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Lights on! Significant photo enhancement effect on ATRP by ambient laboratory light

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Abstract

Recently we reported on the photoinduced ATRP using a household fluorescent lamp as the light source (T. Zhang et al. *Polym. Chem.* 2014, 5, 4790). Results implied that typical laboratory light might have a considerable impact on the ATRP reaction as fluorescent lamps are commonly used for ceiling and fume hood illumination. Here, we show the influence of ambient laboratory light on AGET, ARGET, and classical ATRP reactions. Except for ARGET ATRP, for all other ATRP types a significant photo enhancement effect by light originating only from fluorescent lamps was observed. A standard fume hood illumination caused the strongest influence.

Since the introduction of atom transfer radical polymerization (ATRP) by Matyjaszewski,[1, 2] this facile and versatile method is frequently used for the synthesis of well-defined polymers from a broad variety of monomers. The usefulness of ATRP was further augmented by the development of activator (re-)generation by electron transfer (A(R)GET) ATRP.[3] Yagci and coworkers demonstrated that this can also be realized *in situ* by a photochemical process without the need of an additional photoactivator (photoinduced ATRP or CRP).[4-6] Several other groups demonstrated the versatility of photoATRP for the facile preparation of defined polymers with well-defined architectures.[7-13]

Recently, we reported on the photoATRP in solution as well as photoinduced surface-initiated ATRP (PSI-ATRP) using a simple household fluorescent lamp as the only light source.[14] The photoinduced ATRP was found to be highly controlled and only converted monomers when

Cu^{II} is steadily reduced to Cu^{I} by irradiation with the fluorescent lamp. An important role plays the used ligand, PMDETA, as it forms a photoredox active copper complex. Since, many other copper complexes can mediate photoredox reactions and fluorescent lamps are typical light sources in a chemical fume hood we stated that *"it most probably will make a difference if one is performing an ATRP reaction with the hood lights on or off."*[14]

This initiated a recent study by Matyjaszewski et al.[15] on the contribution of the photochemistry in activator regeneration in ATRP. Specifically, they investigated the contributions of the photochemical and the chemical processes on the regeneration of the Cu^{I} species. The system they investigated was the so-called "initiators for continuous activator regeneration" (ICAR) ATRP using a photoreactor at $\lambda = 392$ nm and a light intensity of 0.3 mW/cm^2 which equals the light intensity of one fluorescent lamp at a distance of 1 m. The ICAR ATRP was performed with AIBN as the source of free radicals to regenerate the Cu^{I} activator, methyl acrylate (MA) as the monomer, EBiB as the alkyl halide initiator, TPMA as the ligand and $CuBr_2$ at a ratio of [MA]:[EBiB]:[TPMA*2]:[$CuBr_2$]:[AIBN] = 300:1:0.12:0.03:0.2 in anisole 50% (v/v) at 60 °C. For this system, only a negligible influence of visible light on the monomer conversion was observed. However, a large excess of AIBN was employed to continuously regenerate the Cu^{I} species which is otherwise consumed in termination reactions which allows the use of such a low Cu concentrations. Furthermore, photolysis of AIBN is almost negligible because of its very low extinction coefficient at the used wavelength.[16] Therefore, the reported results are, in our view, correct but very specific on this ICAR ATRP system investigated in the study by Matyjaszewski et al.[15] and may not be applicable in general to the photochemical contribution to activator regeneration ATRP. Our previously reported results suggest that for many other ATRP types, the influence of ambient laboratory light mostly originating from sunlight and/or fluorescent lamps at the laboratory ceiling and in chemical fume hood should be significant.[14]

Here, we report on our results of a follow-up study to elucidate the effect of non-standardized but rather typical laboratory light settings on a series of frequently used ATRP types including AGET, ARGET, and classical ATRP. A significant influence of ambient laboratory light from fluorescent lamps on all ATRP reactions except for ARGET ATRP was observed.

For all following ATRP experiments, the same initiator (EBiB), monomer (MMA), ligand (PMDETA), solvent (DMF:methanol, 2:1), type of reaction vial (Schlenk flask made of Duran glass) and reaction conditions ([M], reaction temperature) were used. Under strict exclusion of light, the reaction solution for each ATRP type was prepared in one vial under stirring, degassed by freeze-thaw cycles and then divided into two or three equal portions for the polymerization reactions under different light conditions at room temperature. This allowed a direct comparison of results for each respective ATRP type. Three different light conditions were used. First, under strict exclusion of light (D) with the aid of aluminum foil wrapped around the glassware, second, ambient light with two fluorescent lamps (type L58W/880 "SKYWHITE" from Osram®) 1 m away from the reaction vial and the laboratory ceiling light consisting of 6 fluorescent lamps (type Master TL-D 58W/840 from Philips® at a distance of approx. 3-5 m from the vial) (L, Fig. 1a). Finally, under hood light illumination with the ceiling lights and two fluorescent lamps in the hood on (type Master TL-D 58W/840, Philips® at a distance of 1.4 m to the reaction vial (H, Fig. 1b). These illumination scenarios were chosen to reflect non-standardized but common light settings in an average chemical laboratory and to allow comparison to previous reports on photoinduced ATRP [14] and ICAR ATRP.[15] With a digital lux meter (Luzchem) a light intensity of 5.35±0.15 mW/cm^2 for illumination scenario "L" and 6.19±0.29 mW/cm^2 for "H" was determined.

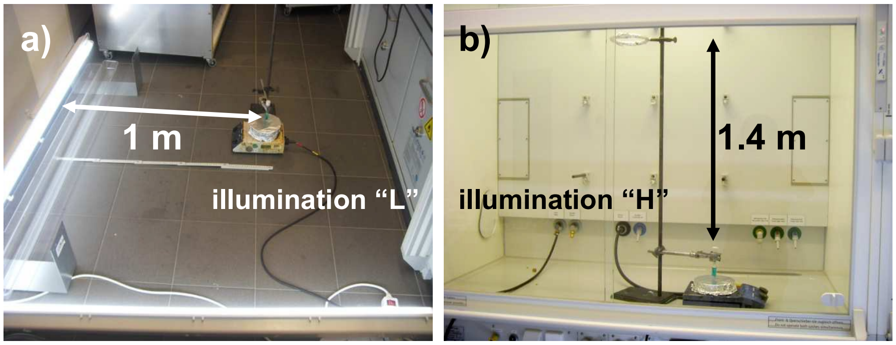

Fig. 1 Photos of the two illumination settings. a) "L" as a standardized ambient laboratory light condition with two fluorescent lamps at a distance of 1 m to the reaction vial and the ceiling illumination consisting of 6 common fluorescent lamps on. At the location of the reaction vial a light intensity of 5.35±0.15 mW/cm^2 was determined by a digital lux meter. b) "H" is a typical hood light illumination condition, with the hood lights (two fluorescent lamps) and ceiling lights on. At the location of the reaction vial a light intensity of 6.19±0.29 mW/cm^2 was determined. Please note that neither the ceiling nor the hood light sources were specifically chosen, replaced or manipulated for the experiments but used as installed by the manufacturers including lamp covers, mounts, reflectors etc. It is noteworthy that the experiments were performed in a basement laboratory with no sunlight.

In Table 1 the results for the various ATRP reaction types are summarized. The recipes were derived from typical ATRP experiments as referenced below and were only slightly adjusted to allow a direct comparison. Please note that all the ATRP reactions conditions are not optimized to yield maximum monomer conversion or best polymerization control.

Table 1 Summary of experimental conditions and results for the various ATRP types at different light conditions. D: exclusion of light; L: two fluorescent lamps at a distance of 1 m and ceiling light; H: hood light and ceiling light.

		light intensity [mW/cm^2]	MMA:EBiB:Cu^I:Cu^{II}: PMDETA:Sn(EH)$_2$: ascorbic acid	T [°C]	t [h]	$M_{n,theo}$ ^{a} [g/mol]	$M_{n,GPC}$ [g/mol]	Đ	conversion ^{b} [%]
ARGET ATRP	1D	0	200:1:-:0.01:0.3:0.3:-	r.t.	22	3706	67780	1.35	17.53
	1L	5.35±0.15	200:1:-:0.01:0.3:0.3:-	r.t.	22	3974	68065	1.35	18.23
	1H	6.19±0.29	200:1:-:0.01:0.3:0.3:-	r.t.	22	3846	68326	1.34	18.87
classical ATRP (Cu^I/Cu^{II})	2D	0	100:1:0.1:0.01:0.3:-:-	r.t.	45	813	-	-	6.17
	2L	5.35±0.15	100:1:0.1:0.01:0.3:-:-	r.t.	45	1458	10826	1.16	12.62
	3D	0	100:1:0.35:0.15:1:-:-	55	10	6686	12476	1.15	64.83
	3H	6.19±0.29	100:1:0.35:0.15:1:-:-	55	10	6865	12200	1.15	66.68
	4D	0	200:1:0.35:0.15:1:-:-	55	45	7885	11651	1.14	38.41
	4H	6.19±0.29	200:1:0.35:0.15:1:-:-	55	45	12149	12195	1.17	59.75
classical ATRP (Cu^I)	5D	0	100:1:0.1:-:0.3:-:-	r.t.	24	737	-	-	5.41
	5L	5.35±0.15	100:1:0.1:-:0.3:-:-	r.t.	24	1658	9799	1.18	14.61
	6D	0	100:1:0.1:-:0.3:-:0.015	r.t.	8	2385	10260	1.13	21.87
	6L	5.35±0.15	100:1:0.1:-:0.3:-:0.015	r.t.	8	3977	13949	1.17	37.77
AGET ATRP	7D	0	100:1:-:0.1:0.3:-:0.05	r.t.	7	4546	11344	1.17	43.45
	7L	5.35±0.15	100:1:-:0.1:0.3:-:0.05	r.t.	7	5336	12786	1.26	51.34
	8D	0	100:1:-:0.1:0.3:0.05:-	r.t.	24	5164	27559	1.24	49.63
	8L	5.35±0.15	100:1:-:0.1:0.3:0.05:-	r.t.	24	5755	28437	1.27	55.53

$^a M_{n,theo}=([MMA]_0/[EBiB]_0\times conversion\times M_{monomer})+M_{initiator}$; ^{b}The conversion was determined by ^1H NMR spectroscopy from the ratio of the OCH_3 signal intensity of the polymer (3.60 ppm) and the monomer (3.75 ppm).

1. Activator regenerated by electron transfer (ARGET) ATRP [17]

In ARGET ATRP very low copper concentrations are used ([I]:[Cu] = 1:0.01) along with an excess of a reducing agent to constantly regenerate the Cu^I complex by chemical means. Analogue to the findings of Matyjaszewski et al.[15] for ICAR ATRP, the influence of visible light on ARGET ATRP is not significant and monomer conversions are almost identical for the different light scenarios (entry #1D, 1L, 1H). This is expectable, as the efficient chemical reduction of Cu^{II} to Cu^I is ensured by the excess of the reducing agent under light as well as under dark conditions.

2. Classical ATRP (Cu^I/Cu^{II}) [2, 18]

In classical ATRP, a higher copper concentration ([I]:[Cu^I]:[Cu^{II}] = 1:0.1-1:0.01-0.1) has to be used in order to maintain the control of the radical polymerization throughout the reaction to cope with the persistent radical effect.[19] As expected, at room temperature and in organic solvents the polymerization is controlled but extremely slow. After 45 h under light exclusion only 6% of the initial monomer was converted, and not enough polymer was formed for a reliable analysis of molar mass and dispersity by gel permeation chromatography (GPC) (#2D). However, under an ambient laboratory light condition (#2L) the monomer conversion almost doubled to a value of 12.6 %. GPC analysis of the resulting PMMA revealed a good control of the polymerization ($Đ$ = 1.16).

Although a significant photo effect was observed, one may easily argue that for an optimized ATRP recipe at elevated temperatures the light effect may be less pronounced or even negligible. Thus, we performed ATRP with MMA as the monomer at 55 °C with a quite standard or "classical" ATRP recipe (MMA:EBiB:Cu^I:Cu^{II}:PMDETA = 200:1:0.35:0.15:0.6) in a common chemical fume hood with the standardly installed lights on (Table 1 entry #4H) as shown in Fig. 1 b, and the same reaction was performed under exclusion of light (vial wrapped with aluminum foil, Table 1 entry #4D). Both reaction tubes were placed in a same heating and stirring apparatus. After 45h polymerization time, the polymers from both reactions were isolated and analyzed with identical procedures and instrumentation. The low dispersity ($Đ$) values for both ATRP reactions (#4D, #4H) indicate a good control of the polymerization with a good agreement between the theoretical and experimental molar mass (M_n). However, the ATRP under light exclusion only gave 38% monomer conversion after 45 h while for the same ATRP with irradiation with the fume hood lights, the monomer conversion exceeded 59 %. Thus, the contribution of photochemical processes to classical ATRP has to be considered as significant even at high temperatures. Interestingly, for an MMA:initiator =100:1, the ATRP proceeds fast with a conversion of around 65% within 10 h polymerization time. As in this case the initial activator is sufficient to carry the ATRP over the entire polymerization time, the activator photoregeneration by ambient light is of minor importance and almost no difference between irradiated and non-irradiated reactions was found (Table 1 entries #3D & #3H).

3. Classical ATRP (initial Cu^I only)

Additionally, we also investigated a variant of the classical ATRP in which initially only the activator Cu^I is added to the polymerization solution. It has been shown that in water, DMSO, DMF and methanol Cu^I readily disproportionate to the (arguably) supplemental Cu^0 activator and the deactivating Cu^{II} complex.[20-22] From the data in Table 1, entry #5D to #5L it is apparent that polymerization proceeds noticeably faster as compared to ATRP with initial Cu^I/Cu^{II} addition. Under the exclusion of light (D), this ATRP did not yield sufficient polymer for reliable characterization, and monomer conversion after 24 h was only around 5-6 % (#5D). Under ambient light conditions (#5L), however, the monomer conversion nearly tripled to 14-15% and narrow distributed PMMA with $Đ$ = 1.18 and M_n = 9799 g/mol was obtained. Additionally, we performed experiments with added ascorbic acid as an reducing agent at very low concentrations ([I]:[Cu^I]:[ascorbic acid] = 1:0.1:0.015). As expected, this substantially improved the performance of the polymerization under light exclusion condition because of the chemical reduction of Cu^{II} to Cu^I (#6D). Interestingly, the same reaction performed under ambient light conditions (#6L), gave even higher monomer conversion (#6D: 22% vs. #6L: 38%). Apparently, the photo enhancement is substantial even in the presence of chemical reducing agents.

4. Activator generated by electron transfer (AGET) ATRP [3, 23]

Finally, the influence of laboratory light on AGET ATRP was investigated. In AGET ATRP, Cu^{II} and a reducing agent is added to the initial reaction solution at a typical ratio of [I]:[Cu^{II}]:[reducing agent] = 1:0.1:0.05 in order to partially convert Cu^{II} to the Cu^I activator. As reducing agents for AGET ATRP, the ascorbic acid [3] and tin(II) 2-ethylhexanoate ($Sn(EH)_2$) [23] are commonly used. After 7 h reaction time under light exclusion (#7D), the polymerization with ascorbic acid reached 44% monomer conversion which was again slightly enhanced by ambient light to a value of 51% (#7L). With $Sn(EH)_2$ as a milder reducing agent and after 24 h reaction time, the effect of light accounted to an increase of the monomer conversion by 6% (#8D vs #8L). All AGET ATRP polymer products showed good to acceptable molar mass distributions of $Đ$ = 1.17-1.27.

The acceptable monomer conversion of AGET ATRP even in the dark allowed a study on the polymerization kinetics under these three illumination conditions. The first-order kinetic plots for AGET ATRP under the three light scenarios (D, L, H) clearly show the significant influence of ambient laboratory light on the polymerization (Fig. 2a). While for all reactions a strictly linear dependency of $\ln([M]_0/[M]_t)$ with the reaction time indicates the good control of the radical polymerization, the remarkable effect of ambient light upon AGET ATRP is apparent. Initially, we were surprised by the significant acceleration of AGET ATRP under fume hood illumination (H, Fig. 1b), which was found to be even higher as compared to the ambient light irradiation (L, Fig. 1a). However, measurement of the respective light intensities at the location of the reaction vials gave 5.35±0.15 mW/cm^2 for ambient light (L) and 6.19±0.29 mW/cm^2 for hood light (H). Thus, the results are reasonable as the acceleration of ATRP scales nicely with the light intensity. Our findings are in agreement with earlier reports by Guan and Smart [24] who discovered that visible light significantly effects the ATRP by using a 275 W sunlight lamp. Moreover, under exclusion of light (D) or ambient light conditions (L) a leveling of the first order kinetic plot is noticeable and indicates an increase of chain termination at longer reaction times. This, however, is not the case if the ATRP is running under fume hood illumination (H). This is further corroborated by the development of the average polymer molar mass as a function of the polymerization time (Fig. 2b). For AGET ATRP under exclusion of light (D), monomer conversion stopped after 10 h at 28%. Illuminated by the fume hood lights (H), the same reaction proceeded nicely to a conversion of 56% within 13 h. Under ambient light condition (L) the monomer conversion only slightly increases after 10 h.

Finally, the development of the number average molar mass with the monomer conversion for all three reactions settings (Fig. 2c) shows again a linear dependency but also the low initiator efficiency of EBiB [9, 25] especially at room temperature as apparent from the discrepancy of M_n and $M_{n,theo}$. The dispersity remains narrow with $Đ$ = 1.09-1.20 indicating a good control of the AGET ATRP at all three conditions.

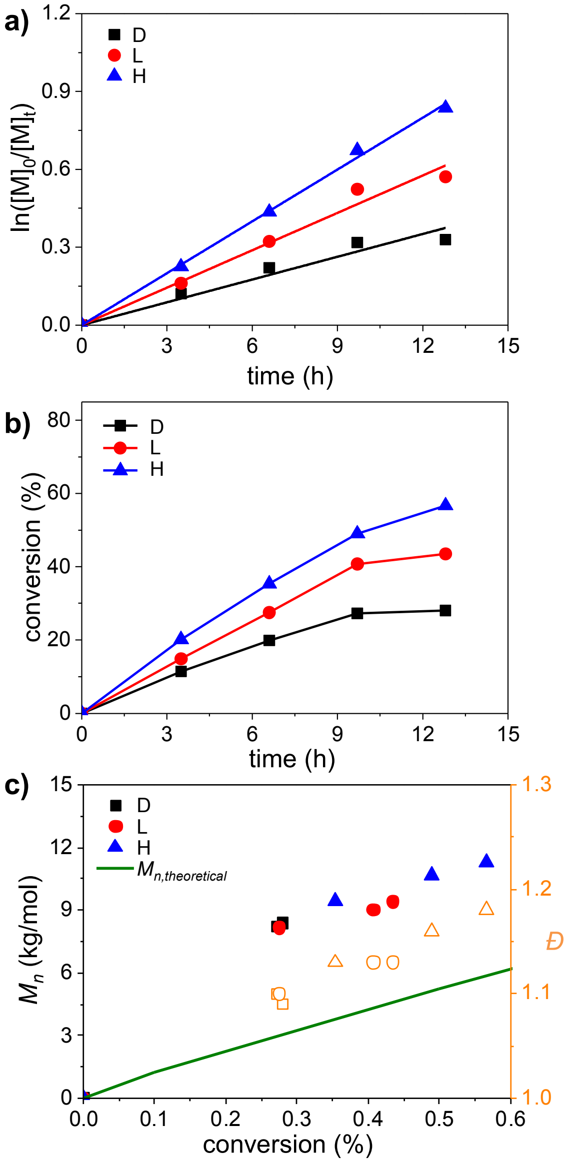

Fig. 2 Influence of laboratory light settings on AGET ATRP. a) First-order kinetic plot for polymerization under light exclusion (D), ambient laboratory light (L) and hood light (H). b) Monomer conversion as a function of the reaction time. c) Development of the number average molar mass (M_n) and dispersity (*Đ*) with the monomer conversion. Polymerizations were performed at a molar ratio of [MMA]:[EBiB]:[$CuBr_2$]:ascorbic acid:[PMDETA] = 100:1:0.1:0.05:0.3. A mixture of DMF:methanol = 2:1 was used as the solvent.

In normal ATRP, Cu^{II} deactivating species can accumulate through either the persistent radical effect (PRE) mechanisms,[19] which increases continuously as the polymerization time. The photochemical effect may be through the reactivation of the Cu^{II} complex by an *in situ* reduction process.[14, 26] If lower Cu^{I} concentration or longer reaction times were used, the influence of photochemical process could be greater. Additionally, if higher Cu^{I} concentrations were used, the generation of deactivating complex by PRE can be neglected and the polymerization itself (in dark) would also be in a good control. In the case of ARGET ATRP and ICAR ATRP, both of the methods employ chemical reducing agents such as ascorbic acid (ARGET) or radical initiator (ICAR) to regenerate the Cu^{I} activating species. The contribution of the photochemical process is therefore negligible. Furthermore, the additional amine ligand is essential to the photochemical pathway in ATRP, since it is a good electron-donor in the photo reduction of Cu^{II} to Cu^{I} complex.[11, 14]

Conclusion

The influence of non-standardized but typical laboratory light scenarios on various ATRP reactions was investigated. Except for ICAR ATRP, as reported previously by Matyjaszewski et al.[15] and ARGET ATRP in this study, all other ATRP types showed a remarkable photo enhancement effect by ambient light, originating from common fluorescent lamps. The influence of ambient light on the monomer conversion is stronger the less Cu complex is used in the respective ATRP recipe. Even in the presence of other reducing agents this effect is significant. In general it can be stated that the slower the ATRP reaction proceeds (low propagation rates), the more pronounced can be the effect of ambient laboratory light.

As previously assumed,[14] we can now conclude that it makes a difference if one is performing an ATRP reaction with the hood lights on or off. Surely, more detailed studies are needed to better understand the mechanism of the effect of ambient light on ATRP with various catalysts, ligands, solvents, monomers and additives. However, the influence of ambient laboratory light can no longer be neglected. It would therefore be helpful to report the light conditions during ATRP experiments to ensure reproducibility.

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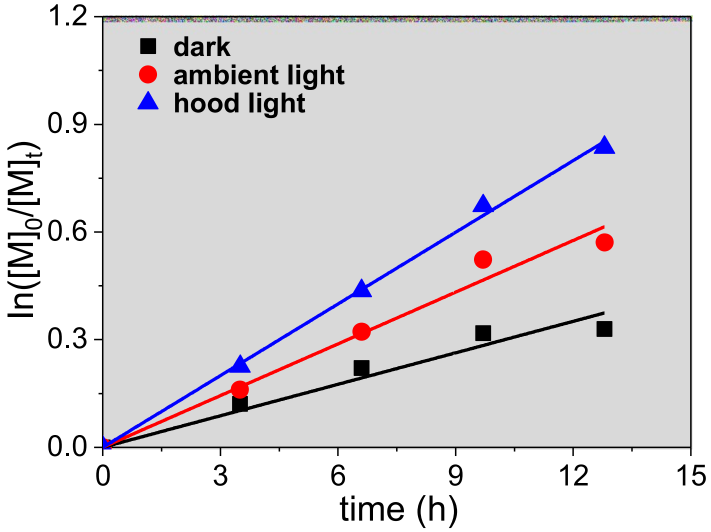

TOC entry:

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