Their ^2A_g ground state, based on the configuration $[(yz)^2 - (z^2)^2(xz)^2(x^2 - y^2)^1]$, is at variance with the results of paramagnetic anisotropy and esr measurements which favor the ground configuration $[(yz)^2(xz)^2(x^2 - y^2)^2(z^2)^1]$.[36] The large magnetic anisotropy observed in the CoS$_4$ plane then originates from the proximity in energy of the z^2 and xz levels relative to the more stable yz level. For the above reasons the detailed assignments of Siimann and Fresco, based on semiempirical MO calculations, must be regarded with caution.

The principal absorption bands of the palladium(II) and platinum(II) complexes are also listed in Table VIII. The bands appear to fall in similar energy regions to those of Ni(OEtSacSac)$_2$. The spectra of *cis*- and *trans*-Pt(OEtSacSac)$_2$ differ little (see Figure 5) providing direct evidence that, although the effect of differing symmetry is readily detectable, the presence of one OEt group per ligand does not greatly modify the spectra. For the palladium and platinum complexes, only Pd(OEtSacSac)$_2$ exhibits a band (ν 19,100 cm^{-1}) with a molar absorbance (ϵ 900) sufficiently low to be assigned as a ligand field transition. Pt(OEtSacSac)$_2$ exhibits a strong absorption (ϵ 5300) at 19,700 cm^{-1} which is suffi-

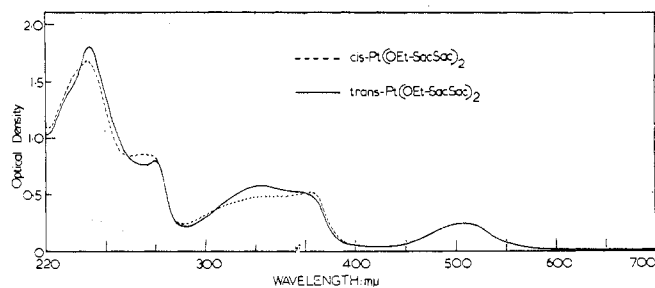(36) A. K. Gregson, R. L. Martin, and S. Mitra, *Chem. Phys. Lett.*, 5, 310 (1970).

Figure 5. Electronic spectra of *cis*- and *trans*-Pt(OEtSacSac)$_2$.

ciently intense to mask weaker bands. Although the tabulated spectrum of Pd(OEtSacSac)$_2$ has been obtained from a mixture of cis and trans isomers, this is not expected to introduce spurious results. This conclusion is based on the close similarity of the spectra of *cis*- and *trans*-Pt(OEtSacSac)$_2$ (Figure 5).

# Synthetic Approaches to 14-, 15-, and 16-Membered Tetraaza Macrocycles and Their Metal Complexes

S. C. TANG, S. KOCH,[1] G. N. WEINSTEIN, R. W. LANE, and R. H. HOLM*

A nonmetal template synthesis of bis(β-imino amine) macrocycles possessing 14-, 15-, and 16-membered rings has been devised. The method is based on the electrophilic reactivity of 1,2-dithiolium cations and vinylogous β-amino thiones with primary amines. The 4-phenyl-1,2-dithiolium cation with ethylenediamine and trimethylenediamine yields the precursor bis(β-amino thiones) 20 and 21. These compounds are smoothly cyclized by reaction with diamines to afford the 14- and 16-membered macrocycles 24 and 26, respectively, in high yield. The 15-membered cycle 25 was obtained in lower yield from 21 and ethylenediamine. Reaction of the amino thione complex 23 with trimethylenediamine results in formation of metal-free 26 in good yield by an apparent template process. Ring closure could not be effected by reaction of diamines with the bis(β-amino thiones) obtained from the 3-phenyl-1,2-dithiolium cation, indicating that this method of macrocyclic synthesis is best applied to precursors containing thioaldehyde groups. Cu(II), Ni(II), and Co(II) complexes of the three macrocycles were prepared. The development of a nontemplate synthesis of macrocycles was undertaken because of the inability to extend a previous reaction sequence yielding 15 from 12 and ethylenediamine to the synthesis of larger tetraaza ring systems. Alternative preparations of 15 are described. The nontemplate approach allows the synthesis of series of macrocyclic complexes of the basic chelate ring-size patterns 1-3 with the desired sets of metal ions. Together with the template cyclization reactions originated by Jager and the recently reported reactivity features of the β-imino amine chelate rings, it affords entry to a broad variety of tetraaza macrocyclic systems.
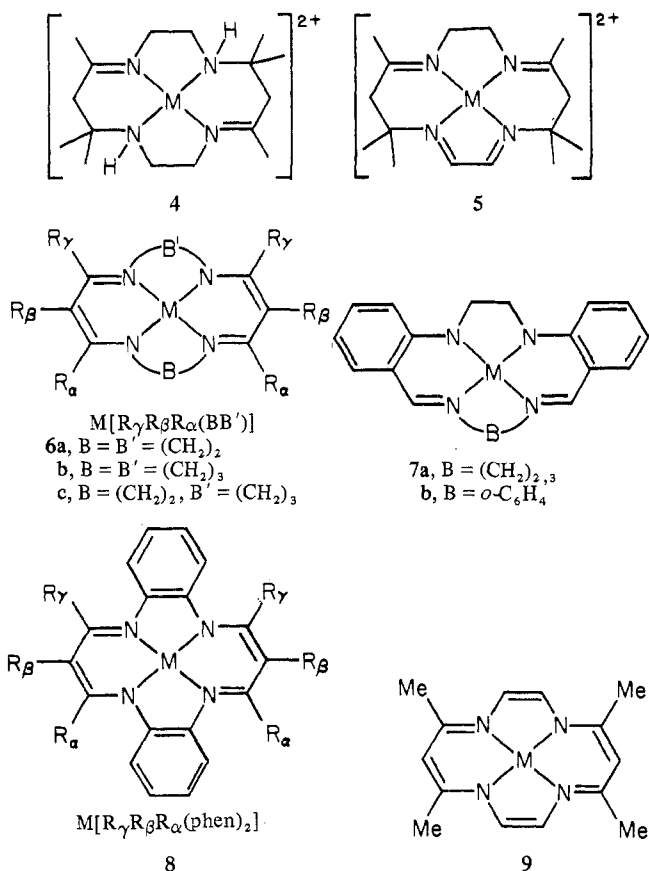
Introduction

Central to the problem of understanding the structural, electronic, and reactivity properties of natural and synthetic tetraaza macrocyclic complexes is an elucidation of the effects of chelate ring size and ligand rigidity and extent of unsaturation on these properties. Of the six ring-size patterns generated by fusion of four five- and/or six-membered chelate rings, those of the 6-5-6-5, 6-5-6-6, and 6-6-6-6 types, represented schematically by 1, 2, and 3, respectively, are of
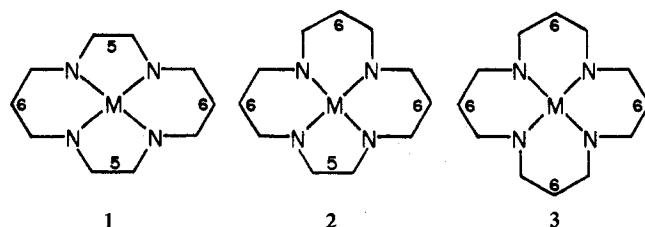
pertinence here. Patterns 2 (corrins) and 3 (porphyrins) are the only types found in natural macrocycles whereas all three

are known in synthetic complexes[2] with **1** being by far the most common.[3-7] Macrocyclic complexes of these types may be further classified according to the degree of unsatura-tion of the ligand structure internal to the chelate rings. For example, the Curtis macrocycle **4**,[2b,8] its oxidatively dehy-drogenated derivatives such as **5**,[9] and the generalized species **6**,[10-15] **7**,[16] and **8**,[10,15] all representative of important groups of complexes, present ligand unsaturation ranging from 4 π to 16 π electrons.

4

5

M[R$_\gamma$R$_\beta$R$_\alpha$(BB')]
6a, B = B' = (CH$_2$)$_2$
 b, B = B' = (CH$_2$)$_3$
 c, B = (CH$_2$)$_2$, B' = (CH$_2$)$_3$

7a, B = (CH$_2$)$_{2,3}$
 b, B = *o*-C$_6$H$_4$

M[R$_\gamma$R$_\beta$R$_\alpha$(phen)$_2$]

8

9

10

The large majority of 0-16-π macrocycles with size patterns **1-3** have been prepared by metal ion template reactions[2] in which the metal ion acts as an organizing center around which ring closure occurs. Of the many cases of efficacious syn-thesis by this method, the formation of corrin,[17] tetradehy-drocorrin,[18] and the 6-6-6-6 16-π TAAB[19] ring systems are examples *par excellance*. The template method is at present the most generally useful procedure for the synthesis of many types of tetraaza macrocycles. However, it suffers from the disadvantage that the encycled metal ions are fre-quently difficult to remove or cannot be removed without destruction of the ligand. While nondestructive demetala-tion reactions for certain 6-5-6-5 0-π,[20] 8-π,[9c] 12-π,[11] 16-π,[21] 6-5-6-6 12-π,[11] and 6-6-5-5 2-π[5a] complexes, among others, have been effected, a more desirable procedure would be direct synthesis of the desired macrocycle by a nonmetal ion template route. With the exclusion of phthalo-cyanine, porphyrins, and porphines,[2] nontemplate methods have been directed principally toward the preparation of basic Curtis macrocycle in **4** and its hydrogenated or dehy-drogenated derivatives.[2,22]

We are currently engaged in an investigation of the struc-tural, electronic, and reactivity features of macrocyclic com-plexes with size patterns **1, 2**, and **3** and possessing degrees of ligand unsaturation equal to or exceeding 12 π. A prere-quisite to this investigation is the development of a synthetic procedure affording 12-π macrocycles in a form such that the desired metal complexes can be prepared and subjected to oxidative dehydrogenation reactions affording 14-π-16-π species. The basic systems selected are the β-imino amine cycles present in **6**, the first examples of which had been prepared by Jager[10,11] as Cu(II) and Ni(II) complexes using template reactions. Previously we have reported[13] the non-template synthesis of the 6-5-6-5 macrocycle H$_2$[MeHMe-(en)$_2$] and its 12-π complexes M[MeHMe(en)$_2$] (**6a**). The latter may be dehydrogenated to 16-π complexes **9**.[13b] However, this method has not proven capable of extension to 6-5-6-6 and 6-6-6-6 systems whose size patterns corre-spond to those of natural macrocycles. Consequently, a new synthetic procedure has been developed for metal-free macro-cycles of the 12-π 6-5-6-5, 6-5-6-6, and 6-6-6-6 types and is described here. These compounds readily form metal complexes and, as reported recently,[14] undergo oxidative de-hydrogenation reactions, one of which affords the species **10** containing the disubstituted corrin inner-ring structure.

Experimental Section

Preparation of Compounds. Characterization data for new com-pounds are given in Table I. Pmr data are summarized in Table II.

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(3) Complexes of the 6-5-5-5[4] and 6-6-5-5[5] types have been prepared. Size considerations[6] dictate that 5-5-5-5 systems are unlikely to be planar and cyclen complexes, which contain this pat-tern, are of the cis-octahedral type.[7]

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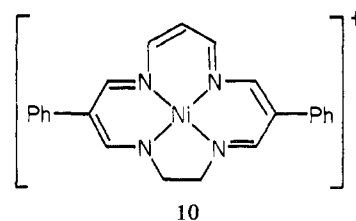(11) E.-G. Jager, *Z. Chem.*, 8, 470 (1968).

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Table I. Characterization Data for Macrocyclic Ligands and Complexes

Compd	Mp,[a] °C	% calcd			% found		
		C	H	N	C	H	N
H_3[MeHMe(tn)$_3$]	180–182	69.52	10.21	20.27	69.50	10.09	20.23
H_2[SHPhHen]	183–184	68.14	5.72	7.95	68.21	5.74	7.96
H_2[SHPhHtn][b]	133–134	68.81	6.05	7.64	68.72	6.09	7.74
H_2[SPhHHen]	187–188	68.14	5.72	7.95	67.92	5.65	7.74
H_2[SPhHHtn]	148–149	68.81	6.05	7.64	68.84	6.13	7.56
H_2[HPhH(en)$_2$]	286–289	76.71	7.02	16.29	76.48	7.20	16.29
H_2[HPhH(tn)$_2$]	146–147	77.38	7.58	15.04	77.21	7.42	14.98
H_2[HPhH(en)tn]	222–223	77.06	7.31	15.63	77.29	7.34	15.54
Ni[SHPhHen]	250–251	58.70	4.43	6.85	58.78	4.66	6.48
Ni[SHPhHtn]	221–222	59.59	4.76	6.62	59.69	4.51	6.56
Ni[SPhHHen]	243–245	58.70	4.43	6.85	58.57	4.45	7.26
Ni[SPhHHtn]	210–212	59.59	4.76	6.62	59.56	4.54	6.52
Cu[HPhH(en)$_2$]	316–318	65.12	5.42	13.80	65.03	5.55	13.66
Ni[HPhH(en)$_2$]	322–324	65.87	5.53	13.97	65.78	5.60	13.83
Co[HPhH(en)$_2$]	336–338	65.83	5.52	13.96	65.41	5.51	14.32
Cu[HPhH(en)tn]	231–233	65.80	5.72	13.34	65.77	5.66	13.17
Ni[HPhH(en)tn]	276–277	66.54	5.83	13.49	66.73	5.90	13.41
Co[HPhH(en)tn]	263–265	66.53	5.82	13.48	66.39	5.84	13.32
Cu[HPhH(tn)$_2$]	222–223	66.41	6.04	12.91	65.94	6.04	12.61
Ni[HPhH(tn)$_2$]	267–268	67.16	6.10	13.05	66.98	6.02	12.92
Co[HPhH(tn)$_2$]	263–265	67.13	6.10	13.05	67.18	5.78	13.12

[a] Sealed tube, uncorrected. [b] Per cent S: calcd, 15.15; found, 15.27.

Table II. Pmr Data for Macrocycles and Complexes

Compd	Solvent	Chem shifts, ppm			
		Bridge[a]	Unsatd ring[d]	Ph	NH
H_3[MeHMe(tn)$_3$] (14)	CDCl$_3$	1.88[b] (β), 3.25[c] (α)	1.88 (Me), 4.40 (β)		11.1[e]
H_2[SHPhHen] (20)	DMSO-d_6	3.65	7.65[k] (α), 9.86[k] (γ)	7.19	[j]
Ni[SHPhHen] (22)	CDCl$_3$	3.72	7.56 (α), 8.17 (γ)	7.35	
H_2[SHPhHtn] (21)	CDCl$_3$	2.12[b] (β), 3.65[c] (α)	7.44[f] (α), 7.76[f] (α), 10.3[g] (γ)	7.31	14.3[d]
Ni[SHPhHtn] (23)	CD$_2$Cl$_2$	1.98[b] (β), 3.87[h] (α)	7.09 (α), 7.47 (γ)	7.22	
Ni[SPhHHen]	CDCl$_3$	3.46	6.30[i] (β), 7.17[i] (α)	7.1–7.7	
H_2[SPhHHtn]	CDCl$_3$	2.08[b] (β), 3.63[c] (α)	6.61[i] (β), 7.37[i] (α)	7.2–7.9	13.7[d]
Ni[SPhHHtn]	CDCl$_3$	1.90[b] (β), 3.78[h] (α)	6.27[i] (β), 7.25[i] (α)	7.1–7.7	
H_2[HPhH(en)$_2$] (24)	CD$_2$Cl$_2$	3.60	7.74	7.10	[j]
Ni[HPhH(en)$_2$] (27)	CS$_2$	3.35	7.12	7.01	
H_2[HPhH(en)tn] (25)	CD$_2$Cl$_2$	1.90[b] (β), 3.46, 3.70[b] (α)	7.62	7.19	10.5[d]
Ni[HPhH(en)tn] (28)	CS$_2$	1.87[b] (β), 3.13, 3.33[b] (α)	6.91	6.99	
H_2[HPhH(tn)$_2$] (26)	CD$_2$Cl$_2$	1.82[b] (β), 3.45[b] (α)	7.52	7.09	[j]
Ni[HPhH(tn)$_2$] (29)	CDCl$_3$	1.89[b] (β), 3.25[c] (α)	6.92	7.18	

[a] Notation for tn bridges: N–CH$_2$(α)–CH$_2$(β)–CH$_2$(α)–N; $J_{αβ}$ = 6–7 Hz. [b] Multiplet. [c] Apparent quartet. [d] Notation as in 6, 31, and 32. [e] Center of broad signal. [f] Doublet of doublets: $J_{α-NH}$ = 14 Hz; $J_{αγ}$ = 3–4 Hz. [g] Doublet. [h] Triplet. [i] Doublet: $J_{αβ}$ = 6–7 Hz. [j] Not observed. [k] Doublet, $J_{αγ}$ = 4 Hz.

Structural formulas are set out in Schemes I and II and in the text. These together with the systematic nomenclature given below make apparent the abbreviations for ligand anions, which correspond to those employed previously for α,β-unsaturated β-imino amines[13] and β-amino thiones.[23]

A. Macrocycles of the MeHMe Series. 1. 5,7,12,14-Tetra-methyl-1,4,8,11-tetraazacyclotetradeca-4,6,11,13-tetraene, H_2-[MeHMe(en)$_2$] (15). (a) From H_2[OMeHMe(en)] (16). Triethyl-oxonium tetrafluoroborate (6.78 g, 35.1 mmol) in 200 ml of dichloromethane was added under nitrogen to 4.00 g (17.8 mmol) of bis(acetylacetone)ethylenediamine[24] (16). After 30 min of stirring, 1.07 g (17.8 mmol) of ethylenediamine in 40 ml of ethanol was added dropwise to give a white precipitate. Solvent was removed under vacuum and replaced with ethanol. A solution of 1.90 g (35.1 mmol) of sodium methoxide in 40 ml of methanol was added with stirring. The resulting precipitate was filtered and suspended in 100 ml of chloroform. NaBF$_4$ was removed by filtration and the chloroform was evaporated, affording 1.70 g of crude product. Recrystallization from ethanol gave 1.10 g (25%) of the pure macrocycle 15 whose pmr spectrum and melting point are identical with those of samples prepared by a different route.[13]

(b) From H_2[SMeHMe(en)] (18). Bis(thioacetylacetone)ethylenediamine[25] (18, 3.50 g, 13.2 mmol) was refluxed in 200 ml of benzene with 2.00 g (33.3 mmol) of ethylenediamine for 4 days. Removal of solvent, addition of methanol, and filtration gave 0.50 g of

Scheme I. Synthesis of Macrocycles of the MeHMe Series (en = Ethylenediamine, tn = Trimethylenediamine)
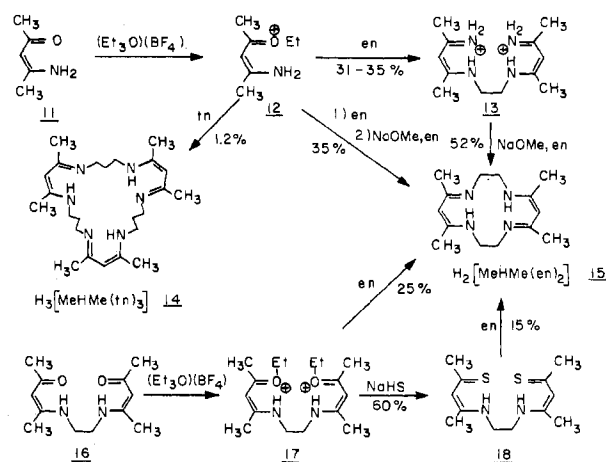

product. This material was purified by recrystallization from ethanol and obtained in 15% yield. It was identified as 15 by melting point and pmr spectrum.

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(25) This compound was prepared by a method[23] (Scheme I, 60% yield based on 16) identical with that reported while this work was in progress: R. M. C. Wei and S. C. Cummings, *Inorg. Nucl. Chem. Lett.*, **9**, 43 (1973).

Scheme II. Synthesis of Macrocycles and Their Metal Complexes of the HPhH Series from the 4-Phenyl-1,2-dithiolium Cation (en = Ethylenediamine, tn = Trimethylenediamine)
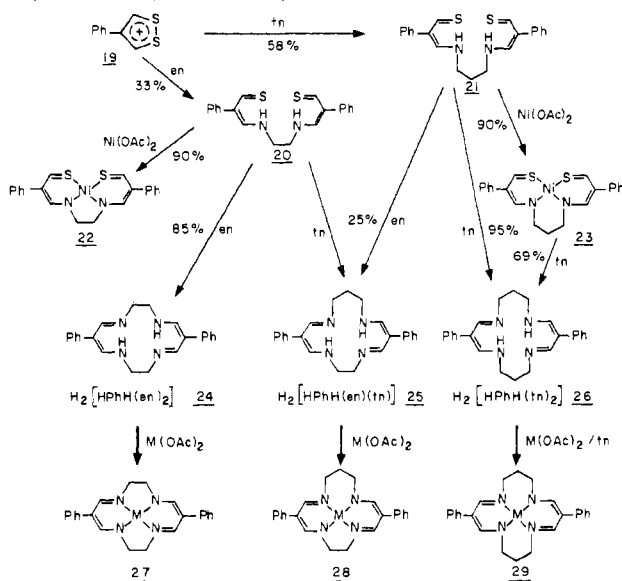
2. **6,8,14,16,22,24-Hexamethyl-1,5,9,13,17,21-hexaazacyclo-tetracosa-5,7,13,15,21,23-hexaene, H₃[MeHMe(tn)₃]** (14). To a solution of 30.0 g (0.30 mol) of 4-aminomethyl-3-en-2-one[26] in 200 ml of dry dichloromethane was added 57.0 g (0.30 mol) of triethyloxonium tetrafluoroborate dissolved in 150 ml of dry dichloromethane. The solution was stirred under an atmosphere of dry nitrogen for 30 min. Trimethylenediamine (11.2 g, 0.15 mol) was added over a 30-min period. The bright yellow solution was stirred for an additional 3 hr at room temperature. Dichloromethane was removed under reduced pressure and replaced with 400 ml of absolute methanol. To this solution was added 16.2 g (0.30 mol) of sodium methoxide in 150 ml of methanol and immediately thereafter an additional 11.2 g (0.15 mol) of trimethylenediamine was introduced. The reaction was allowed to proceed for 4 hr with stirring during which time ammonia was evolved. Half of the methanol was then removed under reduced pressure and the solution was filtered. No product was recovered from the filtrate. White crystals were obtained by extracting the residue with 300 ml of hot chloroform, reducing the volume, and adding methanol. The solid was recrystallized from absolute ethanol to afford 0.50 g of pure product in very low yield (1.2%). No other product was isolated from the reaction mixture. Molecular weight: calcd, 414; found, 407 (osmometry, chloroform solution). Mass spectrum: calcd for $^{12}C_{24}{}^1H_{42}{}^{14}N_6$ parent ion, *m/e* 414.3470; found, *m/e* 414.3469.

B. **Macrocycles of the HPhH Series.** 1. **Bis(β-amino thione) Precursors.** *N,N'*-Bis(2-thioformyl-2-phenylvinyl)ethylenediamine, H₂[SPhHHen] (20). 4-Phenyl-1,2-dithiolium perchlorate[27] (19, 20 g, 70 mmol) was suspended in 300 ml of chloroform and 4.2 g (70 mmol) of ethylenediamine in 50 ml of chloroform was added dropwise with vigorous stirring at room temperature. The suspension was heated to 60° and the crude product was collected by filtration of the hot suspension. This material was twice recrystallized from DMF–ethanol at 40° affording 4.0 g (33%) of essentially pure product suitable for ring closure (*vide infra*). Final purification was achieved by recrystallization from chloroform–methanol and from benzene, yielding yellow crystals which were dried for 2 days *in vacuo* at 80°.

N,N'-Bis(2-thioformyl-2-phenylvinyl)trimethylenediamine, H₂[SPhHHtn] (21). 4-Phenyl-1,2-dithiolium perchlorate[27] (50.0 g, 0.180 mol) was suspended in 600 ml of benzene at room temperature and 14.7 g (0.198 mol) of trimethylenediamine dissolved in 100 ml of benzene was added dropwise with vigorous stirring. The suspension was warmed to 80°, and the red-orange solution was decanted from the residue and allowed to cool to room temperature whereupon crystallization began. The solution was concentrated to *ca.* 100 ml; the product was collected by filtration and washed thoroughly with anhydrous ether affording 19.1 g (58%) of pure material. Recrystallization from benzene gave the product as a yellow microcrystalline product.

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(27) E. Klingsberg, *J. Amer. Chem. Soc.*, 83, 2934 (1961).

N,N'-Bis(3-phenyl-3-thioxo-1-propenyl)ethylenediamine, H₂-[SPhHHen] (32, Rγ = Ph, Rβ = Rα = H, B = (CH₂)₂). 3-Phenyl-1,2-dithiolium perchlorate[27] (2 g, 7 mmol) was suspended in 50 ml of absolute ethanol and heated with ethylenediamine (0.4 g, 7 mmol). The mixture was stirred at room temperature for 1 hr and warmed to 60–70° for 3 hr, and the product was filtered off. Recrystallization from chloroform yielded orange crystals (0.5 g, 20%) which were dried *in vacuo* for 3 days at 60°.

N,N'-Bis(3-phenyl-3-thioxo-1-propenyl)trimethylenediamine, H₂[SPhHHtn] (32, Rγ = Ph, Rβ = Rα = H, B = (CH₂)₃). This compound was prepared by the same procedure used for the ethylenediamine analog, except that the orange crystalline material was recrystallized twice from a 4:1 chloroform–heptane mixture to afford 0.5 g (20%) of product.

2. **Macrocycles. 6,13-Diphenyl-1,4,8,11-tetraazacyclotetradeca-4,6,11,13-tetraene, H₂[HPhH(en)₂]** (24). H₂[SHPhH(en)] (3.00 g, 8.52 mmol) was suspended in 600 ml of hot benzene and 1.02 g (17.1 mmol) of ethylenediamine in 100 ml of benzene was added dropwise with vigorous stirring. The stirring was continued while the reaction mixture was maintained at *ca.* 80° for 6 hr. The yellow solution was cooled, and the benzene and excess diamine were removed on a rotary evaporator. Addition of 100 ml of methanol caused separation of 2.5 g (85%) of essentially pure product as a light yellow solid. Final purification was achieved by recrystallization from chloroform, affording the macrocycle as white crystals. Mass spectrum: calcd for $^{12}C_{22}{}^1H_{22}{}^{14}N_4$ parent ion, *m/e* 342.1844; found, *m/e* 342.1864.

7,15-Diphenyl-1,5,9,13-tetraazahexadeca-5,7,13,15-tetraene, H₂[HPhH(tn)₂] (26). Method 1. H₂[SHPhHtn] (17.4 g, 47.6 mmol) was dissolved in 280 ml of hot benzene, the hot solution was filtered, and 8.70 g (118 mmol) of trimethylenediamine dissolved in 100 ml of benzene was added dropwise with vigorous stirring to the solution maintained at *ca.* 80°. The yellow solution was decanted from a small amount of red oil and the benzene and excess diamine were removed on a rotary evaporator. Addition of 100 ml of methanol to the resultant yellow oil caused separation of 16.9 g (95%) of essentially pure product. Final purification was carried out by recrystallization from chloroform–methanol, affording the macrocycle as a white solid. Mass spectrum: calcd for $^{12}C_{24}{}^1H_{28}{}^{14}N_4$ parent ion, *m/e* 372.2314; found, *m/e* 372.2304.

Method 2. Ni[SHPhHtn] (23, *vide infra*) (4.00 g, 9.47 mmol) and 40 ml of 1,3-diaminopropane were stirred for 1 hr at *ca.* 35°. The mixture was filtered and the diamine was removed *in vacuo*. To the resultant oil chloroform (40 ml) was added and the mixture was refluxed for 45 min. The solution was decanted from the residue and heated to boiling. Dropwise addition of methanol resulted in precipitation of the product, which was collected by filtration. Concentration of the filtrate gave a second crop, yielding a total of 2.56 g of crude product. Recrystallization from chloroform–methanol afforded 2.44 g (69%) of pure product.

6,14-Diphenyl-1,4,8,12-tetraazacyclopentadeca-4,6,12,14-tetraene, H₂[HPhH(en)tn] (25). To a vigorously stirred solution of 36.5 g (0.10 mol) of H₂[SHPhHtn] in 2 l. of benzene maintained at 45° 6.0 g (0.10 mol) of freshly distilled ethylenediamine in 500 ml of benzene was added over a period of 6 hr. The solution was decanted from a small amount of dark oil, the volume was reduced to 150–200 ml, and the solution was filtered to afford the first crop of solid material. The second crop was obtained by addition of just enough methanol to the hot filtrate to induce precipitation. Combination of the two crops gave 18.5 g of a light yellow material which was found by pmr (*cf.* Table II) to be an approximate 2:1 mixture of H₂[HPhH(en)tn]–H₂[HPhH(en)₂]. Purification was achieved by fractional recrystallizations from chloroform–methanol, H₂[HPhH(en)-tn] being the more soluble fraction. By this procedure the pure macrocycle (7.8 g, 25%) was obtained as pale yellow platelets. Mass spectrum: calcd for $^{12}C_{23}{}^1H_{26}{}^{14}N_4$ parent ion, *m/e* 358.2157; found, *m/e* 358.2148. No parent ion due to H₂[HPhH(en)₂] was observed nor were signals of this compound found in the pmr spectrum of the final product.

C. **Complexes. Ni[SHPhHen] (22) and Ni[SHPhHtn] (23).** These complexes were prepared by the reaction of equimolar amounts of nickel acetate in methanol and the appropriate ligand in hot chloroform. They were recrystallized from chloroform–methanol and obtained as dark brown crystals in >90% yield.

Ni[SPhHHen] and Ni[SPhHHtn]. The above procedure was employed. Pure products were obtained in *ca.* 70% yield after recrystallization from acetone (dark brown crystals) and drying at 60° *in vacuo* for 2 days.

M[HPhH(en)₂] (27), M = Cu(II), Ni(II), Co(II). Reaction of equimolar amounts of the appropriate metal(II) acetate hydrate and

$H_2[HPhH(en)_2]$ in hot DMF afforded the desired complexes in crystalline form. Final purification was achieved by recrystallization from DMF: Cu(II), bronze platelets, 65%, 1.73 BM; Ni(II), red platelets, 85%; Co(II) (prepared under nitrogen), red-brown platelets, 65%, 2.05 BM. The Co(II) complex is unstable to air in solution.

M[HPhH(en)tn] (28), M = Cu(II), Ni(II), Co(II). Reactions of equimolar amounts of the appropriate metal(II) acetate hydrate and $H_2[HPhH(en)tn]$ in hot degassed DMF for $1/2$ hr afforded the desired complexes in crystalline form. Final purification was achieved by recrystallization from DMF: Cu(II), bronze platelets, 70%; Ni(II), green platelets, 80%; Co(II) (prepared under nitrogen), dark red platelets, 50%. The Co(II) complex is unstable to air in solution. The following m/e values together with observed (calculated) relative intensities were obtained under low resolution in the parent ion region of Ni[HPhH(en)tn]: 414, 100 (100); 415, 30 (27); 416, 42 (39); 417, 12 (11); 418, 6.7 (5.4); 419, 1.6 (1.1); 420, 1.2 (1.1).

M[HPhH(tn)_2] (29), M = Cu(II), Ni(II), Co(II). The following operations were performed under a dry nitrogen atmosphere. The preparation of the Ni(II) complex is typical. To a suspension of $H_2[HPhH(tn)_2]$ (3.00 g, 8.07 mmol) in 20 ml of degassed DMF at 80° was added 2.21 g (8.88 mmol) of nickel(II) acetate tetrahydrate in 15 ml of DMF. Upon the addition of 0.7 ml of trimethylenediamine, green crystals began to separate from the solution. The reaction mixture was stirred at 80° for 18 hr, cooled, and filtered. The green microcrystalline solid (1.72 g, 50%) was washed with 50 ml of degassed ethanol and dried *in vacuo* at room temperature for 16 hr. Recrystallization from DMF afforded the complex as green platelets. The other two complexes were prepared similarly and recrystallized from DMF: Cu(II), brown needles, 30%, 1.72 BM; Co(II), red-brown, 45%, 1.96 BM. The Co(II) complex is unstable to air in solution.

Physical Measurements. Magnetic susceptibility measurements were made by the Faraday method using $HgCo(NCS)_4$ or $Ni(en)_3S_2O_3$ as calibrants. A Mechrolab Model 302 osmometer operating at 37° was used for solution molecular weight determinations. Pmr spectra were obtained on a Varian T-60 or a Hitachi Perkin-Elmer R-20B spectrometer (operating in the CW or FT mode) using TMS as an internal standard. Low-resolution mass spectra were recorded on a Hitachi Perkin-Elmer RMU-6D spectrometer operating at 70 eV. High-resolution mass spectra were determined with a CEC21-11B double-focusing spectrometer employing photoplate recording and operating at 70 eV.

Results and Discussion

Prior to our descriptions[13,14] of the synthesis of the bis(β-imino amine) complexes M[MeHMe(en)_2] (6a), Jager[10,11] had demonstrated template cyclization based on the reactions of the complexes 30 with primary diamines. These reactions afford the complexes 6a-c (R_α = H, R_γ = Me, Ph) and 8 (R_α = H, R_γ = Me, Ph;[10,13b] R_α = R_γ = Me[10]). The basic macrocyclic structure 8 has been confirmed for Fe[MeHMe(phen)_2](CO)(N_2H_4) by X-ray diffraction.[21] While Jager's work represents an admirable contribution to the further definition of the reactivity of coordinated ligands in general and metal template cyclization reactions[2b] in particular, we were stimulated by a number of observations to seek nontemplate methods of synthesis of the macrocycles 31.

30   **31**
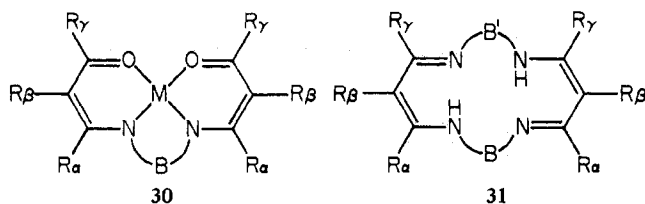
Template cyclization with aliphatic diamines appears dependent on the presence of an activating group R_β = COR or COOR,[12,13b] which is undesirable in oxidative dehydrogenation reactions[13b,14] of macrocyclic complexes currently under study. Cyclization has been reported only for Ni(II) and Cu(II) complexes[10,11,28] and indications of demetalation of bridged aliphatic compounds (with H_2S)

are presently limited to several 6-5-6-5 and 6-5-6-6 Cu(II) species.[11] Synthesis of the Ni(II) complexes 6b (R_α = H, R_β = COMe, COOR, R_γ = Me, Ph) was accomplished in low yield and the corresponding Cu(II) species were not obtained.[10] Prior work in this laboratory had not led to the successful preparation of stable iron complexes of type 30 using 16 (Scheme I) and similar tetradentate bis(β-keto amines) as test ligands.[29] Inasmuch as the effects of ring size and ligand unsaturation on the properties of Fe(II,III) complexes is of prime interest in this research, the difficulty in obtaining suitable precursors for template cyclization is an obvious problem. Generation of 31 (B, B' = $(CH_2)_{2,3}$) as the first cyclized product of synthesis obviates demetalation reactions and allows preparation of an extensive series of 12-π M(II,III) complexes of each of the size patterns 1, 2, and 3. Additionally, the formation of 14-, 15-, and 16-membered unsaturated tetraaza ring systems by other than metal template routes is an inherently interesting synthetic problem which has attracted little systematic investigation. This report is confined to synthetic approaches affording the macrocycles 31 and certain of their M(II) complexes. Future articles will deal with their structural, electronic, and reactivity properties and those of other complexes derived from them by oxidation dehydrogenation.[13b,14]

MeHMe 6-5-6-5 Macrocycles: Alternative Methods and Attempts to Prepare Larger Rings. Previously we have described[13] the nontemplate synthesis of the 6-5-6-5 macrocycle $H_2[MeHMe(en)_2]$ (15). The procedure, outlined in Scheme I, is initiated by *O*-alkylation of the β-keto amine 11. The cation 12 undergoes nucleophilic attack by ethylenediamine giving 13, which is readily closed by a second equivalent of diamine to yield 15. Alternatively, 12 may be converted directly to the macrocycle in 35% yield based on 11 without isolation of the intermediate 13. A related route to 15, reported here, utilizes the readily accessible bis(β-keto amine)[24] 16 which upon alkylation to the dication 17 and treatment with ethylenediamine affords the macrocycle in 25% yield based on 16. Attempts to synthesize larger tetraaza ring systems by replacement of ethylenediamine with trimethylenediamine in these procedures were uniformly unsuccessful. The desired macrocycles, if formed at all, could not be isolated from the reaction mixtures. The reaction of the cation 12 with trimethylenediamine was carried out a number of times under somewhat different conditions. The only product isolated was a white crystalline solid whose analysis, pmr and mass spectra, and solution molecular weight are fully consistent with a cyclic 21-membered ring structure 14 which, according to CPK models, is relatively strainless. This compound was obtained in very low yield and, inasmuch as $H_2[MeHMe(tn)_2]$ was the desired product, no attempts to optimize its yield were made. In view of our present inability to extend the reactions of 12 and 17 to the synthesis of 15- and 16-membered rings, alternative methods have been sought.

HPhH Macrocycles: Synthesis from a Dithiolium Salt. This approach is based on the reactivity of 1,2-dithiolium cations with nucleophiles.[30] It is now well established that aryl-substituted cations afford α,β-unsaturated β-amino thiones upon treatment with a wide variety of primary monoamines.[23,30-35] These compounds may also be ob-

(28) C. J. Hipp and D. H. Busch, *Inorg. Chem.*, 12, 894 (1973).

(29) D. H. Gerlach and R. H. Holm, unpublished observations.
(30) H. Prinzbach and E. Futterer, *Advan. Heterocycl. Chem.*, 7, 39 (1967).
(31) D. Leaver, D. M. McKinnon, and W. A. H. Robertson, *J. Chem. Soc.*, 32 (1965).
(32) C. Palmier, Y. Mollier, and N. Lozac'h, *Bull. Soc. Chim. Fr.*, 2463 (1965).

tained in good yield by reaction of isothiazolium cations with amines[36] or *O*-alkyl-β-keto amine cations (Scheme I) with hydrosulfide ion.[23,25] Of particular pertinence to the synthetic scheme devised in this work were the prior observations that ethylenediamine reacts with the 3,5-diphenyl-1,2-dithiolium cation to afford the tetradentate ligand $H_2[S$-$PhHPh(en)]^{35}$ (**32**, $R_\gamma = R_\alpha = Ph$, $R_\beta = H$, $B = (CH_2)_2$) and that the 4-phenyl-1,2-dithiolium cation (**19**, Scheme II) with excess aniline[32] or *p*-toluidine[33] yields the β-imino amines **33**. The latter finding implies the susceptibility of the initially formed β-amino thiones **34** to nucleophilic attack at the γ carbon.

32　　　　　　　　　**33**

34
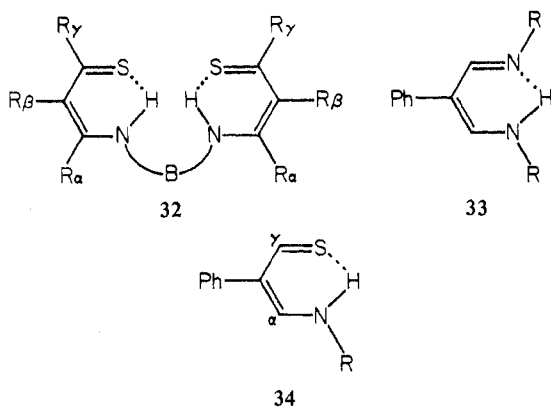
The cation **19** was selected as the starting material. It is readily synthesized by oxidation of 4-phenyl-1,2-dithiole-3-thione,[27] which in turn is easily prepared from sulfur and cumene,[37] and its perchlorate salt has been routinely obtained in lots of 500 g or more. The synthetic method is set out in Scheme II. The bis(β-amino thiones) **20** and **21** were prepared from **19** and the indicated diamines in moderate yield after purification. The isomeric compounds $H_2[SPhHH(B)]$ ($B = (CH_2)_{2,3}$) were obtained from the 3-phenyl cation[27] by the same method.[38-40] These tetradentate ligands, like other β-amino thiones,[23,25,34] form stable Ni(II) complexes (*e.g.*, **22**, **23**). That the tautomeric form of these ligands is the amino thione indicated in **32** is readily shown by pmr spectra. A simple case is afforded by the compound **34** (R = CH_2Ph) whose spectrum in $CDCl_3$ reveals a methylene doublet ($J = 6$ Hz), a doublet of doublets for α-H with $J_{\alpha-NH} = 14$ Hz and $J_{\alpha\gamma} = 4$ Hz, and a doublet for γ-H. These assignments were confirmed by deuteration and double-resonance experiments. Related spectral features are evident for several of the bis(β-amino thiones) in Table II. These

(33) J. Bignebat and H. Quiniou, *Bull. Soc. Chim. Fr.*, 1180 (1966); J. Bignebat, H. Quiniou, and N. Lozac'h, *ibid.*, 127 (1969); G. L. Coustumer and Y. Mollier, *ibid.*, 3076 (1970).

(34) E. Uhlemann, *Z. Naturforsch. B*, 21, 592 (1966).

(35) D. M. McKinnon and E. A. Robak, *Can. J. Chem.*, 46, 1855 (1968).

(36) P. Sykes and H. Ullah, *J. Chem. Soc., Perkin Trans. 1*, 2305 (1972).

(37) E. K. Fields, *J. Amer. Chem. Soc.*, 77, 4255 (1955).

(38) This reaction does not appear to extend to alkyl-substituted cations. Under similar conditions 3,5-dimethyl-1,2-dithiolium perchlorate[39] and ethylenediamine did not yield 18 but instead gave an unidentified purple solid. Similar behavior has been noted in the reaction of 3-methyl-5-phenyl-1,2-dithiolium perchlorate with ammonia which also afforded a purple solid instead of isothiazoles.[40] Presumably the acidities of the methyl protons are responsible for this behavior. However, alkylated forms of 32 and other β-amino thiones are readily obtained by a different route[23,25] (Scheme I).

(39) M. Schmidt and H. Schulz, *Chem. Ber.*, 101, 277 (1968); G. A. Heath, R. L. Martin, and I. M. Stewart, *Aust. J. Chem.*, 22, 83 (1969).

(40) R. A. Olofson, J. M. Landesberg, R. O. Berry, D. Leaver, W. A. H. Robertson, and D. M. McKinnon, *Tetrahedron*, 22, 2119 (1966).
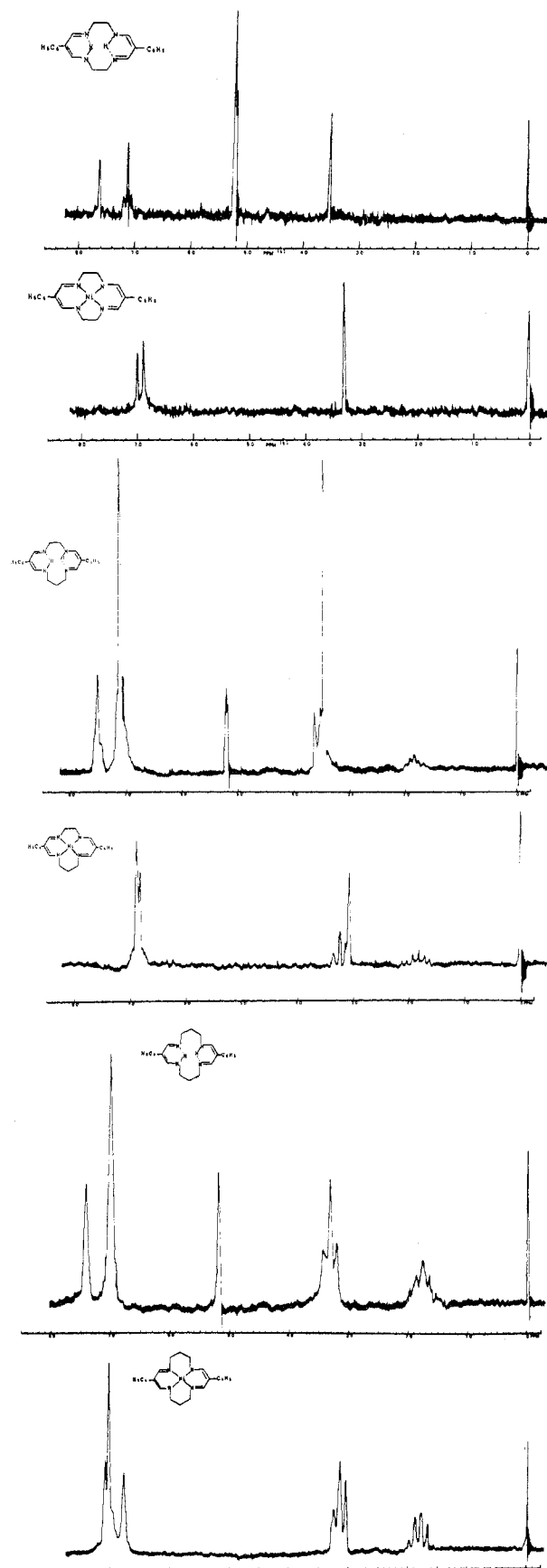
Figure 1. Pmr spectra (60 MHz) of the macrocycles of the HPhH series and their Ni(II) complexes. Solvents are listed in Table II. The signals at ~5.1 ppm in the first and third spectra and that at ~7.2 ppm in the bottom spectrum are due to proton-containing solvent molecules.

results together with others presented earlier[23] substantiate the amino thione structure (in weakly polar solvents) for the reaction products of 3- and 4-phenyl-1,2-dithiolium cations and aliphatic amines. These compounds are among the relatively few of any kind containing a thioaldehyde group,[41] which in the present examples is stabilized as a vinylogous amino thione.

The amino thiones **20** and **21**, which can be obtained readily in substantial quantity, serve as immediate precursors to the bis(β-imino amine) macrocycles of size patterns **1-3**. Reaction of **20** with ethylenediamine and **21** with trimethylenediamine in hot benzene results in smooth conversion to the macrocycles **24** and **26**, respectively, isolated in excellent yield. The closure reaction **21 → 26** in particular has been repeated many times in nearly quantitative yield. The 6-5-6-6 macrocycle **25** is best obtained from equimolar amounts of **21** and ethylenediamine in warm benzene. The crude product is contaminated with the less soluble **24**, formed by amine exchange, which may be separated by fractional recrystallization affording the desired cycle **25** in 25% yield. Under similar experimental conditions this compound can be obtained in *ca.* 30% yield from **20** and trimethylenediamine and **26** can be prepared from **20** utilizing amine exchange. However, these reactions offer no significant synthetic advantage compared to those detailed in the Experimental Section. The closure reactions involve attack by the amine nucleophile at the thione carbon followed by elimination of the elements of H_2S. Reactions of ethylenediamine or trimethylenediamine with the potential precursors **32** ($R_\gamma \neq H$) gave no evidence of macrocycle formation (H_2-[SPhHHen], H_2[SPhHHtn]) or low-yield closure under prolonged reaction (Scheme I: **18 → 15**, 4 days at 80°). The ease with which closure to macrocycles can be effected with **20** and **21** compared to the latter compounds is presumably a reflection of the relative reactivity of thioaldehydes and thioketones toward nucleophiles. The macrocycles **24-26** have been characterized by high-resolution mass spectrometry, which revealed intense parent ion peaks for the indicated structures, and by pmr. Pmr data are collected in Table II and spectra are set out in Figure 1.

Complexes. Consistent with their structures macrocycles **24-26** form neutral planar complexes of Cu(II), Ni(II) (diamagnetic by pmr: Table II and Figure 1), and Co(II) (low spin). Iron(II,III) complexes have also been prepared and their properties, together with those of other complexes, will be described in a future report. Species **27** and **28** are readily isolated from the reaction of the ligand and metal(II) acetate in DMF. In contrast the preparation of the 6-6-6-6 complexes **29** requires the addition of *ca.* 1 equiv of trimethylenediamine to the DMF solution, whereupon the complexes are easily obtained in 30-50% yield after purification. Sodium methoxide, pyridine, diethylamine, *n*-propylamine, and *N,N,N',N'*-tetramethyl-1,3-propanediamine have no evident effect on the Ni(II) complexation reaction, indicating that the role of trimethylenediamine is not that of a general base. The difficulty of inserting metal ions into **26** is presumably due to its larger "hole" size compared to **24** and **25**, but at present we have no clear-cut evidence as to the function of the diamine in promoting the complexation reaction.

Template Synthesis. In addition to the metal-free procedures just described, metal template macrocyclic synthe-

sis has been investigated in this work, although less extensively. The potential susceptibility of bis(β-amino thione) complexes such as **22** and **23** to ring closure is suggested by the reaction **35 → 36** briefly described by Chaston, *et al.*[42]

35   **36**
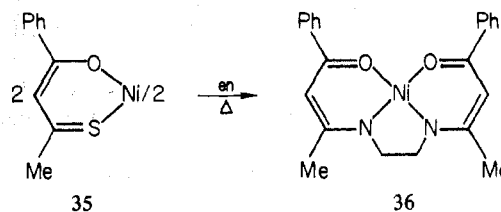
In neat trimethylenediamine **23** is smoothly converted to the metal-free macrocycle **26** (Scheme II) in 69% yield with formation of NiS. The reactions of **22** in neat ethylenediamine or trimethylenediamine under similar conditions or with these diamines in refluxing xylene yielded no macrocyclic products.

The reactions summarized in Scheme II clearly offer simple and effective routes to the 12-π tetraaza macrocycles **31** and are best applied to the synthesis of compounds with $R_\alpha = R_\gamma = H$. Unlike the Jager metal template method carbonyl-containing R_β substituents are not required for cyclization. While this work was in progress Hipp and Busch[43] reported that the Jager complex Ni[Me(COMe)H-(en)tn][10] can be deacylated by mineral acid to Ni[MeHH-(en)tn]. This reaction, which also applies to Ni[Me(COMe)·H(en)$_2$],[44] extends the scope of cyclization reactions based on **30** to the synthesis of macrocyclic Ni(II) and Cu(II) complexes with $R_\beta = H$. Complexes of these ions which are accessible by template reactions now appear restricted only by lack of formation of the obligatory precursors **30**[45] with the desired R_γ, R_α sets of substituents. Thus, the template and nontemplate methods together afford entry to a broad variety of tetraaza macrocyclic systems. The accessible range of such systems will be further enhanced if the β-carbon reactivity of complexes with $R_\beta = $ COMe toward electrophiles[28] and demetalation of complexes provided by template synthesis are of general occurrence.

(41) S. McKenzie and D. H. Reid, *Chem. Commun.*, 401 (1966).

(42) S. H. H. Chaston, S. E. Livingstone, T. N. Lockyer, and J. S. Shannon, *Aust. J. Chem.*, 18, 1539 (1965).

(43) C. J. Hipp and D. H. Busch, *J. Chem. Soc., Chem. Commun.*, 737 (1972).

(44) G. S. Patterson and R. H. Holm, unpublished observations.

(45) L. Wolf and E.-G. Jager, *Z. Anorg. Allg. Chem.*, 346, 76 (1966); E.-G. Jager, *ibid.*, 349, 139 (1967).