

Direct evidence for ν_1 -mode excitation in the infrared multiphoton excitation of SO_2

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We investigated the infrared multiphoton excitation of SO_2 in bulk samples and in a supersonic jet with the 9R(22), 9R(32), and 9P(32) CO_2 -laser lines. Coherent anti-Stokes Raman spectra reveal unambiguously that only the ν_1 -mode at 1151.3 cm^{-1} is actually pumped; no $2\nu_2$ overtone pumping at 1035.2 cm^{-1} is observed. From the spectra we directly determine the anharmonic constants $x_{11} = -3.65 \pm 0.06 \text{ cm}^{-1}$ and $x_{12} = -3.3 \pm 0.3 \text{ cm}^{-1}$.

1. Introduction

The study of infrared multiphoton excitation of small polyatomic molecules such as SO_2 has received considerable attention in the literature [1–6]. This molecule is representative of small size systems which, according to the quasicontinuum model [7], can be difficult to excite to high vibrational levels since the density of states at low excitation is relatively small. While observation of inverse electronic excitation in SO_2 clearly demonstrated that infrared multiphoton excitation to high vibrational levels is possible [1], it is not clear from these studies through which vibrational mode(s) the excitation proceeds. Using time-resolved coherent anti-Stokes Raman spectroscopy (CARS) [8,9], we are able to directly observe the vibrational mode populations of an excited molecular ensemble and hence accurately determine which modes are excited.

The SO_2 molecule is an asymmetric top (C_{2v} symmetry) having three vibrational modes (table 1). Since the ν_1 -mode is Raman active, we can pump any infrared active mode while simultaneously observing the ν_1 CARS spectrum. For an anharmonic potential the vibrational energy levels are given by [10]

Table 1

Vibrational frequencies for SO_2 (refs. [14,15]) and CO_2 -laser lines used in this experiment

SO_2 mode	ν (cm^{-1})	Activity	CO_2 -line	ν (cm^{-1})
ν_1	1151.3	R, IR	9R(32)	1085.8
ν_2	517.6	R, IR	9R(22)	1079.8
$2\nu_2$	1035.2	IR	9P(32)	1035.5
ν_3	1361.7	R, IR		

$$E(v_1, v_2, v_3) = \sum_{i=1}^3 \omega_i(v_i + \frac{1}{2}) + \frac{1}{2} \sum_{i,j=1}^3 x_{ij}(v_i + \frac{1}{2})(v_j + \frac{1}{2}), \quad (1)$$

where v_i is the vibrational quantum number of mode i , ω_i the mode frequency, and x_{ii} and x_{ij} are the self and cross anharmonicities, respectively. For such a potential the CARS signal contains three main features: (1) a ground state peak at the resonant frequency of the Raman probed mode, (2) peaks shifted by multiples of $2x_{ii} \text{ cm}^{-1}$ from the ground state which correspond to excited levels of the Raman probed mode i , and (3) peaks shifted by multiples of $x_{ij} \text{ cm}^{-1}$ from each of the peaks in (1) and (2) corresponding to population in any other vibrational mode $j \neq i$ (see table 2 below). The intensity of each peak is proportional to the square of the population difference

between the two vibrational levels of the corresponding Raman transition [9].

Ambiguity in previous infrared multiphoton excitation experiments on SO₂ arose primarily because there is no available CO₂-laser line resonant to the ν_1 -mode. The 9R(32) line is a strong CO₂-laser line close to ν_1 -mode resonance (see table 1); the 9P(32) line is resonant with the first overtone of the ν_2 -mode; and the 9R(22) line, one of the more intense CO₂ lines in the 9 μm region, lies between these two bands (71 cm^{-1} detuned from ν_1 and 44 cm^{-1} from $2\nu_2$). Because infrared multiphoton excitation is intensity dependent for a small molecule like SO₂ [2,11], the strong 9R(22) line is historically the one most often utilized in the literature. It is not immediately clear, however, which of the two aforementioned modes undergoes infrared multiphoton excitation when this line is used.

2. Experiment and results

The experimental setup has been described previously [12]. Briefly, we use 100 ns pulses from a 10 Hz grating-tuned TEA CO₂-laser focused down to a 100 μm spot size by a 0.15 m focal length cylindrical lens to pump SO₂ (Matheson, anhydrous grade). The experiments were carried out in bulk samples at 13 kPa (100 Torr) and in a pulsed supersonic jet at variable distance x from a jet nozzle of diameter $D=0.94$ mm. Varying the distance x allows fine control of the degree of adiabatic cooling and collision rate. At $x/D=10$ the vibrational temperature is about 50 K and the collision rate about 0.1 collisions per 100 ns, the width of the excitation pulse. Close to the nozzle, at $x/D=2$, the vibrational temperature is closer to room temperature and the collision rate about 10 collisions per 100 ns. The Raman active ν_1 -mode is probed using a multiplex CARS technique [13]. The probe beams, two narrowband (0.05 cm^{-1}) at 532 nm and one broadband (100 cm^{-1}) centered at 567 nm, are phase-matched in a BOX-CARS geometry [9] aligned perpendicular to the infrared and molecular beams. The time delay between pump and probe can be adjusted electronically; the results presented here were obtained at a delay of 200 ns. The signal is dispersed by a 1 m grating spectrograph and collected with a Hamamatsu streak cam-

era, which is synchronized with the CO₂-laser (40 ns jitter) and which yields a spectrally and temporally resolved spectrum. The spectra are typically averaged over 1000 shots to improve the signal-to-noise ratio. The resulting spectra have a resolution of 0.1 cm^{-1} .

The multiplex spectrometer is extremely useful since it produces the entire ν_1 -spectrum in a single shot, revealing all excited modes, self and cross anharmonicities, and relative vibrational populations. We studied the effect of using different CO₂-laser lines on the ν_1 -spectrum in order to determine through which mode(s) the infrared multiphoton excitation proceeds.

Fig. 1 shows spectra obtained in bulk samples. In fig. 1a the large peak at 1151 cm^{-1} is the ground state peak of the unexcited molecules at the resonant frequency of the probed ν_1 -mode. Following 2 J/cm^2 pumping with the 9R(22) line, a number of excited peaks with a distinct, repeating pattern appear, see fig. 1b. The strongest of these new peaks (b) appear at positions shifted by a multiple of -7.3 cm^{-1} from the ground state peak (a). Furthermore, smaller peaks (c) are visible at a shift of -3.3 cm^{-1} from each of the peaks a and b.

Spectra obtained in a supersonic jet appear much cleaner and exhibit fewer peaks compared to the bulk data, see figs. 2 and 3. In general, excitation is less efficient in the jet than in bulk samples. Fig. 2 shows a ground state spectrum taken close to the nozzle ($x/D=2$). When the intensity scale is expanded (see fig. 3a), the thermal vibrational population of the excited states becomes visible. These peaks lie at the same spacing as before, -7.3 (b) and -3.3 cm^{-1} (c), but now only one of each type of peak is visible. Following 9R(22) excitation (fig. 3b), peak b dramatically grows and the ground state peak diminishes, while peak c is unchanged. Spectra taken far from the nozzle ($x/D=10$) show only a ground state peak. We did not observe any depletion of this peak under these circumstances, not even at the maximum available laser fluence of 2.5 J/cm^2 .

When we tuned to the 9R(32) line, which is closer to resonance with the ν_1 -mode, a maximum fluence of only 1 J/cm^2 was attainable. Yet even at this reduced fluence identical excitation to the 9R(22) data was observed in the bulk, indicating a much higher pumping efficiency at this wavelength.

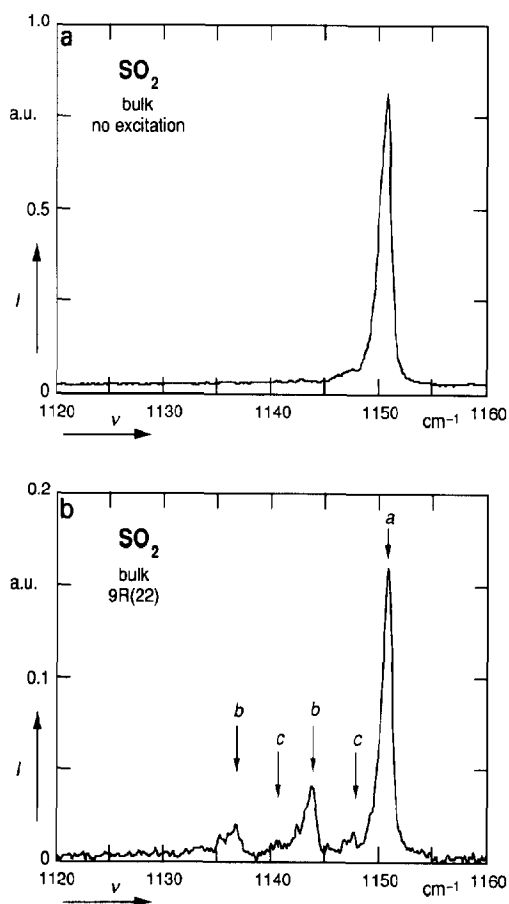


Fig. 1. Vibrational CARS spectrum of SO_2 . (a) At room temperature and a pressure of 13 kPa (100 Torr). The large peak corresponds to the ν_1 ground state. (b) At a pressure of 13 kPa (100 Torr) 1.2 μs after 2 J/cm^2 excitation with the 9R(22) CO_2 -laser line. A number of excited state peaks b and c appear.

Finally, we attempted to pump the SO_2 ν_2 first overtone band with the 9P(32) line. However, even with as much as 3 J/cm^2 of infrared fluence in bulk and beam samples no excitation beyond the thermal excitation shown in fig. 2a was observed.

3. Discussion

The above sequence of observations suggests that the CO_2 -laser excites the ν_1 -mode. This is substantiated by the higher efficiency of the 9R(32) excitation, since 9R(32) is closer to resonance with ν_1 than with $2\nu_2$, and by the fact that 9P(32), in res-

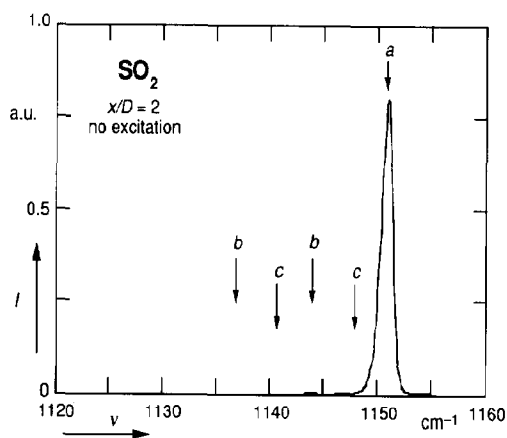


Fig. 2. Vibrational CARS spectrum of SO_2 obtained in a supersonic beam at $x/D=2$. Notice the reduced thermal population of peak c compared to fig. 1a.

onance with the $2\nu_2$ overtone, produces no observable excitation at all. There are no other overtone or combination bands in this frequency range with significant absorption [14,15]. Hence we are led to the conclusion that figs. 3a and 3b must be a direct observation of infrared multiphoton excitation in the ν_1 -mode.

Table 2 lists the anharmonic shifts of all possible peaks that might appear in the SO_2 CARS spectrum. To establish the identity of the b and c peaks we first note the absence of both peaks far from the nozzle without CO_2 -laser excitation. This proves that these peaks must be hot bands with detectable room temperature population that disappear when the ensemble is vibrationally cooled by adiabatic expansion in the jet. From the dramatic growth of the b peak in fig 3b it then follows that the b peaks correspond to the ν_1 -mode; the two b peaks in fig. 1b are the ν_1 -mode $\nu=1$ and $\nu=2$ levels. The satellite peaks c then correspond to thermal (unpumped) population in the $\nu=1$ level or another mode.

The location of the b peaks yields a value for the ν_1 self anharmonicity of $x_{11} = -3.65 \text{ cm}^{-1}$, in close agreement with published values of around -3.7 cm^{-1} (table 3). The c peaks can be assigned to the $010 \rightarrow 110$ and $110 \rightarrow 210$ Raman transitions based on their positions relative to the a and b peaks and the observation that their intensities are unaffected by IR pumping. Thus the c peaks represent thermal ν_2

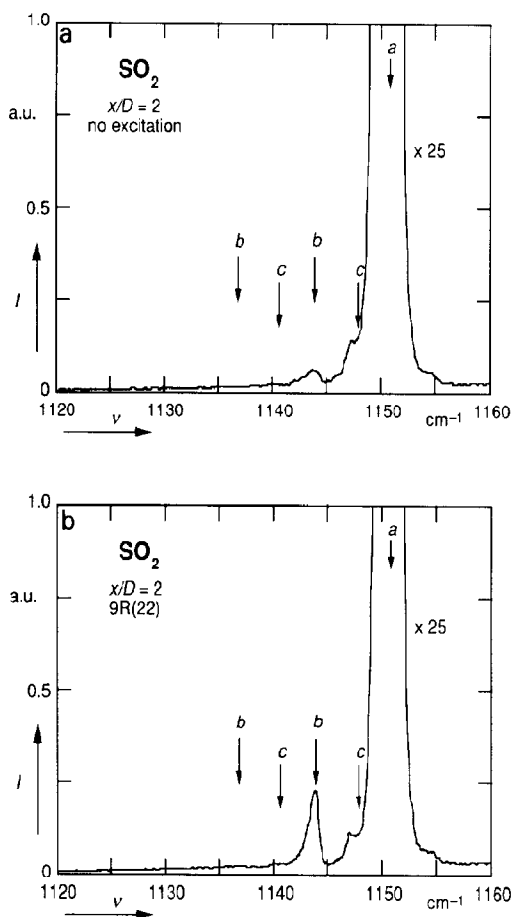


Fig. 3. (a) Same as fig. 2 with scale expanded by a factor of 25 to reveal the thermal population of the excited state peaks. (b) Vibrational CARS spectrum of SO_2 in a supersonic beam at $x/D=2$, 200 ns after 1 J/cm^2 excitation with the 9R(22) CO_2 -laser line. As a result of the excitation, peak b grows (cf. (a)).

population, and yield a value for x_{12} of $-3.3 \pm 0.3 \text{ cm}^{-1}$.

A comparison of the peak intensities in figs. 1b and 3b, after correction for the spectral profile of the broadband dye-laser, shows that the vibrational temperatures following excitation in the bulk and in the beam are roughly 1200 and 700 K, respectively. There are two possible reasons for the much less efficient excitation of the ν_1 -mode in the molecular beam. First, since the collision rate in the beam is much lower, collisionally assisted excitation may be reduced. Second, rotational cooling due to adiabatic expansion limits the spectral overlap with the CO_2 -laser line. To estimate the importance of this effect,

we first assume that SO_2 can be approximated as a prolate symmetric top molecule [10]. For such a molecule, ν_1 and $2\nu_2$ are categorized as type-B bands [10], whose infrared absorption spectra are characterized by a number of overlapping Q-branches. From the expression for the rotational energy of a symmetric top [18],

$$E_{J,K} = BJ(J+1) + (A-B)K^2, \quad (2)$$

where A and B are rotational constants related to the molecular moments of inertia, we see that the Q-branch lines ($\Delta J=0$, $\Delta K = \pm 1$) occur at frequencies given by

$$\begin{aligned} \nu &= \nu_0 + (A' - B') \pm 2(A' - B')K \\ &+ [(A' - B') - (A'' - B'')]K^2 \\ &\approx \nu_0 + (A' - B') \pm 2(A' - B')K, \end{aligned} \quad (3)$$

where the single and double primes refer to the final and initial states, respectively. Thus, the Q-branch lines are separated approximately by $2(A-B) \text{ cm}^{-1}$. For the SO_2 ν_1 -band one has $2(A-B) = 3.4 \text{ cm}^{-1}$ [15], so the 71 cm^{-1} detuning from band center for the 9R(22) CO_2 -laser line overlaps with the rotational band around $K=21$. At room temperature the rotational distribution for SO_2 peaks at $J=17$, so pumping by 9R(22) at a nominal detuning of 71 cm^{-1} is not surprising.

Far from the nozzle in a supersonic jet, after the adiabatic expansion, the rotational distribution is greatly cooled to low J -value, as evidenced by narrowing of the ground state peak in the spectrum. As a result of this, the overlap between the CO_2 -line and the rotational bands is reduced and the pumping becomes less efficient to the point where it is not observed at all.

The absence of ν_2 first overtone excitation is probably due to an extremely small cross section for this excitation [4]. While it is an allowed transition, it is not observed in absorption spectra [4], nor in collisional energy transfer experiments [19].

Finally we note that no peaks attributable to the isotopic species $^{34}\text{SO}_2$ or S^{18}O_2 and reported in the literature [5,14,15,20] were observed in our experiment. Since the intensity of the peaks in CARS spectra is proportional to the square of the density [9], the intensities of the peaks for these isotopes are reduced by the square of the corresponding abun-

Table 2

Coherent anti-Stokes Raman peaks and their anharmonic shifts for SO₂. The first three columns show the two ν_1 -mode levels involved in the CARS probe, the corresponding anharmonic shift and the literature value for this shift. The next column indicates how intensity of peak changes after IR-pumping, and the last two columns give the assignment and observed shift

CARS transition	Anharmonicity	Shift (cm ⁻¹) [16]	Observed behavior	Assignment	Observed shift (cm ⁻¹)
$lmn \rightarrow (l+1)mn$	$2lx_{11} + nx_{12} + mx_{13}$				
000→100	none	0.0	↓	a	0.0
100→200	$2x_{11}$	-7.3	↑	b	-7.3
200→300	$4x_{11}$	-14.6	↑	b	-14.6
010→110	x_{12}	-3.1	-	c	-3.3
110→210	$2x_{11} + x_{12}$	-10.4	-	c	-10.6
$l20 \rightarrow (l+1)20$	$2lx_{11} + 2x_{12}$	$-7.3l - 6.2$			

Table 3

Values of the anharmonic constants x_{11} and x_{12} in cm⁻¹ as reported in this Letter and in the literature

	This work	Ref. [10]	Ref. [17]	Ref. [15]	Ref. [16]
x_{11}	-3.65 ± 0.06	-3.99	-3.71	-3.711	-3.655
x_{12}	-3.3 ± 0.3	-2.05	-3.03	-4.236	-3.129

dance. For ³⁴SO₂, with a 4.2% abundance, for example, the ground state peak intensity will be reduced by a factor of 1.8×10^{-3} with respect to the naturally abundant isotope, ³²SO₂. Consequently these peaks are too weak to be detected using CARS.

4. Conclusion

Our results unambiguously show that 9R(22) and 9R(32) pumping of SO₂ lead to excitation of the ν_1 -mode at 1151.3 cm⁻¹. While these lines are significantly detuned from the band head, they fall near the peak of the rotational Q-branch of the ν_1 -mode at room temperature. The data presented here also illustrate the utility of the multiplex BOXCARS technique for direct observation of mode-selective excitation.

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