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Equilibrium Acidities of Nitroalkanes in an Ionic Liquid

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ABSTRACT

The acidity ladder scale in [BMPY][NTf_2] was successfully expanded towards weak acidity region for about five more p*K* units compared to the previously established one. This allows the acidities of a series of 13 aliphatic and aromatic nitroalkanes to be determined accurately by UV-vis spectroscopic method. The acidity of nitroalkane in [BMPY][NTf_2] covers ~8 p*K* units and is significantly weaker than those in DMSO and water. Hammett plot for 4-substituted phenylnitromethanes shows an excellent linearity with a slope of 2.06, which is rather close to that in DMSO but significantly larger than that in water (0.80). The regression analyses reveal that the solvation behavior of [BMPY][NTf_2] on the acidic dissociations of C-H acids is similar to that of DMSO.

INTRODUCTION

Carbon acids (C-H acids) are ubiquitous in organic chemistry, since practically almost all organic compounds contain C-H bonds.[1] C-H acids are one of chemical curiosities to organic chemists for many years. Our interest in thermodynamic properties and kinetic behaviors of C-H acids extends into contemporary chemical research.[1,2] In general, most C-H acids, such as hydrocarbons, are rather weak Brönsted acids, but with the presence of nearby electron-withdrawing group(s) (EWGs), or under sufficiently strong basic conditions, they are capable of undergoing deprotonation and producing the corresponding carbanions. Carbanions are one of the most well-known and -studied nucleophiles and have been widely used in many important biological and synthetic reactions for building up various carbon-carbon and carbon-heteroatom bonds.[3] Research on the C-H acidities has a long and rich history and has laid the foundation for the establishment of general theories of

organic chemistry, in this respect, the determination of C-H acidity is of fundamental importance to the progress in physical organic chemistry.[1,3] Accordingly, previously tremendous effort has been devoted to establish acidity scales for C-H acids in various solvent systems by different methods,[1,4,5] and several reliable acidity scales have been achieved in commonly used organic solvents.[4,5]

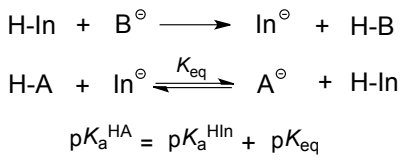
Conceptually different from molecular solvents, ionic liquids (ILs) are entirely composed of charged species, which endows them with a number of distinctive physicochemical properties such as negligible vapor pressure, low flammability, high conductivity, a wide liquid range and good thermal stability.[6] Furthermore, their tuneable features which can be achieved through varying the identities of composing ions, make ILs a versatile functional material that may potentially fulfill various task-specific jobs.[7] Owing to these favorable characteristics, ILs have received tremendous amount of research attention, and have found their broad applications in catalysis, material and biological science as well as energy storage, etc.[8] However, compared with the knowledge that has been accumulated in molecular solvents,[9] currently our understanding on some fundamental aspects of ILs, especially at the molecular level, such as explicit solvent structure and solvation behavior, etc., still remains in a primitive stage. Unavoidably, the incipient theories for ILs were based on only very limited work in this connection and are often subject to debates.[10] It is well-known that the study of acid-base equilibria in molecular solvents can provide some crucial information on the solvation behaviors and solvent effects.[9c,11] In recent years, we have precisely measured several series of organic Brönsted acids in both aprotic and protic ILs by a classical UV-vis spectroscopic method,[12] a number of unique solvation patterns of ILs which are distinctive from those of molecular solvents were revealed.[12c,12e,12g]

Nitroalkanes are important branch of C-H acids and have been widely used in organic synthesis for C-C bond formations.[13] Due to a strong electron-withdrawing power of the mesomeric nitro group, nitroalkanes are normally more acidic than other types of C-H acids. To date, there has been a considerable amount of research into the determination of acidities for nitroalkanes in both protic and aprotic molecular solvents,[4d] however, surprisingly, there is no relevant study on the acidic dissociation of nitroalkanes in ILs. Previously we measured a number of C-H acids in 4 imidazolium and pyrrolidinium based aprotic ILs, but the C-H acids involved were mainly fluorene, malononitrile and ylide derivatives.[12a,12e] Herein we wish to report the equilibrium acidities of several commonly seen nitroalkanes in an aprotic IL, i.e. [BMPY][NTf_2] ([BMPY] = 1-butyl-1-methylpyrrolidinium,

[NTf_2] = bis(trifluoromethanesulfonimide), whereby linear free energy analyses were established and utilized in order to understand the solvation behaviors of ILs.

RESULTS AND DISCUSSION

Expanding the acidity ladder. In the pK_a determination by the UV-vis spectroscopic approach, one first needs to establish an acidity ladder which can be used as a standard scale for the acidity measurement of target acids (HA) in a specific solvent. The acidity ladder contains the acidities of a series of standard indicator acids (HIn) whose pK_a^{HIn}s are carefully measured with high precision. The span of the acidity ladder dictates the number and identities of target acids that can be potentially measured.



Scheme 1. The Principle of pK_a Determination by the UV-vis Spectroscopic Method in Solutions.

As shown in Scheme 1, the pK_a determination by the UV-vis spectroscopic method in solutions requires a base (B^-) which is strong enough to firstly deprotonate the indicator acid (HIn) with a known pK_a value (*in the same solvent which the measurement is conducted*), then the resulting indicator anion (In^-) is titrated with a target acid (HA). The acidity of HA (pK_a^{HA}) then can be derived from the equilibrium constant (K_{eq}) and the acidity of indicator (pK_a^{HIn}).[4a,4b] Normally in order to establish an equilibrium whereby K_{eq} can be accurately measured by UV-vis approach, the acidity gap (ΔpK_a) between pK_a^{HIn} and pK_a^{HA} should be less than 2 pK units.[4a,14] In addition, the ideal base (B^-) should have no UV-vis absorbance and should be strong enough to fully deprotonate the indicator acids but without destroying the solvent system. Furthermore, it must have a sufficient solubility and should be free from various modes of ion associations, such as ion-pairs, in the solvent of measurement.[15] Therefore, the selection of appropriate indicator acids and bases (B^-) requires a series of stringent tests and is critical for the pK_a determination by the UV-vis spectroscopic method. Fortunately, the choice of indicators (HIn) and target acid (HA) for the pK_a determination in ILs can be facilitated by the acidity comparisons in DMSO,[4a] since we have shown that there exist good linear correlations between the acidities of the C-H acids in both protic and aprotic ILs and those in

DMSO.[12]

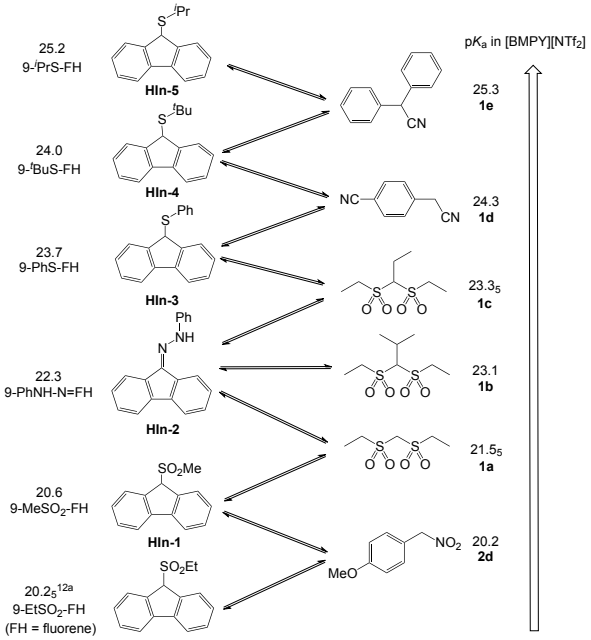


Figure 1. The Extended Acidity Ladder in [BMPY][NTf_2]

Based on the acidities of aliphatic nitroalkanes in DMSO (pK_as ≈ 17[4d]), such as nitromethane (**2a**) and nitroethane (**2b**), the indicators and base precursor (**1b**) which were used previously[12] are no longer suitable for the pK_a determination of the nitroalkanes involved in this work (For details, see SI). Accordingly, a stronger base, i.e., the potassium salt of diethyl isopropylmalonate (**base-2**, Figure S4), and several fluorene-based indicator acids (**HIn-1** to **HIn-5**, Figure 1) with a higher pK_a^{HIn} were synthesized and rigorously tested for the acidity measurement in [BMPY][NTf_2]. As have noted, the pK_a determination in solution should avoid ion-associations, typically ion-pair formations between the indicator anions (In^-) and the metal cation which is introduced into the system by the adding of base in the first place. If this occurs, it would result in an "apparent pK_a" (or called ion-pair pK_a)[15] rather than the desired true pK_a (or "free-ion pK_a").[4a] Since the **base-2** is a potassium salt, if the ion-pair formation occurs between the carbanion of diethyl isopropylmalonate or indicator anion (In^-) and potassium cation in the IL solution, the measured acidity value should be affected by the addition of an equal molar (relative to the base) of chelating reagent, i.e., 2,2,2-cryptand, a well-known potassium cation scavenger.[14a] Our test results showed that there is no change in the pK_as of 2 representative C-H acids with and without adding 2,2,2-cryptand (SI, Table S2), which indicates that our pK_a measurements in [BMPY][NTf_2] are free from ion-pair complications. This is in line with our previous findings that salts are totally free in ILs under our

experimental conditions.[12e] Further tests on the **base-2** showed that it can perfectly repeat the pK_a values of several C-H acids which were obtained previously by using the old base (**base-1**, SI) without compromising the precision. (Table S1). Subsequently, an extended acidity ladder was realized, which is about 5 more pK units wider than the previous established one (Figure 1). In addition, the acidities of several weak C-H acids that are not available previously, i.e., disulfone (**1a-1c**) and benzylnitrile (**1d**, **1e**) derivatives, were also obtained. In principal, current acidity ladder enables us to measure the weaker acids with a pK_a up to ~27 in [BMPY][NTf_2], combining with the previously established ones in this IL,[12a,12f] the overall acidity ladder covers more than 20 pK units now (Figure S5 provides our previously established acidity ladder).

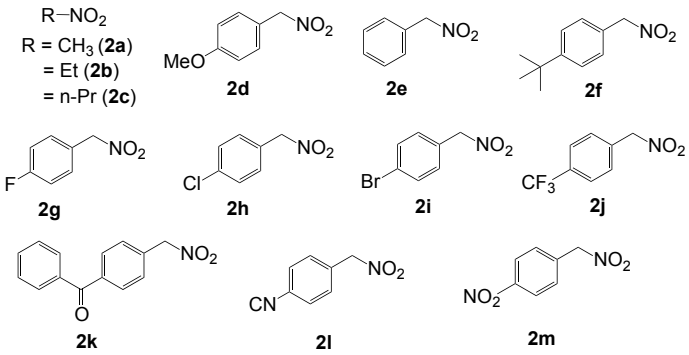


Figure 2. Structures of Nitroalkanes Involved in This Work.

Table 1. pK_a Values of Nitroalkanes in Various Solvents

[a]nitroalkane	[b]p$K_a^{[BMPY][NTf_2]}$	[c]pK_a^{DMSO}	[c]p$K_a^{H_2O}$
C**H**$_3$NO$_2$ (**2a**)	24.6	17.2	10.2
CH$_3$C**H**$_2$NO$_2$ (**2b**)	24.0$_5$	16.7	8.6
CH$_3$CH$_2$C**H**$_2$NO$_2$ (**2c**)	24.3$_5$	17.0	9.0
4-MeOC$_6$H$_4$C**H**$_2$NO$_2$ (**2d**)	20.2		
C$_6$H$_5$C**H**$_2$NO$_2$ (**2e**)	19.8	12.0	6.9
4-^{t}BuC$_6$H$_4$C**H**$_2$NO$_2$ (**2f**)	19.8		
4-FC$_6$H$_4$C**H**$_2$NO$_2$ (**2g**)	19.5		
4-ClC$_6$H$_4$C**H**$_2$NO$_2$ (**2h**)	19.2		
4-BrC$_6$H$_4$C**H**$_2$NO$_2$ (**2i**)	19.0$_5$	11.1	
4-CF$_3$C$_6$H$_4$C**H**$_2$NO$_2$ (**2j**)	18.3$_5$		
[d]4-BzC$_6$H$_4$C**H**$_2$NO$_2$ (**2k**)	17.9		
4-CNC$_6$H$_4$C**H**$_2$NO$_2$ (**2l**)	17.6$_5$	9.3	6.2
4-NO$_2$C$_6$H$_4$C**H**$_2$NO$_2$ (**2m**)	16.9	8.6	5.9

[a]The acidic hydrogens are indicated by boldface type. [b]In pK_a units, SD: ≤ ± 0.05 pK unit. [c]ref.4d. [d]Bz = benzoyl.

Acidities of nitroalkanes in [BMPY][NTf_2]. With the expanded acidity ladder in our hands, next

the acidities of a series of nitroalkanes (Table 1 and Figure 2) were precisely measured (SD ≤ ± 0.05 p*K* unit), including aliphatic (**2a-2c**) and aromatic ones (**2d-2m**), the results are listed in Table 1, together with the available data in molecular solvents. Table 1 shows that the acidity scale of nitroalkanes covers a range of about 8 p*K* units in [BMPY][NTf_2], and the acidities of aliphatic nitroalkanes (**2a-2c**) are significantly lower (~4-7 p*K* units) than those of aromatic ones (**2d-2m**), which is mainly due to the absence of a resonance stabilization of incipient anions from benzene ring. In general, the acidity of nitroalkane is much weaker in [BMPY][NTf_2] than those in DMSO and water, which is consistent with the acidity order observed in our previous studies.[12] Presumably, this is because of large negative Gibbs transfer energy of proton from ILs to DMSO or water [$\Delta G^*_{trans}(H^+, IL \rightarrow S)$]. In specific, the absolute single-ion solvation free energies of proton $\Delta G^*(H^+)$ in DMSO, water and an aprotic IL [EMIM][NTf_2] ([EMIM] = 1-ethyl-3-methylimidazolium) were obtained both experimentally and theoretically[16] as -273.3,[16a] -265.9[16a] and -257.1[16c,d] kcal mol^{-1}, respectively, which yields a Gibbs transfer energy of proton from the IL to water or DMSO [$\Delta G^*_{trans}(H^+, IL \rightarrow S)$] of -8.8 or -16.2 kcal mol^{-1}. In addition, the dielectric constant of [BMPY][NTf_2] (ε_r = 14.7[17]), is much lower than those for water (80.1) and DMSO (46.5).[9c] This may also be part of a reason for a weaker acidity of nitroalkane in [BMPY][NTf_2], though there exist controversies on the suitability of the microwave dielectric spectroscopy or electrical capacitance method for measuring the dielectric constants for ILs.[6c]

From Table 1, one can also find that the acidity for the aliphatic nitroalkane follows an order of nitroethane (**2b**) > 1-nitropropane (**2c**) > nitromethane (**2a**) in [BMPY][NTf_2] as well as in molecular solvents. The gas-phase acidity difference between **2a** and **2b** is practically negligible (349.7 and 349.5 kcal mol^{-1}, respectively),[4d] being only 0.2 kcal mol^{-1}, in addition, there is no available gas-phase acidity data for **2c** (and other aromatic nitroalkanes). In solution, the acidity of **2b** is about 4 times (ΔpK_a = 0.6) stronger than **2a** in [BMPY][NTf_2], which is similar to that found in DMSO, but the acidity difference between **2a** and **2b** is significantly smaller than in water (ΔpK_a = 1.6). Although the acidity order for the aliphatic nitroalkanes in protic solutions has been rationalized through hyperconjugation effects in previous literature,[18] since the magnitude for the acidity differences observed here for **2a**, **2b** and **2c** in [BMPY][NTf_2] are relatively small, this could also be understood, alternatively, on the basis of the subtle solvation differences in the IL.[9c]

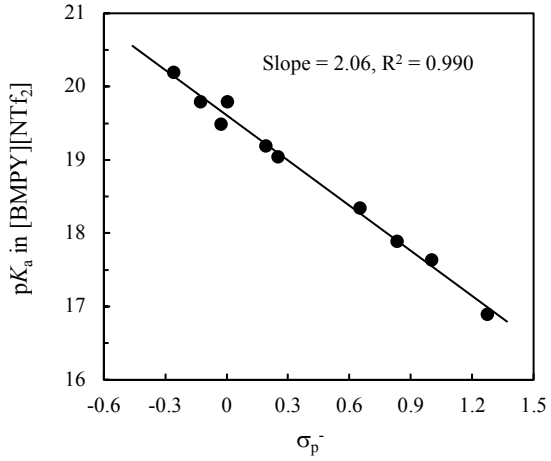
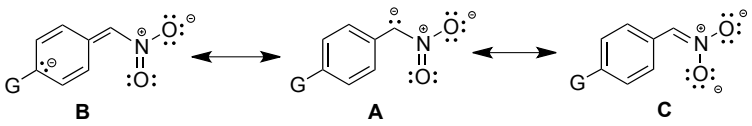


Figure 3. Hammett Type Plot for 4-Substituted Phenylnitromethanes (**2d-2m**) in [BMPY][NTf$_2$]

Hammett analyses and acidity correlations. In order to probe the solvation difference for these nitro compounds, the substituent effect for the aromatic nitroalkanes was studied through constructing Hammett type plots in [BMPY][NTf$_2$] and compared with those in molecular solvents. The Hammett correlation for 4-substituted phenylnitromethanes (**2d-2m**) shows a good linear relationship (R^2 = 0.990) with a slope of 2.06 (Figure 3), which is rather close to that found in DMSO (2.60, R^2 = 0.997, Figure S6), but significantly larger than those in water (0.80, R^2 = 0.993) and 50% (v/v) aqueous methanol (0.91, R^2 = 0.978) (Figures S7 and S8). This indicates that the substituent dependence for these phenylnitromethanes in the IL is similar to that in DMSO but not like that in protic solvents. In the protic solvent water or aqueous binary solvent system, due to a strong hydrogen-bonding solvation stabilization,[19] the internal resonance stabilization through benzene ring is less important. Consequently, the incipient negative charge can be readily delocalized into the nitro group and hence the resonance structure **C** is favored (Scheme 2). On the other hand, aprotic DMSO is well-known for its relatively weak solvability towards the charge less delocalized anions, such as phenoxides and azides, etc.[20] Therefore, the relative importance of resonance structure **B** in DMSO, as well as in [BMPY][NTf$_2$], is greater than that of **C** in protic solvents, and thus, leading to a more pronounced substituent effect (a larger Hammett ρ value).



Scheme 2. The Resonance Structures of 4-Substituted Phenylnitromethane Anions

It is also worth noting that the Hammett ρ value for the 4-substitutited phenylmalononitriles in DMSO and [BMPY][NTf_2] is 4.77 and 3.66, respectively (Figures S9 and S10), using the data we measured previously in this IL.[12a]

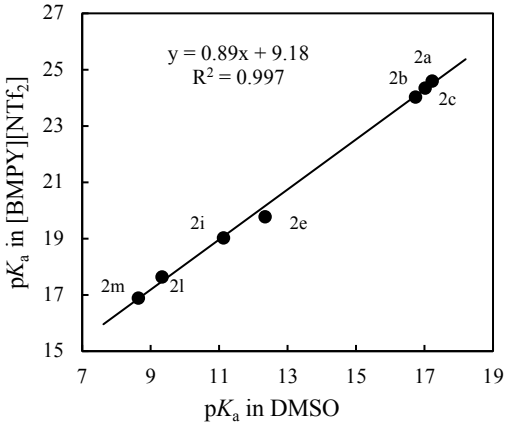


Figure 4. The Acidity Correlation of Nitroalkanes in [BMPY][NTf_2] and DMSO

The acidity correlations between solvents of various properties can be a powerful tool to detect the differential solvation on a series of substrates of interest. As shown in Figure 4, the acidities of nitroalkanes correlate excellently (R^2 = 0.997) with those available data in DMSO, which is consistent with our previous findings for C-H acids in ILs.[12a] This is not unexpected since the pK_as measured in the IL and DMSO are free from ion-pairing perturbation and specific solvation which are generally found in the solvents of low polarity and strong hydrogen-bonding.[9c,21] Indeed, a comprehensive correlation of acidities for nearly 30 structurally different C-H acids, i.e., fluorenes, nitriles, disulfones and nitroalkanes in [BMPY][NTf_2] and those in DMSO shows a very good linear relationship (R^2 = 0.991, Figure S11) over more than 19 pK units in DMSO, from which the pK_a of an unknown C-H acid in [BMPY][NTf_2] and DMSO can be conveniently estimated through the correlation equation described in Equation. 1.

$$pK_a^{[BMPY][NTf_2]} = 0.922pK_a^{DMSO} + 8.84 \qquad \text{Eqn. 1}$$

CONCLUSIONS

To summarize, based on our previous work on the acidity determination of C-H acids in ILs, in this work we have successfully expanded the acidity ladder scale in an aprotic IL [BMPY][NTf_2], which is about 5 more pK units wider than that previously established. The newly enlarged scale enables us to precisely measure the acidities of a series of aliphatic and aromatic nitroalkanes. The

Hammett type plots and excellent linear correlations exhibit in the regression analyses for these nitroalkanes suggest that the solvation behavior of [BMPY][NTf_2] on the acidic dissociations of these C-H acids is similar to that of dipolar aprotic DMSO. The equilibrium acidities of these nitroalkanes and the solvation behavior revealed in this work may potentially serve either as a benchmark or as reliable references for the development of appropriate computational methods in [BMPY][NTf_2].

EXPERIMENTAL SECTION

General considerations. [BMPY][NTf_2] was synthesized and purified as described in our previous work.[12] In addition, [BMPY][NTf_2] was dried in vacuum at 70 °C for 5 hours and stored in desiccators with argon protection. The water content is less than 15 ppm, which was determined by the Karl-Fischer titration and was routinely monitored before each individual pK_a determination. All the chemicals, solvents were purchased from commercially available sources and used directly except otherwise noted. The indicator acids, bases and nitroalkanes involved in this work are not new compounds, except otherwise noted, were synthesized and purified as reported before.

Synthesis of indicator acids. The indicator acids (**HIn-1** to **HIn-5**) were prepared by previously reported procedures.[22]

9-(methylsulfonyl)fluorene (**HIn-1**) was synthesized according to the reported procedures (Figure S1).[22a] In specific, 20 mmol 9-bromofluorene and 20 mmol thiourea were dissolved in 100 ml THF, the mixture was refluxed for 3h and the solvent was removed. Then 100 ml aqueous NaOH (~3 mol L^{-1}) was added, the reaction mixture was further heated and stirred at 100 °C for 4h. After cooling down to room temperature, 125 ml aqueous H_2SO_4 (10% wt) was added slowly to the mixture which was cooled with an ice-bath. The liquid mixture was extracted with $CHCl_3$ (50 ml*3). The organic phase was dried with anhydrous Na_2SO_4, and evaporated in vacuo to afford crude 9-mercaptofluorene. Next, the crude 9-mercaptofluorene, together with 9 mmol of NaOMe and 90 ml MeI were dissolved in 70 ml dry MeOH, the reaction mixture was stirred at 30 °C for 4h. The solvent was removed and 36 ml H_2SO_4 aqueous (5% wt) was added to the reaction residue. The aqueous layer was extracted with DCM (90 ml*3) and dried with anhydrous Na_2SO_4, evaporated in vacuo to give a crude product 9-methylthiofluorene. Then, the crude 9-methylthiofluorene was dissolved in a mixture of 80 ml AcOH and 30 ml aqueous H_2O_2 (30% wt). The reaction mixture was stirred

vigorously at 50 °C for 30 min, then cooled and poured into 360 ml ice water. The precipitate was collected by filtration and then dissolved in DCM. This DCM solution was filtered and the filtrate was dried with anhydrous Na_2SO_4 and evaporated to afford a crude 9-(methylsulfonyl)fluorene (**HIn-1)** product. 0.63 g **HIn-1** was obtained as white needles after multiple crystallization from MeOH.

1-(9*H*-fluoren-9-ylidene)-2-phenylhydrazine (**HIn-2**) was synthesized according to the reported procedures (Figure S2).[22b] 8.3 mmol 9*H*-fluoren-9-one was dissolved in 30 ml dry EtOH, then 1 ml AcOH was added to the mixture which was cooled with an ice-bath. After 10 mins, 9.3 mmol phenylhydrazine was added to the mixture. The reaction mixture was stirred at 78 °C for 0.5h until all the solid suspended in solution. 0.70 g 1-(9*H*-fluoren-9-ylidene)-2-phenylhydrazine (**HIn-2**) was obtained as yellow solid after multiple crystallization from EtOH.

9-alkylthiofluorenes (**HIn-3** to **HIn-5**) was synthesized according to the known procedures (Figure S3).[22c] 10 mmol thiol (R-SH, R = Ph, ^{i}Pr and ^{t}Bu) was dissolved to 150 ml dry menthol, 0.21 ml sodium methylate solution (5.4 mol/L) was added to the mixture dropwise which was cooled with an ice-bath. After 0.5h, 10 mmol 9-bromo-9*H*-fluorene was added to the mixture under inert atmosphere. The mixture was stirred at 78 °C for about 1h to allow all the solid to suspend in the solution. The mixture was filtered and the corresponding 9-alkylthiofluorenes were then obtained as a white solid after repeated crystallization from MeOH.

9-(methylsulfonyl)fluorene (**HIn-1**), white needles (0.63 g, the overall yield: 13%). ^{1}H NMR (400 MHz, DMSO-d_6): δ 8.00 (d, J = 7.6 Hz, 2H), 7.83 (d, J = 7.6 Hz, 2H), 7.56 (t, J = 7.5 Hz, 2H), 7.45 (t, J = 7.5 Hz, 2H), 5.86 (s, 1H), 2.49 (d, J = 13.2 Hz, 3H). ^{13}C{^{1}H} NMR (100 MHz, DMSO-d_6) δ 141.4, 136.0, 129.6, 127.9, 126.6, 120.8, 69.4, 36.0 ppm.[22a]

1-(9H-fluoren-9-ylidene)-2-phenylhydrazine (**HIn-2**), yellow solid (0.70 g, yield: 31%). ^{1}H NMR (400 MHz, DMSO-d_6) δ 10.34 (s, 1H), 8.44 (d, J = 7.0 Hz, 1H), 8.03–7.93 (m, 1H), 7.91–7.78 (m, 2H), 7.59–7.43 (m, 4H), 7.42–7.30 (m, 4H), 6.95 (t, J = 7.3 Hz, 1H). ^{13}C{^{1}H} NMR (100 MHz, DMSO-d_6) δ 145.3, 139.9, 139.2, 137.7, 137.4, 129.3, 129.1, 129.0, 128.0, 127.7, 127.6, 125.8, 121.1, 120.5, 120.4, 120.0, 114.1 ppm.[22b]

9-(phenylthio)fluorene (**HIn-3**), white solid (1.84 g, yield: 67%). ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.81 (d, J = 7.5 Hz, 2H), 7.49 (d, J = 7.4 Hz, 2H), 7.38 (t, J = 7.3 Hz, 2H), 7.34–7.24 (m, 4H), 7.23–7.16 (m, 3H), 5.66 (s, 1H). ^{13}C{^{1}H} NMR (100 MHz, DMSO-d_6) δ 144.1, 139.9, 133.1, 132.0,

128.8, 128.1, 127.6, 127.4, 125.0, 120.2, 50.3 ppm.[22c]

9-(*tert*-butylthio)fluorene (**HIn-4**), white solid (1.91 g, yield: 75%). ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.99–7.76 (m, 2H), 7.63 (d, J = 6.7 Hz, 2H), 7.49–7.30 (m, 4H), 5.12 (s, 1H), 1.47 (s, 9H). ^{13}C{H} NMR (100 MHz, DMSO-d_6) δ 146.7, 139.5, 127.6, 127.5, 125.6, 119.9, 47.1, 44.2, 31.8 ppm.[22c]

9-(isopropylthio)fluorene (**HIn-5**), white solid (1.44 g, yield: 60%). ^{1}H NMR (400 MHz, DMSO-d_6) δ 7.87 (d, J = 6.8 Hz, 2H), 7.64 (d, J = 7.3 Hz, 2H), 7.50–7.30 (m, 4H), 5.18 (s, 1H), 2.69 (dt, J = 13.5, 6.7 Hz, 1H), 1.00 (d, J = 6.7 Hz, 6H). ^{13}C{^{1}H} NMR (101 MHz, DMSO-d_6) δ 145.4, 139.8, 127.8, 127.5, 125.3, 120.2, 47.7, 33.6, 24.1 ppm.[22c]

Synthesis of base precursors. The bis(ethylsulfonyl)methanes (**1a-1c**) were synthesized according to the reported procedures.[23] These disulfone derivatives are the base precursors whose potassium salts were used to deprotonate the indicator acids in our previous pK_a determinations in ILs.[12] Although the basicities of their conjugated bases are not sufficient strong to undergo a measurable deprotonation of indicator acids used in current work, they are crucial components for the building up the expanded acid ladder in a stepwise fashion (Figure 1).

50 mmol aldehyde (RCHO, R = H, Et and ^{i}Pr) and 100 mmol ethanethiol were dissolved in 300 ml chloroform. 91 ml chlorotrimethylsilane was added dropwise into the mixture with the evolution of gas. The solution was cooled with an ice-bath and stirred for 2h until it became clear. Then aqueous Na_2CO_3 (5% wt) was added to the solution until the reaction mixture became alkaline. Subsequently, the solution was washed with deionized water and the organic layer was dried with anhydrous Na_2SO_4. The crude product bis(ethylthio)methane was obtained after the organic layer was evaporated. Next, cooled with an ice-bath, the crude bis(ethylthio)methane, together with 605 ml aqueous H_2O_2 (30% wt) were dissolved in 1140 ml CH_3COOH. After 30 mins, the reaction mixture was stirred at 50 ^{o}C for 2h. Then the mixture was poured into 3000 ml ice water. The aqueous layer was extracted with DCM (800 ml*3) and was washed with deionized water (500 ml*2). The organic phase was evaporated to afford crude bis(ethylsulfonyl)methanes. **1a-1c** was obtained as white solid after multiple crystallization from EtOH.

$EtSO_2CH_2SO_2Et$ (**1a**), white solid (4.01 g, yield: 40%). ^{1}H NMR (400 MHz, DMSO-d_6) δ 5.43 (s, 2H), 3.35 (dd, J = 14.7, 7.3 Hz, 4H), 1.27 (t, J = 7.4 Hz, 6H). ^{13}C{^{1}H} NMR (100 MHz, DMSO-d_6) δ 67.0, 48.6, 5.9 ppm.[23]

$EtSO_2CH(^iPr)SO_2Et$ (**1b**), white solid (5.09 g, yield: 42%). ^1H NMR (400 MHz, $CDCl_3$-d_1) δ 4.01 (d, J = 1.5 Hz, 1H), 3.60 (dq, J = 14.9, 7.5 Hz, 2H), 3.27 (dq, J = 14.9, 7.4 Hz, 2H), 2.95 (heptd, J = 7.1, 1.5 Hz, 1H), 1.55–1.33 (m, 12H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ 83.9, 49.2, 28.2, 21.0, 5.8 ppm.[23]

$EtSO_2CH(Et)SO_2Et$ (**1c**), white solid (5.25 g, yield: 46%). ^1H NMR (400 MHz, DMSO-d_6) δ 5.14 (t, J = 5.7 Hz, 1H), 3.40 (q, J = 7.4, 4H), 2.24-2.12 (m, 2H) 1.28 (t, J = 7.4 Hz, 6H). 1.19 (t, J = 7.4, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, DMSO-d_6) δ 78.5, 47.1, 17.9, 13.1, 5.4 ppm.[23]

Synthesis of nitroalkanes. The aliphatic nitroalkanes (**2a**-**2c**) were purchased from the available commercial sources, and were purified from multiple reduced pressure distillations before used as the substrates. The aromatic nitroalkanes (**2d**-**2m**) were synthesized and purified according to the known procedures.[24] The mass and yield for the following specific aromatic nitroalkane were based on 20 mmol starting material respectively.

4-$MeOC_6H_4CH_2NO_2$ (**2d**), clear oil (2.88 g, yield: 86%). ^1H NMR (400 MHz, $CDCl_3$-d_1) δ 7.51–7.29 (m, 2H), 7.06–6.81 (m, 2H), 5.37 (s, 2H), 3.83 (s, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ 161.0, 131.7, 122.1, 114.6, 79.7, 55.5 ppm.[24b]

$C_6H_5CH_2NO_2$ (**2e**), clear oil (1.73 g, yield: 63%). ^1H NMR (400 MHz, $CDCl_3$-d_1) δ 7.45 (d, J = 2.3 Hz, 5H), 5.45 (s, 2H). $^{13}C\{^1H\}$ NMR (101 MHz, $CDCl_3$-d_1) δ 130.2, 130.1, 129.9, 129.2, 80.2 ppm.[24c]

4-$^tBuC_6H_4CH_2NO_2$ (**2f**), clear solid (1.93 g, yield: 50%). ^1H NMR (400 MHz, $CDCl_3$-d_1) δ 7.45 (d, J = 8.3 Hz,2H), 7.39 (d, J = 8.3 Hz, 2H), 5.42 (s, 2H), 1.33 (s, 9H). $^{13}C\{H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ 153.3, 129.8, 126.9, 126.1, 79.8, 34.9, 31.3 ppm.[24c]

4-$FC_6H_4CH_2NO_2$ (**2g**): clear oil (1.99 g, yield: 65%). ^1H NMR (400 MHz, $CDCl_3$-d_1) δ 7.45 (dd, J = 8.5, 5.2 Hz, 2H), 7.11 (t, J = 8.6 Hz, 2H), 5.41 (s, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ 163.7(d, J = 250.0 Hz), 132.2 (d, J = 8.7 Hz), 125.8 (d, J = 3.3 Hz), 116.3 (d, J = 22.0 Hz), 79.2 ppm.[24c]

4-$ClC_6H_4CH_2NO_2$ (**2h**), white solid (2.40 g, yield: 70%). ^1H NMR (400 MHz, $CDCl_3$-d_1) δ 7.41 (m, 4H), 5.41 (s, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ 136.5, 131.5, 129.5, 128.2, 79.3 ppm.[24c]

4-$BrC_6H_4CH_2NO_2$ (**2i**), white solid (1.64 g, yield: 38%). ^1H NMR (400 MHz, $CDCl_3$-d_1) δ 7.58 (d, J = 8.4 Hz, 2H), 7.34 (d, J = 8.3 Hz, 2H), 5.40 (s, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ

132.5, 131.8, 128.6, 124.7, 79.4 ppm.[24a]

4-$CF_3C_6H_4CH_2NO_2$ (**2j**), white solid (3.04 g, yield: 74%). ^{1}H NMR (400 MHz, $CDCl_3$-d_1) δ 7.72 (d, J = 8.2 Hz, 2H), 7.60 (d, J = 8.1 Hz, 2H), 5.51 (s, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ 133.3, 132.3 (q, J = 32.8 Hz), 126.2 (q, J = 3.8 Hz), 123.8 (q, J = 272.5 Hz), 79.3 ppm.[24c]

4-$BzC_6H_4CH_2NO_2$ (**2k**), white solid (3.23 g, yield: 67%). ^{1}H NMR (400 MHz, $CDCl_3$-d_1) δ 7.86 (d, J = 8.2 Hz, 2H), 7.83–7.77 (m, 2H), 7.61 (dd, J = 15.5, 7.8 Hz, 3H), 7.50 (t, J = 7.6 Hz, 2H), 5.54 (s, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ 195.9, 139.2, 137.2, 133.5, 133.0, 130.8, 130.2, 130.1, 128.6, 79.7 ppm.[24b]

4-$CNC_6H_4CH_2NO_2$ (**2l**), white solid (2.59 g, yield: 80%). ^{1}H NMR (400 MHz, $CDCl_3$-d_1) δ 7.75 (d, J = 8.3 Hz, 2H), 7.59 (d, J = 8.3 Hz, 2H), 5.51 (s, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ 134.1, 133.0, 130.9, 118.0, 114.4, 79.2 ppm.[24c]

4-$NO_2C_6H_4CH_2NO_2$ (**2m**), white solid (1.86 g, yield: 51 %). ^{1}H NMR (400 MHz, $CDCl_3$-d_1) δ 8.32 (d, J = 8.6 Hz, 2H), 7.67 (d, J = 8.6 Hz, 2H), 5.56 (s, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$-d_1) δ 149.0, 135.8, 131.3, 124.4, 78.9 ppm.[24a]

pK_a Measurement of nitroalkanes in [BMPY][NTf_2].

The procedures for pK_a determination in [BMPY][NTf_2] were similar to those described previously.[12] In specific, the pK_a measurement was initiated by the adding of 1.5 ml [BMPY][NTf_2] solution of **base-2** (~5 × 10^{-4} M) into an empty UV cell with a specially made 3-way valve,[12f] and then the spectrum for baseline was recorded on a UV instrument. Next an IL solution of an appropriate indicator acid (HIn) with the known pK_a was added dropwisely until the UV absorbance was not increasing with a further addition. Then a [BMPY][NTf_2] solution of nitroalkane (~0.06 M) was added in several portions (the final concentration of the nitroalkane in the IL solution was about 10^{-4} M). The weight of the UV cell and the corresponding spectrum were also recorded upon each addition. The pK_a of nitroalkane was then calculated from the change of absorbance and the amount of nitroalkane added.

ASSOCIATED CONTENT

Supporting Information

Detailed experimental procedures; regression analyses; representative UV-vis and NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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