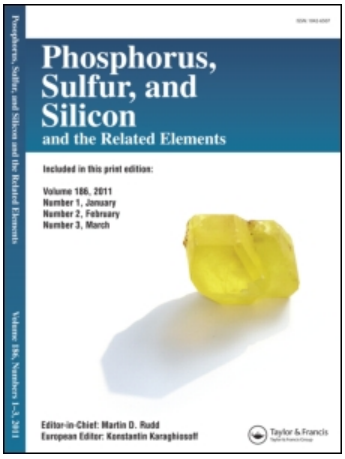

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Novel Thiofomylation of Primary and Secondary Amines Using *N*-Aryl-1,2,3,4,5,7-Pentathiazocanes

Kazuaki Shimada[a]; Hiroki Shibuya[a]; Kenshiro Makino[a]; Tatsuya Otsuka[a]; Yuki Onuma[a]; Shigenobu Aoyagi[a]; Yuji Takikawa[a]

[a] Department of Chemical Engineering, Faculty of Engineering, Iwate University, Morioka, Iwate, Japan

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NOVEL THIOFOMYLATION OF PRIMARY AND SECONDARY AMINES USING *N*-ARYL-1,2,3,4,5,7-PENTATHIAZOCANES

Kazuaki Shimada, Hiroki Shibuya, Kenshiro Makino, Tatsuya Otsuka, Yuki Onuma, Shigenobu Aoyagi, and Yuji Takikawa
Department of Chemical Engineering, Faculty of Engineering, Iwate University, Morioka, Iwate, Japan

Heating of N-aryl-1,2,3,4,5,7-pentathiazocanes 1 in the presence of primary and secondary amines afforded N-Alkyl or N,N-dialkylthioformamides 5, and similar heating of 1 in the absence of amines afforded an inseparable mixture of acyclic polysulfides 4 bearing a thioformanilide moiety on each terminal. Bisthioformanilides 4 were also converted into 5 by treating with these amines, and the thioformylation was assumed to proceed through a pathway involving the ring fission of 1 and the subsequent nucleophilic attack of these amines onto the thioformyl group of 4.

Keywords Bisthioformanilide; 1,2,3,4,5,7-pentathiazocane; polysulfide chain thioformylation; thioformamide

INTRODUCTION

Cyclic polysulfides bearing tri-, tetra-, and pentasulfane moieties have been widely recognized as useful sulfur sources, and synthetic and practical uses of various cyclic polysulfides as syntheric intermediates, potent antibacterial drugs, natural flavors, and industrial vulcanizing agents have also long been extensively studied. However, the difficulty of preparation and the general liability of these compounds often causes limitation in the synthetic application in spite of the potentiality of sulfur-introducing and thiocarbonyl-introducing reactions. Among such compounds, thioacetals having cyclic polysulfide moieties bound with a polysulfane chain have been of great interest in light of the possibility that they could generate reactive sulfur species along with hydrolytic formation of thiocarbonyl groups and polysulfanes. In the course of our extensive studies on the syntheses and reactions of cyclic aminochalcogenoacetals, we previously found an efficient preparation of novel cyclic polysulfides, 1,2,3,4,5,7-pentathiazocanes **1**, possessing a pentasulfide chain connected with an

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Dedicated to Professor Naomichi Furukawa on the occasion of his 70th birthday.

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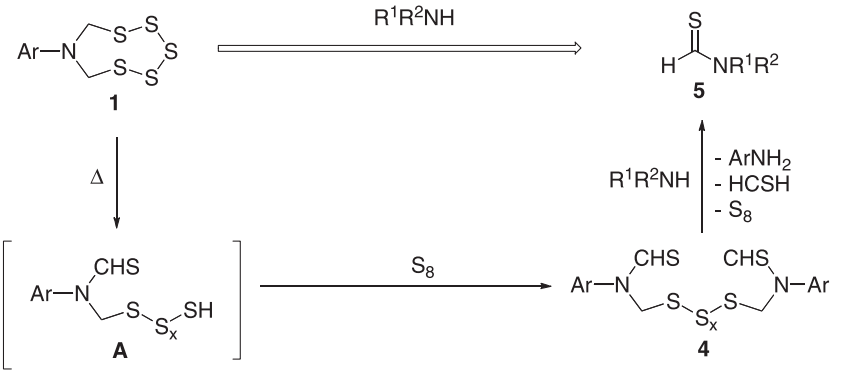
Address correspondence to Kazuaki Shimada, Department of Chemical Engineering, Faculty of Engineering, Iwate University, Morioka, Iwate, Japan. E-mail: shimada@iwate-u.ac.jp



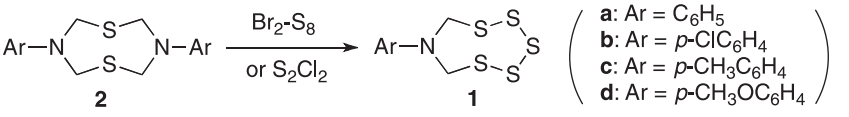
Scheme 1 Thioformylation of primary and secondary amines via thermal ring fission of *N*-aryl-1,2,3,4,5,7-pentathiazocanes **1**.

aminothioacetal moiety in the ring system, through oxidation of 1,5,3,7-dithiadiazocanes **2**.[1,2] Furthermore, we also found an unprecedented thermal ring fission of the ring system of **1** to afford acyclic polysulfide **4** bearing a thioformanilide moiety on each terminal.[1] It was naturally expected that the anilino moieties on the thioformyl group of **4** or their precursors **A** would be easily replaced by the attack of amines possessing higher nucleophilicity than anilines to give the corresponding *N*-alkyl or *N,N*-dialkylthioformamides **5** along with generation of free anilines, and such expectation prompted us to expand the synthetic utility of cyclic polysulfides **1** for novel and environmentally benign thioformylation of amines as shown in Scheme 1. In this article, we wish to describe a full account of the convenient conversion of primary and secondary amines into the corresponding *N*-alkyl- and *N,N*-dialkylthioformamides **5** using cyclic polysulfides **1** as masked thioformylating agents.

RESULTS AND DISCUSSION

Preparation of *N*-Aryl-1,2,3,4,5,7-pentathiazocanes 1 by Treating 1,5,3,7-Dithiadiazocanes 2 with Br_2-Elemental Sulfur or Disulfur Dichloride

1,5,3,7-Dithiadiazocanes **2a**–**d** were prepared from a primary arylamine, formalin, and H_2S gas according to the reported methods.[1–6] A dichloromethane solution of **2** was then treated with bromine-elemental sulfur or disulfur dichloride (S_2Cl_2) at −78°C, and in both cases, *N*-aryl-1,2,3,4,5,7-pentathiazocanes **1a**–**d** were efficiently obtained through oxidative ring contraction of 1,5,3,7-dichalcogenadiazocines as shown in Scheme 2.[7,8] Conversion of **2** into **1** was assumed to proceed through a mechanism involving in situ formation of 1,5,3,7-dithiadiazabicyclo[3.3.0]octane-type mesocyclic dications **3** [9–26] followed by ring contraction and sulfur insertion.[27–30]



Scheme 2 Preparation of *N*-aryl-1,2,3,4,5,7-pentathiazocanes **1**.

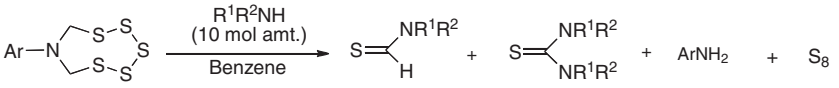
Reaction of *N*-Aryl-1,2,3,4,5,7-pentathiazocanes 1 with Primary or Secondary Amines

When a benzene solution of *N*-phenyl-1,2,3,4,5,7-pentathiazocane (**1a**) was treated with diethylamine (10 mol amt.) at room temperature for a long time, **1a** was gradually converted into *N,N*-diethylthioformamide (**5**, $R^1 = R^2 = C_2H_5$) as expected, and **5** was obtained in 19% yield besides the recovery of **1a** (58%) after 1 week of stirring of the reaction mixture. The yield of **5** ($R^1 = R^2 = C_2H_5$) was dramatically improved by carrying out the same reaction at refluxing temperature in benzene, and free aniline (**7a**) and elemental sulfur were formed along with the desired thioformamide **5** after complete consumption of **1a**. Similar treatment of **1a–d** with various primary or secondary amines also gave the corresponding *N*-alkyl- or *N,N*-dialkylthioformamides **5** in moderate to high yields. Interestingly, treatment of a benzene solution of **1** with a primary amine at higher temperature afforded the corresponding symmetrical *N,N′*-dialkylthioureas **6** in moderate yields. All the results of the reactions of **1** with a primary or secondary amine are shown in Table I.

Thermal Ring Fission of *N*-Aryl-1,2,3,4,5,7-pentathiazocanes 1 in the Absence of Amines

N-Aryl-1,2,3,4,5,7-pentathiazocanes **1** were thermally stable under heating up to the refluxing temperature in benzene (80°C) in the absence of primary or secondary amines, and addition of triethylamine (excess) to the reaction mixture was ineffective for acceleration

Table I Reaction of *N*-aryl-1,2,3,4,5,7-pentathiazocanes **1** with primary or secondary amines

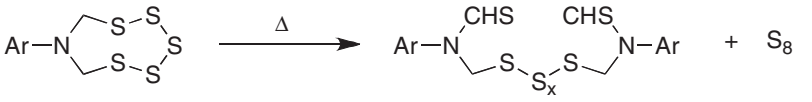


1 **5** **6** **7**

Substrate		Amine		Temp	Time	Yield /%[a,b]			
Ar	**1**	R^1	R^2	/°C	/h	**5**	**6**	**7**	Recov.
C_6H_5	**1a**	C_2H_5	C_2H_5	R.T.	168	19	0	0	58
C_6H_5	**1a**	C_2H_5	C_2H_5	Reflux	7	43	0	(71)[c]	0
C_6H_5	**1a**	C_4H_9	C_4H_9	Reflux	7	46	0	[d]	0
C_6H_5	**1a**	$-(CH_2)_5-$		Reflux	7	63	0	[d]	0
C_6H_5	**1a**	$-(CH_2)_2O(CH_2)_2-$		Reflux	5	62	0	[d]	0
C_6H_5	**1a**	C_4H_9	H	50	4	51	0	[d]	0
C_6H_5	**1a**	C_4H_9	H	Reflux	6	0	41	[d]	0
C_6H_5	**1a**	*n*-C_8H_{17}	H	Reflux	6	25	35	[d]	0
C_6H_5	**1a**	$C_6H_5CH_2$	H	Reflux	5	Trace	41	[d]	0
C_6H_5	**1a**	*c*-C_6H_{11}	H	Reflux	4	Trace	55	[d]	0
p-ClC_6H_4	**1b**	C_2H_5	C_2H_5	Reflux	6	57 (62)[e]	0	69	0
p-$CH_3C_6H_4$	**1c**	C_2H_5	C_2H_5	Reflux	6	51 (60)[e]	0	62	0

[a]Isolated yields.
[b]No products originated from thioformaldehyde was isolated at all.
[c]The yield was estimated from the integration of the ^1H NMR spectrum of the crude mixture.
[d]Aniline (**7a**) was detected in the crude reaction mixture.
[e]NMR yield is presented in parenthesis.

Table II Thermal ring fission of *N*-aryl-1,2,3,4,5,7-pentathiazocanes **1** in the absence of amines



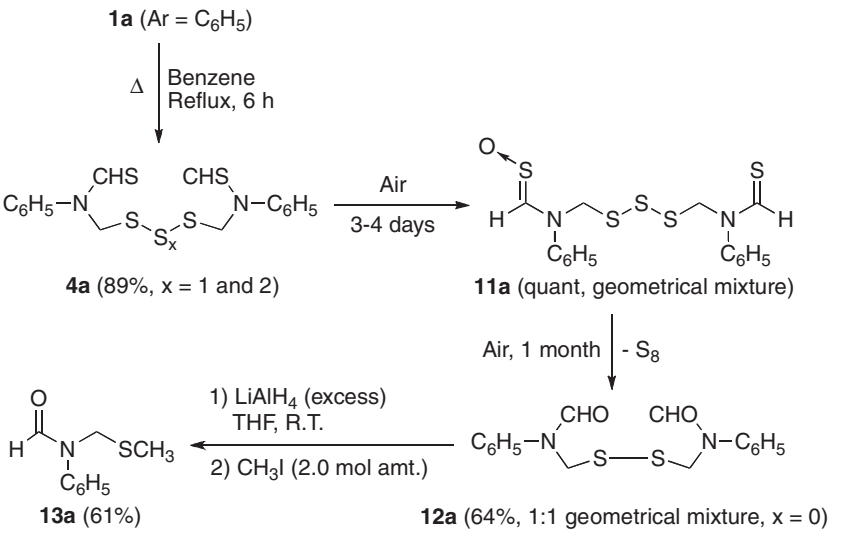
1 **4**

Substrate		Solvent	Temp	Time	Yield/%		
Ar	**1**		/°C	/h	**4**	S_8	Recovery of **1**
C_6H_5	**1a**	Benzene	Reflux	24	0	–	98
C_6H_5	**1a**	Toluene	Reflux	7	89 (**4a**)[a]	+	0
p-$CH_3OC_6H_4$	**1d**	Toluene	Reflux	7	93 (**4d**)[a]	+	0

[a]Estimation of the yields was based on the average value of x to be 1.5 for **4a** and **4d**.

of ring fission of **1**. However, heating of a toluene solution of **1** at refluxing temperature in the presence or absence of triethylamine afforded an inseparable mixture of polysulfide **4** with a thioformanilide moiety on each terminal in all cases. The mass spectra of mixtures of **4** revealed the set of parent ion peaks of the main components consistent with the numbers of sulfur atoms ($x = 1$ and 2), and the ^{1}H NMR spectra of the mixture of **4** also showed several characteristic singlet signals at the $\delta = 9.20$–9.40 region, assignable to the thioformyl protons, and the $\delta = 5.20$–5.50 region, assignable to the methylene protons, in all cases. The ^{13}C NMR spectra of **4** also exhibited several thioformyl carbon signals at the $\delta = 189$–190 region and several methylene carbon signals at the $\delta = 55$–60 region, respectively. The elemental analysis data of **4** suggested that the average values of x for **4** were approximately estimated to 1.5 in all cases. Especially, trisulfide **4a** (Ar = C_6H_5, $x = 1$) was isolated in 8% yield as an inseparable *syn*/*anti* geometrical mixture (major:minor = 2:1) after repeated chromatographic separation. All the results of thermal conversion of **1** into **4** are shown in Table II.

Compounds **4** were thermally stable enough even at the refluxing temperature of toluene. However, compounds **4** were sensitive to aerobic exposure, and the corresponding mixtures of sulfines **11** having a trisulfide chain were formed almost quantitatively when a dichloromethane solution of the mixture of **4** was stirred under an aerobic condition at room temperature for several days. Actually, elemental analysis data of **11a** (Ar = C_6H_5) was much consistent with the trisulfide structure, and the mass spectrum of **11a** revealed a parent ion peak at *m/z* 412. The ^{1}H NMR spectrum of **11a** also showed several singlet signals at the $\delta = 9.2$–9.4 region, assignable to thioformyl and the *syn*/*anti* mixture of sulfinyl protons. Furthermore, the mixture of **11a** was gradually converted into an inseparable mixture of bisformamides **12a** (Ar = C_6H_5, $x = 0$, approximately 1:1 geometrical mixture, 64% from **11a**) along with extrusion of elemental sulfur by stirring at room temperature for 1 month in dichloromethane. Reduction of the resulting mixture of **12a** using $LiAlH_4$ (excess) in THF followed by treating with CH_3I (2.0 mol amt.) afforded methylthio derivative **13a** (Ar = C_6H_5) in 61% yield based on the starting **4a**. These results supported the structures of **4** bearing a thioformanilide moiety on each terminal. All the results of the conversion sequence of **1a** into formanilide **13a** are shown in Scheme 3.



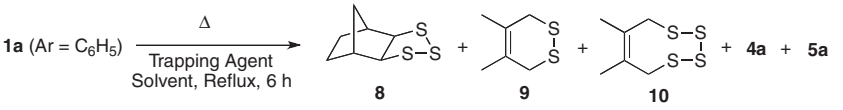
Scheme 3 Structural confirmation of bisthioformanilide **4a**.

Attempts for Detection or Trapping of Reactive Intermediates

When a benzene solution of **1a** was treated with diethylamine at refluxing temperature for 6 h in the presence of norbornene (10 mol amt.), 1,2,3-trithiolane **8** was obtained in 63% yield besides *N,N*-diethylthioformamide **5a** ($R^1 = R^2 = C_2H_5$). Similar trapping experiment of reactive sulfur species was carried out by using 2,3-dimethyl-1,3-butadiene, by which a mixture containing **5a** (43%), 1,2-dithiin **9** (25%), and 1,2,3,4-tetrathiocine **10** (25%) was also obtained. Heating of a toluene solution of **1a** and norbornene (5.0 mol amt.) under refluxing in the absence of amines afforded **8** (28%) along with **4a** (48%), and a mixture of **9**(14%), **10** (20%), and **4a** (32%) was formed in a similar case using 2,3-dimethyl-1,3-butadiene as a trapping agent. All these results suggested in situ generation of some reactive sulfur species, such as triatomic sulfur (S_3), diatomic sulfur (S_2), and so on, through thermally or amine-induced ring fission of *N*-aryl-1,2,3,4,5-pentathiazocanes **1**.[31–41] However, the yield of **8** obtained through thermal reaction of **1a** and norbornene in the absence of an amine was relatively lower than the case of the similar trapping experiment in the presence of diethylamine. Greer and Brzostowska already reported a novel generation of triatomic sulfur (S_3) through a similar ring fission of varacin by nucleophilic attack of the internal primary amino group toward a sulfur atom of the 1,2,3,4,5-pentathiepin ring,[35,36] and these results suggested that ring fission of **1** was initiated by added amines. All the results of trapping of reactive sulfur species are shown in Table III.

When a C_6D_6 solution of **1a** ($Ar = C_6H_5$) was heated in a sealed NMR tube below 80°C and the reaction was monitored by using ^{1}H NMR, no mean change was observed in the spectrum except for slight broadening of the doublet signals assignable to the methylene protons of **1a**. On the other hand, the spectral pattern became complicated along with decreasing the signals of **1a** when the heating temperature was raised up to 100°C. Especially, several new signals assignable to *N*-phenyl-*N*-sulfanylmethylthioformamide (**14a**, $Ar = C_6H_5$), $\delta = 3.28$ (1H, t, $J = 8.9$ Hz) for N−CH_2−S<u>H</u>, $\delta = 4.71$ (2H, d, $J = 8.9$ Hz) for N−C<u>H$_2$</u>−SH, and $\delta = 9.10$ (1H, s) for N−C<u>H</u>S), and 1,2,4-dithioazolidines **15a** ($Ar = C_6H_5$), $\delta = 4.21$ (4H, s) for N−C<u>H$_2$</u>−S, were observed among the uncharacterizable

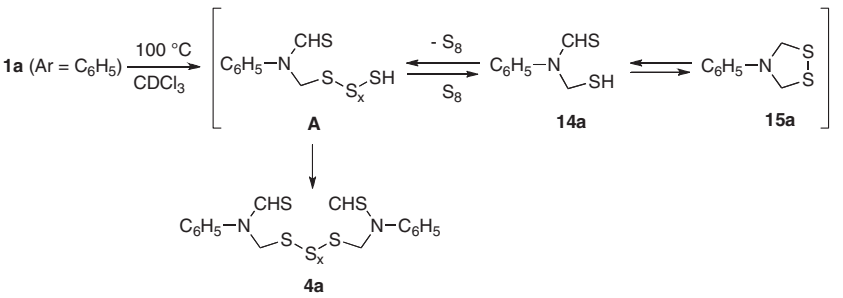
Table III Trapping of reactive sulfur species generated through ring fission of **1a**



Trapping agent[a] (mol amt.)	Diethylamine (10 mol amt.)	Solvent	Yield/% 8[b]	9[c]	10[c]	4a[b]	5a[b]
A (10)	+	Benzene	63	—	—	0	47
B (10)	+	Benzene	—	25	43	0	43
A (5.0)	−	Toluene	28	—	—	48	—
B (5.0)	−	Toluene	—	14	20	32	—
C (5.0)	−	Toluene		Complex mixtutre			—

[a]Trapping agents: A: norbornene, B: 2,3,-dimethyl-1,3-butadiene, C: phenylacetylene.
[b]Isolated yield.
[c]Yields were estimated by the integration of the ^{1}H NMR signals of the mixture of **9** and **10**.

signals for several hours. After a long time heating **1a**, complex signals involving the signals of a mixture of **4a** became mainly observed along with the disappearance of those of **1a**, **14a**, and **15a** in the spectrum. It was assumed that **1** underwent thermal ring fission to generate an equilibration mixture of **A**, **14**, **15**, and elemental sulfur, and **A** may finally afford a mixture of **4** having various polysulfide chains after dimerization as shown in Scheme 4. In contrast, a similar ^{1}H NMR monitoring of the reaction of **1a** (Ar = C_6H_5)



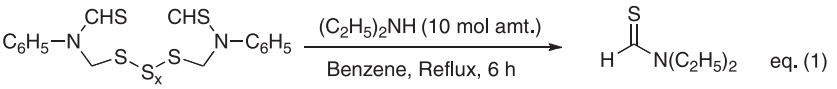
Scheme 4 Plausible generation of *N*-sulfanylmethylthioformanilide **14a** and 1,2,4-dithiazolidine **15a** through thermal ring fission of *N*-phenyl-1,2,3,4,5,7-pentathiazocane **1a**.

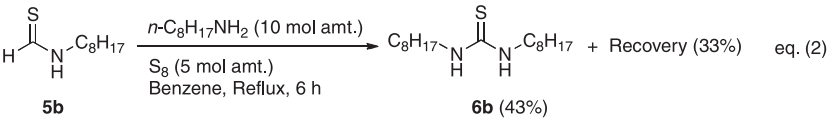
and diethylamine in an NMR tube at room temperature only afforded complicated spectrum. All attempts for isolation of plausible precursors of **4**, i.e., **14a** or **15a**, in the crude reaction mixture obtained by heating **1a** in the absence of an amine were also unsuccessful. Thermal reactions of **1a** in the presence of CH_3I (excess) for trapping of **A** or **14** only gave **4a**, and the trapping experiment using phenylacetylene was also unsuccessful.

Plausible Formation Pathway of Thioformamides 5 and Thioureas 6 Through the Reaction of *N*-Aryl-1,2,3,4,5,7-Pentathiazocanes 1 with Amines

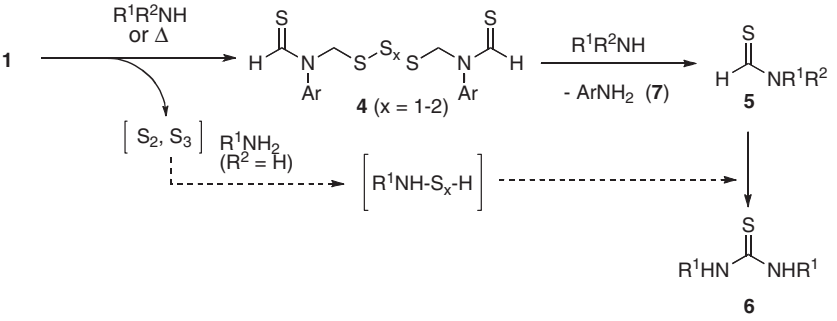
Our experimental results indicated that *N*-aryl-1,2,3,4,5,7-pentathiazocanes **1** were converted into thioformamides **5** even at room temperature in the case of the reactions

carried out in the presence of amines. Furthermore, *N,N*-diethylthioformamide (**5**) ($R^1 = R^2 = C_2H_5$) was obtained in 47% yield when a benzene solution of a mixture of bisthioformanilide **4a** ($R = C_6H_5$, $x = 1–2$) was subjected to heating in the presence of diethylamine (10 mol amt.) as shown in Equation (1). These results suggested that the nucleophilic attack of amines may occur at the S-2 and/or S-3 positions to result in ring contraction of **1** to form an equilibrated mixture of 1,2,4-dithiazolidine intermediates **15**, *N*-sulfanylmethylthioformanilides **14**, polysulfane intermediates **A**, and reactive sulfur species as triatomic sufur (S_3) and diatomic sulfur (S_2). Formation of thioformamides **5** was explained by nucleophilic addition-elimination of thioformanilide moieties of in situ formed **4**, **A**, or **14** along with elimination of anilines.





Furthermore, *N*-butylthioformamide (**5**, $R^1 = C_4H_9$) was obtained in 51% yield when the reaction of **1a** and butylamine was carried out at lower temperture, and *N,N′*-dibutylthiourea (**6**, 41%) became a main product by heating the reaction mixture in benzene. Independent treatment of a benzene solution of *N*-octylthioformamide (**5**, $R^1 = n\text{-}C_8H_{17}$, $R^2 = H$) with *n*-octylamine (10 mol amt.) in the presence of elemental sulfur (5 mol amt.) under heating also afforded *N,N′*-dioctylthiourea (**6**, $R^1 = n\text{-}C_8H_{17}$, $R^2 = H$) in 43% yield along with the recovery of **5** (33%) as shown in Equation (2). This result strongly suggested the formation of thioureas **6** through a Willgerodt–Kindler type oxidation of **5** induced by some reactive sulfur species generated from an amine and elemental sulfur.[42–46] The plausible formation pathway of thioformanides **5** and thioureas **6** through the reaction of **1** was finally summarized as shown in Scheme 5.



Scheme 5 Plausible formation pathway of thioformamides **5** and thioureas **6** by treating *N*-aryl-1,2,3,4,5,7-pentathiazocanes **1** with a primary or a secondary amine.

CONCLUSION

We found a conversion of primary and secondary amines into thioformamides by treating with *N*-aryl-1,2,3,4,5,7-pentathiazocanes **1**. The unique thioformylation reaction was assumed to proceed through a plausible pathway involving ring fission of **1** and the subsequent nucleophilic attack of amines toward the thiocarbonyl carbons of resulting **4** or the intermediary **14** or **A**. Further attempts for the synthetic use of **1** as sulfurating agents are underway in our laboratory.

EXPERIMENTAL

Instruments

The melting points were determined with a Büchi 535 micro-melting-point apparatus. ^{1}H NMR spectra were recorded on a Bruker AC-400P (400 MHz) spectrometer, and the chemical shifts of the ^{1}H NMR spectra are given in δ relative to internal tetramethylsilane (TMS). ^{13}C NMR spectra were recorded on a Bruker AC-400P (100 MHz). Mass spectra were recorded on a Hitachi M-2000 mass spectrometer with electron-impact ionization at 20 or 70 eV using a direct inlet system. IR spectra were recorded for thin-film (neat) or KBr disks on a Jasco FT/IR-7300 spectrometer. Elemental analyses were performed using a Yanagimoto CHN corder MT-5.

Materials

Column chromatography was performed using silica gel (Merck, Cat. No. 7734 or 9385) without pretreatment. Dichloromethane (CH_2Cl_2) and chloroform ($CHCl_3$) were dried over P_4O_{10}, and were freshly distilled before use. Benzene, hexane, triethylamine, and *N,N*-dimethylformamide (DMF) were dried over calcium hydride (CaH_2) and freshly distilled before use. Diethyl ether and tetrahydrofuran (THF) were dried over lithium tetrahydridoaluminate ($LiAlH_4$) and were freshly distilled before use. Ethanol and methanol were dried over anhydrous magnesium sulfate ($MgSO_4$) and were freshly distilled before use. All of the substrates and reagents, including aniline, *p*-chloroaniline, *p*-methoxyaniline, *p*-methylaniline, diethylamine, dibutylamine, piperidine, morpholine, benzylamine, *n*-octylamine, cyclohexylamine, elemental sulfur, disulfur dichloride (S_2Cl_2), lithium tetrahydridoaluminate ($LiAlH_4$), iodomethane, sodium hydroxide, concentrated hydrochloric acid, phenylacetylene, norbornene, 2,3-dimethyl-1,3-butadiene, deuteriochloroform ($CDCl_3$), and benzene-d_6 (C_6D_6) were commercially available reagent grade and were used without any pretreatment.

General Procedure for the Reaction of *N*-Aryl-1,2,3,4,5,7-pentathiazocane 1 with a Primary or a Secondary Amine

A 20 mL benzene solution of *N*-aryl-1,2,3,4,5,7-pentathiazocane **1** (1.10 mmol) was treated with a primary or a secondary amine (10.0 mol amt.) at an ambient temperature. The reaction mixture was cooled to room temperature, quenched with an excess amount of water, and extracted with benzene. The organic layer was then washed with water and dried over anhydrous Na_2SO_4 powder. After removing the solvent in vacuo, the residual yellow oil was subjected to ^{1}H NMR measurement in order to estimate the yields of thioformamides **5**, thioureas **13**, aniline derivatives **14**, and recovery of **1** through the integration of the spectra

of the mixture. Then the crude mixture was subjected to chromatographic purification using silica gel to obtain thioformamides **5** and thioureas **6** as yellow oils.

General Procedure for the Trapping of Reactive Intermediates Generated In Situ Through Heating of *N*-Phenyl-1,2,3,4,5,7-pentathioazocane (1a) in the Presence of Diethylamine and a Trapping Agent (Norbornene or 2,3-Dimethyl-1,3-butadiene)

A 20 mL benzene solution of *N*-phenyl-1,2,3,4,5,7-pentathioazocane (**1a**, 279 mg, 1.00 mmol) was treated diethylamine (10 mmol) and a trapping agent [norbornene (940 mg, 10.0 mmol)] or 2,3-dimethyl-1,3-butadiene (824 mg, 10.0 mmol) at refluxing temperature for 6 h. The reaction mixture was cooled to room temperature and extracted with benzene. The organic layer was washed with water and dried over anhydrous Na_2SO_4 powder. After removing the solvent in vacuo, the residual yellow oil was subjected to chromatographic separation to isolate the corresponding trapping products as 1,2,3-trithiolane **8**, 1,2-dithiin **9** and 1,2,3,4-tetrathiocine **10**, as well as *N,N*-diethylthioformamide (**5**) ($R^1 = R^2 = C_2H_5$). Actually when norbornene was used as a trapping agent, **8** (121 mg, 63%) was obtained in addition to *N,N*-diethylthioformamide (**5a**, 108 mg, 47%), and an approximate 1:1 mixture of **9** and **10** (89 mg, 25% and 25% yields, respectively, estimated by using the integration of the ^{1}H NMR signals of the mixture) was also obtained in addition to **5a** (99 mg, 43%) and a complex mixture when 2,3-dimethyl-1,3-butadiene was used as a trapping agent.

General Procedure for Thermal Ring Fission of *N*-Aryl-1,2,3,4,5,7-Pentathiazocane 1

A 100 mL toluene solution of *N*-aryl-1,2,3,4,5,7-pentathiazocane (**1**, 1.00 mmol) was heated at refluxing temperature for several hours under an Ar atmosphere, and the solvent was removed in vacuo. The residual yellow solid was subjected to chromatographic purification using silica gel to obtain an inseparable mixture of bisthioformanilides **4** ($x =$ 1.5, approximately) as yellow oil. Actually, when **1a** ($Ar = C_6H_5$, 273 mg, 1.00 mmol) was subjected to heating, a mixture of **4a** (179 mg, 89% yield) was obtained, and after repeated chromatographic separation, pure **4a** ($x = 1$, 54 mg, 27% yield) was obtained as yellow oil.

4a [Ar = C_6H_5, approximately 1:1 mixture of 4a ($x = 1$) and 4a (x = 2)]. Yellow oil; MS (*m/z*) 428 (M^+(x = 2); 0.2%), 396 (M^+(x = 1); 0.3%), 364 (M^+(x = 2)-S_2 or M^+(x = 1)-S; 16%,), 182 ($C_6H_5N(CHS)CH_2S$; 98%), 150 ($C_6H_5N(CHS)CH_2$; bp); IR (neat) 2925, 1682, 1593, 1492, 1445, 1347, 1234, 1190, 1059, 939, 759, 694 cm^{-1}; ^{1}H NMR ($CDCl_3$) $\delta = 9.24$ (s), 9.26 (s), 9.27 (s), 9.28 (s), 9.30 (s), 9.38 (s); ^{13}C NMR ($CDCl_3$) $\delta = 189.7$ (s), 189.8 (s). Calcd for $C_{16}H_{16}N_2S_{5.5}$: C, 46.57; H, 3.91; N, 6.79%. Found: C, 46.11; H, 3.84; N, 6.66%.

4a [Ar = C_6H_5, approximately 2:1 mixture of 4a ($x = 1$) after chromatographic purification]. Yellow oil; MS (*m/z*) 396 (M^+; 0.1%), 364 (M^+-S; 0.3%), 182 ((M^+-S)/2; 21%), 135 (C_6H_5NCS; bp); IR (neat) 2924, 1682, 1593, 1493, 1444, 1347, 1234, 1186, 1058, 939, 760, 695 cm^{-1}; ^{1}H NMR ($CDCl_3$) major isomer $\delta = 5.42$ (s), 7.30–7.50 (10H, m), 9.56 (1H, s), minor isomer $\delta = 5.58$ (s), 7.30–7.50 (10H, m), 9.57 (1H, s); ^{13}C NMR ($CDCl_3$) major isomer $\delta = 59.3$ (br.t), 123.3 (d), 128.3 (d), 129.9 (d), 144.2 (s), 189.85 (s), minor isomer $\delta = 58.9$ (br.t), 123.5 (d), 128.1 (d), 130.0 (d), 144.0 (s), 189.92 (s). Calcd for $C_{16}H_{16}N_2S_5$: 48.45; H, 4.07; N, 7.06%. Found: C, 48.34; H, 4.02; N, 6.87%.

4d [R = *p*-$CH_3OC_6H_4$, approximately 1:1 mixture of 4c (*x* = 1) and 4c (x = 2)]. Yellow oil; MS (*m/z*) 488 (M^+(x = 2); 0.1%), 456 (M^+(x = 1); 0.1%), 346 (4%), 212 (ArN(CHS)CH_2S; 40%), 166 (ArN(CHS); bp); IR (neat) 2933, 1608, 1510, 1454, 1343, 1300, 1252, 1182, 1059, 1030, 940, 831, 734 cm^{-1}; ^1H NMR ($CDCl_3$) major components δ = 3.82 (6H, s), 4.98 (s), 5.14 (s), 5.36 (s), 5.51 (s), 5.52 (s), 5.60 (s), 5.62 (s), 6.80–7.00 (m), 7.05–7.30 (m), 9.30–9.40 (2H, m); ^{13}C NMR ($CDCl_3$) major components δ = 25.5 (q), 32.8 (q), 55.7 (dd), 59.5 (dd), 114.8 (d), 125.1 (d), 126.7 (d), 137.1 (s), 137.2 (s), 159.2 (s), 189.3 (s), 190.1 (s). Calcd for $C_{18}H_{20}N_2O_2S_{5.5}$: C, 45.73; H, 4.26; N, 5.93%. Found: C, 45.67; H, 4.26; N, 5.98%.

General Procedure for Aerobic Oxidation of Bisthioformanilide 4

A 20 mL dichloromethane solution of bisthioformanilide **4a** (Ar = C_6H_5, 100 mg, 2.52 mmol) was kept standing at room temperature under an aerobic condition for a few days. After removing the solvent in vacuo, the residual crude mixture was subjected to chromatographic separation on silica gel to give an inseparable geometrical mixture of sulfines **11a** (Ar = C_6H_5, 104 mg) along with extrusion of a small amount of elemental sulfur. A dichloromethane solution of the resulting mixture of **11a** (72 mg, 1.75 mmol) was then subjected to additional standing at room temperature under aerobic condition for 24 days. After removing the solvent in vacuo, the residual crude mixture was subjected to chromatographic separation on silica gel to give an inseparable geometrical mixture of bisformanilides **12a** (Ar = C_6H_5, 37 mg, 64% yield).

11a (Ar = C_6H_5, *x* = 1). Pale yellow oil; MS (*m/z*) 412 (M^+; 0.2%), 364 (M^+-SO; 16%), 300 (M^+-SO-S_2; 7%), 214 (M^+-$C_8H_8NOS_2$; 18%), 182 (M^+-$C_8H_8NOS_3$; 98%), 150 ($C_6H_5N(CHS)CH_2$; bp); IR (neat) 2925, 1682, 1593, 1492, 1445, 1347, 1234, 1190, 1059, 939, 759, 694 cm^{-1}; ^1H NMR ($CDCl_3$) δ = 5.20 (s), 5.27 (s), 5.31 (s), 5.35 (s), 5.36 (s), 5.37 (s), 5.44 (s), 7.20–7.50 (m), 9.24 (s), 9.26 (s), 9.27 (s), 9.28 (s), 9.30 (s), 9.38 (s); ^{13}C NMR ($CDCl_3$) δ = 58.7 (dd), 59.5 (dd), 123.1 (d), 124.3 (d), 128.0 (d), 129.0 (d), 129.8 (d), 130.0 (d), 143.8 (s), 144.0 (s), 189.7 (s), 189.8 (s). Calcd for $C_{16}H_{16}N_2OS_5$: C, 46.57; H, 3.91; N, 6.79%. Found: C, 46.11; H, 3.84; N, 6.66%.

12a (Ar = C_6H_5, *x* = 1, approximately 1:1 syn/anti mixture). Pale yellow oil; MS (*m/z*) 332 (M^+; 20%), 268 (M^+-S_2; 5%), 198 (M^+- $C_8H_8NS_2$; 2%), 135 (bp); IR (neat) 3067, 1682 (sh), 1599, 1494, 1441, 1347, 1239, 1180, 1033, 1010, 920, 760 cm^{-1}; ^1H NMR ($CDCl_3$) δ = 4.99 (s), 5.20 (s), 5.25 (s), 5.31 (s), 7.10–7.60 (10H, m), 8.42 (s), 8.45 (s); ^{13}C NMR ($CDCl_3$) δ = 53.0 (t), 119.3 (d), 124.8 (t), 129.7 (d), 136.9 (d), 162.2 (d). Calcd for $C_{16}H_{16}N_2O_2S_2$: C, 57.81; H, 4.85; N, 8.43%. Found: C, 57.45; H, 4.69; N, 8.32%.

Conversion of a Mixture of Bisthioformanilides 12a (Ar = C_6H_5) into Formanilide 13a

A 100 mL diethyl ether solution of a mixture of bisformanilides **12a** (Ar = C_6H_5, 180 mg, 0.54 mmol) was treated with $LiAlH_4$ (excess) at 0°C for several minutes, and reaction mixture was then treated with ethanol (10 mL, excess) and iodomethane (153 mg, 1.08 mmol). The reaction was quenched with an excess amount of water and extracted with dichloromethane. The organic layer was washed with water and was dried over anhydrous Na_2SO_4 powder. After removing the solvent in vacuo, the residual yellow solid

was subjected to chromatographic purification using silica gel to obtain formanilide **13a** (Ar = C_6H_5, 110 mg, 61%) as a pale yellow oil.

13a (Ar = C_6H_5). Yellow oil; MS (*m/z*) 182 (M^+; 5%), 151 (3%), 124 (4%), 107 (bp); IR (neat) 3067, 1682, 1599, 1491, 1441, 1347, 1239, 1180, 1033, 1010, 920, 760 cm^{-1}; ^1H NMR ($CDCl_3$) δ = 1.26 (3H, s), 5.00 (2H, s), 7.20–7.50 (5H, m), 8.46 (1H, s); ^{13}C NMR ($CDCl_3$) δ = 29.7 (q), 53.0 (t), 124.8 (d), 127.6 (d), 139.7 (s), 162.3 (d). Calcd for $C_9H_{11}NOS$: C, 59.64; H, 6.12; N, 7.73%. Found: C, 60.12; H, 6.38; N, 7.75%.

Trapping of Reactive Sulfur Species Generated In Situ Through Heating of *N*-Phenyl-1,2,3,4,5,7-pentathioazocane (1a) Using Norbornene, 2,3-Dimethyl-1.3-butadiene, or Phenylacetylene

A 20 mL toluene solution of *N*-phenyl-1,2,3,4,5,7-pentathioazocane (**1a**) (279 mg, 1.00 mmol) was treated with a trapping agent [norbornene (470 mg, 5.00 mmol), 2,3-dimethyl-1,3-butadiene (412 mg, 5.00 mmol), or phenylacetylene (515 mg, 5.00 mmol)] at refluxing temperature for 6 h. The reaction mixture was cooled to room temperature and extracted with benzene. The organic layer was washed with water and dried over anhydrous Na_2SO_4 powder. After removing the solvent in vacuo, the residual yellow oil was subjected to chromatographic separation to isolate the trapping products as **8**, **9**, and **10**. Actually when norbornene was used as a trapping agent, **8** (53 mg, 28%) and **4a** (101 mg, 48%) were obtained, and when 2,3-dimethyl-1,3-butadiene was used, an approximately 1:1 mixture of **9** and **10** (64 mg, 14% and 20% yield, respectively, estimated by using the integration of the ^1H NMR signals of the mixture) was obtained, in addition to **4a** (183 mg, 32%). On the other hand, only a complex mixture was obtained when phenylacetylene was used as a trapping agent.

^1H NMR Monitoring of Thermal Reaction of *N*-Phenyl-1,2,3,4,5,7-pentathiazocane (1a)

Thermal reaction of a C_6D_6 solution of *N*-phenyl-1,2,3,4,5,7-pentathiazocane (**1a**) (28 mg, 0.100 mmol) in a sealed NMR tube was monitored by ^1H NMR at an ambient temperature for 2 h. As soon as the C_6D_6 solution of **1a** was heated to 100°C, the signals assignable to *N*-phenyl-*N*-sulfanylmethylthioformamide (**14a**) [δ = 3.28 (1H, t, J = 8.9 Hz) for N−CH_2−S<u>H</u>, δ = 4.71 (2H, d, J = 8.9 Hz) for N−C<u>H_2</u>−SH, and δ = 9.10 (1H, s) for N−C<u>H</u>S)] and *N*-phenyl-1,2,4-dithiazolidine (**15a**) [δ = 4.21 (4H, s) for N−C<u>H_2</u>−S)] were observed among a complex signal of uncharacterized species along with decreasing the signals of **1a** and increasing the signals of **4a**.

Reaction of Bisthioformanilide 4a (Ar = C_6H_5) with Diethylamine

A 20 mL benzene solution of bisthioformanilide **4a** (Ar = C_6H_5, 178 mg, 0.45 mmol) was treated with diethylamine (329 mg, 4.50 mmol) at refluxing temperature for 6 h. The reaction mixture was cooled to room temperature, quenched with an excess amount of water, and extracted with benzene. The organic layer was then washed with water and dried over anhydrous Na_2SO_4 powder. After removing the solvent in vacuo, the residual yellow oil was subjected to chromatographic purification using silica gel to obtain *N,N*-diethylthioformamides (**5a**) ($R^1 = R^2 = C_2H_5$, 99 mg, 47% yield) as a yellow oil.

Reaction of *N*-Octylthioformamide (5) with Octylamine in the Presence of Elemental Sulfur

A 20 mL benzene solution of *N*-octylthioformamide (**5**) ($R^1 = n\text{-}C_8H_{17}$, $R^2 = H$, 36 mg, 0.21 mmol) was treated with *n*-octylamine (258 mg, 2.10 mol amt.) and elemental sulfur (34 mg, 1.05 mmol) at refluxing temperature for 6 h. The reaction mixture was cooled to room temperature, quenched with an excess amount of water, and extracted with benzene. The organic layer was washed with water and dried over anhydrous Na_2SO_4 powder. After removing the solvent in vacuo, the residual yellow oil was subjected to chromatographic purification using silica gel to obtain *N,N′*—dioctylthiourea (**6**) ($R^1 = n\text{-}C_8H_{17}$, $R^2 = H$, 27 mg, 43% yield) as colorless solids in addition to the recovery of the starting thioformamide **5** (11 mg, 33%).

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