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Raman and X-ray investigations of $LiFeSi_2O_6$ pyroxene under pressure

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***In situ* Raman spectroscopy at high pressure was utilized to follow the phase transition of a synthetic sample of Li-aegerine pyroxene ($LiFeSi_2O_6$) from its low-pressure ($C2/c$) phase to its high-pressure ($P2_1/c$) phase. The phase change occurred between 0.7 and 1 GPa and was accompanied by a change in coordination of the Li atom from 4 to 5, which was confirmed by single-crystal X-ray diffraction. This is the first report of the Raman spectrum of Li-aegerine in the $P2_1/c$ phase. As was previously observed with other pyroxenes, additional changes in the Raman spectra were observed at pressures higher than the phase transition, including the splitting of the peak near 700 cm^{-1}, which has traditionally been utilized to indicate the phase transition. Comparisons with the Raman spectra of spodumene in both symmetries are utilized for a discussion of modes. Copyright © 2005 John Wiley & Sons, Ltd.**

KEYWORDS: pyroxene; phase transition; pressure

INTRODUCTION

Li-aegerine ($LiFeSi_2O_6$) is a monoclinic, optically biaxial synthetic member of the pyroxene group of minerals. Pyroxenes (general formula $M2M1Si_2O_6$) comprise ~25% of the Earth's volume to a depth of 400 km.[1] There are a variety of symmetries exhibited by pyroxenes, most notably $C2/c$, $P2_1/c$, $Pbca$ and $Pbcn$, and most pyroxenes appear to undergo phase transitions between these various symmetries as a function of pressure, temperature and composition. Exposing a sample to low temperature often induces the same or similar phase transitions as high pressure because both are associated with a decrease in cell volume. The atomic scale mechanisms for these changes has been the subject of much study.[2] A recently discovered phase transition in Mg–Fe-rich pyroxenes, accompanied by a volume change, is now accepted as an origin of deep-focus earthquakes that cluster at a depth of about 225 km.[3–5]

In Li-aegerine, chains of FeO_6 (M1) octahedra separate chains of SiO_4 tetrahedra (Fig. 1). Li occupies the M2 site. Generally, in pyroxenes the M2 site is observed to be 4-, 5-, 6- or 8- coordinated, depending on pressure, temperature and composition of the pyroxene. In $C2/c$ symmetry there are three symmetrically non-equivalent oxygens, designated O1, O2, and O3. O1 oxygens are at the apices of the SiO_4 tetrahedra, O2 are on the base of the tetrahedra and O3 are on the base of the tetrahedra bridging the silicon atoms.

Recently, a vibrational study utilizing infrared spectroscopy was performed on Li-aegirine ($LiFeSi_2O_6$) through the low-temperature-induced phase transition from $C2/c$ to $P2_1/c$.[6] While no Raman spectra were reported for the $P2_1/c$ phase, an increase in the number of infrared modes was observed at 220 K. At room temperature, the mineral displays space group symmetry of C_{2h}^6 ($C2/c$). In this phase, both Li and Fe occupy positions of C_2 site symmetries. The Si and three types of oxygen display C_1 site symmetry. According to factor group analysis, there are 14 A_g and 16 B_g Raman-active modes associated with the $C2/c$ phase. X-ray data providing structural information on the $C2/c$ phase were first reported by Clarke *et al.*[7] The detailed crystallographic structure of the low-temperature LT-$P2_1/c$ phase was given by Redhammer *et al.*[8] An analysis of the procrystal electron density distribution using the X-ray data indicates an increase in coordination for the Li atom from four to five at the phase transition as a new bond to one of the Si—O bridging oxygens (O3) is formed[8] (Fig. 1). In this coordination, the bonding is similar to spodumene in the $P2_1/c$ phase, which is also 5-coordinated.[9] The coordination change destroys the C_2 symmetry displayed by the M2 cations, and all atoms occupy

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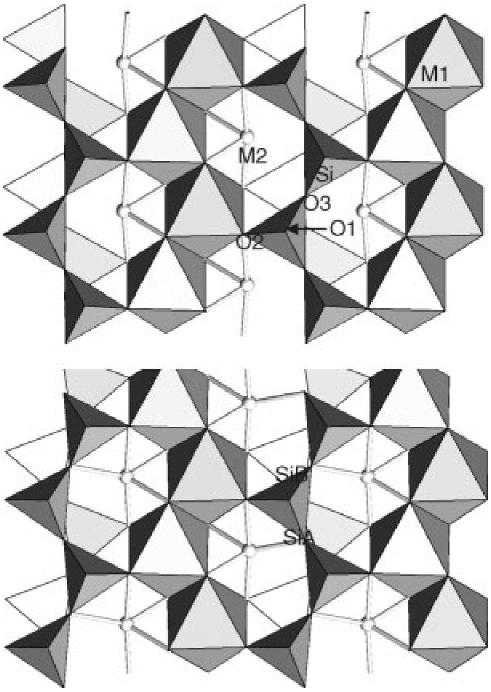

Figure 1. Depiction of $LiFeSi_2O_6$ at 0.70 GPa in $C2/c$ phase (top) and at 1.08 GPa in $P2_1/c$ phase (bottom) viewed down a*. Tetrahedra are SiO_4, FeO_6 are octahedra and the Li atoms are shown as spheres. Fe is M1, Li is M2, the oxygens on the apices of the tetrahedra are designated O1, O3 oxygens bridge between the Si atoms and the O2 atoms are the other bases of the tetrahedra. The bonding around the M2 atom changes from being bound to four oxygens, no O3 atoms, two O1 atoms and two O2 atoms, to being bound at five positions when a bond forms between the M2 atom and an O3 atom. The B-chains of the SiO_4 tetrahedra appear on the bottom.

sites with C_1 symmetry. There should be 30 Raman-active A_g modes and 30 Raman-active B_g modes when Li-aegerine is in the $P2_1/c$ phase.

The purpose of this work was to investigate the pressure-induced bonding changes of $LiFeSi_2O_6$ and the accompanying changes in the Raman spectra. To date, this is the first Raman study of $P2_1/c$ Li-aegirine.

EXPERIMENTAL

Synthesis

The sample was a 60 × 70 × 100 μm green crystal of $LiFeSi_2O_6$ as described previously.[10] Single crystals of $LiFeSi_2O_6$ (LiHP4a) were synthesized at 1523 K and a pressure of 3 GPa over a period of 78 h in a piston–cylinder apparatus at the Institute of Crystallography, RWTH Aachen. About 25 mg of a carefully ground stoichiometric mixture of $LiCO_3$, Fe_2O_3 and SiO_2 were placed in a small platinum tube, welded shut, and, in turn, placed in a graphite–pyrophyllite furnace. This synthesis resulted in green, short, prismatic crystals up to 100 μm in length, associated with minor amounts of greenish black glass.

High-pressure Raman spectroscopy

The crystal was loaded into a four pin Merrill–Basset-type diamond cell with reciprocal vector (110) parallel to the cell axis. Diamond anvil culet size was 600 μm. A stainless-steel gasket was used. The gasket was 250 μm thick, pre-indented to 70 μm, with a 250 μm diameter sample chamber. The cell was loaded with a $LiFeSi_2O_6$ crystal and a small ruby fragment, and filled with 4 : 1 methanol–ethanol pressure medium. Pressures were determined from fitted positions of the R_1 and R_2 ruby fluorescence spectra using the calibration of Mao *et al.*[11] The estimated error in pressure was 0.05 GPa. Pressure was measured before and after each spectrum acquisition and the reported value is an average of these two. Both ruby fluorescence and Raman spectra were excited with radiation of 514.5 nm from an argon ion laser. Utilizing an 1800 grooves mm^{-1} grating centered at 529.5 nm, the region from 82 to 992 cm^{-1} was acquired using WinSpec software. The region from 401 to 1276 cm^{-1} was acquired with the spectrometer's grating centered at 538 nm.

There was no specific polarization alignment along the crystal axes. Raman scattering was collected in the backscattered geometry. Data were imported into GRAMS 32 software and peak positions were found using the peak fitting utility. The average error in peak position was 0.9 cm^{-1}. Spectra shown are background corrected and normalized for peak height comparison.

RESULTS AND DISCUSSION

There are several changes apparent in the spectra over the pressure range studied. One occurs between 0.23 and 0.74 GPa, one occurs between 2 and 3 GPa, several occur between 6 and 7 GPa and another change occurs at 8.71 GPa. The changes that occur at 0.74 GPa include the appearance of ν_5, ν_{10}, ν_{18}, ν_{21}, ν_{31}, ν_{36} and ν_{39} and the appearance of a broad peak at ν_{37} (Figs 2 and 3). The broad peak is similar to features noted in other pyroxenes under pressure, including spodumene ($LiAlSi_2O_6$).[9] The mode at 883 cm^{-1} (peak ν_{32}) and the broad peak near 1040 cm^{-1} are assigned to the pressure medium, as they are not apparent in the spectrum of the sample with no medium, and they appear in the same place in other high-pressure experiments but not in Raman experiments performed on other $LiFeSi_2O_6$ crystals.[6,9] Additionally, a peak appears in the Raman spectrum of ethanol at 884 cm^{-1}, which is due to the symmetric CCO stretch.[12] Unfortunately, this peak is very close to a mode due to the pyroxene (ν_{30}).[2] The CCO stretch for methanol, which comprises four times the amount of pressure medium as ethanol, appears at 1033 cm^{-1}.[12] This is probably the broad peak assigned as ν_{37}. Also occurring at this pressure are the disappearances of the shoulders at ν_8 and ν_{12}, while ν_{15} becomes stronger and better resolved.

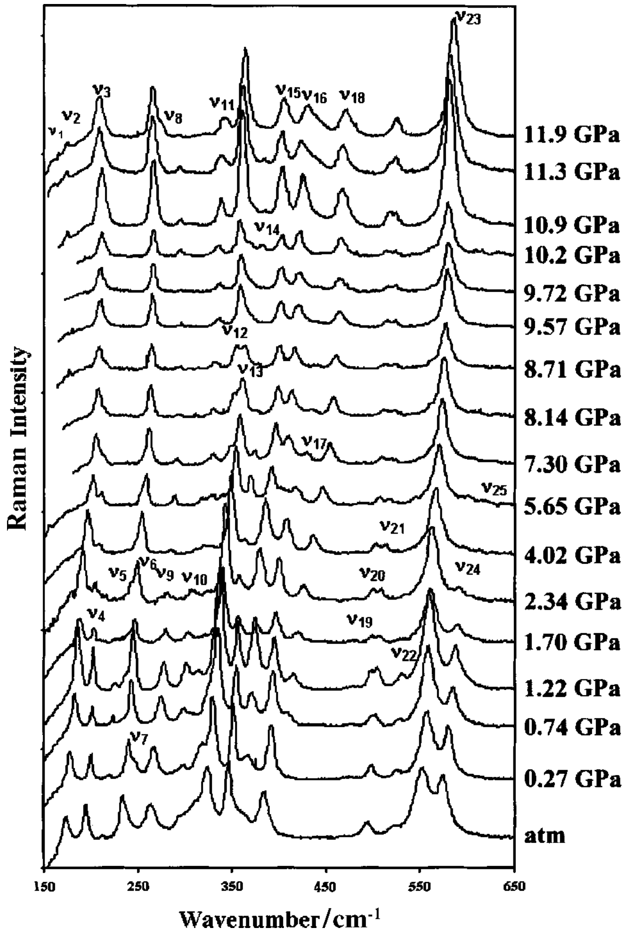

Figure 2. Low-wavenumber region of the Raman spectra of Li-aegirine as pressure is increased. X-ray data indicate that the phase transition from $C2/c$ to $P2_1/c$ occurs between 0.7 and 1.22 GPa. There are changes in the Raman spectra in this pressure region, but changes that are more readily apparent occur in the pressure region near 6 GPa. Other changes occur between 8 and 10 GPa. No X-ray data were collected at these pressures.

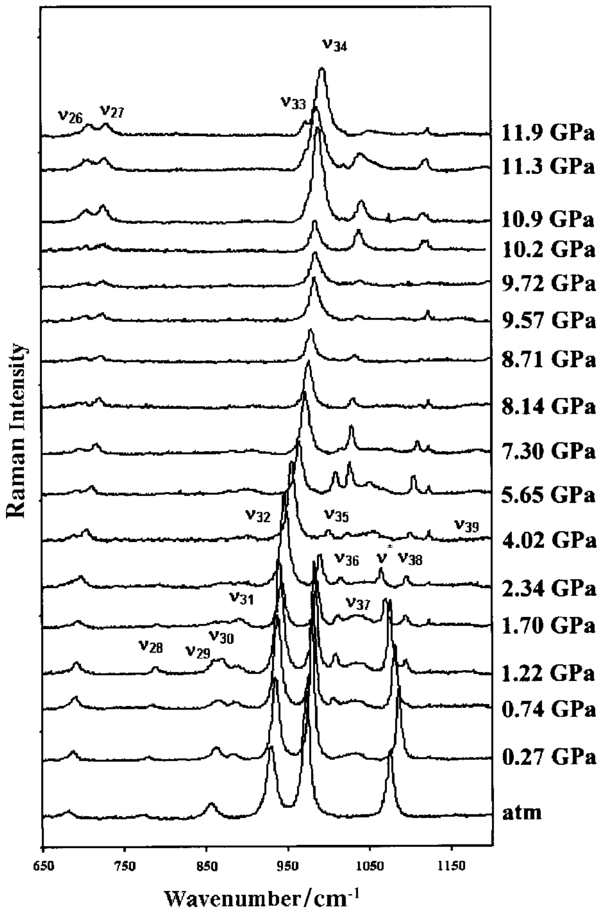

Figure 3. High-wavenumber region of the Raman spectra as pressure is increased. This region of the Raman spectra display changes in the same pressure regions as described for Fig. 2. Note the soft mode, ν^*.

Between 0.70 and 1.00 GPa, a phase transition from $C2/c$ to $P2_1/c$ was confirmed by X-ray diffraction. When the sample changed symmetry, the Li atom went from 4- to 5-coordinated with the formation of a bond between Li and the O3a atom. There are several changes in the Raman spectra near 2 GPa. First, there is a change in slope (wavenumber/pressure) (see Figs 6–8). More significant is the apparent splitting of peaks near 600 and 675 $\mathrm{cm^{-1}}$. The peaks in this region have previously been assigned as Si—O chain stretches, and used as benchmarks for the phase transition from $C2/c$ to $P2_1/c$. According to crystallographic evidence, the phase transition occurs at least 1 GPa below the appearance of the splitting of the peak at 675 $\mathrm{cm^{-1}}$. As first pointed out in Ref. 9, this is additional evidence suggesting that the splitting of this peak is not a good indicator of the phase transition in Li-pyroxenes. There is, however, no crystallographic or diffraction evidence of a phase transition near 2 GPa.

Figure 4 shows Raman spectra of $LiAlSi_2O_6$ and $LiFeSi_2O_6$ in both the $C2/c$ phase and the $P2_1/c$ phase. The difference in peak intensities between the two phases is probably due to different orientations of the crystals when the spectra were acquired and different polarizabilities of the modes due to the change in chemical composition of the materials. Interestingly, in $C2/c$, even though the two materials do not have the same number of Li—O3 bonds (none for $LiFeSi_2O_6$ and two for $LiAlSi_2O_6$), the Raman spectra are very similar. Arrows indicate peaks or groups of peaks that appear to have the same assignments. At 0 GPa, the peaks for $LiFeSi_2O_6$ are shifted to lower wavenumbers than the same peaks in spodumene. The substitution of iron for aluminum atom changes the M—O bonds and probably also the Si—O bonds.

Table 1 shows the Li—O3 bond lengths for spodumene in both symmetries and $LiFeSi_2O_6$ in the $P2_1/c$ phase.[2] Although the $P2_1/c$ data for the $LiFeSi_2O_6$ were acquired through a T-induced phase transition rather than a P-induced phase

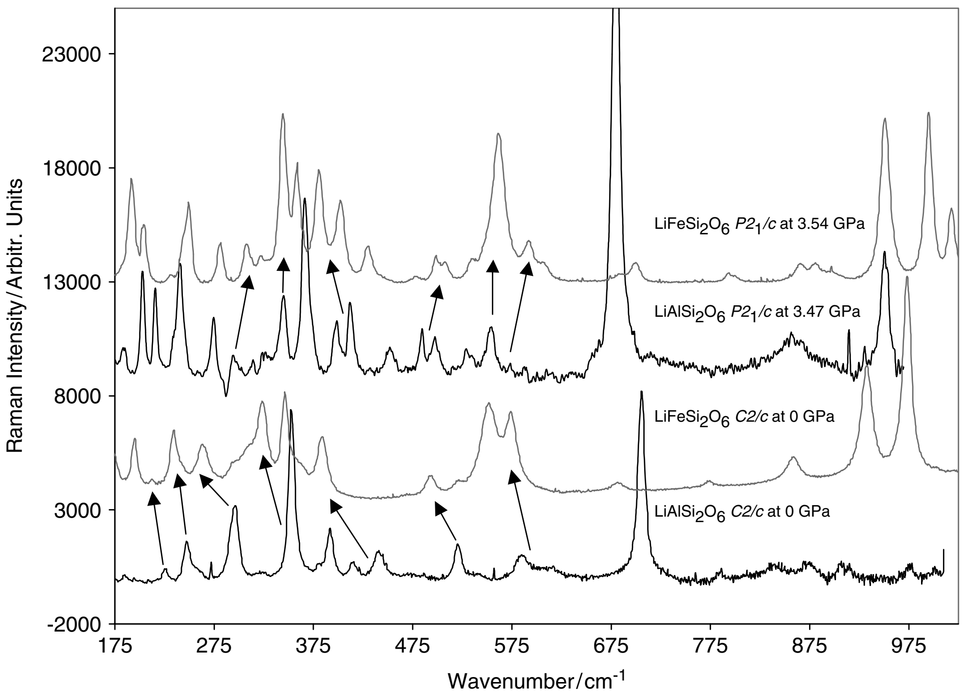

Figure 4. Raman spectra of spodumene ($LiAlSi_2O_6$) and Li-aegirine ($LiFeSi_2O_6$) in low-pressure $C2/c$ phase and high-pressure $P2_1/c$ phase. These plots display the similarities between the spectra of the two pyroxenes, which allows a possible assignment of Raman bands of $LiFeSi_2O_6$ by analogy with the spectra of spodumene.

Table 1. Bond length and electron density data at the bond critical (saddle) point between Li and O3 for $LiAlSi_2O_6$ and $LiFeSi_2O_6$ (data from Downs,[2] except for $LiFeSi_2O_6$ at 1.08 GPa)[a]

Mineral	Space group	Conditions	Li—O3 bond length/Å	Electron density/e Å^{-3}
$LiAlSi_2O_6$	$C2/c$	0 GPa	2.249	0.08843
$LiAlSi_2O_6$	$P2_1/c$	3.34 GPa	2.150	0.10733
$LiAlSi_2O_6$	$P2_1/c$	8.84 GPa	2.085	0.12429
$LiFeSi_2O_6$	$C2/c$	298 K	None	None
$LiFeSi_2O_6$	$P2_1/c$	200 K	2.381	0.05262
$LiFeSi_2O_6$	$P2_1/c$	100 K	2.358	0.05510
$LiFeSi_2O_6$	$P2_1/c$	1.08 GPa	2.411	0.05364

[a] This table demonstrates the increase in electron density in the Li—O3 bonds as pressure is increased for spodumene. Similarly, the electron density increases in $LiFeSi_2O_6$ as the temperature decreases. There is no Li—O3 bond in the $C2/c$ symmetry, so no electron density is recorded.

transition, the data acquired at 200 K are comparable to those acquired at 3.34 GPa, as both sets of data are very close to the phase transition in both materials. The O3 bond radius along the Li—O3 bond (distance from the center of the atom to the bond critical point) is smaller and the electron density is larger in $LiAlSi_2O_6$ than in $LiFeSi_2O_6$. The smaller electron density is reflected by the shift of the Raman peaks to lower wavenumbers. As expected, with increase in pressure or decrease in temperature, the electron density of the Li—O3 bonds increases along with the Raman shift.

The $P2_1/c$ spectra of the two different compounds at 3.47 and 3.54 GPa are not as comparable as the data acquired for the compounds at 0 GPa, as the phase transition occurs in $LiAlSi_2O_6$ near 3.3 GPa and in $LiFeSi_2O_6$, between 0.7 and 1.0 GPa so the $LiFeSi_2O_6$ spectrum is much further from its transition than the $LiAlSi_2O_6$ spectrum. This difference accounts for the shift to higher wavenumbers of some peaks in the $LiFeSi_2O_6$ spectrum compared with the same peaks in the $LiAlSi_2O_6$ spectrum.

The absence of the peaks near 442 and 418 cm^{-1} in the $LiFeSi_2O_6$ spectra is an argument for assigning these bands in spodumene to modes associated with vibrations of the Li—O3 bonds, as $LiFeSi_2O_6$ has no bonds from Li to O3 in the $C2/c$ phase. Even stronger evidence is the appearance of a peak at 432 cm^{-1} (ν_{18}) in the $P2_1/c$ spectrum of $LiFeSi_2O_6$. The smaller peak at lower wavenumbers, which would correspond to the peak at 418 cm^{-1} in $C2/c$ spodumene, is not readily evident owing to the proximity of the higher intensity bands in the approximate location where that mode would appear. The Raman data indicate that modes at ν_3, ν_6, ν_9, ν_{12}, ν_{15} and ν_{18} display the most dramatic changes in slope between 1 and 3 GPa.

Comparison of the $C2/c$ Li-aegirine Raman modes with the peaks assigned to the $C2/c$ phase of spodumene leads to the following peak assignments based only on the visual similarity of Raman spectra: ν_7, Si–O3–Li; ν_9, O1–Si coupled to O3; ν_{14}, Li–O3; and ν_{16}, Si–O3.

The changes in the Raman spectrum near 6 GPa are characterized by the splitting of ν_{27} into ν_{26} and ν_{27}, in addition to the appearance of ν_{11}, ν_{12} and ν_{16}. The following peaks become much stronger at 5.65 GPa: ν_{18}, ν_{36} and ν_{39}. Peaks disappearing at 5.65 GPa include ν_4, ν_9, ν_{24}, ν_{29}, ν_{30} and the broad peak due to the pressure medium. The splitting of the mode at ν_{27} has been used as a benchmark for the $C2/c$ to $P2_1/c$ transition.[13–16] However, X-ray diffraction confirms that the crystal is in a $P2_1/c$ symmetry at pressures below the peak split. The changes in the Raman spectra may be a result of other $P2_1/c$ to $P2_1/c$ transitions and perhaps related to pressure-induced electron spin crossovers. Redhammer[8] has determined that there is a change in the magnetic structure of the material that occurs near 15 K. This change in the magnetic structure may be a spin–spin crossover and could be what is affecting the Raman spectra near 6 GPa. Although most studies of spin crossovers utilize temperature to achieve the transition, pressure has also been observed to induce the transition.[17,18]

Most of the studies involving electron high-spin–low-spin crossovers have investigated octahedral Fe(II) compounds,[19] but there have been some studies that demonstrate spin crossover in iron(III) compounds.[17,18,20–24] In the current study, the cation is Fe(III), which is d^5, and the ligands are the oxygens in octahedral coordination with the iron. For octahedral d^5 compounds, the $^6A_1$ state is the low-energy state for high volume and the $^2T_2$ state is favored at low volume because of the increase in ligand field strength brought about by the ligands being in closer proximity to the metal ion in the low-volume state. The $^6A_1$ state is the totally symmetric state; all of the energy levels have one electron in them. The doublet $^2T_2$ state is indicative of the one unpaired electron in the energy state. Though the iron center in $LiFeSi_2O_6$ is not technically in an O_h symmetry (it is C_2), the local symmetry of the cation is O_h, or very close to O_h, so the use of the energy level model is appropriate.

In a spin–spin crossover, some Fe sites within the crystal could change spin states, inducing site non-equivalence. Increasing the pressure would change more of the iron sites to the low-spin state, and so forth until all of the iron sites had transformed to the low-spin state from the high-spin state. König *et al.*[25] put forth the idea that spin state transitions occur in domains, with cooperative interactions carrying neighboring sites across the energy barrier to spin state transition, thereby creating domains in the crystal where all sites have changed spin states. These domains are large enough to display crystallographic differences and, as such, two separate phases are observable by X-ray crystallography.

Spodumene was observed to undergo a phase change which began at one side of the crystal and continued through the rest of the crystal,[26] so phase changes originating in one location of the crystal and continuing throughout as pressure is increased are not unprecedented. Haddad and co-workers[23,24] identified a cooperative spin-crossover mechanism leading to domain formations in a solid iron(III) compound. König *et al.*[25] also put forth the theory that all first-order (discontinuous) spin state transitions are associated with hysteresis, as an effect of the formation of domains.[27] Observation of hysteresis in $LiFeSi_2O_6$ would then further support the argument that a spin state transition occurs in the material. However, on examination of the peak positions versus pressure, no significant hysteresis is observable (Fig. 5). In fact, the Raman shift measured as the pressure was decreased shows a slight decrease over the shift measured as the pressure was increased – exactly the opposite of what is expected with hysteresis. Additionally,

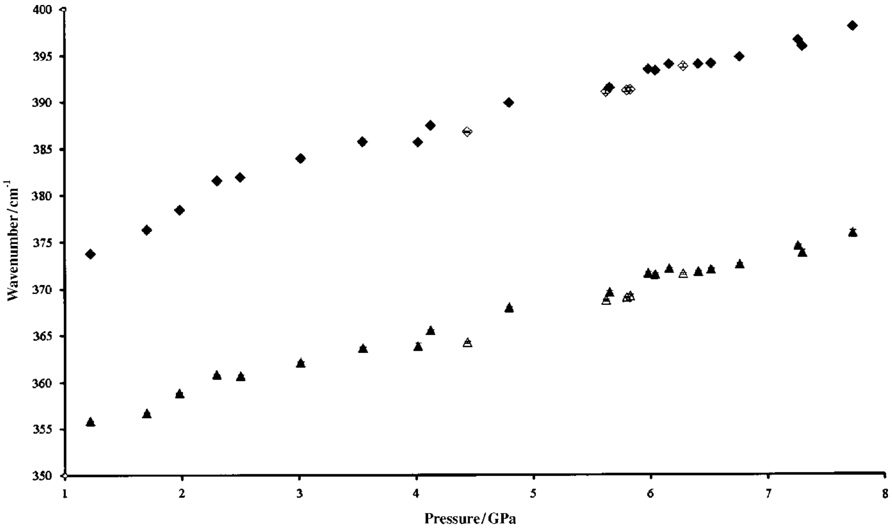

Figure 5. Plot of two different Raman peak positions as pressure is increased (solid symbols) and decreased (open symbols) in the pressure region 4.0–8 GPa. There is no significant change in wavenumber as pressure is increased versus decreased, as would be observed with hysteresis. This is evidence that domains may not be forming in the material, but is inconclusive on its own.

visual inspection of the crystal showed no discontinuous color change such as would be expected with a large change in the ligand field energy. From 0 to 6 GPa the crystal remained dark green. There has been a report of a crystal also in the $P2_1/c$ space group [tris(α-picolylamine)iron(II) chloride–ethanol] that displayed abrupt changes in the lattice parameters, a and c, without changing space groups but with anomalies in the Mössbauer and magnetic susceptibility data of the compound.[28] Therefore, similar behavior in $LiFeSi_2O_6$ is not inconsistent with previous literature. The absence of hysteresis and the absence of a crystallographic phase change seems to suggest that the spin transition, if it occurs, is of a continuous nature and is likely due to the formation of domains within the crystal.[25] However, absence of evidence is a poor way to prove a hypothesis and more study is required.

The Raman peak at ν^* displays anomalous peak shift with pressure (Fig. 3). Most of the other peaks increase in wavenumber as the pressure is increased, but ν^* appears to be a soft mode, decreasing in wavenumber with increasing pressure. Soft modes are modes that show a weakening of the bond associated with displacive phase transitions.[29–31] Interestingly, the soft mode appearing in $LiFeSi_2O_6$ disappears by 7 GPa. The shift of all peaks with pressure is illustrated in Figs 6–8. Soft modes are frequently associated with instability in the structure and frequently disappear at phase transitions, which is further evidence of a second structural transition of $LiFeSi_2O_6$ at high pressures.

The final observed changes in the spectra occur at 8.71 GPa. Spectroscopic changes noted at this pressure are the

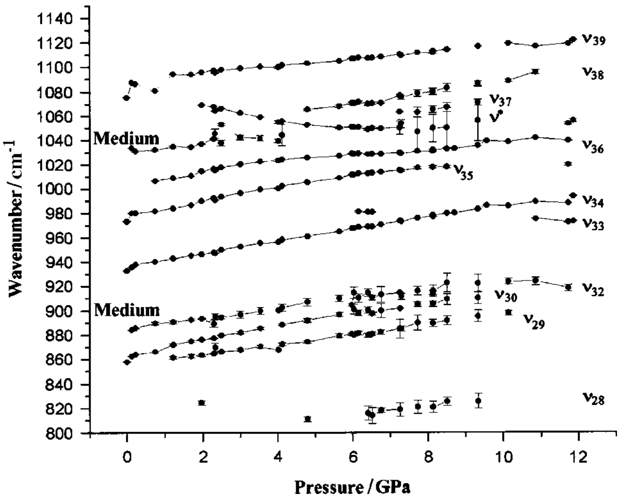

Figure 6. Variation of peak positions with pressure, all data collected as pressure was increased. Error bars were from the peak-fitting program and represent the error in peak position after fitting a mixed Gaussian–Lorentzian peak to either a convergence or a local minimum of the chi-squared value. The error in pressure is estimated as 0.05 GPa. The peak at 1127 cm^{-1} is emission from the LCD monitors in the laboratory and as such does not shift with pressure. This fact was utilized to ensure the uniformity of calibration in the spectra in which the peak appeared. Lines connecting the data points serve as guides to the eye, they should not be taken to imply the modes are necessarily related.

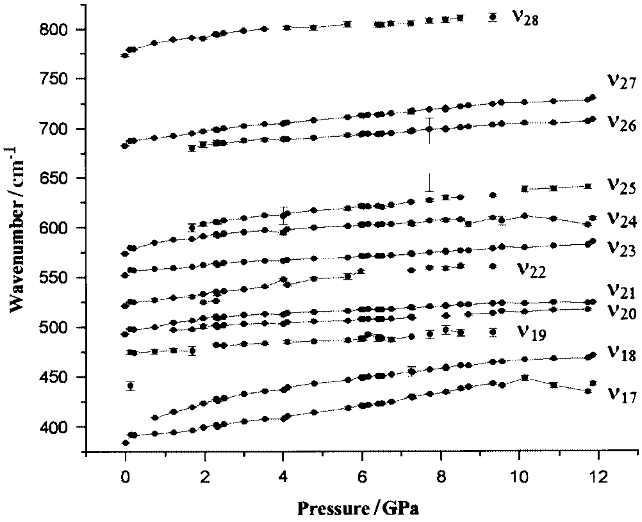

Figure 7. Variation of peak positions with pressure, mid-wavenumber region of spectra. The same pressure conditions as in Fig. 6 are displayed here. Note the appearance of several peaks at the phase transformation, near 1 GPa, and the disappearance of peaks at higher pressures, near 10 GPa.

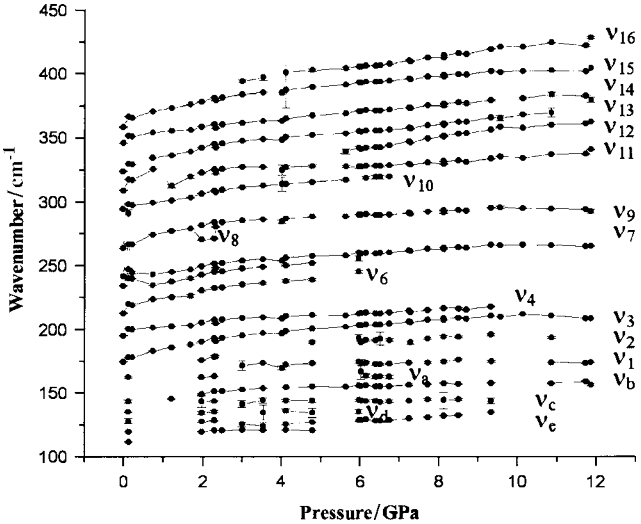

Figure 8. Variation of peak positions with pressure, low-wavenumber portion of spectra. The same pressure region as in Figs 6 and 7 is displayed. Note the many changes in the spectra at the phase transformation, near 6 GPa, and near 10 GPa. The use of holographic notch filters allows data to be collected close to the Rayleigh line. There is much information in the region from 100 to 200 cm^{-1} that would be lost if this region were not studied.

disappearance of ν_4, ν_{13}, ν_{17}, ν_{35}, ν_{36} and ν_{39}, the strengthening of ν_1 and ν_2 and the reappearance of ν_{14}. Spodumene also displays changes in the Raman spectra at pressures above the phase transition (from 8 to 10 GPa).[9] The second change in spodumene is also characterized by a decrease in the number of peaks present, just as is observed in $LiFeSi_2O_6$. This change was attributed to a secondary change in the structure of spodumene that retained the symmetry – possibly a change in coordination number of the Li atom from 5 to 6.[9] The same change in coordination of the Li atom is possible for $LiFeSi_2O_6$. Further investigations by X-ray diffraction are being carried out to determine if this is the case.

Raman spectra were not acquired above 11.87 GPa. The pressure medium was examined visually to ensure that no freezing occurred and, as such, the pressure applied was hydrostatic through all pressures reported here. No band broadening, such as that detected under non-hydrostatic conditions, was observed.

There are several peaks that remain apparent throughout the entire pressure range. These include ν_3, ν_7, ν_{16}, ν_{21}, ν_{23}, ν_{27} and ν_{34}. The Raman modes at 284 and 519 cm^{-1} reported in previous Raman spectra of the $C2/c$ phase of Li-aegirine[6] were not apparent in this study; however, peaks at 246 and 529 cm^{-1} are observed. Raman modes previously reported at 1012 or 1038 cm^{-1} are also not apparent in this study. These modes may not be apparent in the crystal orientation studied because of the previously discussed dependence of Raman peak intensity on orientation. Additionally, this study assigns the longest wavenumber band at atmospheric pressure at 1079 cm^{-1}, whereas previously it was reported at 1084 cm^{-1}.

Spectra were also acquired while decreasing pressure in small increments from 5.89 to 0.27 GPa. The crystal shattered during the process, but still gave high-quality spectra that display the first and second changes in the spectra. As discussed above, no significant hysteresis was apparent.

The peak designated as ν_{27} splits to form a doublet at pressures above 2.30 GPa. The formation of a doublet from a singlet is indicative of the removal of the degeneracy of this mode with the symmetry change. That is, the loss of the C_2 symmetry element makes vibrations that were formerly of equal energy unequal. A doublet in this region of the spectrum has previously been utilized as a benchmark for the $P2_1/c$ phase in pyroxenes. However, this study shows that the doublet does not appear at the phase change, but at pressures about 1.3 GPa above the phase change. That is, the decrease in symmetry is not manifested in the Raman spectra until 1.3 GPa above the pressure where X-ray diffraction indicates the bonding change occurs. It may be that the doublet does not appear in this material until the Si—O3—Si angles in the A and B chains are different by more than 2° or the O3—O3—O3 angles in the A and B chains are different by more than 30°. The Si—O3—Si angles in $LiFeSi_2O_6$ at 3.1 GPa, are different by 2.3° and the difference is 2.5° at 3.9 GPa. However, in spodumene, the Si—O3—Si angles are different by 2.9° at 8.8 GPa.[26] No doublet is apparent in spodumene, so the difference in chain angles is not responsible for the doublet in the Raman spectrum near 700 cm^{-1}.

CONCLUSIONS

This work is the first report of the Raman spectra of the pressure-induced phase transition from $C2/c$ to $P2_1/c$ in $LiFeSi_2O_6$. The spectra appear to be similar to the spectra for spodumene ($LiAlSi_2O_6$), especially in the $P2_1/c$ phase, where both have 5-coordinated Li atoms.[9] The similarity between the spectra allows some comparison between them and tentative mode assignments based on previous work. The changes in the Raman spectra near 6 GPa may be indicative of spin crossovers brought about by the increase in lattice energy. Finally, the Raman spectrum displays an additional change above 8 GPa, characterized by the disappearance of several peaks, which is similar to what occurs in spodumene. These changes may also be due to a phase transition that retains the $P2_1/c$ symmetry but changes the bonding around the Li atom. Current X-ray studies are under way to determine if this is indeed the case. Determination of the origins of the secondary change in the spectrum can give additional information about the mechanism of the high-pressure phase changes in Li-pyroxenes.

REFERENCES

1. Maaloe S, Aoki K. *Contrib. Mineral. Petrol.* 1977; **63**: 161.
2. Downs RT. *Am. Mineral.* 2003; **88**: 556.
3. Downs RT, Gibbs GV, Boisen MB. *EOS Trans. AGU Fall Meet. Suppl.* 1999; **80**: F1140.
4. Woodland AB. *Geophys. Res. Lett.* 1998; **25**: 1241.
5. Revenaugh J, Jordan TH. *J. Geophys. Res.* 1991; **96**: 19 781.
6. Zhang M, Redhammer GJ, Salje EKH, Mookherjee M. *Phys. Chem. Miner.* 2002; **29**: 609.
7. Clarke JR, Appleman DE, Papike JJ. *Mineral. Soc. Am. Pap.* 1969; **2**: 31.
8. Redhammer GJ, Roth G, Paulus W, André G, Lottermoser W, Amthauer G, Treutmann W, Koppelhuber-Bitschnau B. *Phys. Chem. Miner.* 2001; **28**: 337.
9. Pommier CJS, Denton MB, Downs RT. *J. Raman Spectrosc.* 2003; **34**: 769.
10. Redhammer GJ, Roth G. *Z. Kristallogr.* 2002; **217**: 63.
11. Mao HK, Bell PM, Shaner JW, Steiner DJ. *J. Appl. Phys.* 1978; **49**: 3276.
12. Dollish FR, Fately WG, Bentley FF. *Characteristic Raman Frequencies of Organic Compounds*. Wiley: New York, 1974.
13. Mernagh TP, Hoatson DM. *J. Raman Spectrosc.* 1997; **28**: 647.
14. Huang E, Chen CH, Huang T, Lin EH, Xu JA. *Am. Mineral.* 2000; **85**: 473.
15. Ross NL, Reynard B. *Eur. J. Mineral.* 1999; **11**: 585.
16. Wang A, Jolliff BL, Haskin LA, Kuebler KE, Viskupic KM. *Am. Mineral.* 2001; **85**: 790.
17. Haller KJ, Johnson PL, Feltham RD, Enemark JH, Ferraro JR, Basile LJ. *Inorg. Chim. Acta* 1979; **33**: 119.
18. Martin RL, White AH. In *Transition Metal Chemistry*, vol. 4, Carlin RL (ed). Marcel Dekker: New York, 1968; 113.

19. Guetlich P, Spiering H. In *Inorganic Electronic Structure and Spectroscopy. Applications and Case Studies*, Vol. II: Solomon EI, Lever ABP (eds). Wiley: New York, 1999; 575.
20. Stahl K. *Acta Crystallogr. Sect. B* 1983; **39**: 612.
21. Leipolt JG, Coppens P. *Inorg. Chem.* 1973; **12**: 2269.
22. Scheidt WR, Geiger DK, Haller KJ. *J. Am. Chem. Soc.* 1982; **104**: 495.
23. Haddad MS, Federer WD, Lynch MW, Hendrickson DN. *Inorg. Chem.* 1981; **20**: 131.
24. Haddad MS, Lynch MW, Federer WD, Hendrickson DN. *Inorg. Chem.* 1981; **20**: 123.
25. Koenig E, Ritter G, Kulshreshtha SK. *Chem. Rev.* 1985; **85**: 219.
26. Arlt T, Angel RJ. *Phys. Chem. Miner.* 2000; **27**: 719.
27. Everett DH, Whitton WI. *Trans. Faraday Soc.* 1952; **48**: 749.
28. Mikami M, Konno M, Saito Y. *Acta Crystallogr., Sect. B* 1980; **36**: 275.
29. Dove MT. *Am. Mineral.* 1997; **82**: 213.
30. Dove MT, Gambhir M, Heine V. *Phys. Chem. Miner.* 1999; **26**: 344.
31. Heyns AM, Harden PM, Prinsloo LC. *J. Raman Spectrosc.* 2000; **31**: 837.