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1,2,4-Triazole-Based Tunable Aryl/Alkyl Ionic Liquids

Dirk Meyer and Thomas Strassner*

Physikalische Organische Chemie, Technische Universität Dresden, Bergstrasse 66, 01069 Dresden, Germany

thomas.strassner@chemie.tu-dresden.de

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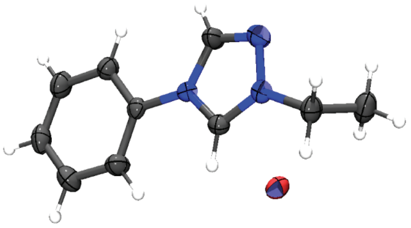
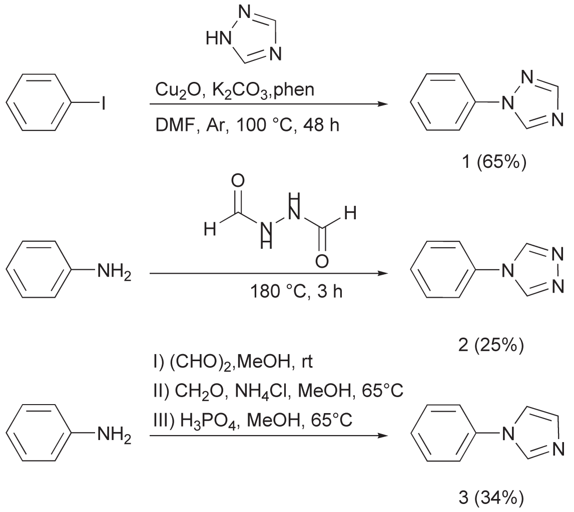


Ionic liquids based on aryl-/alkyl-substituted imidazolium salts constitute a new generation of ionic liquids with a high degree of flexibility. The new concept could now also be extended to aryl-/alkyl-substituted 1,2,4-triazolium salts. The two different phenyl-substituted 1*H*- and 4*H*-1,2,4-triazoles have been synthesized by a coupling reaction or a one-pot synthesis with diformylhydrazine, respectively. Reaction with alkyl bromides provided the 1,2,4-triazolium bromides, and an anion-exchange reaction led to the corresponding bis(trifluoromethylsulfonyl)imide salts with melting points well below 100 °C.

SCHEME 1. **Synthesis of 1-Phenyl-1*H*-1,2,4-triazole, 1, 4-Phenyl-4*H*-1,2,4-triazole, 2,[21] and 1-Phenyl-1*H*-imidazole, 3[22,23]**



Ionic liquids (ILs) have recently received a lot of attention as alternative solvents for organic synthesis,[1−5] plating,[6] the dissolution of cellulose[7] or as a component of dye sensitized solar cells.[8] Several classes of ionic liquids based on different organic cations have been investigated throughout the last years with bisalkylimidazolium salts being the most prominient, while only some examples of ILs based on 1,2,4-triazolium cations have been reported.[9−18]

Last year we introduced a new generation of ionic liquids which differ from all previously known imidazolium ionic liquids by the introduction of aryl substituents (*TAAILs* = **T**unable **A**ryl/**A**lkyl **I**onic **L**iquids) at the imidazolium core.[19] They allow the introduction of additional +M/−M effects to tune their properties, a new concept with quite beneficial effects.[20] We decided to investigate whether the underlying principle can also be transferred to other heterocycles and present the results on the synthesis of phenyl-1,2,4-triazole-based *TAAILS* with different chain lengths.

Synthesis of the different salts starts with the preparation of the phenyl-substituted triazoles **1** and **2** (Scheme 1). 1-Phenyl-1*H*-1,2,4-triazole, **1**, is accessible by the well-established copper(I)-catalyzed coupling reaction of 1*H*-1,2,4-triazole and iodobenzene, while 4-phenyl-4*H*-1,2,4-triazole, **2**, was synthesized according to a published procedure from 1,2-diformylhydrazine and aniline (Scheme 1).[21]

Two types of aryl-/alkyl-substituted 1,2,4-triazolium salts (**1**→ **4a−g** and **2**→ **5a−g**) have been synthesized by reaction of the corresponding triazoles with alkyl bromides of different chain lengths (Table 1). For comparison, the analogous

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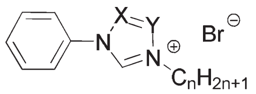
TABLE 1. **Triazolium Salts 4a−g and 5a−g, Imidazolium Salts 6a−g**

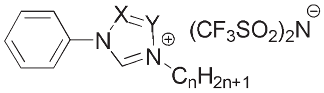


4a-g X=N, Y=CH
5a-g X=CH, Y=N
6a-g X=CH, Y=CH

n		mp [°C]	yld %		mp [°C]	yld %		mp [°C]	yld %
2	**4a**	224	61	**5a**	187	97	**6a**	111	37
3	**4b**	189	40	**5b**	137	97	**6b**	93	99
5	**4c**	116	80	**5c**	118	78	**6c**	116	82
6	**4d**	133	74	**5d**	121	82	**6d**	100	53
7	**4e**	123	69	**5e**	127	69	**6e**	65	30
11	**4f**	160	37	**5f**	151	64	**6f**	–[a]	53
14	**4g**	156	59	**5g**	154	74	**6g**	56	59

[a] Liquid at room temperature, no melting point observed.

TABLE 2. **Triazolium Salts 7a−g and 8a−g, Imidazolium salts 9a−g**



7a-g X=N, Y=CH
8a-g X=CH, Y=N
9a-g X=CH, Y=CH

n		mp [°C]	yld %		mp [°C]	yld %		mp [°C]	yld %
2	**7a**	51	98	**8a**	55	80	**9a**	33	71
3	**7b**	99	88	**8b**	73	90	**9b**	23	66
5	**7c**	46	90	**8c**	45	90	**9c**	18	52
6	**7d**	39	62	**8d**	36	83	**9d**	27	37
7	**7e**	41	91	**8e**	44	100	**9e**	–[a]	86
11	**7f**	40	84	**8f**	51	83	**9f**	10	57
14	**7g**	38	87	**8g**	68	81	**9g**	13	81

[a] Liquid at room temperature, no melting point observed.

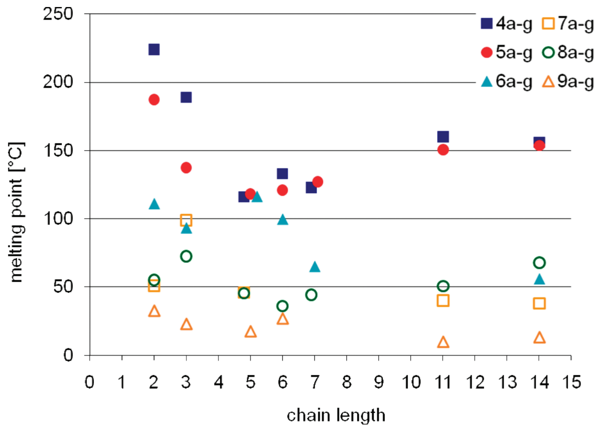


FIGURE 1. Melting points of the triazolium and imidazolium salts.

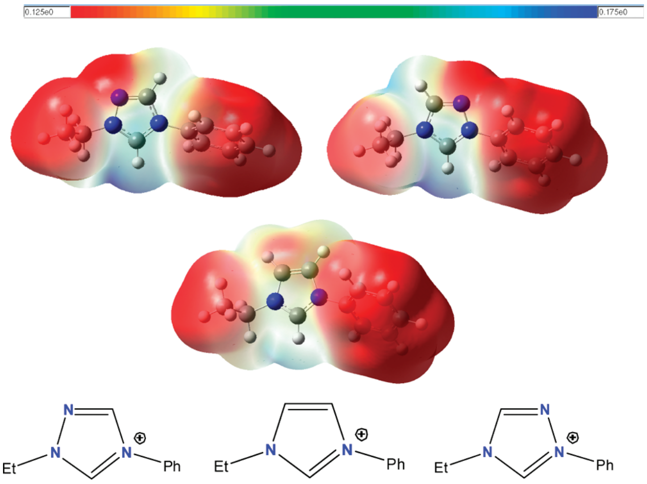


FIGURE 2. Charge distribution in the imidazolium (center) and triazolium cations.

N-phenyl-substituted imidazolium bromides **6a−g** have been prepared from 1-phenyl-1*H*-imidazole **3**.[22,23] In general (with the exception of **6c**), the imidazolium salts show lower melting points compared to those of both types of triazolium salts. The position of the third, not substituted nitrogen atom has no significant influence on the observed melting point. The lowest melting points of the triazolium-based ILs are observed for chains of medium lengths (C_5-C_7). The short chains lead to significantly higher melting points while the C_{11} and C_{14} chains seem to level out at around 150 °C.

Single crystals were grown from one of the triazolium salts with a higher melting point (**5a**) by slow evaporation of a methanol solution and subjected to X-ray diffraction. An ORTEP style representation of the structure of **5a** is given in the Supporting Information.

Exchange of the bromide anions by anion metathesis with lithium-bis(trifluoromethylsulfonyl)imide leads to the corresponding bis(trifluoromethylsulfonyl)imide salts (**4a−g** → **7a−g** and **5a−g** → **8a−g**) (Table 2). The imidazolium bis(trifluoromethylsulfonyl)imide salts **9a−g** were prepared from the bromides **6a−g** using the same reaction conditions. As expected, the melting points of the triazolium salts decreased dramatically (differences of up to 173 °C were observed) because of the counterion exchange (Figure 1). Both types of triazolium salts investigated do not qualify as room temperature ionic liquids (RTILs), as their melting points are around 45 °C (±10 °C). Also in the case of the bis(trifluoromethylsulfonyl)imide salts, the melting points of the triazolium *TAAILs* are significantly higher compared to those of the corresponding imidazolium *TAAILs* (Table 2).

It is obvious that for all bis(trifluoromethylsulfonyl)imide salts with alkyl chains longer than C_5 the influence of the different alkyl chains is small. However, the exchange of the counterions leads to a higher temperature stability, the phenyl alkyl triazolium salts **7a−g** and **8a−g** start to decompose at temperatures of 360−400 °C (see Supporting Information for TGA spectra).

We also calculated the ESP surfaces (Figure 2) of both types of phenyl-substituted triazolium cations by high-level density functional theory calculations (B3LYP/6-311++G(d,p))[24] and compared the results to those of the corresponding imidazolium salts. The ESP surface representations of the triazolium and imidazolium cations show a similar charge distribution with the exception that the electron density of the additional nitrogen in the triazolium backbone shows up as a center of negative charge.

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We have synthesized a series of novel triazolium bromide salts **4a−g** and **5a−g** containing one phenyl substituent and an alkyl side chain. By changing the central heterocyclic core from an imidazolium to a triazolium core we could prove that the concept of an aryl(sp^2)/alkyl(sp^3) substitution can be extended to other heterocycles. The additional nitrogen atom in the central heterocycle leads to an increase of the melting point compared to the corresponding imidazolium bromides **6a−g**. After exchange of the counterion, the triazolium salts **7a−g** and **8a−g** show melting points around 45 °C together with a high temperature stability (TGA spectra given in the Supporting Information). The position of the third triazole nitrogen atom does not have a significant influence on the melting point of the systems studied here. But we know that substituents at phenyl rings have an significant effect on the properties of the resulting *TAAILs* and therefore plan to study the effect of substituents on the aryl ring also for this new class of triazolium *TAAILs*.

Experimental Section

4-Phenyl-4*H*-1,2,4-triazole, **2**,[21] and 1-phenyl-1*H*-imidazole, **3**,[22] were prepared according to literature procedures.

Synthesis of 1-Phenyl-1*H*-1,2,4-triazole, 1. After standard cycles of evacuation and refilling with argon, an oven-dried Schlenk tube equipped with a magnetic stir bar was charged with 0.21 g of Cu_2O (0.0015 mol), 0.52 g of 1,10-phenanthroline (0.0029 mol), 1.00 g of 1*H*-1,2,4-triazole (0.0145 mol), and 6.01 g of K_2CO_3 (0.044 mol). The tube was evacuated, filled with argon, and capped with a rubber septum. Iodobenzene (2.42 mL, 4.43 g, 0.022 mol) was added via a syringe, followed by anhydrous and degassed DMF (10 mL). The reaction mixture was stirred for 48 h at 120 °C under a positive pressure of argon. After cooling to room temperature, it was diluted with 20 mL of dichloromethane and filtered through a plug of Celite, the filter cake being further washed with dichloromethane (~20 mL). The resulting organic layer was washed with water and brine and then dried over Na_2SO_4. The solvent was removed in vacuo. The crude product was purified by flash column chromatography on silica gel (gradient ethyl acetate/petroleum ether 2:8 to ethyl acetate) to provide **1** (1.36 g, 65%) as a pale-yellow solid. Found: C 66.0, H 5.0, N 28.9. Calcd for $C_8H_7N_3$: C 66.0, H 4.9, N 29.0. δ_H (300 MHz, DMSO-d_6, 25 °C) 7.41 (1 H, t, *J* 7.4), 7.58 (2 H, t, *J* 7.4), 7.87 (2 H, d, *J* 7.5), 8.25 (1 H, s), 9.31 (1 H, s). δ_C (75.5 MHz, DMSO-d_6, 25 °C) 119.4, 127.8, 129.8, 136.7, 142.3, 152.4.

Synthesis of 1-Phenyl-4-ethyl-1*H*-1,2,4-triazolium Bromide, 4a. A sealed ACE pressure tube was charged with 0.22 g (0.0015 mol) of 1-phenyl-1*H*-1,2,4-triazole, **1**, and 1.00 mL (0.013 mol) of bromoethane. The reaction mixture was stirred for 24 h at 110 °C. After cooling to room temperature 2 mL of petroleum ether was added. The formed precipitate was separated by filtration, washed with THF/petroleum ether (1:1), and dried in vacuum. Yield: 0.23 g (61%); mp 224 °C. Found: C 47.25, H 4.9, N 16.5. Calcd for $C_{10}H_{12}N_3Br$: C 47.3, H 4.8, N 16.5. δ_H (300 MHz, DMSO-d_6, 25 °C) 1.57 (3 H, t, *J* 7.3), 4.37 (2 H, q, *J* 7.3), 7.69 (3 H, m), 7.94 (2 H, d, *J* 7.5), 9.52 (1 H, s), 11.01 (s, 1 H). δ_C (75.5 MHz, DMSO-d_6, 25 °C) 14.2, 43.4, 120.5, 130.1, 130.3, 135.0, 141.4, 144.8.

Synthesis of **4b−4g** follows an analogous procedure and is described in detail in the Supporting Information.

Synthesis of 4-Phenyl-1-ethyl-4*H*-1,2,4-triazolium Bromide, 5a. An ACE pressure tube was charged with 0.15 g (0.001 mol) of 4-phenyl-4*H*-1,2,4-triazole, **2**, and 0.22 mL (0.003 mol) of bromoethane. The reaction mixture was stirred for 24 h at 110 °C. After cooling to room temperature, 2 mL of petroleum ether was added. The formed precipitate was separated by filtration, washed with THF/petroleum ether (1:1), and dried in vacuo. Yield: 0.23 g (97%); mp 187 °C. Found: C 46.9, H 4.75, N 16.8. Calcd for $C_{10}H_{12}N_3Br$: C 47.3, H 4.8, N 16.5. δ_H (300 MHz, DMSO-d_6, 25 °C) 1.56 (3 H, t, *J* 7.3), 4.49 (2 H, q, *J* 7.3), 7.71 (3 H, m), 7.86 (2 H, d, *J* 7.5), 9.81 (1 H, bs), 10.87 (1 H, bs). δ_C (75.5 MHz, DMSO-d_6, 25 °C) 13.4, 47.4, 122.4, 130.1, 130.3, 132.1, 141.2, 142.6.

Synthesis of **5b−5g** follows an analogous procedure and is described in detail in the Supporting Information.

Synthesis of 1-Phenyl-3-ethyl-1*H*-imidazolium Bromide, 6a. An ACE pressure tube was charged with 0.20 g (0.0014 mol) of 1-phenyl-1*H*-imidazole, **3**, and 0.11 mL (0.16 g, 0.015 mol) of bromoethane in 5 mL of THF. The reaction mixture was stirred for 72 h at 90 °C. After cooling to room temperature, a solid separated from the reaction solvent. After decantation of the solvent, the crude product was washed with THF or THF/diethyl ether 1:2 and dried in vacuo. Yield: 0.13 g (37%); mp 111 °C. Found: C 49.9, H 5.15, N 10.6. Calcd for $C_{11}H_{13}N_2Br \cdot 0.6\,H_2O$: C 50.1, H 5.4, N 10.6. δ_H (300 MHz, DMSO-d_6, 25 °C) 1.52 (3 H, t, *J* 7.3), 4.30 (2 H, q, *J* 7.3), 7.67 (3 H, m), 7.81 (2 H, d, *J* 7.4), 8.08 (1 H, s), 8.34 (1 H, s), 9.86 (1 H, s). δ_C (75.5 MHz, DMSO-d_6, 25 °C) 14.8, 44.7, 121.0, 121.8, 123.0, 129.7, 130.2, 134.8, 135.2.

Synthesis of **6b−6g** follows an analogous procedure and is described in detail in the Supporting Information.

Synthesis of 1-Phenyl-4-ethyl-1*H*-1,2,4-triazolium Bis(trifluoromethylsulfonyl)imide, 7a. 4a [0.10 g (0.0004 mol)] was dissolved in 5 mL of water and reacted with 0.12 g (0.0004 mol) of lithium bis(trifluoromethylsulfonyl)imide. The product separated from the aqueous phase. After addition of 10 mL of dichloromethane, the phases were separated. The aqueous phase was extracted twice with 5 mL of dichloromethane. The combined organic phases were washed with 10 mL of water and dried over Na_2SO_4. The solvent was removed in vacuo, yielding the product as a white solid. Yield: 0.17 g (98%); mp 51 °C. Found: C 31.9, H 2.6, N 12.5, S 13.7. Calcd for $C_{12}H_{12}F_6N_4O_4S_2$: C 31.7, H 2.7, N 12.3, S 14.1. δ_H (300 MHz, DMSO-d_6, 25 °C) 1.56 (3 H, t, *J* 7.3), 4.35 (2 H, q, *J* 7.3), 7.71 (3 H, m), 7.92 (2 H, m), 9.46 (1 H, s), 10.87 (1 H, s). δ_C (75.5 MHz, DMSO-d_6, 25 °C) 14.1, 43.4, 117.3, 120.5, 130.1, 130.4, 135.0, 141.3, 144.8. δ_F (282 MHz, DMSO-d_6, 25 °C) −78.71.

Synthesis of **7b−7g** follows an analogous procedure and is described in detail in the Supporting Information.

Synthesis of 4-Phenyl-1-ethyl-1,2,4-triazolium Bis(trifluoromethylsulfonyl)imide, 8a. 5a [0.10 g (0.0004 mol)] was dissolved in 5 mL of water and reacted with 0.12 g (0.0004 mol) of lithium bis(trifluoromethylsulfonyl)imide. The product separated from the aqueous phase. After addition of 10 mL of dichloromethane, the phases were separated. The aqueous phase was extracted twice with 5 mL of dichloromethane. The combined organic phases were washed with 10 mL of water and dried over Na_2SO_4. The solvent was removed in vacuo, yielding the product as a white solid. Yield: 0.14 g (80%); mp 55 °C. Found: C 31.8, H 2.4, N 12.2, S 14.3. Calcd for $C_{12}H_{12}F_6N_4O_4S_2$: C 31.7, H 2.7, N 12.3, S 14.1. δ_H (300 MHz, DMSO-d_6, 25 °C) 1.56 (3 H, t, *J* 7.3), 4.46 (2 H, q, *J* 7.3), 7.71 (3 H, m), 7.80 (2 H, m), 9.75 (1 H, s), 10.71 (1 H, s). δ_C (75.5 MHz, DMSO-d_6, 25 °C) 13.4, 47.4, 117.3, 122.4, 130.2, 130.4, 132.1, 141.2, 142.8. δ_F (282 MHz, DMSO-d_6, 25 °C) −78.71.

Synthesis of **8b−8g** follows an analogous procedure and is described in detail in the Supporting Information.

Synthesis 1-Phenyl-3-ethyl-1*H*-imidazolium bis(trifluoromethylsulfonyl)imide, 9a. 6a (0.06 g [0.0002 mol]) was dissolved in 5 mL of water and reacted with 0.08 g (0.0003 mol) of lithium bis(trifluoromethylsulfonyl) imide. Due to the anion exchange, the product separated from the aqueous phase. After addition of 10 mL of dichloromethane, the phases were separated. The aqueous phase was extracted twice with 5 mL of dichloromethane. The combined organic phases were washed with 10 mL of water and dried over Na_2SO_4. The solvent was removed in vacuo, yielding the product as a colorless oil. Yield: 0.07 g (71%). mp 33 °C. Found: C 34.3, H 2.8, N 9.4, S 13.9. Calcd for $C_{13}H_{13}F_6N_3O_4S_2$: C 34.4, H 2.9, N 9.3, S 14.1. Yield: 0.07 g (71%). δ_H (500 MHz, DMSO-d_6, 25 °C) 1.51 (3 H, t, *J* 7.3), 4.28 (2 H, q, *J* 7.3), 7.59 (1 H, t, *J* 7.5), 7.68 (2 H, t, *J* 7.4), 7.78 (2 H, d, *J* 8.3), 8.06 (1 H, t, *J* 1.7), 8.32 (1 H, t, *J* 1.7), 9.78 (1 H, s). δ_C (125.8 MHz, DMSO-d_6, 25 °C) 14.7, 44.7, 118.1, 121.1, 121.8, 129.7, 130.1, 130.1, 134.8, 135.1.

Synthesis of **9b−9g** follows an analogous procedure and is described in detail in the Supporting Information.

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Supporting Information Available: Cartesian coordinates, details of the quantum chemical calculations, references (*Gaussian 03*, ref 4 in SI), experimental details, and ^1H and ^{13}C spectra for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.