Kinetic *versus* Thermodynamic Control in the Selective Functionalization of Nickel(II) Cyclidene Macrocyclic Complexes†

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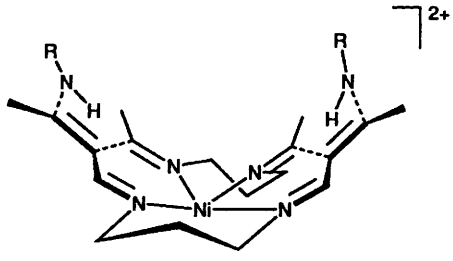
Alkylation reactions on the periphery of nickel(II) cyclidene macrocyclic complexes were carried out with a high degree of selectivity, to produce a family of 17 new complexes encompassing asymmetric monofunctionalized, symmetric or asymmetric difunctionalized products, and incorporating a range of useful structural features. The origin of the remarkable control of reactivity exhibited by these systems is ascribed, based on NMR studies, to kinetic control of the alkylation reaction, and is associated with the conformations adopted by the pendant groups of the macrocycle in solution and also depends on both the steric bulk and the relative reactivity of the alkylating agent.

There is enormous current interest in the use of macrocyclic and other multidentate ligands in the production of complexes of defined size and shape. By careful design it is possible to produce host molecules containing suitably oriented electronic and steric groups which control the approach and binding of selected guest molecules to the host.[1] An early example of this was Baldwin's capped porphyrin complexes, which used benzenoid caps supported by four side-arms to define a sterically restricted cavity, accessible only to small molecules, which could then interact with the metal centre.[2] More recently, with the phenomenal growth in interest in supramolecular chemistry,[3] and in the modelling of enzymic reactions,[4] numerous other examples have been reported. For example, Lehn and co-workers[5] prepared a zinc(II)–porphyrin complex with a superstructure incorporating aza crown ether groups and showed that it acted as receptor for α,ω-diammonium cations. Also, Busch and co-workers[6] have developed a family of host molecules based upon macrobicyclic cyclidene ligands and have studied extensively the inclusion of various guest substrates as a function of host cavity size and shape.

We have recently reported on the structural modification of various macrocyclic ligands, including both bridged and unbridged cyclidenes, to allow their incorporation into the matrix of a range of synthetic polymers.[7] The oxygen adducts of the cobalt(II) complexes of these polymer-supported systems display greatly enhanced stability to autoxidation, relative to the same complexes in the solution phase.[8] The cyclidene ligands possess a well defined three-dimensional geometry, even in the unbridged state,[9] the so-called 'saddle structure' **I**, and hence the ligand structure naturally provides the basis of a cavity for guest inclusion. Modification of the peripheral groups can play a very significant role in the size, shape, reactivity and binding behaviour of the host complex.[10]

In this work we report the synthesis and characterization of some new, unbridged cyclidene molecules, where the nature of the product can be controlled to a remarkable degree by minor modifications to the synthetic procedure. Specifically it is possible to produce selectively from the same apparently symmetric precursor, symmetric difunctionalized (**IIa**), asymmetric difunctionalized (**IIb**) or asymmetric monofunctionalized



I

(**IIc**) macrocyclic products. These last species are of particular interest since they have a single site on the complex for reaction with a polymer. This obviates problems with cross-linking of the polymer during incorporation of the macrocycle, observed using difunctionalized reagents, and which results in the production of insoluble polymers that are unsuitable for further processing.[11] A preliminary account of some of this work has appeared.[12]

Results and Discussion

The aim of this work was the preparation of a sterically protected site in the vicinity of a metal centre, and complex **1** was selected as a suitable parent species due to the presence of the two relatively bulky benzyl groups. This complex was prepared by the literature method[13] and characterized by spectroscopy. Nuclear magnetic resonance spectroscopy is particularly useful in this regard since it gives information on both the dynamic behaviour of the molecule and its structure. Analysis of the ^{13}C and ^{1}H NMR spectra of **1** as a function of temperature in CD_3CN solution indicates that the molecule is fluxional on the NMR time-scale. As with other molecules in this class, complex **1** adopts the so-called 'lid-on' structure **IIIa**, characterized by the chemical shift of C(5) at δ *ca.* 15. In this structure the R group points up and away from the region around the metal centre, thus minimizing steric interactions with the methyl group in the 6 position. In the alternative 'lid-off' structure **IIIb**, the corresponding resonance for C(5), would appear at δ *ca.* 20.[14]

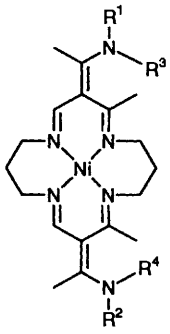
The NMR spectra are consistent with the occurrence of three fluxional processes: rotation about the C(1)–C(4) bond, which results in broadening of the C(4) resonance at room temperature, rotation about the N–CH_2Ph bond, and rotation about the C(1)–N bond, which interconverts the 'lid-on' and 'lid-off'

† *Supplementary data available* (No. SUP 57067, 2 pp.): ^{1}H and ^{13}C NMR spectroscopic data for the nickel(II) cyclidene complexes. See Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1995, Issue 1, pp. xxv–xxx.

conformers. The results of variable-temperature studies on the chemical shift of C(5) suggest that this last process is significant only at elevated temperatures. The same fluxional behaviour has been observed for other examples of this type of secondary amine complex.[11]

At low temperature (233 K) the ^{1}H NMR spectrum is rather broad and thus difficult to assign but in contrast, the ^{13}C NMR spectrum is sharp and a number of the carbon atoms display two or even three separate signals. This arises from the freezing out of various conformers, producing a mixture of a major isomer with both benzyl groups in the lid-on position, the 'lid-on–lid-on' isomer, and a minor component where one of the benzyl groups is in the alternative 'lid-off' position, the 'lid-on–lid off' isomer. Similar behaviour has been observed in macrobicyclic cyclidenes having very long alkyl chain bridges.[15] The ^{13}C NMR spectrum of complex **1** in the solid state shows discrete resonances for all four Me groups, implying a degree of asymmetry in the structure. The chemical shifts of these signals imply that one benzyl group is 'lid-on' while the other is 'lid-off'.

Of particular import to the present work is the nature of the ^{1}H NMR signals assigned to the four aliphatic protons of the benzyl groups. At room temperature these appear in the region δ 4.2–4.8 as two broad singlets of relative intensity 3:1, indicating that the complex exists in an asymmetric conformation. At elevated temperature (353 K) the broad signals are replaced by a sharp singlet at δ 4.65, as averaging of the signals takes place. The room-temperature spectrum is interpreted as arising from the relative orientation of the two benzyl groups. For one benzyl group, the phenyl ring lies above the metal centre, pointing inwards and effectively capping the cavity defined by the rest of the ligand (see structure **IV**). This leaves the two protons on the aliphatic carbon atom of the benzyl group pointing out, away from the cavity. Molecular models suggest that for steric reasons only one aromatic group at a time can be accommodated within the molecular cavity and thus the aromatic group of the second benzyl group is constrained to point out of the cavity, along with one of its aliphatic protons. The remaining aliphatic proton of this second benzylic group points into the cavity and is thus in a slightly different environment than the other three, and experiences a slight upfield shift in the position of its resonance. As rotation about the N–CH_2Ph bonds takes place and one aromatic group moves out of the cavity, it is replaced by the other, resulting in the observed spectrum. The results suggest a strong preference for an aromatic group to lie within the cavity of the molecule. A very similar phenomenon is seen in the crystal structure of a related cyclidene compound bearing two pyrazole substituents where one of the pyrazole rings is found to lie inside the pseudo-cavity of the structure, with the other pointing out.[9] This orientational preference of the aryl group is rationalised in terms of a polarity effect, with the aromatic ring being more compatible with the relatively less polar cavity rather than with the high relative permittivity environment of the acetonitrile solvent. This behaviour proves to be highly significant with regard to the chemical reactivity of complex **1**.



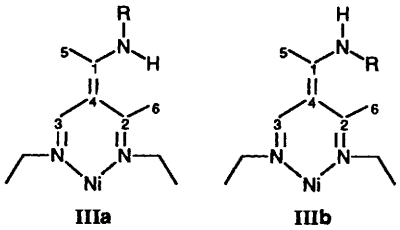
IIa $R^1 = R^2 = CH_2Ph$, $R^3 = R^4$
IIb $R^1 = R^2 = CH_2Ph$, $R^3 \neq R^4 \neq H$
IIc $R^1 = R^2 = CH_2Ph$, $R^3 \neq H$, $R^4 = H$

$[PF_6]_2$

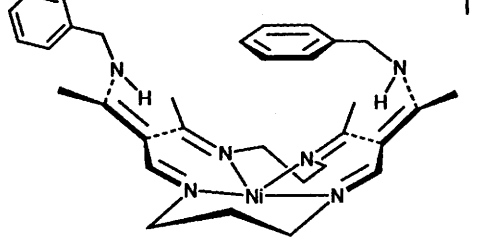
	R^1	R^2	R^3	R^4
1	CH_2Ph	CH_2Ph	H	H
2	CH_2Ph	CH_2Ph	Pr	H
3	CH_2Ph	CH_2Ph	Bu	H
4	CH_2Ph	CH_2Ph	$(CH_2)_3CO_2Et$	H
5	CH_2Ph	CH_2Ph	Me	Me
6	CH_2Ph	CH_2Ph	$CH_2CH{=}CH_2$	$CH_2CH{=}CH_2$
7	CH_2Ph	CH_2Ph	CH_2Ph	CH_2Ph
8	Pr	Pr	H	H
9	Bu	Bu	H	H
10	CH_2Ph	CH_2Ph	Pr	Pr
11	CH_2Ph	CH_2Ph	Bu	Bu
12	CH_2Ph	CH_2Ph	Pr	Me
13	CH_2Ph	CH_2Ph	Bu	Me
14	CH_2Ph	CH_2Ph	Pr	$CH_2CH{=}CH_2$
15	CH_2Ph	CH_2Ph	Bu	$CH_2CH{=}CH_2$
16	CH_2Ph	CH_2Ph	Pr	$CH_2C_6H_4(CH{=}CH_2)$-3
17	CH_2Ph	CH_2Ph	Bu	$CH_2C_6H_4(CH{=}CH_2)$-3
18	Pr	Pr	Pr	H
19	Pr	Pr	Pr	Pr
20	CH_2Ph	CH_2Ph	$-(CH_2)_6-$	
21	CH_2Ph	CH_2Ph	$(CH_2)_6O_3SC_6H_4Me$	H
22	CH_2Ph	CH_2Ph	$(CH_2)_5O_3SC_6H_4Me$	H

Synthesis of Derivatives of Complex **1**.—Busch *et al.*[16] have exploited a reaction scheme involving deprotonation of secondary amine cyclidenes, followed by reaction with difunctional electrophiles, such as α,ω-ditosylates or dibromides, to produce fascinating macrobicyclic systems. In this work, similar methods were used to produce unbridged, tertiary amine complexes. Results from studies utilizing a variety of alkyl halides or tosylates indicate a remarkable dependence of the nature of the products upon the steric and electronic nature of these electrophilic reagents (see Scheme 1).

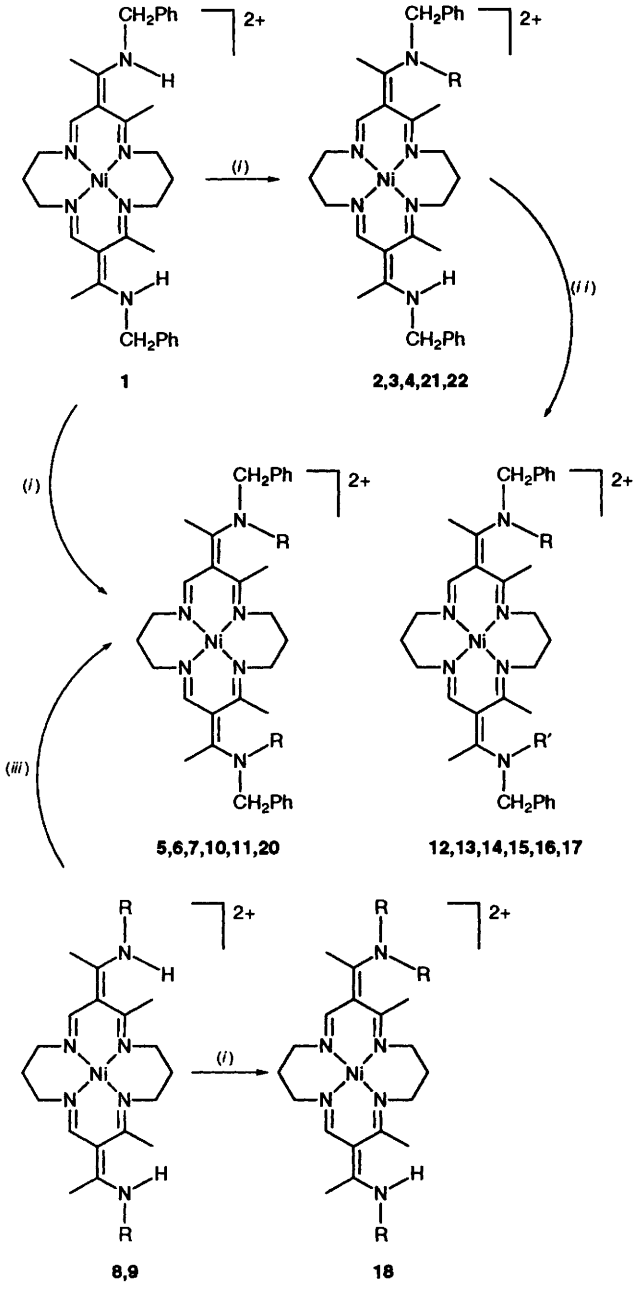
With alkyl bromides where the alkyl chain was three or more carbon atoms long, alkylation of **1** took place at only one of the secondary amine nitrogen atoms, producing exclusively the monofunctionalized products **2**–**4** in good yield (typically 50–72%). This occurred even when a large excess of the alkylating agent was used over prolonged reaction times. In sharp contrast, the use of a smaller alkylating agent, such as methyl iodide, readily produced the expected dimethylated product **5**. Notably the three carbon unit allyl bromide, and also benzyl bromide, readily produced dialkylated products, **6** and **7**, respectively. From these last results, and Busch and co-workers[17] observation of the formation of bridged species from **1**, clearly there is no thermodynamic problem in producing unbridged bis(tertiary amine) complexes. Also the observed



IIIa **IIIb**



IV

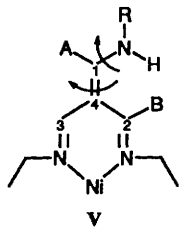


Scheme 1 (*i*) BuO^-, RX, MeCN; (*ii*) BuO^-, R'X, MeCN; (*iii*) BuO^-, $PhCH_2Br$, MeCN

selectivity does not stem from simple steric effects arising from the combination of benzyl and extended chain alkyl pendant groups. This was verified simply by examining the reactivity of the secondary amine cyclidene complexes containing propyl or butyl substituents on the nitrogen atoms, **8** and **9**. After deprotonation, both of these complexes reacted smoothly with benzyl bromide to produce the desired tertiary amine complexes, **10** and **11**.

The monoalkylated derivatives, **2** and **3**, were further alkylated at the secondary amino group with small, or highly reactive alkyl halides to produce the unsymmetrically substituted bis(tertiary amine) complexes **12**–**17**. Extensive attempts under a variety of forcing conditions to bring about alkylation of **2** and **3** using propyl or butyl bromide failed to yield the desired products.

The specific nature of these alkylation reactions was at first sight peculiar but can be rationalized in terms of kinetic control of the reactions. As discussed above, the ^1H NMR spectrum of **1** implies that a phenyl ring of one of the benzyl groups occupies



V

the cavity of the complex, and that, on steric grounds, only one phenyl ring may be accommodated at any one time. Crystal structures of *N*-dialkylated cyclidenes show that, to avoid unfavourable steric interactions between the two substituents on the tertiary nitrogen atom and the ring methyl groups, A and B (structure **V**), the molecule twists about the C(1)–C(4) bond by about 40°, and also about the C(1)–N bond by about 10–20°.[9] The NMR spectra of the dialkylated cyclidenes indicate that these complexes do not undergo rotation about the C(1)–C(4) bond on the NMR time-scale, and thus, at room temperature, they are essentially conformationally locked, with one alkyl group pointing into the cavity and the other pointing out.[11]

In this work, after monoalkylation has occurred at one end of the molecule, the structure twists as described above, forcing one alkyl group to occupy the cavity. Alkylation at the second nitrogen atom would now induce an equivalent twist at that end of the molecule, forcing a bulky alkyl or benzyl group to try to enter the already filled cavity. This is strongly disfavoured on steric grounds and produces a high energy of activation for this reaction. Thus the second alkylation reaction does not occur except under certain conditions: (*a*) where the second alkyl group is small enough to be accommodated within the cavity without severely increasing the steric contribution to the activation energy, for example with methyl iodide; (*b*) where the alkyl halide is reactive enough to lower the activation energy for the reaction, overcoming the unfavourable steric effect, for example with benzyl and allyl bromides.

This form of steric discrimination occurs so long as the group pointing in is sufficiently bulky to increase substantially the activation energy for the second alkylation reaction, although the monoalkylated products are not necessarily the exclusive product. As an example, complex **8**, which has propyl substituents on the secondary nitrogen atoms, reacts in its deprotonated form in the presence of 6 equivalents of propyl bromide to produce mixtures of the corresponding monoalkylated (**18**) and dialkylated species (**19**) in a ratio that is dependent upon the time-scale of the reaction; after 30 min reaction the ratio of **18**:**19** was 85:15, after 60 min 67:33 and after 200 min 43:57, as determined by integration of the ^1H NMR spectra.

The selectivity in the reaction of the deprotonated unbridged cyclidenes has some interesting and very important consequences. Busch and co-workers[17] have reported the preparation of bridged cyclidenes, for example **20** where a hexamethylene chain connects the tertiary amine nitrogen atoms, which each also carry a benzyl group. We have found that the product of the reaction of doubly deprotonated **1** with the ditosylate of hexane-1,6-diol is condition dependent; at gentle reflux for periods of less than 1 h the product was the monoalkylated complex **21**, which bears a pendant tosylate function. Similar results were found for the pentamethylene analogue, with complex **22** being isolated as the product. More vigorous reflux for longer periods produced the bridged species observed by Busch and co-workers.[17] The sluggishness of these bridging reactions, compared to bridging less bulky complexes, is ascribed to the desire of the benzyl aromatic ring to lie within the cavity of the molecule. As the molecule twists during the first alkylation step, it appears that the benzyl group moves into the cavity, forcing the alkyl tosyl group to point out and away from the molecule in an orientation that disfavours the bridging reaction. If the benzyl group displayed no preference for its

Table 1 Yield, analytical, infrared and electronic spectroscopic data

Complex	IR/cm^{-1}			λ_{max}/nm (log ε)			Analysis (%)[a]			Yield
	ν_{N-H}	$\nu_{C=O}$	$\nu_{C=C,C=N}$				C	H	N	(%)
1	3395, 3364		1610, 1563	443 (3.00)	363 (4.30)	333 (4.60)	46.4 (46.6)	5.5 (5.3)	9.0 (9.3)	78
2	3394		1608, 1575, 1523		385 (4.43)	342 (4.60)	47.2 (47.2)	5.5 (5.5)	9.0 (9.2)	72
3[b]	3391		1608, 1575, 1526		381 (4.19)	343 (4.36)	47.6 (47.2)	5.0 (5.5)	8.6 (8.5)	50
4	3389	1725	1610, 1576		382 (4.41)	348 (4.57)	46.1 (46.0)	5.6 (5.2)	9.7 (9.5)	57
5[b]			1609, 1546		385 (4.38)	355 (4.48)	49.2 (48.9)	5.4 (5.5)	8.8 (8.8)	64
6[c]			1610, 1576, 1527		387 (4.05)	358 (4.22)	53.9 (53.6)	5.2 (5.5)	7.7 (7.8)	50
7			1609, 1576, 1533		385 (4.57)	354 (4.63)				93
8	3367		1610, 1566	443 (3.00)	363 (4.26)	333 (4.28)				85
9	3370		1610, 1571	448 (3.04)	363 (4.30)	333 (4.41)	48.8 (48.4)	5.6 (5.7)	8.8 (8.9)	61
10			1611, 1578, 1535		385 (4.48)	346 (4.60)	49.9 (49.4)	5.9 (6.0)	8.5 (8.7)	67
11[c]			1605, 1576, 1526		385 (4.66)	343 (4.78)	48.0 (47.9)	6.0 (5.8)	9.2 (8.8)	40
12[c]			1609, 1540		387 (4.11)	348 (4.32)	48.5 (48.5)	6.0 (5.9)	9.3 (8.7)	60
13			1607, 1533		389 (4.60)	344 (4.76)	48.6 (48.5)	5.2 (5.5)	8.8 (8.9)	68
14			1608, 1530		385 (4.39)	347 (4.51)	49.3 (49.0)	5.4 (5.7)	8.7 (8.8)	65
15[d]			1608, 1530		385 (4.53)	347 (4.64)	50.3 (50.6)	5.4 (5.7)	7.8 (8.0)	21
16[e]			1607, 1576, 1526		381 (4.31)	348 (4.54)	50.1 (50.6)	5.5 (5.8)	7.9 (7.9)	24
17			1605, 1572, 1529		380 (4.40)	350 (4.59)	41.9 (42.2)	6.3 (6.3)	10.0 (10.1)	
18	3370		1608, 1577, 1543		389 (4.32)	344 (4.43)				
19			1605, 1575, 1533							
21	3388		1625, 1574, 1530				48.8(48.5)	5.7 (5.4)	6.9 (7.5)	60
22	3370		1619, 1584, 1554		377 (4.57)	343 (4.60)	46.7 (47.0)	5.1 (5.2)	8.4 (7.8)	68

[a] Calculated values in parentheses. [b] 0.25 Et_2O. [c] 0.5 Et_2O. [d] 1.5 H_2O. [e] 2 H_2O.

position, then the first alkylation would produce a mixture of tertiary amine orientations, with the alkyl tosyl group either in or out of the cavity. An orientation with the alkyl tosyl group within the cavity should react readily to produce the bridged product. The intermolecular reaction of the pendant tosylate group to produce dimers is disfavoured for the same reason as the second alkylation of the monoalkylated derivatives, described above. Over extended periods of heating, bridging eventually occurs because the monoalkylated product slowly equilibrates to produce the alternative conformer, in which the second tosylate group is within the cavity and thus able to react with the second amino group. In this work, preparation of the bridged macrocycle **20** was also achieved, in a facile series of reactions, by first bridging the bis(methoxy) precursor complex with hexane-1,6-diamine, then deprotonating and alkylating the bridged complex with benzyl bromide. The latter sequence avoids the kinetic factors that control the alkylation reaction and as a result product formation is rapid.

As exemplified by the synthesis of **20**, careful choice of the reaction sequence and experimental conditions can allow the selective production of cyclidene macrocycles with desired structural features incorporated into the ligand superstructure. As a further example of this control, complexes containing a single polymerizable functional group have been specifically prepared. Previous work in this laboratory has shown that cyclidene complexes bearing 4-vinylphenyl groups can be incorporated into the structure of various copolymers *via* free radical initiated polymerization reactions with suitable comonomers such as styrene or acrylate esters.[11] Because these complexes were symmetrical and difunctional, bearing two 4-vinylphenyl groups, the polymers they produced were extensively cross-linked, and hence intractable and difficult to process. Using the methodology described above, complexes **16** and **17** were prepared, which contain a single styrene-like substituent and these species readily undergo copolymerization reactions with styrene and various acrylate esters to produce soluble copolymers. For example, complex **16** and styrene in a 1% by weight ratio, with azoisobutyronitrile as initiator, reacted to form a yellow soluble copolymer. Details of the preparation and physical properties of these polymers will appear elsewhere.

Rather than incorporate the complexes into the polymer *via* copolymerization it is often desirable to functionalize pre-formed polymers with suitably modified reagents. Such a monofunctionalized cyclidene, **4**, was prepared by monoalkylation of **1** using the ethyl ester of 4-bromobutanoic acid. Hydrolysis of **4** yields the corresponding acid, a versatile functional group for reaction with the polymers. The single site for reaction with the polymer is again of key importance in avoiding any undesirable cross-linking reactions.

Characterization of the Cyclidene Complexes.—The new complexes were characterized by a combination of spectroscopy and microanalysis, with ^1H and ^{13}C NMR spectroscopy proving to be particularly useful. The NMR data are reported in detail as supplementary material (SUP 57067), and the results from IR and electronic spectroscopy and the microanalytical data are given in Table 1. The products are all yellow to orange solids and are isolated as hexafluorophosphate(v) salts, displaying characteristic IR bands for this anion, at 840 and 560 cm^{-1}.

Monofunctionalized derivatives of **1**. The IR spectra of all of these complexes had a band at *ca.* 3380 cm^{-1}, assigned to ν_{N-H} of the secondary amine group, the ^{13}C NMR spectra showed peaks assignable to the added alkyl substituent and the integrals of the ^1H NMR spectra indicated the incorporation of only 1 equivalent of each alkylating agent, all supporting the fact that alkylation occurred at only one of the secondary amine sites of complex **1**. The asymmetric nature of the products was clear from the appearance of the ^{13}C and ^1H NMR spectra at room temperature. Separate signals appeared for every carbon atom in the molecules, indicative of the loss of the plane of symmetry during the alkylation process. As expected, the spectra displayed features characteristic of both the parent complex **1** and of its bis(alkylated) derivatives. The remote possibility that the products were 1:1 mixtures of parent and bis(alkylated) species was eliminated by the results from thin layer chromatography studies using alumina plates, the products running as single spots of R_f values clearly different from that of the starting material.

Assignment of resonances to specific carbons and protons was carried out by reference to data from other complexes of this type and the results of ^{13}C-{^1H} correlation, DEPT (distortionless enhancement by polarization transfer) and NOESY (nuclear Overhauser enhancement) spectroscopy. The

secondary amine ends of the molecules displayed the fluxional behaviour observed in the starting material (see above) but the tertiary amine ends had a sharp resonance for C(4), indicative of no rotation about the C(1)–C(4) bond on the NMR time-scale. This was supported by the observed sharpness of some of the other signals on both the ^{13}C and ^{1}H NMR spectra following alkylation.

The most notable features of the NMR spectra are: (*i*) significant downfield shifts of the ^{13}C resonances of various carbon atoms upon alkylation of the secondary amine nitrogen atom, *viz.* (*a*) benzyl aliphatic carbon atom, from δ *ca.* 49 to *ca.* 59, consistent with this carbon atom being deshielded by being placed closer to the Ni^{2+} ion. A similar effect has been observed in other cyclidenes;[15] (*b*) macrocycle carbon atom, C(1), from δ *ca.* 169 to *ca.* 174; (*c*) methyl carbon atom A, from δ *ca.* 15 to *ca.* 20. Similar shifts have been observed in related species and result from the twisting of the alkylated part of the molecules out of planarity *via* rotation about the C(1)–C(4) and C(1)–N bonds.[11] This twisting has the effect of moving pairs of alkyl groups away from close proximity to one another, *i.e.* it removes the eclipsed orientation of methyl carbon A with the benzyl aliphatic carbon, and moves the newly added alkyl group away from the vicinity of methyl carbon B.[9] Hence this removes the effects of steric compression on ^{13}C chemical shifts which are observed in the precursor.[14] (*ii*) The ^{1}H NMR signals of the aliphatic protons of the benzyl groups appear as two separate signals, one relatively sharp at δ 4.7, assigned to the tertiary amine end of the molecule, and the other as a broad signal at δ *ca.* 4.2. This is consistent with the above structural arguments for complex **1**, with the protons of the benzyl methylene group of the secondary amine end of the molecule pointing in toward the cavity and being slightly shielded by the influence of the phenyl ring residing there.

Difunctionalized derivatives of **1**. The IR spectra of these materials had no peaks assignable to ν_{N-H}, the ^{13}C NMR spectra had peaks assignable to the various substituents and the integrals of the ^{1}H NMR spectra were consistent with the expected ratio of substituents in the predicted products. Assignments were made with reference to other compounds of this general type. The ^{13}C NMR spectra of the difunctionalized species fall into two different groups: (*a*) with alkyl groups of relatively small size (both methyl or allyl) the spectra are relatively simple, indicating the presence of only one conformer at room temperature; (*b*) where at least one of the alkyl groups is larger (propyl, butyl, benzyl, *etc.*) extra peaks appear in the spectra. It would appear that in the sterically crowded dialkylated species, as both ends of the molecule twist to accommodate the substituents on the amino groups, the bulky substituents adopt different conformations to minimise steric interactions. Busch and co-workers[15] have observed a similar effect in the NMR spectra of some bridged cyclidenes at low temperature, where the interconversion of conformers is slow on the NMR time-scale. In the present work, the steric bulk of the alkyl groups hinders the rotations which result in the interconversion of the conformers and discrete signals are seen for each conformer even at room temperature. While this leads to very complex ^{13}C NMR spectra, this behaviour is not unexpected, and lends weight to the importance of steric effects in determining the physical and chemical properties of the cyclidene complexes.

Conclusion

It is known that unbridged cyclidene complexes adopt well defined three-dimensional structures in solution, and as such contain a pseudo-cavity around the metal co-ordination site. By careful selection of substituent groups on the periphery of the cyclidene ligand, and judicious choice of alkylating agents, this work has shown that precise control of the reactivity of cyclidene ligands can be achieved, based upon the steric and electronic properties of the electrophilic reagents. The remarkable selectivity that is observed is rationalized in terms of kinetic control of the reaction, with steric factors playing an important role in determining the activation energy of the alkylation process. Alternative reaction pathways, using smaller or more reactive reagents, produce the expected thermodynamic products. Thus it is possible to prepare, from the same symmetrically substituted parent complex, asymmetric monoalkylated and asymmetric or symmetric dialkylated cyclidenes incorporating a variety of useful structural features.

This work sheds some light on an important observation from Busch's work. It was noted that bridging the bis(methoxy) substituted cyclidene with α,ω-primary diamines produced mixtures of monomeric and dimeric species, while bridging with *N,N'*-dimethyl-α,ω-diamines (or bridging the bis NHMe substituted cyclidene with either the ditosylates of α,ω-diols or with α,ω-dibromides) yielded solely the monomeric product.[16] In the former case, the intermediate formed by reaction at one end of the cyclidene has a secondary amine structure, and adopts the lid-on geometry well established for this group, with the alkyl chain and its terminal primary amine group pointing up, away from the N_4 plane of the molecule. This primary amine group can then react intramolecularly to form the monomer, or intermolecularly, to form the dimer. In the case where the intermediate of the bridging reaction contains a tertiary amine group, this is subject to the conformational twist described above, forcing either a methyl group or, more likely on the grounds of polarity, the longer alkyl chain to occupy the cavity of the molecule. In the latter situation, the second amino group is placed in close proximity to its intramolecular reactive partner and hence is favourably oriented for the bridging reaction to proceed smoothly to produce the observed monomeric complex, to the exclusion of any dimeric product.

Experimental

All materials were reagent grade and were used as received. Solvents were purified and dried using standard methods. The ^{1}H and ^{13}C NMR spectra were run on a Bruker WP200 spectrometer, operating at 200.133 (^{1}H) or 50.323 MHz (^{13}C), or a Bruker WH400, operating at 400.150 (^{1}H) or 100.62 MHz (^{13}C). Chemical shifts are reported with respect to an external tetramethylsilane reference (positive to low field). Infrared spectra were recorded as Nujol mulls, on Perkin-Elmer 983 or 580 spectrophotometers and electronic spectra on a Shimadzu UV-160 spectrophotometer.

Preparation of the Complexes.—All of the new complexes were prepared by the same general method, and details are presented only for complex **2**.

[3-(1-*Benzylaminoethylidene*)-11-(1-*benzylpropylaminoethylidene*)-2,12-*dimethyl*-1,5,9,13-*tetraazacyclohexadeca*-1,4,9,12-*tetraene*-$\kappa^4N^1,N^5,N^9,N^{13}$]*nickel*(II) *bis*(*hexafluorophosphate*) **2**. In a typical experiment, a solution of complex **1** (1.5 g, 1.75 mmol) in acetonitrile (100 cm^3) was heated at reflux in the presence of KOBu^t (0.39 g, 3.5 mmol). To the resulting dark brown solution was added propyl bromide (1 cm^3, 11 mmol) and the mixture was heated at reflux for several hours. The volume of the solution was reduced by rotary evaporation and the residue chromatographed on neutral alumina with acetonitrile as eluent. The fast moving dark orange band was collected and the solvent removed to yield the product as an orange solid (1.23 g, 78%). For complexes **21** and **22**, the reaction time was limited to *ca.* 1 h.

Acknowledgements

We thank Dr. O. Howarth of the SERC solution NMR service for the NMR spectra at high field. Dr. A. S. F. Boyd for help in obtaining the other solution-phase NMR spectra, and Dr. D. Apperley of the SERC solid-state NMR service. We are grateful to the SERC and British Petroleum plc for the provision of a CASE award (to E. L. S.).

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Received 14*th September* 1994; *Paper* 4/05620E