



Photo-Fries rearrangement of 1-pyrenyl esters



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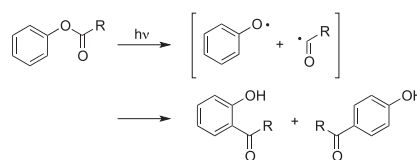
ABSTRACT

Photo-Fries rearrangement reactions of 1-pyrenyl esters were investigated. Photoreaction of 1-pyrenyl benzoate in benzene generates 1-hydroxy-2-pyrenyl phenyl ketone along with 1-pyrenol. The exceptionally down field ^1H NMR chemical shift of OH proton in the photoproduct indicates the existence of intramolecular hydrogen bonding. Photorearrangements of analogs that have electron-withdrawing or electron-releasing group on the phenyl ring, and related heteroaromatic carboxylates also take place to form the corresponding ketones. However, photoreactions of 1-pyrenyl aliphatic carboxylate esters do not occur. The results of spectroscopic and theoretical studies suggest the mechanistic pathway for this process is initiated by homolytic C–O bond cleavage in an aroyl group localized $^1(\pi \rightarrow \pi^*)$ excited state of the 1-pyrenyl esters. The radical pair generated in this fashion then undergoes in-solvent-cage coupling to yield the 1-hydroxy-2-pyrenyl aryl ketone selectively.

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Introduction

Photo-Fries rearrangement reactions of aromatic esters are fundamentally important processes that have received a great deal of attention.¹ Many studies have been conducted that focus on synthetic and mechanistic features of this excited state rearrangement reaction.² Also, photo-Fries rearrangements have been utilized in the total synthesis of natural products,³ reformation of polymers,⁴ patterning and etching,⁵ and they have been employed as part of photoinitiation,⁶ photostabilization,⁷ and refractive index modulation processes.⁸ Most of photo-Fries rearrangement reactions explored thus far have concentrated on phenyl ester substrates, which are transformed to corresponding *ortho*- and *para*-substituted phenols via a general mechanistic pathway involving photo-promoted homolytic C–O bond cleavage followed by C–C bond formation between the acyl radical and the *ortho* and *para* positions of the aryloxy radical (Scheme 1). This process has been performed often within a solvent cage. Microcavities of zeolites,⁹ cyclodextrins,¹⁰ polyethylene film,¹¹ liquid crystals,¹² Nafion membranes¹³ and silica surfaces along with a magnetic field¹⁴ have been utilized to control the ratio of the *ortho* and *para* regioisomers produced and the reaction efficiency. Moreover, rearrangement reactions of 1-naphthyl and 2-naphthyl esters generate 2- and 4-acyl¹⁵ and 1-, 3-, 6- and 8-acyl naphthols,^{15f, h, n, 16} respectively. Here again, the product ratios can be controlled by utilizing materials that contain confined microcavities.¹⁷ However, to the



Scheme 1. Photo-Fries rearrangement of phenyl esters.

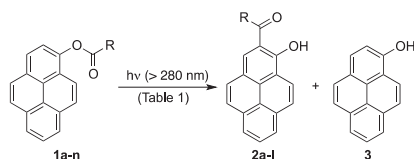
best of our knowledge, photo-Fries rearrangements of more highly fused polyaromatic esters, which have inherently low excitation energies, have not been explored. In the study described below, we demonstrated that photo-Fries rearrangements of 1-pyrenyl aryl-carboxylate esters occur to produce 2-aroxy-1-hydroxypyrene products with excellent levels of regioselectivity. The results demonstrate that in contrast the corresponding pyrenyl alkyl-carboxylate esters are unreactive under the photochemical conditions.

Results and discussion

Esters **1a–n**, the substrates selected to explore the photo-Fries rearrangement reactions of 1-pyrenyl esters, were prepared by reactions of 1-pyrenol **3** with the corresponding acid chlorides in THF containing NaH. Initial photochemical studies were carried out using 1-pyrenyl benzoate **1a** as the substrate. Benzene solutions of **1a** (0.02 M) in Pyrex vessels (>280 nm) were photoirradiated using a 450 W high-pressure mercury lamp for time periods ranging from 0.5 to 24 h (Scheme 2, Table 1, entries 1–5). The photolysates were concentrated in vacuo and the produced residues

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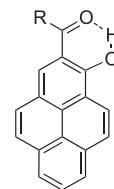
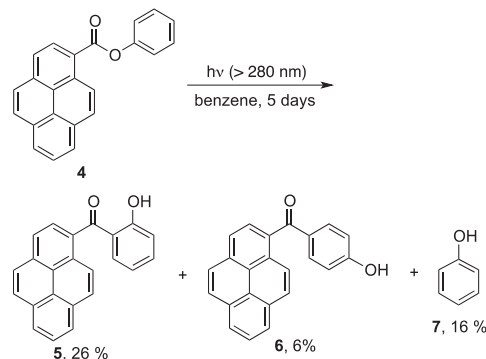
E-mail address: maeda-h@se.kanazawa-u.ac.jp (H. Maeda).

Scheme 2. Photo-Fries rearrangement of 1-pyrenyl esters **1a–n**.

were subjected to silica gel column chromatography to give 1-hydroxy-2-pyrenyl phenyl ketone (**2a**) and 1-pyrenol (**3**). The structure of **2a** was determined by using ^1H and ^{13}C NMR and IR spectroscopy, and mass spectrometry.

Conclusive information about the location of the benzoyl group in **2a** comes from analysis of the coupling pattern in the ^1H NMR spectrum, and the observation that chemical shift of the O–H proton is exceptionally downfield (CDCl_3 , 13.0 ppm) in contrast to that of 1-pyrenol (5.7 ppm). This finding suggests the presence of an highly acidic O–H group in **2a** and the existence of intramolecular hydrogen bonding (Scheme 3).¹⁸

Inspection of the yield vs. time data indicate that the optimal yield of **2a** occurs when a 0.02 M benzene solution of **1a** is irradiated for 2 h (entry 3). Results of an investigation of the effect of solvent (eg., acetone, EtOH, THF and CH_2Cl_2) on the efficiency of the process (entries 6–9) show that benzene is optimal (entry 3). 1-Pyrenyl benzoates **1b–g**, containing electron-withdrawing and electron-donating *p*-substituents, and the 2,6-dimethylphenyl derivative **1h** all undergo photo-Fries rearrangement reactions (benzene, 2–4 h) to generate corresponding 1-hydroxy-2-pyrenyl aryl ketones **2b–h** (entries 10–16). Photoreactions of the 1-pyrenyl esters of heteroaryl-carboxylates **1i–l**, bearing 2-furyl, 2-thienyl, 2-pyridyl and 3-pyridyl groups, respectively, also proceed smoothly to produce the corresponding 1-hydroxy-2-pyrenyl heteroaryl ketones **2i–l** (entries 17–20). However, in these processes longer irradiation times (3–4 days) are required to promote complete consumption of the substrates. Finally, in contrast to the aryl esters, the aliphatic carboxylic acid esters analogs **1m** ($\text{R} = \text{Me}$) and **1n** ($\text{R} = t\text{-Bu}$) do not undergo photo-Fries rearrangement reactions when irradiated for even extended time periods (3 days).

Scheme 3. Intramolecular hydrogen bonding in **2**.Scheme 4. Photo-Fries rearrangement of phenyl 1-pyrenecarboxylate **4**.

The reverse ester analog of **1a**, phenyl 1-pyrenecarboxylate (**4**), was prepared and subjected to photochemical study (Scheme 4). Irradiation of a benzene solution of **4** for 5 days results in low yielding production of the *ortho*- (**5**, 26%) and *para*- (**6**, 6%) photo-Fries rearrangement products along with phenol (**7**, 16%).

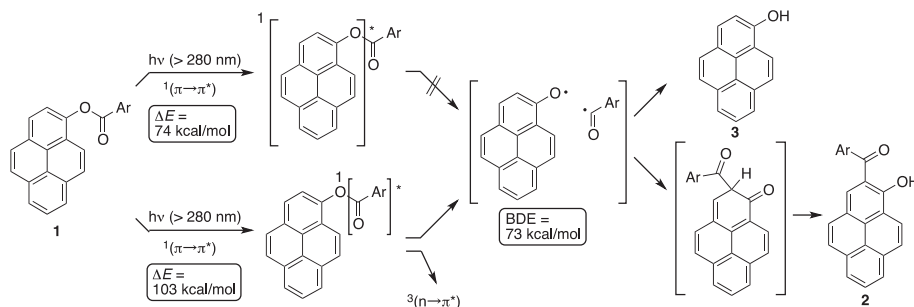
Possible mechanistic pathways for the photo-Fries rearrangement reactions described above, differing in the nature of the excited state undergoing homolytic C–O bond cleavage, are shown in Scheme 5. Spectroscopic data along with the results of theoretical studies were used to gain information about which of these pathways is operative. The electronic energies of pyrenyl benzoate **1a** (–1029.7 a.u.), pyrenoxy radical (–686.6 a.u.), and benzoyl

Table 1
Photo-Fries rearrangement of 1-pyrenyl esters **1**.^a

Entry	Substrate		Solvent	Time	Yields (%) ^b		Recovery of 1 (%) ^b
	R	1			2	3	
1	Ph	1a	Benzene	30 min	14	<1	69
2	Ph	1a	Benzene	1 h	30	14	15
3	Ph	1a	Benzene	2 h	46	14	6
4	Ph	1a	Benzene	4 h	42	18	<1
5	Ph	1a	Benzene	24 h	37	14	<1
6	Ph	1a	Acetone	2 h	12	61	6
7	Ph	1a	EtOH	2 h	22	11	28
8	Ph	1a	THF	2 h	40	5	<1
9	Ph	1a	CH_2Cl_2	2 h	27	<1	17
10	<i>p</i> -NO ₂ C ₆ H ₄	1b	Benzene	4 h	42	16	<1
11	<i>p</i> -CF ₃ C ₆ H ₄	1c	Benzene	4 h	17	5	<1
12	<i>p</i> -ClC ₆ H ₄	1d	Benzene	3 h	30	20	<1
13	<i>p</i> -BrC ₆ H ₄	1e	Benzene	3 h	18	9	<1
14	<i>p</i> -MeC ₆ H ₄	1f	Benzene	4 h	27	15	<1
15	<i>p</i> -MeOC ₆ H ₄	1g	Benzene	3 h	14	6	<1
16	2,6-Me ₂ C ₆ H ₃	1h	Benzene	2 h	25	10	<1
17	2-Furyl	1i	Benzene	4 days	37	14	<1
18	2-Thienyl	1j	Benzene	4 days	29	8	<1
19	2-Pyridyl	1k	Benzene	3 days	19	13	<1
20	3-Pyridyl	1l	Benzene	3 days	31	9	<1
21	Me	1m	Benzene	3 days	0	0	>99
22	<i>t</i> -Bu	1n	Benzene	3 days	0	0	>99

^a Conditions: **1** (0.16 mmol), benzene (8 mL), r.t., 450 W high pressure mercury lamp, Pyrex vessel.

^b Isolated yield.



Scheme 5. Possible mechanistic pathways for the photo-Fries rearrangement reactions of 1-pyrenyl esters **1**.

radical (−343.0 a.u.) were calculated by using the Gaussian 03 program and the B3LYP/3-21G basis set. These data were employed to determine that the bond dissociation energy (BDE) of the C–O ether bond in ester **1a** is 73 kcal/mol. Moreover, using the 0–0 band in the fluorescence spectrum of **1a** (389 nm), the excitation energy of the pyrene group is estimated to be 74 kcal/mol. Finally, based on fluorescence (276 nm) and phosphorescence (397 nm) spectroscopic analysis of methyl benzoate, the respective $^1(\pi \rightarrow \pi^*)$ and $^3(n \rightarrow \pi^*)$ excitation energies of the aryl group of **1a** are estimated to be 103 and 72 kcal/mol.¹⁹

Under the irradiation conditions (>280 nm) used, both the pyrenyl and aryl groups in **1** are electronically excited. The C–O bond dissociation energy estimate suggests that the excitation energy of pyrene group is not high enough to promote homolytic C–O bond cleavage. In contrast, the aryl group localized $^1(\pi \rightarrow \pi^*)$ excited state of **1** has sufficient energy to cleave C–O bond homolytically to form a radical pair. The singlet aryl-pyrenoxy radical pair generated in a solvent cage by C–O bond cleavage combines by C–C bond formation to produce a 2,4-cyclohexadien-1-one type intermediate that aromatizes to form the 1-hydroxy-2-pyrenyl aryl ketone product **2**.

The unreactivity of aliphatic esters **1m–n** provides support for the conclusion that C–O bond cleavage in the pathway for photo-Fries rearrangements of the pyrenyl ester originates from the excited state of the aryl rather than the pyrene moiety, because acetyl and *tert*-butylcarbonyl group are hardly excited under the present irradiation conditions. From a survey of the results of **1a–l**, the reaction efficiency might depend on excitation energy of aryl groups rather than BDE of the C–O bond. As the reason why the reactions of heteroaryl substrates **1i–l** require long irradiation time, we would like to suggest that it is a consequence of the lower excitation energies of the heteroaroyl groups than those of the benzoyl groups. In reverse ester analog **4**, both pyrenylcarbonyl and phenoxy groups are excited, then phenoxy group localized $^1(\pi \rightarrow \pi^*)$ excited state having higher energy cleaves the C–O bond.

Two possible reasons exist for why radical recombination takes place exclusively at the 2-position of pyrene moiety. Firstly, although the spin density of 1-pyrenoxy radical is highly delocalized throughout the arene ring system,²⁰ ESR spectroscopic results suggest that it is highest at the 2-position.²¹ Secondly, less disruption of the solvent cage would be required in order to create a proper orientation of the aryl-pyrenoxy radical pair for C–C bonding at the 2- rather than other-positions throughout the arene ring system.

Pyrenol **3** is likely produced by cage escape of the pyrenoxy radical followed by hydrogen abstraction. The high yielding production of pyrenol **3** in the photoreaction of **1a** in acetone (Table 1, entry 6) may be a consequence of light absorption by acetone, rapid inter-system crossing to form its triplet and triplet energy transfer to **1a** to form $^3\mathbf{1a}^*$. C–O bond cleavage in the triplet $^3\mathbf{1a}^*$ should gen-

erate a triplet radical pair which would have a slowed rate of radical recombination. Lower viscosity (0.296 mPa·s)²² of this solvent compared to those of other solvents would also lead to an accelerated rate of escape of radicals from the solvent caged pair.

Conclusions

In the effort described above, we explored photo-Fries rearrangement reactions of 1-pyrenyl esters. The results show that photorearrangement reactions of 1-pyrenyl aryl- and heteroaryl-carboxylates **1a–l** occur efficiently to form 1-hydroxy-2-pyrenyl aryl ketones **2a–l** regioselectively. In contrast, 1-pyrenyl alkyl-carboxylates **1m–n** do not participate in this rearrangement reaction. Finally, photorearrangement of the switched analog, phenyl 1-pyrenecarboxylate **4** occurs to produce *ortho*- and *para*-rearranged photo-Fries products **5** and **6** but in low efficiency. Based on spectroscopic and computational results, it is possible to suggest that photorearrangements of **1a–l** proceed via aryl group localized $^1(\pi \rightarrow \pi^*)$ excited states, which undergo C–O homolytic bond cleavage. The singlet pyrenoxy-aryl radical pair then undergo in-solvent-cage coupling. It is worthy of note that this study has uncovered the first examples of photo-Fries rearrangement reactions of pyrenyl ester derivatives and, as such, it should stimulate work on synthetic applications for photorearrangement of fused aromatic compounds.

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A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.tetlet.2017.10.007>.

References

- (a) Bellus D, Hrdlovic P. *Chem Rev.* 1967;67:599–609;
(b) Gu W, Weiss RG. *J. Photochem Photobiol C.* 2001;2:117–137;
(c) Miranda MA, Galindo F. In: Ramamurthy V, Schanze KS, eds. *Molecular and Supramolecular Photochemistry, Vol. 9, Photochemistry of Organic Molecules in Isotropic and Anisotropic Media*. New York: Marcel Dekker Inc; 2003:43–131;
(d) Miranda MA, Galindo F. In: Horspool W, Lenci F, eds. *CRC Handbook of Organic Photochemistry and Photobiology*. 2nd Ed. Boca Raton: CRC Press LLC; 2004, pp 42/1–42/11.

2. (a) Coppinger GM, Bell ER. *J Phys Chem*. 1966;70:3479–3489;
(b) Schutte L, Havinga E. *Tetrahedron*. 1967;23:2281–2284;
(c) Sandner MR, Hedaya E, Trecker DJ. *J Am Chem Soc*. 1968;90:7249–7254;
(d) Kalmus CE, Hercules DM. *Tetrahedron Lett*. 1972;13:1575–1577;
(e) Adam W, de Sanabia JA, Fischer H. *J Org Chem*. 1973;38:2571–2572;
(f) Adam W. *J Chem Soc, Chem Commun*. 1974:289–290;
(g) Kalmus CE, Hercules DM. *J Am Chem Soc*. 1974;96:449–456;
(h) Shine HJ, Subotkowski W. *J Org Chem*. 1987;52:3815–3821;
(i) Grimme S, Dreeskamp H. *J Photochem Photobiol, A*. 1992;65:371–382;
(j) Arai T, Tobita S, Shizuka H. *Chem Phys Lett*. 1994;223:521–526;
(k) Arai T, Tobita S, Shizuka H. *J Am Chem Soc*. 1995;117:3968–3975;
(l) Mori T, Wada T, Inoue Y. *Org Lett*. 2000;2:3401–3404;
(m) Mori T, Inoue Y, Weiss RG. *Org Lett*. 2003;5:4661–4664;
(n) Lochbrunner S, Zissler M, Piel J, Riedle E, Spiegel A, Bach T. *J Chem Phys*. 2004;120:11634–11639;
(o) Gohdo M, Wakasa M. *Chem Lett*. 2010;39:106–107;
(p) Harris SJ, Murdock D, Grubb MP, et al. *Chem Sci*. 2014;5:707–714.
3. (a) Kende AS, Belletire J, Bentley TJ, Hume E, Airey J. *J Am Chem Soc*. 1975;97:4425–4427;
(b) Lown JW, Sondhi SM. *J Org Chem*. 1984;49:2844–2856;
(c) Lown JW, Sondhi SM, Plambeck JA. *J Med Chem*. 1986;29:2235–2241;
(d) Magnus P, Lescop C. *Tetrahedron Lett*. 2001;42:7193–7196;
(e) Ferrini S, Ponticelli F, Taddei M. *J Org Chem*. 2006;71:9217–9220;
(f) Magauer T, Martin HJ, Mulzer J. *Angew Chem Int Ed*. 2009;48:6032–6036;
(g) Guerrini G, Taddei M, Ponticelli F. *J Org Chem*. 2011;76:7597–7601;
(h) Kashinath K, Vasudevan N, Reddy DS. *Org Lett*. 2012;14:6222–6225.
4. (a) Lo J, Lee SN, Pearce EM. *J Appl Polym Sci*. 1984;29:35–43;
(b) Creed D, Griffin AC, Gross JRD, Hoyle CE, Venkataram K. *Mol Cryst Liq Cryst*. 1988;155B:57–71;
(c) Creed D, Griffin AC, Hoyle CE, Venkataram K. *J Am Chem Soc*. 1990;112:4049–4050;
(d) Subramanian P, Creed D, Griffin AC, Hoyle CE, Venkataram K. *J Photochem Photobiol, A*. 1991;61:317–327;
(e) Whitcombe MJ, Gilbert A, Mitchell GR. *J Polym Sci A*. 1992;30:1681–1691;
(f) Whitcombe MJ, Gilbert A, Mitchell GR. *Polymer*. 1993;34:1347–1353;
(g) Kawatsuki N, Takatsuka H, Yamamoto T. *Jpn J Appl Phys*. 2001;40:L209–L211;
(h) Tejedor RM, Oriol L, Piñol M, et al. *J Polym Sci A*. 2005;43:4907–4921;
(i) Daschiel U, Höfler T, Jakopic G, Schmidt V, Kern W. *Macromol Chem Phys*. 2007;208:1190–1201;
(j) Griesser T, Höfler T, Temmel S, Kern W, Trimmel G. *Chem Mater*. 2007;19:3011–3017;
(k) Hernandez-Sosa G, Simbrunner C, Höfler T, et al. *Org Electron*. 2009;10:326–332;
(l) Ramil AM, Hernandez-Sosa G, Griesser T, et al. *Appl Phys A*. 2012;107:985–993;
(m) Petriz A, Wolfberger A, Fian A, Krenn JR, Griesser T, Stadlober B. *Org Electron*. 2013;14:3070–3082.
5. (a) Loong W, Su A. *Microelectron Eng*. 1991;13:101–104;
(b) Loong W, Su A, Wang J, Chu C. *Microelectron Eng*. 1991;14:237–248;
(c) Griesser T, Adams J, Wappel J, Kern W, Leggett GJ, Trimmel G. *Langmuir*. 2008;24:12420–12425;
(d) Höfler T, Track AM, Pacher P, et al. *Mater Chem Phys*. 2010;119:287–293.
6. Aydin M, Temel G, Balta DK, Arsu N. *Polym Bull*. 2015;72:309–322.
7. Ohkatsu Y, Takenaka H, Kamiyama N. *J Jpn Petrol Inst*. 2008;51:95–101.
8. (a) Höfler T, Grießer T, Gstrein X, Trimmel G, Jakopic G, Kern W. *Polymer*. 2007;48:1930–1939;
(b) Zanutta A, Colella L, Bertarelli C, Bianco A. *Opt Mater*. 2013;35:2283–2289.
9. (a) Pitchumani K, Warrier M, Ramamurthy V. *J Am Chem Soc*. 1996;118:9428–9429;
(b) Tung C-H, Ying Y-M. *J Chem Soc Perkin Trans*. 1997;2:1319–1322;
(c) Balkus Jr KJ, Khanmamedova AK, Woo R. *J Mol Catal A*. 1998;134:137–143;
(d) Sanjuán A, Aguirre G, Álvaro M, García H, Scaiano JC. *Appl Catal B*. 2000;25:257–265;
(e) Tung C-H, Wu L-Z, Zhang Li-P, et al. *Pure Appl Chem*. 2000;72:2289–2298.
10. (a) Nassetta M, de Rossi RH, Cosa JJ. *Can J Chem*. 1988;66:2794–2798;
(b) Syamala MS, Rao BN, Ramamurthy V. *Tetrahedron*. 1988;44:7234–7242;
(c) Veglia AV, Sanchez AM, de Rossi RH. *J Org Chem*. 1990;55:4083–4086;
(d) Veglia AV, de Rossi RH. *J Org Chem*. 1993;58:4941–4944;
(e) Tung CH, Ying YM, Yang ZQ, Wang XH. *Chin Chem Lett*. 1995;6:27–30.
11. Chen Y-Z, Weiss RG. *Photochem Photobiol Sci*. 2009;8:916–925.
12. (a) Stumpe J, Selbmann C, Kreysig D. *J Photochem Photobiol, A*. 1991;58:15–30;
(b) Kawatsuki N, Neko T, Kurita M, Nishiyama A, Kondo M. *Macromolecules*. 2011;44:5736–5742;
(c) Kawatsuki N, Matsushita H, Washio T, Kurita M, Kondo M. *Macromolecules*. 2012;45:8547–8554.
13. Tung C-H, Xu X-H. *Tetrahedron Lett*. 1999;40:127–130.
14. Tung C-H, Wang X-H, Ying Y-M, Yang Z-Q. *Res Chem Intermed*. 1995;21:613–620.
15. (a) Escobar C, Fariña F, Martínez-Utrilla R, Paredes MC. *J Chem Res (S)*. 1977;266–267;
(b) Crouse DJ, Hurlbut SL, Wheeler DMS. *Synth Commun*. 1979;9:877–881;
(c) Fariña F, Martínez-Utrilla R, Paredes MC. *Tetrahedron*. 1982;38:1531–1537;
(d) Sharma PK, Khanna RN. *Indian J Chem*. 1984;23B:891;
(e) Sharma PK, Khanna RN. *Monatsh Chem*. 1985;116:353–356;
(f) Chauhan RPS, Singh MP, Dubey VK, Singh UB. *Asian J Chem*. 1993;5:831–835;
(g) Gritsan NP, Tsentlovich YP, Yurkovskaya AV, Sagdeev RZ. *J Phys Chem*. 1996;100:4448–4458;
(h) Molokov IF, Tsentlovich YP, Yurkovskaya AV, Sagdeev RZ. *J Photochem Photobiol, A*. 1997;110:159–165;
(i) Mori T, Takamoto M, Wada T, Inoue Y. *Photochem Photobiol Sci*. 2003;2:1187–1199;
(j) Mori T, Takamoto M, Saito H, Furo T, Wada T, Inoue Y. *Chem Lett*. 2004;33:254–255;
(k) Park KK, Jeong J. *Tetrahedron*. 2005;61:545–553;
(l) Baalamurugan K, Bhama M, Sridar V. *Indian J Chem*. 2010;49B:251–252;
(m) Chen Y-Z, Tian Y-H, Kertesz M, Weiss RG. *Photochem Photobiol Sci*. 2010;9:1203–1211;
(n) López CS, Erra-Balsells R, Bonesi SM. *Tetrahedron Lett*. 2010;51:4387–4390;
(o) Gohdo M, Takamasu T, Wakasa M. *Phys Chem Chem Phys*. 2011;13:755–761.
16. (a) Sharma KS, Goel VK. *Indian J Chem*. 1982;21B:674;
(b) Pathak VP, Saini TR, Khanna RN. *Monatsh Chem*. 1983;114:1269–1270.
17. (a) Nakagaki R, Hiramatsu M, Watanabe T, Tanimoto Y, Nagakura S. *J Phys Chem*. 1985;89:3222–3226;
(b) Holden DA, Jordan K, Safarzadeh-Amiri A. *Macromolecules*. 1986;19:895–901;
(c) Xie R-Q, Liu Y-C, Lei X-G. *Res Chem Intermed*. 1992;18:61–69;
(d) Cui C, Weiss RG. *J Am Chem Soc*. 1993;115:9820–9821;
(e) Allen NS, Edge M, Rahman A, et al. *Polym Degrad Stab*. 1994;44:249–255;
(f) Andrew D, Islet BTD, Margaritis A, Weedon AC. *J Am Chem Soc*. 1995;117:6132–6133;
(g) Vasenkov S, Frei H. *J Am Chem Soc*. 1998;120:4031–4032;
(h) Nowakowska M, Storsberg J, Zapotoczny S, Guillet JE. *New J Chem*. 1999;23:617–623;
(i) Banu HS, Pitchumani K, Srinivasan C. *Tetrahedron*. 1999;55:9601–9610;
(j) Gu W, Hill AJ, Wang X, Cui C, Weiss RG. *Macromolecules*. 2000;33:7801–7811;
(k) Gu W, Bi S, Weiss RG. *Photochem Photobiol Sci*. 2002;1:52–59;
(l) Koodanjeri S, Pradhan AR, Kaanumalle LS, Ramamurthy V. *Tetrahedron Lett*. 2003;44:3207–3210;
(m) Arumugam S, Vutukuri DR, Thayumanavan S, Ramamurthy V. *J Am Chem Soc*. 2005;127:13200–13206;
(n) Arumugam S, Kaanumalle LS, Ramamurthy V. *Photochem Photobiol*. 2006;82:139–145;
(o) Kaanumalle LS, Gibb CLD, Gibb BC, Ramamurthy V. *Org Biomol Chem*. 2007;5:236–238;
(p) Höfler T, Grießer T, Gruber M, Jakopic G, Trimmel G, Kern W. *Macromol Chem Phys*. 2008;209:488–498;
(q) Marin M, Lhiaubet-Vallet V, Miranda MA. *J Phys Chem B*. 2011;115:2910–2915;
(r) Mizusaki M, Enomoto S, Hara Y, Kikuchi H, Yamada Y. *J Appl Phys*. 2013;113:174502.
18. Shulgin AT, Kerlinger HO. *Chem Commun*. 1966;249–250.
19. (a) Kamei S, Abe H, Mikami N, Ito M. *J Phys Chem*. 1985;89:3636–3641;
(b) Viegut TR, Pisano PJ, Mueller JA, Kenney MJ, Hossenlopp JM. *Chem Phys Lett*. 1992;195:568–573.
20. Pohlers G, Dreeskamp H, Grimme S. *J Photochem Photobiol, A*. 1996;95:41–49.
21. (a) Lewis IC, Singer LS. *J Phys Chem*. 1981;85:354–360;
(b) Miura Y, Yamano E, Miyazawa A, Tashiro M. *Chem Lett*. 1994;23:867–870.
22. Makitra RG, Karpayak NM, Midyana GG, Pal'chikova EY, Marshalok GA. *Russ J Gen Chem*. 2010;80:1786–1791.