The electronic spectrum of Si$_3$ I: Triplet D$_{3h}$ system

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We report the measurement of a jet-cooled electronic spectrum of the silicon trimer. Si$_3$ was produced in a pulsed discharge of silane in argon, and the excitation spectrum examined in the 18 000–20 800 cm$^{-1}$ region. A combination of resonant two-color two-photon ionization (R2C2PI) time-of-flight mass spectroscopy, laser-induced fluorescence/dispersed fluorescence, and equation-of-motion coupled-cluster calculations have been used to establish that the observed spectrum is dominated by the $^1A''_1$ – $^3A''_1$ transition of the D$_{3h}$ isomer. The spectrum has an origin transition at 18 600 ± 4 cm$^{-1}$ and a short progression in the symmetric stretch with a frequency of ∼445 cm$^{-1}$, in good agreement with a predicted vertical transition energy of 2.34 eV for excitation to the $^1A''_1$ state, which has a calculated symmetric stretching frequency of 480 cm$^{-1}$. In addition, a ∼505 cm$^{-1}$ ground state vibrational frequency determined from sequence bands and dispersed fluorescence is in agreement with an earlier zero-electron kinetic energy study of the lowest D$_{3h}$ state and with theory. A weaker, overlapping band system with a ∼360 cm$^{-1}$ progression, observed in the same mass channel (m/z = 84) by R2C2PI but under different discharge conditions, is thought to be due to transitions from the (more complicated) singlet C$_{2v}$ ground state ($^1A_1$) state of Si$_3$. Evidence of emission to this latter state in the triplet dispersed fluorescence spectra suggests extensive mixing in the excited triplet and singlet manifolds. Prospects for further spectroscopic characterization of the singlet system and direct measurement of the energy separation between the lowest singlet and triplet states are discussed. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4704672]

I. INTRODUCTION

Small silicon clusters play an important role in the photochemistry of silicon- and carbon-rich evolved stars and in vapor deposition of silicon films, and they are a first step in developing an understanding of larger clusters. To date, 11 silicon-containing molecules have been detected in the interstellar medium, primarily via their pure rotational transitions, with some so abundant that their rare isotopomers are easily observed. The study of Si$_3$ in the optical region is of astronomical interest because it is isovalent with SiC$_2$ - a highly conspicuous ionic ring - and C$_3$, both of which have been detected in space by their electronic spectra. Because of its small permanent electric dipole moment (0.3–0.4 D; Refs. 7 and 8), astronomical detection of Si$_3$ may be more favorable in the optical rather than the radio band.

Understanding the differences in structure and bonding between silicon- and carbon-rich species provides further motivation for the experimental study of small silicon clusters. Although silicon is isovalent with carbon, its larger atomic radius results in weaker π-bonding. Calculations predict that silicon prefers to form non-linear and three-dimensional structures containing single bonds, a conclusion which is broadly supported experimentally by photoelectron and matrix infrared spectroscopy of Si$_3$–Si$_7$. This is in contrast to carbon, which forms single and multiple bonds and generally prefers linear and planar monocyclic structures.

The silicon trimer is the most thoroughly studied small polyatomic silicon cluster. *Ab initio* calculations predict that the singlet C$_{2v}$ form is the electronic ground state while a non-polar triplet D$_{3h}$ isomer lies within ∼1 kcal/mol. The first experimental evidence for the C$_{2v}$ form was obtained by Li et al., who recorded infrared absorption spectra of several silicon clusters including Si$_3$ in three different rare gas matrices. They measured vibrational frequencies of approximately 550 cm$^{-1}$ and 525 cm$^{-1}$, in agreement with those calculated for the symmetric and asymmetric stretching modes, respectively, of the C$_{2v}$ form. Four electronic transitions, all assigned to the C$_{2v}$ form, were observed in absorption by Fulara et al., following deposition of mass-selected silicon clusters in a neon matrix. Two of the transitions lie in the near infrared and ultraviolet regions, with origin bands reported at 778.9 nm and 388.3 nm, respectively, while two lie within the spectral region (555–480 nm) covered in this work. Of these latter two transitions, the stronger one, assigned as $^1E_1$ – $^1A_1$ in Ref. 16, has an origin near 580 nm and a vibrational spacing of 235–270 cm$^{-1}$, which has been assigned to the bending mode ($v_2$). The other transition, $^1B_1$ – $^1A_1$, has a progression in a ∼360 cm$^{-1}$ vibrational mode, and an origin tentatively assigned near 522 nm. These assignments...
agree with a recent theoretical investigation of the structures and electronic spectra of small silicon clusters by Park and coworkers.\textsuperscript{17} Most recently, McCarthy and Thaddeus\textsuperscript{18} measured the rotational spectrum of the $C_{2v}$ form and showed that it is strongly bent, with a bond angle of $78.10^\circ$, in marked contrast to $C_3$, which is linear.\textsuperscript{19} From the inertial defect, a frequency of 178 cm$^{-1}$ was estimated for $v_2$.

Further experimental attempts to understand the electronic structure of the silicon trimer by photoelectron spectroscopy have furnished little additional insight on the lowest $C_{2v}$ state but instead much new information on the $D_{3h}$ triplet isomer. In 1990, Kitsopoulos et al. measured the 266 nm photoelectron spectrum (PES) of Si$_3^-$ and observed five bands which correspond to electronic states of the neutral.\textsuperscript{20} The unusual profile of the lowest energy band (the X-band in their reported PES), corresponding to the Si$_3$ ground electronic state, was proposed to result from a convolution of features from both the $C_{2v}$ and $D_{3h}$ forms, a view supported in an ab initio study of the Si$_3^-$ PES.\textsuperscript{15} Subsequently, the near threshold photodetachment zero-electron kinetic energy (ZEKE) spectrum of Si$_3^-$, probing the same band at much higher resolution, was reported by Arnold and Neumark in 1994.\textsuperscript{21} The spectrum showed well-resolved vibrational structure, and was assigned to transitions from a Jahn-Teller distorted anion to the $3A_2^\prime$ electronic state of the $D_{3h}$ neutral. The frequencies of the symmetric stretch and degenerate $e'$ modes in the $3A_2^\prime$ state were determined to be 501 and 337 cm$^{-1}$ ($\pm 10$ cm$^{-1}$), respectively, in good agreement with earlier calculations\textsuperscript{22, 23} performed on the lowest triplet state. Surprisingly, the X-band probed in the ZEKE spectrum contained no evidence of the $C_{2v}$ ground state. Instead, a result attributed to a convolution of features from both the $C_{2v}$ and $D_{3h}$ states in the singlet and triplet manifolds, it is surprising that no recent measurements have furnished little additional insight on the lowest $C_{2v}$ state but instead much new information on the $D_{3h}$ triplet isomer. In 1990, Kitsopoulos et al. measured the 266 nm photoelectron spectrum (PES) of Si$_3^-$ and observed five bands which correspond to electronic states of the neutral.\textsuperscript{20} The unusual profile of the lowest energy band (the X-band in their reported PES), corresponding to the Si$_3$ ground electronic state, was proposed to result from a convolution of features from both the $C_{2v}$ and $D_{3h}$ forms, a view supported in an ab initio study of the Si$_3^-$ PES.\textsuperscript{15} Subsequently, the near threshold photodetachment zero-electron kinetic energy (ZEKE) spectrum of Si$_3^-$, probing the same band at much higher resolution, was reported by Arnold and Neumark in 1994.\textsuperscript{21} The spectrum showed well-resolved vibrational structure, and was assigned to transitions from a Jahn-Teller distorted anion to the $3A_2^\prime$ electronic state of the $D_{3h}$ neutral. The frequencies of the symmetric stretch and degenerate $e'$ modes in the $3A_2^\prime$ state were determined to be 501 and 337 cm$^{-1}$ ($\pm 10$ cm$^{-1}$), respectively, in good agreement with earlier calculations\textsuperscript{22, 23} performed on the lowest triplet state. Surprisingly, the X-band probed in the ZEKE spectrum contained no evidence of the $C_{2v}$ ground state. Instead, a result attributed to a convolution of features from both the $C_{2v}$ and $D_{3h}$ states in the singlet and triplet manifolds, it is surprising that no recent measurements have furnished little additional insight on the lowest $C_{2v}$ state but instead much new information on the $D_{3h}$ triplet isomer.

In light of the substantial effort to understand the electronic structure of the silicon trimer, it is surprising that no recent measurements have furnished little additional insight on the lowest $C_{2v}$ state but instead much new information on the $D_{3h}$ triplet isomer. In 1990, Kitsopoulos et al. measured the 266 nm photoelectron spectrum (PES) of Si$_3^-$ and observed five bands which correspond to electronic states of the neutral.\textsuperscript{20} The unusual profile of the lowest energy band (the X-band in their reported PES), corresponding to the Si$_3$ ground electronic state, was proposed to result from a convolution of features from both the $C_{2v}$ and $D_{3h}$ forms, a view supported in an ab initio study of the Si$_3^-$ PES.\textsuperscript{15} Subsequently, the near threshold photodetachment zero-electron kinetic energy (ZEKE) spectrum of Si$_3^-$, probing the same band at much higher resolution, was reported by Arnold and Neumark in 1994.\textsuperscript{21} The spectrum showed well-resolved vibrational structure, and was assigned to transitions from a Jahn-Teller distorted anion to the $3A_2^\prime$ electronic state of the $D_{3h}$ neutral. The frequencies of the symmetric stretch and degenerate $e'$ modes in the $3A_2^\prime$ state were determined to be 501 and 337 cm$^{-1}$ ($\pm 10$ cm$^{-1}$), respectively, in good agreement with earlier calculations\textsuperscript{22, 23} performed on the lowest triplet state. Surprisingly, the X-band probed in the ZEKE spectrum contained no evidence of the $C_{2v}$ ground state. Instead, a result attributed to a convolution of features from both the $C_{2v}$ and $D_{3h}$ states in the singlet and triplet manifolds, it is surprising that no recent measurements have furnished little additional insight on the lowest $C_{2v}$ state but instead much new information on the $D_{3h}$ triplet isomer. In 1990, Kitsopoulos et al. measured the 266 nm photoelectron spectrum (PES) of Si$_3^-$ and observed five bands which correspond to electronic states of the neutral.\textsuperscript{20} The unusual profile of the lowest energy band (the X-band in their reported PES), corresponding to the Si$_3$ ground electronic state, was proposed to result from a convolution of features from both the $C_{2v}$ and $D_{3h}$ forms, a view supported in an ab initio study of the Si$_3^-$ PES.\textsuperscript{15} Subsequently, the near threshold photodetachment zero-electron kinetic energy (ZEKE) spectrum of Si$_3^-$, probing the same band at much higher resolution, was reported by Arnold and Neumark in 1994.\textsuperscript{21} The spectrum showed well-resolved vibrational structure, and was assigned to transitions from a Jahn-Teller distorted anion to the $3A_2^\prime$ electronic state of the $D_{3h}$ neutral. The frequencies of the symmetric stretch and degenerate $e'$ modes in the $3A_2^\prime$ state were determined to be 501 and 337 cm$^{-1}$ ($\pm 10$ cm$^{-1}$), respectively, in good agreement with earlier calculations\textsuperscript{22, 23} performed on the lowest triplet state. Surprisingly, the X-band probed in the ZEKE spectrum contained no evidence of the $C_{2v}$ ground state. Instead, a result attributed to a convolution of features from both the $C_{2v}$ and $D_{3h}$ states in the singlet and triplet manifolds, it is surprising that no recent measurements have furnished little additional insight on the lowest $C_{2v}$ state but instead much new information on the $D_{3h}$ triplet isomer.

In light of the substantial effort to understand the electronic structure of the silicon trimer, it is surprising that no gas-phase excitation spectrum has been reported for either isomer. In this article, we focus on the jet-cooled gas-phase spectrum of Si$_3$ in the 555–480 nm region, probed by resonant mass-selected two-color two-photon ionization (R2C2P1) and laser-induced fluorescence (LIF)/dispersed fluorescence (DF) spectroscopy. The excitation spectrum is dominated by the $1^3A'^\prime_2 \rightarrow 3^3A'^\prime_2$ transition of the $D_{3h}$ form, and is assigned on the basis of vibrational sequence band analysis and dispersed fluorescence spectra from several of the strongest bands. The assignment is supported by ab initio calculations of electronic states in the singlet and triplet manifolds using the equation-of-motion coupled-cluster (EOM-CCSD) approach.\textsuperscript{25, 26} A weaker band system, overlapped with the $D_{3h}$ transition and extending to the blue, is tentatively assigned to the $C_{2v}$ form that has been observed in the matrix by Fulara et al.\textsuperscript{16} and will be discussed elsewhere. The electronic structure of Si$_3$ is conveniently represented in terms of the electron configuration and resulting states at the high symmetry $D_{3h}$ geometry, where the electron configuration is $\left(5a_1^a\right)^2\left(2a_2^a\right)^2\left(6e^a\right)^2\left(2e'^a\right)^0$, and the transitions comprised in the current spectra are those involving promotion of an electron from the (half-filled) $6e'$ orbital to the $2e''$ orbital (see Fig. 1 and its caption).

II. EXPERIMENTAL DETAILS

Resonance-enhanced multi-photon ionization experiments were performed in parallel at two laboratories, one in Cambridge, the other in Basel. The experimental setups in both laboratories are similar and each has been described elsewhere.\textsuperscript{27, 28} At Cambridge, Si$_3$ was produced in the throat of a supersonic nozzle by electrical discharge (varying from 500 V to 1.5 kV, with 10 kΩ ballast resistance) through a gas stream containing a dilute mixture of SiH$_4$ (1%) in argon, just prior to supersonic expansion into a vacuum chamber. The discharge nozzle is based on the design in Ref. 29. The stagnation pressure was varied from 3 to 8 atm; typical operating pressure within the chamber was 10$^{-6}$ Torr. At Basel, Si$_3$ was produced by laser ablation of a pure silicon rod in the presence of supersonically expanding helium. The pressure behind the pulsed valve was $\sim$10 atm and the chamber operating pressure was $7 \times 10^{-5}$ Torr.

In these experiments, tunable radiation between 480 and 555 nm was generated by a 355 nm-pumped dye laser operating with Coumarin 300 and 540 A. The typical dye laser output over the tuning range was $\sim$10 mJ per pulse, with a linewidth of $\sim$0.4 cm$^{-1}$. Absolute wavelength calibration was provided by an external wavemeter. Because Si$_3$ has an ionization potential of $\sim$8.5 eV,\textsuperscript{30} the excimer laser was operated with ArF (193 nm or 6.42 eV) to be certain that the
1+1’ process was sufficiently energetic (~8.7 eV at 540 nm) to yield a positive ion.

Fluorescence experiments were also performed at Arizona State University, with a reactive molecule source similar to that used in Cambridge. Specifically, a discharge (700 V, 20 μs, 6 kΩ ballast resistor) was struck in a 1% SiH4 in Ar gas pulse. The backing pressure was 15 atm, the repetition rate 20 Hz, and the operating chamber pressure $7 \times 10^{-5}$ Torr. The supersonic free jet expansion was crossed with pulsed laser radiation approximately 5 cm downstream from the source. Two types of experiments were performed: (a) LIF excitation in the 510–550 nm range; (b) DF emission in the 500–610 nm range. In both experiments, the excitation source was a pulsed dye laser pumped by 308 nm radiation from an excimer laser. The fluorescence signal was viewed through a 0.67 m scanning monochromator, detected with a cooled photomultiplier tube and processed using gated photon counting. In the LIF excitation measurements, the slits on the monochromator were opened to 3 mm, resulting in a resolution of ±3.7 nm, and the peak transmission scanned to track the laser wavelength. In the DF measurements, the slits on the monochromator were reduced to 1 mm for a resolution of ±1.24 nm. Typically, 50 pulses were averaged at each step of the laser or monochromator.

III. COMPUTATIONAL METHODOLOGY

Ab initio calculations were performed on the triplet $D_{3h}$ isomer of the silicon trimer. Vertical excitation energies were calculated using the EOM-CCSD approach. Geometries of the ground and first excited state were optimized using analytical gradients; this was done at the CCSD level for the ground state (a $3A_g'$) and at the EOM-CCSD level for the excited state (1 $3A'_1$). The basis set used in these calculations was the correlation-consistent polarized weighted core-valence triple-zeta (cc-pwCTZ) basis of Peterson and Dunning. Harmonic vibrational frequencies at the equilibrium geometries were obtained for the ground and excited states from analytic second derivatives for CCSD, and numerical differentiation of analytic first derivatives for EOM-CCSD, respectively. At the geometry of the ground state, the vertical excitation energy was also calculated with the quite sophisticated EOM-CCSDT method for the triplet state, using the atomic natural orbital basis of Widmark et al., in which only the valence shell electrons were correlated. All calculations were performed using the CFOUR package of electronic structure programs. Table I summarizes the key results of our calculations.

IV. RESULTS AND ASSIGNMENT

R2C2PI spectra of the $m/ε$ = 84 products of a SiH4 (1%) in Ar discharge, recorded between 18000 and 20500 cm$^{-1}$ (555–480 nm) under two different expansion conditions, are shown in Fig. 2; a similar $m/ε$ = 84 spectrum was also observed using the pure silicon rod ablation source at Basel. The lower spectrum in Fig. 2 was recorded under “cold” discharge conditions, i.e., using a low discharge voltage, a short discharge pulse, and a high (8 atm) backing pressure. At least two overlapping progressions are evident: a stronger progression, with a ~445 cm$^{-1}$ interval and an origin near 18 600 cm$^{-1}$; and a much weaker one, with a regular spacing of ~360 cm$^{-1}$ but which does not have the same origin. As indicated in Fig. 2, the two progressions have a coincidental overlap near 19 500 cm$^{-1}$. Under the experimental conditions which produced the best S/N for the 445 cm$^{-1}$ progression, no strong or sharp spectral features were observed in survey scans that extended down to 17 240 cm$^{-1}$, near where the strongest transition of the $C_{2v}$ form was observed in a neon matrix.

The same wavelength region was re-scanned under “hotter” beam conditions (higher discharge voltage, longer discharge pulse, backing pressure reduced to 3 atm). The resulting spectrum is shown in the upper trace in Fig. 2. The increase in the intensity of the 360 cm$^{-1}$ progression, relative to the 445 cm$^{-1}$ progression suggests that they do not share a common lower state. A second 360 cm$^{-1}$ progression, presumably due to vibrational hot bands, is now evident under these conditions.
Two band systems of Si$_3$, both from the C$_{2v}$ singlet ground state, have been observed in this spectral region in a neon matrix: the first, assigned $\tilde{E}^1A_1 - \tilde{X}^1A_1$, has an origin at 580 cm$^{-1}$ and a 235–270 cm$^{-1}$ progression in $\nu_2$; the second, assigned $\tilde{F}^1B_1 - \tilde{X}^1A_1$, has a tentatively assigned origin near 520 nm and a $\sim$360 cm$^{-1}$ progression. On the basis of the reported matrix spectrum, transitions within the $\tilde{E}^1A_1 - \tilde{X}^1A_1$ band system are expected to be weak in this region but probably contribute to the broad background observed to the red of the 18 600 cm$^{-1}$ feature. The second band system is likely responsible for the 360 cm$^{-1}$ progression observed in Fig. 2. These “singlet” features, which exhibit richer vibrational structure, result from transitions within a manifold of states that correlate to degenerate states in D$_{3h}$ symmetry (see Fig. 2 in Ref. 24). Unlike the quite simple triplet manifold, vibronic interactions are both numerous and complicated in the singlet spectrum, and their study will be addressed in a forthcoming publication. Assignment of the transition that exhibits the 445 cm$^{-1}$ transition that exhibits the 445 cm$^{-1}$ feature will be addressed in a forthcoming publication. Assignment of the transition that exhibits the 445 cm$^{-1}$ progression is the primary focus of the present study.

The features at 18 534 cm$^{-1}$ and 18 986 cm$^{-1}$ are remarkably strong in the hotter spectrum. Both of these bands (indicated in the cold spectrum with asterisks) appear red-shifted from bands in the 445 cm$^{-1}$ progression by approximately 60 cm$^{-1}$. Assigning them as sequence bands of the 445 cm$^{-1}$ progression yields a putative lower state frequency of $\sim$505 cm$^{-1}$, in excellent agreement with 501 $\pm$ 10 cm$^{-1}$ observed by ZEKE for the symmetric stretch ($\nu_1$) of the D$_{3h}$ a $^3A_2$ state. We calculate $\nu_1$ frequencies in the a $^3A_2$ and 1 $^3A_1^*$ states of Si$_3$ of 520 cm$^{-1}$ and 480 cm$^{-1}$, respectively (see Table I), in reasonable agreement with experiment, and a vertical transition between these states at 2.34 eV (compared to the observed origin at 18 600 cm$^{-1}$ (2.31 eV)) with an oscillator strength of 0.0037. In addition, we calculate an excited state frequency of 133 cm$^{-1}$ for the degenerate deforming mode $\nu_2$, and a lower state one of 351 cm$^{-1}$, also in agreement with the 337 cm$^{-1}$ determined in the same ZEKE study. One might therefore expect 2$^1_1$ sequence bands to appear approximately 200 cm$^{-1}$ red-shifted from the 1$^0_1$ progression in the D$_{3h}$ spectrum. While we hesitate to make such an assignment with certainty until the 360 cm$^{-1}$ progression is better understood, the appearance in the hotter spectrum of a weak band at 18 845 cm$^{-1}$, 200 cm$^{-1}$ to the red of the 1$^0_1$ band, is consistent with this interpretation; furthermore, this feature is accompanied by a slightly weaker feature approximately 50–60 cm$^{-1}$ to the red, the latter of which can be plausibly assigned as 1$^2_1^1$, reminiscent of the other sequence bands in the D$_{3h}$ spectrum.

For the a $^3A_2$ state, the calculated CCSD/cc-pwCTZ equilibrium structure has an Si-Si bond length of 2.280 Å which increases to 2.294 Å in the 1 $^3A_1^*$ state. Unlike many of the states in the singlet manifold, neither triplet state is Jahn-Teller active; as a result, one might expect the 1$^3A_1^*$ $\rightarrow$ a $^3A_2$ transition to have a simple spectrum consisting only of a short progression in the symmetric stretch ($\nu_2$) is Franck-Condon inactive, as shown in Fig. 2. The strength of the sequence bands in the hotter spectrum provides additional evidence that the 360 cm$^{-1}$ progression must arise from a different lower state, as none of these bands have a comparably intense band $\sim$60 cm$^{-1}$ to the red. While this proposed assignment seemed reasonable, the absence of the I$^2_0$ sequence is puzzling, given the strength of the I$^1_0$ sequence. Some confirmation was therefore sought using fluorescence spectroscopy.

Figure 3 contains the LIF spectrum (left) of the 1% SiH$_2$/Ar discharge in the region 18100–19200 cm$^{-1}$. The

![Image of laser-induced fluorescence spectrum of Si$_3$ (left) and (right) dispersed fluorescence spectra obtained from the LIF bands labeled A, B, and D.](http://jcp.aip.org/about/rights_and_permissions)
spectrum contains no evidence of the 360 cm\(^{-1}\) progression, possibly because the fluorescence was selectively detected using a monochromator with a 3.7 nm bandwidth that tracked the laser excitation. The \(v_1\) progression is also shorter, probably due to lower laser power in the region of the \(1^1\) band. The spectrum also includes some sharp features (C and E) near 19 300 cm\(^{-1}\) and 19 334 cm\(^{-1}\); based on a ground state frequency of \(\sim 540\) cm\(^{-1}\) from DF (not shown), an excited state interval of \(\sim 334\) cm\(^{-1}\), and a very recent theoretical study,\(^{36}\) these bands almost certainly belong to the \(2^2\Pi \leftrightarrow D^3\Pi\) transition of Si\(_2\), which is predicted to occur near 19 000 cm\(^{-1}\).

DF spectra recorded from the LIF bands labeled A (1\(^1\)), B (0\(^0\)), and D (1\(^2\)) are also shown in Fig. 3. The spectra are similar: each contains a short 505 cm\(^{-1}\) progression, and a relatively weak but long one with a spacing of \(\sim 173\) cm\(^{-1}\). The assignment of the 505 cm\(^{-1}\) intervals in each spectrum to \(v_1\) is entirely consistent with our assignment of sequence band structure in the R2CP2I spectra. For example, the \(1^1\) DF spectrum contains a feature blue-shifted from the laser frequency by 505 cm\(^{-1}\) - coincident with the \(\tilde{A}^3\) \(A_2^\prime\) \(v_1\) frequency inferred earlier - that has an obvious assignment of \(1^1\). On the basis of the R2CP2I spectra, the dominant features in the DF spectra, and our calculations on the \(\tilde{A}^3\) \(A_2^\prime\) and \(1^3\) \(A_1^\prime\) states, assignment of the 445 cm\(^{-1}\) progression to the \(1^3\) \(A_1^\prime\) \(\rightarrow\) \(\tilde{A}^3\) \(A_2^\prime\) transition is therefore secure and is summarized in Table II.

V. DISCUSSION

While the singlet manifold is replete with Jahn-Teller and pseudo-Jahn-Teller interactions, the triplet transition probed in this work is free of such effects and exhibits a very simple spectrum (once the overlapping singlet transitions are identified). However, there are several aspects of this seemingly uncomplicated system that are surprising, and worthy of further discussion.

A. Evidence of the \(\tilde{X}\) \(1^1\)A\(_1\) state in triplet emission

The dominant features in the triplet DF spectra are readily assigned to \(v_1\) in the \(\tilde{A}^3\) \(A_2^\prime\) state, but rationalizing the long \(\sim 173\) cm\(^{-1}\) progression that appears in all three spectra is more problematic. Calculations on the \(\tilde{X}\) \(1^1\)A\(_1\) ground state of the C\(_{2v}\) isomer of Si\(_3\) have predicted a frequency for the bending mode of 146 cm\(^{-1}\) (Ref. 15) and 196 cm\(^{-1}\).\(^{24}\) From the rotational spectrum of the C\(_{2v}\) isomer, McCarthy and Thaddeus estimated a frequency of 178 cm\(^{-1}\) based on the inertial defect,\(^{18}\) in fairly close agreement with the spacing in the DF progressions. If these weaker features in the \(1^3\) \(A_1^\prime\) \(\rightarrow\) \(\tilde{A}^3\) \(A_2^\prime\) DF spectra are indeed due to the C\(_{2v}\) form, they may have at least two distinct explanations. First, if either the C\(_{2v}\) \(E^1\) \(A_1\) \(\rightarrow\) \(\tilde{X}\) \(1^1\)A\(_1\) and \(F^1\) \(B_1\) \(\rightarrow\) \(\tilde{X}\) \(1^1\)A\(_1\) band systems accidentally coincide in wavelength with the triplet transitions that have been probed by DF, emission to the singlet ground state might be observed. However, we have been so far unable to observe by LIF any of the putative C\(_{2v}\) features that were observed in REMPI (see Sec. V C).

A more likely explanation for the \(\sim 173\) cm\(^{-1}\) progression is that the \(1^3\) \(A_1^\prime\) state undergoes an intersystem crossing, and emission then follows to the \(\tilde{X}\) \(1^1\)A\(_1\) state through either the \(E^1\) \(A_1\) \(\rightarrow\) \(\tilde{X}\) \(1^1\)A\(_1\) and \(F^1\) \(B_1\) \(\rightarrow\) \(\tilde{X}\) \(1^1\)A\(_1\) transitions. Seeking evidence in support of the latter hypothesis, the LIF spectrum was re-measured with the monochromator tuned to 610 nm using a bandpass of approximately 3 nm (see Fig. 4, in which the detection window is indicated above the origin DF spectrum). Because the progression in \(v_1\) is quite short, we can be confident that any Si\(_3\) bands observed by LIF at this detection wavelength emit to a member of the \(\sim 173\) cm\(^{-1}\) progression, rather than through the symmetric stretching mode of the triplet. Other than a strong, unrelated band centered on 19 200 cm\(^{-1}\) (due to the \(A^1\) \(B_1\) \(\rightarrow\) \(\tilde{X}\) \(1^1\)A\(_1\) transition of SiH\(_2\) (Ref. 37)), the resultant spectrum contains only the previously observed \(1^3\) \(A_1^\prime\) \(\rightarrow\) \(\tilde{A}^3\) \(A_2^\prime\) features, and none of the other Si\(_3\) features observed by R2CP2I. Consequently, the argument that overlapping transitions of the C\(_{2v}\) isomer contribute to the DF spectra can almost certainly be rejected. Instead, a singlet-triplet mixing in the upper state is probably responsible for the long \(\sim 173\) cm\(^{-1}\) progressions that are observed in the DF spectra, which arises from bending levels in the ground singlet state. Because of the large change in geometry between the triplet and singlet states, emission to many \(v_2\) levels in the \(\tilde{X}\) \(1^1\)A\(_1\) ground state occurs facilely.

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<thead>
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<th>Frequency (cm(^{-1}))</th>
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<td>18 534</td>
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<td>18 600</td>
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<td>18 790</td>
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<td>19 497</td>
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B. Discharge temperature effects

Two unusual temperature effects observed in the hotter R2C2PI spectrum require comment. The first is that, although the $1^1$ sequence bands are similar in intensity to the origin and $1^3$ bands, the $1^3$ sequence is absent. For the $\tilde{a}^1A_2^\prime$ state, with experimentally determined vibrational frequencies of $v_1 = 505 \text{ cm}^{-1}$ and $v_2 = 337 \text{ cm}^{-1}$, the $1^1$ and $2^1$ levels are almost coincident; intramolecular vibrational redistribution from $1^1$ into the $2^1$ level, which can be cooled more effectively in the free jet, is a plausible explanation for the absence of higher sequences.

More puzzling is the relative strength of the singlet and triplet transitions under the two different expansion conditions employed. Because the $C_{2v}$ isomer is slightly more stable, one might expect it to be the more abundant isomer in the discharge. However, experimental evidence suggests that the $D_{3h}$ form is instead much more abundant under “cold” experimental conditions, while “hot” conditions slightly enhance the relative strength of the $C_{2v}$ isomer$^{18}$ were observed with the same discharge source and similar experimental conditions to those used to record the hotter R2C2PI spectrum (Fig. 2). Because $S_2$ is almost certainly formed by recombination of smaller silicon fragments in the discharge, symmetry arguments may be relevant in formation. For example, $S_2$ and $S_3$ both possess triplet ground states, suggesting that recombination might facilitate produce triplet $S_3$; singlet $S_3$ may instead require recombination of electronically excited fragments.

C. Singlet-triplet mixing and the search for singlet fluorescence

The observation of what seems to be singlet emission following triplet excitation would appear to re-open the possibility of directly measuring the energy separation between the singlet and triplet ground states - one of the unresolved issues for the silicon trimer. On the basis of several calculations the singlet is predicted to lie approximately 1 kcal/mol below the triplet, implying that emission to the vibrationless singlet ground state might appear a few hundred cm$^{-1}$ to the blue of the laser in the triplet DF spectra. Unfortunately, with a bond angle change of $\sim17^\circ$ (Ref. 18) between the $X^3A_1^\prime$ and $1^3A_2^\prime$ states, the Franck-Condon overlap at the geometry of the intersystem crossing for such emission is highly unfavorable. The $1^1$ DF spectrum does show a feature approximately $720 \text{ cm}^{-1}$ to the blue of the laser, but this is most likely due to the presence of interfering SiH$_2$ (see Ref. 38 and also Refs. 37 and 39).

Evidence of the $\tilde{X}^1A_1^\prime$ bending mode in emission also suggests that transitions of the singlet isomer should be detectable by fluorescence, enabling more detailed study of the ground singlet surface. The $v_2$ progressions in the DF spectra are similar to the 360 cm$^{-1}$ progression assigned to $v_2$ in the matrix absorption spectrum (both extending to at least 15 quanta), implicating the $\tilde{F}^1B_1^\prime$ state in the singlet-triplet mixing. This state, which corresponds to the upper part of the conical intersection in the excited singlet manifold, is nearly degenerate with the excited triplet state at the $D_{3h}$ geometry (based on the predicted 1 kcal/mol separation between the singlet and triplet ground states, and assuming an origin transition near 525 nm). By varying the temporal delay between the tunable and ionizing radiation in R2C2PI, upper state relaxation rates of approximately 20 $\mu$s were observed both for triplet and singlet transitions in the 500–540 nm region; for the triplet transitions, no short 1 $\mu$s component, corresponding to the triplet fluorescence lifetime, was observable above the slower relaxation component, suggesting that relaxation from the singlet is the dominant process. However, searches for the singlet transitions in LIF were unsuccessful. While small Franck-Condon factors resulting from the large bond angle change make this a challenging problem, the most severe obstacle to detection is spectral contamination by $S_2$ (via the aforementioned $2^3\Pi_g \rightarrow 3^3\Pi_u$ transition$^{36}$), which is abundantly produced under the experimental conditions that optimize singlet S/N, and exhibits extensive rotational contours overlapping most of the sought-after $S_1$ transitions in this region; such contamination would be similarly problematic using an ablation source. Two-dimensional fluorescence, which has been applied to hydrocarbon discharges to extricate spectra which in 1D are obscured by $C_2$ and $C_3$,$^{40, 41}$ could prove a powerful approach to detecting the singlet.

Detection of the $C_{2v}$ isomer by LIF may also be more fruitful in the near-UV, as our calculations indicate stronger transitions in this region: in particular, the $\tilde{G}^1B_2^\prime \rightarrow \tilde{X}^1A_1^\prime$ transition,$^{16}$ which has been detected recently by R2C2PI by the Harvard group, has a calculated oscillator strength nearly an order of magnitude greater than any other transition of either isomer in the optical region. Spectral congestion from other abundant silicon species might also be less severe at these wavelengths.

VI. CONCLUSION

An optical excitation spectrum of the silicon trimer has been observed in a free jet expansion. While the $C_{2v}$ form is believed to be the lower energy isomer of $S_3$, mass-selective spectroscopic detection, laser-induced fluorescence, and $ab$ initio calculations confirm that the observed spectrum near 535 nm is dominated by the $1^3A_1^\prime \rightarrow \tilde{a}^3A_2^\prime$ transition of the $D_{3h}$ triplet isomer. Vibrational frequencies calculated for the $\tilde{a}^3A_2^\prime$ and $1^3A_1^\prime$ states are generally in good agreement with those determined from the R2C2PI and DF spectra, and from an earlier ZEKE study of the $\tilde{a}^3A_2^\prime$ state. Weak overlapping features from the $\tilde{E}^1A_1^\prime \rightarrow \tilde{X}^1A_1^\prime$ and $\tilde{F}^3B_1^\prime \rightarrow \tilde{X}^1A_1^\prime$ transitions of the $C_{2v}$ isomer are evident in R2C2PI spectra, but we have so far been unable to observe the $C_{2v}$ isomer in fluorescence. The $\tilde{X}^1A_1^\prime$-state bending mode progressions observed in emission spectra from the triplet most likely result from intersystem crossing from the upper triplet state. Follow-up studies of the $C_{2v}$ form in the vicinity of its relatively strong $\tilde{G}^1B_2^\prime \rightarrow \tilde{X}^1A_1^\prime$ transition in the near UV are now underway.

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38The strongest feature in Fig. 4 is the $1^1\Sigma^+$ band of the $A^3\Sigma^+ - X^1\Sigma^+$ transition of SiH$_2$, as reported by Ishikawa and Kajimoto. $^{39}$SiH$_2$ has harmonic bending frequencies in its $X^1\Sigma^+$ and $A^3\Sigma^+$ states of 1000 cm$^{-1}$ and 854 cm$^{-1}$, respectively. $^{37}$ Its $1^1\Sigma^+$ hot band thus occurs near 19040 cm$^{-1}$, coincident with the Si$_3^1\Sigma^+$ band, and can emit to the blue of the laser in the DF spectrum. (Levels involving the bending mode of SiH$_2$ also coincide with the Si$_3^1\Sigma^+$ level in this DF spectrum, so a Franck-Condon simulation of the Si$_3^1\Sigma^+$ DF intensities has little value.) Under slightly different expansion conditions, this hot band was extremely strong in survey LIF spectra. The observed Si$_3^1\Sigma^+$ fluorescence decay profile is characterized by a single exponential with a lifetime - about 1 ns - similar to that of SiH$_2$, so fluorescence from the latter cannot be temporally gated out. While a definitive assignment of the particular lower state involved in the blue-shifted transition is not obvious, there are several transitions of SiH$_2$ near 19750 cm$^{-1}$ that could produce the appropriate blue-shift, within the monochromator resolution. $^{39}$Moreover, no transitions of Si$_3^1\Sigma^+$ were observed when the laser was scanned with the monochromator fixed over the blue-shifted feature, and so such feature appears at the same blue-shift in DF spectra from the Si$_3$ origin and sequence bands. It thus seems unlikely that this blue-shifted feature comes from Si$_3$; in particular, it is not associated with the triplet system studied here.