar to two lone pairs. This conclusion is supported by the presence of a Bohlmann band at 2698 cm^{-1} in the IR spectrum ($CHCl_3$) of salt **4**. Closely similar conformations are known to be preferred by other 2-substituted dihydrobenzimidazoles capable of participating in intramolecular hydrogen bonding (6). Direct evidence for the presence of an intramolecular hydrogen bond was provided by the concentration-independence of the chemical shift of the anilinium hydrogen.

Unfortunately, conformation **4a** is not suitable for the gen-

[4] The estimated hydride affinity of benzimidazolium is 200 kcal/mol (6*d*).

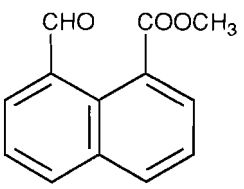
[5] The nitrogen atoms in dihydrobenzimidazoles are known to be distinctly pyramidal (6).

[6] Other dihydrobenzimidazoles are known to be effective reducing agents (11).



5 (R^1 = CH_3, R^2 = HOOC)

6 (R^1 = CH_3, R^2 = CH_3OOC)



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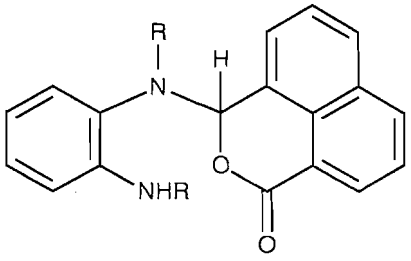
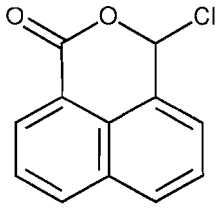


8 (R = CH_3)



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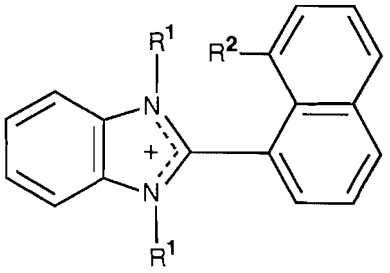


10 (R^1 = CH_3, R^2 = ^-OOC)

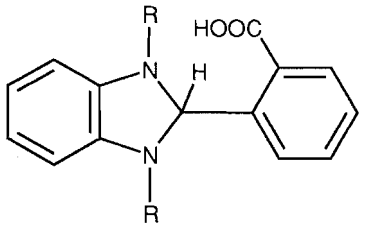
eration of H_2 by intramolecular protonolysis of the carbon–hydrogen bond at C2. The carbon–hydrogen bond is activated as a formal source of hydride by two antiperiplanar lone pairs, but the acidic hydrogen of the dimethylanilinium group is not nearby. Although more reactive conformers are presumably accessible, thermal decomposition of salt **4** led only to complex mixtures, and neither H_2 nor benzimidazolium salt **3** could be detected among the products.

A similar molecule designed to be able to undergo intramolecular protonolysis of a carbon–hydrogen bond is dihydrobenzimidazole **5**, which juxtaposes a carboxylic acid and a carbon–hydrogen bond that can serve as a good formal donor of hydride. We attempted to prepare this compound from the corresponding methyl ester **6**, which was obtained in 43% yield by acid-catalyzed condensation of *N,N'*-dimethyl-1,2-benzenediamine (7) with methyl 8-formyl-1-naphthalenecarboxylate (**7**). Ester **7** was made by adding CH_2N_2 to 1,8-naphthaldehydic acid (12), which was synthesized from acenaphthenequinone by a modification of the standard method (13). Unfortunately, basic hydrolysis of ester **6** and subsequent acidification did not provide the expected acid **5**, but gave instead the isomeric aminolactone **8** in 60% yield. Alternatively, compound **8** could be prepared more directly in 80% yield by treating *N,N'*-dimethyl-1,2-benzenediamine (7) in CH_2Cl_2 at 0°C with chlorolactone **9** (14), which was synthesized from 1,8-naphthaldehydic acid by a modification of the standard method (15).

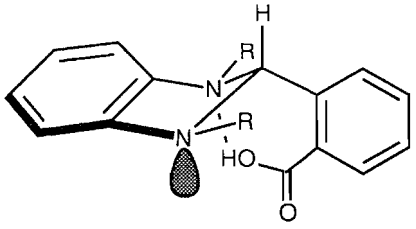
Although aminolactone **8** is not a dihydrobenzimidazole, it nevertheless incorporates a carbon–hydrogen bond activated as a formal donor of hydride by adjacent lone pairs on nitrogen and oxygen. As a result, it is readily oxidized. For example, treatment with methanolic I_2 in the presence of K_2CO_3 provided a 73% yield of internal salt **10**, which is the product expected as a result of intramolecular protonolysis in hypothetical dihydrobenzimidazole **5**. We suspected that compound **8** might be in equilibrium with the desired isomeric dihydrobenzimidazole **5**, so we subjected it to pyrolysis. Unfortunately, thermal decomposition generated only a complex mixture, and neither H_2 nor internal salt **10** was detected among the products.

We reasoned that the closely related dihydrobenzimidazole **11** would be less likely than compound **5** to isomerize to the corresponding isomeric aminolactone. In fact, direct condensation of *N,N'*-dimethylbenzene-1,2-diamine (7) with phthalaldehydic acid gave dihydrobenzimidazole **11** in 87% yield. The presence of a carbonyl band at 1719 cm^{-1} and Bohlmann bands at 2692 and 2637 cm^{-1} in the IR spectrum of compound **11** ($CHCl_3$) provided evidence that the product incorporates a carboxylic acid group and a carbon–hydrogen bond antiperiplanar to two lone pairs on nitrogen. This indicates that the product is in fact compound **11** and not the isomeric aminolactone **12**, and it suggests that intramolecularly hydrogen-bonded structure **11a** is the preferred conformation (6).

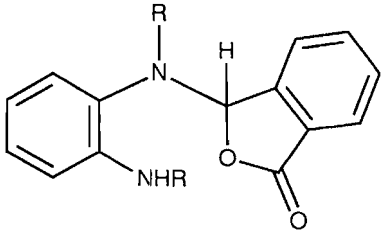
Dihydrobenzimidazole **11** is particularly susceptible to oxidation, and it even reacts with atmospheric oxygen at 25°C to produce internal salt **13** (16) in quantitative yield. However, despite the juxtaposition of a hydridic carbon–hydrogen bond and a carboxylic acid in dihydrobenzimidazole **11**, and despite its demonstrated ability to participate in redox reactions, it does not undergo intramolecular protonolysis to form H_2.



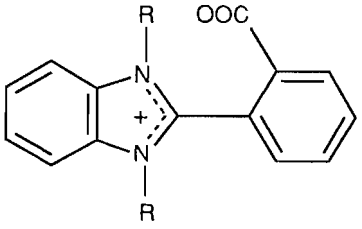
11 (R = CH_3)



11a (R = CH_3)



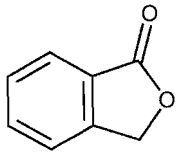
12 (R = CH_3)



13 (R = CH_3)

Instead, a complex mixture containing three principal components was formed when compound **11** was heated without solvent at 180°C. One of these products, isolated in 32% yield, is internal salt **13**, which is the expected result of intramolecular protonolysis; however, no H_2 could be detected. The other principal products are phthalide (**14**), which was recovered in 19% yield, and bis(benzimidazole) **15**, which was obtained in 14% yield.

We believe that these products result from rearrangement of dihydrobenzimidazole **11** to its less stable aminolactone isomer **12** by a process closely related to the one that intervened in the attempted synthesis of dihydrobenzimidazole **5**. Subsequent protonation then causes cleavage to *N,N'*-dimethyl-1,2-benzenediamine and cation **16**, which is reduced to phthalide by a formal intermolecular transfer of hydride from dihydrobenzimidazole **11**. This transfer yields an equivalent amount of internal salt **13**. Compound **13** and related dimethybenzimidazolium salts are capable of effecting intermolecular methylations (16), ultimately leading to the formation of bis(benzimidazole) **15**, as well as to *N,N,N'*-trimethyl-1,2-benzenediamine and *N,N,N',N'*-tetramethyl-1,2-benzenediamine (17), which are both detected in low yields among the products of pyrolysis. Support for this hypothesis is provided by the observation that a similar pyrolysis of internal salt **13** in the presence of two molar equivalents of *N,N'*-dimethyl-1,2-benzenediamine yielded bis(benzimidazole) **15** and *N,N,N'*-trimethyl-1,2-benzenediamine as major products.



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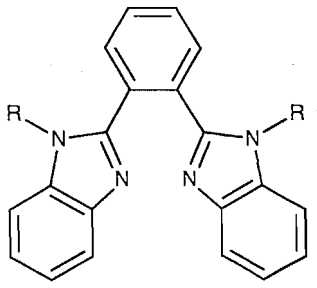
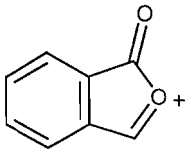


15 (R = CH_3)



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Conclusions

By providing structures in which carbon–hydrogen bonds are activated as formal donors of hydride by adjacent lone pairs and are simultaneously held close to acidic sites, dihydrobenzimidazoles **4** and **11** and related compounds are designed to favor the generation of H_2 by intramolecular protonolyses of carbon–hydrogen bonds. Both compounds **4** and **11** are effective reducing agents and react readily in intermolecular redox processes with active oxidants such as I_2 and O_2. Nevertheless, neither undergoes protonolysis of the activated carbon–hydrogen bond, and pyrolysis does not produce detectible quantities of H_2. To be faster than alternative reactions, protonolysis therefore appears to require carbon–hydrogen bonds that are even more highly activated as formal donors of hydride than those in dihydrobenzimidazoles **4** and **11**, or nearby sites that are even more acidic. In pyrolyses of compounds **4** and **11**, other reactions intervene before protonolysis of the activated carbon–hydrogen bonds can take place.

Experimental section

General procedures

Infrared (IR) spectra were recorded on Perkin-Elmer model 783 or 1600 spectrometers. Varian VXR-300, Bruker AMX-300, or Bruker ARX-400 spectrometers were used to obtain ^1H and ^{13}C nuclear magnetic resonance (NMR) spectra. Chemical shifts are reported in parts per million downfield from internal tetramethylsilane (δ). Mass spectra were recording on a Kratos MS-50 TATC instrument or a VG Autospec instrument using chemical ionization (CI), electron impact (EI), or fast atom bombardment (FAB). Melting points were recorded on a Thomas–Hoover capillary apparatus. Elemental analyses were performed by Galbraith Laboratories, Knoxville, Tenn. Flash chromatography was performed in the normal way (18).

Toluene was dried by distillation from sodium, CH_3OH by distillation from magnesium, CH_2Cl_2 by distillation from CaH_2, and ether by distillation from the sodium ketyl of benzophenone. Other commercial reagents were used without further purification.

2-[2-(Dimethylamino)phenyl]-1,3-dimethyl-2,3-dihydro-1*H*-benzimidazole (2)

A solution of *N,N*-dimethyl-1,2-benzenediamine (0.921 g, 6.76 mmol) (7), 2-(dimethylamino)benzaldehyde (1.01 g, 6.77 mmol) (8), and (1*S*)-10-camphorsulfonic acid (0.081 g, 0.35 mmol) in benzene (15 mL) was heated at reflux for 16 h under N_2 in an apparatus fitted with a Dean–Stark trap. The mixture was then washed with 5% aqueous NaOH and water, the organic phase was dried with anhydrous $MgSO_4$, and volatiles were removed by evaporation under reduced pressure. Crystallization of the residue from 95% aqueous C_2H_5OH provided 2-[2-(dimethylamino)phenyl]-1,3-dimethyl-2,3-dihydro-1*H*-benzimidazole (**2**; 1.35 g, 5.05 mmol, 75%) as an analytically pure colorless solid: mp 105–106°C; IR ($CHCl_3$): 2862, 2826, 2790 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ: 2.63 (s, 6H), 2.75 (s, 6H), 5.86 (s, 1H), 6.43–6.47 (m, 2H), 6.72–6.77 (m, 2H), 7.23 (ddd, ^3J = 7.8 Hz, ^3J = 7.2 Hz, ^4J = 1.3 Hz, 1H), 7.29 (dd, ^3J = 8.1 Hz, ^4J = 1.3 Hz, 1H), 7.39 (ddd, ^3J = 8.1 Hz, ^3J = 7.2 Hz, ^4J = 1.7 Hz, 1H), 7.94 (dd, ^3J = 7.8 Hz, ^4J = 1.7 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ: 33.0, 46.1, 86.1, 105.3, 119.0, 120.1, 124.8, 129.4, 129.4, 134.5, 142.5, 154.9; MS (CI) *m/e*: 268, 267, 252, 147; HRMS (EI) calcd. for $C_{17}H_{22}N_3$: 268.1814; found: 268.1802. Anal. calcd. for $C_{17}H_{21}N_3$: C 76.35, H 7.92, N 15.72; found: C 76.43, H 7.92, N 15.65.

2-[2-(Dimethylamino)phenyl]-1,3-dimethylbenzimidazolium iodide (3)

A stirred mixture of 2-[2-(dimethylamino)phenyl]-1,3-dimethyl-2,3-dihydro-1*H*-benzimidazole (**2**; 73 mg, 0.27 mmol) and K_2CO_3 (54 mg, 0.39 mmol) in CH_3OH (2 mL) was treated dropwise at 25°C with a solution of I_2 (73 mg, 0.29 mmol) in CH_3OH (8 mL). After 1 h, volatiles were removed by evaporation under reduced pressure, the residue was extracted with $CHCl_3$, and the extracts were decolorized with activated carbon. Removal of solvent from the extracts by evaporation under reduced pressure yielded 2-[2-(dimethylamino)phenyl]-1,3-dimethylbenzimidazolium iodide (**3**; 89 mg, 0.23 mmol, 85%) as a yellow solid, which was purified by recrystallization from CH_2Cl_2–benzene: mp 224-226°C; ^1H NMR (400 MHz, $CDCl_3$) δ: 2.59 (s, 6H), 4.01 (s, 6H), 7.18–7.22 (m, 2H), 7.63 (ddd, ^3J = 8.5 Hz, ^3J = 7.3 Hz, ^4J = 1.6 Hz, 1H), 7.63–7.67 (m, 2H), 7.76 (dd, ^3J = 7.7 Hz, ^4J = 1.6 Hz, 1H), 7.95–8.00 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 33.8, 43.3, 110.4, 113.5, 118.6, 121.7, 127.4, 131.7, 133.0, 134.6, 150.5, 153.3; MS (FAB) *m/e*: 266; HRMS (EI) calcd. for $C_{17}H_{20}N_3 - CH_3$: 251.1422; found: 251.1410.

Hydriodide of 2-[2-(dimethylamino)phenyl]-1,3-dimethyl-2,3-dihydro-1*H*-benzimidazole (4)

A solution of 2-[2-(dimethylamino)phenyl]-1,3-dimethyl-2,3-dihydro-1*H*-benzimidazole (**2**; 113 mg, 0.423 mmol) in deoxygenated ether (1 mL) was stirred at 0°C under N_2 and treated with 57% aqueous HI (90 μL, 0.40 mmol). The precipitated solid was separated by centrifugation, washed with cold absolute C_2H_5OH and ether, and dried in vacuo to give the hydriodide of 2-[2-(dimethylamino)phenyl]-1,3-dimethyl-2,3-dihydro-1*H*-benzimidazole (**4**; 138 mg, 0.349 mmol, 87%) as a beige solid. Recrystallization from CH_2Cl_2–ether under N_2 provided an analytically pure sample: mp 156–157°C (dec.); IR ($CHCl_3$): 2803, 2698 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ: 2.72 (s, 6H), 3.61 (s, 6H), 4.83 (s, 1H), 6.76–6.80 (m, 2H), 6.93–6.97 (m, 2H), 7.44 (dd, ^3J = 7.6 Hz, ^4J = 1.3 Hz, 1H), 7.61 (dd, ^3J = 7.7 Hz, ^3J = 7.6 Hz, 1H), 7.80 (ddd, ^3J = 8.1 Hz, ^3J = 7.7 Hz, ^4J = 1.3 Hz, 1H), 8.64 (d, ^3J = 8.1 Hz, 1H), 12.16 (bs, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 34.6, 48.0, 94.5, 110.1, 122.5, 124.3, 126.6, 130.6, 132.3, 133.0, 140.3, 142.9; MS (EI) *m/e*: 267, 252, 147; HRMS (EI) calcd. for $C_{17}H_{22}IN_3 - HI$: 267.1736; found: 267.1726. Anal. calcd. for $C_{17}H_{22}IN_3$: C 51.63, H 5.61; found: C 51.59, H 5.68.

1,8-Naphthaldehydic acid

1,8-Naphthaldehydic acid was prepared by a modification of the standard method (13). A mixture of acenaphthenequinone (10.0 g, 54.9 mmol) and 30% aqueous KOH (70 mL) was heated at 140°C for 20 min in a poly(ethylene) bottle. The resulting blue solution was cooled, diluted with H_2O (180 mL), and acidified with concentrated aqueous HCl. This gave a precipitate that was separated by filtration, washed with H_2O, and dissolved in hot 95% aqueous C_2H_5OH. The resulting solution was decolorized with activated carbon, solvent was removed by evaporation under reduced pressure, and the residue was recrystallized from CH_3CN to give 1,8-naphthaldehydic acid (7.43 g, 37.1 mmol, 68%) as cream-colored needles: mp 166°C (lit. (13) mp 169–171°C); IR (KBr): 3300, 1690 cm^{-1}; ^1H NMR (400 MHz, CD_3CN) δ: 5.79 (s, 1H), 6.81 (s, 1H), 7.64–7.72 (m, 3H), 8.03 (dd, ^3J = 7.6 Hz, ^4J = 1.9 Hz, 1H), 8.24 (dd, ^3J = 8.3 Hz, ^4J = 1.1 Hz, 1H), 8.34 (dd, ^3J = 7.3 Hz, ^4J = 1.1 Hz, 1H); ^{13}C NMR (100 MHz, CD_3CN) δ: 97.0, 121.0, 126.4, 127.5, 127.9, 128.1, 129.4, 130.2, 130.4, 133.0, 134.8, 164.2; MS (CI) *m/e*: 201, 183.

3-Chloro-1*H*,3*H*-naphtho[1,8-*cd*]pyran-1-one (9)

Chloro-1*H*,3*H*-naphtho[1,8-*cd*]pyran-1-one (**9**) was prepared by a modification of the standard method (15). A stirred suspension of 1,8-naphthaldehydic acid (1.08 g, 5.39 mmol) in H_2O (10 mL) was treated dropwise with 1 N aqueous KOH until the solid dissolved. The resulting solution was diluted with H_2O (20 mL) and extracted with CH_2Cl_2, solvent was removed from the aqueous phase by evaporation under

reduced pressure, and the residue was dried at 80°C in vacuo. A suspension of the dried solid in dry toluene (7 mL) was treated with oxalyl chloride (1.75 g, 13.8 mmol). The mixture was stirred at 25°C for 24 h under dry air and then was heated at reflux for 1 h. Volatiles were removed by evaporation under reduced pressure to give a residue of 3-chloro-1*H*,3*H*-naphtho[1,8-*cd*]pyran-1-one (**9**), which was used without purification in subsequent procedures.

Methyl 8-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)-1-naphthoate (6)

A solution of *N,N'*-dimethyl-1,2-benzenediamine (1.10 g, 8.08 mmol) (**7**), methyl 8-formyl-1-naphthoate (**7**; 1.50 g, 7.00 mmol) (12), and (1*S*)-10-camphorsulfonic acid (0.152 g, 0.654 mmol) in deoxygenated benzene (50 mL) was heated at reflux for 17 h under N_2 in an apparatus fitted with a Dean–Stark trap. The mixture was then diluted with benzene and washed with 5% aqueous NaOH, H_2O, and saturated aqueous $CuSO_4$. The organic phase was dried with anhydrous $MgSO_4$, and solvent was removed by evaporation under reduced pressure. Recrystallization of the residue from CH_3CN gave methyl 8-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)-1-naphthoate (**6**; 1.00 g, 3.01 mmol, 43%) as a yellow solid: mp 160–161°C; IR ($CHCl_3$); 2867, 2804, 1717 cm^{-1}; ^1H NMR (400 MHz, CD_3CN) δ: 2.54 (s, 6H), 3.89 (s, 3H), 5.84 (s, 1H), 6.37–6.42 (m, 2H), 6.70–6.74 (m, 2H), 7.49 (dd, ^3J = 7.4 Hz, ^3J = 7.1 Hz, 1H), 7.63–7.68 (m, 2H), 7.95 (d, ^3J = 8.0 Hz, 1H), 8.05 (d, ^3J = 8.2 Hz, 1H), 8.41 (d, ^3J = 7.2 Hz, 1H); ^{13}C NMR (100 MHz, CD_3CN) δ: 32.5, 52.8, 87.6, 105.1, 119.0, 124.0, 126.5, 128.5, 128.9, 129.0, 130.0, 130.4, 132.3, 134.1, 135.9, 141.8, 171.7; HRMS (EI) calcd. for $C_{21}H_{20}N_2O_2$ − H: 331.1447; found: 331.1433.

3-[Methyl[(2-methylamino)phenyl]amino]-1*H*, 3*H*-naphtho[1,8-*cd*]pyran-1-one (8)

*Method A. By hydrolysis of methyl 8-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)-1-naphthoate (**6**)*

A solution of methyl 8-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)-1-naphthoate (**6**; 358 mg, 1.08 mmol) in THF (4 mL) was treated with 1.1 N aqueous LiOH (10 mL, 11 mmol). The resulting mixture was heated at reflux for 2 h, and then the volatiles were removed by evaporation in vacuo. The dried residue was extracted with $CHCl_3$ (50 mL), and solvent was removed from the extract by evaporation under reduced pressure. The residue was redissolved in deoxygenated H_2O (13 mL) and acidified at 0°C with deoxygenated 1 N aqueous HCl (1.05 mL, 1.05 mmol). The precipitated solid was separated by centrifugation, washed with H_2O, and dried in vacuo to give 3-[methyl[(2-methylamino)phenyl]amino]-1*H*, 3*H*-naphtho[1,8-*cd*]pyran-1-one (**8**; 208 mg, 0.653 mmol, 60%) as a white solid: IR ($CHCl_3$): 3418, 2815, 1711 cm^{-1}; ^1H NMR (400 MHz, CD_3CN) δ: 2.64 (s, 3H), 2.90 (d, ^3J = 3.2 Hz, 3H), 4.63 (bs, 1H), 6.64 (d, ^3J = 7.9 Hz, 1H), 6.72 (m, 1H), 6.78 (s, 1H), 7.13 (m, 1H), 7.60–7.72 (m, 4H), 7.95 (d, ^3J = 8.0 Hz, 1H), 8.14 (dd, ^3J = 8.3 Hz, ^4J = 1.1 Hz, 1H), 8.49 (dd, ^3J = 7.2 Hz, ^4J = 1.1 Hz, 1H); ^{13}C NMR (100 MHz, CD_3CN) δ: 30.5, 34.8, 95.5, 110.0, 116.9, 120.1, 124.9, 125.6, 126.3, 126.5, 127.0, 128.2, 128.3, 128.7, 129.5, 131.9, 133.5, 134.9, 144.6, 164.7; MS (CI) *m/e*: 319, 183; HRMS (FAB) calcd. for $C_{20}H_{18}N_2O_2$ − H: 317.1290; found: 317.1276.

Method B. By the direct reaction of N,N'*-dimethyl-1,2-benzenediamine with 3-chloro-1*H*, 3*H*-naphtho-[1,8-cd]pyran-1-one (**9**)*

A solution of *N,N'*-dimethyl-1,2-benzenediamine (1.72 g, 12.6 mmol) (**7**) in dry CH_2Cl_2 (6 mL) was stirred at 0°C under dry N_2 and treated dropwise with a solution of 3-chloro-1*H*, 3*H*-naphtho[1,8-*cd*]pyran-1-one (**9**) in CH_2Cl_2 (10 mL), which was prepared by the procedure described above. The mixture was kept at 25°C for 40 min, diluted with CH_2Cl_2, and washed successively with deoxygenated 5% aqueous NaOH, H_2O, and saturated aqueous $CuSO_4$. The organic phase was dried with anhydrous $MgSO_4$, and volatiles were removed by evaporation under reduced pressure. This yielded a sample of 3-[methyl[(2-methylamino)phenyl]amino]-1*H*, 3*H*-naphtho-[1,8-*cd*]pyran-1-one (**8**; 1.37 g, 4.30 mmol, 80%) identical to the product of method A.

8-(1,3-Dimethylbenzimidazolium-2-yl)-1-naphthoate (10)

A stirred mixture of 3-[methyl[(2-methylamino)phenyl]amino]-1*H*, 3*H*-naphtho[1,8-*cd*]pyran-1-one (**8**; 202 mg, 0.634 mmol) and K_2CO_3 (158 mg, 1.14 mmol) in CH_3OH (5 mL) was treated dropwise at 25°C with a solution of I_2 (169 mg, 0.666 mmol) in CH_3OH (10 mL). After 2 h, volatiles were removed by evaporation under reduced pressure, the residue was extracted with $CHCl_3$, and solvent was removed from the extracts by evaporation under reduced pressure. The residue was redissolved in CH_3OH and decolorized with activated carbon. Evaporation of solvent under reduced pressure left a residue of 8-(1,3-dimethylbenzimidazolium-2-yl)-1-naphthoate (**10**; 146 mg, 0.461 mmol, 73%) as a beige solid, which was purified by recrystallization from CH_3OH–ether: mp 305°C (dec.); IR (KBr): 1597 cm^{-1}; ^1H NMR (300 MHz, D_2O) δ: 3.77 (s, 6H), 7.68–7.76 (m, 2H), 7.76–7.81 (m, 2H), 7.83–7.86 (m, 2H), 7.88–7.94 (m, 2H), 8.16 (dd, ^3J = 7.8 Hz, ^4J = 1.8 Hz, 1H), 8.36–8.42 (m, 1H); ^{13}C NMR (75.4 MHz, D_2O) δ: 32.8, 113.5, 117.6, 126.0, 127.4, 127.5, 127.9, 129.0, 131.0, 132.3, 133.0, 134.8, 135.1, 136.9, 152.1, 176.3; MS (FAB) *m/e*: 317; HRMS (FAB) calcd. for $C_{20}H_{16}N_2O_2$ + H: 317.1290; found: 317.1276.

2-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)benzoic acid (11)

In a sealable tube, a solution of *N,N'*-dimethyl-1,2-benzenediamine (0.770 g, 5.65 mmol) (**7**) in deoxygenated ether (3 mL) was added to a stirred solution of phthalaldehydic acid (0.819 g, 5.46 mmol) in deoxygenated ether (1 mL). This caused the rapid precipitation of a yellow solid. The mixture was kept at 25°C for 15 min, and then volatiles were removed by evaporation in vacuo. Deoxygenated CH_3OH (12 mL) was added to the residue, the mixture was degassed, and the tube was sealed in vacuo. The tube was then heated in an oil bath at 140–150°C until the yellow solid had dissolved. Crystallization occurred when the solution was cooled. The tube was opened under Ar in a glove box, the mother liquors were removed, and the crystals were washed with CH_3OH and dried in vacuo. This provided 2-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)benzoic acid (**11**; 1.27 g, 4.73 mmol, 87%) as air-sensitive yellow needles: mp 198–199°C; IR ($CHCl_3$): 2804, 2692, 2637, 1719 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ: 2.61 (s, 6H), 4.90 (s, 1H), 6.62–6.67 (m, 2H), 6.87–6.91 (m, 2H), 7.45–7.49 (m, 1H), 7.54–7.60 (m, 2H), 8.05–8.10 (m, 1H),

12.4–13.5 (bs, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ: 33.9, 95.1, 109.1, 121.8, 130.5, 131.4, 131.9, 133.4, 133.6, 134.7, 140.9, 169.5; MS (CI) *m/e* 269, 267, 253; HRMS (EI) calcd. for $C_{16}H_{16}N_2O_2$: 268.1212; found: 268.1202. Anal. calcd. for $C_{16}H_{16}N_2O_2$: C 71.61, H 6.01, N 10.45; found: C 71.26, H 6.12, N 10.62.

2-(1,3-dimethylbenzimidazolium-2-yl)benzoate (13) (ref. 16)

A solution of 2-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)benzoic acid (**11**; 200 mg, 0.745 mmol) in CH_3OH (10 mL) was stirred at 25°C for 1 h under O_2. Volatiles were then removed by evaporation under reduced pressure, and the residue was dried in vacuo. This yielded 2-(1,3-dimethylbenzimidazolium-2-yl)benzoate (**13**; 198 mg, 0.743 mmol, 100%) (16) as a beige solid, which was purified by recrystallization from CH_2Cl_2–ether: mp 275-277°C (lit. (16) mp 294–295°C); IR ($CHCl_3$): 1622 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ: 3.73 (s, 6H), 7.23 (dd, ^3J = 7.6 Hz, ^4J = 0.7 Hz, 1H), 7.57–7.68 (m, 5H), 7.77 (ddd, ^3J = 7.6 Hz, ^3J = 7.6 Hz, ^4J = 1.3 Hz, 1H), 8.51 (dd, ^3J = 7.8 Hz, ^4J = 0.7 Hz, 1H); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ: 32.0, 112.2, 120.9, 126.2, 127.8, 129.5, 131.6, 131.9, 132.8, 142.6, 156.1, 167.2; MS (CI) *m/e*: 267; HRMS (EI) calcd. for $C_{16}H_{14}N_2O_2$: 266.1055; found: 266.1026.

Pyrolysis of 2-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)benzoic acid (11)

One arm of an H-tube was charged with a mixture of *trans*-stilbene (100 mg, 0.55 mmol) and 10% Pd on activated carbon (50 mg) in deoxygenated 95% aqueous C_2H_5OH (2 mL), and the other arm was charged with 2-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)benzoic acid (**11**; 47 mg, 0.18 mmol). The tube was sealed, the ethanolic suspension was stirred at 25°C in one arm, and the solid was heated in the other at 185°C for 8 days. The tube was then opened, the suspension was filtered, and solvent was removed from the filtrate by evaporation under reduced pressure. Examination of the residue by ^{1}H NMR spectroscopy showed that no 1,2-diphenylethane had been formed from *trans*-stilbene and therefore that no H_2 had been generated by the pyrolysis.

In a similar experiment, 2-(1,3-dimethyl-2,3-dihydro-1*H*-benzimidazol-2-yl)benzoic acid (**11**; 250 mg, 0.93 mmol) was pyrolyzed in a sealed tube at 180°C for 150 h. The pyrolysate was taken up in CH_3OH (1.3 mL), and the solution was diluted with H_2O. The aqueous mixture was then extracted with ether and with $CHCl_3$. Volatiles were removed from the aqueous phase by evaporation in vacuo to give a residue of 2-(1,3-dimethylbenzimidazolium-2-yl)benzoate (**13**; 79 mg, 0.30 mmol, 32%). The combined ether extracts were washed with 5% aqueous HCl and dried with anhydrous Na_2SO_4, and volatiles were removed from the dried solution by evaporation under reduced pressure. Flash chromatography (silica, hexane (75%) – ethyl acetate (25%)) of the residue yielded phthalide (**14**; 24 mg, 0.18 mmol, 19%), which was shown by ^{1}H NMR spectroscopy to be identical with an authentic sample.

The combined acidic washings were made basic by the addition of 50% aqueous NaOH, and the basic mixture was then extracted with CH_2Cl_2. The combined organic extracts were dried with Na_2SO_4, and volatiles were removed from the dried solution by evaporation under reduced pressure. Gradient chromatography (neutral alumina, hexane (80%)/ethyl acetate (20%) – hexane (65%)/ethyl acetate (35%)) of the residue gave 1-methyl-2-[2-(1-methylbenzimidazol-2-yl)phenyl]benzimidazole (**15**; 45 mg, 0.13 mmol, 14%) as a colorless solid. Recrystallization from C_2H_5OH/H_2O (7:3) provided an analytically pure sample: mp 239–240°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ: 3.27 (s, 6H), 7.13–7.17 (m, 2H), 7.21–7.31 (m, 4H), 7.70–7.74 (m, 2H), 7.77–7.81 (m, 2H), 7.83–7.87 (m, 2H); MS (EI) *m/e*: 338, 323; HRMS (EI) calcd. for $C_{22}H_{18}N_4$: 338.1531; found: 338.1533. Anal. calcd. for $C_{22}H_{18}N_4$: C 78.07, H 5.36, N 16.56; found: C 77.79, H 5.39, N 16.42.

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