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*Solar*ylations via 4-Aminophenyl Cations

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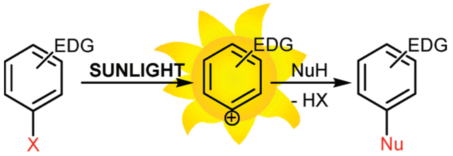

The application of the photo-S_N1 reaction on some 4-chloroanilines was explored under solar irradiation in view of obtaining a convenient metal-free arylation method. Several reactions previously carried out by UV irradiation, as well as some new ones, where either a new trap (α-methylstyrene) or a new halide (*N*,*N*-dimethyl-4-fluoroaniline) were adopted, were studied under these conditions and found to occur conveniently. Furthermore, at least in some cases the halide starting concentration could be raised up to 0.2 M, the excess trapping agent reduced from 20:1 to 2.5:1, and the solvent replaced by more environmentally friendly (co)solvents including water. Under these improved conditions, the photoarylation was carried out in a gram scale by merely exposing the solution to solar irradiation. This process has a low impact on the environment and can be considered a serious competitor of metal-catalyzed arylations.

Introduction

The close relation between photochemistry and what is now called green chemistry was suggested for the first time by the Italian chemist Giacomo Ciamician, at the beginning of the 20th century.[1,2] In a talk addressed to the French Chemical Society,[3] he underlined that light is able to promote under mild conditions reactions not observed thermally.[4] The later development of photochemistry has demonstrated that the photon can be considered as the ideal clean reagent for organic synthesis,[5] in contrast to toxic/dangerous chemical activators. Furthermore, it leaves no residue that has to be eliminated after the reaction. Ciamician and contemporary scientists[6] used solar light for promoting a variety of reactions, but in later times photoreactions have been generally carried out by using artificial light. As a matter of fact, a photochemical reaction does not "automatically" classify as green despite the peculiar advantages, primarily because of the considerable amount of energy from nonrenewable sources that has to be supplied for the lamp.[7] An obvious opportunity of minimizing energy consumption in photochemical reactions is to leave artificial lamps and return to sunlight, a clean, renewable, and free energy source.[5,8] An important advancement has been the application of solar mediated processes to a few reactions on a large scale,[9] (products in the kilogram scale) and the use of light-concentrators for making solar irradiation available in a more concentrated form than the natural flux (although of course one still needs a large surface for collecting enough light).[9] Furthermore, a number of examples of viable syntheses have been reported in the last years (and have been recently reviewed)[9a] in which the reaction occurs by simply exposing the reaction vessel to sunlight (e.g., on a window ledge). However, these processes remain a tiny

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(1) Albini, A.; Fagnoni, M. *Green Chem.* **2004**, *6*, 1–6.

(2) (a) Ciamician, G. *Science* **1912**, *36*, 385–394. (b) Ciamician, G.; Silber, P. *Ber. Dtsch. Chem. Ges.* **1900**, *33*, 2911–2913.

(3) Ciamician, G. *Bull. Soc. Chim. Fr.* **1908**, *3* (4), i–xxxvi.

(4) Albini, A.; Dichiarante, V. *Photochem. Photobiol. Sci.* **2009**, *8*, 248–254.

(5) Protti, S.; Manzini, S.; Fagnoni, M.; Albini, A. The contribution of photochemistry to green chemistry. In *Eco-Friendly Synthesis of Fine Chemicals*; Ballini, R., Ed.; RSC Green Chemistry Series; Royal Society of Chemistry: Cambridge, UK, 2009; pp 80−111.

(6) See, for example: (a) Stobbe, H. *Liebigs Ann. Chem.* **1908**, *359*, 1–48. (b) Stobbe, H. *Z. Elektrochem.* **1908**, *33*, 473–483. (c) Paternò, E.; Chieffi, G.; Perret, G. *Gazz. Chim. Ital.* **1914**, *44*, 151–164. (d) Paternò, E.; Chieffi, G. *Gazz. Chim. Ital.* **1909**, *39*, 341–361.

(7) Cian, C.-L.; Bochet, C. G. *Chimia* **2007**, *61*, 650–654.

(8) Albini, A.; Fagnoni, M. The greenest reagent in organic synthesis: light. In *Green Chemical Reactions*; Tundo, P., Esposito, V., Eds.; Springer Science + Business Media B.V.: London, UK, 2008; pp 173−189.

(9) (a) Protti, S.; Fagnoni, M. *Photochem. Photobiol. Sci.* **2009**, *8*, 1499–1516. (b) Oelgemöller, M.; Jung, C.; Mattay, J. *Pure Appl. Chem.* **2007**, *79*, 1939–1947. (c) Esser, P.; Pohlmann, B.; Scharf, H.-D. *Angew. Chem., Int. Ed.* **1994**, *33*, 2009–2023.

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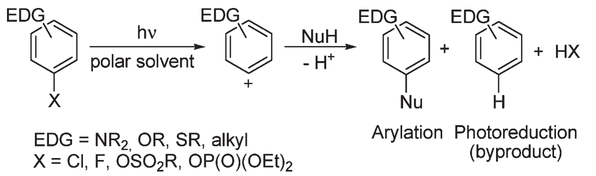
SCHEME 1. Photogeneration and Reactivity of Aryl Cations



fraction of those carried out by artificial light and it appears appropriate to extend the scope of solar-induced syntheses by adding new classes of photochemical reactions.

A field where photochemistry has recently acquired a role is that of arylations,[10] an important class of reactions in modern organic synthesis, in particular when leading to the formation of a carbon−carbon bond. It has been found that the photochemical method may be a valid alternative to metal-catalysis for the activation of an Ar−Y bond.[10,11] The use of solar light for such a reaction is not common, however. For example, Rajan et al. reported an efficient phenylation of dimsyl anion by a solar-stimulated ArS_{RN}1 reaction in DMSO in the presence of iodo- or bromobenzene.[12] The sunlight-induced nucleophilic substitution of an alkoxy group by *n*-butylamine has been likewise successfully applied to the synthesis of a nitrobenzacrown aminoether.[13]

On the other hand, a new metal-free photochemical arylation procedure based on the intermediacy of aryl cations has recently emerged (an ArS_N1 process)[10,14] and allows the formation of Ar−C bonds. Irradiation of electron-rich aryl chlorides, fluorides, and esters[15] (such as phosphates and sulfonates), in polar solvents, generates phenyl cations through a heterolytic cleavage of the Ar−X bond as illustrated in Scheme 1.

The cation is trapped by nucleophiles (e.g., alkenes, alkynes, and arenes) and yields a variety of arylation products under mild conditions through a simple experimental protocol. However, labeling the process as eco-sustainable requires confronting the negative aspects, viz. the consumption of nonrenewable energy for powering the lamp, as well as the use of expensive and harmful solvents such as 2,2,2-trifluoroethanol (TFE) to make heterolysis efficient, of a large excess of the nucleophile (10 to 20 times with respect to Ar−X) in order to suppress side-processes, in particular hydrogen abstraction from the solvent by the cation intermediate,[16] and of a base as a buffering agent. These issues are confronted for some known reactions and for some new ones in the present work.

FIGURE 1. The reactions were carried out on 100 mL solution corresponding to a layer of about 1 cm thick with a surface area of about 1 dm^2 in the cylindrical Pyrex vessel used.

Results and Discussion

Before actually exploring the effect of solar light, the process was optimized by carrying out comparative experiments by using a solar simulator (SolarBox) as a nonvariable light source. Screw-capped cylindrical Pyrex vessels were used (100 mL solution, see Figure 1).[20] Small scale experiments were carried out in vessels containing 5 mL.

Under these conditions, 4-chloroanisole and 4-chlorophenol showed very little reaction after 24 h. With the latter compound, a partial conversion was obtained only when using a TFE solution in a quartz tube. The inefficiency is due to the poor absorption of these compounds above 300 nm and to the fact that the tiny fraction of low-wavelength radiation present in this source is filtered by the Pyrex walls.

On the contrary, 4-chloro-*N*,*N*-dimethylaniline (**1a**) reacted due to the absorption tailing in the UV-A region and was thus chosen for optimizing the reaction with representative nucleophiles in the SolarBox. A convenient reaction was performed by using mesitylene (**2a**) as the π-trap, with which the photogenerated 4-*N*,*N*-dimethylaminophenyl cation afforded the corresponding polymethyl-substituted biaryl **3** (Scheme 2, path a).

Experiments with a solar simulator were compared with the same reaction performed in acetonitrile but using UV lamps (six phosphor-coated lamps, emission centered at 310 nm, Table 1, entry 1).[18] Irradiations were continued until the total consumption of the starting aniline.

With the SolarBox apparatus the yield of biphenyl **3** was similar (ca. 60%) to that obtained under artificial light and that of reduced **3** dropped from 12% to less than 3% (entry 2). In this and in all of the other reactions considered,

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[10] Dichiarante, V.; Fagnoni, M.; Albini, A. Photochemical arylation reactions. In *Modern Arylation Methods*; Ackermann, L., Ed.; Wiley-VCH: Weinheim, Germany, 2009; pp 513−535.

[11] Protti, S.; Dondi, D.; Fagnoni, M.; Albini, A. Photochemistry for mild metal-free arylation reactions. In *Experiments in green and sustainable chemistry*; Roesky, H. W., Kennepohl, D. K., Eds.; Wiley-VCH Verlag GmbH & Co.: Weinheim, Germany, 2009; pp 260−265.

[12] Rajan, S.; Muralimohan, K. *Tetrahedron Lett.* **1978**, *5*, 483–486.

[13] Samoshin, A. V.; Samoshin, V. V. *J. Undergrad. Chem. Res.* **2006**, *2*, 13–16.

[14] (a) Dichiarante, V.; Fagnoni, M. *Synlett* **2008**, 787–800. (b) Penenory, A. B.; Argüello, J. E. Aromatic and heteroaromatic substitution by S_{RN}1 ans S_N1 reactions. In *Handbook of Synthetic Photochemistry*; Albini, A., Fagnoni, M., Eds.; Wiley-VCH: Weinheim, Germany, 2010; pp 319−352.

[15] De Carolis, M.; Protti, S.; Fagnoni, M.; Albini, A. *Angew. Chem., Int. Ed.* **2005**, *44*, 1232–1236.

[16] The irradiation of electron-rich aromatic chlorides in hydrogen donating media (e.g., 2-propanol) or in the presence of a reducing agent (e. g., H_3PO_2) causes a quite efficient hydrodehalogenation reaction via photogenerated phenyl cations (see ref 17). In a less H donating solvent such as MeCN this reduction occurs to some extent, depending on the concentration and type of nucleophile present in solution. Reduction of phenyl cations by hydrogen or electron transfer has been demonstrated by laser flash photolysis experiments (see refs 18 and 19).

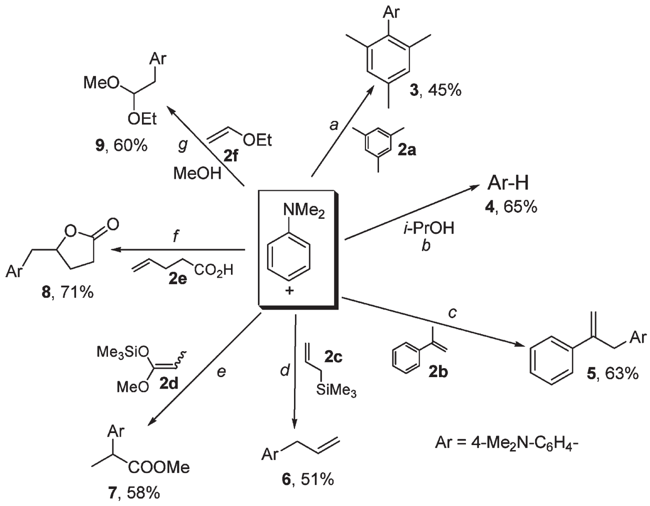
[17] Dichiarante, V.; Fagnoni, M.; Albini, A. *Green Chem.* **2009**, *11*, 942–945.

[18] Guizzardi, B.; Mella, M.; Fagnoni, M.; Freccero, M.; Albini, A. *J. Org. Chem.* **2001**, *66*, 6353–6363.

[19] Manet, I.; Monti, S.; Grabner, G.; Protti, S.; Dondi, D.; Dichiarante, V.; Fagnoni, M.; Albini, A. *Chem.*—*Eur. J.* **2008**, *14*, 1029–1039.

[20] Similar vessels were recently used in solar photocatalyzed reactions. See: Protti, S.; Ravelli, D.; Fagnoni, M.; Albini, A. *Chem. Commun.* **2009**, 7351–7353.

SCHEME 2. Arylation Products from the Solar-Induced Generation of 4-*N*,*N*-Dimethylaminophenyl Cation



no other volatile byproducts except aniline **4** was detected. Thus, this reaction was well suited for confronting the environmental limitations. In previous reports, arylations via phenyl cation[10,14] have been reported by using a 0.05 M solution of ArX in the presence of a large excess of the nucleophile (0.5−1 M). Clearly, a 20:1 molar ratio between the reagents is far from being desirable from the point of view of atom economy. However, the yield of biphenyl **3** decreased to 40% upon halving the mesitylene concentration (to 0.5 M) and a significant amount of aniline **4** (14%) was formed (entry 3). At any rate, the concentration of the reagent is too low for an environmentally sound process and indeed using such a large amount of solvent has been shown to be the main adverse factor on the eco-sustainability of the photo-ArS_N1 arylations.[21,22]

The explorative study was carried out by maintaining the 0.5 M concentration of the trap and varying the other parameters. A move was the use of water as a (co)solvent. This was possible because the intermediate triplet 4-*N*,*N*-dimethylaminophenyl cation was known not to react with water or alcohols.[24] Adding water reduced the amount of organic solvents and it was hoped that it may give further advantages, that is that highly polar water both favored the photoheterolytic step[14a,25] and buffered the acidity produced in the reaction, allowing a base to be omitted. All of this was verified in the experiment, and when a 1:5 water−acetonitrile mixture was used (entry 4), a satisfactory 55% yield of **3** was obtained with no significant concurrent reduction or solvolysis. The negative side was that extraction with methylene chloride was required in this case.

Increasing the concentration of aniline **1a** is another possibility for diminishing the proportion of solvent. When increasing the amount of the starting aniline up to 0.1−0.2 M (entries 5 and 6) a longer irradiation time (up to 40 h) was required, but a complete consumption of **1a** was obtained and biphenyl **3** was formed in a yield (48%) that could be considered decent when taking into account that only 2.5 mol excess mesitylene was used.

The substitution of acetonitrile with the less toxic and less expensive acetone was next tested. The above experiments were thus repeated in a 1:5 water−acetone mixture (entries 7−9). The result was that in acetone the arylation yield was acceptable as long as the concentration of **1a** did not exceed 0.1 M (entry 8).

Finally, compound **3** was isolated in 45% yield after 40 h SolarBox irradiation of a solution of **1a** (0.2 M, the highest concentration as yet used for a preparative photo-ArS_N1 reaction) and **2a** (0.5 M) in 5:1 MeCN/water (Table 2). A similar yield of **3** was obtained when the same mixture was placed on a window ledge of the Department and exposed to sunlight for 6 consecutive days (from 9 a.m. to 5 p.m., see the Supporting Information). To summarize, the above data show that (i) the arylation reaction is effective also under solar light irradiation, (ii) aqueous acetonitrile and acetone could be likewise used as reaction media, (iii) the concentration of the starting chloride can be increased up to 0.2 M, and (iv) the molar excess of the nucleophile can be lowered.

The reaction of chloroaniline **1a** was then extended to other nucleophiles, likewise comparing the solar simulator and solar light. Preparative experiments were carried out on 100 mL solution samples, and thus on a gram scale. In Table 2 the results under optimized reaction conditions are reported, showing that there is no significant difference in the products yield (±5%) with the two sets of experiments.

Thus, irradiation of **1a** was carried out in neat *i*-PrOH, a good hydrogen-donor medium that induced hydrodehalogenation as recently demonstrated (Scheme 2, path b).[17] *N*,*N*-Dimethylaniline **4** was obtained in 65% yield after 40 h SolarBox irradiation even with [**1a**] raised to 0.2 M. Six days of solar exposure of the reaction mixture gave similar results.

The reaction with alkenes was next tested, namely, with α-methylstyrene (**2b**), allyltrimethylsilane (**2c**), 1-methoxy-1-[(trimethylsilyl)oxy]propene (**2d**), 4-pentenoic acid (**2e**), and ethyl vinyl ether (**2f**). Addition of phenyl cations to alkenes has been observed in a large number of cases[14] and was followed by the loss of an electrofugal group, either a proton or a trimethylsilyl cation. A new reaction following the first path was that with α-methylstyrene that gave the allylation product **5** in 63% yield (see Scheme 3).

Elimination of Me_3Si^+ took place from the adduct cation with both allyltrimethylsilane (**2c**) and ketene silyl acetal (**2d**) leading respectively to the corresponding allyl derivative **6** (51%, Scheme 2 path d)[14] and the α-aryl propionic ester **7** (58%, path e).[14]

With alkenes containing a tethered nucleophilic moiety, as in the case of 4-pentenoic acid (**2e**), intermolecular trapping of the aryl cation was followed by intramolecular cyclization to give benzyl γ-lactone **8** (45%, path f).[14] In the preparation of **5**, **6**, and **8** a satisfactory isolated yield was obtained even

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(21) Protti, S.; Dondi, D.; Fagnoni, M.; Albini, A. *Green Chem.* **2009**, *11*, 239–249.

(22) In a recent paper,[21] the environmental impact and the cost (euros per gram of product) of photo-S_N1 arylations have been assessed by means of the EATOS software.[23] From the economical point of view, photochemical reactions via phenyl cations were more expensive, if compared with the corresponding metal-catalyzed reactions, and the main negative influence was due to the solvent (usually 2,2,2-trifluoroethanol).

(23) Eissen, M.; Metzger, J. O. *EATOS, Environmental Assessment Tool for Organic Syntheses*, http://www.chemie.uni-oldenburg.de/oc/metzger/eatos/.

(24) Lazzaroni, S.; Dondi, D.; Fagnoni, M.; Albini, A. *J. Org. Chem.* **2010**, *75*, 315–323.

(25) Manet, I.; Monti, S.; Bortolus, P.; Fagnoni, M.; Albini, A. *Chem.—Eur. J.* **2005**, *11*, 4274–4282.

TABLE 1. Arylation of Mesitylene by Irradiating 4-Chloro-*N*,*N*-Dimethylaniline by Means of a Solar Simulator (SolarBox)

entry	[**1a**], M	solvent	[**2a**], M	light source	time,[a] h	**3**,[b] %	**4**,[b,c] %
1[d]	0.05	MeCN[e]	1	UV lamps[f]	3	65[d,g]	12[d,g,h]
2	0.05	MeCN[e]	1	SolarBox[i]	6	60	2.4
3	0.05	MeCN[e]	0.5	SolarBox[i]	6	40	14
4	0.05	H_2O/MeCN (1:5)	0.5	SolarBox[i]	6	55	4
5	0.1	H_2O/MeCN (1:5)	0.5	SolarBox[i]	22	46	1.5
6	0.2	H_2O/MeCN (1:5)	0.5	SolarBox[i]	40	48	0
7	0.05	H_2O/Me_2CO (1:5)	0.5	SolarBox[i]	6	42	3
8	0.1	H_2O/Me_2CO (1:5)	0.5	SolarBox[i]	20	50	8
9	0.2	H_2O/Me_2CO (1:5)	0.5	SolarBox[i]	40	25	3

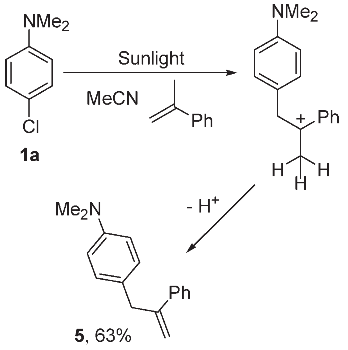
[a] Minimum time required for the total consumption of **1a**. [b] The yields in entries 2−9 were determined by GC analysis by comparative peak areas with the reaction in entry 1. [c] *N*,*N*-Dimethylaniline. [d] See ref 18. [e] 0.05 M NEt_3 added. [f] Irradiated in a multilamp apparatus by using six phosphor-coated lamps (emission centered at 310 nm). [g] Isolated yields. [h] Traces of 5-chloro-2,4′-bis(dimethylamino)biphenyl were also detected. [i] Irradiated in a solar simulator (SolarBox, Xe lamp, see the Supporting Information).

TABLE 2. Metal-Free Arylation by Solar Exposure of 4-Chloro(fluoro)-*N*,*N*-dimethylaniline

ArX	[ArX] (M)	solvent	Nu, concn	time (h,[a] $\underline{\text{d}}$[b])	product and yield (%)[c−e]
ArCl, **1a**	0.2	H_2O/MeCN (1:5)	**2a**, 0.5 M	40, $\underline{6}$	**3** (48, *45*)
1a	0.2	*i*-PrOH		40, $\underline{6}$	**4** (71, *65*)
1a	0.1	MeCN	**2b**, 0.5 M	23, $\underline{3}$	**5** (72, *63*)
1a	0.1	H_2O/MeCN (1:5)	**2c**, 0.5 M	24, $\underline{3}$	**6** (68, *51*)
1a	0.1	H_2O/Me_2CO (1:5)	**2c**, 0.5 M	24, $\underline{3}$	**6** (64)
1a	0.05	MeCN + NEt_3 0.05M	**2d**, 0.7 M	6, $\underline{1}$	**7** (*58*)
1a	0.1	H_2O/MeCN (1:5)	**2e**, 0.5 M	24, $\underline{3}$	**8** (52, *45*)
1a	0.1	H_2O/Me_2CO (1:5)	**2e**, 0.5M	24, $\underline{3}$	**8** (77, *71*)
1a	0.05	MeOH + Cs_2CO_3 0.03M	**2f**, 0.5M	8, $\underline{1}$	**9** (81, *60*)
1a	0.05	$MeOH/Me_2CO$ (1:3) Cs_2CO_3 0.03M	**2f**, 0.5M	6, $\underline{1}$	**9** (40)
ArF, **1b**	0.1	H_2O/MeCN (1:5)	**2c**, 0.5 M	22, $\underline{3}$	**6** (52)
1b	0.05	MeOH + Cs_2CO_3 0.03M	**2f**, 0.5M	16, $\underline{2}$	**9** (88)

[a] Hours of irradiation in SolarBox. [b] Underlined, days of exposition to sunlight (each day for 8 h, from 9 a.m. to 5 p.m.). [c] GC yields, in *italics* isolated yields. [d] Aniline **4** was also formed in variable amounts (see the Supporting Information and text). [e] The arylation yields obtained by exposing the Pyrex vessel directly to sunlight differed by ±5% of that obtained in the SolarBox.

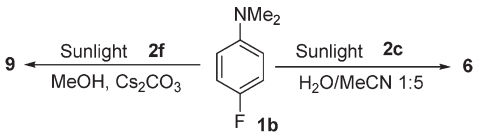
SCHEME 3. Sunlight-Induced Arylation of α-Methylstyrene



starting from a 0.1 M solution of **1a** and with a 5-fold excess nucleophile. Moreover, in the preparation of allylaniline **6** and lactone **8**, acetonitrile could be replaced by cheaper acetone, maintaining or even increasing (from 45% to 71% in the case of **8**) the arylation yield.

Another synthetic application of phenyl cations is the reaction with vinyl ethers (e.g., ethyl vinyl ether, **2f**) where the stabilized cation, resulting from the attack onto the alkene, adds a nucleophilic solvent such as methanol.[26] 3-Aryl acetal **9** was thus prepared by this three-component reaction (60%, path g) along with 13% of reduced **4**. Using methanol only as cosolvent decreased the yield of compound **9** to 40% in 1:3 methanol/acetone (see Table 2). Notice also that a total consumption of **1a** in the reaction with both enol ethers **2d** and **2f** was only reached with the concentration of **1a** ≤ 0.05 M, although [**2d**] could be lowered to 0.7 M.

SCHEME 4. Arylation Reactions via Sunlight Activation of the Ar−F Bond



The exploration was extended to the activation of the Ar−F bond and new arylations were found in the solar light-induced reactions of 4-fluoro-*N*,*N*-dimethyl aniline (**1b**, Scheme 4). As it appears in Table 2, anilines **6** and **9** were obtained in a yield comparable to that obtained in the case of the chloroaniline **1a**.

Further structural variations in the starting material were then tested with the same optimized solar protocol, with consistently good results. As an example, 4-chloro-3-methyl-*N*,*N*-dimethylaniline (**1c**, 0.1 M) was photoreduced to **10** in a high yield (89%, isolated yield) by irradiation in neat 2-propanol (Scheme 5).

Using 4-chloroaniline (**1d**) with the free NH_2 group required some care. In fact, exposure of 0.1−0.2 M solutions of **1d** to sunlight led to incomplete consumption of the starting aniline and to a rapid darkening of the reaction mixtures. However, under more dilute conditions (0.05 M) in the presence of a base (cesium carbonate) satisfactory arylation yields were obtained, as shown in Scheme 6 for the synthesis of acetal **11**.

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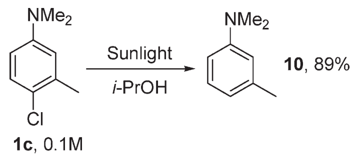
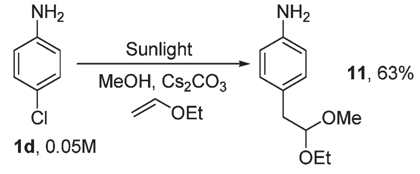
[26] Lazzaroni, S.; Protti, S.; Fagnoni, M.; Albini, A. *Org. Lett.* **2009**, *11*, 349–352.

SCHEME 5. **Sunlight-Induced Hydrodehalogenation of 1c**



SCHEME 6. **β-Arylacetals via Sunlight-Induced Photoreaction of 4-Chloroaniline**



Conclusion

The present work demonstrates that the performance of the photo-ArS$_{\rm N}$1 method for arylation reactions can be improved in terms of higher concentration of the starting material, lower proportion of the trap, and use of solvents in a lower amount and chosen among the more environment-friendly ones, including water. Furthermore, UV lamps could be replaced by solar irradiation with no adverse effect on the yields and requiring essentially the same time (6 h UV irradiation $\equiv$ 8 h, 1 d, exposure to the sun). Under the conditions of Table 2, arylations can be carried out in gram scale by simply exposing 100 mL of a solution with a really simple setup (see Figure 1).

The introduction of such conditions drastically improves the environmental performance and makes the photochemical method a better competitor of thermal catalytic arylations in terms of atom economy. Limitations remain, such as the difficult extension to non-*N*-alkylated anilines, and the impossibility of lowering the concentration of the trap below 0.5 M (in some cases above that) and of eliminating the side paths completely. These are due to the fact that in the present method an aggressive electrophile, the phenyl cation, is the intermediate, whereas a more stable complex is formed in catalysis.[27] Therefore, competing processes (e.g., reduction by reaction with the solvent, attack to the nucleophilic starting material) become significant unless trapping is quite effective. On the other hand, this is also the strength of the photochemical method and gives to it an unparalleled versatility, since the intermediate is generated by (solar) irradiation, a step that is limitedly affected by the conditions. Thus one can freely choose the conditions best suited to direct the reactions of the cation, giving less attention to those favoring its generation. On the contrary, the activation of the starting material is the key issue in thermal catalytic methods and is often much less tolerating in terms of experimental conditions. Furthermore, the environmental impact of our arylation protocol is modest. The use of energy and manipulations are kept to a minimum. The nonstirred solution is exposed to solar light, then the solvent is evaporated and the products, in the most favorable cases, simply distilled. Under this condition, yields are decent and the fact that GC yields are higher suggests that they may be improved when working with larger amounts. The impact can be minimized, at least for chloro (and fluoro!) anilines, simply by replacing UV lamps with sunlight, by increasing the concentration of substrates, and by optimizing the atom economy of the process. In conclusion, the above data strengthen the idea that photo-ArS$_{\rm N}$1 arylations (and photochemistry, in general) represent a simple, yet extremely versatile tool for organic synthesis and, in particular in the solar version, easily comply with the green chemistry postulates. Therefore, this may be advantageously used in synthetic laboratories, in conjunction with solar concentrator when a faster transformation is desired.

Experimental Section

A. General. NMR spectra were recorded on a 300 MHz spectrometer. The attributions were made on the basis of ^{1}H and ^{13}C NMR, as well as DEPT experiments; chemical shifts are reported in ppm downfield from TMS. Compounds **1a**−**c** were obtained by methylation of the corresponding anilines following the procedure of Giumanini et al.[28] Commercial 4-chloroaniline (**1d**) was crystallized from ethanol before use. Mesitylene, α-methylstyrene, allyltrimethylsilane, 4-pentenoic acid, and ethyl vinyl ether were all commercially available and were freshly distilled before use. Compound **2d** (as an $E + Z$ mixture) was synthesized starting from methyl propionate.[29] All the solvents were of HPLC purity grade and were used as received. All the photochemical products were isolated from preparative irradiations and characterized. The photochemical reactions were performed by using nitrogen-purged solutions in Pyrex glass reactors, in Pavia (Italy, latitude 45°11′ N, 9°09′ E, 77 m above sea level) in the June−July 2009 period. Detailed information for the sunlight flux and solar simulator used can be found in the Supporting Information.

B. General Procedure for Preparative Sunlight-Induced Arylations. A solution (100 mL) of the starting aniline (**1a**−**d**, 0.05−0.2 M) and the nucleophile (**2**, 0.5−0.7 M) in the chosen solvent was poured into a Pyrex vessel (see Figure 1) and purged for 10 min with nitrogen, then screw-capped and exposed to sunlight on a window ledge or irradiated in a solar simulator. After the completion of the reaction (detected by GC analysis), the solvent was removed in vacuo. When water was used as cosolvent, the irradiated mixture was extracted with dichloromethane and then concentrated. The end arylation products were purified from the residue by using flash silica gel, using cyclohexane/ethyl acetate mixtures as eluant containing 0.2% triethylamine. Compounds **4** and **10** were isolated by bulb-to-bulb distillation.

4-(*N*,*N*-Dimethylamino)-2′,4′,6′-trimethylbiphenyl (3). **1a** (3.1 g, 20 mmol, 0.2 M) and **2a** (6.8 mL, 50 mmol, 0.5 M) were dissolved in a 1:5 water/acetonitrile mixture (100 mL) and irradiated for 40 h in the SolarBox or 6 days on a window ledge. Purification afforded 1.9 g of biaryl **3** (45% yield, colorless solid, mp 105−108 °C, lit.[30] mp 111−112 °C). *N*,*N*-Dimethylaniline **4** was also detected (4%, GC yield). Spectroscopic data of compound **3** were in accordance with the literature.[18] IR (neat) ν (cm^{-1}) 2917, 1608, 1521, 1349, 810. Anal. Calcd for C$_{18}$H$_{23}$N: C, 85.30; H, 8.84; N, 5.85. Found: C, 85.3; H, 8.8; N, 5.8.

***N*,*N*-Dimethylaniline (4).** Aniline **1a** (3.1 g, 20 mmol, 0.2 M) was dissolved in 2-propanol (100 mL) and irradiated for 40 h in the SolarBox or 6 days on a window ledge. Bulb-to-bulb

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distillation at reduced pressure gave 1.6 g of **4** (colorless oil, 65% yield), which was identified by comparison with a commercial sample. Anal. Calcd for $C_8H_{11}N$: C, 79.29; H, 9.15; N, 11.56. Found: C, 79.3; H, 9.2; N, 11.6.

***N*,*N*-Dimethyl-4-(2-phenylallyl)aniline (5).** A solution of **1a** (1.5 g, 10 mmol, 0.1 M) and α-methylstyrene (6.7 mL, 50 mmol, 0.5 M) in acetonitrile (100 mL) was irradiated for 23 h in the SolarBox or 3 days on a window ledge. Allylaniline **5** was isolated in 63% yield (1.5 g, solid, mp 55−58 °C). GC analysis also detected *N*,*N*-dimethylaniline **4** (5% yield). Data for **5**: ^{1}H NMR ($CDCl_3$) δ 7.50−7.20 (m, 5 H), 7.10 and 6.70 (AA′XX′, 4 H), 5.50 (s, 1 H), 5.05 (s, 1 H), 3.75 (s, 2 H), 2.90 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 149.0, 147.6, 141.1, 129.4 (CH), 128.7, 128.0 (CH), 127.2 (CH), 126.0 (CH), 113.9 (CH), 112.8 (CH_2), 40.7 (CH_3), 40.5 (CH_2); IR (neat) ν (cm^{-1}) 2892, 1613, 1519, 1346, 1189, 808. Anal. Calcd for $C_{17}H_{19}N$: C, 86.03; H, 8.07; N, 5.90. Found: C, 86.2; H, 8.1; N, 5.8.

4-Allyl-*N*,*N*-dimethylaniline (6). Compound **1a** (1.5 g, 10 mmol, 0.1 M) and allyltrimethylsilane (8 mL, 50 mmol, 0.5 M) were dissolved in a 1:5 water/acetonitrile mixture (100 mL) and irradiated for 24 h in the SolarBox or 3 days on a window ledge. Allylaniline **6** was obtained as the exclusive product in 51% yield (815 mg, colorless oil). Spectroscopic data were in accordance with the literature.[31] IR (neat) ν (cm^{-1}) 2925, 1641, 1343, 837. Anal. Calcd for $C_{11}H_{15}N$: C, 81.94; H, 9.38; N, 8.69. Found: C, 82.1; H, 9.2; N, 8.7.

2-(4-*N*,*N*-Dimethylaminophenyl)propionic Acid Methyl Ester (7). A mixture of **1a** (780 mg, 5 mmol, 0.05 M), triethylamine (700 μL, 5 mmol, 0.05 M), and 1-methoxy-1-[(trimethylsilyl)-oxy]propene (11.3 g, 70 mmol, 0.7 M) in acetonitrile (100 mL) was irradiated in the SolarBox for 6 h or 1 day on a window ledge. Ester **7** was obtained in 58% yield (oil, 600 mg). GC analysis showed traces of *N*,*N*-dimethylaniline **4**, not isolated. Data for **7**: NMR data were in accordance with the literature.[32] IR (neat) ν (cm^{-1}) 1740, 1621, 1519, 1170. Anal. Calcd for $C_{12}H_{17}NO_2$: C, 69.54; H, 8.27; N, 6.76. Found: C, 69.7, H, 8.1; N, 6.8.

5-(*N*,*N*-Dimethyl-4-aminobenzyl)-2,3,4,5-tetrahydro-2-furanone (8). A solution of **1a** (1.5 g, 10 mmol, 0.1 M) and 4-pentenoic acid (5.1 mL, 50 mmol, 0.5 M) in a 1:5 water/acetonitrile mixture (100 mL) was irradiated in the Solarbox for 24 h or 3 days on a window ledge. Purification of the mixture gave lactone **8** (940 mg, 45% yield, colorless solid, mp 54−57 °C) and *N*,*N*-dimethylaniline **4** (77 mg, 6% yield). The same reaction was repeated by using a 1:5 water/acetone mixture as the solvent. Lactone **8** (1.5 g) was formed in 71% yield along with 90 mg of **4** (7% yield). Data for **8**: Spectroscopic characterization was in accordance with the literature.[33] IR (neat) ν (cm^{-1}) 2956, 1616, 1524, 1061, 975, 803. Anal. Calcd for $C_{13}H_{17}NO_2$: C, 71.21; H, 7.81; N, 6.39. Found: C, 71.1; H, 7.9; N, 6.4.

4-(2-Ethoxy-2-methoxyethyl)-*N*,*N*-dimethylaniline (9). Aniline **1a** (780 mg, 5 mmol, 0.05 M), cesium carbonate (814 mg, 2.5 mmol, 0.025 M), and ethyl vinyl ether (4.8 mL, 50 mmol, 0.5 M) were dissolved in methanol (100 mL) and irradiated for 8 h in the SolarBox or 1 day on a window ledge. Flash chromatography afforded acetal **9** (colorless oil, 670 mg, 60% yield) and *N*,*N*-dimethylaniline **4** (colorless oil, 77 mg, 13% yield). Data for **9**: Spectroscopic data were in accordance with the literature.[26] IR (neat) ν (cm^{-1}) 2927, 1618, 1523, 1120, 1061, 809. Anal. Calcd for $C_{13}H_{21}NO_2$: C, 69.92; H, 9.48; N, 6.27. Found: C, 69.9; H, 9.6; N, 6.2.

3-Methyl-*N*,*N*-dimethylaniline (10). Aniline **1c** (1.7 g, 10 mmol, 0.1 M) was dissolved in 2-propanol (100 mL) and irradiated for 30 h in the SolarBox or 4 days on a window ledge. Bulb-to-bulb distillation at reduced pressure afforded 1.2 g of **10** (oil, 89% yield), which was identified by comparison with a commercial sample. Anal. Calcd for $C_9H_{13}N$: C, 79.95; H, 9.69; N, 10.36. Found: C, 79.9; H, 9.6; N, 10.3.

4-(2-Ethoxy-2-methoxyethyl)aniline (11). A mixture of **1d** (640 mg, 5 mmol, 0.05 M), cesium carbonate (815 mg, 2.5 mmol, 0.025 M), and ethyl vinyl ether (4.8 mL, 50 mmol, 0.5 M) in methanol (100 mL) was irradiated in the SolarBox for 12 h or 1.5 days on a window ledge. Acetal **11** was isolated in 63% yield (533 mg, oil). Traces of aniline **10** were also detected by GC analysis. Data for **11**: ^{1}H NMR ($CDCl_3$) δ 7.05 and 6.60 (AA′XX′, 4 H), 4.55 (t, 1 H, J = 5.6 Hz), 3.75−3.60 (m, 1 H), 3.55−3.40 (m, 1 H), 3.35 (s, 3 H), 2.85 (d, 2 H, J = 5.6 Hz), 1.20 (t, 3 H, J = 7 Hz); ^{13}C NMR ($CDCl_3$), δ: 144.7, 130.2 (CH), 126.9, 115.0 (CH), 104.9 (CH), 61.9 (CH_2), 53.2 (CH_3), 39.3 (CH_2), 15.2 (CH_3); IR (neat) ν (cm^{-1}) 3364, 2927, 1626, 1519, 1122, 1061. Anal. Calcd for $C_{11}H_{17}NO_2$: C, 67.66; H, 8.78; N, 7.17. Found: C, 67.5; H, 8.9; N, 7.1.

C. Irradiations of 4-Fluoro- *N*,*N*-dimethylaniline (1b). With allyltrimethylsilane. A solution (5 mL) of the starting aniline (**1b**, 70 mg, 0.5 mmol, 0.1 M) and allyltrimethylsilane (0.4 mL, 2.5 mL, 0.5 M) in a 1:5 water/acetonitrile mixture was poured into a Pyrex vessel and purged for 5 min with nitrogen, then capped and exposed to sunlight on a window ledge (3 days) or irradiated in a solar simulator (22 h). After the completion of the reaction, GC analysis showed the formation of product **6** in 52% yield.

With Ethyl Vinyl Ether. Aniline **1b** (35 mg, 0.25 mmol, 0.05 M), ethyl vinyl ether (0.24 mL, 2.5 mmol, 0.5 M), and cesium carbonate (40 mg, 0.125 mmol, 0.025 M) were dissolved in methanol (5 mL). After irradiation (16 h in the Solarbox or 2 days on the window ledge), the resulting mixture was analyzed by GC and product **9** was detected in 88% yield along with **4** (8% yield).

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Supporting Information Available: Experimental details and ^{1}H spectra for products **3−11**. This material is available free of charge via the Internet at http://pubs.acs.org.

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