SYNTHESIS OF CYCLOHEPTA-1,3,5-TRIENES BY THE REACTION OF AROMATIC HYDROCARBONS WITH DIAZO COMPOUNDS IN THE PRESENCE OF TRANSITION METAL COMPLEXES

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A preparative method has been developed for the synthesis of cyclohepta-1,3,5-trienes, using the reaction of aromatic hydrocarbons with diazomethane, methyldiazoacetate, adamantanoyldiazomethane, and 1-diazo-3-phenylpropan-2-one, with rhodium trifluoroacetate as catalyst. The order of activity and the relative reactivity coefficients of substituted benzenes have been determined, and the link between these characteristics and the energy of the highest occupied molecular orbital of the aromatic ring has been established. In catalyzed reactions of benzenes with diazomethane or methyldiazoacetate, leading to cycloheptatrienes, effects of chemical polarization of the ring have not been observed.

The cycloaddition of carbenes generated from diazo compounds (DAC) in the presence of Cu and/or Rh complexes to benzenes is one of the most promising methods for the synthesis of cyclohepta-1,3,5-trienes (CHT) [1-5], this route having been particularly well reported as an example of the reaction of benzene and its derivatives with alkyldiazoacetates [4-7] and also with diazomethane (DAM) [8, 9].

In the present work we report the results of a detailed study of the reactions of benzene and its derivatives with the diazo compounds DAM, methyldiazoacetate (MDA), adamantanoyldiazomethane (I), 1-diazo-3-phenylpropan-2-one (II), 9-diazofluorenone (III), and diazodimedon (IV), under the influence of complexes of V, Fe, Co, Ni, Cu, Zr, Mo, Rh, Pd, Ag, W, Ir, Hg, Cl, Pr, and Nd. In this work, we have also studied the way in which the reactivity of carbenes in the cycloaddition process with arenes is affected by the nature and structure of substituents on the arene benzene nucleus.

We studied the effect of the nature and structure of the components of the catalyst (Cat) and the process conditions on the yield of cyclohepta-1,3,5-triene (V) in a typical reaction for the catalytic methylenation of benzene by DAM. The experiments were carried out by adding a solution of DAM in benzene at 80°C to a solution of catalyst, in molar proportions C_6H_6:DAM:Cat = 1000:50:1, or by passing a given quantity of gaseous DAM through a solution of catalyst in benzene.

It turned out that the yield of (V) was strongly dependent on the nature of the central atom of the catalyst and the structure of the anion linked to the metal, and varied between limits of 1 to 100%: Rh/C (100%), $Rh_2(OCOCF_3)_4$ (57%), CuCl (39%), CuBr (37%), $Rh_2(OCOMe)_4$ (17%), activated carbon (15%), $CuSO_4$ (5%), $Cu(OSO_2CF_3)_2$ (4%), $Cu(salicylate)_2$ (3%), $AgNO_3$ (2%), $Mo(CO)_6$ (2%), $W(CO)_6$ (2%), $Cr(acac)_3$ (1%), $Rh(CO)_2Cl$ (1%), Al_2O_3 (1%), SiO_2 (1%), $NdCl_3$ (1%), $PrCl_3$ (1%).

The mononuclear complexes of rhodium $RhCl_3$, $Rh(acac)_3$, $Rh(PPh_3)_3Cl$, and also the compounds Pt/Al_2O_3, $VO(acac)_2$, $FeBr_2$, $Fe(acac)_3$, CoI_2, $Co(acac)_2$, $Co(acac)_3$, $Ni(acac)_2$, Cu(N-α-phenylethylsalicylaldiminate)$_2$, $Zr(acac)_4$, Pd/C, $Pd(OAc)_2$, $PdCl_2$, $PdCl_2(PPh_3)_2$, $Pd(acac)_2$, K_2IrCl_6, $Hg(OAc)_2$, and $CeCl_3$ in general appeared to be inactive in this reaction.

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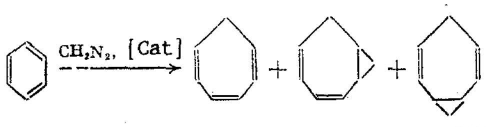
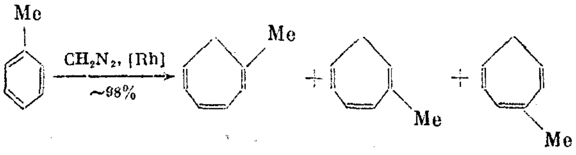
Since the greatest yields of (V) were obtained using Rh/C and rhodium trifluoroacetate (TFAR) as catalysts, all subsequent experiments were carried out with the binuclear Rh-complex, which although inferior to Rh/C with respect to activity, nevertheless in contrast to the latter gives reproducible results. Moreover, the reaction of benzene and DAM in the presence of TFAR at 10°C and with molar proportions of reagents Rh:DAM:C_6H_6 equal to 1:200:4000 leads to (V) with a yield of ca. 95%. If the concentration of DAM in the reaction mixture is increased to a molar proportion (with respect to C_6H_6) of 1:15, the formation of bicyclo[5.1.0]octa-2,4-diene (VI) and bicyclo[5.1.0]octa-2,5-diene (VII), with a combined yield of about 5%, is observed.

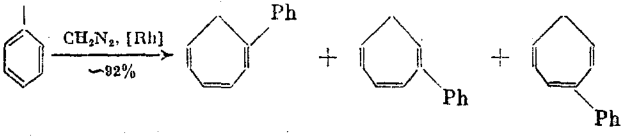


(V) (VI) (VII)

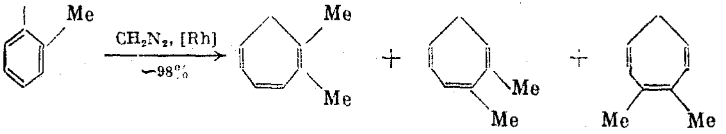
Under the conditions adopted (10°C, Rh:DAM:arene = 1:200:4000) toluene, diphenyl, and the xylenes can be similarly efficiently methylenated, to give corresponding alkyl- and aryl-substituted CHT (VIII)-(XVIII) in yields of 92-98%.



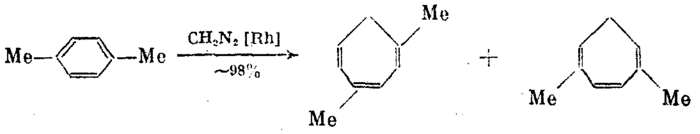
(VIII), 24% (IX), 26% (X), 50%



(XI), 23% (XII), 28% (XIII), 49%

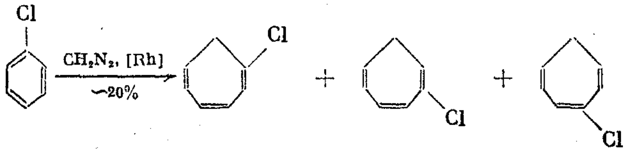


(XIV), 18% (XV), 30% (XVI), 52%

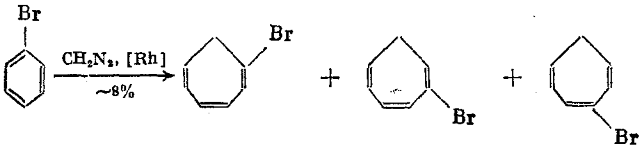


(XVII), 75% (XVIII), 25%

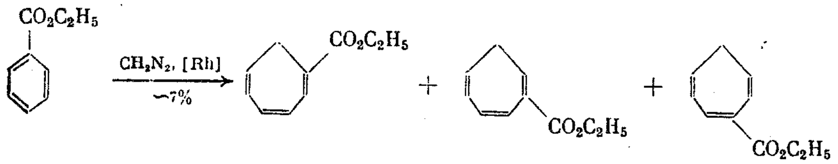
In contrast, the reaction of DAM with chlorobenzene, bromobenzene, and ethylbenzoate gives cycloheptatrienes (XIX)-(XXVII) in yields of only 7-20%, and anisole, benzaldehyde, benzonitrile, nitrobenzene, and pyridine in general show no reaction with DAM under the specified conditions.



(XIX) 25% (XX) 11% (XXI) 64%

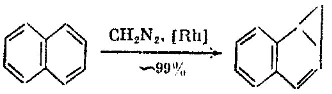


(XXI) 19% (XXIII) 27% (XXIV) 55%



(XXV) 12% (XXVI) 33% (XXVII) 55%

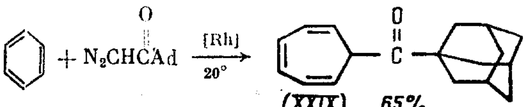
The reaction of DAM with naphthalene proceeds with exceptionally high directional specificity, producing 4,5-benzobicyclo[4.1.0]hept-2-ene (XXVIII) in a yield of about 98%. All our attempts to isomerize (XXVIII) to benzocyclohepta-1,3,5-triene proved to be unsuccessful.



(XXVIII)

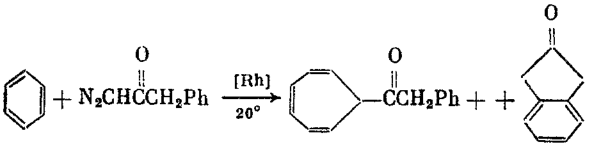
The structure of the cycloheptatrienes obtained (VIII)-(XXVIII) was confirmed by comparison of their physicochemical properties with data in the literature [8-14]. The isomeric composition of the substituted cycloheptatrienes was determined from PMR spectra, using chemical shifts and the multiplicity of signals due to the hydrogen atom at the C^7 position in reference trienes [11-14]. The results obtained indicate that, regardless of the nature of the substituents on the benzene ring, for the most part (≥49%) the corresponding isomers (X), (XIII), (XVI), (XVIII), (XXI), (XXIV), and (XXVII) are formed, with the substituent at atom C^3 on the cycloheptatriene molecule. It should be noted that the cycloaddition of carbenes to the six-electron π-systems of substituted aromatic compounds takes place in the main at the C^3—C^4 bond in the benzene ring, which according to [15] has the greatest electron density and the highest reactivity index (partial electron densities of the highest occupied molecular orbital) [15, 16]. Thus, in naphthalene the carbene attacks the C^2—C^3 bond, for which the sum of the partial electron densities making up this carbon—carbon bond has the highest value (0.500).

The reaction of benzene with diazo compounds of more complex structure has also been studied. The reaction of C_6H_6 with (I) in the presence of TFAR (20°C) produces cyclohepta-2,4,6-trienyladamantylketone (XXIX) with a yield of about 65%, whereas in the case of (II), together with the ketone (XXX) (yield 64%), indanone-2 (XXXI) is formed with a yield of 18%, apparently the product of intramolecular insertion of the benzylcarbonylcarbene at a C—H link of the benzene nucleus.



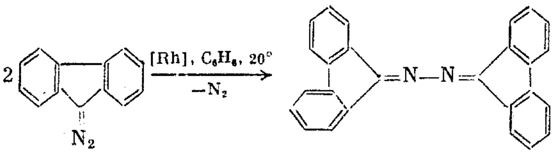
(XXIX), 65%

(I)



(II) (XXX), 64% (XXXI), 18%

Unlike the diazo compounds referred to above, (III) is converted under the influence of TFAR to ketazine (XXXII) with a yield of about 98%, and diazodimedon (IV) in general resists change.



(III) (XXXII)

TABLE 1. Relative Reactivity of Arenes in Rh-Catalyzed Reactions with Diazo Compounds

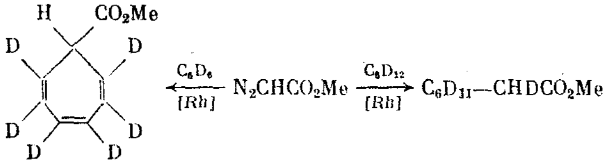
	DAM	MDA	E_{ion}, eV [17]
Naphthalene	1,71	–	8,13
ortho-Xylene	1,11	1,53	8,45
meta-Xylene	–	1,38	8,50
para-Xylene	1,09	1,30	8,37
Toluene	1,02	1,22	8,72
Anisole	0	1,20	8,42
Benzene	1	1	9,24
Diphenyl	0,93	–	8,41
Chlorobenzene	0,16	0,02	9,06
Ethylbenzoate	0,07	0,01	–
Bromobenzene	0,06	–	9,04

To determine the comparative reactivity of arenes with respect to diazo compounds, we studied their reaction with DAM and MDA in the presence of TFAR using the method of concurrent reactions. The experiments were carried out at 10°C by adding the diazo compound to a solution of C_6H_6 and its derivative, these being taken in equimolar proportion at 10-20-fold molar excess with respect to the DAC (the reactivity of benzene is assumed to be unity).

As can be seen from Table 1, the reactivity of arenes increases with the accumulation on the benzene nucleus of substituents having a positive inductive effect, and is closely linked to the value of the energy of the highest occupied molecular orbital, determined by photoelectron spectroscopy (PES) [17]. The higher value of the relative reactivity for the reaction of methoxycarbonylcarbene in comparison with methylene, and also its increase as the electron density of the benzene nucleus rises, indicates the electrophilic nature of this reaction. Benzonitrile, benzaldehyde, nitrobenzene, and pyridine not only do not react with DAM and MDA, but indeed completely inhibit the formation of CHT, probably as a result of binding strongly with the rhodium atom to form stable coordination-saturated complexes which are catalytically inert in the present reaction.

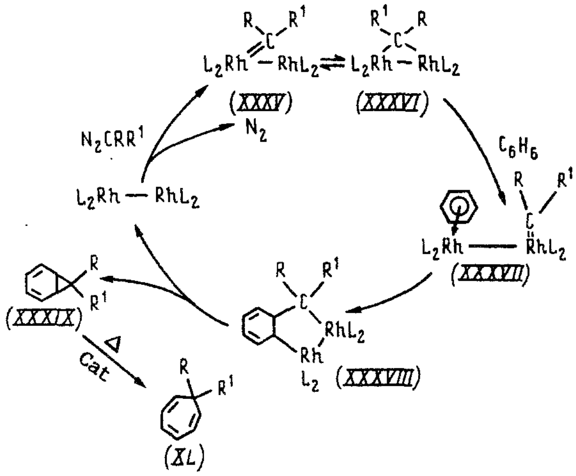
We have examined these reactions still further by the method of chemical polarization of nuclei. According to [18], the simplest carbenes react with $CDCl_3$ and CCl_4 to form insertion products across the C–D and C–Cl bonds and, as a rule, transmit the effect of chemical polarization of nuclei, which indicate the existence of a homolytic stage in this process.

In experiments on the decomposition of DAM and MDA under the influence of TFAR, the formation of ethylene and dimethyl esters of maleic and fumaric acids was observed, evidently the products of the recombination of the corresponding carbenes, and similarly in the reactions of MDA with hexadeuterobenzene and dodecadeuterocyclohexane, the corresponding hexadeutero-CHT (XXXIII) and some addition product (XXXIV) were observed. Effects due to chemical polarization of nuclei were not detected in any of these experiments.

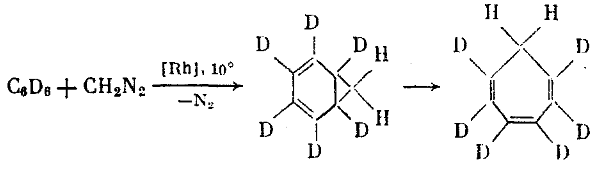


(XXXIII) (XXXIV)

From our results and data in the literature on the cycloaddition of carbenes to the benzene ring with the participation of binuclear Rh complexes, it is possible to propose a scheme in the first stage of which there occurs a reaction of DAC with the central Rh atom, to form the complexes (XXXV) and (XXXVI). Coordination of a molecule of benzene with the binuclear carbene complex (XXXV) leads to (XXXVII). Intramolecular 1,3-addition gives a metallocycle (XXXVIII). A subsequent regenerating elimination in the complex (XXXVIII) takes place with the production of a norcaradiene derivative (XXXIX). Simultaneous electrocyclic opening of the cyclopropane ring in (XXXIX) under thermal or catalytic reaction conditions [16, 19] leads to the corresponding CHT (XL).



To demonstrate that the formation of CHT results from intramolecular isomerization of a norcaradiene, we reacted DAM with hexadeuterobenzene under the influence of TFAR (10°C, C_6D_6:DAM:Rh = 1125:47:1), and obtained 1,2,3,4,5,6-hexadeuterocyclohepta-1,3,5-triene (XLI) with a selectivity of 100% in a yield of about 95%. A two-proton singlet at 2.12 ppm in the PMR spectrum of (XLI) corresponds to the two H atoms on atom C^7 of the CHT molecule, and this points unambiguously to an initial formation of norcaradiene, which by simultaneous electrocyclic opening of the cyclopropane ring is converted solely into CHT.



(XLI)

Thus, the reaction of benzene with diazo compounds, catalyzed by the binuclear rhodium complex rhodium trifluoroacetate, is a convenient preparative method for the synthesis of cycloheptatrienes.

EXPERIMENTAL

PMR and ^{13}C NMR spectra were obtained, respectively, on a Tesla BS-567 60-MHz spectrometer and on a JEOL FX-90Q 22.5-MHz spectrometer with a broad-band and off-resonance proton decoupling in $CDCl_3$ using TMS internal standard. IR spectra were recorded on a UR-20 instrument. Chromatographic analysis of the reaction mixtures was carried out on Tsvet-100 and Chrom-5 chromatographs, the columns being 120 × 0.3 cm with 5% SE-30 on a N-W-HMDS support and 370 × 0.3 cm with 15% PEG-6000 on a N-AW-HMDS support. The carrier gas was helium.

The benzene solution of diazomethane (DAM) was obtained by alkaline hydrolysis of N-nitroso-N-methylurea (NMU) with a yield of about 57% (by titration). The aromatic compounds used were ca. 99.9% pure. The cycloheptatrienes (CHT) obtained (V)-(XXVIII) were identified by comparison of their properties with literature data [6-14].

General Procedure for the Reaction of DAM with Benzene. To 0.14 mmole of catalyst (molar proportions C_6H_6:CH_2N_2:catalyst = 1000:50:1) in 2 ml benzene is added 12 ml of a benzene solution of DAM (from 1.2 g NMU); the mixture was stirred vigorously over a period of 5 min. The yield of cyclohepta-1,3,5-triene (V) is determined chromatographically, using decane as an internal standard.

Concurrent Reactions of DAM with Benzene and Its Derivatives. To 0.03 g (0.045 mmole) $Rh_2(OCOCF_3)_4$ is added a solution of DAM (from 1 g NMU) in 10 ml (0.11 mole) of benzene and 0.11 mole of the second arene (molar proportions C_6H_6:arene:CH_2N_2:Rh = 1234:1234:61:1) at 10°C with vigorous stirring over 8 min. (For naphthalene and diphenyl the molar proportion C_6H_6:arene = 4.52:1, in view of their organic solubility.) The relative reactivity was calculated from the formula

$$k_{\mathrm{rel}} = \frac{S^1}{S^0 ab}$$

where S^0 is the area of the peak due to (V), S^1 is the area of the peak due to substituted CHT, a is the molar ratio arene:C_6H_6 (based on the number of benzene nuclei), and b is the calibration factor of the substituted CHT relative to (V).

Concurrent Reactions of Methyldiazoacetate (MDA) with Benzene and Its Derivatives. To 7.81 g (0.1 mole) of benzene and 0.1 mole of the other arene in the presence of 0.0329 g (0.05 mmole) of TFAR is added 1 g (0.01 mole) of MDA (molar proportions C_6H_6:arene:MDA:Rh = 1000:1000:100:1) at 20°C over the course of 30 min with vigorous stirring. The relative reactivity was determined using the formula quoted above.

Reaction of Aromatic Compounds with Gas-Phase DAM. Gaseous DAM from 3.88 g NMU is passed in a stream of argon through a solution of TFAR (0.098 mmole) in 19 mmoles of the arene at 10°C over the course of 1 h. The products are worked up in the usual way.

Reaction of Benzene with Diazo Compounds (I)-(IV). At 22°C, with vigorous stirring, 9.6 mmoles DAC in 22 ml benzene is added to 0.092 g (0.14 mmole) TFAR (molar proportions C_6H_6:DAC:Rh = 884:34:1) over a period of 15 min. The products of reaction are filtered through Al_2O_3, the benzene is evaporated, and the residue distilled or recrystallized.

Cyclohepta-2,4,6-trienyladamantylketone (XXIX). Yield 65%, poorly crystallizing oil. ^{13}C NMR spectrum (δ, ppm): 27.94 d (CH, Ad); 36.56 t (CH_2, Ad); 37.99 t (CH_2, Ad); 46.87 s (C, Ad); 91.06 d [CH, cyclohepta-2,4,6-trienyl (CHT)]; 125.72 d (=CH, CHT); 128.01 d (=CH, CHT); 239.50 s (C=O). PMR spectrum (δ, ppm): 1.50-1.92 m (15H, Ad); 2.45 t (1H, CH, CHT, J = 5.1 Hz); 4.58-4.71 m (2H, =CH, CHT); 6.04-6.18 m (2H, =CH, CHT); 6.34-6.41 m (2H, =CH, CHT). IR spectrum (ν, cm^{-1}): 700, 740, 1020, 1280, 1445, 1675, 1700, 2850, 2900, 3010. m/z 252.

Cyclohepta-2,4,6-trienylbenzylketone (XXX). Yield 64%, n_D^{20} 1.5802. PMR spectrum (δ, ppm): 2.23 t (1H, J = 6 Hz, −CHC−); 3.65 s (2H, CH_2Ph); 4.75-4.98 m (2H, =CH); 5.94-6.46 m (4H, =CH); 6.96-7.11 m (5H, Ph). IR spectrum (ν, cm^{-1}): 700, 750, 1085, 1180, 1330, 1495, 1600, 1690, 1715, 3015, 3030, 3045. m/z 210.

Indanone-2 (XXXI), yield 18%.

Ketazine fluorenone (XXXII), yield 98%.

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