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Mechanistic studies of intramolecular CH insertion reaction of arylnitrenes: isotope effect, configurational purity and radical clock studies

Shigeru Murata,[1]* Yasuhiro Tsubone,[2] Reina Kawai,[2] Daisuke Eguchi[2] and Hideo Tomioka[2]

[1]Department of Basic Science, Graduate School of Arts and Sciences, The University of Tokyo, Meguro-ku, Tokyo 153-8902, Japan
[2]Chemistry Department for Materials, Faculty of Engineering, Mie University, Tsu, Mie 514-8507, Japan

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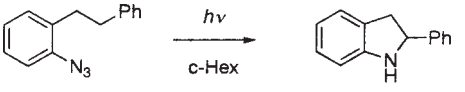
ABSTRACT: In order to reveal the mechanism of the intramolecular CH insertion of arylnitrenes, three experiments were carried out: measurement of isotope effects, determination of the extent of configurational retention and radical clock studies. Irradiation of the deuterium-substituted azide **4-*d*** in an inert solvent exclusively afforded the indolines **5-*h*** and **5-*d***, in which the kinetic isotope effect k_H/k_D on the intramolecular CH insertion of the nitrene was evaluated as 12.6–14.7 at room temperature. A chiral chromatographic analysis of the indoline **11** obtained from the optically active azide (*S*)-**6** revealed that the enantiomeric purity of the starting azide was almost completely lost during the intramolecular CH insertion of the photolytically generated nitrene (enantiomeric excess $<10\%$). The thermolysis of the azide **7** at 180 °C mainly gave a mixture of the cyclopropyl ring-opened products **20–22**, together with the intramolecular CH insertion product with an intact cyclopropyl ring **19**. On the basis of these observations, we concluded that the intramolecular CH insertion of the nitrene proceeds primarily by the hydrogen abstraction–recombination mechanism. We propose, however, a small contribution of the concerted mechanism to the intramolecular CH insertion, based on the solvent dependence of the isotope effect and the extent of the configurational retention. Copyright © 2004 John Wiley & Sons, Ltd.

KEYWORDS: nitrenes; hydrogen abstraction; deuterium isotope effect; optical purity; radical clock

INTRODUCTION

Arylnitrenes are known to be short-lived intermediates produced in photochemical and thermal decomposition of aryl azides (for reviews on nitrene chemistry see, e.g., Ref. 1). The scheme of the photochemical decomposition of phenyl azide (**1**) has been established, in which singlet phenylnitrene (**2S**) is identified as the temperature-dependent branching point (Scheme 1).[2] Recently, two groups have independently reported the direct observation of **2S** in fluid solutions.[3] The activation energy for the ring expansion of **2S** to didehydroazepine (**3**) has been estimated to be 6.2 kcal mol^{-1} (1 kcal = 4.184 kJ) and the absolute rate constant for intersystem crossing to triplet nitrene (**2T**) has been directly determined to be 3.2×10^6 s^{-1}.[4] Moreover, Gritsan *et al.* established that on the basis of the agreement between the experimental and theoretical absorption spectra, **2S** has an open-shell electronic structure with two singly occupied non-bonding orbitals.[4]

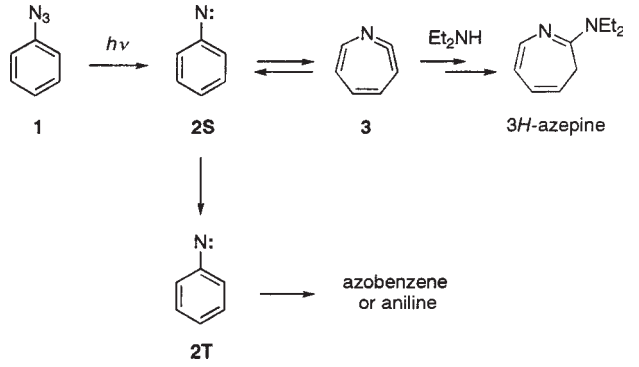
The reactivity of arylnitrenes has been of great interest because of their practical applications, including photoresist systems and biochemical photoaffinity labeling.[1] The insertion of a photolytically generated nitrene into a CH bond is believed to be an important bond-forming reaction in many systems with practical applications, while very few mechanistic studies of the CH insertion of arylnitrenes have been reported. Although it is well known that the CH insertion of arylnitrenes generated photolytically in solutions is an unfavorable process,[1] we recently found that arylnitrenes can insert favorably into a reactive CH bond, such as benzylic, which is located close to the nitrenic center.[5] Thus, the photolysis of 2-(2-phenylethyl)phenyl azide (**4**) in cyclohexane exclusively afforded 2-phenylindoline (**5**), which was produced by intramolecular insertion of the nitrene into a β-CH bond of the 2-phenylethyl group.



4 **5**

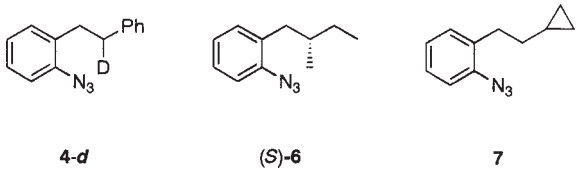
In order to shed light on the mechanism of the intramolecular CH insertion of arylnitrenes, we have

Correspondence to: S. Murata, Department of Basic Science, Graduate School of Arts and Sciences, The University of Tokyo, Meguro-ku, Tokyo 153-8902, Japan.
E-mail: cmura@mail.ecc.u-tokyo.ac.jp



Scheme 1

designed three approaches. The first is the measurement of the kinetic isotope effect on the intramolecular CH insertion using the deuterium-substituted azide **4-*d*** (for a preliminary report, see Ref. 6). If the CH insertion of the nitrene generated from **4-*d*** proceeds by the concerted mechanism, small deuterium isotope effects are expected. On the other hand, large values of k_H/k_D, which indicate a high degree of CH bond cleavage in the transition state, support the hydrogen abstraction–recombination mechanism. The second study is the determination of the extent of configurational retention using optically active (*S*)-2-(2-methylbutyl)phenyl azide [(*S*)-**6**].[7] A large extent of configurational retention during the insertion of the nitrene into a CH bond at an asymmetric carbon atom is expected in the concerted mechanism, while a loss of optical purity of the intramolecular CH insertion product gives a strong piece of evidence in support of the hydrogen abstraction–recombination mechanism. Finally, we have designed 2-(2-cyclopropylethyl)phenyl azide (**7**), where the nitrene can be expected to react with a β-CH bond of the 2-cyclopropylethyl group, to apply the 'cyclopropylcarbinyl clock' approach (for recent mechanistic studies with the cyclopropylcarbinyl clock see, for example, Ref. 8). If the CH insertion proceeds by the concerted mechanism, the cyclopropane ring is intact. On the other hand, if the attack of the nitrene on the β-CH bond proceeds by the hydrogen abstraction mechanism, the formation of cyclopropyl ring-opened products is expected because of the generation of the cyclopropylcarbinyl radical.



4-*d* **(*S*)-6** **7**

In this paper, based on the results obtained from these three approaches, we propose that the intramolecular CH insertion of arylnitrenes generated by photolysis, in addition to thermolysis, of the azides proceeds predominantly by the hydrogen abstraction–recombination mechanism, while the concerted mechanism could contribute slightly but significantly to the reaction. Further, taking into account the electronic structure of singlet phenylnitrene (**2S**) established recently,[4,9] the spin state of the nitrene involved in the CH insertion is discussed.

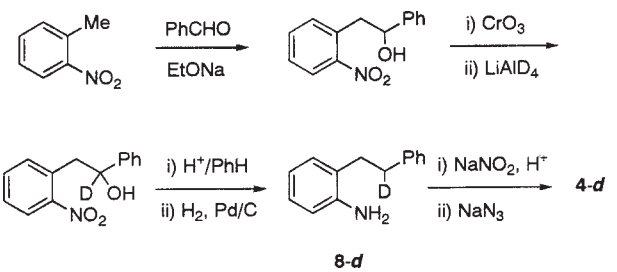
RESULTS

Measurement of deuterium isotope effects using the azide 4-*d*

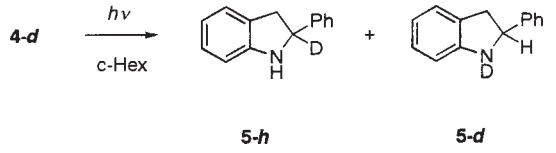
The synthetic route used to prepare the deuterium-substituted azide **4-*d*** is summarized in Scheme 2. Deuterium was introduced in the course of the reduction of 2-nitrobenzyl phenyl ketone with $LiAlD_4$ (Aldrich, 98%). It was confirmed by the integration of ^{1}H NMR that the deuterium isotope purity of the starting reagent was held in 2-(2-deuterio-2-phenylethyl)aniline (**8-*d***), which was converted to the azide **4-*d*** in a usual manner.[5]

Irradiation of **4-*d*** in cyclohexane with a high-pressure mercury lamp through a Pyrex filter at 20 °C gave a mixture of the indolines **5-*h*** and **5-*d***. The total yield of **5** was 52% based on the consumed starting azide. In the ^{1}H NMR spectrum of the photoreaction mixture, a signal assigned to one of the methylene protons of **5-*h*** and **5-*d*** appeared at δ 3.44 and a methine signal of **5-*d*** appeared at δ 4.95. Thus, the ratio of **5-*h*** to **5-*d*** was readily obtained by the integration of ^{1}H NMR in the reaction mixture, which was evaluated to be 14.7 ± 0.3. The product ratio remained constant during the photoreaction, although continued irradiation caused a decrease in the total yield of **5**, which was due to the photochemical decomposition of **5**. No other products such as the corresponding aniline **8-*d*** or azobenzene could be detected in the photoreaction mixture.

It seems reasonable to assume that the kinetic isotope effect k_H/k_D on the intramolecular insertion of the nitrene generated photolytically from **4-*d*** into a β-CH bond of the 2-phenylethyl group is equal to the product ratio [**5-*h***]/[**5-*d***]. Thus, we obtained an unusually large deuterium isotope effect at room temperature. The values of the isotope effects, and also the total yields of **5**, gained in the irradiation of **4-*d*** under various conditions are summarized in Table 1. As shown, the isotope effect obtained



Scheme 2



in the photolysis with the longer-wavelength light (>350 nm) was identical to that obtained with the Pyrex-filtered light (>300 nm) within the experimental error. Further, it was found that the isotope effects were dependent on the solvent employed in the photolysis: slightly smaller values were obtained both in benzene and in acetonitrile, compared with the value in cyclohexane. In methanol, we could not obtain an accurate value of the product ratio [**5**-***h***]/[**5**-***d***] owing to the minor formation of **5**. Instead, irradiation of **4**-***d*** in methanol gave predominantly 2-(2-methoxy-2-phenylethyl)anilines, **9**-***h*** and **9**-***d*** (69% in total), the formation of which has previously reported in the photolysis of **4**-***h*** and rationalized in terms of methanol trapping of the polarized biradical formed by the intramolecular hydrogen abstraction of the nitrene.[5] In an analogous manner, we obtained the ratio of **9**-***h*** to **9**-***d*** by integration of the ^{1}H NMR spectrum, from which the deuterium isotope effect for the formation of **9** was evaluated as 10.2 ± 0.2, which is included in Table 1.

Extremely large deuterium isotope effects, $k_H/k_D = 12.6$–14.7, observed for the formation of **5** suggest that a quantum-mechanical tunneling mechanism contributes to the reaction process.[10] It is known that a nonlinear plot of $\ln(k_H/k_D)$ versus T^{-1} is a general feature in hydrogen transfer reactions which proceed by a quantum-mechanical tunneling mechanism.[10–12] Thus, the temperature dependence of k_H/k_D for the formation of **5** was closely examined in cyclohexane (20–55 °C) and in acetonitrile (−14–59 °C). Although we found that the deuterium isotope effect k_H/k_D depended considerably on the irradiation temperature, the isotope effect increasing with decreasing irradiation temperature, Arrhenius plots of the observed isotope effect, $\ln(k_H/k_D)$ versus T^{-1}, gave a straight line within the experimental errors in the limited temperature ranges employed in our experiments, as illustrated in Fig. 1. To validate the contribution of a tunneling mechanism, the measurement of the rate constants for the intramolecular H and D abstraction of the nitrene in a wide temperature range should be required, which is difficult under our experimental conditions, unfortunately.

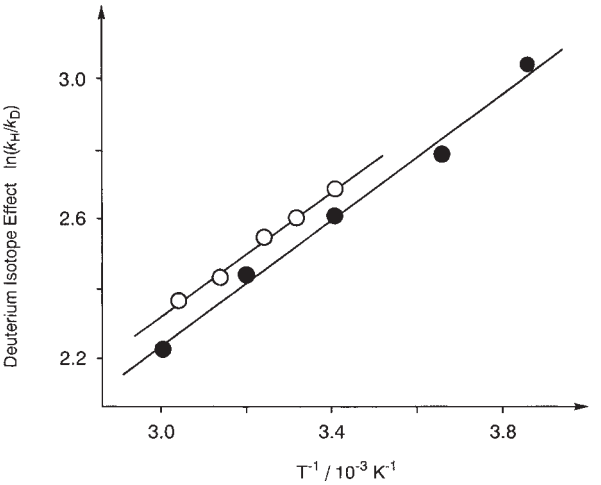


Figure 1. Temperature dependence of the deuterium isotope effects for the intramolecular CH insertion of the nitrene generated by the photolysis of **4**-***d*** in cyclohexane (○) and in acetonitrile (●)

Table 1. Products and kinetic isotope effects obtained in the photolysis of **4**

Conditions		Yield (%)		
Solvent	Light (nm)	**5**	**9**	k_H/k_D[a]
Cyclohexane	>300	52	—	14.7 ± 0.3
Cyclohexane	>350	78	—	14.2 ± 0.3
Acetonitrile	>300	40	—	13.6 ± 0.3
Benzene	>300	49	—	12.6 ± 0.3
Benzene	>350	74	—	13.0 ± 0.2
Methanol	>300	17	69	10.2 ± 0.2[b]

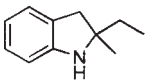
[a] At 20–22 °C.
[b] Obtained from **9**.

Moreover, we examined the deuterium isotope effect on the intramolecular CH insertion of the thermally generated nitrene. Thermolysis of **4**-***d*** in 1,2,4-trichlorobenzene at 180 °C for 30 min afforded not only a mixture of **5**-***h*** and **5**-***d*** (45% in total), but also 2-phenylindole (**10**, 45%). The ratio of **5**-***h*** to **5**-***d*** was evaluated as 5.9. However, we found that the ratio [**5**-***h***]/[**5**-***d***], and also the product distribution, were very dependent on the reaction time: prolonged thermolysis at 180 °C for 1 h resulted in an increase in the yield of **10** to 55% with a decrease in that of **5**, and an increase in the ratio [**5**-***h***]/[**5**-***d***] to 7.8. The formation of the indole **10** is reasonably interpreted in terms of the dehydrogenation of **5** in the course of the thermolysis. Further, the dependence of the ratio [**5**-***h***]/[**5**-***d***] on the reaction time appears to be attributable to the deuterium isotope effect on the dehydrogenation process. Thus, because of the unexpected dehydrogenation reaction of **5**, we failed to gain an intrinsic value of the isotope effect on the CH insertion of the nitrene generated by thermolysis of **4**-***d***.

Determination of the extent of configurational retention using the azide (*S*)-6

In 1964, Smolinsky and Feuer reported the solution-phase thermolysis of optically active (*S*)-2-(2-methylbutyl)phenyl azide [(*S*)-**6**], in which they concluded that 65% of optical purity was retained during the intramolecular CH insertion of the nitrene to give

2-ethyl-2-methylindoline (**11**).[7] However, their result was based on the assumption that the specific rotation of **11** obtained from the vapor-phase thermolysis of (*S*)-**6** is nearly that of optically pure **11**, which appears extremely doubtful. We have found that the racemic indoline (±)-**11** can be perfectly resolved by the use of high-performance liquid chromatograph (HPLC) with a column packed with optically active resin (DAISEL Chiralcel OJ). By employing this method, we examined the extent of the retention of enantiomeric purity during the intramolecular CH insertion of the nitrene generated by photolysis, and also by thermolysis, of (*S*)-**6**.



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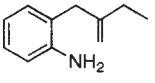


12

The optically active azide **6** was synthesized from commercially available optically active (*S*)-(−)-2-methyl-1-butanol according to the synthetic route presented by Smolinsky and Feuer.[7] The absolute configuration of **6** was reasonably assigned to be *S*, in agreement with that of the starting material, because the asymmetric carbon atom was intact in the course of synthesis. The optical purity of **6** was evaluated as $>90\%$ on the basis of chiral chromatographic analysis of its precursor 2-(2-methyl)butylaniline. Prior to configurational studies, the structure and the distribution of photoproducts were examined by using the racemic azide (±)-**6**.[7] Irradiation of (±)-**6** in cyclohexane with Pyrex-filtered light gave mainly 2-ethyl-2-methylindoline (**11**, 44%), which was produced by the intramolecular CH insertion of the nitrene at an asymmetric carbon atom. A minor photoproduct was also formed, which was tentatively identified as 2-(2-methylenebutyl)aniline (**12**, 6%). Although the unchanged starting material and tarry products were readily removed by the use of gel permeation liquid chromatography (GPLC) and thin-layer chromatography (TLC), all attempts to isolate the indoline **11** from the mixture of photoproducts were unsuccessful. However, the analysis of **11** containing a small amount of **12** by the use of HPLC with a chiral column gave two large, well-separated peaks, together with small additional peaks, as shown in Fig. 2. Since the intensities of the large two peaks were identical within the experimental error (±2%), these peaks were reasonably assigned to the enantiomers of the indoline **11**. Thus, it was found that contamination of the by-product **12** did not interfere with the determination of enatiomeric purity of **11**. The photolysis of (±)-**6** was also carried out in methanol, where a considerable amount of 2-(2-methoxy-2-methylbutyl)aniline (**13**, 20%) was produced together with **11** and **12** (43% and 3%, respectively). Furthermore, we found that the photolysis of (±)-**6** in diethylamine (DEA) afforded a small amount of **11** (3%), although the 3*H*-azepine derivative **14**, which is established as a characteristic photoproduct of aryl azides in DEA,[1] was

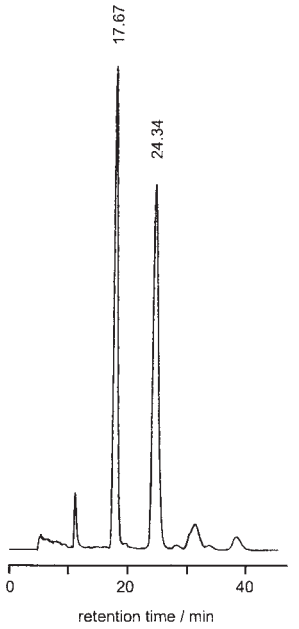
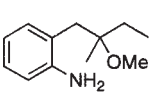


Figure 2. Chromatogram obtained by the injection of **11** produced by the photolysis of (±)-**6** in cyclohexane. Column, DAISEL Chiralcel OJ; eluent, hexane–2-propanol (30:1); flow-rate, 0.6 ml min^{-1}; detection, 255 nm

predominantly obtained (24%). Dilution of DEA with cyclohexane resulted in an increase in the yield of **11** with a decrease in that of **14**.



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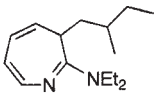
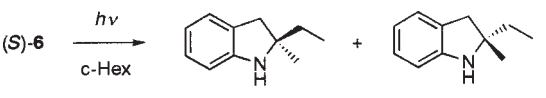


14

An enantiomeric excess of the indoline **11** produced in the irradiation of the optically active azide (*S*)-**6** was directly determined by the chiral chromatographic analysis of **11** which was separated from the photoreaction mixture by the use of GPLC and TLC. The values of the enantiomeric excess, and also the yield of **11**, obtained in the irradiation of (*S*)-**6** under various conditions are summarized in Table 2. These values remained constant during the photoreaction within the experimental error, which excluded the possibility of racemization of **11** through the secondary photochemical cleavage of the bond linking a nitrogen atom with an asymmetric carbon atom. As shown in the table, the enantiomeric purity of the starting azide **6** is found to be almost completely lost during the intramolecular CH insertion of the nitrene generated photolytically under all conditions studied. It should be pointed out, however, that small but significant values of enantiomeric excess (*ee*) are observed, which



(*R*)-**11** (*S*)-**11**

Table 2. Products and enantiomeric excess of **11** obtained in the photolysis and thermolysis of (*S*)-**6**

Conditions		Yield (%)		*ee* of **11** (%)
Solvent	Light (nm)	**11**[a]	Others	
Cyclohexane	>300	50		3.2 ± 1.0
Cyclohexane	>250	—[b]		10.9 ± 0.3
Cyclohexane	>350	—[b]		2.6 ± 1.0
Methanol	>300	46	20[c]	6.2 ± 1.4
DEA	>300	3	24[d]	9.4 ± 0.6
Cyclohexane–DEA (9:1)	>300	11	6[d], 8[e]	6.5 ± 0.2
1,2,4-Trichlorobenzene	180 °C	30	2[f]	26.3 ± 2.0

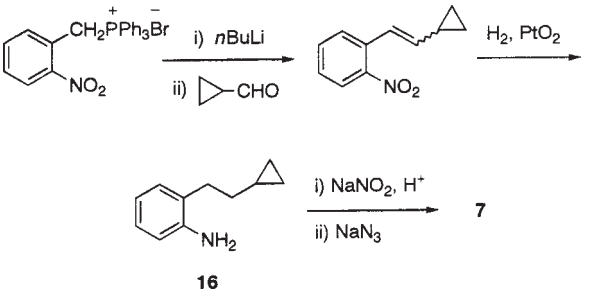
[a] Containing a small amount of **12**.
[b] Not determined.
[c] **13**.
[d] **14**.
[e] 2-(2-Methylbutyl)aniline.
[f] **15**.

are clearly dependent on the solvent employed in the photolysis. Although the absolute configuration of the predominantly produced enantiomer, which is eluted later in the chromatographic analysis of **11**, cannot be determined, it is tentatively identified as *R* by assuming that the intramolecular CH insertion proceeds partially with a configurational retention of the starting azide. This assumption was supported by the result obtained in the thermolysis of (*S*)-**6**, which mainly afforded the enantiomer of **11** identical with that produced predominantly in the photolysis. It has been reported that the thermolysis of (*S*)-**6** gives an intramolecular CH insertion product having a retained configuration.[7]

Thermolysis of the racemic azide (±)-**6** in 1,2,4-trichlorobenzene at 180 °C gave a mixture of **11** and **12** (21% and 9%, respectively). A trace amount of 2,3-dimethyl-1,2,3,4-tetrahydroquinoline (**15**, 2%), the formation of which was previously reported in the thermolysis of **6**,[7] was isolated from the reaction mixture. The enantiomeric excess of **11** obtained in the thermolysis of (*S*)-**6** was determined in an analogous manner, which is included in Table 2.

Photochemical and thermal decomposition of the azide 7

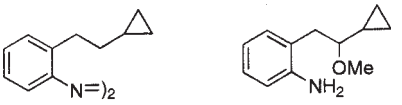
The ring opening of cyclopropylcarbinyl radical to the 3-butenyl radical has been used as a mechanistic probe for reactions thought to involve free radicals.[8] The formation of ring-opened products from the material having a cyclopropylcarbinyl group gives unambiguous evidence for the formation of a free radical at the position adjacent to the cyclopropane ring. In order to apply this approach to gain information about the mechanism of the intramolecular CH insertion of arylnitrenes, we designed the azide **7** and examined its photochemical and thermal reactivities.



Scheme 3

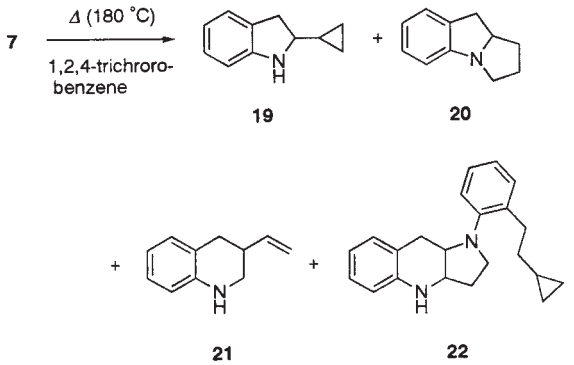
We could obtain the azide **7** according to the synthetic route described in Scheme 3. Hydrogenation (PtO_2/EtOH, 0 °C) of β-cyclopropyl-2-nitrostyrene gave a mixture of 2-(2-cyclopropylethyl)aniline (**16**) and 2-pentylaniline (6:1, 96% in total). After the conversion of the aniline mixture into the corresponding azides, the azide **7** was successfully separated from the cyclopropyl ring-opened azide by the use of GPLC.

Disappointingly, irradiation of **7** in cyclohexane with Pyrex-filtered light afforded a very complicated mixture. Isolation and purification of the photoproducts were unsuccessful, although the azobenzene **17** was detected in the crude reaction mixture, the ^{1}H NMR spectrum of which showed a characteristic doublet centered at δ 7.63, which was assigned to the proton at the *ortho* position of N═N. This photoreactivity of **7** contrasts strikingly with those of the azides **4** and **6**, the photolysis of which in an inert solvent exclusively gives the corresponding intramolecular CH insertion product of the nitrene. These results are possibly interpreted in terms of a greater binding energy of the β-CH bond of **7**, compared with that of the benzylic and the tertiary β-CH bond of **4** and **6**, respectively. Curiously, although no CH insertion products were obtained in the irradiation of **7** in methanol, the methoxylated aniline **18** was isolated in 23% yield, together with the aniline **16** (4%). This observation indicates that the nitrene generated from **7** can attack a β-CH bond of the 2-cyclopropylethyl group with the aid of a polar solvent. The participation of the solvent would lead to a polarized transition state for the hydrogen abstraction, which directly gives the intermediate having a large zwitterionic character. Hence it is reasonable to think that the biradical having a cyclopropylcarbinyl moiety cannot participate in the formation of the methoxylated aniline **18**.



17 **18**

Thus, it is found that the photolysis of the azide **7** is not suitable for radical clock studies. It seems reasonable to assume that an elevated temperature is favorable for the intramolecular insertion to the CH bond having a greater binding energy. Therefore, the thermolysis of **7** was examined next. A solution of **7** in 1,2,4-trichlorobenzene was heated at 180 °C. After separation by the use of GPLC and TLC, four reaction products were obtained. The first product was identified as 2-cyclopropylindoline (**19**, 9%), the ^{1}H NMR spectrum of which showed the cyclopropyl ring protons in a highly shielded area (δ 0.2–1.1). The second product was assigned to the pyrroloindoline **20** (7%). The ^{1}H NMR spectrum of **20** showed the absence of a cyclopropyl ring and a hydrogen attached to a nitrogen atom. The ^{1}H–^{1}H COSY spectrum of **20** exhibited a correlation of the methine proton at δ 3.91–3.96 with both the benzylic protons (δ 2.96 and 3.15–3.22) and the methylene protons located remote from a nitrogen atom (δ 1.29–1.38 and 1.81–1.93). The structure of **20** was confirmed by the agreement of its ^{1}H and ^{13}C NMR data with those of **20** reported by Ziegler and Jeroncic.[13] The third product, which showed a set of signals due to a vinyl group in its ^{1}H NMR spectrum, was identified as 3-vinyltetrahydroquinoline (**21**, 6%). The position of the vinyl group was determined from its ^{1}H–^{1}H COSY spectrum, in which the sequence of protons —CH_2—CH(CH=CH_2)—CH_2— was established. The fourth product, the ^{1}H, ^{1}H–^{1}H COSY and ^{13}C NMR spectra of which exhibited its unsymmetirical dimeric structure having an intact 2-(cyclopropylethyl)-phenyl group, was assigned to the pyrroloquinoline **22** (8%). Prolonged heating of the reaction mixture simply resulted in a decrease in the yields of these reaction products, which excluded the possibility of thermal interconversion among the reaction products. Judging from the ^{1}H NMR spectrum of the reaction mixture obtained after the thermolysis, there were no other products formed in an appreciable yield. The use of a hydrogen-donating solvent, such as decahydronaphthalene, in the thermolysis caused great difficulty in separating the reaction products from polymeric products derived from the solvent. We finally confirmed by separate experiments that the cyclopropyl ring was unchanged under conditions employed in the thermolysis of **7**.



It should be pointed out that three of the products, the pyrroloindoline **20**, the tetrahydroquinoline **21** and the dimeric pyrroloquinoline **22**, are definitely cyclopropyl ring-opened products, which can be produced through the cyclopropylcarbinyl radical rearrangement. Hence this observation provides unambiguous evidence supporting that the free radical having a cyclopropylcarbinyl radical moiety is generated during the thermolysis of **7**. Furthermore, it seems reasonable to expect that the intramolecular attack on a β-CH bond of the nitrene produced thermally from **7** is responsible for the generation of the cyclopropylcarbinyl radical.

DISCUSSION

Mechanism of intramolecular CH insertion of arylnitrenes

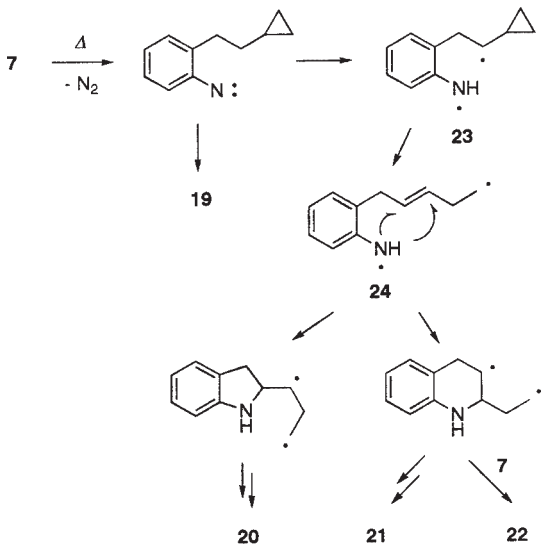
Photochemical decomposition of azides. The photolysis of the azides **4** and **6** in an inert solvent exclusively afforded the intramolecular CH insertion product **5** and **11**, respectively. Extremely large deuterium isotope effects, $k_H/k_D = 12.6$–14.7, are obtained in the photolysis of **4-*d*** at room temperature. These results present an unambiguous evidence supporting that the intramolecular CH insertion proceeds not by the concerted mechanism, but by the hydrogen abstraction–recombination mechanism. The same conclusion can be drawn from the results obtained in the configurational studies of the photochemistry of (*S*)-**6**, where the extent of the configurational retention during the intramolecular insertion of the nitrene into a CH bond at an asymmetric carbon atom is found to be $<10\%$. Thus, based on the results obtained in these two independent experiments, it is safely concluded that the intramolecular insertion of the photolytically generated nitrene into the reactive CH bond located close to the nitrenic center proceeds primarily by the hydrogen abstraction–recombination mechanism.

It should be pointed out that the deuterium isotope effect and the extent of the configurational retention are dependent slightly but significantly on the solvent employed in the photolysis, as shown in Tables 1 and 2. The largest value of the kinetic isotope effect, and also the smallest value of the enantiomeric retention, are observed in cyclohexane, while a smaller value of the isotope effect and a larger value of the enantiomeric retention compared with those in cyclohexane are observed in an electron-donating solvent. We propose that the solvent effects observed are attributed to a small contribution of the concerted mechanism to the intramolecular CH insertion of the nitrene. It could be assumed that in the concerted mechanism, the insertion of the nitrene into the CH bond is initiated by the charge-transfer interaction of the occupied σ orbital of the CH bond with the vacant orbital on the nitrogen atom. On the other hand, the nitrene

responsible for the intramolecular hydrogen abstraction should have an open-shell electronic structure with two singly occupied molecular orbitals on the nitrogen atom. Thus, the interaction of the vacant orbital on the nitrogen atom with a lone pair of the solvent employed in the photolysis would stabilize the electronic structure of the nitrene participating in the former mechanism. Alternatively, a more polar transition state of the concerted CH insertion, compared with that of the hydrogen abstraction, would be stabilized in an electron-donating solvent. It seems reasonable to think that these effects increase the contribution of the concerted mechanism in an electron-donating solvent. Because of a low degree of CH bond cleavage in the transition state of the concerted CH insertion, an increase in the contribution of the concerted mechanism results in a decrease in the kinetic isotope effect and an increase in the extent of the configurational retention. The spin state and electronic structure of the reactive intermediate responsible for the concerted mechanism are extensively discussed in a following section.

Thermal decomposition of azides. Previously, Smolinsky and Feuer presented the first report on the partial retention of optical activity during the intramolecular CH insertion of the nitrene generated thermally from (*S*)-**6**.[7] Now, we have strictly determined the extent of the configurational retention as 26.3% in 1,2,4-trichlorobenzene at 180 °C. Thus, we could conclude that the intramolecular CH insertion reaction of the thermally generated nitrene also proceeds by the hydrogen abstraction–recombination mechanism predominantly. It should be pointed out, however, that the value of the configurational retention is considerably larger than those obtained in the photolysis, which would be reasonably explained in terms of a larger contribution of the concerted mechanism.

This interpretation is not inconsistent with the results obtained in the thermolysis of **7**, where the cyclopropyl ring-opened products **20**–**22** are predominantly produced. This observation definitely indicates the generation of the cyclopropylcarbinyl radical **23** during the thermolysis, the formation of which is reasonably explained in terms of the intramolecular hydrogen abstraction of the thermally generated nitrene (Scheme 4). Moreover, it should be noted that we have obtained a significant amount of the intramolecular CH insertion product with an intact cyclopropyl ring **19**. Arrhenius parameters for the cyclopropylcarbinyl radical rearrangement of 1-cyclopropylethyl radical have been estimated to be $\log(A/s^{-1}) = 13.15$ and $E_a = 7.5\,\text{kcal mol}^{-1}$.[14] Assuming that these parameters are applicable in a high temperature range, the rate constant for the ring opening of the 1-cyclopropylethyl radical is evaluated to be ca $3 \times 10^9\,s^{-1}$ at 180 °C. Although the possibility that **19** is produced through the simple recombination of the biradical **23** generated by the intramolecular hydrogen abstraction cannot be ruled out yet, an extremely large rate constant



Scheme 4

estimated for the ring-opening reaction leads us to assume that the concerted CH insertion of the thermally generated nitrene gives **19** (Scheme 4). Again, this assumption is in harmony with the conclusion that the concerted mechanism contributes relatively largely to the intramolecular CH insertion of the thermally generated nitrene.

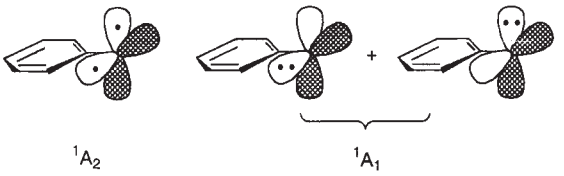
Although the detailed process of the formation of the cyclopropyl ring-opened products **20**–**22** has not been elucidated yet, we tentatively propose a scheme involving the intramolecular cyclization of the biradical **24** resulting from the cyclopropylcarbinyl opening of **23** (Scheme 4). The intramolecular attack of the aminyl radical on the 2-position of the 2-pentenylene moiety in **24** would give the biradical with a five-membered ring, which would be a precursor of the pyrroindoline **20**. If the intramolecular cyclization occurs at the 3-position, the biradical with a six-membered ring would be formed, which could give not only **21** by the recombination, followed by the re-cleavage of the resulting four-membered ring, but also **22** by the reaction with the unchanged azide **7**. It seems reasonable to think that a variety of the interconversion between reactive intermediates is allowed at the reaction temperature of 180 °C, and that the isolation of the products **20**–**22** is primarily attributable to their high thermostability. Although isotope labeling studies, and also theoretical studies of the relative stability of intermediate biradicals, are required to validate this scheme, it should be emphasized again that these products **20**–**22** obtained in the thermolysis of the azide **7** are definitely produced through the cyclopropylcarbinyl radical rearrangement.

Spin state and electronic structure of the nitrene responsible for the intramolecular CH insertion

The CH insertion of photolytically generated arylcarbenes has been fully investigated, and it is established that the reaction proceeds generally by the concerted

mechanism involving a singlet state carbene (for reviews on carbene chemistry see, for example, Ref. 15). Recently, based on low stereoselectivities and large deuterium isotope effects ($k_H/k_D = 4–8$), Kirmse and co-workers reported that a triplet-state carbene participated in the intramolecular CH insertion with steric constraints in its transition state.[16] The assumption underlying the discussion on the spin state of arylcarbenes involved in the reaction is a difference in the electronic structure between singlet- and triplet-state carbenes. It is generally accepted that singlet carbene has a closed-shell electronic structure with one filled and one vacant non-bonding orbital, whereas triplet carbene has an open-shell electronic structure with two singly occupied non-bonding orbitals. In contrast to arylcarbenes, recent theoretical and experimental studies have clearly demonstrated that singlet, in addition to triplet, phenylnitrene (**2**) has an open-shell electronic structure.[4,9] Assuming that the alkyl substituent at the *ortho*-position has no influence on the electronic structure of **2**, the intramolecular CH insertion of the nitrene is expected to proceed by the hydrogen abstraction–recombination mechanism, regardless of its spin state. Our observations described in the preceding sections are primarily consistent with this expectation. It should be emphasized, however, that we have demonstrated a contribution of the concerted mechanism, which cannot be expected from an open-shell electronic structure, to the intramolecular CH insertion of the nitrene generated by photolysis, in addition to thermolysis. Here we have a discussion on the spin state and electronic structure of the reactive intermediate involved in the CH insertion which proceeds by the concerted mechanism.

We propose the following four possible mechanisms for the concerted intramolecular CH insertion of nitrenes. The first is a contribution of the electronically excited singlet state. The first electronically excited singlet state of phenylnitrene (**2S**) is expected to have a closed-shell electronic structure, which is designated as the $^1A_1$ state.[4,9] It is unlikely, however, that the singlet nitrene with the $^1A_1$ state is thermally populated, even under the conditions employed in the thermolysis, because the energy gap between the ground singlet state ($^1A_2$) and $^1A_1$ is estimated to be ca 18 kcal mol^{-1} by both CASSCF calculation[9] and the modern CASPT2 method.[4] The second possibility is the participation of an electron transfer from the CH bond to the electronegative nitrogen atom in the intramolecular CH insertion. The interaction of the electron localized on the CH bond with one of the singly occupied orbitals of the nitrenic center would lead to the polarized three-centered transition state of the CH insertion, in which the extent of the CH bond cleavage is relatively low. The polarized transition state of the intramolecular CH insertion of the nitrene has been demonstrated by the formation of the methoxylated anilines **9** and **13** in the photolysis of the azides **4** and **6**, respectively, in methanol. Moreover, the participation of an electron transfer in the nitrene chemistry has been



proposed recently.[17,18] The third possibility is an interaction between the azide moiety and the CH bond in a ground state of the azide. The electron-donating interaction of the occupied molecular orbital localized on the CH bond with the unoccupied molecular orbital of the azide moiety could lead to the transition state of the concerted intramolecular CH insertion without passing through the nitrene. The interaction between the azide moiety and an electron-donating group substituted at the *ortho*-position of phenyl azide has been established in the thermolysis of various aryl azides.[1,19] Finally, we propose that the electronically excited azides could be a candidate for the intermediate responsible for the concerted intramolecular CH insertion of the photochemically generated nitrene. (In the photochemistry of diazirines, the participation of their electronically excited state in the product formation has been proposed.[20]) It seems that a single electronically excited state of the azide was involved in the photolysis with the Pyrex-filtered light (>300 nm), because the isotope effect and the enantiomeric excess obtained in the photolysis of **4-*d*** and (*S*)-**6**, respectively, with the light of >350 nm are identical with those obtained with the Pyrex-filtered light. As shown in Table 2, however, the use of the shorter-wavelength light (>250 nm) afforded a significantly large value of the configurational retention during the intramolecular CH insertion of the nitrene generated from (*S*)-**6**. This observation appears to be interpretable in terms of the contribution of the higher excited state of (*S*)-**6** to the intramolecular CH insertion.

At the present stage, we cannot specify the mechanism of the concerted intramolecular CH insertion of the nitrenes, which is observed as a minor process in our experiments. Further experimental and theoretical studies are required to elucidate the details of the reactivity of arylnitrenes.

CONCLUSION

In order to gain experimental information about the mechanism of the intramolecular CH insertion of arylnitrenes, we carried out three experiments: measurement of deuterium isotope effects, determination of configurational purities and cyclopropylcarbinyl radical clock studies. On the basis of the results obtained, we concluded that the intramolecular CH insertion of the nitrenes proceeds primarily by the hydrogen abstraction–recombination mechanism. The spin state of the nitrenes involved in the hydrogen abstraction cannot be determined, because recent theoretical and experimental

studies have established that singlet in addition to triplet, phenylnitrene (**2**) has an open-shell electronic structure.[4,9] We should point out, however, a small but significant contribution of the concerted mechanism to the intramolecular CH insertion, which cannot be explained by an open-shell electronic structure of the nitrenes.

EXPERIMENTAL

^{1}H NMR spectra were recorded at 270 or 500 MHz. ^{13}C NMR spectra were recorded at 126 MHz. GC analyses were performed on a column prepared from 5% silicone OV-17 on Diasolid L (5.0 mm × 1.0 m). HPLC analysis was performed on a Hitachi L-6000 system. Gel permeation liquid chromatography (GPLC) was carried out on a JASCO HLC-01 high-performance liquid chromatograph equipped with a Shodex GPC H-2001 column. Thin-layer chromatography (TLC) was carried out on Merck Kieselgel 60 PF_{254}.

Materials. The synthesis of (±)- and (*S*)-2-(2-methylbutyl)phenyl azide (**6**) has been reported previously.[7]

*Preparation of 2-(2-deuterio-2-phenylethyl)phenyl azide (**4**-d). 1-Phenyl-2-(2-Nitrophenyl)-1-ethanone.* To a solution of 3.68 ml of benzaldehyde (36.1 mmol) and 4.29 ml of 2-nitrotoluene (36.4 mmol) in 50 ml of freshly distilled DMSO was added a solution of sodium ethoxide in EtOH (0.43 M, 10 ml). The mixture was stirred for 2 days at room temperature and concentrated to ca 5 ml by distillation under reduced pressure. After the addition of 20 ml of water, the reaction mixture was extracted with diethyl ether. The organic layer was washed with water and dried over Na_2SO_4. The solvent was removed under reduced pressure to afford 3.88 g (44%) of 1-phenyl-2-(2-nitrophenyl)ethanol. The resulting alcohol (3.60 g, 14.8 mmol) was dissolved in 50 ml of acetone. To the solution was added dropwise an acidic chromium reagent, which was prepared by the dilution of aqueous solution of chromium(VI) oxide (5.5 M, 3.6 ml) with sulfuric acid (4.4 M, 7.4 ml), until the starting alcohol was no longer detected by TLC. The mixture was further stirred for 10 min and concentrated to ca 10 ml by evaporation. After the addition of 30 ml of water, the organic material was extracted with CH_2Cl_2. The extract was washed with water and dried over Na_2SO_4. The solvent was removed under reduced pressure and the residue was developed on a silica gel column with hexane–CH_2Cl_2 (1:1) to give 2.12 g (59%) of 1-phenyl-2-(2-nitrophenyl)-1-ethanone. The identity and purity of the material were established by ^{1}H NMR spectrum: light yellow granules; m.p. 64–65 °C; ^{1}H NMR ($CDCl_3$), δ 4.74 (2H, s), 7.38 (1H, d, $J = 6.3$ Hz), 7.43–7.67 (5H, m), 8.05 (2H, d, $J = 6.9$ Hz), 8.17 (1H, d, $J = 8.3$ Hz); EIMS, *m/z* 165 (14), 105 (100).

1-Deuterio-1-phenyl-2-(2-nitrophenyl)ethene. To a solution of 1.00 g (4.15 mmol) of 1-phenyl-2-(2-nitrophenyl)-1-ethanone in 20 ml of dry diethyl ether was added 174 mg (4.15 mmol) of $LiAlD_4$ (Aldrich, 98%) at 0 °C. The reaction mixture was stirred for 1 h at room temperature. After the successive addition of MeOH and 10% sulfuric acid to the mixture, and the organic material was extracted with diethyl ether. The extract was washed with water and dried over Na_2SO_4. The solvent was removed under reduced pressure to afford 972 mg (96%) of 1-deuterio-1-phenyl-2-(2-nitrophenyl)ethanol. A solution of the resulting alcohol (815 mg, 3.34 mmol) and 50 mg of 4-toluenesulfonic acid monohydrate in benzene (50 ml) was refluxed for 1 h. The mixture was washed successively with saturated $NaHCO_3$ solution and water and dried over Na_2SO_4. The solvent was removed under reduced pressure, and the residue was developed on a silica gel column with hexane–CH_2Cl_2 (3:1) to give 680 mg (90%) of 1-deuterio-1-phenyl-2-(2-nitrophenyl)ethene. The identity and purity of the material were established by ^{1}H NMR spectrum: yellow granules; m.p. 66–67 °C; ^{1}H NMR ($CDCl_3$), δ 7.29–7.49 (5H, m), 7.53–7.63 (3H, m), 7.77 (1H, d, $J = 7.9$ Hz), 7.97 (1H, d, $J = 8.3$ Hz).

*2-(2-Deuterio-2-phenylethyl)phenyl azide (**4**-d).* A solution of 650 mg (2.88 mmol) of 1-deuterio-1-phenyl-2-(2-nitrophenyl)ethene in 50 ml of acetic acid was stirred with 50 mg of 10% Pd/C under a hydrogen atmosphere overnight at room temperature. The solid was filtered and washed several times with acetic acid. The solvent was removed under reduced pressure. To the residue were added 20 ml of water and the mixture was neutralized with Na_2CO_3. The organic material was extracted with diethyl ether and the extract was washed with water and dried over Na_2SO_4. The solvent was removed under reduced pressure to give 562 mg (99%) of 2-(2-deuterio-2-phenylethyl)aniline (**8**-***d***). The deuterium isotope purity of **8**-***d*** was found by NMR integration to be > 95%; ^{1}H NMR ($CDCl_3$), δ 2.78 (2H, d, $J = 8.3$ Hz), 2.92 (1H, d, $J = 8.3$ Hz), 6.66–6.77 (2H, m), 7.02–7.07 (2H, m), 7.19–7.33 (5H, m). To a solution of 562 mg (2.83 mmol) of **8**-***d*** in 15 ml of dioxane were added 15 ml of 6 N sulfuric acid. The mixture was cooled to 0–5 °C and a solution of 195 mg (2.83 mmol) of $NaNO_2$ in 2 ml of water was added dropwise to the mixture. The reaction mixture was stirred for 30 min at this temperature. The mixture was added dropwise to a solution of 3.68 g of NaN_3 in 22 ml of water with stirring at room temperature. After the addition, the reaction mixture was stirred for 2 h. The organic material was extracted with CH_2Cl_2 and the extract was washed with water and dried over Na_2SO_4. The solvent was removed under reduced pressure and the residue was developed on a silica gel column with hexane to give 431 mg (68%) of the azide **4**-***d***. The identity and purity of the azide were established by ^{1}H NMR and IR spectra, which were completely identical with those of **4**-***h***,[5] except that the ^{1}H NMR spectrum showed only three methylene protons at δ 2.85; EIMS, *m/z* 224 (M^+, 3), 196 (89), 195 (100), 119 (20).

*Preparation of 2-(2-cyclopropylethyl)phenyl azide (**7**). (2-nitrobenzyl)triphenylphosphonium bromide.* A solution of 15.0 g of 2-nitrotoluene (109 mmol), 17.6 g of *N*-bromosuccinimide (99 mmol) and 0.14 g of benzoyl peroxide in 66 ml of CCl_4 was refluxed for 5 h. The precipitate was filtered and washed with hot CCl_4. The solvent was removed under reduced pressure. The residual 2-nitrobenzyl bromide was dissolved in 40 ml of benzene and to the solution were added 26.0 g (99 mol) of triphenylphosphine. The reaction mixture was allowed to stand overnight at room temperature. A viscous material was produced that solidified slowly. The solid was filtered, washed with diethyl ether and dried *in vacuo* to afford 36.0 g (76%) of (2-nitrobenzyl)triphenylphosphonium bromide. This phosphonium salt was insoluble in organic solvents and used without further purification: yellow granules; m.p. 226–228 °C; IR (KBr disk), 1540, 1440, 1340, 1120, 1000 cm^{-1}.

β-Cyclopropyl-2-nitrostyrene. Under an N_2 atmosphere, to a suspension of 5.36 g of (2-nitrobenzyl)triphenylphosphonium bromide (11.2 mmol) in 30 ml of dry benzene was added a solution of *n*-butyllithium in hexane (1.69 M, 6.64 ml, 11.2 mmol) at 0 °C with vigorous stirring. After stirring for 1 h at this temperature, to the reaction mixture was added slowly a solution of 561 mg of cyclopropanecarbaldehyde (8.00 mmol) in 8 ml of dry benzene. The mixture was stirred overnight at room temperature. Water was added to the mixture and the organic material was extracted with diethyl ether. The extracted was washed with water and dried over Na_2SO_4. The solvent was removed under reduced pressure and the residue was developed on a silica gel column with hexane–CH_2Cl_2 (5:1) to give 609 mg (39%) of β-cyclopropyl-2-nitrostyrene as a mixture of *cis* and *trans* isomers (*cis*: *trans* = 2.5). The identity and purity of the material were established from the ^{1}H NMR spectrum: light yellow liquid; ^{1}H NMR ($CDCl_3$), δ 0.40–0.44 (2H, m), 0.68–0.75 (2H, m), 1.41–1.50 (1H, m), 5.11 (1H, dd, J = 11.2, 10.6 Hz), 6.54 (1H, d, J = 11.2 Hz), 7.18–7.58 (3H, m), 7.91 (1H, d, J = 9.2 Hz) for the *cis* isomer; δ 0.45–0.51 (2H, m), 0.77–0.84 (2H, m), 1.51–1.63 (1H, m), 5.66 (1H, dd, J = 15.5, 9.2 Hz), 6.85 (1H, d, J = 15.5 Hz), 7.18–7.58 (3H, m), 7.77 (1H, d, J = 8.9 Hz) for the *trans* isomer; EIMS, *m/z* 189 (M^+, 6), 172 (13), 144 (32), 128 (47), 115 (100).

*2-(2-Cyclopropylethyl)phenyl azide (**7**).* A solution of β-cyclopropyl-2-nitrostyrene (267 mg, 1.41 mmol) in 10 ml of absolute ethanol was stirred in the presence of 10 mg of PtO_2 under a hydrogen atmosphere for 2.5 h at 0 °C. The solid was filtered and washed several times with ethanol. The solvent was removed under reduced pressure to give 218 mg of the product containing 2-(2-cyclopropylethyl)aniline (**16**), which showed signals at δ 0.05–0.10 (2H, m), 0.42–0.49 (2H, m), 0.70–0.83 (1H, m), 1.51 (2H, q, J = 7.5 Hz), 2.60 (2H, t, J = 7.8 Hz), 3.60 (2H, brs), 6.66–6.75 (2H, m) and 6.99–7.06 (2H, m) in the ^{1}H NMR spectrum. Although ^{1}H NMR and GC analyses revealed that the product contained small amounts of 2-pentylaniline (ca 15%), the product was used without further purification. To a solution of 418 mg of the crude aniline in 16 ml of dioxane were added 16.8 ml of 6 N sulfuric acid. The mixture was cooled to 0–5 °C and a solution of 188 mg (2.72 mmol) of $NaNO_2$ in 3.5 ml of water was added dropwise to the mixture. The reaction mixture was stirred for 1 h at this temperature. The mixture was added dropwise to a solution of 338 mg of NaN_3 in 7.4 ml of water with stirring at room temperature. After the addition, the reaction mixture was stirred for 2 h. The organic material was extracted with CH_2Cl_2 and the extract was washed with water and dried over Na_2SO_4. The solvent was removed under reduced pressure and the residue was developed on a silica gel column with hexane to give 332 mg (68%) of the crude azide. The azide **7** was separated from 2-pentylphenyl azide and purified by the use of GPLC. The identity and purity of the azide were established by ^{1}H NMR and IR spectra: light yellow liquid; ^{1}H NMR ($CDCl_3$), δ 0.00–0.09 (2H, m), 0.38–0.45 (2H, m), 0.64–0.77 (1H, m), 1.45 (2H, q, J = 7.5 Hz), 2.65 (1H, t, J = 7.8 Hz), 7.03–7.23 (4H, m); IR (NaCl), 2110, 1280, 750 cm^{-1}.

Irradiation for preparative experiments. A solution of 20–30 mg of an azide in 20–30 ml of a solvent was placed in a Pyrex tube, purged with N_2 for 10 min and irradiated with a 300 W high-pressure mercury lamp for 60 min at room temperature. The solvent was removed under reduced pressure and the residue was separated by GPLC with $CHCl_3$ eluent or preparative TLC. The identity and purity of photoproducts were established from the ^{1}H and ^{13}C NMR spectra. The yield of products described in the text was determined by isolation on the basis of the reacted material. 2-Phenylindoline (**5**), 2-(2-phenylethyl)aniline (**8**) and 2-(2-methoxy-2-phenylethyl)aniline (**9**), which were obtained by the irradiation of the azide **4**, were identified by comparison of the spectroscopic data with those of authentic material.[5]

*Irradiation of (±)-**6**.* Irradiation of (±)-**6** in cyclohexane, followed by separation by preparative TLC with hexane–CH_2Cl_2 (1:1), gave 2-ethyl-2-methylindoline (**11**), which was identified by comparison of the data with those of authentic material.[7] The indoline **11** was contaminated by small amounts of the product, which showed signals at δ 1.06 (3H, t, J = 7.3 Hz), 2.04 (2H, q, J = 7.3 Hz), 3.30 (2H, s), 4.73 (1H, s) and 4.87 (1H, s) in the ^{1}H NMR spectrum. The minor product was tentatively identified as 2-(2-methylenebutyl)aniline (**12**). Attempts to isolate **11** from the mixture were unsuccessful. Irradiation of (±)-**6** in methanol gave 2-(2-methoxy-2-methylbutyl)aniline (**13**), together with **11**. **13**: oil; ^{1}H NMR ($CDCl_3$), δ 0.98 (3H, t, J = 7.5 Hz), 1.09 (3H, s), 1.52–1.59 (1H, m), 1.66–1.74 (1H, m), 2.47 (1H, d,

$J = 14.2$ Hz), 2.99 (1H, d, $J = 14.2$ Hz), 3.15 (3H, s), 6.63–6.70 (2H, m), 6.69 (1H, d, $J = 7.3$ Hz). 7.04 (1H, t, $J = 7.6$ Hz); ^{13}C NMR ($CDCl_3$), δ 8.2, 21.6, 30.1, 41.8, 48.8, 79.4, 116.1, 117.9, 124.3, 127.2, 132.6, 146.8. In order to avoid the oxidation of photoproducts by molecular oxygen,[5,21] the photoreaction mixture obtained by the irradiation of (±)-**6** in diethylamine was worked up as follows: the photolyzed solution was added dropwise to a flask containing 50 ml of boiling MeOH under an N_2 atmosphere. The mixture was refluxed for 1 h. After cooling, the solvent was removed and the residue was separated by GPLC to afford 2-(diethylamino)-3-(2-methylbutyl)-3*H*-azepine (**14**), together with **11**. **14**: oil; ^{1}H NMR ($CDCl_3$), δ 0.77–0.89 (6H, m), 1.12–1.16 (9H, m), 1.21–1.29 (1H, m), 1.31–1.36 (1H, m), 3.38–3.46 (4H, m), 4.10–4.15 (1H, m), 5.08–5.15 (1H, m), 5.58–5.61 (1H, m), 6.23–6.27 (1H, m), 7.04 (1H, d, $J = 7.6$ Hz); ^{13}C NMR ($CDCl_3$), δ 11.2, 11.3, 13.3, 13.4, 19.0, 19.9, 29.2, 29.6, 29.9, 30.1, 32.5, 32.7, 39.7, 39.8, 43.9, 108.2, 108.3, 115.8, 116.3, 128.0, 128.2, 139.3, 146.8, 147.3.

*Irradiation of **7**.* Irradiation of **7** in methanol, followed by GPLC separation, gave the aniline **16** and 2-(2-cyclopropyl-2-methoxyethyl)aniline (**18**). **18**: oil; ^{1}H NMR ($CDCl_3$), δ 0.05–0.10 (1H, m), 0.41–0.48 (1H, m), 0.49–0.52 (1H, m), 0.63–0.69 (1H, m), 0.77–0.84 (1H, m), 2.72–2.76 (1H, m), 2.85 (2H, d, $J = 4.9$ Hz), 3.38 (3H, s), 6.67–6.72 (2H, m), 7.03 (2H, m); ^{13}C NMR ($CDCl_3$), δ 5.0, 13.8, 37.7, 56.6, 87.2, 115.6, 117.9, 124.5, 126.8, 130.9, 145.5.

Irradiation for analytical experiments. In a typical run, a solution of an azide (3 mg) in a solvent (3 ml) was placed in a Pyrex tube, purged with N_2 for 10 min and irradiated with a 300 W high-pressure mercury lamp. The consumption of the material (<50%) and the yield of the photoproducts were determined by the integration of the ^{1}H NMR spectrum in the crude reaction mixture. Identification of the product was established by the agreement of the ^{1}H NMR spectra with those of authentic samples. The ratio of **5-*h*** to **5-*d*** obtained by the irradiation of **4-*d*** was also determined by the integration of the ^{1}H NMR spectrum. The optical purity of **11** obtained by the irradiation of (*S*)-**6** was determined by HPLC with a column packed with DAISEL Chiralcel OJ using hexane–2-propanol (30:1) as eluent.

Thermolysis. Under an N_2 atmosphere, 1 ml of 1,2,4-trichlorobenzene in a flask was heated at 180 °C. A solution of an azide (10 mg) in 1,2,4-trichlorobenzene (1 ml) was added dropwise to the flask with stirring. The mixture was stirred for 30 min at this temperature. After cooling to room temperature, the mixture was developed on a silica gel column with hexane to remove the solvent. Elution with CH_2Cl_2 gave a mixture of products. After evaporation of the solvent, the residue was separated by GPLC with $CHCl_3$ as eluent. The identity and purity of products were established from the ^{1}H NMR spectrum. The yield of products described in the text was determined by isolation. 2-Phenylindole (**10**)[5] obtained by the thermolysis of **4**, and 2,3-dimethyl-1,2,3,4-tetrahydroquinoline (**15**)[7] obtained from (±)-**6**, were identified by comparison of the spectroscopic data with those of authentic material. Thermolysis of **7**, followed by GPLC separation, gave four products, the structures of which were determined from the ^{1}H, ^{13}C NMR and ^{1}H–^{1}H COSY spectra. 2-Cyclopropylindoline (**19**): oil; ^{1}H NMR ($CDCl_3$), δ 0.22–0.29, (2H, m), 0.48–0.54 (2H, m), 1.03–1.10 (1H, m), 2.87–2.95 (1H, m), 3.11–3.19 (2H, m), 3.92 (1H, brs), 6.62 (1H, d, $J = 7.6$ Hz), 6.69 (1H, t, $J = 7.3$ Hz), 7.01 (1H, t, $J = 7.6$ Hz), 7.09 (1H, d, $J = 7.3$ Hz); ^{13}C NMR ($CDCl_3$), δ 2.2, 3.1, 16.7, 36.0, 65.0, 109.1, 118.5, 124.7, 127.2, 128.7, 150.7; EIMS, *m/z* 159 (M^+, 100), 130 (47), 118 (57). 2,3,3*a*,4-Tetrahydro-1*H*-pyrrolo[1,2-*a*]indole (**20**):[13] oil; ^{1}H NMR ($CDCl_3$), δ 1.29–1.38 (1H, m), 1.81–1.93 (3H, m), 2.96 (1H, dd, $J = 16.2$, 2.4 Hz), 3.15–3.22 (2H, m), 3.42–3.46 (1H, m), 3.91–3.96 (1H, m), 6.60 (1H, d, $J = 7.9$ Hz), 6.76 (1H, t, $J = 7.3$ Hz), 7.08–7.12 (2H, m); ^{13}C NMR ($CDCl_3$), δ 25.8, 31.3, 33.9, 52.3, 65.3, 111.0, 119.3, 124.9, 127.6, 129.9, 154.7. 3-Vinyl-1,2,3,4-tetrahydroquinoline (**21**): oil; ^{1}H NMR ($CDCl_3$), δ 2.60–2.67 (1H, m), 2.68 (1H, t, $J = 10.1$ Hz), 2.82–2.85 (1H, m), 3.07 (1H, t, $J = 9.8$ Hz), 3.34–3.37 (1H, m), 3.88 (1H, brs), 5.07 (1H, d, $J = 10.4$ Hz), 5.15 (1H, d, $J = 17.1$ Hz), 5.87 (1H, ddd, $J = 17.1$, 10.4, 6.4 Hz), 6.50 (1H, d, $J = 7.6$ Hz), 6.62 (1H, t, $J = 7.3$ Hz), 6.96–6.99 (2H, m); ^{13}C NMR ($CDCl_3$), δ 32.9, 36.2, 46.9, 113.9, 114.6, 117.1, 120.5, 126.9, 129.6, 140.2, 144.1. 2-[2-(2-Cyclopropylethyl)phenyl]-1*H*-2,3,3*a*,4,9,9*a*-hexahydropyrrolo[2,3-*b*]quinoline (**22**): oil; ^{1}H NMR ($CDCl_3$), δ 0.09–0.12 (2H, m), 0.47–0.51 (2H, m), 0.76–0.82 (1H, m), 1.49–1.55 (2H, m), 1.65–1.72 (1H, m), 2.35–2.41 (1H, m), 2.60 (2H, t, $J = 7.8$ Hz), 3.14 (1H, dd, $J = 16.2$, 2.5 Hz), 3.25 (1H, dd, $J = 16.5$, 9.2 Hz), 3.32–3.37 (1H, m), 3.56–3.60 (1H, m), 3.61–3.66 (1H, m), 3.65 (1H, brs), 3.76–3.80 (1H, m), 6.60 (1H, d, $J = 8.2$ Hz), 6.66 (1H, d, $J = 7.9$ Hz), 6.70 (1H, t, $J = 7.3$ Hz), 6.80 (1H, t, $J = 7.3$ Hz), 7.06–7.11 (3H, m), 7.14 (1H, t, $J = 7.6$ Hz); ^{13}C NMR ($CDCl_3$), δ 4.7, 11.0, 31.1, 33.1, 33.4, 34.0, 51.5, 58.1, 70.8, 110.8, 111.1, 117.4, 119.8, 125.0, 126.5, 127.0, 127.7, 129.1, 129.1, 145.1, 154.4.

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