Structural Stability of L-Cystine under Extreme Conditions

Meng Song, Weiwei Li, Xiaoliang Zhang, Junxiu Liu, Kuo Li, and Hengzhong Zhang*

ABSTRACT: Cystine is important in sustaining the three-dimensional structures of proteins, and hence it might have played an important role in the origin of life as a prebiotic molecule. As harsh environments may have been involved in producing the “prebiotic soup” either from chemical syntheses or sourced from extraterrestrial objects, understanding the structural stability of cystine in extreme environments is essential. Nevertheless, investigations of the stability of cystine at extreme conditions are very limited. In this work, using high-pressure X-ray diffraction (XRD) and Raman and infrared spectroscopies, we studied the structural stability of a hexagonal l-cystine crystal. Results show that the l-cystine crystal is structurally stable at pressures up to ∼25 GPa at room temperature. However, there are changes in the intermolecular hydrogen bonding and/or atomic bond rotations/torsions at three transition pressures of ∼1 to 3, 5–6, and 13–15 GPa. The l-cystine crystal is highly compressible, with a bulk modulus of 32.2 GPa (with B_0' = 4) or 18.6 GPa (with B_0' = 6.9) at an average size of ∼20 to 40 nm. When the compression is above ∼32 GPa, the structural relaxation is retarded in decompression, yet the original structures can still be largely recovered if enough time is given after full decompression. It was also found that even at pressures up to ∼20 GPa and temperatures up to 150 °C, the l-cystine crystal is still stable in essence. These findings would have important implications to postulate and rationalize credible theories on the origin of life at extreme conditions.

KEYWORDS: origin of life, l-cystine, structural stability, high pressure, X-ray diffraction, Raman spectroscopy, infrared spectroscopy, hydrogen bonding

1. INTRODUCTION

In the origin of life, cysteine might have acted as both the catalyst and precursor in prebiotic synthesis of the first peptide that was needed for forming complex proteins. As the oxidized dimer of cysteine, cystine possesses the biological functions of acting as a site for redox reactions and a mechanical linkage for proteins to retain their three-dimensional structures. Thus, cystine might have also played an important role in the origin and evolution of life. As very harsh environments might have been involved in creating the very first form of life, it is necessary to study the structural stability of cystine in extreme conditions to better understand its functions and roles in the process.

In the 1920s, Oparin and Haldane first proposed the “chemical origin” of life on Earth. They hypothesized that the “building blocks” of life (like amino acids) could be produced from inorganic molecules in the prebiotic Earth, which then polymerized to form even more complex molecules from which life gradually evolved. In the 1950s, Miller and Urey provided experimental evidence to show that the life-essential organic molecules such as amino acids, sugars, and lipids could be formed from sparking in a reducing gas mixture (H_2O, CH_4, NH_3, and H_2). Later studies showed that prebiotic organic molecules might also be produced in submarine hydrothermal vents, hot surfaces like those left by lava flow, and surfaces of clays, such as montmorillonite. A more contemporary view is that the origin of life required highly diverse and dynamic environments that were closely connected with each other rather than from a single setting. An alternative theory on the origin of life is the extraterrestrial hypothesis, which assumed that some biologically important organic compounds were brought to Earth from outer space by meteorites, and these compounds might have seeded the formation of prebiotic organic compounds on Earth.

In light of the above theories, extreme conditions like those in hydrothermal vents, hot surfaces, and meteorite impacts might have been involved in the origin of life. Thus, understanding the effects of high pressure (P) and/or high temperature on structural stability and reactivity of amino acids is essential. A previous study of l-cystine at pressures up to ∼6 GPa (at room temperature) showed that pressure prominently
caused closing up of voids between molecules in a L-cystine crystal, causing shortening of intermolecular hydrogen bonds and lessening of N—C—C—O /C—S—S—C torsional angles. Another study on the thermal stability of L-cystine showed that at ambient pressure, the L-cystine crystal is stable up to its melting point (∼230 °C), above which it decomposes. Beyond these, the molecular behaviors of L-cystine at even higher pressures or at both high pressures and high temperatures are still unknown. Thus, in this work, we investigate the effect of high pressure (up to ∼50 GPa) and the effect of combined high pressure and temperature (up to ∼20 GPa and ∼150 °C) on the structural stability of L-cystine using multiple experimental techniques, aiming at providing a new and comprehensive understanding of the molecular properties and behaviors of L-cystine at extreme conditions. The obtained knowledge will be valuable not only for reevaluating and developing credible theories on the origin of life but also for assessing the sustainability of life in future extraterrestrial colonization.

2. EXPERIMENTAL SECTION

2.1. Sample and Crystal Structural Characterization. The L-cystine chemical (purity 99.5%) was purchased from Macklin Biochem. Co., Ltd. (Shanghai) and used without further purification.

For determining the X-ray diffraction (XRD) pattern of L-cystine at ambient conditions, the sample was ground to form micron-sized powders. Then, the powder XRD pattern was collected using an X-ray diffractometer (Malvern Panalytical) operated at 40 kV and 40 mA, with Cu Kα radiation (X-ray wavelength 1.5406 Å). The 2θ angle was varied from 5 to 90° with a scanning rate of 0.4 °/min.

For XRD and Raman and infrared (IR) spectroscopies of L-cystine at high pressures (HP) or at both high pressures and high temperatures (HPHT), a certain amount of the chemical was ground for ∼30 min to form very fine powders. Such fine powders were needed for producing powder XRD/Raman/IR data by reducing the preferred orientation of the sample at high pressures.

The morphology of the finely ground L-cystine sample and that of a sample quenched from ∼10 GPa in a DAC were examined using a scanning electron microscope (SEM) (FEI Versa 3D dual-beam FIB/SEM) operated at 2.0 kV.

2.2. In Situ High-Pressure XRD and Raman and Infrared Spectroscopy. A diamond anvil cell (DAC) with a 300 μm culet size of anvils was used for the HP-XRD and HP-Raman measurements. A hole with a diameter of 130 μm was drilled through a stainless steel gasket using a laser beam, serving as the sample chamber. A piece of a precompressed thin sample sheet was loaded into the sample chamber together with a few ruby chips as the pressure calibrant, followed by loading of neon into the chamber as the pressure transmitting medium (P-medium). The ruby fluorescence method was used to measure the sample pressure.

The HP-XRD experiments were conducted at the beamline station 15U1 of the Shanghai Synchrotron Radiation Facility (SSRF) with an X-ray beam energy of 20 keV (wavelength 0.6199 Å). The XRD images were collected using a MAR165 CCD detector. The sample-to-detector distance was calibrated using a CeO2 powder standard. The L-cystine sample was compressed at different pressures up to ∼20 GPa, followed by consecutive decompressions; a collection time of 300 s was used for XRD pattern collection at each pressure. The collected two-dimensional images were converted to the numerical intensity vs 2θ data using Dioptas software. The lattice parameters and the average crystallite sizes of L-cystine were derived from Rietveld fitting using the Maud program.

The HP-Raman spectra of L-cystine were collected with a Raman spectrometer (inVia Reflex, Renishaw) using a 532 nm excitation laser (power 83.3 mW). In our measurements, the instrument used different gratings to scan sectionally a wide range of Raman shifts (∼50 to 3500 cm⁻¹). We used 50% of the laser power and an exposure time of 20 s at each grating. Each Raman spectrum was generated from two accumulated measurements for reducing the signal noise. The collection time of each spectrum was ∼5 min, which was spent on changing gratings, sample exposure, and signal reading and storing. Two samples were measured with different maximum pressures (∼25 and 50 GPa). To ensure that the samples were not damaged by the laser, we measured the Raman spectra of a sample at the ambient condition using different laser powers (see Figure S1 in the Supporting Information (SI)). The test results showed that with the chosen operational parameters, the laser beam did not damage the L-cystine sample (Figure S1).

The HP-IR spectra were collected with an IR spectrometer (Bruker VERTEX 70v, Germany) in a wavenumber range of 600–3500 cm⁻¹. In a DAC, about half of the sample chamber was filled with the L-cystine sample on top of a thin KBr layer for measuring the sample light transmission and the other half was filled fully with KBr for measuring the background light transmission. At a given pressure, the IR collection time of each spectrum was ∼1 min and the spectrum stacking number was 64 times. The maximum pressure was ∼35 GPa.

2.3. In Situ High-Pressure and High-Temperature (HPHT) Raman Spectroscopy. To study the structural stability of L-cystine at both high pressure and high

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**Figure 1.** XRD pattern of L-cystine at ambient pressure (X-ray wavelength 1.5406 Å). The XRD pattern and peak positions calculated from a COD file (#1513328) are included for comparison. The inset shows the minor (006) peak at 2θ ∼ 9.5°.
temperature, HPHT-Raman experiments were performed with a sample loaded in a DAC heated using an external heating band. Before heating, the initial pressures of the samples in four sets of HPHT-Raman experiments were adjusted and determined as 2.2, 7.6, 13.9, and 19.4 GPa. In heating, the temperature was set to increase from room temperature to 150 °C at a step size of 30 °C. At each step, the temperature was held constant for 10 min. The Raman data collection procedure was similar to that at room temperature and ambient pressure (above).

3. RESULTS AND DISCUSSION

3.1. Structural Characterization of the L-Cystine Sample. The crystal structure of the l-cystine sample was determined by comparing the experimental XRD pattern with those calculated using l-cystine crystal structures searched in the Crystallography Open Database (COD). It was found that the experimental data matched best the crystal structure described by COD file #1513328 (see Figure 1), which was sourced from the work of Moggach et al. Figure 2 illustrates the hexagonal structure of l-cystine (space group P6122): the unit cell contains six l-cystine molecules (Figure 2a) and there is intermolecular hydrogen bonding among l-cystine molecules in the crystal (Figure 2b). Using Rietveld fitting of the ambient XRD data (Figure S2a), we obtained the lattice parameters of the l-cystine sample: \(a = 5.414 \text{ Å}\) and \(c = 56.197 \text{ Å}\), which are close to the literature values (\(a = 5.4203 \text{ Å}\) and \(c = 55.980 \text{ Å}\)).

SEM images of the finely ground sample (Figure S2b,c) show that there were many small grains formed by grinding, which were distributed in a wide range of sizes and most of which were distributed at \(\sim 150\) nm (Figure S2d). These fine powders would benefit producing diffraction rings other than diffraction spots in the HP-XRD images (below).

3.2. Crystal Structural Stability Determined by HP-XRD. Figure 3a shows the XRD patterns of l-cystine in compression. As expected, near the ambient pressure (0.4 GPa), the XRD peak positions match quite well those calculated from the structure model (COD CIF file #1513328\(^2\)\)). In compression up to 20.5 GPa, there are no new peaks appearing or existing peaks disappearing, showing that no phase transitions have occurred. However, there are apparent peak shifts toward higher 2θ angles due to the shortening in various lattice spacing. In particular, the (0 0 18) peak shifts more than the (1 0 0) peak, indicating that the l-cystine crystal is more compressible along the c-axis than the a-axis (or b-axis), consistent with previous work.\(^2\) Upon decompression to ambient pressure, the XRD pattern can be recovered essentially back to the initial one (Figure 3b). These HP-XRD data show that the l-cystine crystal is structurally stable at pressures of at least up to \(\sim 21\) GPa. Rietveld fitting was used to derive the lattice parameters of the l-cystine sample as a function of pressure, as shown in Figure 3c and Table S1. Representative fitting curves are shown in Figure S3. Then, the unit cell volumes at different pressures were calculated (Figure 3d). From ambient pressure...
to 20.5 GPa, the unit cell volume contracts by \(\sim 29\%\), showing a rather high compressibility owing to the relatively weak intermolecular interactions (hydrogen bonding and van der Waals forces).

To obtain the compressibility of L-cystine, the experimental pressure-volume data were fitted using the third-order Birch–Murnaghan (BM) equation of state (EOS)\(^2\)

\[
P(V) = \frac{3B_0}{2} \left[ \left( \frac{V_0}{V} \right)^{7/3} - \left( \frac{V_0}{V} \right)^{5/3} \right] + \frac{3}{4}(B'_0 - 4) \left[ \left( \frac{V_0}{V} \right)^{2/3} - 1 \right]
\]

where \(V_0\) is the initial unit cell volume at ambient pressure and \(V\) is the volume at pressure \(P\); \(B_0\) is the bulk modulus and \(B'_0\) is its first derivative, which is commonly set to 4 for bulk materials in a hydrostatic condition.\(^2\) The fitting results (Figure 3d) show that the L-cystine sample has a bulk modulus of \(B_0 = 32.2 \pm 1.4\) GPa while setting \(B'_0 = 4\). In comparison, \(B_0\) obtained from previous work is 29.1 GPa.\(^*\) If \(B'_0\) is a variable, then \(B_0 = 18.6 \pm 0.7\) GPa and \(B'_0 = 6.9 \pm 0.2\). Figure 3d shows that the latter case fitted the data much better than the former case. Either way, the relatively low bulk modulus compared to those of inorganic compounds (often over 100 GPa)\(^2\) indicates that the molecular crystal of L-cystine is highly compressible.

### 3.3. Pressure-Induced Pulverization of L-Cystine.

Rietveld fitting of the HP-XRD data (Figure 3a,b) also deduced the average particle sizes (Figure 4 and Table S1) and microstrains of L-cystine at different pressures (Table S1). It is seen that the average particle size decreases from \(\sim 40\) nm at low pressures to \(\sim 20\) nm at \(\sim 20\) GPa (Figure 4), while the microstrain is \(\sim 0.005\). This indicates that at high pressures, the originally submicron-sized L-cystine crystals can be easily pulverized to form small nanoparticles. This is related to its relatively low bulk modulus (above) and correspondingly relatively low shear modulus, which makes it easy to deform plastically and then crack at high pressures. Figure S4 shows the morphology by SEM and the grain size distribution of an L-cystine sample quenched from compression at \(\sim 10\) GPa.

Although the SEM was unable to detect the nanocrystallites (nanoparticles) in the textured surface of the sample formed from compression (Figure S4a), some L-cystine grains can still be easily identified (Figure S4b). Most grains are \(\sim 75\) nm (Figure S4c), while the average nanoparticle size is \(\sim 20\) to 40 nm by XRD Rietveld fitting (Figure 4). This indicates that each grain contained more than one nanoparticle.

### 3.4. Effect of Pressure on Molecular Vibrations Revealed by HP-Raman Spectra.

The Raman spectrum of L-cystine at ambient pressure (and room temperature) is

![Figure 3. High-pressure XRD patterns of L-cystine in compression (a) and decompression (b) in a neon pressure medium (X-ray wavelength 0.6199 Å) and derived pressure dependences of the lattice parameters (c) and the unit cell volume (d). The two lines in (d) are the EOS fittings with and without setting \(B'_0 = 4\). The data from Moggach et al. (ref 2) are included for comparison.](https://doi.org/10.1021/acsearthspacechem.1c00068)
shown in Figure S5a (for comparison, the corresponding infrared spectra are shown in Figure S5b). Usually, Raman spectra can be divided into two regions, the low-frequency region (60–200 cm\(^{-1}\)) and the high-frequency region (200–3500 cm\(^{-1}\)). The vibrational modes observed in the low-frequency region are mainly due to the lattice vibrations, which are relevant to the relative movements of the primitive cell.\(^{22}\) 

For molecular crystals like L-cystine, the strengths of the lattice vibrations are related to the van der Waals forces and the hydrogen bonding between molecules.\(^{23}\) The vibrational modes observed in the high-frequency region are mainly due to the vibrations of intramolecular bonds.

We assigned the Raman bands according to the literature,\(^{24–26}\) as shown in Figure S5a and Table 1. Among them, the five lattice vibrational modes at 103, 147, 154, 174, and 198 cm\(^{-1}\) (labeled \(\nu_1−\nu_5\)) are associated with intermolecular hydrogen bond (H\(\cdots\)O) vibrations,\(^{27}\) as caused by the relative motions of two adjacent L-cystine monomers in the crystal. The strongest Raman mode located at 497 cm\(^{-1}\) is associated with the S\(\cdots\)S stretching vibration, which is the most representative Raman peak of L-cystine. Another two peaks located at 616 and 675 cm\(^{-1}\) are associated with the C\(\cdots\)S stretching vibrations (Table 1).

Figure 5a,b shows the Raman spectra of L-cystine under compressions up to 24.6 GPa in a Ne P-medium. In this P\(-\)range, the vibration modes of L-cystine experienced four stages of changes marked by three turning pressures of 1.1, 5.7, and 14.3 GPa, as revealed by the appearance of new (or disappearance of old) peaks. In decompression, L-cystine experienced the same four stages and the Raman spectra can be reversed essentially back to the original one before compression (Figure 5b). As L-cystine is highly compressible (above), it is quasi-hydrostatic at high pressures. Thus, the transition pressures of L-cystine measured with and without using a P-medium should be similar, as shown below.

In compression, in compressions up to 52.0 GPa (without using a P-medium), L-cystine experienced five stages of changes with four turning pressures of 1.8, 5.6, 13.0, and 32.5 GPa (Figure 5c). At \(P \geq 32.5\) GPa, the Raman peaks broadened significantly, suggesting a large structural distortion of the L-cystine sample. In decompression to ambient pressure, the broadened Raman spectra could not be reversed back immediately to the original one (Figure 5d). However, after fully decompressing the sample to ambient pressure and letting the structure be relaxed for 48 h, the remeasured Raman spectra resemble closely the original low-pressure one (see Figure S6). This shows that the HP-caused L-cystine molecular structural changes can be recovered after long-time relaxation at room temperature.

3.5. HP-IR Data Confirming Observations from HP-Raman. Figure 6 shows the IR spectra of L-cystine under compressions up to 35.2 GPa. In this P\(-\)range, the vibrational modes of L-cystine experienced four stages of changes as marked by three turning pressures of 3.0, 6.4, and 14.8 GPa, supporting similar observations from HP-Raman (above). The vibrational modes marked 1a and 1b split at 3.0 GPa. At 6.4 GPa, vibration modes 2a and 2c started to split and a new

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<th>Band Assignments and Experimental Wavenumbers (in cm(^{-1})) of the Hexagonal L-Cystine</th>
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\(\delta, \omega, \tau\) are bending, stretching and twisting vibrations, respectively; v, s, m, w, vs, mw, vw are very strong, strong, medium, weak, very weak, and medium strong, respectively; \(\rho\) is rocking vibration. 

\(^a\)Peak intensity: vs—very strong; s—strong; m—medium strong; w—weak; vw—very weak. 

\(^b\)Band assignments are based on the literature.\(^{24–26}\)
mode 2b appeared. When the pressure reached 14.8 GPa, the two modes at 3a merged, while mode 3b appeared and mode 3c disappeared. Thus, both the HP-Raman and HP-IR data show that the L-cystine crystal had undergone at least two prominent vibrational changes at \(\sim 5\) to 6 and \(\sim 13\) to 15 GPa, respectively.

In decompression, the IR spectra tend to recover to the ones in compression, however, with significant delays (Figure 6b). This again indicates that a significantly long time is needed to recover the inter- and intramolecular interactions after experiencing high-P external compressions, similar to that revealed by HP-Raman (Figure S6). This is because a higher maximum pressure could introduce a higher degree of intra- and inter-molecular changes in the L-cystine crystal, and hence a longer time was needed to relax it to the original state in kinetics.

3.6. Effect of Pressure on Intermolecular Hydrogen Bonding. While the HP-XRD data show that the L-cystine crystal is stable at \(P\) up to \(\sim 21\) GPa (see above), the HP-Raman spectra (Figure 5a) show that there are vibrational mode changes in several pressure regions at pressures up to \(\sim 25\) GPa, as marked by three turning pressures at 1.1, 5.7, and

Figure 5. High-pressure Raman spectra of L-cystine under compression up to 24.6 GPa in a neon medium (a) and subsequent decompression (b) and under compressions up to 52.0 GPa without pressure medium (c) and subsequent decompression (d). There are no apparent Raman peaks in the undrawn Raman shift range of 1700–2200 cm\(^{-1}\). The “*” symbol indicates the appearance of new peaks or the disappearance of old peaks. The Raman signals around 1333 cm\(^{-1}\) are from the diamond anvils in the DAC.
14.3 GPa (see above). These changes are related to the rearrangements of the hydrogen bonds and the changes in the bond angles at different pressures.

To analyze the pressure dependences of various Raman modes, we labeled out major Raman modes of L-cystine using numbers (Figures S7, 7 and Table 1). Figure 7 shows that with the increase of pressure, most vibrational modes exhibit blue shifts because a higher pressure reduces the lattice spacing and increases the interatomic force constants. Only the vibrational modes 4, 4a, 19, and 25, which are related to the NH···O hydrogen bonds, exhibit apparent red shifts at ∼5 GPa because of the breakage and rearrangements of the NH···O hydrogen bonds.

As shown in Figures 7a and S7a, modes 1−5 are very sensitive to P because they arise from the vibrations of intermolecular hydrogen bonds. When P increases to 3.2 GPa, two new modes 1a and 4a appear; when P increases to 5.7 GPa, modes 2, 3, and 5 disappear. At the same time, modes 4 and 4a show abnormal red shifts, suggesting that the hydrogen bonds are broken and rearranged. When P increases to 14.3 GPa, modes 7, 8, and 9 disappear, followed by the appearance of modes 7a, 8a, 9a, and 4b. Modes 7, 8, and 9 correspond to torsional vibration of NH$_3^+$ (marked τ(NH$_3^+$)), which is closely related to the intermolecular hydrogen bonding. Figure S7a shows that the intensity of τ(NH$_3^+$) (modes 7, 8, and 9) weakens at P from ~0 to 11.5 GPa, while at P from 14.3 to 24.6 GPa, its intensity increases sharply. This can be interpreted as the continuous strengthening of the NH···O hydrogen bonds with increasing P up to ∼11.5 GPa, which makes the torsional vibration of NH$_3^+$ harder, and thus decreasing the intensity, and then the breakage of the hydrogen bonds at ∼14.3 GPa, which makes the torsional vibration of NH$_3^+$ easier, thus increasing the intensity of τ(NH$_3^+$) (now labeled as modes 7a, 8a, and 9a) significantly.

In Figures 7b and S7b, the strongest band ν(SS) (mode 10) shows blue shifts consistently with increasing P. The ν(CS) band (mode 13) splits into two new modes 13a and 13b at above 5.7 GPa. Boyd argued that when the dihedral angle of CS−SC is 90°, the repulsive force between the 3p orbitals of sulfur is the lowest, the S−S bond length is the shortest, and hence the bond energy is the highest. With increasing P, the dihedral angle decreases, increasing the repulsive force and the S−S bond length and hence decreasing the bond energy. This also causes changes in the internal rotations of the C−S and C−C bonds, leading to the changes in the stretching frequencies of the S−S bond and C−S bond, producing the ν(CS) band splitting.

The band associated with the CH$_2$ twist vibration (mode 20) splits into two bands (modes 20a and 20b) with increasing P, which becomes more apparent above 5.7 GPa (Figures 7b and S7b). Below 5.7 GPa, the largely overlapping CH$_2$ waggle vibrations (modes 21 and 22) show red shifts with increasing P, and then they split more while mode 22 exhibits a blue shift above 5.7 GPa. This is because as P increases, the molecular torsion intensifies, making −CH$_2$ valence involve more in the formation of hydrogen bonds. This causes splitting of the CH$_2$ twist energy level and weakening of the C−H band energy. At above ∼14.3 GPa, mode 22a appears, while the ρ(NH$_3^+$) (mode 19) disappears, suggesting rearrangement of the hydrogen bonds. The participation of −CH$_2$ valence in the hydrogen bond also causes the change of the ν$_s$(CH$_2$) band, which is marked mode 28 in Figures 7d and S7d. At 1.1 GPa, a new vibration mode 28a appears next to the ν$_s$(CH$_2$) band, which is associated with the antisymmetric vibration of ν$_as$(CH$_2$).

Another vibrational mode closely related to hydrogen bonding is the ν(COO$^-$) band (mode 23 in Figures 7c and S7c). As P increases, this band splits at 5.7 GPa because of the modification of hydrogen bonds, which makes the initially degenerate energy level divided into two levels. When P
increases to 21.6 GPa, a new yet very weak vibrational mode (28b) appears, which might be associated with the v(NH) vibration because of the weakening of the NH···O hydrogen bond.

All of the above observations show that under compressions up to ∼25 GPa, while the crystal of L-cystine remains structurally stable, there are numerous changes in the intermolecular hydrogen bonding at different pressure regions. The hydrogen bonds include the relatively stronger NH···O bonds and the relatively weaker CH···O bonds. At ∼0 to 6 GPa, the hydrogen bonds are strengthened because of the shortening of the bond lengths. At ∼6 to 32 GPa, the hydrogen bonds are rearranged because of the twist of the bonds by the high pressure. Above ∼32 GPa, the hydrogen bonds tend to be damaged, accounting for the long-time structural relaxation after decompression. Other bonds such as the CS−SC one also experience changes under high pressure, such as torsion in its dihedral angles.

3.7. Structural Stability at High Pressures and High Temperatures. Figure 8 shows the HPHT-Raman spectra of L-cystine. It is seen that heating up to 150 °C did not change appreciably the Raman spectra relative to those measured at low temperatures (27 or 50 °C, see the spectrum at the bottom of Figure 8a−d). One exception is that when the sample was heated to 150 °C at an initial pressure of 19.4 GPa (Figure 8d), there was a faint new Raman peak that appeared at 780 cm⁻¹ and another new one at 3164 cm⁻¹ which is associated with the v(NH) vibration. The latter is stronger than the corresponding one without heating (Figure 8a) owing to the weakening of the hydrogen bond at high temperatures. Thus, the l-cystine crystal is quite structurally stable at pressures up to ∼20 GPa and temperatures up to 150 °C.

4. CONCLUSIONS

At room temperature and at pressures up to ∼25 GPa, the l-cystine crystal is structurally stable as revealed by HP-XRD, though there is pressure-induced pulverization forming ∼20 to 40 nm l-cystine nanoparticles. The l-cystine crystal is highly compressible, with a bulk modulus of 32.2 GPa (while setting B₀ = 4) or 18.6 GPa (with a fitted B₀ = 6.9). However, there
are some changes in the intermolecular hydrogen bonding and/or atomic bond rotations/torsions at three transition pressures of ∼1 to 3, 5–6, and 13–15 GPa, as unveiled by HP-Raman and HP-IR data. When L-cystine is further compressed to ∼50 GPa, there is significant structural distortion in the crystal over ∼32 GPa, which retards the structural relaxation in decompression. Even so, a fully decompressed sample can still be recovered largely to the original structure. Results of HPHT experiments further show that the L-cystine crystal is basically structurally stable at pressures up to ∼20 GPa and temperatures up to 150 °C, even though the high temperature may promote hydrogen bond breaking at a high pressure. This work uncovers the structural stability of L-cystine at high pressures and/or mild–high temperatures, providing new knowledge for exploring its functions or roles in the origin of life.

**ASSOCIATED CONTENT**

*Supporting Information*

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsearthspacechem.1c00068.

- Selection of Raman laser power; XRD and SEM characterizations of L-cystine at ambient pressure; lattice parameters of L-cystine at high pressures as derived from Rietveld fitting; representative Rietveld fitting curves; SEM images of a pressure-quenched L-cystine sample; Raman and IR band assignments of L-cystine; and Raman spectra of a decompressed sample relaxed for different times (PDF)

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Figure 8. In situ HPHT-Raman spectra of L-cystine upon heating from 27 to 150 °C at an initial pressure of 2.2 GPa (a), 7.6 GPa (b), 13.9 GPa (c), and 19.4 GPa (d). The actual pressure changed at a different temperature, as labeled above each spectrum. “D” prefixing a pressure value denotes decompression. The star sign marks the changes in the spectrum relative to the very initial spectrum at the bottom.
Complete contact information is available at: https://pubs.acs.org/10.1021/acsearthspacechem.1c00068

Notes
The authors declare no competing financial interest.

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