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Tetrahedron 60 (2004) 459–467
Tetrahedron

Alternative synthesis and novel oxidizing ability of 6,9-disubstituted cyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(6*H*),10(9*H*)-dione derivatives

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Received 19 September 2003; revised 1 November 2003; accepted 4 November 2003

Abstract—Synthesis of 6,9-disubstituted cyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(6*H*),10(9*H*)-diones **7a**–**g** was accomplished by ring opening and ring closure sequences of 9-substituted cyclohepta[*b*]pyrimido[5,4-*d*]furan-8,10(9*H*)-dione derivatives induced by several amines. Furthermore, alternative synthetic methodology for compounds **7a**–**e** was also accomplished by single-step reaction of 2-chlorotropone with 6-aminouracil derivatives under mild conditions. X-ray crystal analysis of **7a** was carried out to clarify the structural characteristics. The properties of **7a**–**e** were studied by the UV–vis spectra and reduction potentials (−1.24 to −1.39 V vs $Ag/AgNO_3$). Novel photo-induced oxidation reaction of **7a**–**d** toward some amines under aerobic conditions was carried out to give the corresponding imines in more than 100% yield [based on compounds **7a**–**d**], suggesting the oxidation reaction occurs in an autorecycling process.

1. Introduction

Dehydrogenation reactions represent a major category of processes mediated by a subclass of flavoenzymes known as oxidases.[1] Included in this group are the oxidative transformations of alcohols to carbonyl compounds, of amines to imines, and of fatty acid esters to their α,β-unsaturated analogs.[2] The photo-induced oxidizing reaction of amines by 3-methyllumiflavin (**1**) (Fig. 1) and its related cations has been investigated to clarify the mechanistic aspects.[3] Furthermore, the flavin-redox systems have been investigated extensively through synthetic model systems and theoretical calculations.[4] Among these, 5-deazaflavins **2a** have been studied extensively in both enzymatic[5] and model systems,[6,7] in the hope of gaining mechanistic insight into flavin-catalyzed reactions. In this relation, 5-deaza-10-oxaflavin **2b** (2*H*-chromeno[2,3-*d*]pyrimidine-2,4(3*H*)-dione),[8] in which the nitrogen atom is replaced by an oxygen, has also been synthesized and found to possess a strong function to oxidize alcohols to the corresponding carbonyl compounds. On the basis of the above observations, we have recently reported the synthesis, properties, and reactivity of 7,9-dimethylcyclohepta[*b*]pyrimido[5,4-*d*]furan-8(7*H*),10(9*H*)-dionylium tetrafluoroborate (**3a**·BF_4^-)[9,10] and its sulfur and nitrogen analogues **3b**–**d**·BF_4^-.[11,12]

Furthermore, novel photo-induced autorecycling oxidizing reactions of **3a**–**d**·BF_4^- toward some alcohols are studied as well.[10–12] Thus, the uracil-annulated heteroazulenes such as **3a**–**d**·BF_4^- are very interesting from the viewpoint of exploration of novel functions.

On the other hand, we have previously studied preparations of 6-substituted 9-methylcyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(6*H*),10(9*H*)-diones (**7a**–**d**)[13] (Scheme 3) and 9-substituted cyclohepta[*b*]pyrimido[5,4-*d*]furan-8,10(9*H*)-diones (**4a**,**f**,**g**)[14] (Fig. 1), which are structural isomers of 5-deazaflavin **2a** and 5-deaza-10-oxaflavin **2b**. In the studies, we have clarified that **4a**,**f**,**g** have oxidizing ability toward

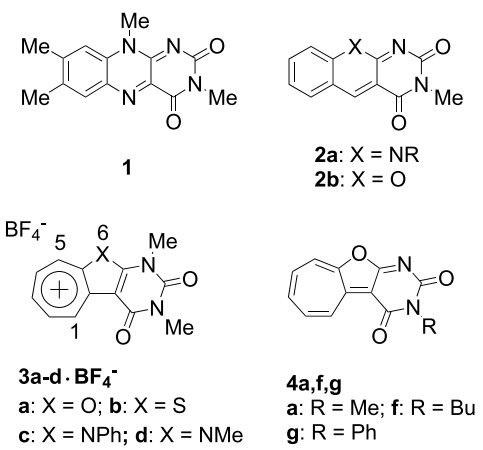

Figure 1.

Keywords: 6,9-Disubstituted cyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(6*H*),10(9*H*)-diones; Ring-transformation; Reduction potential; Photo-induced oxidation reaction.

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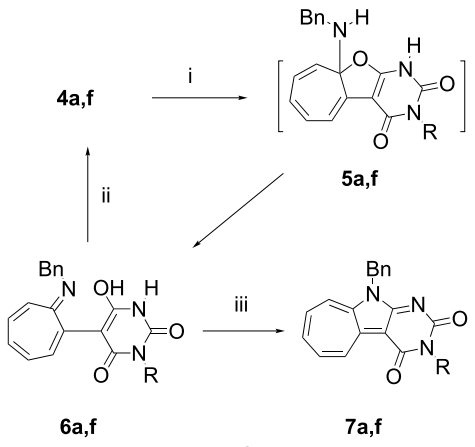
0040–4020/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2003.11.004

some alcohols. In a search for the reactivity and functions of uracil-anuulated heteroazulenes, we investigated the ring-transformation of **4a**,**f**,**g** to **7a**–**g**. Furthermore, alternative synthetic methodology for compounds **7a**–**e** was also accomplished, and their oxidizing ability toward some amines was studied as well. We report herein the results in detail.

2. Results and discussion

2.1. Ring-transformation of 4a,f,g to 7a,f,g

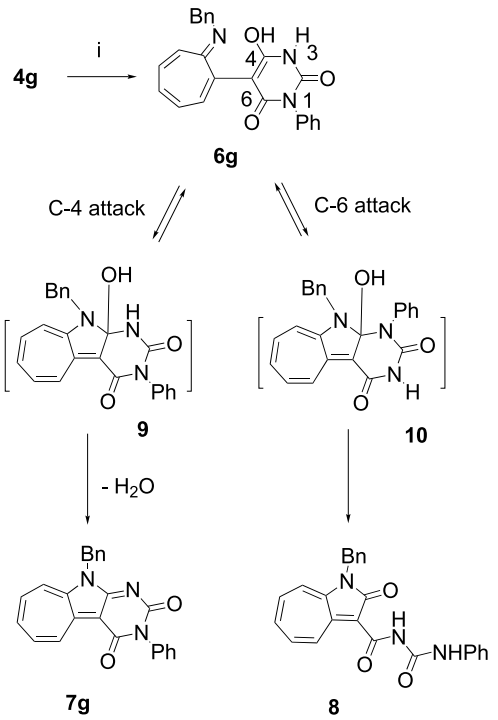
The reactions of **4a**,**f** with benzylamine afforded compounds **6a**,**f**, respectively, which were derived from 5a-adducts **5a**,**f** (Scheme 1, Table 1, Entries 1 and 2). When compounds **6a**,**f** were kept at room temperature for 10 h in the presence of benzylamine, no reaction proceeded. Upon treatment with TFA in $CHCl_3$, compounds **6a**,**f** regenerated **4a**,**f** in good yields. On the contrary, heating of the solutions of compounds **6a**,**f** in 1,4-dioxane at 90 °C afforded compounds **7a**,**f** in good yields (Scheme 1, Table 1, Entries 1 and 2). Thus, the thermal cyclization of **6a**,**f** would proceed via nucleophilic attack of the nitrogen of the troponeimine moiety. Unlike in the cases of **4a**,**f**, reaction of compound **6g** generated by the reaction of **4g** with benzylamine at room temperature proceeded under mild conditions to give **7g** and **8** (Scheme 2). The ring cleavage reaction giving **8** proceeded more quickly as compared with the dehydration reaction to give **7g** (Table 1, Entries 3 and 4): the reaction of **4g** with benzylamine for 0.5 h afforded **6g** and **8**, while the longer reaction time (24 h) resulted in the formation of **7g**



Scheme 1. *Reagents and conditions*: (i) $BnNH_2$, CH_2Cl_2, rt, 0.5 h; (ii) TFA–$CHCl_3$ (1/10), rt, 0.5 h; (iii) 1,4-dioxane, reflux, 5 h.

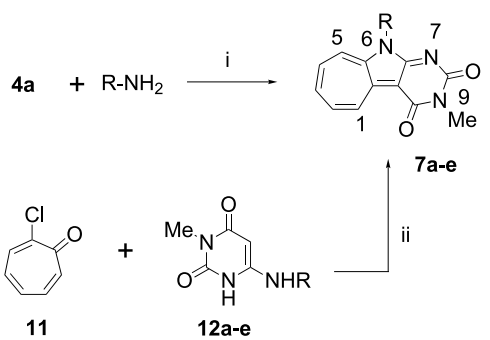
Table 1. Results for the reactions of **4a**,**f**,**g** with benzylamine and thermal cyclization of **6a**,**f**

Entry	4	R	Reaction with benzylamine		Thermal cyclization of 6a,f	
			Time (h)	Product (Yield (%))	6	Product (Yield (%))
1	**4a**	Me	0.5	**6a** (89)	**6a**	**7a** (70)
2	**4f**	Bu	0.5	**6f** (93)	**6f**	**7f** (72)
3	**4g**	Ph	0.5	**6g** (55), **8** (24)	–	–
4	**4g**	Ph	24	**7g** (17), **8** (70)	–	–



Scheme 2. *Reagents and conditions*: (i) $BnNH_2$, CH_2Cl_2, rt.

and **8**. The features are explained as follows: intermediate **9** generated by the C-4 attack underwent dehydration to give **7g**. On the contrary, intermediate **10** generated by the C-6 attack underwent a ring-opening reaction to give **8**. The facility of the latter reaction is probably due to the resonance effect of the Ph-group toward the nitrogen anion. Compounds **6a**,**f**,**g**, were fully characterized on the basis of the ^1H and ^{13}C NMR, IR, and mass spectral data as well as high-resolution mass spectra. Compounds **7f**,**g** and **8** were also characterized on the basis of the ^1H and ^{13}C NMR, IR, and mass spectral data as well as elemental analyses. Furthermore, we have accomplished convenient preparation of **7a**–**e** from **4a** and amines without isolation of troponeimine **6a** and its derivatives. The mixtures of **4a** with some amines in 1,4-dioxane were heated at 90 °C to afford compounds **7a**–**e** in good yields (Scheme 3, Table 2). Compounds **7a**–**d** were identified on the basis of a comparison of the physical data with those reported in the literature.[13] In addition, new



a: R = Bn; **b**: R = 4-Cl-C_6H_4
c: R = Ph; **d**: R = 4-$MeOC_6H_4$; **e**: R = 4-$Me_2NC_6H_4$

Scheme 3. *Reagents and conditions*: (i) 1,4-dioxane, 90 °C; (ii) Bu^tNH_2, EtOH, rt, 40 h.

Table 2. Results for the preparation of **7a–e** from **4a** and primary amine

Entry	4	Amine	Time (h)	Product	Yield (%)
1	**4a**	$BnNH_2$	24	**7a**	84
2	**4a**	$4\text{-}ClC_6H_4NH_2$	40	**7b**	75
3	**4a**	$PhNH_2$	40	**7c**	81
4	**4a**	$4\text{-}MeOC_6H_4NH_2$	20	**7d**	86
5	**4a**	$4\text{-}Me_2NC_6H_4NH_2$	10	**7e**	90

compound **7e** was fully characterized on the basis of the ^1H and ^{13}C NMR, IR, and mass spectral data as well as elemental analysis.

2.2. Alternative synthetic method for 7a–e

Previously, we have reported that the reaction of 2-chlorotropone **11** with 6-aminouracil derivatives **12a–d** in the presence of Et_3N and K_2CO_3 in 1,4-dioxane afforded compounds **7a–d**.[13] However, this reaction was carried out under reflux, and thus, column chromatography was necessary to purify the products. In the present study, we have accomplished the facile preparation of **7a–e** from similar starting materials. Thus, the reactions of **11** with **12a–e** in EtOH in the presence of Bu^tNH_2 at room temperature were carried out to give **7a–e** in good to moderate yields (Scheme 3, Table 3). In this reaction, few by-products were generated due to the mild conditions. Moreover, the products **7a–e** were slightly soluble in EtOH at room temperature. Thus, filtration of the reaction mixtures afforded pure samples of **7a–e**.

2.3. Properties and reactivity

The UV–vis spectra of **7a–e** in acetonitrile are shown in Figure 2. The spectra of **7a–e** are similar and the longest wavelengths absorption maxima show similar values (Table 4). Although benzylamine was added to the solution, the visible region of the spectra of **7a–e** was not changed. Thus, addition reaction of **7a–e** with benzylamine would not proceed under the measurement conditions of the UV–vis spectra. A single crystal of **7a** was obtained by recrystallization from EtOH. Thus, in order to clarify the structural details, X-ray structure analysis was carried out and the ORTEP drawing of **7a** is shown in Figure 3.[15] The π-system of compound **7a** has a nearly planar structure. The bond lengths of C1–C2, C3–C4, and C5–C6 are shorter than those of C2–C3, C4–C5, C6–C7, and C7–C1. This fact suggests the existence of large bond alternation in the seven-membered ring. In contrast to the cations **3a–d**·BF_4^-,[9–12] the bond length of N1–C9 of **7a** is slightly longer than that of N1–C6. The reduction potentials of **7a–e** were determined by cyclic voltammentry (CV) in CH_3CN. The reduction waves of **7a–e** were irreversible under the conditions of the CV measurements; the peak potentials are summarized in Table 4, together with those of the reference compounds **3c**·BF_4^-.[12] The $E1_{red}$ of **7a–e** are more negative by 0.40–0.55 V than that of **3c**·BF_4^-. The irreversible nature is probably due to the formation of tropyl

Table 3. Results for the preparation of **7a–e** from 2-chlorotropone **11** and 6-aminouracil **12a–e**

Entry	12	R	Product	Yield (%)
1	**12a**	Bn	**7a**	90
2	**12b**	$4\text{-}ClC_6H_4$	**7b**	73
3	**12c**	Ph	**7c**	83
4	**12d**	$4\text{-}MeOC_6H_4$	**7d**	71
5	**12e**	$4\text{-}Me_2NC_6H_4$	**7e**	36

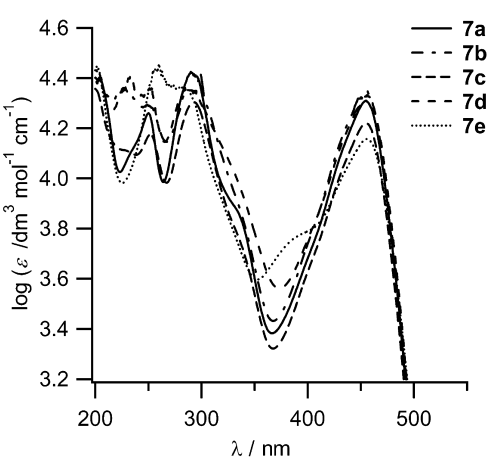


Figure 2. UV–vis spectra of **7a–e** in CH_3CN.

Table 4. The longest wavelength absrobtion maxima and reduction potentials[a] of **7a–e** and reference compound **3a**·BF_4^-

Compound (R)	λ_{max} (nm) (log ε (dm^3 mol^{-1} cm^{-1}))	Reduction potential $E1_{red}$ (V)
7a (Bn)	455 (4.31)[b]	−1.39
7b (4-ClC_6H_4)	456 (4.35)[b]	−1.24
7c (Ph)	456 (4.22)[b]	−1.31
7d (4-$MeOC_6H_4$)	456 (4.33)[b]	−1.32
7e (4-$Me_2NC_6H_4$)	456 (4.16)	−1.35
3c·BF_4^-[c]	414 (4.11)	−0.84

[a] V vs $Ag/AgNO_3$; cathodic peak potential.
[b] Ref. 13.
[c] Ref. 12.

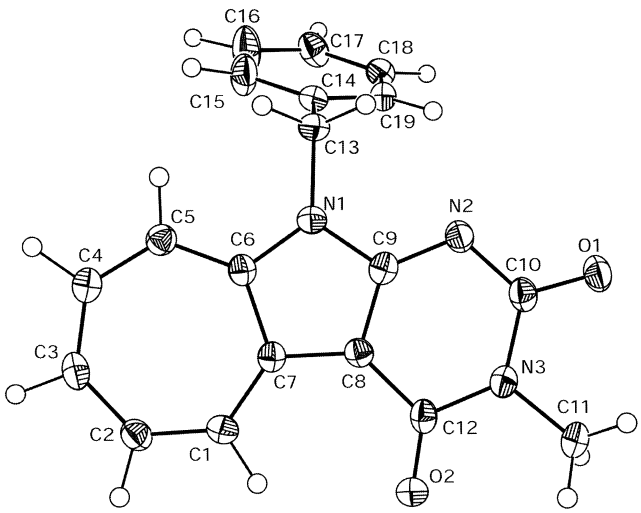
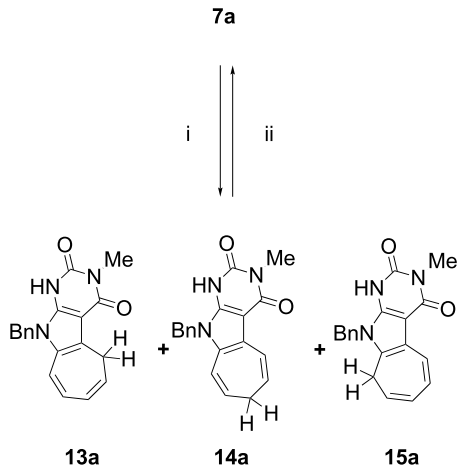


Figure 3. ORTEP drawing of **7a** with thermal ellipsoid plot (50% probability). Selected bond lengths (Å); N1–C6 1.376(4), N1–C9 1.381(4), C1–C2 1.380(4), C2–C3 1.404(4), C3–C4 1.380(4), C4–C5 1.394(4), C5–C6 1.381(4), C6–C7 1.463(4), C1–C7 1.403 (4), C7–C8 1.398(4), C8–C9 1.404 (4).



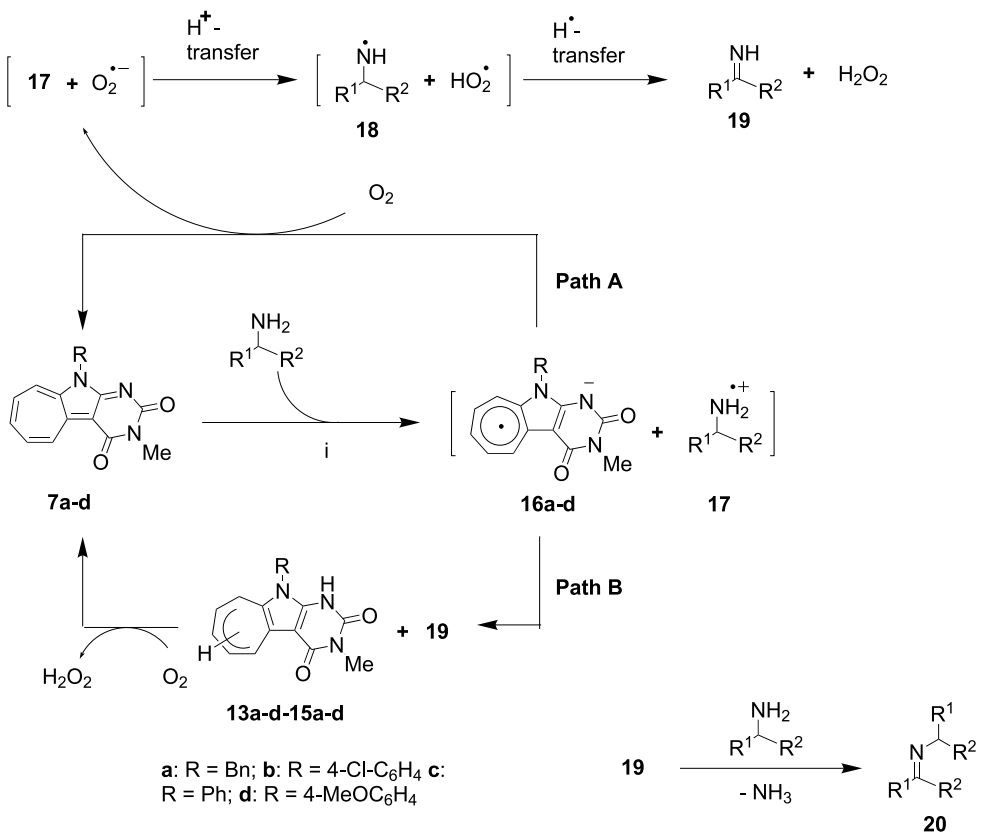
Scheme 4. *Reagents and conditions*: (i) $NaBH_4$, EtOH, rt, 1 h; (ii) DDQ, CH_2Cl_2, rt, 1 h.

radicals and their dimerization. This reduction behavior seems to be a typical property of uracil-annulated heteroazulenes, such as **3a**–**d**·BF_4^-.[9–12] Compound **7a** was reduced with $NaBH_4$ to give a mixture of three compounds **13a**–**15a**, and the mixture was oxidized by DDQ to regenerate **7a** in quantitatively yield. Since the regioisomers could not be separated, the structural assignments were based on the NMR, IR, mass spectral data as well as high-resolution mass spectrum of the mixture. The ^1H NMR spectra of the mixture of three regioisomers could be assigned by using the H–H COSY spectra (Scheme 4).

2.4. Autorecycling oxidation

We have previously reported that compounds **3a**–**d**·BF_4^- undergo autorecycling oxidation toward some alcohols under photo-irradiation.[10–12] In this context and in a search for the functions of **7a**–**e**, we examined the oxidation of some amines by using **7a**–**e** under aerobic and photo-irradiation conditions (RPR-100, 350 nm lamps). Although compound **7e** did not oxidize amines, we found that compounds **7a**–**d** have oxidizing ability toward some amines to give the corresponding imines. Imine **19** is produced at first; however, it reacts with another amine to result in the formation of $R^1R^2C{=}N{-}CHR^1R^2$ (**20**) (Scheme 5). The results are summarized in Table 5. Direct irradiation of the amines in the absence of **7a**–**e** (named 'blank') gives the imines in low to modest yields. Thus, the yields are calculated by subtraction of the blank yield from the yields in the presence of **7a**–**e**. More than 100% yields are obtained [based on compounds **7a**–**d**] (Table 5), and thus, autorecycling oxidation clearly proceeds; however, cyclohexylamine was not oxidized (Table 5, Entry 22).

In a previous study, the fluorescence spectra of **3a**,**b**·BF_4^- were quenched by addition of 1-phenylethanol, suggesting an interaction of the singlet excited state of the cations with the alcohol.[10,11] Thus, in a search for the mechanistic aspect of the photo-induced oxidation reaction, the fluorescence spectrum of **7a** was studied; however, very weak fluorescence of **7a** appeared at 514 nm. The quantum yield (Φ) of **7a** was determined to be 0.001 by using quinine bisulfate as standard.[18] In addition, by addition of benzylamine (500 equiv.) to the solution of **7a** (under similar conditions



Scheme 5. *Reagents and conditions*: (i) *hv*, aerobic, CH_3CN, rt.

Table 5. Autorecycling oxidation of some amines by **7a**–**e** under photo-irradiation[a]

Entry	Compound	(6-R)	Amine	Time (h)	Imines[b]	Yield[c] (%)
1	**7a**	(Bn)	$PhCH_2NH_2$	1	$PhCH{=}NCH_2Ph$	371
2	**7a**	(Bn)	$PhCH_2NH_2$	2	$PhCH{=}NCH_2Ph$	874
3	**7a**	(Bn)	$PhCH_2NH_2$	4	$PhCH{=}NCH_2Ph$	1413
4	**7a**	(Bn)	$PhCH_2NH_2$	8	$PhCH{=}NCH_2Ph$	2224
5	**7a**	(Bn)	$PhCH_2NH_2$	12	$PhCH{=}NCH_2Ph$	4762
6	**7a**	(Bn)	$PhCH_2NH_2$	16	$PhCH{=}NCH_2Ph$	8573
7	**7a**	(Bn)	$PhCH_2NH_2$	24	$PhCH{=}NCH_2Ph$	12825
8	**7a**	(Bn)	$PhCH_2NH_2$	32	$PhCH{=}NCH_2Ph$	14238
9	**7b**	(4-ClC_6H_4)	$PhCH_2NH_2$	16	$PhCH{=}NCH_2Ph$	9343
10	**7c**	(Ph)	$PhCH_2NH_2$	16	$PhCH{=}NCH_2Ph$	7993
11	**7d**	(4-$MeOC_6H_4$)	$PhCH_2NH_2$	16	$PhCH{=}NCH_2Ph$	6049
12	**7e**	(4-$Me_2NC_6H_4$)	$PhCH_2NH_2$	16	$PhCH{=}NCH_2Ph$	0[d]
13	**7a**	(Bn)	$PhCH(Me)NH_2$	16	$PhMeC{=}NCHMePh$	6447
14	**7b**	(4-ClC_6H_4)	$PhCH(Me)NH_2$	16	$PhMeC{=}NCHMePh$	4693
15	**7c**	(Ph)	$PhCH(Me)NH_2$	16	$PhMeC{=}NCHMePh$	4760
16	**7d**	(4-$MeOC_6H_4$)	$PhCH(Me)NH_2$	16	$PhMeC{=}NCHMePh$	3927
17	**7e**	(4-$Me_2NC_6H_4$)	$PhCH(Me)NH_2$	16	$PhMeC{=}NCHMePh$	0[d]
18	**7a**	(Bn)	4-$MeOC_6H_4CH_2NH_2$	16	4-$MeOC_6H_4CH{=}NCH_2$(4-$MeOC_6H_4$)	4753
19	**7a**	(Bn)	4-$MeC_6H_4CH_2NH_2$	16	4-$MeC_6H_4CH{=}NCH_2$(4-MeC_6H_4)	8293
20	**7a**	(Bn)	4-$ClC_6H_4CH_2NH_2$	16	4-$ClC_6H_4CH{=}NCH_2$(4-ClC_6H_4)	8573
21	**7a**	(Bn)	4-$PyCH_2NH_2$	16	4-$PyCH{=}NCH_2$(4-Py)	3101
22	**7a**	(Bn)	Cyclohexylamine	16	*N*-Cyclohexylcyclohexanone imine	0[d]

[a] CH_3CN solution was irradiated by RPR-100, 350 nm lamps under aerobic conditions.
[b] Isolated by converting to the corresponding 2,4-dinitrophenylhydrazone.
[c] Based on **7a**–**e** used; the yield is calculated by subtraction of the 'blank' yield from the total yield of carbonyl compound in the presence of **7a**–**e**.
[d] The 'blank' yield was higher than the yield in the presence of **7**.

for the oxidation reaction), no quenching of the fluorescence was observed. These features suggest very small interaction of the singlet excited state of **7a** with amines, but the triplet excited state may intervene in the oxidation reaction.

In order to clarify the details of the oxidizing reaction, time dependency was investigated. The results are summarized in Table 5 (Entries 1–8) and Figure 4. As the irradiation time was prolonged to 24 h, the yield of benzaldimine was increased simply. After irradiation for 32 h, the yield of benzaldimine is not so increased, suggesting plausible decomposition of **7a**. When the photo-irradiation of CD_3CN solution of **7a** in the absence of amines under aerobic conditions was carried out, no decomposition of **7a** was observed. Thus, **7a** would be decomposed in the oxidation cycle. Furthermore, in the oxidation of benzylamine by using **7b**–**e**, the yields of the imines became larger in the order **7e** (0%) ≪**7d**<**7c**<**7b**. This fact is probably due to the more positive $E1_{red}$ values in the order **7e**<**7d**<**7c**<**7b**

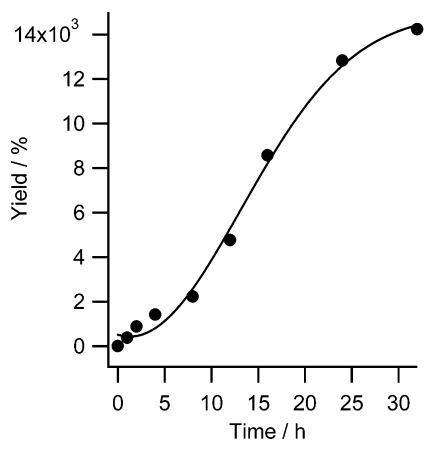


Figure 4. Time dependency of autorecycling oxidation of benzylamine by **7a**.

(Table 5, Entries 9–12). [The reduction potentials of **7b**–**e** in the ground state would be correlated with their LUMO's, and thus, the LUMO's of these compounds would be lower in the order **7e**>**7d**>**7c**>**7b**. In the excited state of these compounds, the electron-accepting orbital would be the singly occupied HOMO's. In as much as the UV–vis spectra of these compounds are similar, and the energy level of HOMO's of the compounds is expected to be lower in the order **7e**>**7d**>**7c**>**7b**, the autorecycling oxidation of amines thus seems to be more efficient in the order **7e**<**7d**<**7c**<**7b**.] A similar tendency was obtained in the case of the oxidation of 1-phenylethylamine (Table 5, Entries 14–17). However, in spite of the more negative $E1_{red}$ value, compound **7a** has high oxidizing ability toward benzylamine and 1-phenylethylamine (Table 5, Entries 6 and 13).

In a search for the substituent effect of benzylamine, the oxidation reactions of 4-substituted benzylamines and picolylamine were carried out by using **7a** under aerobic and photo-irradiation conditions (Table 5, Entries 18–21). The yields of imines are plotted against Hammet constants σ_p[16] of substituents on the phenyl group and 4-picolylamine in Figure 5. The plots seem to show a maximum value, and the yield of photo-induced oxidation of amines becomes low at either the high value (σ_p 0.23, 4-$ClC_6H_4CH_2NH_2$) or the low value (σ_p −0.27, 4-$MeOC_6H_4CH_2NH_2$). The yields of the imine derived from 4-picolylamine, which corresponds to the benzylamine having strong electron-withdrawing substituent, becomes low and may be close to the yield expected from 4-nitrobenzylamine. Thus, the oxidizing reaction by using **7a** becomes less effective for the amines, which have both lower and higher oxidation potential. This feature is similar to the case of photo-induced oxidation reaction of benzylalcohol by using a flavin analoge,[17] and it is rationalized by the electron-transfer pathways (vide infra).

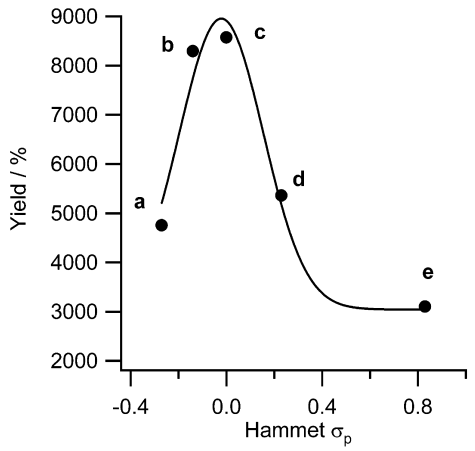


Figure 5. The Hammet plot of autorecycling oxidation of 4-substituted benzylamine by **7a**. (**a**, 4-$MeOC_6H_4CH_2NH_2$; **b**, 4-$MeC_6H_4CH_2NH_2$; **c**, $PhCH_2NH_2$; **d**, 4-$ClC_6H_4CH_2NH_2$; **e**, 4-$PyCH_2NH_2$).

The postulated mechanistic pathways for the present photo-induced oxidation of amines are depicted in Scheme 5.[17] The electron-transfer from amine to the excited triplet state of **7a**–**d** would occur to produce anions radical **16a**–**d** and a cation radical **17**. An electron transfer from radical species **16a**–**d** to molecular oxygen may give the superoxide anion radical and **7a**–**d**, since tropyl radical derivatives are known to be readily oxidized by molecular oxygen.[19] Then, a proton-transfer from cation radical **17** to a superoxide anion radical may occur, followed by formation of the products **19** and H_2O_2 (Path A). Compound **19** reacts with excess amine to give imine **20**. Substituted benzylamine having a more negative oxidation potential favors the electron transfer process from amine to the excited triplet **7a**, but disfavors the proton transfer process from cation radical **17** to the superoxide anion radical. On the contrary, substituted benzylamine having a more positive oxidation potential disfavors the electron transfer process from amine to the excited triplet state of **7a**, while the proton transfer process from cation radical **17** to the superoxide anion radical becomes more favorable. As such, a sensitive balance between the electron donor ability of amines and the proton donor ability of cation radical **17** is required to achieve the efficient photo-induced oxidation reaction of amines by using **7a**. On the other hand, there is an alternative mechanistic pathway (Path B), in which compounds **13a**–**d**–**15a**–**d** in addition to the imines are generated from **16a**–**d** and **17**; the former compounds are oxidized under aerobic and photo-irradiation conditions to regenerate **7a**–**d**. Under aerobic and photo-irradiation conditions, the CD_3CN solution of **13a**–**15a** was easily oxidized to regenerated **7a** quantitatively. Thus, autorecycling oxidation would also be possible in this Path B. However, attempted detection of compound **16a** or its dimers or compounds **13a**–**15a** is unsuccessful in the oxidation reaction of benzylamine under degassed and photo-irradiation conditions (degassed by freeze-pump-thaw cycles). Thus, further investigations are required to clarify the mechanistic aspect of the reaction.

3. Conclusion

The reaction of 9-substituted cyclohepta[*b*]pyrimido[5,4-*d*]furan-8,10(9*H*)-diones **4a**,**f**,**g** with benzylamine was investigated to explore the ring-transformation of **4a**,**f**,**g** to 6,9-disubstituted cyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(6*H*),10(9*H*)-diones **7a**–**g**. Furthermore, alternative synthetic methodology for compounds **7a**–**e** was also accomplished. X-ray crystal analysis of **7a** was carried out to clarify the structural characteristics. The properties of **7a**–**e** were studied by the UV–vis spectra and reduction potentials (−1.24 to −1.39 V vs $Ag/AgNO_3$). The photo-induced oxidation reactions of **7a**–**d** toward some amines under aerobic conditions were carried out to give the corresponding imines in more than 100% yield [based on compounds **7a**–**d**], suggesting that the oxidation proceeds in an autorecycling process.

4. Experimental

4.1. General

IR spectra were recorded on a HORIBA FT-710 spectrometer. Mass spectra and high-resolution mass spectra were run on JMS-AUTOMASS 150 and JMS-SX102A spectrometers. Unless otherwise specified, ^1H NMR spectra and ^{13}C NMR spectra were recorded on JNM-AL 400, JNM-lambda 500, and AVANCE 600 spectrometers using $CDCl_3$ as the solvent, and the chemical shifts are given relative to internal $SiMe_4$ standard: *J*-values are given in Hz. Mps were recorded on a Yamato MP-21 apparatus and were uncorrected.

4.2. Reaction of 4a,f with benzylamine

A solution of **4a**,**f** (0.5 mmol) and benzylamine (107 mg, 1.0 mmol) in CH_2Cl_2 (5 mL) was stirred at rt for 0.5 h. To the mixture was added EtOH (50 mL) and the precipitates were collected by filtration to give **6a**,**f**. The results are summarized in Table 1.

4.2.1. 5-(1′-Benzyliminocycloheptatrien-2′-yl)-4-hydroxy-1-methylpyrimidine-2(3*H*),6(1*H*)-dione (6a). Reddish powder; mp 169–171 °C dec (from CH_2Cl_2). ^1H NMR (500 MHz, DMSO-d_6) δ 3.32 (3H, s, Me), 4.69 (2H, s, CH_2), 7.20 (1H, d, *J*=12.2 Hz, H-7), 7.27–7.34 (2H, m, *p*-Ph, H-5), 7.33–7.37 (2H, m, *m*-Ph), 7.50–7.54 (3H, m, *o*-Ph, H-4), 7.69 (1H, dd, *J*=12.2, 8.1 Hz, H-6), 8.17 (1H, d, *J*=9.6 Hz, H-3), 9.81 (1H, br s, NH), 9.97 (1H, s, OH); ^{13}C NMR (125.7 MHz, DMSO-d_6) δ 26.4, 47.2, 89.2, 123.2, 127.0, 127.3, 128.5, 133.6, 135.4, 137.9, 142.0, 143.2, 145.6, 151.9, 161.3, 162.2, 165.8; IR (KBr) ν 3402, 3226, 1685, 1620, 1589 cm^{-1}; MS (FAB) *m/z* 336 (M^++H); HRMS calcd for $C_{19}H_{17}N_3O_3$: 336.1348 (M+H). Found: 336.1346 (M^++H).

4.2.2. 5-(1′-Benzyliminocycloheptatrien-2′-yl)-1-butyl-4-hydroxypyrimidine-2(3*H*),6(1*H*)-dione (6f). Reddish powder; mp 163–165 °C dec (from CH_2Cl_2). ^1H NMR (500 MHz, DMSO-d_6) δ 0.88 (3H, t, *J*=7.6 Hz, Bu-4), 1.28 (2H, sex, *J*=7.6 Hz, Bu-3), 1.49 (2H, quint, *J*=7.6 Hz, Bu-2), 3.72 (2H, t, *J*=7.6 Hz, Bu-1), 4.68 (2H, s, CH_2), 7.19 (1H, d, *J*=12.0 Hz, H-7), 7.26–7.30 (1H, m, *p*-Ph), 7.30 (1H, dd, *J*=10.2, 8.1 Hz, H-5) 7.33–7.37 (2H, m, *m*-Ph), 7.52 (1H, dd, *J*=10.2, 9.8 Hz, H-4) 7.52–7.55 (2H, m, *o*-Ph), 7.69 (1H, dd, *J*=12.0, 8.1 Hz, H-6), 8.17 (1H, d, *J*=9.8 Hz,

H-3), 9.87 (1H, br s, NH), 9.91 (1H, s, OH); ^{13}C NMR (150.9 MHz, DMSO-d_6) δ 13.8, 19.7, 30.3, 39.6, 47.2, 89.3, 123.0, 126.9, 127.3, 128.4, 133.5, 135.4, 137.9, 142.0, 143.0, 145.5, 151.7, 161.4, 161.9, 166.0; IR (KBr) ν 3410, 3255, 1670, 1589, 1576 cm^{-1}; MS (FAB) *m/z* 378 (M^++H); HRMS calcd for $C_{22}H_{23}N_3O_3$: 378.1881 (M+H). Found: 378.1849 (M^++H).

4.3. Reaction of 6a,f with TFA

A solution of **6a**,**f** (0.5 mmol) in $CHCl_3$ (5 mL) and TFA (0.5 mL) was stirred at rt for 0.5 h. To the mixture was added EtOH (50 mL) and the precipitates were collected by filtration to give **4a**,**f** (**4a**: 95%, **4b**: 100%).

4.4. Thermal cyclization of 6a,f

A solution of **6a**,**f** (0.05 mmol) in 1,4-dioxane (5 mL) was stirred at 90 °C for 5 h. The mixture was cooled to rt, and the resulting precipitates were collected by filtration to give **7a**,**f**. The results are summarized in Table 1. Compound **7a** was identical with the authentic specimen.[13]

4.4.1. 6-Benzyl-9-buthylcyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(6*H*),10(9*H*)-dione (7f). Orange plates; mp 203–205 °C (from EtOH). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.98 (3H, t, *J*=7.3 Hz, Bu-4), 1.45 (2H, sex, *J*=7.3 Hz, Bu-3), 1.73 (2H, quint, *J*=7.3 Hz, Bu-2), 4.13 (2H, t, *J*=7.3 Hz, Bu-1), 5.68 (2H, s, CH_2), 7.23–7.36 (5H, m, Bn), 7.65 (1H, dd, *J*=9.3, 9.3 Hz, H-3), 7.71 (1H, dd, *J*=9.3, 9.3 Hz, H-4), 7.76 (1H, d, *J*=9.3 Hz, H-5), 7.88 (1H, dd, *J*=10.5, 9.3 Hz, H-2), 9.29 (1H, d, *J*=10.5 Hz, H-1); ^{13}C NMR (125.7 MHz, $CDCl_3$) δ 13.9, 20.4, 30.3, 40.6, 45.2, 99.2, 122.7, 127.1, 128.2, 129.0, 132.3, 134.6, 135.7, 136.0, 138.4, 143.6, 148.2, 159.3, 161.4, 164.0; IR (KBr) ν 1683, 1635, 1588, 1508 cm^{-1}; MS (FAB) *m/z* 360 (M^++H); HRMS calcd for $C_{22}H_{21}N_3O_2$: 360.1712 (M+H). Found: 360.1669 (M^++H). Anal. calcd for $C_{22}H_{21}N_3O_2{\cdot}1/5H_2O$: C, 72.79; H, 5.94; N, 11.57. Found: C, 73.0; H, 5.9; N, 11.7%.

4.5. Reaction of 4g with benzylamine

A solution of **4g** (145 mg, 0.5 mmol) and benzylamine (107 mg, 1.0 mmol) in CH_2Cl_2 (5 mL) was stirred at rt for 0.5 h. To the mixture was added EtOH (50 mL) and the precipitates were collected by filtration to give **6g** (109 mg, 55%). The filtrate was concentrated in vacuo and the resulting residue was purified by column chromatography on SiO_2 using AcOEt as the eluent to give **8** (48 mg, 24%).

On the other hand, a solution of **4g** (145 mg, 0.5 mmol) and benzylamine (107 mg, 1.0 mmol) in CH_2Cl_2 (5 mL) was stirred at rt for 24 h. The mixture was concentrated in vacuo and the resulting residue was chromatographed on SiO_2 using AcOEt as the eluent to give **7g** (32 mg, 17%) and **8** (139 mg, 70%).

4.5.1. 5-(1′-Benzyliminocycloheptatrien-2′-yl)-4-hydroxy-1-phenylpyrimidine-2(3*H*),6(1*H*)-dione (6g). Orange powder; mp 167–169 °C dec (from CH_2Cl_2). ^{1}H NMR (500 MHz, DMSO-d_6) δ 4.71 (2H, s, CH_2), 7.20 (1H, d, *J*=8.2 Hz, H-7), 7.26–7.41 (9H, m, Ph, H-5, *o*-Bn, *p*-Bn), 7.33–7.37 (2H, m, *m*-Bn), 7.70 (1H, dd, *J*=10.0, 8.2 Hz, H-6), 8.19 (1H, d, *J*=9.8 Hz, H-3), 10.05 (1H, br s, NH), 10.14 (1H, s, OH); ^{13}C NMR (150.9 MHz, DMSO-d_6) δ 47.2, 89.2, 123.1, 126.7, 127.0, 127.3, 127.9, 128.5, 129.6, 133.6, 135.4, 137.3, 137.9, 142.1, 143.1, 145.2, 151.5, 161.8, 161.9, 166.1; IR (KBr) ν 3410, 3286, 1685, 1581 cm^{-1}; MS (FAB) *m/z* 398 (M^++H); HRMS calcd for $C_{24}H_{19}N_3O_3$: 398.1504 (M+H). Found: 398.1530 (M^++H).

4.5.2. 6-Benzyl-9-phenylcyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(6*H*),10(9*H*)-dione (7g). Yellow powder; mp 299–301 °C (from EtOH). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.73 (2H, s, CH_2), 7.27–7.38 (7H, m, *o*-Ph, Bn), 7.41 (1H, t, *J*=7.4 Hz, *p*-Ph), 7.51 (2H, dd, *J*=8.3, 7.4 Hz, *m*-Ph), 7.67 (1H, dd, *J*=9.3, 9.3 Hz, H-3), 7.74 (1H, dd, *J*=9.7, 9.3 Hz, H-4), 7.83 (1H, d, *J*=9.7 Hz, H-5), 7.88 (1H, dd, *J*=10.6, 9.3 Hz, H-2), 9.24 (1H, d, *J*=10.6 Hz, H-1); ^{13}C NMR (125.7 MHz, $CDCl_3$) δ 45.4, 99.5, 123.0, 127.2, 128.1, 128.4, 128.8, 129.2, 129.3, 132.6, 134.6, 136.0, 136.4, 136.8, 138.8, 144.1, 148.5, 159.3, 161.6, 164.8; IR (KBr) ν 1684, 1654, 1586, 1508 cm^{-1}; MS (FAB) *m/z* 380 (M^++H); HRMS calcd for $C_{24}H_{17}N_3O_2$: 380.1399 (M+H). Found: 380.1379 (M^++H). Anal. calcd for $C_{24}H_{17}N_3O_2{\cdot}1/2\ H_2O$: C, 74.21; H, 4.67; N, 10.82. Found: C, 74.3; H, 4.4; N, 10.7%.

4.5.3. *N*-(1-Benzyl-1,2-dihydro-2-oxocyclohepta[*b*]pyrrol-3-yl)carbonyl-*N*′-phenylurea (8). Yellow needles; mp 232–233 °C (from AcOEt). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.30 (2H, s, CH_2), 7.09 (1H, t, *J*=7.5 Hz, *p*-Ph), 7.21–7.36 (7H, m, *m*-Ph, Bn), 7.43 (1H, dd, *J*=10.0, 9.0 Hz, H-6), 7.46 (1H, d, *J*=9.5 Hz, H-8), 7.54 (1H, dd, *J*=10.0, 9.5 Hz, H-7), 7.63 (2H, d, *J*=7.5 Hz, *o*-Ph), 7.72 (1H, dd, *J*=11.0, 9.0 Hz, H-5), 9.45 (1H, d, *J*=11.0 Hz, H-4), 10.89 (1H, s, NH), 10.91 (1H, s, NH); ^{13}C NMR (125.7 MHz, $CDCl_3$) δ 43.9, 99.1, 118.8, 120.1, 123.7, 127.0, 128.1, 128.9, 129.1, 131.7, 133.5, 135.2, 137.6, 138.1, 145.5, 148.1, 151.3, 165.0, 167.1; IR ($CHCl_3$) ν 1675, 1653, 1589, 1539, 1478, 1447 cm^{-1}; MS (FAB) *m/z* 398 (M^++H); HRMS calcd for $C_{24}H_{19}N_3O_3$: 398.1505 (M+H). Found: 398.1469 (M^++H). Anal. calcd for $C_{24}H_{19}N_3O_3$: C, 72.53; H, 4.82; N, 10.57. Found: C, 72.3; H, 4.9; N, 10.3%.

4.6. Ring transformation of 4a to 7a–e

To a solution of **4a** (46.5 mg, 0.2 mmol) in 1,4-dioxane (20 mL) was added amine (0.4 mmol). The mixture was stirred at 90 °C until the reaction was completed (Table 2). The mixture was cooled to rt and the resulting precipitates were collected by filtration to give **7a**–**e**. The results are summarized in Table 2. Compounds **7a**–**d** were identical with the authentic specimen.[13]

4.6.1. 6-Dimehtylaminophenyl-9-methylcyclohepta[*b*]-pyrimido[5,4-*d*]pyrrole-8(6*H*),10(9*H*)-dione (7e). Reddish powder; mp>310 °C (from MeOH/CH_2Cl_2). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.05 (6H, s, NMe_2), 3.49 (3H, s, NMe), 6.85 (2H, d, *J*=9.0 Hz, H-3′, H-5′), 7.24 (2H, d, *J*=9.0 Hz, H-2′, H-6′), 7.65–7.80 (3H, m, H-2, H-4, H-5), 7.86–7.93 (1H, m, H-3), 9.33 (1H, d, *J*=10.5 Hz, H-1); ^{13}C NMR (125.7 MHz, $CDCl_3$) δ 27.5, 40.5, 99.0, 113.0, 120.8, 123.5, 128.8, 132.3, 135.7, 136.1, 138.2, 142.9, 150.5, 151.2, 159.7, 161.9, 165.2; IR (KBr) ν 1682, 1635, 1592,

1510 cm^{-1}; MS (FAB) *m/z* 347 (M^++H); HRMS calcd for $C_{20}H_{18}N_4O_2$: 347.1508 (M+H). Found: 347.1467 (M^++H). Anal. calcd for $C_{20}H_{18}N_4O_2 \cdot 1/5\ H_2O$: C, 68.65; H, 5.30; N, 16.01. Found: C, 69.0; H, 5.2; N, 16.2%.

4.7. Althernative synthetic method for 7a–e

To a solution of **11** (28 mg, 0.2 mmol) and **12a–e** (0.2 mmol) in EtOH (20 mL) was added Bu^tNH_2 (36.5 mg, 0.5 mmol). The mixture was stirred at rt for 40 h and the precipitates were collected by filtration to give **7a–e**. The results are summarized in Table 3. Compounds **7a–d** were identical with the authentic specimen.[13]

4.8. Cyclic voltammetry of 7a–e

The reduction potential of **7a–e** was determined by means of CV-27 voltammetry controller (BAS Co). A three-electrode cell was used, consisting of Pt working and counter electrodes and a reference $Ag/AgNO_3$ electrode. Nitrogen was bubbled through an acetonitrile solution (4 mL) of **7a–e** (0.5 mmol dm^{-3}) and Bu_4NClO_4 (0.1 mol dm^{-3}) to deaerate it. The measurements were made at a scan rate of 0.1 V s^{-1} and the voltammograms were recorded on a WX-1000-UM-019 (Graphtec Co) X–Y recorder. Immediately after the measurements, ferrocene (0.1 mmol) ($E_{1/2}$=+0.083) was added as the internal standard, and the observed peak potential was corrected with reference to this standard. Compounds **7a–e** exhibited one irreversible reduction wave, and they are summarized in Table 4.

4.9. Reaction of 7a with $NaBH_4$

A solution of **7a** (1.0 mmol) and $NaBH_4$ (76 mg, 2.0 mmol) in EtOH (30 mL) was stirred at rt for 1 h and concentrated in vacuo. The residue was dissolved in 3% HCl and the solution was extracted with CH_2Cl_2. The extract was dried over Na_2SO_4 and concentrated in vacuo to give a mixture of **13a–15a** (314 mg, 98%, **13a**:**14a**:**15a**=2:1:10).

4.9.1. A mixture of 6-benzyl-1,7-dihydro-9-methylcyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(7*H*),10(9*H*)-dione (13a), 6-benzyl-3,7-dihydro-9-methylcyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(7*H*),10(9*H*)-dione (14a), and 6-benzyl-5,7-dihydro-9-methylcyclohepta[*b*]pyrimido[5,4-*d*]pyrrole-8(7*H*),10(9*H*)-dione (15a). Pale yellow powder; mp 198–199 °C (from CH_2Cl_2); IR (KBr) ν 3276, 1703, 1645, 1614 cm^{-1}; MS (FAB) *m/z* 320 (M^++H); HRMS calcd for $C_{19}H_{17}N_3O_2$: 320.1417 (M+H). Found: 320.1390 (M^++H).

Compound **13a**. ^{1}H NMR (500 MHz, DMSO-d_6) δ 3.34 (2H, d, *J*=6.5 Hz, H-1), 3.35 (3H, s, Me), 5.40 (2H, s, CH_2Ph), 5.53 (1H, dd, *J*=10.1, 6.5 Hz, H-2), 6.03 (1H, dd, *J*=10.1, 6.1 Hz, H-3), 6.25 (1H, dd, *J*=11.4, 6.1 Hz, H-4), 6.75 (1H, d, *J*=11.4 Hz, H-5), 7.31–7.44 (5H, m, Ph).

Compound **14a**. ^{1}H NMR (500 MHz, DMSO-d_6) δ 2.33 (2H, dd, *J*=6.9, 6.5 Hz, H-3), 3.28 (3H, s, Me), 5.30–5.40 (2H, m, H-2, 4), 5.46 (2H, s, CH_2Ph), 6.57 (1H, d, *J*=9.7 Hz, H-5), 7.09 (1H, d, *J*=9.7 Hz, H-1), 7.31–7.44 (5H, m, Ph).

Compound **15a**. ^{1}H NMR (500 MHz, DMSO-d_6) δ 3.02 (2H, d, *J*=6.4 Hz, H-5), 3.25 (3H, s, Me), 5.44 (2H, s, CH_2Ph), 5.22 (1H, dd, *J*=10.0, 6.4 Hz, H-4), 6.07 (1H, dd, *J*=10.0, 6.0 Hz, H-3), 6.32 (1H, dd, *J*=11.2, 6.0 Hz, H-2), 7.29 (1H, d, *J*=11.2 Hz, H-1), 7.31–7.44 (5H, m, Ph).

4.10. Oxidation of a mixture of 13a–15a by using DDQ

To a stirred solution of a mixture of **13a–15a** (64 mg, 0.2 mmol) in CH_2Cl_2 (10 mL) was added DDQ (70 mg, 0.3 mmol), and the mixture was stirred at rt for 1 h. After evaporation of the CH_2Cl_2, the residue was purified by column chromatography on Al_2O_3 using AcOEt as the eluent to give **7a** (63 mg, 100%).

4.11. X-ray structure determination of 7a[†]

Yellow prism, $C_{19}H_{15}N_3O_2$, *M*=317.35, monoclinic, space group *C*2/*c*, *a*=15.147(9) Å, *b*=16.52(1) Å, *c*=14.06(1) Å, β=123.99(5)°, *V*=2917.5(4) $Å^3$, *Z*=8, *Dc*=1.445 g mL^{-1}, crystal dimensions 0.40×0.40×0.30 mm^3. Data were measured on a Rigaku RAXIS-RAPID radiation diffractometer with graphite monochromated Mo Kα radiation. Total 13722 reflections were collected, using the ω–2θ scan technique to a maximum 2θ value of 55.0°. The structure was solved by direct methods and refined by a full-matrix least-squares method using SIR92 structure analysis software,[15] with 232 variables and 3274 observed reflections [$I>3.00\sigma(I)$]. The non-hydrogen atoms were refined anisotropically. The weighting scheme $w=[0.1000\times\sigma_c^2(F_0)+0.0010\times F_0^2+0.0200]^{-1}$ gave satisfactory agreement analysis. The final *R* and *Rw* values were 0.0360 and 0.0510. The maximum peak and minimum peak in the final difference map were 0.22 and −0.18 $e^-Å^{-3}$.

4.12. General procedure for the autorecycling oxidation of amines catalyzed by 7a–e

A CH_3CN (16 mL) solution of compounds **7a–e** (0.005 mmol) and amines (2.5 mmol, 500 equiv.) in a Pyrex tube was irradiated by RPR-100, 350 nm lamps under aerobic conditions for the period indicated in Table 5. The reaction mixture was concentrated in vacuo and diluted with Et_2O and filtered. The ^{1}H NMR spectra of the filtrates revealed the formation of the corresponding imines (Table 5). The filtrate was treated with a saturated solution of 2,4-dinitrophenylhydrazine in 6% HCl to give 2,4-dinitrophenylhydrazone. The results are summarized in Table 5.

Acknowledgements

Financial support from a Waseda University Grant for Special Research Project and 21COE 'Practical Nano-Chemistry' from MEXT, Japan is gratefully acknowledged. We thank the Materials Characterization Central Laboratory, Waseda University, for technical assistance with the spectral data, elemental analyses and X-ray analysis.

[†] CCDC reference number 219710.

References and notes

1. Muller, F. *Chemistry and Biochemistry of Flavoenzymes*; Muller, F., Ed.; CRC: Boca Raton, 1991; Vol. 1, pp 1–71 and references cited therein.
2. Hamilton, G. A. *Progress in Bioorganic Chemistry*; Kaiser, E. T., Kezdy, F. J., Eds.; Wiley: New York, 1971; Vol. 1, p 83.
3. Kim, J.; Bogdan, M. A.; Mariano, P. S. *J. Am. Chem. Soc.* **1993**, *115*, 10591–10595.
4. (a) Chiu, C. C.; Pan, K.; Jordan, F. *J. Am. Chem. Soc.* **1995**, *117*, 7027–7028. (b) Kim, J.; Hoegy, S. E.; Mariano, P. S. *J. Am. Chem. Soc.* **1995**, *117*, 100–105. (c) Murahashi, S.; Ono, S.; Imada, Y. *Angew. Chem., Int. Ed. Engl* **2002**, *41*, 2366–2368. (d) Bergstad, K.; Jonsson, S.; Bächvall, J. *J. Am. Chem. Soc.* **1999**, *121*, 10424–10425. (e) Van Houten, K. A.; Kim, J.; Bogdan, M. A.; Ferri, D. C.; Mariano, P. S. *J. Am. Chem. Soc.* **1998**, *120*, 5864–5872. (f) Zheng, Y.; Ornstein, R. L. *J. Am. Chem. Soc.* **1996**, *118*, 9402–9408. (g) Breinlinger, E. C.; Keenan, C. J.; Rotello, V. M. *J. Am. Chem. Soc.* **1998**, *120*, 8606–8609. (h) Hasford, J. J.; Rizzo, C. J. *J. Am. Chem. Soc.* **1998**, *120*, 2251–2255. (i) Antony, J.; Medvedev, D. M.; Stuchebrukhov, A. A. *J. Am. Chem. Soc.* **2000**, *122*, 1057–1065.
5. Walsh, C. *Acc. Chem. Res.* **1986**, *19*, 216–221, and references cited therein.
6. Yoneda, F.; Tanaka, K. *Med. Res. Rev.* **1987**, *4*, 477–506, and references cited therein.
7. Yoneda, F.; Kokel, B. *Chemistry and Biochemistry of Flavoenzymes*; Muller, F., Ed.; CRC: Boca Raton, 1991; Vol. 1, pp 121–169 and references cited therein.
8. Yoneda, F.; Hirayama, R.; Yamashita, M. *Chem. Lett.* **1980**, 1157–1160.
9. Naya, S.; Nitta, M. *Tetrahedron* **2003**, *59*, 3709–3718.
10. Naya, S.; Miyama, H.; Yasu, K.; Takayasu, T.; Nitta, M. *Tetrahedron* **2003**, *59*, 1811–1821.
11. Naya, S.; Miyama, H.; Yasu, K.; Takayasu, T.; Nitta, M. *Tetrahedron* **2003**, *59*, 4929–4938.
12. Naya, S.; Nitta, M. *Tetrahedron* **2003**, *59*, 7291–7299.
13. Nitta, M.; Tajima, Y. *Synthesis* **2000**, 651–654.
14. Takayasu, T.; Mizuta, Y.; Nitta, M. *Heterocycles* **2001**, *54*, 601–606.
15. Altomare, A.; Burla, M. C.; Camalli, M.; Cascarano, M.; Giacovazzo, C.; Guagliardi, A.; Polidori, G. *J. Appl. Crystallogr.* **1994**, *27*, 435.
16. Hansch, C.; Leo, A.; Taft, W. *Chem. Rev.* **1991**, *91*, 165–195.
17. Fukuzumi, S.; Kuroda, S. *Res. Chem. Intermed.* **1999**, *25*, 789–811.
18. Melhuish, W. H. *J. Phys. Chem.* **1961**, *65*, 229–235.
19. (a) Jacobi, D.; Abraham, W.; Pischel, U.; Grubert, L.; Schnabel, W. *J. Chem. Soc., Perkin Trans. 2* **1999**, 1241–1248. (b) Jacobi, D.; Abraham, W.; Pischel, U.; Grubert, L.; Stösser, R.; Schnabel, W. *J. Chem. Soc., Perkin Trans. 2* **1999**, 1695–1702.