Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron
Tetrahedron 63 (2007) 11349–11354

Arylation of anilines: formation of diarylamines using diaryliodonium salts

Michael A. Carroll* and Reice A. Wood

School of Natural Sciences—Chemistry, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

Received 20 June 2007; revised 6 August 2007; accepted 23 August 2007
Available online 30 August 2007

Abstract—Extensive studies on the reaction of the fluoride ion with diaryliodonium salts demonstrated that this is a generic process for the formation of fluoroarenes and has particular advantages for the preparation of fluorine-18 radiopharmaceuticals. During these studies it became apparent that nucleophiles other than the fluoride ion may be employed for generating substituted aromatics. This approach can be applied, using substituted anilines as the nucleophilic reagent, to the formation of a range of diarylamines in good yield. Optimised conditions for the reaction of a diaryliodonium salt with an aniline utilise TFA as the preferred counter-ion in DMF (130 °C, 24 h).

1. Introduction

Iodine, like the other halogens, is found typically in its monovalent form (oxidation state: −1). However, due to its large size and polarisability, it is able to form stable polycoordinate, multivalent compounds. Compounds of this type, containing hypervalent iodine, have been known for over a century and continue to receive considerable attention. The ability of these compounds to act as both selective reagents and useful intermediates has formed the basis of this interest.[1–7]

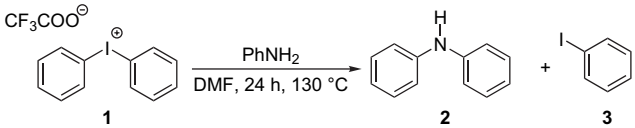
Our studies on the most numerous member of this group, the diaryliodonium salts, arose from the demonstration that they are suitable precursors for the formation of fluoroarenes by the action of the fluoride ion.[8–10] This project,[11,12] and others,[13–17] have exploited this observation in the production of fluorine-18 labelled radiopharmaceuticals for use as receptor radioligands in clinical research using positron emission tomography (PET). PET is an imaging technique for the absolute measurement, in vivo, of positron emitters, enabling their pharmacokinetics and biodistribution to be elucidated by non-invasive means.[18] A key advantage of this synthetic approach is that, unlike conventional nucleophilic aromatic substitution, the process places little or no restriction on the nature of aromatic substituents or their position, thus providing a versatile method for the formation of fluoroarenes. During these investigations it became evident that nucleophiles other than fluoride may be employed in an analogous manner and we now wish to report our studies on the formation of diarylamines using diaryliodonium salts.

2. Results and discussion

There is substantial interest in the synthesis of diarylamines as the diarylamino functionality is present in a wide range of natural products and has found extensive use in pharmaceuticals and as structural motifs in materials applications.[19] Although a variety of methods[20] have been developed for the formation of this key functional group, with recent efforts concentrating on metal catalysed processes,[21–25] the challenge of efficient, generic and practical formation of aryl-nitrogen bonds remains.

Our preliminary study (Scheme 1), to investigate the formation of diarylamines, utilised diphenyliodonium trifluoroacetate with aniline using conditions known to be successful for the addition of the fluoride ion—DMF at 130 °C.[26,27] The result of this initial reaction provided the desired diarylamine—*N*,*N*-diphenylamine **2**—in good yield (89%) and prompted us to explore the scope of this process further.[28]

Alternative solvents (DMSO at 130 °C, MeCN at 90 °C) have also been employed successfully in the fluoridation of diaryliodonium salts and as a result their use was also considered for the synthesis of diarylamines. The reaction of



Scheme 1. Formation of *N*,*N*-diphenylamine from diphenyliodonium trifluoroacetate.

Keywords: Hypervalent iodine; Diarylamine.
* Corresponding author. Tel.: +44 (0)191 2227074; fax: +44 (0)191 2226929; e-mail: m.a.carroll@ncl.ac.uk

0040–4020/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2007.08.076

diphenyliodonium trifluoroacetate, **1** with aniline proceeded, over the same time period, as expected in DMSO albeit in a much reduced yield (35%), however, much lower amounts (12%) of the desired product were isolated from the reaction using acetonitrile as the solvent. DMF was therefore used as the solvent of choice in all subsequent studies.

Unlike the application using [^{18}F]fluoride (fluorine-18: $t_{1/2}$= 109.7 min) the time taken for the reaction was no longer an overriding consideration. The results in Table 1 demonstrate that the yield increased with extended reaction times but that there was little improvement beyond 24 h. It is also of note that the addition of TEMPO (2,2,6,6-tetramethyl-1-piperidinyloxy free radical) to the reaction (Table 1; entry 6) had a detrimental effect on the yield, whereas this modification improved both the yield of the product and the reproducibility of the process in the corresponding production of fluoroarenes.[29,30] However, like the fluoridation reaction, it was evident that the amount of by-products generated during the reaction were reduced slightly when TEMPO was employed facilitating the purification process. The different response to the inclusion of a radical scavenger may suggest that the accepted mechanistic rationale, for the nucleophilic substitution of diaryliodonium salts, may not be generic and that, in this case the formation of aromatic radicals[31] may be involved and that optimisation of each system should be evaluated separately.

An investigation into the effect of temperature on the reaction (Table 2) demonstrated that the yield improved with increasing temperature. This highlighted that 130 °C was a suitable temperature for the reaction and that the conditions examined in our preliminary study (based on knowledge of the fluoridation process) could be considered general for the nucleophilic substitution of diaryliodonium salts.

The potential for isotopic dilution during the formation of fluorine-18 radiopharmaceuticals, using the nucleophilic substitution of diaryliodonium salts, limited the type of counter-ion that could be employed. As this restriction would not be necessary in the formation of diarylamines we also considered the effect of the counter-ion on the formation of *N*,*N*-diphenylamine, **2** (Table 3).

It is evident from the results in Table 3 that when the counter-ion may also act as a nucleophile, and therefore be in competition with the amine (Table 3; entries 1–3), the product is the result of counter-ion addition rather than the desired *N*,*N*-diphenylamine. Where the counter-ion is less nucleophilic in nature the aniline addition proceeds as expected providing **2** in good yields (Table 3; entries 5–9). It is not clear why the non-nucleophilic tetrafluoroborate counter-ion is not as successful in this role. Although, in this particular system, there is very little difference in the use of trifluoroacetate or triflate as the counter-ions, prior results on the fluoridation of diaryliodonium salts highlighted that triflate was less compatible with the preparation of complex polyfunctional iodine(III) materials.[26] As a result all further studies have been carried out with trifluoroacetate as the counter-ion.

The results in Table 4 demonstrate that a range of diarylamines may be prepared, in good yield, using this approach. It is not surprising that electron-rich materials are very effective, however, electron-deficient anilines such as 4-nitroaniline (Table 4; entry 6) and systems with increased steric demands (Table 4; entry 2) also provide the target diarylamine in a practical yield.

The studies so far have all employed a symmetrical diaryliodonium salt—diphenyliodonium trifluoroacetate **1**. When unsymmetrical systems (Scheme 2) are employed observations by us,[32,33] and others,[34,35] have suggested that nucleophilic substitution occurs preferentially on the sterically

Table 1. Effect of time on the formation of *N*,*N*-diphenylamine **2**

Entry[a]	Time (h)	**2**, Yield[b] (%)
1	1	18
2	2	32
3	4	47
4	8	50
5	24	89
6	24	60–67[c]
7	48	90

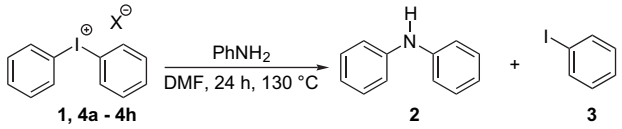
[a] DMF, 130 °C.
[b] Isolated yield.
[c] TEMPO (10 mol %) added.

Table 2. Effect of temperature on the formation of *N*,*N*-diphenylamine **2**

Entry[a]	*T* (°C)	**2**, Yield[b] (%)
1	50	9
2	70	17
3	90	49
4	110	73
5	130	89
6	150	86

[a] DMF, 24 h.
[b] Isolated yield.

Table 3. Effect of counter-ion on the formation of *N*,*N*-diphenylamine **2**

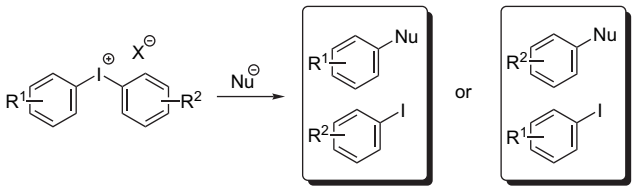


1, 4a - 4h **2** **3**

Entry		X	Yield[a] (%)
1	**4a**	Cl	—[b]
2	**4b**	Br	—[c]
3	**4c**	I	—[d]
4	**4d**	NO_3	—[e]
5	**4e**	TsO	83
6	**1**	CF_3COO	89
7	**4f**	CF_3SO_3	90
8	**4g**	PF_6	79
9	**4h**	BF_4	53

GC yields were determined relative to naphthalene as an internal standard.
[a] Isolated yield.
[b] PhCl (93%) and trace of **2** by GC.
[c] PhBr (78%) by GC.
[d] Compound **3** only.
[e] Compound **2** (12%) by GC, isolation of an analytical sample was not achieved.

demanding aromatic ring (the so-called *ortho*-effect) and/or the more electron-deficient ring.

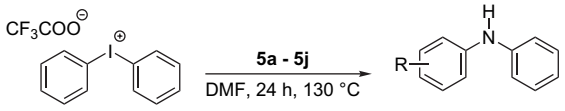


Scheme 2. Nucleophilic substitution of unsymmetrical iodonium salts.

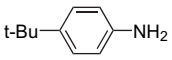
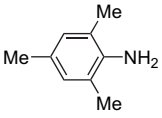
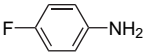
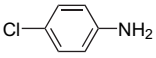
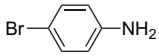
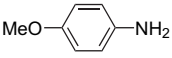
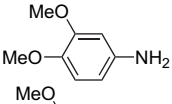
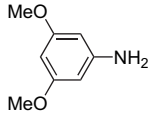
The fluoridation of representative unsymmetrical diaryliodonium salts (Table 5; Nu=F) highlights this selectivity. Although extensive studies have refined the selection rules for [^{18}F]fluoridation, and in light of the effect of TEMPO on the yield of the process (Table 1; entry 6), it is of fundamental interest whether other nucleophiles, in this case aniline leading to the formation of diarylamines, obey the same general rules.

The iodonium salts bearing functionality to assess electronic control in the amination process (Table 5; Nu=NHPh, entries 1 and 2) demonstrate that preferential substitution of the electron-deficient ring still occurs although the degree of selectivity is much reduced. Surprisingly the option of steric control in the process (Table 5; Nu=NHPh, entry 3) resulted in substitution of the less hindered ring (**2**) as the major product in an apparent reversal of the *ortho*-effect. This may be a result of the significant size difference between aniline and fluoride affecting the preferred orientation of the aromatic rings in the transition state or may just reflect the relative stability of the corresponding aromatic radical.

Table 4. Reaction of diphenyliodonium trifluoroacetate with substituted anilines



1 **6a - 6j**

Entry		Aniline, **5**	**6**[a]	Yield[b] (%)
1	**5a**		**6a**	74
2	**5b**		**6b**	72
3	**5c**		**6c**	74
4	**5d**		**6d**	74
5	**5e**		**6e**	74
6	**5f**		**6f**	50
7	**5h**		**6h**	92
8	**5i**		**6i**	72
9	**5j**		**6j**	78

[a] Some diarylamines may be light sensitive.
[b] Isolated yield.

3. Conclusion

In summary we have demonstrated a new practical approach to the formation of diarylamines by the addition of anilines to diaryliodonium salts. Good yields of the desired products are obtained in DMF at 130 °C for 24 h.

For the examples studied it is of note that, in the case of electronic control, the observed selectivity of the nucleophilic substitution process obeys the same general rules that have been established for the fluoridation of diaryliodonium salts albeit at a reduced degree. However, the evidence of apparent reversal of steric control (the *ortho*-effect) and the effect of TEMPO on the outcome suggests that an alternative arylation mechanism may be involved. Studies to establish further the scope/versatility of this transformation and to determine more detailed rules governing the selectivity of the process are currently underway.

4. Experimental

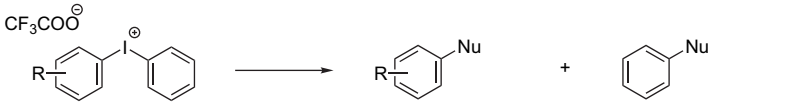
4.1. General information

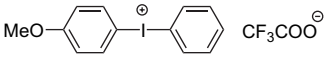
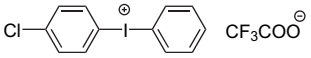
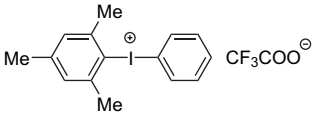
Reactions requiring anhydrous conditions were performed using oven-dried glassware and conducted under a positive pressure of nitrogen. Anhydrous solvents were prepared in accordance with standard protocols. Infrared spectra were recorded on a Nicolet Avatar 370DTGS FT-IR spectrometer with internal calibration. ^{1}H, ^{13}C and COSY NMR spectra were recorded on a Bruker Avance 300 spectrometer with residual protic solvent as an internal reference. ^{19}F NMR were recorded on a Jeol λ 500 MHz spectrometer with $CFCl_3$ as an external reference. Elemental analyses were carried out at London Metropolitan University. Mass spectra and accurate masses were recorded at the EPSRC Mass Spectrometry Service, Swansea. Melting points were recorded on a Gallenkamp MF-370 melting point apparatus and are uncorrected. Iodonium salts **4a**–**4g** are commercially available, **4h** was prepared according to a reported procedure.[36] *Caution*: hypervalent iodine compounds are potentially explosive and should be handled taking appropriate precautions.[37,38]

4.2. Typical procedure for the preparation of diphenyliodonium trifluoroacetate (1)

Trifluoroacetic acid (0.77 mL, 10 mmol) was added dropwise, at −30 °C, to a stirred suspension of diacetoxyiodobenzene (1.61 g, 5 mmol) in dichloromethane (50 mL). After 30 min the mixture was allowed to warm to room

Table 5. Fluoride versus aniline substitution of unsymmetrical diaryliodonium salts



Entry[a]		Iodonium salt	8:9[a]	Nu=NHPh[b]
1	**7a**		**9** only	**6h**:**2** 1:1.6
2	**7b**		1.7:1	**6d**:**2** 1.3:1
3	**7c**		20:1	**6b**:**2** 1:2.5

[a] CsF, MeCN, 90 °C, 1.5 h, ratios by ^{19}F NMR analysis of the crude reaction mixture.
[b] $PhNH_2$, DMF, 130 °C, 24 h, ratios by GC analysis of the crude reaction mixture.

temperature and stirred for a further hour when it was recooled (−30 °C) and benzeneboronic acid (0.61 g, 5 mmol) was added. The resulting mixture was allowed to warm to room temperature overnight and the solvent was removed in vacuo to give the crude product. Subsequent crystallisation gave the product as a white crystalline solid (1.27 g, 3.22 mmol, 64%). Mp 185–187 °C (dec from dichloromethane–ether (lit.[36] mp 186–190 °C from acetone–ether); IR (neat) 1650, 1443, 1410, 1178, 1124 cm^{-1}; ^{1}H NMR (DMSO-d_6) δ 8.25 (4H, d, H2/H2′/H6/H6′ J 8 Hz), 7.65 (2H, t, H4/H4′ J 7 Hz), 7.52 (4H, m, H3/H3′/H5/H5′); ^{13}C NMR (DMSO-d_6) δ 135.7, 132.5, 132.2, 117.3; *m/z* (FAB) 282 (M+H$^+$, 11%), 281 (M$^+$, 100). Found: M$^+$, 280.9822. $C_{12}H_{10}I$ requires 280.9827. Anal. Calcd for $C_{14}H_{10}F_3IO_2$: C, 42.66; H, 2.56. Found: C, 42.52; H, 2.53.

4.2.1. 4-Methoxydiphenyliodonium trifluoroacetate (7a). Using diacetoxyiodobenzene (1.61 g, 5 mmol) and anisole (0.55 mL, 5 mmol). White crystalline solid (1.50 g, 3.54 mmol, 71%). Mp 146–148 °C from dichloromethane–hexane (lit.[39] mp 158–162 °C from benzene); IR (KBr) 3054, 2946, 2844, 1661, 1571, 1492 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.91 (2H, d, H2′/H6′ J 7 Hz), 7.89 (2H, d, H2/H6 J 9 Hz), 7.55 (1H, t, H4′ J 7 Hz), 7.41 (2H, t, H3′/H5′ J 7 Hz), 6.93 (2H, d, H3/H5 J 9 Hz), 3.84 (3H, s, OCH_3); ^{13}C NMR ($CDCl_3$) δ 163.1, 137.2, 134.4, 132.0, 131.9, 118.1, 117.6, 105.6, 55.9; *m/z* (FAB) 312 (M+H$^+$, 13%), 311 (M$^+$, 100). Found: M$^+$, 310.9937. $C_{13}H_{12}I$ requires 310.9933. Anal. Calcd for $C_{15}H_{12}F_3IO_3$: C, 42.48; H, 2.85. Found: C, 42.40; H, 2.81.

4.2.2. 4-Chlorodiphenyliodonium trifluoroacetate (7b). Using 4-(diacetoxyiodo)chlorobenzene[40] (2.42 g, 6.8 mmol) and benzeneboronic acid (0.83 g, 6.8 mmol). White crystalline solid (2.30 g, 5.37 mmol, 81%). Mp 176–177 °C from dichloromethane–petrol; IR (neat) 3053, 2968, 1647, 1472, 1176, 1130, 1012 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.95 (2H, d, H2′/H6′ J 8 Hz), 7.89 (2H, d, H2/H6 J 9 Hz), 7.57 (1H, t, H4′ J 8 Hz), 7.37 (4H, m, H3/H3′/H5/H5′); ^{13}C NMR ($CDCl_3$) δ 139.1, 136.5, 135.2, 132.2 (2C), 132.1, 117.5, 114.5; *m/z* (ESI) 317 ([^{37}Cl]M$^+$, 32%), 315 ([^{35}Cl]M$^+$, 100), 190 (24), 188 (78). Found: M$^+$, 314.9427. $C_{12}H_9{}^{35}ClI$ requires 314.9432. Anal. Calcd for $C_{14}H_9ClF_3IO_2$: C, 39.23; H, 2.12. Found: C, 39.32; H, 2.03.

4.2.3. 2,4,6-Trimethyldiphenyliodonium trifluoroacetate (7c). Using diacetoxyiodobenzene (6.44 g, 20 mmol) and mesitylene (2.40 g, 20 mmol). White crystalline solid (6.71 g, 15.38 mmol, 77%). Mp 138–139 °C from dichloromethane–petrol; IR (neat) 1651, 1472, 1440, 1415, 1195, 1169, 1129 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.69 (2H, d, H2′/H6′ J 8 Hz), 7.47 (1H, t, H4′ J 8 Hz), 7.35 (2H, t, H3′/H5′ J 8 Hz), 7.07 (2H, s, H3/H5), 2.64 (6H, s, 2-CH_3/6-CH_3), 2.34 (3H, s, 4-CH_3); ^{13}C NMR ($CDCl_3$) δ 143.9, 142.5, 133.2, 132.0, 131.4, 130.3, 123.4, 115.3, 27.2, 21.2; *m/z* (ESI) 324 (M+H$^+$, 17%), 323 (M$^+$, 100), 196 (85), 137 (64), 119 (62). Found: M$^+$, 323.0289. $C_{15}H_{16}I$ requires 323.0291. Anal. Calcd for $C_{17}H_{16}F_3IO_2$: C, 46.80; H, 3.70. Found: C, 46.71; H, 3.61.

4.3. Typical procedure for the preparation of *N,N*-diphenylamine (2)

Aniline (0.47 g, 5 mmol) was added to diphenyliodonium trifluoroacetate **1** (1.97 g, 5 mmol) in DMF (50 mL) and the resulting mixture heated at 130 °C for 24 h. After cooling, water (50 mL) was added and the mixture extracted with ether (3×50 mL). The organic extracts were combined and washed with more water (200 mL), dried ($MgSO_4$) and the solvents removed in vacuo to give the crude product as a brown oil. Purification by chromatography (SiO_2, 1:1 ether–petrol) gave the product as a white crystalline solid (0.75 g, 4.44 mmol, 89%). Mp 50–52 °C from petrol (lit.[41] mp 51–53 °C); R_f=0.63 (1:1 ether–petrol); IR (neat) 3404, 3380, 3040, 1582, 1513, 1493, 1457, 1307 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.19 (4H, m, H3/H5), 7.02 (4H, d, H2/H6 J 7 Hz), 6.86 (2H, t, H4 J 7 Hz), 5.79 (1H, br s, NH); ^{13}C NMR ($CDCl_3$) δ 143.6, 129.7, 121.6, 118.6; *m/z* (ESI) 170 (M+H$^+$, 100%).

4.3.1. 4-*tert*-Butyldiphenylamine (6a). White crystalline solid (0.83 g, 3.68 mmol, 74%). Mp 65–67 °C from petrol (lit.[42] mp 66–67 °C from ethanol); R_f=0.71 (1:1 ether–petrol); IR (neat) 3385, 2961, 1593, 1514, 1496, 1361, 1305 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.17 (4H, m, H2/H2′/H6/H6′), 6.98 (4H, m, H3/H3′/H5/H5′), 6.83 (1H, m, H4′), 1.23 (9H, s, $C(CH_3)_3$); ^{13}C NMR ($CDCl_3$) δ 144.9, 144.4, 141.0, 129.6, 126.4, 120.9, 118.8, 117.8, 34.5, 31.8; *m/z* (EI) 255 (M^+, 58%), 210 (100), 92 (38), 91 (43), 90 (49). Found: M+H$^+$, 226.1591. $C_{16}H_{19}N$ requires 226.1590. Anal. Calcd for $C_{16}H_{20}N$: C, 85.29; H, 8.50; N, 6.22. Found: C, 85.16; H, 8.43; N, 6.13.

4.3.2. 2,4,6-Trimethyldiphenylamine (6b). Off-white crystalline solid (0.76 g, 3.58 mmol, 72%). Mp 55–57 °C from petrol (lit.[20] mp 54–56 °C); R_f=0.35 (1:1 ether–petrol); IR (neat) 3062, 1651, 1471, 1441, 1195, 1169, 1129 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.18 (2H, t, H3′/H5′ *J* 7 Hz), 6.96 (2H, s, H3/H5), 6.75 (1H, t, H4′ *J* 7 Hz), 6.54 (2H, d, H2′/H6′ *J* 7 Hz), 2.33 (3H, s, 4-Me), 2.25 (6H, s, 2-Me/6-Me); ^{13}C NMR ($CDCl_3$) δ 147.4, 136.4, 136.2, 135.8, 129.7, 129.6, 118.4, 113.9, 21.2, 18.5; *m/z* (EI) 212 (M+H$^+$, 41%), 211 (M^+, 100), 210 (65), 196 (41), 194 (33). Found: M^+, 211.1371. $C_{15}H_{17}N$ requires 211.1361.

4.3.3. 4-Fluorodiphenylamine (6c). White crystalline solid (0.69 g, 3.69 mmol, 74%). Mp 36–38 °C from petrol (lit.[43] mp 34 °C); R_f=0.65 (1:1 ether–petrol); IR (neat) 3379, 1594, 1503, 1493, 1313, 1228, 742 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.31 (2H, t, H3′/H5′ *J* 8 Hz), 7.06 (6H, m, H2/H2′/H3/H5/H6/H6′), 6.93 (1H, t, H4′ *J* 8 Hz), 5.70 (1H, br s, NH); ^{13}C NMR ($CDCl_3$) δ 158.7 (C4, d, *J* 241 Hz), 144.5, 139.6, 129.7, 121.2, 121.1, 117.6, 116.2 (C3/C5, d, *J* 22 Hz); ^{19}F NMR ($CDCl_3$) −120.46; *m/z* (EI) 187 (M^+, 100%), 186 (60), 185 (41), 83 (29), 75 (41). Found: M+H$^+$, 188.0872. $C_{12}H_{11}FN$ requires 188.0870.

4.3.4. 4-Chlorodiphenylamine (6d). White crystalline solid (0.75 g, 3.68 mmol, 74%). Mp 62–63 °C from petrol (lit.[44] mp 64–66 °C from hexane); R_f=0.80 (1:1 ethylacetate–petrol); IR (neat) 3399, 1580, 1495, 1480, 1307, 1238, 1171, 1070 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.18 (4H, m, H3/H3′/H5/H5′), 6.93 (5H, m, H2/H2′/H4′/H6/H6′), 5.72 (1H, br s, NH); ^{13}C NMR ($CDCl_3$) δ 143.2, 142.3, 129.8, 129.6, 126.3, 122.1, 119.5, 118.9; *m/z* (EI) 205 ([^{37}Cl]M^+, 28%), 203 ([^{35}Cl]M^+, 100), 167 (38), 84 (32). Found: M+H$^+$, 204.0577. $C_{12}H_{11}{}^{35}ClN$ requires 204.0575.

4.3.5. 4-Bromodiphenylamine (6e). White crystalline solid (0.92 g, 3.71 mmol, 74%). Mp 82–84 °C from petrol (lit.[23] mp 84–86 °C); R_f=0.77 (1:1 ethylacetate–petrol); IR (neat) 3399, 1579, 1495, 1479, 1310, 1070 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.34 (2H, d, H3/H5 *J* 9 Hz), 7.27 (2H, m, H3′/H5′), 7.06 (2H, d, H2′/H6′ *J* 7 Hz), 6.97 (1H, t, H4′ *J* 7 Hz), 6.94 (2H, d, H2/H6 *J* 9 Hz), 5.84 (1H, br s, NH); ^{13}C NMR ($CDCl_3$) δ 142.5, 142.5, 132.3, 129.6, 121.8, 119.1, 118.4, 112.7; *m/z* (EI) 249 ([^{79}Br]M+H$^+$, 55%), 247 ([^{81}Br]M+H$^+$, 61), 167 (87), 139 (18), 115 (20), 84 (66). Found: M+H$^+$, 248.0067. $C_{12}H_{11}{}^{79}BrN$ requires 248.0075.

4.3.6. 4-Nitrodiphenylamine (6f). Yellow crystalline solid (0.53 g, 2.48 mmol, 50%). Mp 130–133 °C from petrol (lit.[45] mp 135–136 °C from cyclohexane); R_f=0.36 (1:1 ether–petrol); IR (neat) 3338, 1601, 1580, 1467, 1271, 1249 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.15 (2H, d, H3/H5 *J* 9 Hz), 7.42 (2H, m, H3′/H5′), 7.25 (3H, m, H2′/H4′/H6′), 6.96 (2H, d, H2/H6 *J* 9 Hz), 6.22 (1H, br, NH); ^{13}C NMR ($CDCl_3$) δ 150.3, 139.9, 139.6, 129.8, 126.3, 124.8, 122.0, 113.8; *m/z* (EI) 214 (M^+, 100%), 184 (61), 167 (80). Found: M^+, 214.0739. $C_{12}H_{10}N_2O_2$ requires 214.0737.

4.3.7. 4-Methoxydiphenylamine (6g). White crystalline solid (0.92 g, 4.62 mmol, 92%). Mp 104–106 °C from petrol (lit.[22] mp 105 °C); R_f=0.57 (1:1 ether–petrol); IR (neat) 3065, 1651, 1441, 1417, 1194, 1168, 1125 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.25 (2H, t, H3′/H5′ *J* 8 Hz), 7.12 (2H, d, H3/H5 *J* 8 Hz), 6.95 (2H, d, H2/H6 *J* 8 Hz), 6.91 (3H, m, H2′/H4′/H6′), 5.60 (1H, br s, NH), 3.84 (3H, s, OCH_3); ^{13}C NMR ($CDCl_3$) δ 156.0, 145.7, 136.5, 129.6, 122.7, 120.1, 116.4, 115.3, 56.0; *m/z* (EI) 199 (M^+, 89%), 184 (100), 154 (26), 129 (23), 128 (28), 77 (65). Found: M+H$^+$, 200.1069. $C_{13}H_{14}NO$ requires 200.1070. Anal. Calcd for $C_{13}H_{13}NO$: C, 78.36; H, 6.58; N, 7.03. Found: C, 78.31; H, 6.59; N, 6.92.

4.3.8. 3,4-Dimethoxydiphenylamine (6h). White crystalline solid (0.82 g, 3.58 mmol, 72%). Mp 96–98 °C from petrol (lit.[46] mp 99–100 °C); R_f=0.38 (1:1 ether–petrol); IR (neat) 3379, 1592, 1500, 1456, 1442, 1309, 1230, 1164, 1128, 1023 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.27 (3H, m, H2/H3′/H5′), 7.00 (2H, d, H2′/H6′ *J* 8 Hz), 6.91 (1H, t, H4′ *J* 8 Hz), 6.84 (1H, d, H5 or H6 *J* 8 Hz), 6.74 (2H, m, H6 or H5), 3.90 (3H, s, OMe), 3.86 (3H, s, OMe); ^{13}C NMR ($CDCl_3$) δ 150.2, 145.3, 144.1, 137.7, 129.4, 119.0, 115.9, 114.4, 110.8, 105.4, 56.8, 56.1; *m/z* (EI) 230 (M+H$^+$, 20%), 229 (M^+, 100), 228 (33), 200 (28), 92 (29). Found: M+H$^+$, 230.1175. $C_{14}H_{16}NO_2$ requires 230.1181.

4.3.9. 3,5-Dimethoxydiphenylamine (6i). White crystalline solid (0.89 g, 3.88 mmol, 78%). Mp 70–72 °C from petrol (lit.[44] mp 70.5–71.5 °C from hexane); R_f=0.57 (1:1 ether–petrol); IR (neat) 3348, 1588, 1537, 1495, 1462, 1290, 1250, 1144, 1053 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.30 (2H, t, H3′/H5′ *J* 8 Hz), 7.12 (2H, d, H2′/H6′ *J* 8 Hz), 6.96 (1H, t, H4′ *J* 8 Hz), 6.27 (2H, s, H2/H6), 6.10 (1H, s, H4), 3.78 (6H, 2×OCH_3); ^{13}C NMR ($CDCl_3$) δ 162.3, 145.7, 143.1, 129.6, 122.2, 119.6, 97.0, 94.1, 55.6; *m/z* (EI) 230 (M+H$^+$, 16%), 229 (M^+, 75), 214 (100), 186 (40), 143 (24), 115 (25), 92 (20). Found: M+H$^+$, 230.1175. $C_{14}H_{16}NO_2$ requires 230.1181.

Acknowledgements

We thank Newcastle University and the EPSRC (DTA Scheme) for funding and provision of the Swansea Mass Spectrometry Service.

References and notes

1. Stang, P. J.; Zhdankin, V. V. *Chem. Rev.* **1996**, *96*, 1123–1178.
2. Varvoglis, A.; Spyroudis, S. *Synlett* **1998**, 221–232.
3. Varvoglis, A. *Hypervalent Iodine in Organic Synthesis*; Academic: London, 1997.
4. Wirth, T. *Top. Curr. Chem.* **2003**, *224*.

5. Wirth, T.; Hirt, U. H. *Synthesis* **1999**, 1271–1287.
6. Hossain, M. D.; Ikegami, Y.; Kitamura, T. *J. Org. Chem.* **2006**, *71*, 9903–9905.
7. Ladziata, U.; Zhankin, V. V. *ARKIVOC* **2006**, 26–58.
8. van der Puy, M. *J. Fluorine Chem.* **1982**, *21*, 385–392.
9. Martín-Santamaría, S.; Carroll, M. A.; Carroll, C. M.; Carter, C. D.; Pike, V. W.; Rzepa, H. S.; Widdowson, D. A. *Chem. Commun.* **2000**, 649–650.
10. Carroll, M. A.; Kamara, L. M.; Widdowson, D. A.; Pike, V. W. *J. Labelled Compd. Radiopharm.* **2005**, *48*, 519–520.
11. Shah, A.; Pike, V. W.; Widdowson, D. A. *J. Chem. Soc., Perkin Trans. 1* **1998**, 2043–2045.
12. Shah, A.; Widdowson, D. A.; Pike, V. W. *J. Labelled Compd. Radiopharm.* **1997**, *39*, 65–67.
13. Wüst, F. R.; Hohne, A.; Metz, P. *Org. Biomol. Chem.* **2005**, *3*, 503–507.
14. Wüst, F. R.; Kniess, T. *J. Labelled Compd. Radiopharm.* **2003**, *46*, 699–713.
15. Wüst, F.; Reul, J. M. H. M.; Rein, T.; Abel, A.; Stöcklin, G. *J. Labelled Compd. Radiopharm.* **2001**, *44*, S12–S14.
16. Pike, V. W.; Aigbirhio, F. I. *J. Chem. Soc., Chem. Commun.* **1995**, 2215–2216.
17. Ermert, J.; Hocke, C.; Ludwig, T.; Gail, R.; Coenen, H. H. *J. Labelled Compd. Radiopharm.* **2004**, *47*, 429–441.
18. Phelps, M. J.; Mazziotta, J.; Schelbert, H. *Positron Emission Tomography and Autoradiography: Principles and Applications for the Brain and Heart*; Raven: New York, NY, 1986.
19. *The Chemistry of Anilines*; Rappoport, Z., Ed.; Wiley-VCH: Weinheim, 2007.
20. Liu, Z.; Larock, R. C. *J. Org. Chem.* **2006**, *71*, 3198–3209 and references cited therein.
21. Hartwig, J. F. *Angew. Chem., Int. Ed.* **1998**, *37*, 2046–2067.
22. Desmarets, C.; Schneider, R.; Fort, Y. *J. Org. Chem.* **2002**, *67*, 3029–3036.
23. Das, P.; Basu, B. *Synth. Commun.* **2004**, *34*, 2177–2184.
24. Yang, B. H.; Buchwald, S. L. *J. Organomet. Chem.* **1999**, *576*, 125–146.
25. Dick, A. R.; Remy, M. S.; Kampf, J. W.; Sanford, M. S. *Organometallics* **2007**, *26*, 1365–1370.
26. Carroll, M. A. Unpublished results.
27. Ross, T. L.; Emmert, J.; Hocke, C.; Coenen, H. H. *J. Am. Chem. Soc.* **2007**, *129*, 8018–8025.
28. Diaryliodonium salts are known to decompose (210–220 °C) in the presence of anilines to give diarylamines. Makarova, L. G. *Izvest. Akad. Nauk. S.S.S.R., Oldel. Khim. Nauk.* **1951**, 741–744.
29. Carroll, M. A.; Nairne, J.; Smith, G.; Widdowson, D. A. *J. Fluorine Chem.* **2007**, *128*, 127–132.
30. Wadsworth, H.J.; Widdowson, D.A.; Wilson, E.; Carroll, M.A. Radical trap in fluoridation of iodonium salt, WO 2005/061415, 2005.
31. For diaryliodonium salts in arylation reactions see: (a) Deprez, N. R.; Kalyani, D.; Krause, A.; Sanford, M. S. *J. Am. Chem. Soc.* **2006**, *128*, 4972–4973; (b) See also Ref. 4, pp 154–55 and citations therein.
32. Martín-Santamaría, S.; Carroll, M. A.; Pike, V. W.; Rzepa, H. S.; Widdowson, D. A. *J. Chem. Soc., Perkin Trans. 2* **2000**, 2158–2161.
33. Carroll, M. A.; Martín-Santamaría, S.; Pike, V. W.; Rzepa, H. S.; Widdowson, D. A. *J. Chem. Soc., Perkin. Trans 2* **1999**, 2707–2714.
34. Grushin, V. V. *Acc. Chem. Res.* **1992**, *25*, 529–536 and references therein.
35. Grushin, V. V.; Demkina, I. I.; Tolstaya, T. P. *J. Chem. Soc., Perkin Trans. 2* **1992**, 505–511.
36. Kazmierczak, P.; Skulski, L. *Synthesis* **1995**, 1027–1032.
37. Dess, D. B.; Martin, J. C. *J. Am. Chem. Soc.* **1991**, *113*, 7277–7287.
38. Tohma, H.; Takizawa, S.; Maegawa, T.; Kita, Y. *Angew. Chem., Int. Ed.* **2000**, *39*, 1306–1308.
39. Caserio, M. C.; Glusker, D. L.; Roberts, J. D. *J. Am. Chem. Soc.* **1959**, *81*, 336–342.
40. Leffler, J. E.; Story, L. J. *J. Am. Chem. Soc.* **1967**, *89*, 2333–2338.
41. Gaylord, N. G. *J. Org. Chem.* **1960**, *25*, 1874–1876.
42. Craig, D. *J. Am. Chem. Soc.* **1935**, *57*, 195–198.
43. Smith, N. L. *J. Org. Chem.* **1951**, *16*, 415–418.
44. MacNeil, S. L.; Wilson, B. J.; Snieckus, V. *Org. Lett.* **2006**, *8*, 1133–1136.
45. Johnson, H. W.; Iwata, Y. *J. Org. Chem.* **1971**, *36*, 1921–1925.
46. Kasum, B.; Prager, R. H. *Aust. J. Chem.* **1983**, *36*, 1455–1467.