Magnetic and Spectroscopic Behavior of Amine Adducts of Copper(II)–N-acetyl-β-alaninate

LEDI MENABUE, PAOLO PRAMPOLINI, MONICA SALADINI

Istituto di Chimica Generale ed Inorganica, University of Modena, Via Campi 183, 41100 Modena, Italy

and PAOLA MORINI

Istituto di Chimica, Facoltà di Medicina-Veterinaria, University of Bari, Via Gentile 182, 70126 Bari, Italy

Received April 27, 1982

A series of ternary complexes with the general formula $Cu(ac\text{-}\beta\text{-}ala)_2B_2 \cdot nH_2O$ (ac-β-ala = N-acetyl-β-alaninate ion; n = 0 and B = ethylenediamine (en), 4-methylpyridine (4pic); n = 2 and B = pyridine (py) and 4pic) and $Cu(ac\text{-}\beta\text{-}ala)_2B$ (B = piperazine (pipz), 2,2'-bipyridine (bipy), py, 3-methylpyridine (3pic), 4pic) were synthesized and investigated by means of infrared, electronic, e.p.r. spectroscopy and variable temperature magnetic measurements. The green monoamine adducts of py, 3- and 4pic ($pK_a \leqslant 6$) showed physical properties which indicated a binuclear geometry as in the parent complex $[Cu(ac\text{-}\beta\text{-}ala)_2 \cdot H_2O]_2 \cdot 2H_2O$. The $|2J|$ values of these adducts increased with respect to the hydrate complex, and were comparable to those of carboxylic acids of similar complexity. For this type of complexes the narrow spectral range of $\nu(OCO)_{as}$ and $\nu(OCO)_s$ indicates only slight dependence on N-protected amino acids. The blue or violet monomeric compounds display spectroscopic properties which indicate a tetragonal configuration whose distortion increases with the basic strength of the amine. For en derivatives all the experimental results are in accord with a square geometry with CuN_4 chromophore, the amino acid acting only as a counterion.

Introduction

The tendency of N-protected amino acids to form strongly coupled dimeric copper(II) complexes such as copper acetate monohydrate is well established on the basis of structural [1, 2], magnetic and spectroscopic data [3–8]. For all the previous systems the experimental data indicate that they are discrete dimeric units magnetically isolated from the bulk of the sample, and the Bleaney–Bowers equation adequately described their magnetic properties [9].

These compounds, paralleling the simple carboxylate dimers, easily react with amines [5, 6, 10–14] forming monomeric tetragonally distorted octahedral bis-amine adducts with normal magnetic moments.

In particular, the reaction with unidentate aromatic amines of $pk_a < 6$ seems to be more difficult and often leads to monoamine adducts with subnormal magnetic moments; on the basis of spectroscopic and magnetic measurements it is suggested that these retain the caged-dimer structure [7, 12–14]. Too few compounds have been investigated at present, so that it is not feasible to suggest a binuclear structure for all monoamine adducts.

The high stability of ternary copper(II) complexes with O and N donors makes them very abundant in natural systems [15] and their biological importance has prompted our investigation of the spectral and magnetic properties of mixed amine complexes of the Cu(II)–N-acetyl-β-alaninate system by means of variable temperature magnetic susceptibility, e.p.r., electronic and infrared measurements.

Experimental

All chemicals were reagent grade and were used as received.

Preparation of the Complexes $Cu(ac\text{-}\beta\text{-}ala)_2B$ (B = py, 3- and 4pic)

The complexes were prepared by mixing an excess of the amine to an ethanolic solution of the green $[Cu(ac\text{-}\beta\text{-}ala)_2 \cdot H_2O]_2 \cdot 2H_2O$ and by adding diethyl ether until a green solution was obtained. By cooling to 4–5 °C overnight green compounds crystallized.

$Cu(ac\text{-}\beta\text{-}ala)_2(py)$: *Anal.* Calcd. for $C_{15}H_{21}CuN_3O_6$: C, 44.69; H, 5.26; N, 10.43. Found: C, 44.56;

0020-1693/83/0000-0000/$03.00

H, 5.21; N, 9.93. Cu(ac-β-ala)$_2$(3pic): *Anal.* Calcd. for $C_{16}H_{23}CuN_3O_6$: C, 46.07; H, 5.56; N, 10.08. Found: C, 45.92; H, 5.52; N, 9.74. Cu(ac-β-ala)$_2$-(4pic): *Anal.* Calcd. for: $C_{16}H_{23}CuN_3O_6$: C, 46.07; H, 5.56; N, 10.08. Found: C, 45.76; H, 5.67; N, 9.74.

Cu(ac-β-ala)$_2$(en)$_2$

A violet compound separated by mixing a moderate excess of amine with a concentrated ethanolic solution of the anhydrous Cu(ac-β-ala)$_2$ and by adding diethyl ether. *Anal.* Calcd. for: $C_{14}H_{32}$-CuN_6O_6: C, 37.85; H, 7.27; N, 18.94. Found: C, 37.69; H, 7.31; N, 18.62.

Cu(ac-β-ala)$_2$B (B = bipy and pipz)

These complexes precipitated upon mixing a methanolic solution of the appropriate amine with an ethanolic concentrated solution of blue or green Cu(ac-β-ala)$_2$·2H$_2$O in a molar ratio of 1:1, and by adding diethyl ether.

Cu(ac-β-ala)$_2$bipy: *Anal.* Calcd. for $C_{20}H_{24}CuN_4$-O_6: C, 50.02; H, 5.04; N, 11.68. Found: C, 50.03; H, 5.20; N, 10.63. Cu(ac-β-ala)$_2$pipz: *Anal.* Calcd. for $C_{14}H_{26}CuN_4O_6$: C, 41.00; H. 6.40; N, 13.67. Found: C, 40.96; H, 6.59; N, 13.58.

Cu(ac-β-ala)$_2$B$_2$·2H$_2$O (B = py, 4pic)

These compounds were synthesized by adding a large excess of py or 4pic to a concentrated ethanolic solution of Cu(ac-β-ala)$_2$·2H$_2$O. By adding a moderate amount of diethyl ether from the blue solution light-blue compounds separated.

Cu(ac-β-ala)$_2$(py)$_2$·2H$_2$O: *Anal.* Calcd. for C_{20}-$H_{30}CuN_4O_8$: C, 46.34; H, 5.83; N, 10.82. Found: C, 45.95; H, 5.85; N, 10.74. Cu(ac-β-ala)$_2$(4pic)$_2$·2H$_2$O: *Anal.* Calcd. for $C_{22}H_{34}CuN_4O_8$: C, 48.37; H, 6.28; N, 10.27. Found: C, 48.46; H, 6.29; N, 10.20.

Cu(ac-β-ala)$_2$(4pic)$_2$

This compound was prepared by adding to an ethanolic solution of Cu(ac-β-ala)$_2$ a large excess of amine, and by adding diethyl ether. From the blue resultant solution a blue-violet compound separated upon standing for several days at 4–5 °C. *Anal.* Calcd. for $C_{22}H_{30}CuN_4O_6$: C, 51.78; H, 5.93; N, 10.99: Found: C, 51.49, H, 5.99; N, 10.89.

Physical Measurements

Electronic and infrared spectra of the complexes were recorded as previously described [2]. The magnetic susceptibilities of powdered samples were determined at different temperatures on a Gouy balance (Newport Instruments Ltd.) standardized with $HgCo(SCN)_4$ [7]. The molar susceptibilities were corrected for diamagnetism by using Pascal constants [7]. The effective magnetic moments were calculated by using the expression: $\mu_{eff} = 2.83$ $(\chi_M xT)^{1/2}$. The e.p.r. spectra were recorded as previously described [2]. A list of observed and calculated magnetic susceptibilities is available from the Editor on request.

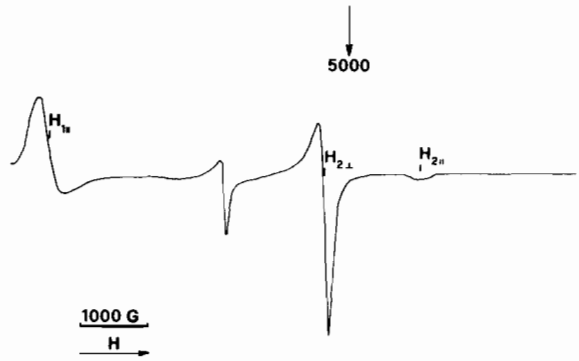

Fig. 1. Room temperature e.p.r. spectrum of Cu(ac-β-ala)$_2$-(3pic).

Results and Discussion

All the complexes are stable in air, although they appear hygroscopic and soluble in commom polar organic solvents.

Colors, magnetic and spectroscopic properties permit us to divide the complexes into two types.

Type 1

This group contains the three green Cu(ac-β-ala)$_2$B (B = py, 3pic, 4pic) which show similar magnetic and spectroscopic properties (Table I).

In the e.p.r. spectra (Fig. 1) an absorption near 3000 G, whose intensity increases as the temperature decreases, assigned to mononuclear impurities of spin S = ½ (16), is also observed for all the complexes and the corresponding g values are reported in Table I.

The other three absorptions are assigned to transitions in the triplet state and can be adequately described by the axial spin Hamiltonian

$$H = g\beta HS + D(S_z^2 - 2/3)$$

where S = 1 and the other symbols have their usual meaning.

It should be noticed (Fig. 1) that no splitting of the perpendicular components were observed, thus supporting our neglect of an E parameter. The spin Hamiltonian parameters calculated from the observed spectra [16] are reported in Table I.

The magnetic susceptibilities are satisfactorily described by the Bleaney–Bowers equation modified for the presence of monomeric impurities [17]. The mean g values obtained from e.p.r. spectra (Table I)

TABLE I. Room Temperature Electronic, Infrared and Magnetic Results and Low Temperature E.p.r. Spectra for Green $Cu(ac\text{-}\beta\text{-}ala)_2B$ Complexes.[a]

B	py	3pic	4pic
Dimer			
$g_\parallel$	2.398	2.384	2.396
$g_\perp$	2.100	2.088	2.095
$\bar{g}$[b]	2.203	2.191	2.199
D (cm^{-1})	0.379	0.386	0.382
$\|2J\|$ (cm^{-1})	353 ± 5	342 ± 9	340 ± 3
$-\Delta \times 10^6$ (c.g.s.u.)[c]	188.75	200.58	200.58
μ_{eff}[d] (at 295 K), (B.M.)	1.55	1.42	1.49
band I (kK)	14.3	14.0	14.0
band II (kK)	27.8sh	27.2sh	27.0sh
$\nu(OCO)_{as}$[e] (cm^{-1})	1620vs	1622vs	1630vs
$\nu(OCO)_s$[e] (cm^{-1})	1425s	1430vs	1432s
$\Delta\nu$[f] (cm^{-1})	195	190	198
Monomer			
Y[g]	0.04	0.03	0.03
$g_\parallel$	2.316	2.278	2.296
$g_\perp$	2.076	2.061	2.076

[a]Abbreviations: ac-β-ala = N-acetyl-β-alaninate ion; py = pyridine; 3- or 4pic = 3- or 4-methylpyridine. [b]$\bar{g} = [(g_\parallel^2 + 2g_\perp^2)/3]^{1/2}$. [c]$-\Delta$ = diamagnetism of the complexes. [d]1 B.M. = 9.2732 × 10^{-24} A × m^2. [e]Carboxylate stretches given are as = asymmetric and s = symmetric. [f]$\Delta\nu = [\nu(OCO)_{as} - \nu(OCO)_s]$. [g]Mol fraction of monomer.

and $N\alpha = 60 \times 10^{-6}$ c.g.s.u./mol are used as constants in the fitting process, allowing $|2J|$ and the mole fraction of monomer Y to change. The best fits for calculated and experimental molar susceptibilities are achieved for Y and $|2J|$ values reported in Table I. The values compared with a $|2J|$ of 324 cm^{-1} for the structurally known parent complex $[Cu(ac\text{-}\beta\text{-}ala)_2 \cdot H_2O]_2 \cdot 2H_2O$ [2] strongly support the hypothesis of isolated copper dimers with negative intradimer exchange [2, 18, 19]. On the other hand they also obey the general trend established for carboxylate complexes [18, 20, 21], namely that $|2J|$ increases with the basicity of the apical ligand as a further conjugated system reduces the positive charge on the copper(II) atom, thus enhancing the exchange interaction [21]; formerly we found a similar behavior also for the N-benzoyl-DL-valinate–Copper(II)–pyridines systems [7].

In Table II comparing a series of $|2J|$ values for monoamine adducts of simple carboxylic and N-protected amino acids, we may note that when the compounds are formed by acids of similar complexity, the $|2J|$ values are very close to one another.

TABLE II. Magnetic Data for Selected Dimeric Monoamine Adducts of Copper(II) Complexes of Carboxylic Acids and N-Protected Amino Acids.

Complex[a]	$\|2J\|$ (cm^{-1})	Ref.
$Cu(C_2H_5COO)_2(py)$	350	20
$Cu(C_2H_5COO)_2(3pic)$	376	20
$Cu(C_2H_5COO)_2(4pic)$	364	20
$Cu(C_3H_7COO)_2(py)$	332	21
$Cu(C_3H_7COO)_2(3pic)$	337	21
$Cu(C_3H_7COO)_2(4pic)$	329	21
$Cu(ac\text{-}\beta\text{-}ala)_2(py)$	353[b]	this work
$Cu(ac\text{-}\beta\text{-}ala)_2(3pic)$	342	this work
$Cu(ac\text{-}\beta\text{-}ala)_2(4pic)$	340	this work
$Cu(bzval)_2(py)$	308[b]	7
$Cu(bzval)_2(3pic)$	350	7
$Cu(bzval)_2(4pic)$	335	7

[a]Abbreviations: bzval = N-benzoyl-DL-valinate ion; for the other abbreviations see footnote a, Table I. [b]The $|2J|$ value for these complexes may be less precise because the presence of a mol fraction of monomer estimated as 4% for $Cu(ac\text{-}\beta\text{-}ala)_2(py)$, and 5.8% for $Cu(bzval)_2(py)$.

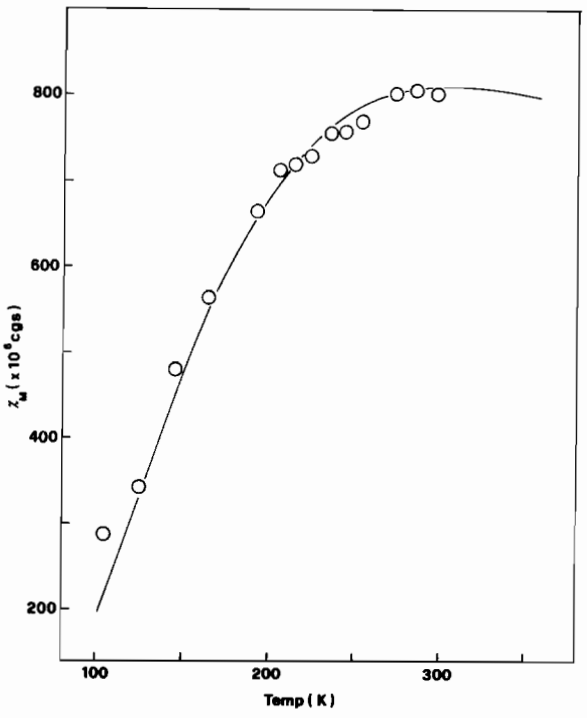

Fig. 2. Corrected molar susceptibility of $Cu(ac\text{-}\beta\text{-}ala)_2(3pic)$, the full line is the calculated best fit to the Bleaney–Bowers equation corrected for monomer [17].

TABLE III. Room Temperature Electronic and E.p.r. Spectra and Magnetic Moments of the Cu(ac-β-ala)$_2$B$_2$ Complexes.[a]

	d–d bands (kK)	μ_{eff}[b] (B.M.)	$g_\parallel$	$g_\perp$	$\langle g \rangle$[c]	$\nu(OCO)_{as}$ (cm^{-1})	$\nu(OCO)_s$ (cm^{-1})	$\Delta\nu$ (cm^{-1})
Cu(ac-β-ala)$_2$(4pic)$_2$	16.3	1.98	2.234	2.074	2.126	1570vs	1410vs	160
Cu(ac-β-ala)$_2$(4pic)$_2$·2H$_2$O[d]	15.4	1.94	2.257	2.132	2.174	1570vs	1405s	165
Cu(ac-β-ala)$_2$(py)$_2$·2H$_2$O[d]	15.5	1.87	2.250	2.072	2.126	1570s	1405vs	165
Cu(ac-β-ala)$_2$(pipz)	18.3	1.85	2.246	2.053	2.117	1570vs	1398vs	172
(ac-β-ala)$_2$[Cu(en)$_2$]	17.9	1.79	2.175	2.050	2.092	1575vs	1400vs	175
Cu(ac-β-ala)$_2$(bipy)[c]	16.3	1.79	2.212	2.087	2.137	1580vs	1400s	180

[a]Abbreviations: en = ethylenediamine, pipz = piperazine, bipy = 2,2′-bipyridine, for the other abbreviations see footnote (a) of Table I. [b]1 B.M. = 9.2732×10^{-24} A × m^2. [c]$\langle g \rangle = 1/3(g_\parallel + 2g_\perp)$. [d]These complexes show also bands at 3510 cm^{-1} and 3440 cm^{-1} assignable to $\nu(OH)_{as}$ and $\nu(OH)_s$ respectively of the water molecules [11].

This may be easily understood if we remember that the N-protected amino acids do not coordinate through their N peptide atoms and thus act as simple carboxylic acids [1, 2, 5, 10, 11].

The electronic and infrared (Table I) data confirm all the above statements, being very close to the values found for the structurally known [Cu(ac-β-ala)$_2$·H$_2$O]$_2$·2H$_2$O [2, 16, 19].

In particular we observe that for a series of Cu(N-protected amino acidate)$_2$L (L = H$_2$O, py, 3- and 4pic, pyridazine) [2, 5, 6, 7, 12, 13, 14, 22, 23] the asymmetric and symmetric stretching frequency of the syn–syn bridging carboxylate group $\nu(OCO)_{as}$ and $\nu(OCO)_s$ respectively, do not appear to be strongly sensitive to the variation of amino acids (the values ranging from 1630–1603 cm^{-1} and 1435–1403 cm^{-1} respectively), the carboxylate group being normally only involved in the copper coordination [1, 2].

For these reasons we may assert that the mono-adducts of unidentate aromatic amines of low basicity retain the dimeric structure of the parent complexes. This structure is only destroyed in the presence of a large excess of amines, with the separation of the corresponding bis-adducts.

This type of complex may then represent a suitable synthetic model for type 3 copper proteins where large antiferromagnetic exchange interactions are considered to be present [6].

Type 2

All the other complexes show normal room temperature magnetic moments and e.p.r. spectra typical of spin S = ½ [24].

The bis amine adducts of py and 4pic and the bipy derivative present room temperature electronic spectra (Table III) with a band envelope in the 15.4–16.3 kK spectral region. These values, close to the values found for the parent blue Cu(ac-β-ala)$_2$·2H$_2$O (15.9 kK) [2] and for diaquabis(N-acetyl-DL-tryptophanato)bis(pyridine)copper(II) (15.9 kK) [5], allow us to suggest also for the present complexes a strongly tetragonal geometry with a CuN_2O_4 chromophore [2, 5].

The d–d bands for the lilac en and pipz adducts (Table III) are at considerably higher energy, suggesting a more planar environment around the copper atom [24]. This is supported by the results of previous investigations on similar complexes, and is expected on the basis of the high electron donating power of en and pipz [5, 6, 14].

The g values of the type 2 complexes, greater for py and 4pic than for en and pipz adducts, are consistent with the proposed geometries since it is well accepted that g increases when the axial field becomes stronger [25]. In particular the g values for en adducts are very close to those of bis-ethylenediamine complexes with CuN_4 chromophore [24] and analogously [14, 23] we believe that the carboxylate ions are not directly involved in copper coordination and we therefore rewrite its formula as (ac-β-ala)$_2$[Cu(en)$_2$].

The i.r. spectra of type 2 complexes (Table III), when compared with that of the blue Cu(ac-β-ala)$_2$·2H$_2$O [2], indicate that the peptide nitrogen atom is not involved in copper coordination, but (at most) in hydrogen bonding interactions only. A more useful comparison should concern the different type of carboxylate coordination, but it is hazardous to make this comparison on the basis of i.r. spectra without structural data, as the low symmetry of carboxylate ions [26] makes stretching frequencies very sensitive to even the smallest perturbations.

Nevertheless the fact that the stretching frequencies of the monomeric amine adducts are close to those found in the Cu(ac-β-ala)$_2$·2H$_2$O complex [2] reasonably suggests that in our complexes, the carboxylate group acts as an essentially mono-

dentate or 'asymmetric' bidentate ligand with a different network of hydrogen bonding which may shift the band position [2, 5].

Acknowledgements

We thank the Centro Strumenti of the University of Modena for recording the i.r. spectra, the Centro di Calcolo Elettronico of the University of Modena for the computing facilities, and the Consiglio Nazionale delle Ricerche (C.N.R.) of Italy for financial support.

References

1 M. R. Udupa and B. Krebs, *Inorg. Chim. Acta, 37,* 1 (1979).
2 L. P. Battaglia, A. Bonamartini Corradi, G. Marcotrigiano, L. Menabue and G. C. Pellacani, *Inorg. Chem., 20,* 1075 (1981).
3 K. E. Hyde, P. L. Bocko, D. Martynec, G. F. Kokoszka and M. Lynch, *J. Inorg. Nucl. Chem., 39,* 703 (1977).
4 P. Sharrock, C. H. Thibaudeau and A. Caillè, *Inorg. Chem., 18,* 510 (1979) and refs. cited therein.
5 L. P. Battaglia, A. Bonamartini Corradi, G. Marcotrigiano, L. Menabue and G. C. Pellacani, *J. Am. Chem. Soc., 102,* 2663 (1980).
6 G. Marcotrigiano, L. Menabue and G. C. Pellacani, *Inorg. Chim. Acta, 46,* 107 (1980).
7 L. Antolini, L. Menabue, P. Prampolini and M. Saladini, *J. Chem. Soc., Dalton Trans.,* in press, and refs. cited therein.
8 F. Cariati, L. Erre, G. Micera, L. Menabue, M. Saladini and P. Prampolini, *Inorg. Chim. Acta,* accepted.
9 B. Bleaney and K. D. Bowers, *Proc. Roy. Soc., A214,* 451 (1952).
10 L. Antolini, L. P. Battaglia, A. Bonamartini Corradi, G. Marcotrigiano, L. Menabue, G. C. Pellacani and M. Saladini, *Inorg. Chem., 21,* 1391 (1982).
11 L. P. Battaglia, A. Bonamartini Corradi, L. Menabue, G. C. Pellacani, P. Prampolini and M. Saladini, *J. Chem. Soc., Dalton Trans.,* 781 (1982).
12 G. Marcotrigiano, L. Menabue, P. Morini and G. C. Pellacani, *Bull. Chem. Soc. Jpn., 52,* 3420 (1979).
13 G. Marcotrigiano, L. Menabue and G. C. Pellacani, *Inorg. Chim. Acta, 19,* 133 (1976).
14 G. Marcotrigiano, L. Menabue and G. C. Pellacani, *J. Chem. Soc., Dalton Trans.,* 1627 (1976).
15 'Metal Ions in Biological Systems', Ed. H. Sigel, Marcel Dekker, New York, 1973, vol. 2.
16 J. R. Wasson, Chin-I. Shyr and C. Trapp, *Inorg. Chem., 7,* 469 (1968).
17 K. E. Hyde, G. Gordon and G. F. Kokoszka, *J. Inorg. Nucl. Chem., 30,* 2155 (1968).
18 a) M. Melnik, *Coord. Chem. Rev., 42,* 259 (1982); b) R. J. Doedens, *Progr. Inorg. Chem., 21,* 209 (1976).
19 J. Catterick and P. Thornton, *Adv. Inorg. Chem. Radiochem., 20,* 291 (1976).
20 W. E. Marsh, G. O. Carlisle and M. V. Hanson, *J. Inorg. Nucl. Chem., 39,* 1839 (1977).
21 R. W. Jotham, S. F. A. Kettle and J. A. Marks, *J. Chem. Soc., Dalton Trans.,* 428 (1972).
22 G. Marcotrigiano, L. Menabue and G. C. Pellacani, *J. Inorg. Nucl. Chem., 39,* 1897 (1977).
23 G. Marcotrigiano and G. C. Pellacani, *Can. J. Chem., 52,* 3607 (1974).
24 B. J. Hathaway and D. E. Billing, *Coord. Chem. Rev., 5,* 143 (1970).
25 H. Yokoi, M. Sai, T, Isobe and S. Oshawa, *Bull. Chem. Soc. Jpn., 45,* 2189 (1972).
26 G. B. Deacon and R. J. Phillips, *Coord. Chem. Rev., 33,* 227 (1980).