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Identification of Serine Conformers by Matrix-Isolation IR Spectroscopy Aided by Near-Infrared Laser Induced Conformational Change, 2D Correlation Analysis, and Quantum Mechanical Anharmonic Computations

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Abstract

The conformers of α -serine were investigated by matrix-isolation IR spectroscopy combined with NIR laser irradiation. This method, aided by 2D correlation analysis, enabled unambiguously grouping the spectral lines to individual conformers. On the basis of comparison of at least nine experimentally observed vibrational transitions of each conformer with empirically scaled (SQM) and anharmonic (GVPT2) computed IR spectra, 6 conformers were identified. In addition, the presence of at least one more conformer in Ar matrix was proved, and a short-lived conformer with a half-life of $(3.7 \pm 0.5) \cdot 10^3$ s in N₂ matrix was generated by NIR irradiation. The analysis of the NIR laser induced conversions revealed that the excitation of the stretching overtone of both the side-chain and the carboxylic OH groups can effectively promote conformational changes, but remarkably different paths were observed for the two kinds of excitations.

Keywords

amino acids; conformational analysis; photochemistry; matrix isolation; IR spectroscopy; generalized two-dimensional correlation spectroscopy; anharmonic computations

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Associated Content

MI-IR spectra recorded after deposition, MI-NIR spectra marked with the wavenumbers of the irradiation experiments, higher-wavenumber region of the differential MI-IR spectra, the two bands of the short-lived conformer measured as the function of time, computed electronic energies, geometries, SQM and anharmonic vibrational transitions and IR intensities of the 14 low-energy conformers. This material is available free of charge via the Internet at <http://pubs.acs.org>.

Notes

The authors declare no competing financial interest.

1 Introduction

In order to understand and explain the behavior of large, biologically relevant molecules, the properties of their fragments need to be well understood. The building blocks of proteins, the amino acids, are among the most thoroughly investigated small molecules. Exploring the conformational space of gas-phase amino acids can be of interest, because in several cases some conformers that on the basis of high-level quantum chemical computations are expected to be present in the gas phase, cannot be experimentally observed. Comparing the observed and the expected conformers can be very useful for understanding the conformational distribution and dynamics of larger systems.

Several amino acids have already been investigated in detail in relation to their conformational space. Among the most used experimental methods for the study of the conformational distribution of gas-phase amino acids are jet-cooled microwave (MW) and matrix-isolation infrared spectroscopy (MI-IR). The latter method has been used for the investigation of glycine,^{1–7} alanine,^{8–12} cysteine,^{13,14} leucine,¹⁵ isoleucine,¹⁶ phenylalanine,¹⁷ proline,^{18,19} tyrosine,²⁰ tryptophan,²¹ asparagine,²² lysine,²³ serine,^{24–26} β -alanine^{27,28} and β -aminoisobutyric acid.²⁹

The application of MI-IR spectroscopy for conformational studies is made possible by the fact that the conformational distribution observable at the inlet temperature is at the first glance retained during the quick freezing of the matrix. However, this does not hold when the conformational barrier between two conformers is too low ($<5 \text{ kJ mol}^{-1}$) or when a conformer can easily convert into a lower-energy conformer *via* tunneling.^{30,31,32} Flexible molecules, like amino acids often have many stable low-energy conformers of which almost all are present to some extent in the matrix. Fully anharmonic vibrational computations, including fundamental, overtones and combination bands³³ permit to simulate either low-intensity features related to non-fundamental transitions of the most abundant conformer and the fundamental transitions of the less abundant ones.^{34,35} However, the presence of several conformers often makes the spectrum very congested. The high accuracy required to distinguish between the conformers, without further information, is hardly achievable even by the state-of-the art quantum mechanical (QM) computations feasible for medium-size molecules. In order to facilitate the assignment of conformers, experiments in which the conformational ratio is shifted are often used. The conformational distribution can be changed non-selectively (e.g., by annealing the matrix,^{1,30,36} or applying broad-band UV irradiation^{4,25}) or selectively (e.g., by NIR laser irradiation^{6,7,11,12,14}). The latter method was used in the present study.

There have been both theoretical and experimental studies on the conformational distribution of serine. Unfortunately, most of the theoretical studies were performed at a low-level of theory or only took subgroups of conformers into account.^{37–39} The most detailed computational investigation was performed by Gronert and O'Hair⁴⁰ starting from all the possible combinations of single-bond rotamers of serine (a total of 324 structures). These structures were first optimized at the semiempirical AM1 level. Based on the results of this optimization, further computations were performed for 71 conformers at the HF/6-31G*

level. Finally those 51 conformers that had a relative energy difference lower than 50 kJ mol⁻¹ were reoptimized at the MP2/6-31+G* level.

Lambie et al. investigated the conformational distribution of serine using MI-IR spectroscopy.²⁴ On the basis of the computations performed by Gronert and O'Hair,⁴⁰ they optimized 12 conformers with the lowest energies at the DFT(B3LYP)/6-31++G** level. Vibrational frequencies were also computed for these conformers and scaled with the Scaled Quantum Mechanical (SQM) force field method. The four lowest energy conformers were identified experimentally. However, the assignments were not supported with experiments in which the conformational ratio was shifted.

One of the authors of the present paper and his coworkers, also used MI-IR spectroscopy for the investigation of the conformational distribution of serine.²⁵ A conformational search was performed, starting again from 324 rotamers, through geometry optimization at the HF/3-21G* level of approximation. At that level of theory, 71 conformers were identified. After reoptimization at the DFT/B3LYP/6-311++G** level of theory, 61 conformers were found. Finally, the MP2/6-311++G** level of theory was used for the optimization of the 9 lowest energy conformers. Vibrational frequencies were also computed for these conformers. Except for OH-stretching, the vibrational frequencies were scaled using a single scaling factor. In those experiments, MI-IR spectroscopy was combined with UV photolysis to change the relative abundance of the different conformers. To further support the assignments, all measurements were also carried out for 3,3-dideutero-serine. The conclusion of that study was that most likely all the 9 low-energy conformers were present in the matrix, but an unambiguous line-by-line assignment was not achieved, especially for the overlapping bands.

Alonso et al. investigated the conformers of serine using Fourier transform microwave spectroscopy.⁴¹ Serine was vaporized by laser ablation and expanded using a supersonic jet. They have performed MP2/6-31++G** computations for the 10 lowest energy conformers reported by Gronert and O'Hair.⁴⁰ The computations predicted rotational constants, nuclear quadrupole coupling parameters and electric dipole moments for these conformers. In the supersonic jet seven conformers of serine were identified (conformers 1, 2, 3, 4, 6, 7 and 10). Most likely due to collisional relaxation a few lower-energy conformers could not be identified.

The goal of the present study was to reinvestigate the conformational distribution of serine using MI-IR spectroscopy together with selective NIR-laser irradiation. As it is shown in detail below, this method, combined with 2D correlation spectroscopic analysis, enabled us to unambiguously assign the lines of a very congested MI-IR spectrum to different conformers, i.e. single conformer spectra could be deduced. On the basis of high-level QM computations, the bands experimentally assigned to the same conformer could unambiguously be ascribed to one of the computationally predicted low-energy conformers.

2 Methods

2.1 MI-IR Measurements

α -Serine (Fluka, puriss) was evaporated into the vacuum chamber using a home-built Knudsen effusion cell. The evaporated sample was mixed with argon (Messer, 99.9999%) or nitrogen (Messer, 99.999%) before deposition. The gas flow was kept at $\sim 0.07 \text{ mmol min}^{-1}$ for MIR and $\sim 0.04 \text{ mmol min}^{-1}$ for NIR measurements; the evaporation temperature was $\sim 441 \pm 5 \text{ K}$. Under the present experimental conditions, serine decomposed to ethanolamine and CO_2 to some extent. However, since the analysis of the spectra has not been focused on the spectra measured after deposition, but on both the difference spectra and the 2D correlation spectra (see Section 2.3.), the presence of ethanolamine did not make the analysis more complicated. In independent experiments, in which we have irradiated an ethanolamine:Ar matrix at the same NIR wavelengths that we used for the serine experiments, we verified that the bands of ethanolamine are not assigned to serine conformers.

The sample–rare gas mixture was deposited onto a cold (8–12 K for MIR, 12–14 K for NIR) CsI window, attached to a Janis CCS-350R cold head cooled by a CTI Cryogenics 22 closed-cycle refrigerator unit. The temperature of the cold window was controlled by a Lake Shore 321 thermostat equipped with a silicon diode thermometer. The cold window was set at 45° to the optical path of the spectrometer, and the irradiating laser beam was perpendicular to the optical path.

All MI-IR spectra were recorded by a Bruker IFS 55 spectrometer, using an MCT detector with a tungsten lamp for the $2500\text{--}8000 \text{ cm}^{-1}$ (NIR) region, and with a Globar source for the $580\text{--}4000 \text{ cm}^{-1}$ (MIR) range. The spectra were recorded at 1 cm^{-1} instrumental resolution. For the measurement of overtones, in the NIR region, at least 2000 scans were accumulated, while in the MIR spectral region spectra consisted of 1024 scans.

Conformational changes were selectively induced by an optical parametric oscillator (VersaScan MB 240 OPO, GWU/Spectra Physics) pumped with the third harmonic (355 nm) of a pulsed (10 Hz, 2–3 ns) Quanta Ray Lab 150 Nd:YAG laser (Spectra Physics). The line width of the idler (NIR) output of the OPO was about 5 cm^{-1} , and the pulse energies were 10–15 mJ. The laser beam was unfocused; its diameter was about 0.8 cm. The OPO was calibrated in preliminary experiments by optimizing for the shortest bleaching time of an irradiated species monitored by FT-IR measurements.

For the lifetime measurements of short-lived conformers (in N_2 matrix), 160 scans were recorded every 5 minutes. An LPW 3860 low pass filter was placed between the detector and the cold window to make measurements during irradiation possible.

2.2 Computational details

In the present study those 14 low-energy conformers were considered that were reported either in Ref. 24 or in Ref. 25 (see Table 1 for notations and Figure 1). Initial geometries for geometry optimizations were roughly set to the previously reported structures, and were optimized at the B3LYP42,43/6-31++G**,44–47 B3LYP-D348/SNSD33 and at the

B2PLYP49,50-D3/maug-cc-pVTZ51 (*d* functions on hydrogens have been removed) levels of theory. The optimizations were followed by second derivative calculations to determine whether the obtained stationary points correspond to minima. Harmonic vibrational frequencies and intensities were computed at the B3LYP/6-31++G** and B2PLYP-D3/maug-cc-pVTZ levels of theory. The B3LYP/6-31++G** vibrational frequencies were scaled using the SQM force field scheme^{52,53} with scaling factors determined for Ar matrix experiments by Fábri et al.⁵⁴ Anharmonic computations were performed within the hybrid B2PLYP-D3/B3LYP-D3 model³³ where B2PLYP-D3/maug-cc-pVTZ harmonic force field has been combined with cubic and semi-diagonal quartic constants obtained by numerical differentiation of the B3LYP-D3/SNSD analytical second derivatives along each active normal coordinate (with the standard 0.01 Å step) at the B3LYP-D3/SNSD geometries optimized with tight convergence criteria.

The computations beyond the double-harmonic approximation have been performed within the VPT2 approach.^{55,56} In particular, thermodynamic properties, vibrational frequencies and intensities for fundamentals, overtones and combination bands, have been obtained by a general VPT2 platform^{57–61} developed and implemented in the GAUSSIAN suite of programs for quantum chemistry by Barone and Bloino. Within the generalized VPT2 scheme (GVPT2), the nearly-resonant contributions are removed from the perturbative treatment and variationally treated in a second step.^{57,61,62} In the present work the criteria proposed by Martin et al.⁶³ have been applied for Fermi resonances along with the ones proposed by Bloino et al.^{59,60} for the 1–1 and 1–3 resonances. In computation of IR intensities resonance thresholds have been varied in order to obtain converged results.

In addition to the simulation of fully anharmonic IR spectra, the B2PLYP-D3/B3LYP-D3 force fields were employed to compute resonance-free hybrid degeneracy-corrected VPT2 (HDCPT2)⁵⁸ vibrational wavenumbers and zero point vibrational energies (ZPVE),^{57,64} which were subsequently used in the evaluation of thermodynamic properties. For the proper treatment of torsional anharmonicity, we employed a Hindered-Rotor Anharmonic Oscillator (HRAO) model, which is a generalization of the Hindered-Rotor Harmonic Oscillator approach.⁶⁵ The HRAO model automatically identifies internal rotation modes and rotating groups in the normal-mode vibrational analysis and employs an effective analytical approximation of the partition function for a one-dimensional hindered internal rotation. The contributions of the remaining modes are then computed by means of HDCPT2 coupled to the simple perturbation theory (SPT)^{58,66} approach to the partition function. In the specific case of serine, for all conformers, the three lowest energy vibrations were treated as hindered rotations.

Transition structures were located and barrier heights were determined at the B2PLYP-D3/maug-cc-pVTZ level of theory using the Synchronous Transit-Guided Quasi-Newton (STQN) method.^{67,68}

SQM computations were carried out by the PQS (Parallel Quantum Solutions) 3.369 program package. All VPT2 computations were performed employing a locally modified version of the GAUSSIAN suite of programs.⁷⁰

2.3 Difference spectra and 2D correlation analysis

For the analysis of the MIR spectra, difference spectra were computed by subtracting the spectrum recorded before from the one recorded after a certain NIR irradiation. In the case of molecules with few conformers this irradiation is usually selective, and consequently the negative bands of a difference spectrum belong to a single conformer. In contrast to this situation, for larger flexible molecules with numerous conformers, like serine, due to overlaps, the laser light can excite a number of conformers. In these cases the negative peaks of the difference spectrum belong to several conformers, making the analysis of the results more complex. In order to facilitate the sorting of the spectral bands to individual conformers, two different (i.e., Noda-type ‘generalized’ and ‘simple’) types of 2D correlation spectroscopic analysis were initially applied.

The principles of generalized 2D correlation spectroscopy were laid down by Noda, who has summarized the basics and the new developments of this method in several reviews^{71–77} and in a recent book.⁷⁸ To construct a Noda-type generalized 2D correlation spectrum, a systematic change in a parameter (e.g., pH, temperature, reaction time) is required. In our case this parameter was the irradiation time. To get the 2D correlation spectra an irradiation at a given wavelength was performed for 2 hours, and single spectra were obtained in every 5 minutes from the average of 160 interferograms. From the spectra recorded as a function of time, a 2D spectrum with a synchronous (Φ) and an asynchronous part (Ψ) can be computed according to eq. 1:

$$\Phi(\tilde{\nu}, \tilde{\nu}') + i\Psi(\tilde{\nu}, \tilde{\nu}') = \frac{1}{\pi T} \int_0^\infty \tilde{Y}_1(\omega) \cdot \tilde{Y}_2(\omega) d\omega, \quad (1)$$

where ω is the dynamic parameter, T is the total time of the NIR irradiation, $\tilde{Y}_i(\omega)$ is a Fourier-transformed spectrum:

$$\tilde{Y}_i(\omega) = \int_{-\infty}^{+\infty} \tilde{A}(\tilde{\nu}_i, t) e^{-i\omega t} dt, \quad (2)$$

where $\tilde{A}(\tilde{\nu}, t)$ is the absorbance measured at ν frequency at t time corrected by the absorbance of the reference spectrum measured at ν frequency. In the present case reference spectrum was considered to be the spectrum measured at the end of the irradiation, therefore:

$$\tilde{A}(\tilde{\nu}_i, t) = A(\tilde{\nu}_i, t) - (\tilde{\nu}_i, T). \quad (3)$$

In the synchronous spectrum the positive off-diagonal peaks belong to bands that evolve similarly upon the investigated irradiation, and therefore might belong to the same conformer. The negative peaks of the synchronous spectrum belong to starting and product conformer pairs. If the irradiation produces a conformer that also absorbs the NIR laser

photons, then its concentration has a maximum as the function of irradiation time. The bands of this conformer are expected to show off-diagonal peaks in the asynchronous spectrum with the bands of both the starting and product conformers. Furthermore, the cross peaks of the starting and the final product conformer also appear in the asynchronous spectrum.

To obtain a general view of the difference spectra, and see which bands tend to change together, a different, simple 2D correlation spectroscopic analysis was used. The construction of this 2D correlation spectrum does not require a systematic change of a parameter. The simple 2D correlation spectrum was generated from the difference spectra of the different irradiation experiments in the following manner:

$$C(\tilde{\nu}, \tilde{\nu}') = \sum_i \Delta A_i(\tilde{\nu}) \Delta A_i(\tilde{\nu}'), \quad (4)$$

where $C(\tilde{\nu}, \tilde{\nu}')$ is the amplitude of the 2D correlation spectrum at $(\tilde{\nu}, \tilde{\nu}')$, and $\Delta A_i(\tilde{\nu})$ is the signed absorbance in the i th difference spectrum at $\tilde{\nu}$. The $\Delta A_i(\tilde{\nu}) \Delta A_i(\tilde{\nu}')$ terms are summed up for all difference spectra. Although in this case there is not a parameter that is monotonously changing, this definition is mathematically equivalent to the evaluation of the synchronous part of the generalized 2D correlation spectrum. This means that there is no phase information (i.e., the asynchronous spectrum), and all irradiations are taken into account together. Thus, the simple 2D correlation spectrum provides a statistics on all the difference spectra at once. The properties of the simple 2D correlation spectrum are the same as that of Noda's synchronous 2D spectrum. For evaluation purposes, 1D cross sections of the spectrum were considered. In the diagonal cross section, each band appears that changed upon at least one irradiation. If a cross section is taken at a wavenumber belonging to a band, each band that correlates with the chosen peak appears with a positive sign, and those that anti-correlate with it appear with a negative sign. The well-separated bands that show anti-correlation cannot belong to the same conformer, while the bands that show correlation can (though not necessarily) originate from the same conformer. For overlapping bands the 2D correlation spectrum shows probabilities. The more difference spectra are included in the construction of the simple 2D correlation spectrum, the less likely bands of two different conformers show strong correlations. For plotting and evaluating the simple 2D correlation spectrum, the TopSpin 3.1 program was used.

The identification of the strong correlation peaks, either in the simple or in the generalized 2D correlation spectra, provides a good starting point for assigning the spectral bands to individual conformers. The bands with the largest intensities in the 1D cross-sections of the 2D correlation spectra were used to identify the conformers. For refining the assignments the original difference spectra were used, because these contain more information than the 2D correlation spectra. By comparing the 2D correlation spectrum sections with the individual difference spectra, the selective irradiations could be identified. If the positive bands appearing in the 2D correlation spectrum section match well the negative bands appearing in the difference spectrum, and no additional large intensity bands were found in the corresponding difference spectrum, the selected irradiation was mostly selective and the difference spectrum can be used for identifying the less intense bands of the investigated

conformer. Furthermore, the comparison of relative band intensities between two or more difference spectra allows distinguishing even between conformers that behave similarly upon the irradiation experiments, if their rates of abundance change are different in at least two irradiations (see Figures 2–4, and the Supporting Information).

3 Results and Discussion

The relative energies and relative Gibbs free-energies at the sample inlet temperature (441 K) computed within the harmonic model at the B3LYP/6-31++G** level of theory and within the anharmonic HRAO/SPT2 model at the B2PLYP-D3/maug-cc-pVTZ//B3LYP-D3/SNSD level of theory are summarized for the 14 low-energy conformers in Table 1. In this paper the conformers are denoted according to the relative energy order at the ZPVE corrected B3LYP/6-31++G** of theory. As can be seen from the Table, more advanced computations substantially lower the energy of conformers 4, 11, 13, and 14. These changes can be attributed mainly to the effects of correlation for conformers 4, 13 and 14, while dispersion contribution is the dominant factor for conformer 11 (see Supporting Information Table S1). As it was discussed in Ref. 26, the entropy contribution to Gibbs free energies is notably different for the conformers with different intramolecular H-bonds. As a result of this, the relative Gibbs free energy order at 441 K of the conformers is markedly different from the electronic energy order. Based on these results many conformers are likely to be present in an observable amount at 441 K. In addition, since many of the higher energy conformers are stabilized against conversions to lower energy conformers by intramolecular H-bonds, it is expected (and it is along the lines of former results)¹⁷ that many of these conformers remain present upon freezing into the matrix.

In line with the expectations, the MI-IR spectrum of serine is very congested. The mid-IR spectrum and the first OH-stretching overtone region of the NIR spectrum recorded in an Ar matrix are shown in the Supporting Information (Figures S1 and S2). The position of the laser line in the different NIR irradiation experiments is indicated by arrows in Figure S2. According to QM results the OH-stretching bands of several overtones are expected to overlap, for example the $2\nu_1$ of conformers 1 and 5 are predicted to differ by only 4 cm^{-1} . As mentioned above, for the analysis of the spectroscopic data difference spectra and 2D correlation were generated. The difference spectra of the most effective irradiations are illustrated in Figures 2–4.

The simple 2D correlation spectrum was generated from the difference spectra corresponding to the 6960 cm^{-1} , 6950 cm^{-1} , 6941 cm^{-1} , 7162 cm^{-1} , 7150 cm^{-1} , 7082 cm^{-1} , 6965 cm^{-1} , and 6934 cm^{-1} irradiations (see Figure 5). In addition, the difference spectra which were generated by subtracting the spectrum measured directly after the irradiation from the spectrum measured ca. 12 hours after the irradiation were also used for the generation of the simple 2D correlation spectrum, if there were significant changes in the spectrum upon waiting. Since the IR source of the spectrometer was switched on during this period, these difference spectra show the effect of a NIR laser irradiation followed by broad-band NIR irradiation. These latter difference spectra were generated from the spectra measured after irradiation at 6941 cm^{-1} , 7082 cm^{-1} and 6965 cm^{-1} .

A generalized 2D correlation spectrum was also used for the analysis. This was generated from the spectra taken during the irradiations at 6941 cm^{-1} (see Figure 5). This irradiation resulted in the most congested difference spectra and, as the analysis revealed (vide infra), almost all the identified conformers are either depleted or generated by this irradiation. Because of this, practically all the peaks appearing in the simple 2D correlation spectrum show up in the generalized 2D correlation spectrum as well. However, the simple 2D correlation spectrum contains more information, because this spectrum collects contributions from all the irradiations. In the generalized 2D correlation spectrum, all bands of the conformers, which are formed during the irradiation are in anti-correlation with bands of the irradiated conformers. In addition, all bands of the simultaneously irradiated or formed conformers correlate with themselves, while in the simple 2D correlation spectrum they might be separated.

For getting started with the conformational assignments, 1D cross-sections of the 2D correlation spectra were used. Sections were taken at each of the most characteristic carboxylic OH-stretching bands (3566.2 cm^{-1} , 3561.0 cm^{-1} and 3556.8 cm^{-1}) as well as at the characteristic non-hydrogen bonded side-chain OH-stretching bands (3658.1 cm^{-1} and 3626.2 cm^{-1}). As an example, the 1D cross section of the simple 2D correlation spectrum along the diagonal, as well as at 3566.2 cm^{-1} , are shown in Figure 6.

3.1 Identification of conformer 4

First, a 1D cross section of the simple 2D correlation spectrum was considered at 3566.2 cm^{-1} (see Figure 6). Among those peaks that correlate well with this carboxylic OH-stretching band, there are three very characteristic peaks at 860.6 cm^{-1} , 784.8 cm^{-1} and 747.5 cm^{-1} . These three well resolved bands very likely belong to conformer 4, because this is the only conformer that has predicted large intensity bands in the vicinity of these wavenumbers. This assumption is further supported by the fact that the carboxylic OH group of conformer 4 does not take part in a hydrogen bond (see Figure 1), and the peak at 3566.2 cm^{-1} is also in the non-hydrogen bonded carboxylic OH-stretching region.

By comparing the 1D cross section of the simple 2D correlation spectrum and the difference spectrum obtained by irradiation at 6960 cm^{-1} , it can be concluded that the irradiation was rather selective, because almost all of the positive peaks seen in the 1D cross section of the correlation spectrum can be observed in the difference spectrum as negative peaks. Upon analysis of the individual difference spectra, it can be observed that the intensity of the three characteristic bands (860.6 cm^{-1} , 784.8 cm^{-1} and 747.5 cm^{-1}) increased upon irradiation at 6941 cm^{-1} and 6950 cm^{-1} (see Figure 2). When identifying the bands and refining the assignments for conformer 4, typically only those bands that decreased upon irradiation at 6960 cm^{-1} and increased upon irradiation at 6941 cm^{-1} and 6950 cm^{-1} were taken into account (some of the positive bands cannot always be observed because of spectral overlap). The complete assignment of conformer 4 is provided in Table 2. The RMS deviation between the computed and the experimental wavenumbers for this conformer is 11.9 cm^{-1} and 9.6 cm^{-1} , respectively for the SQM and GVPT2 computations, which is within the expected error of these methods.

3.2 Identification of conformer 1

Among all the conformers, conformer 1 has the lowest energy and, after conformer 2, the lowest Gibbs free energy at the sample inlet temperature. Therefore, it is expected to be present in a very large amount in the matrix. The most intense bands of the spectrum likely belong to these two conformers (1 and 2). In contrast to conformer 2, the carboxylic OH group of conformer 1 is not H-bonded, thus the corresponding stretching band is expected to be in the 3550–3560 cm^{-1} region. In this region, the largest intensity band occurs at 3556.8 cm^{-1} , and the intensity of this band was found to decrease upon irradiation at 6941 cm^{-1} . Therefore, the difference spectrum obtained by this irradiation, together with a 1D cross section of the 2D correlation spectra taken at 3556.8 cm^{-1} were used for the assignment of conformer 1. As it was expected, the bands that correlate well with the band at 3556.8 cm^{-1} are among the bands with the largest intensity in the spectrum of the deposited matrix. The positions of these bands agree very well with the computed vibrational frequencies of conformer 1. Note that, as mentioned above, the irradiation at 6941 cm^{-1} was not completely selective. The carboxylic OH-stretching band at 3561.0 cm^{-1} also decreased upon this irradiation, along with the small intensity C=O-stretching band at 1754.9 cm^{-1} . As it could be seen from further irradiation experiments, the C=O-stretching band associated to the carboxylic OH-stretching band at 3561.0 cm^{-1} is observed at 1771.4 cm^{-1} , so that one can conclude that at least 3 conformers were excited simultaneously when irradiation is performed at 6941 cm^{-1} . Because of this, not all negative bands in the difference spectrum were assigned to conformer 1. The assignments for conformer 1 are shown in Table 3. The RMS deviations between the computations and experiments for this conformer are similar to those obtained for conformer 4.

3.3 Identification of conformer 5

The third band in the non-hydrogen-bonded carboxylic OH-stretching region is found at 3561.0 cm^{-1} . The intensity of this band decreased upon irradiation at 6950 cm^{-1} . It was found that each negative band that appeared in the difference spectrum of this irradiation also appeared as a negative band in the difference spectrum of the 6941 cm^{-1} irradiation. However, in the latter spectrum a few more negative bands were observed. The reason for this is that, upon the 6941 cm^{-1} irradiation, not only conformer 1, but also the conformer giving rise to the band at 3561.0 cm^{-1} , are being excited, though this latter much less effectively. In contrast to this, the irradiation at 6950 cm^{-1} was selective, since in the carboxylic OH-stretching region only the intensity of the band at 3561.0 cm^{-1} decreased. The fact that only a few extra bands appeared in the difference spectrum of the 6941 cm^{-1} irradiation can be explained by a large spectral overlap of the two conformers. Such a large spectral overlap may occur if the geometry of two conformers is very similar. Among the low-energy conformers, conformer 5 resembles conformer 1 the most. These conformers differ only in rotation of the carboxylic group (see Figure 1). According to the computations, most of the bands of these two conformers differ only by few cm^{-1} , which is comparable to the spectral linewidth in an Ar matrix. Based on these observations, conformer 5 was identified, the assignments of the experimentally observed vibrational bands of this conformer being shown in Table 4.

3.4 Identification of conformers 2 and 6

There is a band in the C=O-stretching region (at $\sim 1788\text{ cm}^{-1}$) whose intensity increased upon all the irradiations performed in the carboxylic OH-stretching overtone region. It can be presumed that this band belongs to a conformer, or conformers, in which the carboxylic OH group participates in a hydrogen bond. Since this band is quite broad, it is probable that it belongs to more than one conformer.

In order to help the identification of the conformers contributing to this band, irradiations were performed in the non-hydrogen-bonded side-chain OH-stretching overtone region, at 7150 cm^{-1} and at 7082 cm^{-1} . The intensity of the band at $\sim 1788\text{ cm}^{-1}$ decreased upon both of these irradiations. For the identification of these conformers the position of the C=O-stretching peak was also considered. Taking into account the above identified conformers and the observations for other amino acids, it can be seen that both the SQM and the GVPT2 computations underestimate the C=O-stretching wavenumber by $10\text{--}20\text{ cm}^{-1}$. According to this, only four low-energy conformers can be considered as candidates for the band at $\sim 1788\text{ cm}^{-1}$. These are conformers 2, 6, 8, and 9. Only in the case of these conformers can the C=O-stretching wavenumber be expected to be around 1790 cm^{-1} . The further identification of the conformers was based on the analysis of the fingerprint region of the difference spectra: (i) the negative bands in the difference spectrum obtained upon irradiation at 7082 cm^{-1} can be assigned to conformer 2 with very good confidence. The full assignments for conformer 2 are shown in Table 5; (ii) To decide which conformer was irradiated at 7150 cm^{-1} , the computed spectra of conformers 6, 8 and 9 were tentatively assigned to the negative bands of the difference spectrum. The geometries of conformers 6, 8 and 9 are very similar (only the conformation of the side chain is slightly different). Thus, their spectra are quite similar. Accordingly, considering the SQM computations, assignment of conformers 6 and 8 to the species to be identified gave similar, $\sim 17\text{--}19\text{ cm}^{-1}$, and the assignment to conformer 9 yielded a somewhat larger RMS error ($>20\text{ cm}^{-1}$). Not counting ν_4 , which seems have a substantial shift due to matrix effects, the RMS errors of the GVPT2 computations are 15 cm^{-1} , 19 cm^{-1} , 19 cm^{-1} for conformers 6, 8 and 9, respectively. Since for conformer 6 all large intensity bands could be assigned, and this was not the case for conformers 8 and 9, the irradiated conformer is most probably conformer 6. This is also in a good agreement with the fact that this conformer has the lowest computed Gibbs free-energy among the three forms. The assignments of the observed vibrational bands of conformer 6 are shown in Table 6.

3.5 Identification of conformer 3

After the identification of the five conformers described above, some bands whose intensity did not decrease upon any of the irradiations still remained unassigned in the spectrum of the deposited matrix. A possible explanation for this is that in the conformer which was responsible for such bands both OH groups are H-bonded, and that the irradiation of the H-bonded OH overtones is not effective. Of the 14 low-energy conformers this is true only for conformer 3. In this conformer the carboxylic OH forms a H-bond with the amino group, while the side-chain OH forms an H-bonded six-member ring with the carbonyl group. Conformer 3 has a low Gibbs free energy, so that it could be expected that its bands were present with relatively large intensity in the spectrum of the deposited matrix, and that the

conformer could be formed easily during irradiations. When assigning bands to conformer 3 it had to be taken into account that, because this conformer has only a few predicted intense bands, only its most intense bands should be observed. In consonance with these considerations, some of the positive bands appearing in the difference spectrum belonging to the irradiation at 6941 cm^{-1} were assigned to the most intense bands of conformer 3 (see Table 7).

3.6 Identification of conformers 7/10

As it was already mentioned, the irradiation of the vibrational overtone of the carboxylic OH-stretching of conformer 1, at 6941 cm^{-1} , was not completely selective. Simultaneously, conformer 5 and another conformer with a C=O-stretching band at 1754.9 cm^{-1} were also irradiated. The intensity of the latter band increases upon irradiation of conformer 5, at 6950 cm^{-1} . By taking into account the above-mentioned systematic error of the computations for the C=O-stretching fundamental wavenumber, of the 14 low-energy conformers of serine, the SQM computations predict the C=O-stretching mode at such a low wavenumber for only two conformers: at 1733 cm^{-1} , for conformer 7, and at 1734 cm^{-1} , for conformer 10. GVPT2 computations further confirm this assumption, with relative wavenumbers of 1745 cm^{-1} and 1747 cm^{-1} , for conformers 7 and 10, respectively. These two conformers have a similar geometry, with only the geometry of their side chains being different, while the relative geometry of their amino- and carboxyl groups is the same. Thus, their vibrational spectra are expected to be very similar. Both conformers have a non-hydrogen-bonded carboxylic OH group, so that their carboxylic OH-stretching overtones are expected to be near to those of the other conformers with a non-hydrogen-bonded carboxylic OH. This means that these conformers, if present, will likely be irradiated along with conformer 1, 4 or 5. According to the SQM computations, conformers 7 and 10 have one more intense band at 1123 cm^{-1} (conformer 7) and at 1129 cm^{-1} (conformer 10), with corresponding GVPT2 values of 1118 cm^{-1} and 1125 cm^{-1} , respectively. In correspondence with this, a band was observed at 1136 cm^{-1} in the experimental spectrum, whose behavior upon irradiations matches that of the band at 1754.9 cm^{-1} ; its intensity decreased upon irradiation at 6941 cm^{-1} and increased upon irradiation at 6950 cm^{-1} . Since these conformers cannot be irradiated selectively, only the two most intense bands of them can be unambiguously identified in the difference spectra. Accordingly, it can be concluded that conformer 7, maybe along with the higher-energy conformer 10, is present with a high probability in the matrix; however, based on the present information no additional band assignments could be made for these forms.

3.7 Identification of a short-lived conformer

In former studies on glycine,^{6,7} alanine,^{11,12} cysteine¹⁴ and β -aminoisobutyric acid²⁹ it was found that some of the NIR irradiations can produce short-lived high-energy conformers that decay quickly after switching off the laser. It was shown that in these conformers the carboxylic group has a *cis* (*E*) conformation and it is not stabilized by a H-bond. It was also proved that the *cis* $\rightarrow$ *trans* conversion is a tunneling process, with a half-life of few seconds for glycine and alanine in Ar and Kr matrices. In the case of these two amino acids, and also in the case of small carboxylic acids^{79–81} substantially longer lifetimes were observed for the short-lived conformers when they were generated in a N_2 matrix.

In an Ar matrix we were not able to observe any short-lived serine conformers with lifetime longer than 1–2 seconds, which is the approximate time resolution of our method. Therefore NIR irradiation experiments were carried out in a N₂ matrix to search for such species. It was found that irradiation at 6921 cm⁻¹ is the most effective at preparing a short-lived conformer of serine. In the MI-IR spectra, bands at 3587.0 cm⁻¹, 1792.8 cm⁻¹ and 1303.2 cm⁻¹ were observed, which increased after turning on the laser, and decreased after switching off the laser. These bands, especially the one at 1792.8 cm⁻¹ (see Figure 3 in the Supporting Information), somewhat overlap with nearby bands of other conformers. Nevertheless, because these other conformers were found to be stable in the dark, these three bands could in principle be used for evaluation of the half-life ($t_{1/2}$) of the short-lived conformer. Discarding the quite broad band at 3587.0 cm⁻¹, the measured absorbance ($A(t)$) of the bands at 1792.8 cm⁻¹ and 1303.2 cm⁻¹ was fitted to an exponential function

$$A(t) = A_0 \cdot \exp\left(-\frac{t}{\tau}\right) + A_\infty \quad (5)$$

to evaluate the lifetime (τ , $\tau = t_{1/2}/\ln 2$). Besides the lifetime, two other parameters were fitted: the absorbance measured when turning off the laser (A_0), and, because of the overlapping bands of stable conformers, the absorbance measured at the given wavenumber of the short-lived conformer at infinite time (A_∞). The measured absorbances as the function of time in the dark and the fitted decay curves are shown in Figure 7, and the fitted parameters are collected in Table 8. Taking into account that the lifetime depends on the quality of the matrix, we estimate the uncertainty of $t_{1/2}$ to be ~500 s, thus our best estimate for $t_{1/2}$ is $3.66 \cdot 10^3 \text{ s} \pm 5 \cdot 10^2 \text{ s}$ in a N₂ matrix. This is comparable with the half-lives of the short-lived conformers of glycine ($6.7 \cdot 10^3 \text{ s}$),⁷ alanine ($2.8 \cdot 10^3 \text{ s}$, $9 \cdot 10^2 \text{ s}$)^{11,12} and cysteine ($3.2 \cdot 10^2 \text{ s}$)¹⁴ observed in the same type of matrix. In the case of glycine it was proved both experimentally and computationally that the short-lived conformer decays by H-atom tunneling.⁷ On the basis of the analogy it is highly probably that the observed short-lived conformer of serine decays by the same mechanism. The product of this reaction is conformer 1.

Although the exact side-chain conformation of the short-lived conformer (not shown in Figure 1) cannot be determined on the basis of the three observed wavenumbers, the backbone conformation can be identified with a high probability. As it was mentioned above, it can be assumed that the carboxylic group has a *cis* (*E*) conformation, and it does not form a H-bond. For the conformer that has this backbone conformation (*i.e.*, the so-called “glycine VIp”),⁸² and the same side-chain conformation as conformer 1, SQM computations predict strong bands at 3612 cm⁻¹, 1784 cm⁻¹ and 1282 cm⁻¹, whereas two bands at 3602 cm⁻¹ and 3548 cm⁻¹, along with very strong transitions at 1794 cm⁻¹ and 1277 cm⁻¹ were computed at the GVPT2 level. These computed wavenumbers match very well the three observed bands of the short-lived conformer.

3.8 Conversion paths

As it was discussed above (and shown in Figure 2), the irradiation at 6941 cm⁻¹ resulted in the most complicated difference spectrum. The analysis of this spectrum showed that this

irradiation depleted two conformers (1 and 5) and enriched other four conformers (2, 3, 4, and 6) in the matrix. In the asynchronous spectrum of the generalized 2D correlation spectrum, strong off-diagonal peaks were found between the bands of conformers 1, 2 and 6, while the bands of conformers 3, 4 and 5 do not show up at all or show only very low intensity off-diagonal peaks with any other conformers. This suggests a sequential conversion scheme of $1 \rightarrow 6 \rightarrow 2$. The $1 \rightarrow 6$ step is induced by the NIR laser radiation, while the $6 \rightarrow 2$ step, which is much less effective, is promoted either by the broad-band NIR irradiation of the source of the spectrometer or by the heating effect of the laser.

The conversions promoted directly by the different NIR laser irradiations are summarized in Figure 8. As can be seen, the 6–7 lowest energy conformers are linked to other conformers, at least in one direction. No effective conversions were identified from conformer 3 to any other conformer, because both OH groups of this conformer are H-bonded and have only broad OH-stretching overtone bands. It is also interesting to note that not only the excitation to the first overtone of the carboxylic OH-stretching mode, but also to that of the side-chain OH-stretching mode induced effectively a conformational change. However, as it can be seen from Figure 6, the conformational changes promoted by the two different excitations are notably different. Although, on the basis of the present data, we cannot exclude that due to fast energy randomization the excitation in some extent can induce a conformation change farther from the excited group, it is more likely that the “long-range” conformational change takes place after the NIR induced conformational change. The driving force of the second step is the reorganization of the intramolecular H-bonding network.

4 Conclusions

In the present work the conformational landscape of serine was investigated by matrix-isolation IR spectroscopy. To go beyond the former matrix-isolation IR studies, NIR laser irradiation was used to change the conformer ratios. Besides this, the conformational assignment was also facilitated by 2D correlation analysis and comparison with IR spectra computed by high-level methods that include electron correlation and dispersion forces together with mechanical and electrical anharmonicity.

Although the 2D correlation spectra are not sufficient to carry out the complete conformational analysis, because some conformers that behave similarly in the irradiations can show correlations, they can efficiently help to start the analysis in complicated cases. Regarding the two different types of 2D correlation spectra, the one that we referred here as “simple” 2D correlation spectrum was found to more be useful for the conformation analysis. This is because in the synchronous part of the “generalized” 2D correlation spectrum the bands that belong to two different conformers can show strong correlations, if both conformers absorb at the wavelength of the given irradiation. In contrast to this, in the “simple” 2D correlation spectra, that constructed from difference spectra obtained by irradiations of different laser wavelengths, the amplitude of these “false” correlation peaks can be reduced, if there is an irradiation in which the two conformers behave differently. The asynchronous part of the “generalized” 2D correlation was also found to be useful. In the present case, the sequential conformational conversion of $1 \rightarrow 6 \rightarrow 2$ upon the 6941 cm^{-1} irradiation could be identified by its help. It is also important to note, that even in a case,

when all the bands of two conformers are partially overlapped, applying irradiation with slightly different wavelengths can result in difference spectra in which the bands of two conformers have different relative intensities. The careful line by line comparison of these difference spectra can be the basis of an unambiguous conformational assignment.

As a result of the analysis six conformers were identified on the basis of at least nine unambiguously assigned vibrational bands. The presence of at least one more conformer, conformer 7 and/or 10 in Ar matrix was also proved. These conformers are stable at 12 K, and all of them are present in the deposited matrix. Conformer 11 remained unobserved despite its low Gibbs energy at 441 K, which is comparable to those of the observed conformers. This can be explained with the low conformational barrier height between conformers 7 and 11, which is only 0.8 kJ mol^{-1} at the B2PLYP-D3/maug-cc-pVTZ level of theory (without zero-point vibrational energy correction). This barrier height is low enough to allow conversion even at the temperature of the matrix. Similarly to this, the low barrier height can be responsible for the lack of conformers 8 and 9. (The barrier heights between conformers 8 and 9, and between 9 and 6 are computed at the B2PLYP-D3/maug-cc-pVTZ level to be 3.1 and 3.4 kJ mol^{-1} , respectively.) It should be noted that in addition to the identified conformers some higher energy forms might also be present in a low concentrations in the matrix. It is also likely that some of the identified conformers are captured in different sites of the matrix. However, because of the complicated nature of the spectra, we did not attempt to assign all the weak bands that might belong to these species.

Compared to the previous matrix-isolation experiment of Maes et al., several bands of conformers 1–6 were reassigned. In the jet-cooled MW spectroscopic study conformers 1, 2, 3, 4, 6, 7 and 10 were observed. In addition to these conformers we could also identify conformer 5. The computed barrier height between conformers 5 and 1 is 5.6 kJ mol^{-1} at the B2PLYP-D3/maug-cc-pVTZ level. This barrier can be high enough to conserve conformer 5 in the matrix upon fast freezing, but at the same time it is low enough for an effective conformation cooling in a jet expansion. Besides the formerly observed stable conformers, a short-lived conformer that most likely decays by H-atom tunneling with a half-life of $(3.7 \pm 0.5) \cdot 10^3 \text{ s}$ in a N_2 matrix, was generated for the first time by NIR irradiation, and its structure was identified with a high probability.

The main paths of the NIR laser induced conversions were also analyzed. It was found that the excitation of the stretching overtone of both the side-chain and the carboxylic OH groups can effectively promote conformational changes, but the two kinds of excitations induced different type of conversions. Although it cannot be excluded that due to fast energy randomization the excitation can induce in some extent a conformational change farther from the excited group, it is more probable that the conformational changes far from the excited group are promoted by the reorganization of the intra-molecular H-bonding network. In order to prove this hypothesis further model molecules should to be studied by the presently used approach and also by time-resolved methods in the future. At the same time, combination of sophisticated experimental techniques with state-of-the-art quantum mechanical computations including the leading anharmonic effects for both small and large amplitude motions paves the route for comprehensive yet accurate characterization of

flexible systems with multiple low-energy minima in terms both of thermodynamic quantities and of spectroscopic signatures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
The 14 low-energy conformers of serine.

Figure 2.

Low-wavenumber region of the differential MI-IR spectra of the most effective irradiations as observed in an Ar matrix. (Only 2–6 bands of each conformer are labelled.)

Figure 3.
C=O-stretching region of the differential MI-IR spectra of the most effective irradiations as observed in an Ar matrix.

Figure 4.

The non-H-bonded OH-stretching region of the differential MI-IR spectra of the most effective irradiations as observed in an Ar matrix.

Figure 5.

Low-wavenumber region of the simple (a), as well as the synchronous (b) and the asynchronous (c) part of the generalized 2D correlation spectrum. The 2D correlation spectra were obtained the difference spectra measured in an Ar matrix, see text for details. (The intensity scales are different in the three cases.)

Figure 6. Diagonal cross section (a) and the cross section at 3566.2 cm^{-1} (b) of the simple 2D correlation spectrum. The 2D correlation spectra were obtained the difference spectra measured in an Ar matrix, see text for details.

Figure 7.

Half-life determination of the short-lived conformer in a N_2 matrix; measured absorbances at (a) 1792.8 cm^{-1} and (b) 1303.2 cm^{-1} as the function of time after switching off the laser, and the fitted decay curves.

Figure 8.

Scheme of conformational conversions promoted directly by different NIR laser irradiations in an Ar matrix. Irradiations in the region of the first overtone of the carboxylic OH-stretching: 6941 cm^{-1} (red), 6950 cm^{-1} (green), 6960 cm^{-1} (black); and in the region of the first overtone of the side-chain OH-stretching 7082 cm^{-1} (orange), and 7150 cm^{-1} (blue).

Table 1

The 14 low-energy conformers of serine with relative Gibbs free energies at 0 K and 441 K (in kJ mol⁻¹), and the correlation between the conformer notation of different publications.

Conformer notation				G°_{0K}		G°_{441K}
This work	Ref. 25	Ref. 24	Ref. 40	B3LYP/6-31++G** (Harmonic ZPVE)	B2PLYP-D3/maug-cc-pVTZ ^a (Anharmonic ZPVE)	B2PLYP-D3/maug-cc-pVTZ ^b (Anharmonic ZPVE)
1	1	1	Ia	0.00	0.00	1.48
2	2	2	IIb	0.51	0.36	0.00
3	3	3	IIc	2.16	2.96	4.41
4	4	4	I'b	3.76	2.92	6.01
5	6	5	III _a a	6.51	6.65	6.55
6	5		IIa	6.62	7.01	10.27
7	7	6	III _b b	6.73	5.08	5.72
8	8	7		6.86	7.90	12.50
9	9			7.05	6.79	12.99
10		8	III _b c	8.73	7.50	11.66
11		9	Ib	9.76	7.48	7.60
12		10	Ic	10.93	10.33	10.32
13		11		12.70	11.44	14.75
14		12		16.62	15.09	17.71

^aElectronic energy at the B2PLYP-D3/maug-cc-pVTZ level and anharmonic ZPVE correction from hybrid B2PLYP-D3/maug-cc-pVTZ//B3LYP-D3/SNSD computations.

^bElectronic energy at the B2PLYP-D3/maug-cc-pVTZ level and thermodynamic contributions computed by means of the HRAO58 model using the hybrid B2PLYP-D3/maug-cc-pVTZ//B3LYP-D3/SNSD force field, in conjunction with HDCPT258 computations and simple perturbation theory. 58,66 The three lowest vibrations have been described by hindered-rotor contributions computed by an automatic procedure.⁶⁵

Table 2Assignments of the experimentally observed vibrational transitions of conformer **4** of serine.

Experimental Ar matrix		Computed SQM		Computed GVPT2		Assignment
$\tilde{\nu}/\text{cm}^{-1}$	intensity	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	
3566.2	vs	3580	80	3577	76	ν_1
3538.6	w	3539	59	3560	49	ν_2
3426.4	w	3449	23	3451	19	ν_3
1778.4	vs	1757	293	1768	156	ν_8
1411.3	vw	1409	46	1405	7	ν_{11}
1394.9	vw	1394	33	1392	10	ν_{12}
1305.6	w	1301	33	1301	39	ν_{14}
1204.0	w	1198	22	1205	15	ν_{16}
1186.1	vw	1188	47	1187	18	ν_{17}
1137.4	s	1134	167	1137	166	ν_{18}
1107.8	vs	1091	79	1101	55	ν_{19}
1056.3	s	1050	89	1051	84	ν_{20}
899.4	vw	887	35	892	54	ν_{22}
860.6	s	868	82	849	17	ν_{23}^a
784.8	s	801	77	788	78	ν_{24}
747.5	s	736	31	745	36	ν_{25}
616.6	s	634	80	613	55	ν_{26}
586.5	w	595	122	585	6	ν_{27}
RMS		11.9		9.6		
MAE		9.8		7.0		
[MAX]		22.3		24.1		

^aThe observed and the measured intensities show a major deviation, uncertain assignment.

Table 3Assignments of the experimentally observed vibrational transitions of conformer **1** of serine.

Experimental Ar matrix		Computed SQM		Computed GVPT2		Assignment
$\tilde{\nu}/\text{cm}^{-1}$	intensity	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	
3556.8	s	3567	65	3566	54	ν_1
3540.4	w	3538	69	3554	61	ν_2
3403.6	w	3425	12	3425	8	ν_3
1773.0	vs	1753	306	1760	198	ν_8
1410.1	m	1405	66	1409	5	ν_{11}
1400.5	w	1398	15	1398	10	ν_{12}
1328.3	w	1311	54	1325	37	ν_{14}
1278.9	w	1263	10	1272	16	ν_{15}
1264.8	vw	—	—	1262	3	$\nu_{22} + \nu_{33} + \nu_{35}$
1162.8	s	1159	56	1164	12	ν_{17}^a
1149.6	s	1136	98	1138	49	ν_{18}
1105.5	vs	1095	126	1094	148	ν_{19}
1066.2	vs	1054	143	1058	93	ν_{20}
927.0	w	926	78	919	22	ν_{22}
817.5	vs	830	112	822	140	ν_{24}
721.8	w	722	28	724	14	ν_{25}
645.3	w	649	17	647	9	ν_{26}
RMS		11.7		9.1		
MAE		9.5		7.2		
[MAX]		21.9		21.4		

^aThe observed and the measured intensities show a major deviation, uncertain assignment.

Table 4

Assignments of the experimentally observed vibrational transitions of conformer **5** of serine.

Experimental Ar matrix		Computed SQM		Computed GVPT2		Assignment
$\tilde{\nu}/\text{cm}^{-1}$	intensity	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	
3561.0	s	3574	75	3568	69	ν_1
3516.9	w	3542	66	3558	49	ν_2
1771.4	vs	1756	302	1765	193	ν_8
1400.5	w	1404	69	1406	27	ν_{11}
1328.3	w	1318	41	1338	29	ν_{14}
1265.1	w	1259	29	1266	13	ν_{15}
1168.0	m	1163	33	1161	11	ν_{17}
1149.6	s	1132	197	1130	72	ν_{18}
1105.4	(s) ^a	1102	22	1110	5	ν_{19}
1073.5	vs	1055	130	1057	74	ν_{20}
932.6	s	902	114	883	68	ν_{22}
815.9	vs	806	114	794	108	ν_{24}
722.2	w	727	30	730	20	ν_{25}
645.2	w	635	50	633	32	ν_{26}
RMS		14.8		20.2		
MAE		12.5		14.9		
 MAX 		30.7		49.1		

^aThis band is very close to one of the strongest bands of conformer 1, which can contribute to the intensity of this negative band even in the difference spectrum of the 6950 cm^{-1} irradiation.

Table 5Assignments of the experimentally observed vibrational transitions of conformer **2** of serine.

Experimental Ar matrix		Computed SQM		Computed GVPT2		Assignment
$\tilde{\nu}/\text{cm}^{-1}$	intensity	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	
3626.2	s	3632	44	3642	39	ν_1
3418.6	vw	3430	17	3432	10	ν_2
3317.9	(vw) ^a	3280	283	3350	393	ν_3
1789.2	vs	1775	320	1786	174	ν_8
1400.0	s	1395	283	1387	90	ν_{11}
1385.6	w	1350	18	1372	25	ν_{12}
1344.7	m	1373	150	1351	102	ν_{13}^b
1139.7	w	1154	6	1158	6	ν_{18}
1095.4	m	1073	67	1083	34	ν_{19}
1062.4	w	1053	17	1063	13	ν_{20}
975.2	m	964	82	967	57	ν_{21}
914.5	w	922	92	913	20	ν_{22}
846.4	w	874	68	846	61	ν_{23}
RMS		20.7		13.8		
MAE		17.8		10.8		
[MAX]		37.6		32.4		

^a Broad and overlaps with the nearby band of conformer 6. Since the signs of the bands of conformers 2 and 6 are opposite in the difference spectra, this band is almost completely cancelled.

^b The observed and the measured intensities show a major deviation, uncertain assignment.

Table 6Assignments of the experimentally observed vibrational transitions of conformer **6** of serine.^a

Experimental Ar matrix		Computed SQM		Computed GVPT2		Assignment
$\tilde{\nu}/\text{cm}^{-1}$	intensity	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	
3658.1	s	3658	47	3680	41	ν_1
3406.0	m	3419	21	3421	15	ν_2
3317.6	vs	3272	288	3238 ^b	243	ν_4
1788.9	vs	1784	342	1790	114	ν_8
1376.3	vs	1389	389	1355	241	ν_{12}
1339.8	w	1344	35	1346	23	ν_{13}
1208.9	m	1209	23	1218	13	ν_{16}
1056.9	s	1079 (1032)	36 (98)	1091 (1040)	31 (58)	ν_{19} (ν_{20})
1038.3	m	1032 (–)	98 (–)	1040 (1034)	58 (34)	ν_{20} ($\nu_{34} + \nu_{24}$)
1002.8	w	1004	40	1005	18	ν_{21}
942.7	m	944	92	929	53	ν_{22}
872.8	m	877	71	867	69	ν_{23}
824.2	w	843	15	838	36	ν_{24}
815.9	m	863	61	823	36	ν_{25}
725.3	w	716	14	720	9	ν_{26}
RMS:		19.5 (20.3)		24.8 (23.7) ^b		
MAE		12.9 (13.5)		15.8 (14.9) ^b		
 MAX 		47.5 (47.5)		79.4 (79.4) ^b		

^a Alternative assignments are given in parenthesis.^b The ν_4 mode seemingly has a large matrix shift. A large matrix shift is often observed for OH- and NH-stretching modes, when these vibrations point out to the matrix. (See Ref. 54.) Without ν_4 , GVPT2 results in 14.5 (12.2), 11.2 (10.3), 34.2 (22.0) cm^{-1} RMS, MAE and |MAX| errors, respectively.

Table 7Assignments of the experimentally observed vibrational transitions of conformer **3** of serine.^a

Experimental Ar matrix		Computed SQM		Computed GVPT2		Assignment
$\tilde{\nu}/\text{cm}^{-1}$	intensity	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	$\tilde{\nu}/\text{cm}^{-1}$	$I/\text{km mol}^{-1}$	
3518.6	s	3530	137	3532	123	ν_1
3317.6	s	3304	257	3360	290	ν_3
1778.3	vs	1762	298	1765	79	ν_8
1371.4	vs	1381	479	1356	191	ν_{12}
1202.0	w	1194	25	1201	5	ν_{17}
1042.4	s	1055	111	1063	91	ν_{20}
1037.7	s	1028	50	1026	30	ν_{21}
871.1	w	872 (–)	87 (–)	828 (859)	16 (49)	$\nu_{23} (\nu_{32} + \nu_{29} b)$
832.2	s	833 (871)	142 (87)	789 (828)	86 (16)	$\nu_{24} (\nu_{23} b)$
RMS		10.6 (17.9)		27.3 (18.6)		
MAE		9.3 (15.2)		22.7 (15.0)		
 MAX 		16.3 (39.5)		43.6 (42.5)		

^a Alternative assignments are given in parenthesis.^b The observed and the measured intensities show a major deviation, uncertain assignment.

Table 8

Half-life of the short-lived conformer and parameters obtained for fitting Eq. 5 for the absorbances measured in N₂ matrix at 1792.8 cm⁻¹ and 1303.2 cm⁻¹.

Parameter	1792.8 cm ⁻¹		1303.2 cm ⁻¹	
	value	fitting error	value	fitting error
A_{∞}	$8.6 \cdot 10^{-2}$	$4.8 \cdot 10^{-4}$	$2.9 \cdot 10^{-2}$	$3.9 \cdot 10^{-4}$
A_0	$6.7 \cdot 10^{-2}$	$5.8 \cdot 10^{-4}$	$4.5 \cdot 10^{-2}$	$4.2 \cdot 10^{-4}$
τ / s	$5.38 \cdot 10^4$	$1.3 \cdot 10^2$	$5.24 \cdot 10^4$	$1.4 \cdot 10^2$