Supplementary Material Available: Summaries of single-crystal X-ray analyses, ORTEP drawings, and tables of positional parameters and B(eq), intramolecular distances and bond angles involving the non-hydrogen atoms, torsion or conformation angles, and U values for five structures (59 pages). Ordering information is given on any current masthead page.

Spectroscopic and Reactivity Studies of Lithium Reagent-HMPA Complexes[1]

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The dipolar aprotic solvent hexamethylphosphoramide (HMPA) has superior ability to form cation-ligand complexes and effectively solvates a variety of lithium salts. It is used to activate and modify the chemical behavior of lithium salts and organolithium reagents.[2,3] We report here on the coordination chemistry of lithium using reactivity studies and direct NMR observation. Under suitable conditions, it is possible to detect $^2J_{\mathrm{LiP}}$ coupling for Li$^+$·HMPA complexes in both ^{7}Li and ^{31}P NMR spectra.[1c,4a] This promises to be a powerful tool to study the complexation of lithium by HMPA, to determine how various lithium species compete (as Lewis acids) for HMPA in solution, and to determine the effect of HMPA on ion-pair composition of organolithium species.

During our studies of "ate" complex intermediates in the metal halogen and other lithium-metalloid exchange reactions,[1] we examined the reactivity of solutions in which PhLi and species such as $\mathrm{Ph_2I^-Li^+}$ were present.[1b] Figure 1 presents the results of a model study on the metallation reactivity of PhLi as a function of [HMPA]. Both $\mathrm{Et_3PhB^-Li^+}$ and LiBr inhibit the effect of added HMPA. With 1 equiv of $\mathrm{Et_3PhB^-Li^+}$ present, the rate did not increase significantly up to 2.0 equiv of HMPA.

The reactivity of PhLi can be understood in terms of the NMR spectra (−110 °C) presented in Figures 2 and 3. In pure THF (Figure 2A), the lithium is tetrahedrally solvated, as shown by the chemical shift[5] and narrow line width (2 Hz)[6] of the ^{7}Li signals of $\mathrm{Et_3PhB^-Li^+}$.[7] As HMPA was added, the ^{7}Li and ^{31}P NMR spectra clearly showed the presence of a series of coordination complexes having one to four HMPA molecules attached to lithium. Addition of 0.5 equiv of HMPA converted half of the lithium cations to $\mathrm{Li^+(HMPA)_1}$, giving rise to a 1:1:1:1 quartet in the ^{31}P NMR spectrum and a doublet superimposed on the remaining $\mathrm{Li^+S_4}$ (S = THF) singlet in the ^{7}Li NMR spectrum (Figure 2B).[8a] With 1 equiv (Figure 2C), a mixture of cations was observed, approximately 70% of which is $\mathrm{Li^+(HMPA)_1}$, with 15% each of $\mathrm{Li^+S_4}$ and $\mathrm{Li^+(HMPA)_2}$. This is most clear from the ^{31}P NMR spectrum since ≈70% of HMPA is present as $\mathrm{Li^+(HMPA)_1}$ and 30% is $\mathrm{Li^+(HMPA)_2}$. The association constants for the first two HMPAs are thus quite similar.[8b] The ^{7}Li signals with 2 (Figure 2E) and 3 (Figure 2G) equiv of HMPA resemble a triplet and quartet, showing that HMPA sequentially replaces THF as ligand to form $\mathrm{Li^+(HMPA)_2}$ and $\mathrm{Li^+(HMPA)_3}$. The fourth equivalent of HMPA was complexed weakly, ≈40% of the lithium was converted to $\mathrm{Li^+(HMPA)_4}$, and free HMPA could be seen in the ^{31}P NMR spectra. Complete conversion to $\mathrm{Li^+(HMPA)_4}$ required up to 10 equiv of HMPA.[8c] The $^2J_{\mathrm{LiP}}$ coupling

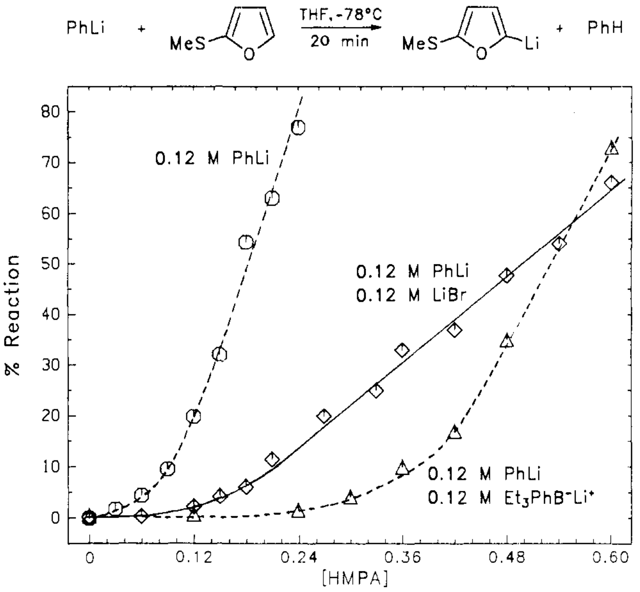

Figure 1. Effect of HMPA on the metalation of 2-methylthiofuran with PhLi in THF at −78 °C in the absence and presence of added lithium salts. The extent of metalation was monitored by trapping with dimethyl disulfide and analyzing the methyl sulfides by GLC. The lines have no mathematical significance.

Table I. Li and P NMR Parameters for PhLi and PhEt$_3$BLi Complexes with HMPA[a]

	$\mathrm{PhEt_3B^-Li^+\cdot(HMPA)}_n$					$\mathrm{(PhLi)_1\cdot(HMPA)}_n$	
	$n = 0$	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 0$	$n = 1$
δ(Li)[b]	−0.66	−0.61	−0.59	−0.55	−0.49	−0.95	0.84
δ(P)[c]		27.5	27.2	27.1	27.2		27.7
$J_{^7\mathrm{LiP}}$ (Hz)[d]		11.2	10.3	9.2	7.5		7.4[d]

[a] Measured at −110 °C in THF on a Brucker AM-360 spectrometer. [b] Referenced to external 0.3 M LiCl in methanol at −100 to −105 °C; ^{6}Li and ^{7}Li data were used. [c] Referenced to internal PPh$_3$ at −6.0 ppm. Free HMPA at 26.4 ppm. [d] Reported for ^{7}Li, the measured ^{6}Li–^{31}P coupling was 2.8 Hz.

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[1] For earlier papers in this area, see: (a) Reich, H. J.; Phillips, N. H. *J. Am. Chem. Soc.* **1986**, *108*, 2102. (b) Reich, H. J.; Reich, I. L.; Phillips, N. H. *J. Am. Chem. Soc.* **1985**, *107*, 4101. (c) Reich, H. J.; Green, D. P.; Phillips, N. H. *J. Am. Chem. Soc.* **1989**, *111*, 3444.

[2] Normant, H. *Angew. Chem., Int. Ed. Engl.* **1967**, *6*, 1046.

[3] (a) Changes in ratio of 1,2- to 1,4-addition of RLi to enones: Cohen, T.; Abraham, W. D.; Myers, M. *J. Am. Chem. Soc.* **1987**, *109*, 7923. (b) Enolate reactivity: House, H. O.; Prabhu, A. V.; Phillips, W. V. *J. Org. Chem.* **1976**, *41*, 1209. Jackman, L. M.; Lange, B. C. *J. Am. Chem. Soc.* **1981**, *103*, 4494. Liotta, C. L.; Caruso, T. C. *Tetrahedron Lett.* **1985**, *26*, 1599. Seebach, D.; Amstutz, R.; Dunitz, J. D. *Helv. Chim. Acta* **1981**, *64*, 2622. Fataftah, Z. A.; Kopka, I. E.; Rathke, M. W. *J. Am. Chem. Soc.* **1980**, *102*, 3959. (c) Increased reactvity: Dolak, T. M.; Bryson, T. A. *Tetrahedron Lett.* **1977**, 1961. Fraser, R. R.; Mansour, T. S. *Tetrahedron Lett.* **1986**, *27*, 331. DePue, J. S.; Collum, D. B. *J. Am. Chem. Soc.* **1988**, *110*, 5524. (d) Unusual ion structures:[1] Fraenkel, G.; Hallden-Abberton, M. P. *J. Am. Chem. Soc.* **1981**, *103*, 5657. Jackman, L. M.; Scarmoutzos, L. M.; Porter, W. *J. Am. Chem. Soc.* **1987**, *109*, 6524. (e) Solubilization of lithium salts: Snaith, R.; Barr, D.; Wright, D. S. *J. Am. Chem. Soc.* **1987**, *109*, 7891.

[4] (a) ^2J ^{7}Li-^{31}P coupling in ^{7}Li NMR for the lithium halide complex $\mathrm{(LiBr)_2\cdot 3HMPA\cdot toluene}$: Barr, D.; Doyle, M. J.; Mulvey, R. E.; Raithby, P. R.; Berd, D.; Snaith, R.; Wright, D. S. *J. Chem. Soc., Chem. Commun.* **1989**, 318. One-bond ^{31}P-^{7}Li couplings have been observed: Lappert, M. F.; Hitchcock, P. B.; Power, P. P.; Smith, S. J. *J. Chem. Soc., Chem. Commun.* **1984**, 1669. (b) Two separate HMPA signals in the ^{1}H NMR spectrum of a dihydroanthracenyllithium have been reported: Panek, E. J.; Rodgers, T. J. *J. Am. Chem. Soc.* **1974**, *96*, 6921.

[5] Fraenkel assigns the region δ 0.55 to −1.3 in ^{7}Li NMR (relative to 0.3 M LiCl in methanol) to solvated lithium cation.[3d]

[6] Lithium-7 has spin $^3/_2$ and usually gives fairly broad resonances because of relaxation caused by interaction of the nuclear quadrupole moment with electric field gradients in the molecule. Sharp lines indicate a symmetrical (usually tetrahedral) environment.

[7] Lithium tetraphenylborate is monomeric in THF (Wong, M. K.; Popov, A. I. *J. Inorg. Nucl. Chem.* **1972**, *34*, 3615) and is largely ion-paired (Bhattacharyya, D. N.; Lee, C. L.; Smid, J.; Swarc, M. *J. Chem. Phys.* **1965**, *69*, 608).

[8] (a) The coalescence temperature for the P-Li couplings in $\mathrm{LiBR_4\cdot(HMPA)}_n$ is approximately −100 °C for both the first and last coordinated HMPA. For $\mathrm{PhLi\cdot(HMPA)_1}$ with a deficiency of HMPA the coalescence is near −110 °C. (b) A variety of samples of $\mathrm{Et_3PhB^-Li^+}$ with varying concentrations of HMPA near 1 equiv have been analyzed and are consistent with this interpretation. (c) In the gas phase, the enthalpy of association for $\mathrm{Li^+(H_2O)}_n$ decreases steadily for n = 1-4 (Dzidic, I.; Kebarle, P. *J. Phys. Chem.* **1970**, *74*, 1466).

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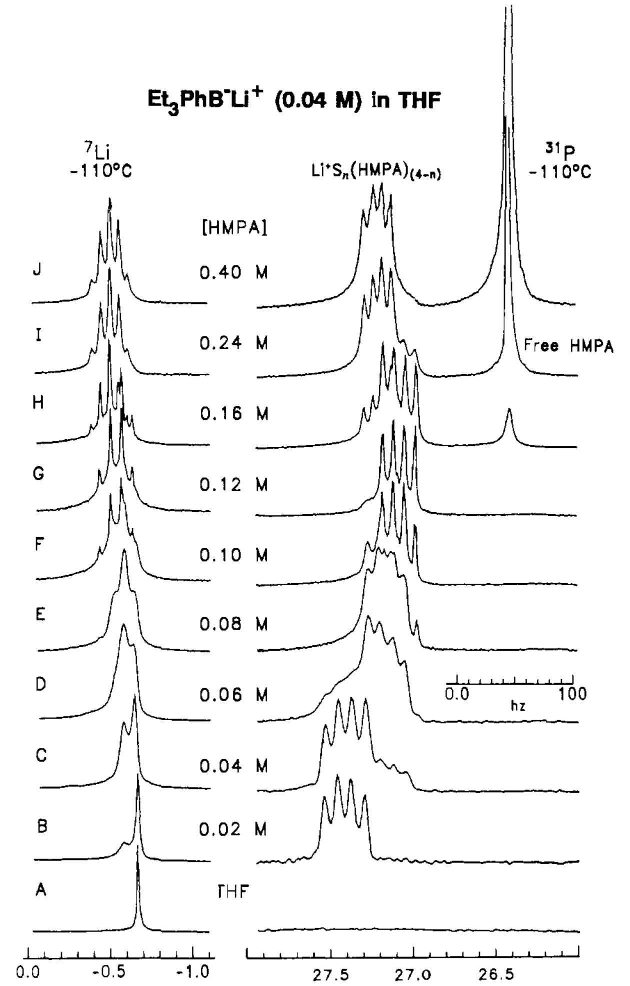

Figure 2. Lithium-7 (139.96 MHz) and phosphorus-31 (145.78 MHz) NMR spectra of 0.04 M Et$_3$PhB$^-$Li$^+$ in THF containing increasing amounts of HMPA (−110 °C). Spectra are plotted on the same frequency scale. ^{7}Li chemical shifts were referenced to external 0.3 M LiCl in methanol.

constant decreased from 11.2 Hz for the mono- to 7.5 for the tetra-HMPA-solvated cation (Table I), perhaps a consequence of the progressively lower electrophilicity and hence weaker complexation to lithium as THF was replaced by the stronger donor HMPA.[9]

A similar series of experiments was performed on a solution containing a 1:1 ratio of PhEt$_3$B$^-$Li$^+$ to PhLi (PhLi is largely monomeric under these conditions[1c]). The ^{31}P and partial ^{13}C NMR spectra pictured in Figure 3 show that the first 2 equiv of added HMPA (1 equiv = 0.04 M) coordinate entirely to the PhEt$_3$B$^-$Li$^+$. As the concentration of HMPA was increased, the characteristic ^{13}C,[1c] ^{31}P (δ 27.7), and ^{7}Li (not shown) signals of PhLi·(HMPA)$_1$ appeared (Figure 3D,E).[10] The lithium of PhLi therefore has similar electrophilicity toward HMPA, as does PhEt$_3$B$^-$Li$^+$·(HMPA)$_2$ (i.e., one Ph$^-$ is as good a donor as two HMPAs). Further additions of HMPA eventually led to complete conversion to PhLi·(HMPA)$_1$ and PhEt$_3$B$^-$Li$^+$·(HMPA)$_4$. Apparently a second equivalent of HMPA coordinates only a small extent to form PhLi·(HMPA)$_2$, since the ^{13}C signals showed little change[1c] and the distinct ^{31}P of PhLi·HMPA broadened and coalesced with that of free HMPA after 4 equiv of HMPA had been added. The rapid exchange of HMPA with PhLi·(HMPA)$_1$ when excess HMPA was present (but not before) could be the result of "S$_N$2" substitution of complexed HMPA by free HMPA or (more likely) because PhLi·(HMPA)$_2$ forms and dissociates rapidly on the NMR time scale even at −110 °C.

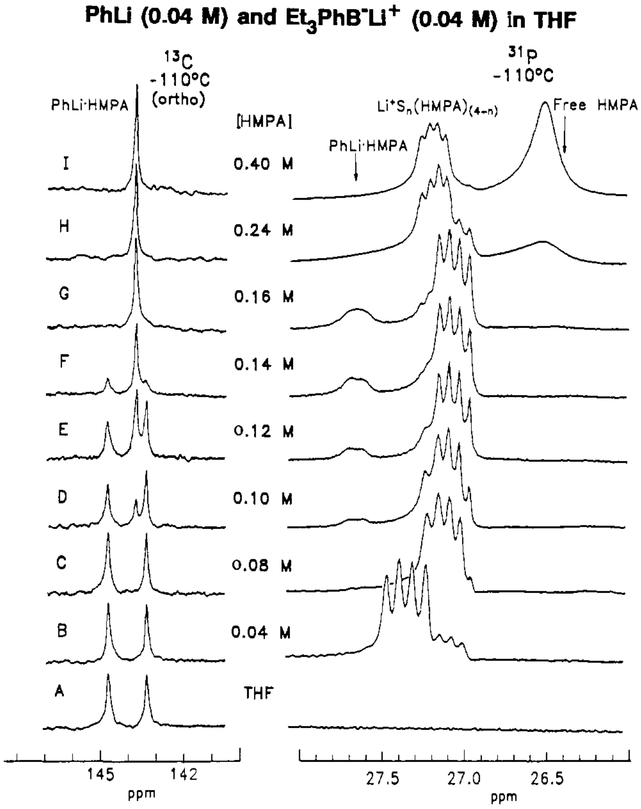

Figure 3. Carbon-13 (90.56 MHz, DEPT) and phosphorus-31 (145.78 MHz) NMR spectra of PhLi (0.04 M) and Et$_3$PhB$^-$Li$^+$ (0.04 M) in THF containing increasing amounts of HMPA (−110 °C). The ^{13}C spectra include only the ortho carbon region of PhLi; the downfield signal is (PhLi)$_2$, and the upfield signal is (PhLi)$_1$.[1c,11]

The spectroscopic behavior shows a striking parallel to the rate data presented in Figure 1 and provides a basis for understanding the effects that added lithium salts have on the reactivity of PhLi/HMPA solutions. No HMPA complexes to PhLi until two molecules have coordinated to PhEt$_3$B$^-$Li$^+$, and no changes in metalation rates were observed. Past this point the HMPA is shared between the PhLi and the borate salt, and the metalation rates reflect this.

A series of NMR studies (not shown) of a LiBr/PhLi mixture provided a similar correlation with the kinetic results. LiBr complexed HMPA consideraby less well than the borate salt; PhLi·(HMPA)$_1$ appeared after only 1 equiv of HMPA had been added.

We know of few well-documented examples where monodentate neutral ligands on lithium were in slow exchange on the NMR time scale.[4] Such effects are more common for polydentate ligands such as ethylenediamines,[12] pentamethyldiethylenetriamine (PMDTA),[13] and the cryptates.[14] Distinct NMR signals for free and coordinated HMPA have been observed, however, for strongly Lewis acidic cations such as Zn^{2+} and Al^{3+}.[15] For the latter, two

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(9) The Gutman donor numbers of THF and HMPA are 20.0 and 38.8, respectively (Gutmann, V. *Coordination Chemistry in Nonaqueous Solvents*; Springer-Verlag: Vienna, 1968). The free energy for ligand displacement of THF by HMPA on lithium is −7.38 kcal/mol (Jackson, M. D.; Gilkerson, W. R. *J. Am. Chem. Soc.* **1979**, *101*, 328).

(10) At −128 °C in THF/Me$_2$O (2:1), both the ^1J ^{13}C-^{6}Li (13 Hz)[1c] and the ^2J ^{6}Li-^{31}P (2.8 Hz) can be observed for this species. The ^{31}P resonance at δ 27.7 (Figure 2C, PhLi·HMPA) has a peculiar shape similar to that observed for the ^{13}C NMR signal of the lithiated carbon of (tri-*tert*-butylphenyl)lithium-^{7}*Li*.[11]

(11) Bauer, W.; Winchester, W. R.; Schleyer, P. v. R. *Organometallics* **1987**, *6*, 2371.

(12) Fraenkel, G.; Pramanik, P. *J. Org. Chem.* **1984**, *49*, 1314. Harder, S.; Boersma, J.; Brandsma, L.; Kanters, J. A.; Bauer, W.; Schleyer, P. v. R.; Schöllhorn, H.; Thewalt, U. *Organometallics* **1989**, *8*, 1688.

(13) Fraenkel, G.; Winchester, W. R. *J. Am. Chem. Soc.* **1988**, *110*, 8720.

(14) (a) Shamsipur, M.; Popov, A. I. *J. Phys. Chem.* **1986**, *90*, 5997. (b) Cahen, Y. M.; Dye, J. L.; Popov, A. I. *J. Chem. Phys.* **1975**, *79*, 1289, 1292.

bond couplings between P and the quadrupolar ^{27}Al have been used to assign coordination number for Al·(HMPA)$_4^{3+}$.[15b]

The experiments above have provided unprecedented detail about the solvation behavior of lithium cations in HMPA. Competition among the lithium species for the coordinating agent causes organolithium solutions containing lithium salts to behave in a complex manner.

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Registry No. HMPA, 680-31-9; Li, 7439-93-2; Et$_2$PhB$^-$Li$^+$, 65859-87-2; LiBr, 7550-35-8; PhLi, 591-51-5; 2-methylthiofuran, 13129-38-9.

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(15) (a) Zn^{2+}: Tkaczuk, M. N.; Lincoln, S. F. *Aust. J. Chem.* **1980**, *33*, 2621. (b) Al^{3+}: Delpuech, J.-J.; Khaddar, M. R.; Peguy, A. A.; Rubini, P. R. *J. Am. Chem. Soc.* **1979**, *101*, 324.

Backscattered Raman Optical Activity with a CCD Detector

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Despite the fact that vibrational optical activity in typical small chiral molecules in the disordered phase was first observed by using the Raman optical activity (ROA) technique,[1,2] the complementary vibrational circular dichroism (VCD) technique has attracted more attention because VCD instruments are easier to construct and use. Nonetheless, many ROA spectra have been measured and discussed.[3,4] This communication reports a major breakthrough in ROA instrumentation based on the use of a backscattering geometry (in place of the usual 90° arrangement) together with a cooled charge-coupled device (CCD) detector which should render the ROA technique much more widely applicable.

Basic theory shows that the signal-to-noise ratio (SNR) of many ROA bands should be enhanced considerably in backscattering as compared with 90° and forward scattering. Specifically, the bond polarizability theory for the case of a molecule composed entirely of idealized axially symmetric bonds predicts that a given ROA SNR should be achieved 8 times faster in backscattering than in polarized 90° scattering, which has been confirmed experimentally.[5] Another virtue of backscattered ROA is that the artifacts that plague ROA measurements in 90° scattering are greatly reduced. Also, as in depolarized 90° scattering, there is no contribution to backscattered ROA from the isotropic polarizability–optical activity tensor invariant: this simplifies the analysis of the spectra since the isotropic contribution is the hardest to deal with. The backscattering strategy has enabled ROA spectra to be obtained from unfavorable samples such as aqueous solutions of amino acids,[5] which, despite considerable effort, have never previously yielded significant ROA in 90° scattering.

To this already considerable advance we now add another of comparable significance accruing from the use of a cooled CCD detector in place of the intensified diode array usually used in multichannel ROA instruments. The ultimate sensitivity of ROA measurements is determined by the shot noise of the primary Raman photon flux at the detector. It would therefore be best to avoid an intensification stage in the detector because this lowers the quantum efficiency considerably. Unfortunately, intensification is essential with diode arrays because of the high intrinsic noise characteristics of the naked array. However, the cooled CCD detectors, which are finding increasing use for spectrochemical measurements,[6-8] have extremely low noise levels and can be used without intensification. The importance of this for ROA measurements is that the speed of acquisition (for a given SNR) increases in the same proportion as the increase in quantum efficiency.

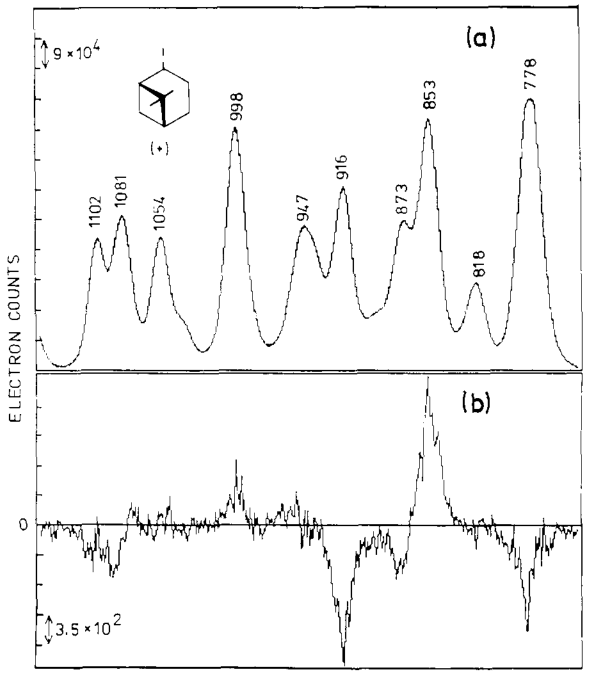

Figure 1. The backscattered Raman spectrum (a) and ROA spectrum (b) of (+)-*trans*-pinane as a neat liquid using a cooled CCD detector. Experimental conditions: laser wavelength 488.0 nm, laser power 600 mW, spectral slit width 6 cm^{-1}, recording time 10 min. The plot is linear in wavelength, but the major band positions are given in wavenumbers (cm^{-1}).

The Glasgow multichannel ROA instrument[9] was used for this study in a backscattering configuration[5] with the intensified diode array detector replaced by a CCD camera. We used the Wright Instruments Model AT1 detector system[10] with the EEV P8603 CCD, which has 385 × 578 pixels, cooled to 200 K with a Peltier cooler. The use of this particular CCD system for the acquisition of conventional Raman spectra has been described previously.[11] The ROA acquisition procedure was similar to that used with the diode array detector:[9] the polarization of the incident laser beam is switched between right and left circular at a suitable frequency in synchronism with the exposure and readout of the detector, the Raman spectrum in left circularly polarized incident light being subtracted from that in right and the difference accumulated. The two-dimensional character of the CCD gives it a great advantage over the diode array for ROA work because the full height of the Raman spectrum can be collected without the need for an optical device such as a cylindrical lens to condense the height of the image to match the height (2.5 mm) of the single pixels in the linear diode array. However, it is essential during readout to bin ver-

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(1) Barron, L. D.; Bogaard, M. P.; Buckingham, A. D. *J. Am. Chem. Soc.* **1973**, *95*, 603-605.

(2) Hug, W.; Kint, S.; Bailey, G. F.; Scherer, J. R. *J. Am. Chem. Soc.* **1975**, *97*, 5589-5590.

(3) Barron, L. D. In *Vibrational Spectra and Structure*; Bist, H. D., Durig, J. R., Sullivan, J. F., Eds.; Elsevier: Amsterdam, 1989; Vol. 17B, pp 343-368.

(4) Nafie, L. A.; Zimba, C. G. In *Biological Applications of Raman Spectroscopy*; Spiro, T. G., Ed.; Wiley: New York, 1987; Vol. 1, pp 307-343.

(5) Hecht, L.; Barron, L. D.; Hug, W. *Chem. Phys. Lett.* **1989**, *158*, 341-344.

(6) Murray, C. A.; Dierker, S. B. *J. Opt. Soc. Am. A* **1986**, *3*, 2151-2159.

(7) Bilhorn, R. B.; Sweedler, J. V.; Epperson, P. M.; Denton, M. B. *Appl. Spectrosc.* **1987**, *41*, 1114-1125.

(8) Bilhorn, R. B.; Epperson, P. M.; Sweedler, J. V.; Denton, M. B. *Appl. Spectrosc.* **1987**, *41*, 1125-1136.

(9) Barron, L. D.; Cutler, D. J.; Torrance, J. F. *J. Raman Spectrosc.* **1987**, *18*, 281-287.

(10) Manufactured by Wright Instruments Ltd., Unit 10, 26 Queensway, Enfield, EN3 4SA, U.K.

(11) Batchelder, D. N. *Eur. Spectrosc. News* **1988**, *No. 80*, 28-33.

0002-7863/89/1511-8731$01.50/0