4-Halo-4*H*-pyrazoles: Cycloaddition with Cyclopentadiene to Azoalkanes of the 2,3-Diazabicyclo[2.2.1]hept-2-ene Type *versus* Electrophilic Addition with Cyclopentene

Waldemar Adam,*,† Horst Ammon,§,† Werner M. Nau,† and Karl Peters‡

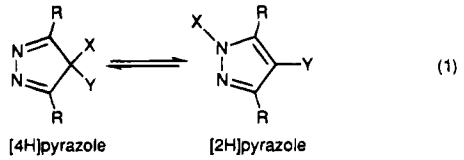
Institut für Organische Chemie der Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany, and the Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-70506 Stuttgart, Germany

Received June 9, 1994®

The acid-catalyzed reactions of the 4-halogen-substituted 4*H*-pyrazoles **3** with cyclopentadiene and cyclopentene in methylene chloride have been examined. The 4,4-dichloro-3,5-diphenyl-4*H*-pyrazole (**3a**) cycloadded quantitatively with cyclopentadiene to the *gem*-dichloro-substituted azoalkane **4a** of the 2,3-diazabicyclo[2.2.1]hept-2-ene type, whose structure was established by X-ray analysis. The azoalkane **4a** was catalytically hydrogenated to the azoalkane **6** with reduced C=C double bond and the relatively persistent (toward autoxidation) hydrazine **7** with reduced C=C and N=N double bonds. The cycloaddition of 4-chloro-4-methyl-3,5-diphenyl-4*H*-pyrazole (**3b**) with cyclopentadiene gave the azoalkane *anti*-**4b** in high yield and diastereoselectivity. The azoalkanes **4a,b** and **6** were reluctant toward photolysis and thermolysis and the expected housanes were not produced under these conditions. The acid-catalyzed reaction of the 4-bromo-substituted 4*H*-pyrazoles **3c–e** with cyclopentadiene gave, instead of the desired cycloadducts, complex product mixtures. In the presence of acid, the 4*H*-pyrazoles **3** gave with cyclopentene the 2-(α-halocyclopentyl)-substituted 2*H*-pyrazoles **5** as products of electrophilic addition.

Introduction

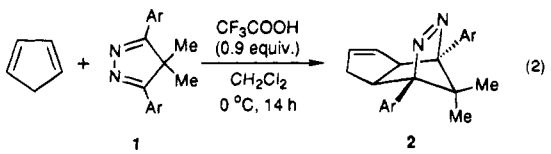
The [4 + 2] cycloaddition of 4,4-disubstituted 4*H*-pyrazoles (as dienes) with olefins (as dienophiles) is made possible by their reluctance toward tautomerization to the 2*H*-pyrazoles. For hydrogen as substituent (X = H), fast tautomerization to the more stable 2*H*-pyrazoles occurs, which do not undergo [4 + 2] cycloadditions (eq 1). Much work has concentrated on 4,4-dialkyl substitution (X, Y = alkyl) since such 4*H*-pyrazoles are persistent



(1)

toward rearrangement and undergo acid-catalyzed cycloadditions with strained (norbornene, norbornadiene, etc.) and electron-rich (cyclopentadiene) olefins[1,2] and only in exceptional cases with simple alkenes (cyclopentene, etc.).[2c]

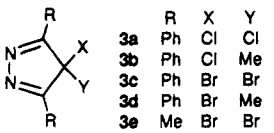
Recently we have examined the effect of aryl substituents on the acid-catalyzed cycloaddition of the 3,5-diaryl-4,4-dimethyl-4*H*-pyrazoles **1** with cyclopentadiene to yield azoalkanes **2** of the 2,3-diazabicyclo[2.2.1]hept-2-ene (DBH) type (eq 2).[1] It has been shown that *para*-nitro greatly enhances and *p*-methoxy retards the reactivity of 3,5-diaryl-4,4-dimethyl-4*H*-pyrazoles **1**, a confirmation of the inverse electron-demand in this reaction. A Hammett correlation with a rather large positive reaction constant ($\varrho = 3.24$) applies, which expresses the pronounced sensitivity of this acid-catalyzed cycloaddition to substituent effects.



1 2

(2)

Surprisingly, the reactivity of the 4-halo-substituted 4*H*-pyrazoles **3** as electron-poor dienes in the [4 + 2] cycloaddition with olefins appears not to have been tested so far. Halogens as substituents (X, Y = Cl, Br) show a high propensity toward 1,3 migration in such pyrazoles, but their 4*H* form **3** persists (eq 1),[3–5] unquestionably due to the labile nature of the N–Cl and N–Br bonds in the corresponding 2*H*-pyrazoles. In view of the expected activation by the electron-accepting halogen substituents, it was anticipated that the 4*H*-pyrazoles **3** should serve as suitable diene partners in the Diels–Alder reactions with olefins; nonetheless, the high migratory aptitude of the halogens in the 4*H* ⇌ 2*H* tautomerism (eq 1) renders this class of 4*H*-pyrazoles **3** unpredictable as to their suitability as dienes in Diels–Alder reactions with reverse electron demand. Indeed, the competitive nature of the 4-halo-substituted 4*H*-pyrazoles **3** to undergo [4 + 2] cycloaddition (4*H* reactivity as dienes) *versus* electro-



	R	X	Y
3a	Ph	Cl	Cl
3b	Ph	Cl	Me
3c	Ph	Br	Br
3d	Ph	Br	Me
3e	Me	Br	Br

† Institut für Organische Chemie.
‡ Max-Planck-Institut für Festkörperforschung.
§ Undergraduate research participant, Spring 1993.
® Abstract published in *Advance ACS Abstracts,* October 15, 1994.

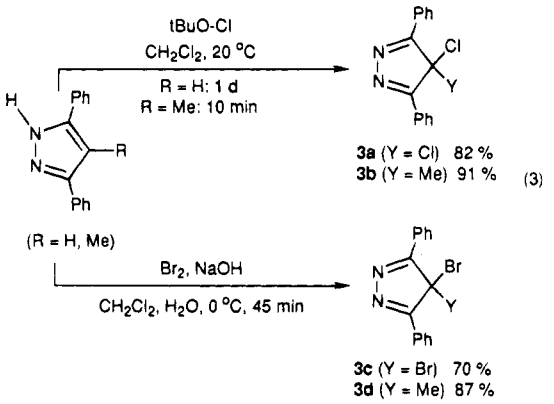
(1) Adam, W.; Harrer, H. M.; Nau, W. M.; and Peters, K. *J. Org. Chem.* **1994**, *59*, 3786.
(2) (a) Beck, K.; Höhn, A.; Hünig, S.; Prokschy, F. *Chem. Ber.* **1984**, *117*, 517. (b) Beck, K.; Hünig, S. *Ibid.* **1987**, *120*, 477. (c) Beck, K.; Hünig, S.; Klärner, F.-D.; Kraft, P.; Artschwager-Perl, U. *Ibid.* **1987**, *120*, 2041. (d) Hünig, S.; Beck, K. *Angew. Chem.* **1987**, *99*, 694, 695. *Angew. Chem. Int. Ed. Engl.* **1987**, *26*, 670, 672.
(3) Ketari, R.; Foucaud, A. *Synthesis*, **1982**, 844.
(4) Hansen, J. F.; Kim, Y. I.; Griswold, L. J.; Hoelle, G. W.; Taylor, D. L.; Vietti, D. E. *J. Org. Chem.* **1980**, *45*, 76.
(5) Freeman, J. P.; Janiga, E. R.; Lorenc, J. F. *J. Org. Chem.* **1977**, *42*, 3721.

0022-3263/94/1959-7067$04.50/0

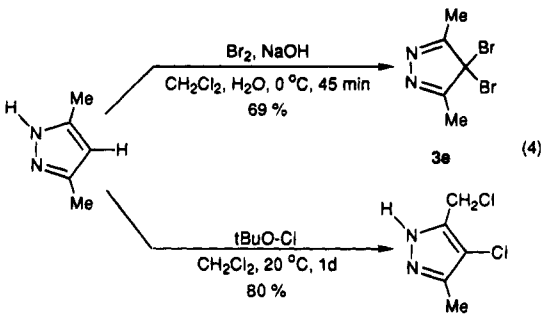
philic addition (2*H* reactivity as halogenating reagents) with cyclopentadiene and cyclopentene is herein demonstrated.

Results and Discussion

The syntheses of the 4-halo-3,5-diphenyl-4*H*-pyrazoles have been reported earlier.[3-5] They comprise chlorination and bromination of the respective 2*H*-pyrazoles (eq 3). Thus, the chloro-substituted 3,5-diphenyl-4*H*-pyrazoles **3a,b** were available by employing *tert*-butyl hypochlorite as chlorination agent.[4,5] The unknown 4-bromo-4-methyl-3,5-diphenyl-4*H*-pyrazole (**3d**) was prepared analogous to the 4,4-dibromo-3,5-diphenyl-4*H*-pyrazole (**3c**) by using base and elemental bromine (eq 3).[3] The same method[3] (eq 4) yielded the 4,4-dibromo-3,5-dimethyl-4*H*-pyrazole (**3e**).[6] Unfortunately, *tert*-butyl hypochlorite failed to convert 3,5-dimethyl-2*H*-pyrazole to the desired 4,4-dichloro-3,5-dimethyl-4*H*-pyrazole due to chlorination of the methyl groups (eq 4).



(3)



(4)

With cyclopentadiene as reaction partner in the absence of acid, no reaction of 4*H*-pyrazoles **3** occurred, but fast cycloaddition was observed with catalytic amounts of trifluoroacetic acid. As a particular advantage, the reactions of the 4-halo-3,5-diphenyl-4*H*-pyrazoles can be conveniently monitored visually by the disappearance of the yellow color. Azoalkanes of the DBH-type with halogen substituents at the methano bridge have not been previously reported, but derivatives with ethoxy groups are known.[8]

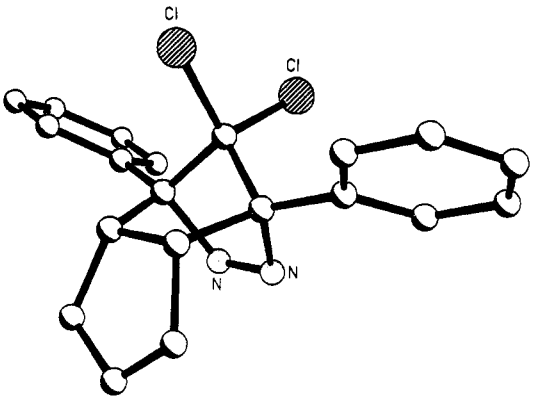
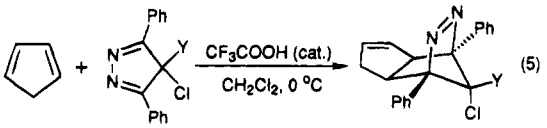


Figure 1. X-ray structure (ORTEP drawing) of the azoalkane **4a**.

On addition of acid in methylene chloride at 0 °C, the dichloro-4*H*-pyrazole **3a** gave within seconds quantitatively the new azoalkane **4a** as cycloadduct (eq 5). The *endo* stereochemistry of the 4*H*-pyrazole cycloadducts has been described elsewhere[1,2] and was proven for **4a** by X-ray analysis (Figure 1).[7a] Despite the extensive substitution in azoalkane **4a**, comparison of its structural parameters with those of the parent DBH (microwave analysis[7b]) reveals essentially the same N=N (124.7 *versus* 124.6 pm) and C–N (150.8 *versus* 150.2 pm) bond lengths.



(5)

The 4-chloro-4-methyl-4*H*-pyrazole **3b** underwent as well cycloaddition with cyclopentadiene under acid catalysis (eq 5). This reaction proceeded somewhat slower (30 min), but still considerably faster than for the corresponding 4,4-dimethyl-3,5-diphenyl-4*H*-pyrazoles (several hours, eq 2). Moreover, the cycloaddition of the 4*H*-pyrazole **3b** yielded predominantly (dr ca. 97:3) the *anti* diastereomer **4b** (relative stereochemistry of the azo linkage with respect to the chloro substituent). The relative stereochemistry of the *syn* and *anti* isomers was assigned by means of NOE effects of the methyl group on the bridgehead hydrogens (6.8 and 8.0%) and *vice versa* (0.9%) for the *syn* isomer, but by their absence for the *anti* form. The preferred formation of the *anti* diastereomer is supposedly due to stereoelectronic effects in the transition states for cycloaddition which have been examined in detail for cyclopentadienes as diene partners (e.g. 5-chlorocyclopentadiene) in Diels–Alder reactions.[9]

Clearly, the reactivity order of the 3,5-diphenyl-4*H*-pyrazoles increases with chlorination in the C-4 position (Cl, Cl > Cl, Me > Me, Me). This is expressed by the

(6) **Hazard warning!** The 4*H*-pyrazoles **3c,e** have been reported to decompose slowly.[3] In our hands, 4*H*-pyrazole **3c** was stable for at least six months when stored at −18 °C, but the 4*H*-pyrazole **3e** decomposed within days at −18 °C. When the latter was allowed to warm up to ambient temperature, quick decomposition occurred and in one case an exothermic reaction with explosion took place. An autocatalytic process seems to be responsible for the vigorous decomposition. Storage of 4*H*-pyrazole **3e** in small portions (ca. 1 g) and refrigeration immediately after recrystallization is essential.

(7) (a) Atomic parameters, isotropic and anisotropic displacement coefficients, bond lengths, and bond angles for the azoalkane **4a** may be obtained from the Fachinformationszentrum Karlsruhe, Gesellschaft für wissenschaftlich-technische Information mbH, D-76344 Eggenstein-Leopoldshafen, FRG, by quoting the depository number CSD-400928, the names of the authors, and the journal citation. This information is also available from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK. (b) For a microwave analysis of the parent DBH cf. R. D. Suenram, *J. Mol. Struct.* **1976**, *33*, 1.

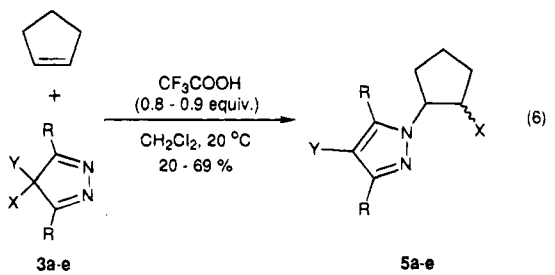
(8) Buchwalter, S. L.; Closs, G. L. *J. Am. Chem. Soc.* **1979**, *101*, 4688.
(9) Macaulay, J. B.; Fallis, A. G. *J. Am. Chem. Soc.* **1990**, *112*, 1136.

reaction times (seconds, minutes, hours), the yields (96, 82, 47%) and by the required amounts of acid catalyst. Thus, 0.9 equiv of trifluoroacetic acid was necessary to ensure efficient reaction of the 4,4-dimethyl-4*H*-pyrazole **1**, but for the derivatives **3a,b** catalytic amounts (ca. 5 mol %) were sufficient. Moreover, since acid-catalyzed cycloreversion of the cycloadducts is retarded by increasing electron demand of the 4*H*-pyrazole partners,[1] the azoalkanes **4a,b** persist while cycloadducts **2** readily revert.

The enhanced reactivity of the 4-chloro-4*H*-pyrazoles was corroborated by MO calculations of the LUMO energies of the corresponding 4*H*-pyrazoles. As a consequence of the inverse electron demand, a decrease in the LUMO energy of the heterodiene should accelerate the cycloaddition and enhance the stability of the adducts. For example, the LUMO energies of the 4,4-disubstituted 3,5-diphenyl-4*H*-pyrazoles were estimated by the AM1 method[10] to be −1.05, −1.32, and −1.58 eV for **1** (Me, Me), **3b** (Me, Cl), and **3a** (Cl, Cl). The observed reactivity order **3a** > **3b** > **1** is, thus, rationalized in terms of lowering of the LUMO energies by chlorine substitution at the C-4 position.

A similar high reactivity was expected for the 4-bromo-4*H*-pyrazoles **3c−e** due to the similar electronegativities of Br and Cl. Indeed, with catalytic amounts of trifluoroacetic acid present, all 4*H*-pyrazoles **3c−e** reacted instantly with cyclopentadiene, even faster than the most reactive dichloro-4*H*-pyrazole **3a**; however, complex product mixtures were obtained for the 3,5-diphenyl derivatives **3c,d**. Nevertheless, for the 3,5-dimethyl case **3e** the azoalkane cycloadduct **4e** was detected by ^{1}H NMR spectroscopy; unfortunately, the latter proved to be rather labile and decomposed on attempted workup (column chromatography). Side reactions of 4*H*-pyrazoles with dienes, in which the 4*H*-pyrazole functions as a 2π rather than a 4π partner, have been observed [2d,11] but not for any of the halo-substituted derivatives **3**.

The exceptionally high reactivity of the 4-halo-4*H*-pyrazoles **3** with cyclopentadiene encouraged the examination of less reactive olefins, e.g. cyclopentene, which is recognized to be a particularly sluggish dienophile in Diels−Alder reactions with inverse electron demand.[12] Instead of cycloaddition, addition of the 4-halo-4*H*-pyrazole to the cyclopentene (adducts **5**) was observed (eq 6) in the presence of trifluoroacetic acid (0.8−0.9



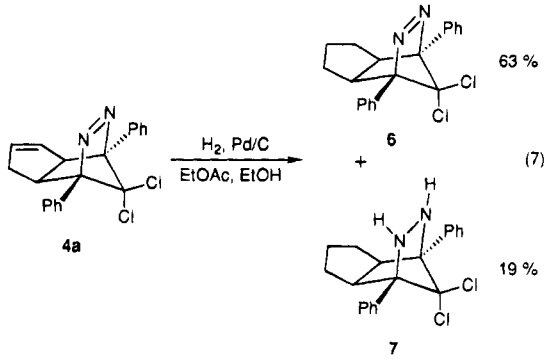
(6)

equiv). Thus, the dienophilic reactivity of cyclopentene toward these pyrazoles is insufficient for cycloaddition to compete and, consequently, other reaction modes prevail.

The bromo derivatives **3c−e** were more reactive toward cyclopentene than the chloro cases **3a,b**, as visualized by faster decoloration (1−5 min for **3c,d**) of the reaction mixture. For the chloro-substituted 4*H*-pyrazoles **3a,b** the reaction had to be stopped before complete conversion due to deterioration of the product mixture. Thus, only 20% of the novel addition product **5a** was isolated for the 4,4-dichloro-4*H*-pyrazole **3a** (eq 6) and traces for the monochloro derivative **3b**. Complete conversion was observed for the bromo derivatives **3c−e**.

The constitution of adducts **5** was unambiguously determined by 2D-INADEQUATE NMR experiments for **5e**; clearly, only one stereoisomer (*cis* or *trans*) was formed. We propose that the mechanism for the formation of the addition products **5** entails electrophilic halogenation. Unquestionably, a proton source is essential, but whether analogous to *N*-halo compounds such as *N*-bromosuccinimide[14] [the 2*H*-pyrazole, produced through acid-catalyzed 4*H* ⇌ 2*H* tautomerism (eq 1), or directly the protonated 4*H*-pyrazole, akin to 2,4,4,6-tetrabromo-2,5-cyclohexadienone,[15] halogenates the cyclopentene] cannot be answered at this point.

The azoalkane **4a** was hydrogenated by using palladium on charcoal as catalyst. Interestingly, whereas for the *gem*-dimethyl azoalkane **2** this method has been reported to give the azoalkane with reduced C=C double bond in high yield,[2b] for the *gem*-dichloro-substituted derivative **4a**, besides azoalkane **6**, the hydrazine derivative **7** was isolated in appreciable amounts (eq 7); its formation increased slowly on prolonged hydrogenation.



(7)

In contrast to other bicyclic hydrazines, which are readily autoxidized to the azoalkanes,[13] hydrazine **7** persists sufficiently to permit full characterization. Autoxidation occurred only slowly (ca. 10% in 5 h) in aerated solutions, as monitored by UV and ^{1}H NMR spectroscopy. Apparently, the electron-accepting chloro substituents stabilize the hydrazine **7** toward oxidation. Indeed, as precedent for a persistent α-chlorinated hydrazine we cite the related 1,4-dichloro-2,3-diazabicyclo[2.2.2]octane.[16]

The spectroscopic properties of the chloro-substituted azoalkanes **4a,b** and **6** (λ_{max} = 362−364 nm) were quite

(10) For the AM1 method, cf. Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902. The VAMP program was used by employing a Silicon Graphics Iris Indigo workstation: Rauhut, G.; Chandrasekhar, J.; Clark, T., *VAMP 4.4* (Universität Erlangen, Erlangen, FRG, 1992).

(11) Fagan, P. J.; Neidert, E. E.; Nye, M. J.; O'Hare, M. J.; Tang, W.-P. *Can. J. Chem.* **1979**, *57*, 904.

(12) (a) Sauer, J.; Wiest, H. *Angew. Chem.* **1962**, *74*, 353. *Angew. Chem. Int. Ed. Engl.* **1962**, *1*, 269. (b) Sauer, J. *Angew. Chem.* **1967**, *79*, 76. *Angew. Chem. Int. Ed. Engl.* **1967**, *6*, 16.

(13) (a) Cohen, S. G.; Zand, R.; Steel, C. *J. Am. Chem. Soc.* **1961**, *83*, 2895. (b) Wang, C.-X.; Sheridan, R. S. *Tetrahedron Lett.* **1993**, *34*, 5673.

(14) (a) Pizey, J. S. In *Synthetic Reagents*, Wiley: New York, 1974; Vol. 2, pp 26−27. (b) Dalton, D. R.; Dutta, V. P. *J. Chem. Soc. B* **1971**, 85.

(15) (a) Brittain, J. M.; de la Mare, P. B. D. In *The chemistry of halides, pseudohalides and azides*; Patai, S., Rappaport, Z., Eds.; Wiley: New York, 1983; Part 1, p 511. (b) Tsubota, M.; Iso, M.; Suzuki, K. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 1252.

(16) Lüttke, W.; Schabacker, V. *Liebigs Ann. Chem.* **1966**, *698*, 86.

similar to the *gem*-dimethyl derivatives **2** (λ_{max} = 360–362 nm).[1] However, while the alkyl-substituted azoalkanes **2** afford readily the corresponding housanes on photoinduced loss of molecular nitrogen,[1] the chlorinated azoalkanes **4a,b** and **6** turned out to be quite photoreluctant when irradiated with the UV lines of a CW argon ion laser. The slow photochemical conversion was monitored by ^{1}H NMR spectroscopy, which revealed a complex product mixture and not even traces of the expected housanes (derivatives of the interesting 5,5-dihalobicyclo-[2.1.0]pentane-type[17,18]) could be detected. The low photoreactivity indicates an unusually high activation energy for deazetation of the excited azoalkanes **4a,b** and **6**.[19]

The azoalkanes **4a,b** and **6** were also quite reluctant toward thermal denitrogenation; at 110 °C very slowly several unidentified products were observed. This is again contrary to the azoalkanes **2**, which in boiling toluene (ca. 110 °C) gave the expected housanes in high yield within hours.[1] The thermal persistence and the photoreluctance of the 7-chloro-2,3-diazabicyclo[2.2.1]-hept-2-enes clearly demonstrate that such substitution stabilizes DBH-type azoalkanes toward deazetation. Consequently, it is not surprising that the novel 2-halo-substituted 1,3-cyclopentanediyl triplet biradicals[18] could not be generated in time-resolved laser-flash and EPR matrix isolation studies. Thus, since electronic substituent effects in 1,3-cyclopentanediyl biradicals are currently under intensive investigation,[20] it is unfortunate that triplet lifetimes and zero-field splitting parameters of the unprecedented 2-halo-substituted 1,3 biradicals[17] are not readily accessible.

The present study has shown that the 7-chloro-substituted azoalkanes **4a,b** of the 2,3-diazabicyclo[2.2.1]-hept-2-ene type are accessible through the 4*H*-pyrazole method by using cyclopentadiene as dienophile. Unexpectedly, the chloro-substituted azoalkanes **4a,b** were thermally and photochemically quite persistent toward denitrogenation. The corresponding bromo azoalkanes could not be obtained through cycloaddition of the bromo-substituted isopyrazoles **3c–e** with cyclopentadiene. Apparently, electrophilic halogenations of the dienophilic alkenes by the 4-halo-4*H*-pyrazoles compete with cycloaddition. This side reaction occurred for cyclopentene, a less reactive dienophile, and adducts **5** were obtained instead of the desired cycloadducts.

Experimental Section

General Aspects. General procedures and common analytical instruments have been described in ref 1. The X-ray analysis was carried out on a Siemens R3m/V diffractometer by using Mo Kα radiation and a graphite monochromator; the Siemens SHELXTL PLUS program, run on a MicroVAX-II station, was used for the structural analysis. Photolyses were carried out by irradiation with the 333-, 353-, and 364-nm UV lines (widened beam) of a CW argon ion laser.

Starting Materials and New Compounds. The 4,4-dichloro-3,5-diphenyl-4*H*-pyrazole (**3a**) was synthesized from 3,5-diphenyl-2*H*-pyrazole with *tert*-butyl hypochlorite[21] according to the literature procedure.[4] The 4-chloro-4-methyl-3,5-diphenyl-4*H*-pyrazole (**3b**) was prepared analogously from 4-methyl-3,5-diphenyl-2*H*-pyrazole.[5] The 4-bromo-4*H*-pyrazoles **3c–e** were obtained by bromination of the corresponding 2*H*-pyrazoles with Br_2.[3] The 4-halo-3,5-diphenyl-4*H*-pyrazoles **3a–d** are yellow with the following spectral properties: $\lambda_{max}(\epsilon)$ = 355 nm (27 000 $M^{-1}cm^{-1}$) for **3a**, 335 (37 000) for **3b**, 367 (12 000) for **3c**, and 346 (21 000) for **3d**.

The 3,5-diphenyl-2*H*-pyrazoles were obtained by treatment of the particular 1,3-diphenylpropane-1,3-dione with hydrazine,[22,23] while the 3,5-dimethyl-2*H*-pyrazole was prepared from acetylacetone and hydrazine sulfate.[24] The 1,3-diphenylpropane-1,3-dione was bought and the 2-methyl-1,3-diphenylpropane-1,3-dione was obtained by methylation of dibenzoylmethane.[25] Only the 4-bromo-4-methyl-3,5-diphenyl-4*H*-pyrazole (**3d**) is unknown and its characterization is reported below together with the other new compounds **4–6**.

4-Bromo-4-methyl-3,5-diphenyl-4*H*-pyrazole (3d). A sample of 2.00 g (8.54 mmol) of 3,5-diphenyl-2*H*-pyrazole was dissolved in 50 mL of CH_2Cl_2 and cooled by means of an ice bath. After addition of 0.50 mL (9.71 mmol) of Br_2, 40 mL of a 1.0 N aqueous Na_2CO_3 solution was added dropwise. After stirring 45 min, 50 mL of a 1.0 N aqueous NaOH solution was added. The organic layer was separated and the aqueous layer extracted twice with 30 mL of CH_2Cl_2. The combined organic layers were dried over Na_2SO_4 and the solvent was removed by distillation (40 °C/30 Torr). Recrystallization from CH_2Cl_2/*n*-pentane yielded 2.31 g (87%) of the 4*H*-pyrazole **3d** as yellow powder: mp 130–132 °C; IR (KBr) ν = 1575 cm^{-1}, 1500, 1460, 1435, 1330, 1030, 1000, 830; UV (benzene) λ_{max} (ϵ) = 346 nm (21000); ^{1}H NMR ($CDCl_3$) δ = 2.09 (s, 3 H), 7.52 (m, 6 H), 8.33 (m, 4 H); ^{13}C NMR ($CDCl_3$) δ = 25.0, 56.8, 128.0, 128.6, 128.8, 131.7, 173.0. Anal. Calcd for $C_{16}H_{13}BrN_2$ (313.2): C, 61.36; H, 4.18; N, 8.95. Found: C, 61.49; H, 3.95; N, 8.85.

8,8-Dichloro-(1α,4α,4aα,7aα)-4,4a,7,7a-tetrahydro-1,4-diphenyl-1,4-methano-1*H*-cyclopenta[*d*]pyridazine (4a). A sample of 1.04 g (3.60 mmol) of the 4*H*-pyrazole **3a** was dissolved in 20 mL of CH_2Cl_2 and cooled by means of an ice bath. After addition of 1 mL of freshly distilled cyclopentadiene, 20 μL (0.260 mmol) of CF_3COOH were administered and decoloration of the solution occurred within a few seconds. Solid K_2CO_3 (2.0 g) was added and after stirring 5 min, the solution was filtered. Since complete removal of the solvent resulted in rapid deterioration, the solution was only concentrated to ca. 2 mL (40 °C/30 Torr) and the residue was submitted to column chromatography on silica gel and CH_2Cl_2 as eluent. Of the azoalkane **4a** were obtained 1.22 g (96%) as colorless powder: mp 151–152 °C dec; R_f = 0.87 (SiO_2, CH_2Cl_2); IR (KBr) ν = 1605 cm^{-1}, 1575, 1495, 1435, 755; UV (benzene) λ_{max} (ϵ) = 330 nm (sh, 20), 351 (sh, 80), 362 (130); ^{1}H NMR ($CDCl_3$) δ = 2.34 (m, 2 H), 3.87 (ddd, 2 × ^3J = 8.2 Hz, ^3J = 6.6 Hz, 1 H), 4.28 (m, 1 H), 5.53 (ddd, ^3J = 5.8 Hz, 3 × ^3J or ^4J = 2.1 Hz, 1 H), 5.63 (ddd, ^3J = 5.8 Hz, 3 × ^3J or ^4J = 2.1 Hz, 1 H), 7.59 (m, 6 H), 8.05 (m, 4 H); ^{13}C NMR ($CDCl_3$) δ = 31.7, 43.2, 56.8, 96.2, 97.4, 101.9, 125.8, 128.2, 128.5, 128.6, 129.2, 129.4, 131.8, 131.9, 134.8. Anal. Calcd for $C_{20}H_{16}Cl_2N_2$ (355.3): C, 67.62; H, 4.54; N, 7.89. Found: C, 67.87; H, 4.54; N, 7.95.

***anti*-8-Chloro-8-methyl-(1α,4α,4aα,7aα)-4,4a,7,7a-tetrahydro-1,4-diphenyl-1,4-methano-1*H*-cyclopenta[*d*]py-**

(17) (a) Wiberg, K. B.; Burgmaier, G. J. *Tetrahedron Lett.* **1969**, *10*, 317. (b) Wiberg, K. B.; Burgmaier, G. J.; Shen, K.; La Placa, S. J.; Hamilton, W. C.; Newton, M. D. *J. Am. Chem. Soc.* **1972**, *94*, 7402. (c) Warner, P.; LaRose, R.; Lee, C.; Clardy, J. C. *J. Am. Chem. Soc.* **1972**, *94*, 7607. (d) Warner, P. M.; LaRose, R. C.; Palmer, R. F.; Lee, C.; Ross, D. O.; Clardy, J. C. *J. Am. Chem. Soc.* **1975**, *97*, 5506. (e) For fluorine substitution see Sargeant, P. B. *J. Am. Chem. Soc.* **1972**, *91*, 3061. (f) For 1,4-diphenyl substitution see Coms, F. D.; Dougherty, D. A. *J. Am. Chem. Soc.* **1989**, *111*, 6894 and Adam, W.; Platsch, H.; Wirz, J. *J. Am. Chem. Soc.* **1989**, *111*, 6896.

(18) (a) Chesnut, D. B.; Ferguson, S.; Smith, L. D.; Porter, N. A. *Tetrahedron Lett.* **1972**, *12*, 3713. (b) Getty, S. J.; Hrovat, D. A.; Borden, W. T. *J. Am. Chem. Soc.* **1994**, *116*, 1521.

(19) (a) Adam, W.; Nau, W. M.; Sendelbach, J. *J. Am. Chem. Soc.* **1994**, *116*, 7049. (b) Engel, P. S.; Horsey, D. W.; Keys, D. E.; Nalepa, C. J.; Soltero, L. R. *J. Am. Chem. Soc.* **1983**, *105*, 7108.

(20) (a) Adam, W.; Reinhard, G.; Platsch, H.; Wirz, J. *Ibid.* **1990**, *112*, 4570. (b) Adam, W.; Fröhlich, L.; Nau, W. M.; Korth, H.-G.; Sustmann, R. *Angew. Chem.* **1993**, *105*, 1383. *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1339. (c) Adam, W.; Fröhlich, L.; Nau, W. M.; Wirz, J. *J. Am. Chem. Soc.* **1993**, *115*, 9824.

(21) Mintz, M. J.; Walling, C. *Org. Synth.* **1969**, *49*, 9.

(22) Knorr, L.; Duden, P. *Ber.* **1893**, *26*, 111.

(23) Lipp, M.; Dallacker, F.; Munnes, S. *Ann.* **1958**, *618*, 112.

(24) Wiley, R. H.; Hexner, P. E. *Organic Syntheses;* Wiley: New York, 1963; Vol. 4, p 351.

(25) Bickel, C. L. *J. Am. Chem. Soc.* **1945**, *67*, 2045.

ridazine (*anti*-4b). A sample of 2.00 g (7.40 mmol) of the 4*H*-pyrazole **3b** was dissolved in 40 mL of CH_2Cl_2 and cooled by means of an ice bath. After addition of 2 mL of freshly distilled cyclopentadiene and 50 μL (0.649 mmol) of CF_3COOH, decoloration of the solution occurred within ca. 30 min. The workup followed exactly the procedure described above for azoalkane **4a**. Of the azoalkane *anti*-**4b** was obtained 2.03 g (82%) as colorless powder: mp 140–142 °C, R_f = 0.74 (SiO_2, CH_2Cl_2), in 97 ± 1% diastereomeric purity, as determined by quantitative ^1H NMR analysis and NOE experiments. The following spectral data refer to the *anti* isomer: IR (KBr) ν = 1585 cm^{-1}, 1565, 1480, 1430, 735, 725; UV (benzene) λ_{max} (ϵ) = 333 nm (sh, 20), 355 (sh, 80), 366 (130); ^1H NMR ($CDCl_3$) δ = 0.83 (s, 3 H), 2.26 (m, 2 H), 3.94 (ddd or *ps*-q, 3 × ^3J = 7.7 Hz, 1 H), 4.36 (m, 1 H), 5.56 (m, 2 H), 7.52 (m, 6 H), 8.00 (m, 4 H); ^{13}C NMR ($CDCl_3$) δ = 19.3, 31.2, 44.7, 58.3, 88.7, 95.3, 96.3, 126.5, 127.5, 127.8, 128.5, 128.6, 133.7, 133.8, 134.2. Anal. Calcd for $C_{21}H_{19}ClN_2$ (334.8): C, 75.32; H, 5.72; N, 8.37. Found: C, 75.51; H, 5.66; N, 8.42.

***syn*-8-Chloro-8-methyl-(1α,4α,4aα,7aα)-4,4a,7,7a-tetrahydro-1,4-diphenyl-1,4-methano-1*H*-cyclopenta[*d*]pyridazine (*syn*-4b)** was not isolated. It possesses an R_f value of 0.61 (SiO_2, CH_2Cl_2) and the following ^1H NMR data ($CDCl_3$): δ = 1.57 (s, 3 H), 2.24 (m, 2 H), 3.60 (ddd or *ps*-q, 3 × ^3J = 7 Hz, 1 H) [6.8%], 4.06 (m, 1 H) [8.0%], 5.4 (m, 2 H), 7.45 (m, 6 H), 7.88 (m, 4 H) [2.5%]. In square brackets are given the NOE effects due to irradiation of the *endo*-8-methyl group.

4-Chloro-2-(α-chlorocyclopentyl)-3,5-diphenyl-2*H*-pyrazole (5a). A sample of 140 mg (0.484 mmol) of the 4*H*-pyrazole **3a** was dissolved in 8 mL of CH_2Cl_2. After addition of 0.5 mL of cyclopentene and 35 μL (0.454 mmol) of CF_3COOH, the solution was stirred for 30 min, but decoloration of the yellow solution was not complete. Solid K_2CO_3 (2.0 g) was added and stirring was continued for 5 min. The solution was filtered and concentrated to ca. 2 mL, and the residue was purified by column chromatography on silica gel with CH_2Cl_2 as eluent to afford 34.0 mg (20%) of the adduct **5a** as colorless powder: mp 87–89 °C, R_f = 0.82 (SiO_2, CH_2Cl_2); IR (KBr) ν = 1560 cm^{-1}, 1475, 1330, 870, 740; ^1H NMR ($CDCl_3$) δ = 1.94 (m, 3 H), 2.20 (m, 2 H), 2.51 (m, 1 H), 4.61 (*ps*-q, ^3J = 7.3 Hz, 1 H), 4.76 (*ps*-q, ^3J = 6.8 Hz, 1 H), 7.58 (m, 8 H), 7.99 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ = 21.6, 31.1, 34.9, 63.0, 67.8, 106.7, 127.4, 128.1, 128.4, 128.8, 129.2, 130.2, 128.5, 132.0, 142.0, 146.9. Anal. Calcd for $C_{20}H_{18}Cl_2N_2$ (357.3): C, 67.24; H, 5.08; N, 7.84. Found: C, 67.29; H, 5.19; N, 7.58.

4-Bromo-2-(α-bromocyclopentyl)-3,5-diphenyl-2*H*-pyrazole (5c). A sample of 500 mg (1.32 mmol) of the 4*H*-pyrazole **3c** was dissolved in 15 mL of CH_2Cl_2. After addition of 1 mL of cyclopentene and 81 μL (1.05 mmol) of CF_3COOH, decoloration of the yellow reaction mixture occurred within a few seconds. Solid K_2CO_3 (2.0 g) was added and stirring was continued for 5 min. The solution was filtered and concentrated to ca. 2 mL, and the residue was purified by column chromatography on silica gel with CH_2Cl_2 as eluent to afford 152 mg (26%) of adduct **5c** as colorless powder: mp 104–105 °C, R_f = 0.86 (SiO_2, CH_2Cl_2); IR (KBr) ν = 1460 cm^{-1}, 1435, 1290, 970, 760; ^1H NMR ($CDCl_3$) δ = 2.00 (m, 5 H), 2.53 (m, 1 H), 4.70 (*ps*-q, ^3J = 7.0 Hz, 1 H), 4.76 (*ps*-q, ^3J = 7.0 Hz, 1 H), 7.48 (m, 8 H), 7.96 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ = 22.5, 31.2, 35.7, 53.2, 68.3, 92.5, 127.8, 128.1, 128.3, 128.7, 129.4, 130.4, 128.5, 132.4, 143.7, 148.6. Anal. Calcd for $C_{20}H_{18}Br_2N_2$ (446.2): C, 53.84; H, 4.07; N, 6.28. Found: C, 53.67; H, 4.16; N, 6.31.

2-(α-Bromocyclopentyl)-4-methyl-3,5-diphenyl-2*H*-pyrazole (5d). A sample of 250 mg (0.800 mmol) of the 4*H*-pyrazole **3d** was dissolved in 10 mL of CH_2Cl_2. After addition of 1 mL of cyclopentene and 55 μL (0.714 mmol) of CF_3COOH, decoloration of the yellow reaction mixture occurred within a few seconds. Solid K_2CO_3 (1.0 g) was added and stirring was continued for 5 min. The solution was filtered and concentrated to ca. 2 mL, and the residue was purified by column chromatography on silica gel with CH_2Cl_2 as eluent to afford 162 mg (53%) of adduct **5d** as colorless powder: mp 79–82 °C, R_f = 0.67 (SiO_2, CH_2Cl_2); IR (KBr) ν = 1585 cm^{-1}, 1545, 1445, 1430, 1295, 1000, 720; ^1H NMR ($CDCl_3$) δ = 2.02 (m, 5 H), 2.12 (s, 3 H, 4-CH_3) 2.53 (m, 1 H), 4.67 (*ps*-q, ^3J = 7.3 Hz, 1 H), 4.79 (*ps*-q, ^3J = 7.3 Hz, 1 H), 7.45 (m, 8 H), 7.75 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ = 9.9, 22.6, 31.3, 35.8, 54.0, 67.4, 112.0, 127.2, 127.7, 128.4, 128.57, 128.64, 130.4, 134.4, 143.1, 149.9. Anal. Calcd for $C_{21}H_{21}BrN_2$ (381.3): C, 66.15; H, 5.55; N, 7.35. Found: C, 66.40; H, 5.56; N, 7.21.

4-Bromo-2-(α-bromocyclopentyl)-3,5-dimethyl-2*H*-pyrazole (5e). A sample of 1.14 g (4.49 mmol) of the 4*H*-pyrazole **3e** was dissolved in 30 mL of CH_2Cl_2. After addition of 1.5 mL of cyclopentene and 310 μL (4.02 mmol) of CF_3COOH, the solution was stirred for 15 min. Solid K_2CO_3 (3.0 g) was added and stirring was continued for 5 min. The solution was filtered and concentrated to ca. 2 mL, and the residue was purified by column chromatography on silica gel with CH_2Cl_2 as eluent, followed by Kugelrohr distillation (bp 97–99 °C/0.01 Torr), to afford 940 mg (65%) of adduct **5e** as colorless powder: mp 69–71 °C; R_f = 0.66 (SiO_2, CH_2Cl_2); IR (KBr) ν = 1535 cm^{-1}, 1465, 1415, 1345, 1300, 1260, 1220, 1060; ^1H NMR ($CDCl_3$) δ = 1.98 (m, 3 H), 2.16 (m, 2 H), 2.20 (s, 3 H), 2.30 (s, 3 H), 2.47 (m, 1 H), 4.45 (*ps*-q, ^3J = 7.2 Hz, 1 H), 4.65 (*ps*-q, ^3J = 6.8 Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ = 10.35, 12.44, 22.4, 30.1, 35.6, 53.6, 68.9, 94.0, 137.7, 146.5; MS (70 eV), *m/z* (%) 324 (8), 322 (15) and 320 (8) [M^+], 243 (8) and 241 (10) [M^+ – Br], 177 (50) and 175 (56) [M^+ – C_5H_6Br], 176 (98) and 174 (100) [M^+ – C_5H_7Br], 173 (10), 95 (19) [M^+ – $C_5H_7Br_2$], 67 (48) [$C_5H_7^+$], 66 (10), 65 (14), 42 (11), 41 (16), 39 (19). Anal. Calcd for $C_{10}H_{14}Br_2N_2$ (322.04): C, 37.30; H, 4.38; N, 8.70. Found: C, 37.32; H, 4.20; N, 8.75. The structural assignment was corroborated by 2D-INADEQUATE experiments.

Catalytic Hydrogenation of Azoalkane 4a. A sample of 950 mg (2.67 mmol) of azoalkane **4a** was dissolved in 20 mL of ethyl acetate and 5 mL of EtOH. After addition of Pd on charcoal catalyst (ca. 100 mg), hydrogenation was conducted at atmospheric pressure for 4 h. The catalyst was removed by filtration, the solution concentrated to ca. 2 mL, and the residue submitted to silica gel column chromatography with CH_2Cl_2 as eluent. As first fraction, 601 mg (63%) of azoalkane **6** was obtained as colorless powder: mp 131–132 °C, R_f = 0.88 (SiO_2, CH_2Cl_2). As second fraction, 182 mg (19%) of hydrazine **7** were obtained as colorless powder: mp 105–106 °C, R_f = 0.63 (SiO_2, CH_2Cl_2). This product was slowly autoxidized (in solution) to azoalkane **6** as monitored by UV and ^1H NMR spectroscopy.

(1α,4α,4aα,7aα)-4,4a,5,6,7,7a-Hexahydro-8,8-dichloro-1,4-diphenyl-1,4-methano-1*H*-cyclopenta[*d*]pyridazine (6): IR (KBr) ν = 1590 cm^{-1}, 1570, 1485, 1475, 1430, 780, 765; UV (benzene) λ_{max} (ϵ) = 331 nm (sh, 30), 353 (sh, 80), 364 (110); ^1H NMR ($CDCl_3$) δ = 1.63 (br m), 3.70 (m, 2 H), 7.55 (m, 6 H), 8.00 (m, 4 H); ^{13}C NMR ($CDCl_3$) δ = 25.5, 28.2, 48.8, 97.6, 102.9, 128.3, 128.4, 129.1, 132.1. Anal. Calcd for $C_{20}H_{18}Cl_2N_2$ (357.3): C, 67.24; H, 5.08; N, 7.84. Found: C, 67.08; H, 4.79; N, 7.80.

(1α,4α,4aα,7aα)-2,3,4,4a,5,6,7,7a-Octahydro-8,8-dichloro-1,4-diphenyl-1,4-methano-1*H*-cyclopenta[*d*]pyridazine (7): IR (KBr) ν = 3265, 3245, and 3200 cm^{-1} (NH), 1585, 1565, 900, 840, 825; ^1H NMR ($CDCl_3$) δ = 1.77 (br m, 6 H), 3.46 (m, 2 H), 4.32 (s, 2 H), 7.65 (m, 6 H), 7.76 (m, 4 H); ^{13}C NMR ($CDCl_3$) δ = 26.3, 29.3, 48.3, 101.2, 127.5, 128.1, 128.4, 128.5, 134.8. Anal. Calcd for $C_{20}H_{20}Cl_2N_2$ (359.3): C, 66.86; H, 5.61; N, 7.80. Found: C, 66.58; H, 5.55; N, 7.52.

Acknowledgment. We express our gratitude to the Deutsche Forschungsgemeinschaft for financial support. W.M.N. thanks the Fonds der Chemischen Industrie for a Kekulé doctoral fellowship (1992–1994).

Supplementary Material Available: Crystallographic section, data collection, and structural analysis and refinement of the X-ray analysis of azoalkane **4a** (1 page). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.