This item is the archived peer-reviewed author-version of:

FTIR and Raman spectra of derivatives of enflurane : experimental and ab initio study

Reference:

Melikova S.M., Rutkowski K.S., Telkova E., Czarnik-Matusewicz B., Rospenk M., Herrebout Wouter.- FTIR and Raman spectra of derivatives of enflurane : experimental and ab initio study

Chemical physics - ISSN 0301-0104 - (2015), p. 1-33

DOI: <http://dx.doi.org/doi:10.1016/j.chemphys.2015.03.010>

Handle: <http://hdl.handle.net/10067/1245420151162165141>

Accepted Manuscript

FTIR and Raman spectra of $\text{CH(D)FCI-CF}_2\text{-O-CHF}$ derivatives of enflurane.
Experimental and ab initio study

S.M. Melikova, K.S. Rutkowski, E. Telkova, B. Czarnik-Matusiewicz, M.
Rospenk, W. Herrebout

PII: S0301-0104(15)00087-7
DOI: <http://dx.doi.org/10.1016/j.chemphys.2015.03.010>
Reference: CHEMPH 9280

To appear in: *Chemical Physics*

Received Date: 28 January 2015

Accepted Date: 30 March 2015

Please cite this article as: S.M. Melikova, K.S. Rutkowski, E. Telkova, B. Czarnik-Matusiewicz, M. Rospenk, W. Herrebout, FTIR and Raman spectra of $\text{CH(D)FCI-CF}_2\text{-O-CHF}$ derivatives of enflurane. Experimental and ab initio study, *Chemical Physics* (2015), doi: <http://dx.doi.org/10.1016/j.chemphys.2015.03.010>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

**FTIR and Raman spectra of CH(D)FCI–CF₂–O–CHF derivatives of enflurane.
Experimental and ab initio study.**

S.M. Melikova^a, K.S. Rutkowski^{a}, E.Telkova^a, B.Czarnik-Matusewicz^b, M. Rospenk^b, W. Herrebout^c*

^a*Department of Physics, Saint-Petersburg State University, Ulianovskaja 3,
198504 St.Petersburg, Russia*

^b*Faculty of Chemistry, University of Wroclaw, Joliot Curie 14, 50-383 Wroclaw, Poland*

^c*Department of Chemistry, University of Antwerp, Groenenborgelaan 171, B-2020, Antwerp,
Belgium.*

Graphical contents entry:

Vibrational bands ascribed to the same mode of 3 conformers (*a*, *b*, *c*) are resolved in few characteristic regions of IR and Raman spectra of enflurane.

Abstract

The vibrational spectra of two H/D derivatives of enflurane are studied with the help of FTIR cryospectroscopy in liquefied Kr and Raman spectroscopy of pure liquid. The majority of fundamental bands are identified. Using MP2/6-311++G(df,pd) calculations the six local minima are found on the potential energy surface and ascribed to the most stable conformers of enflurane. The vibrational frequencies, infrared intensities, and Raman activities are found at the same level of theory. The potential energy distribution is calculated for the most stable conformer. Assignment of the vibrational bands registered is performed using the results of calculations of the frequencies with “anharm” option implemented in Gaussian. The model IR and Raman spectra built with the help of data of ab initio calculations reflect the basic features of experimental spectra. IR spectra of cryosolutions of enflurane and acetone in liquefied Kr suggest weak complex formation stabilized by “blue shifting” H bonds.

* – Corresponding author: K. S. Rutkowski – e-mail: rutkowski@molsp.phys.spbu.ru

Keywords

Enflurane, IR and Raman spectra, liquefied Kr, anharmonicity, ab initio calculations, conformation, H bond.

1. Introduction

The importance of weak intermolecular interactions involving so called CH donors in chemical and biochemical applications is commonly recognized. The widest class of such donors belongs to multiply halogenated alkanes. Some of them, e.g. CHF₃ and CHCl₃ can form H – bonds with unusual spectroscopic and geometric features [1-11]. Modern volatile anesthetics possess at least one CH group which might participate in weak noncovalent intermolecular interactions. Recent experimental and theoretical studies have clearly shown that such general anesthetic as halothane (CHClBrCF₃) participates in complex formation stabilized by weak H – bond of CH...B (B=O, N, F) or CH... π type [12-14].

The consideration of preferable possible paths of intermolecular H – bond formation becomes more complicated in the case of such anesthetics as halogenated derivatives of ethers having two CH groups. Enflurane (CHFCl-CF₂-O-CHF₂) is typical example. As other compounds having asymmetric carbon atoms, it is synthesized and used as a racemic mixture of the *R* and *S* enantiomers. As a result, such a natural mixture is optically inactive and only conventional IR and Raman spectra might be studied. The spatial geometry of enflurane, specifically various orientation of three single bonds in the C – C – O – C skeleton, suggest possible existence at least of different 27 conformational forms. This might result in rich vibrational spectrum of enflurane, with numerous bands assigned to the same normal vibration. In the earlier study based on ab initio MP2/6-311G(2d) calculations, the most stable four conformers were postulated [15]. Qualitatively analogous conclusion was made by the help of comparison of experimental IR spectra of enflurane dissolved in CCl₄ with results of DFT calculations on B3LYP/6-31G(d) level [16]. Meanwhile results of gas electron diffraction were reproduced best considering a mixture of three conformers [15].

Due to nonequivalent electron withdrawing properties of neighbor F and Cl atoms the two CH groups located at opposite parts of enflurane can act as proton donors of different energetic and spectroscopic properties. Recent results on theoretical studies and room temperature spectroscopic measurements performed for enflurane + acetone system confirm the mentioned feature of CH groups [17]. The blue shift and different change of the intensity of CH stretching vibration localized on the CHFCl and CHF₂ groups have been interpreted considering the geometric features of the dipole moment function [18, 19]. However the bands registered at room temperature in pure liquid enflurane or in concentrated solution in conventional CCl₄ solvent are noticeably broadened or sometimes unresolved at all. Additionally interpretation of the IR spectra can be complicated due self association of nearly placed molecules.

The present study revisits a comprehensive consideration of enflurane both by the method of cryospectroscopy and by a set of ab initio MP2 calculations utilizing the Pople-type 6-311++G(df,pd) basis set. The IR spectra of enflurane dissolved in liquefied Kr ($T \sim 120 - 155$ K) have been registered. The frequency range amounts c.a. $800 - 7500 \text{ cm}^{-1}$. Additionally to the IR cryosolution measurements, Raman spectra of liquid enflurane have been measured at room temperature in the range c.a. $150 - 3500 \text{ cm}^{-1}$. To get better interpretation in particular parts of vibrational spectra of enflurane, the derivative of enflurane with H/D exchange at the chlorofluoromethyl carbon was also synthesized and used. The deepest 6 real minima, having close values of energy, were found on the potential energy surface (PES).

The experimental spectra have been compared with the theoretical spectra to assign the bands registered. Relative contributions from the most stable conformers of enflurane were taken into account in this simulation.

2. Experimental and computational methods

The IR spectra of enflurane were registered using Nicolet Nexus and Nicolet - 6700 FTIR spectrometers, in the range $\sim 800 - 7500 \text{ cm}^{-1}$ with a resolution of $0.2 - 0.5 \text{ cm}^{-1}$. The number of scans was varied between 100 and 300. Liquefied Kr was used as an inert solvent in which the solubility of enflurane was relatively good. Measurements have been performed at $T \sim 120 - 155$ K. A homemade cryostat was equipped by a stainless-steel cell of 5 cm optical length. BaF_2 windows were sealed by indium gaskets. The temperature was monitored both by Cu/Constantan thermocouple attached to the body of the cell, and by measuring the vapor pressure over the liquid solutions. The accuracy of temperature measuring was believed better than 3 K. The concentration of enflurane was kept in the range of $\sim 10^{17} - 10^{18} \text{ molecules/cm}^3$.

Raman spectra of pure liquid enflurane were recorded in $50 - 3500 \text{ cm}^{-1}$ spectral range with a resolution of 2.5 cm^{-1} using FT Raman Bruker Multiram unit equipped by LN_2 - cooled germanium detector. The number of scans amounts 1024. The excitation of the sample was performed by CW Nd:YAG laser at 200 mW and frequency $\sim 9394 \text{ cm}^{-1}$. The 180° backscattering geometry/collection optics has been used for collection the scattered radiation. The spectra were measured at room temperature.

The H/D exchange at the chlorofluoromethyl carbon of enflurane has been performed according the reaction described in ref. [20]. Shortly, heating the mixture of enflurane and $\sim 0.4 \text{ M}$ of NaOD to reflux for $\sim 20 - 24$ hours resulted in c.a. $70 - 85 \%$ exchange at the chlorofluoromethyl carbon. This result is quite satisfactory for spectroscopic measuring and assignments of selected bands.

Theoretical calculations were performed using the GAUSSIAN 09 Rev. C.01 [21]. The local minima were searched by relaxed potential energy surface (PES) scan calculations with geometry optimization at each point. The step of 2° has been chosen for these scans. In accordance with the spatial geometry of enflurane (HFCIC-CFF-O-CFFH), the scans over each of three

dihedral angles were selected on the final stage of local minima searching. One angle was defined by four atoms of skeleton (C – C – O – C). Other two were built substituting one of the end (terminal) C atoms by Cl or H atom. All the local minima found were fully optimized using ab initio second order Møller-Plesset perturbation (MP2) frozen core method [22] with the Pople-type 6-311++G(df,pd) basis set. The basis set has been chosen as a compromise between the accuracy of calculations and the available computing resources. The conformations were characterized as these local minima having all real (positive) frequencies. The harmonic frequencies were calculated first. Relative contribution of separate internal coordinates to the normal modes of enflurane has been evaluated using results of potential energy distribution (PED) calculations. PED was calculated according to ref. [23]. The PED values were close to those obtained with the help of the conventional GAR2PED program. They were also controlled by visual inspection for each vibrations using Gaussian view. The procedure of the normal coordinate analysis was analogous to that described in ref. [24]. To improve the comparison procedure between experimental and calculated spectra of enflurane, the final spectroscopic parameters have been calculated using the option “anharm”.

3. Results of measurements.

Figure 1 (top panel) displays the IR spectrum of diluted solution of enflurane HH ($\text{CHFCl}-\text{CF}_2-\text{O}-\text{CHF}_2$) in liquid Kr in the region $\sim 800 - 3200 \text{ cm}^{-1}$. The two weak bands near 3000 cm^{-1} are scaled by a factor of 10 for convenience. They correspond to CH stretching vibrations ν_1 and ν_2 . Wholly overlapped bands situated near $\sim 1100 - 1200 \text{ cm}^{-1}$ correspond to CF stretching vibrations. They might be noticeably modified by the transition dipole – transition dipole interactions of nearly placed molecules in the case of higher concentrations or liquid enflurane [25]. The region of overtone bands was considered in the previous paper [19]. The IR spectrum of enflurane HD ($\text{CDFCl}-\text{CF}_2-\text{O}-\text{CHF}_2$) is shown on top panel of Figure 2. The high frequency CH stretch ν_1 remains at the same position. Naturally, it relates to CH of CHF_2 group. The low frequency CH stretch ν_2 is expected to be appeared in the region of $\sim 2200 - 2300 \text{ cm}^{-1}$. However it is hardly detected, because it is hidden between numerous combination bands of comparable strength. At last, it is worth noting the broadening temperature effect for all the bands registered.

Raman spectra of liquid enflurane HH and enflurane HD have been measured at room temperature. Because Raman scattering activity S_i (in $\text{\AA}^4/\text{amu}$) is the result of ab initio calculations, the measured scattering cross section $\left(\frac{\partial\sigma}{\partial\Omega}\right)_\nu$ has been used to obtain the experimental scattering activity coefficient [26, 27]:

$$S_{exp} \sim \left(\frac{\partial\sigma}{\partial\Omega}\right)_\nu \frac{\nu(1-\exp(-h\nu/kT))}{(\nu_0-\nu)^4} \quad (1)$$

Where $\nu_0 \sim 9394 \text{ cm}^{-1}$ is the wavenumber of excitation laser. The results are presented on top panels of Figures 3 and 4 respectively.

Despite the IR spectrum where the detection of band ν_2 is unsuccessful, this CD stretch localized on CDFCl group is registered at $\sim 2247 \text{ cm}^{-1}$ as a band of middle strength. Previous IR studies performed in pure liquid and in concentrated solutions in conventional CCl_4 solvent have shown that enflurane might form dimers and higher associates [16, 17]. This conclusion was made analyzing the region of these CH stretch bands. In the case of Raman spectrum of liquid enflurane, it is reasonable to suppose that it consists of fundamental bands of monomeric species predominantly. The most valuable information, obtained from the Raman spectra refers to the vibrational bands of enflurane below $\sim 800 \text{ cm}^{-1}$.

4. Results of calculations and discussion.

Figure 5 presents six conformers which correspond to the deepest (real) local minima found in the course of scan calculations over dihedral angles χ_1 ($\text{Cl}_2 - \text{C}_1 - \text{C}_5 - \text{O}_8$) – Figure 6, χ_2 ($\text{H}_{10} - \text{C}_9 - \text{O}_8 - \text{C}_5$) – Figure 7, and χ_3 ($\text{C}_1 - \text{C}_5 - \text{O}_8 - \text{C}_9$). The conformers are denoted as a , b , c going from largest to the smallest dihedral angle χ_1 (see Figure 6). This corresponds to rotation of $\text{C}_1\text{Cl}_2\text{F}_3\text{H}_4$ group around the $\text{C}_1 - \text{C}_5$ axis predominantly. Subscript 1 or 2 refers to a negative or positive value of χ_2 (see Figure 7). It is rotation of $\text{C}_9\text{H}_{10}\text{F}_{11}\text{F}_{12}$ group around the $\text{C}_9 - \text{O}_8$ axis. Figure 7 clearly shows that the barrier between 1 and 2 conformers is very small. Nevertheless all the 6 minima are characterized by real (positive) frequencies. Selected geometric parameters are collected in Table 1. The lowest minimum corresponds to conformer a_2 . Conformer a_1 has a little bit higher energy. However, the thermodynamic analysis based on ab initio calculations shows the conformer a_1 is the most populated in the temperature range of our measurements. Conformer b_2 is situated higher than the conformer a_2 by about 113 cm^{-1} . The rests are placed between those.

The calculated spectroscopic parameters and the potential energy distribution (PED) of conformer a_1 are presented in Table 2 for enflurane HH and in Table 3 for enflurane HD. Additionally to harmonic also anharmonic frequencies are reported. In this work we restricted the anharmonic calculations to those, implemented in GAUSSIAN 09 Rev. C.01 program. Considering a numerous set of Fermi resonances which are omitted in this program, could give additional correction for frequencies, intensities and Raman activities. Generally, results of the present PED analysis are compatible with those performed in earlier work [16]. The serious disagreement is found only in the case of ν_4 and ν_5 vibrations. Our data obtained at noticeably higher level of theory are additionally confirmed by comparative analysis of PED for enflurane HH and enflurane HD. It should be noted, that vibrations ν_1 , ν_2 , ν_3 , have the same PED for both isotopic forms of enflurane. Whereas PED is noticeably different in the case of modes with atom D engaged. At last the difference practically disappears for low frequency vibrations in which heavy atoms and atoms of skeleton are participated. The spectroscopic parameters calculated for all the six conformers are given in Supporting Information section (Table 1S).

The calculated spectra have been drawn taking into account relative populations P_i of the six conformers, found in ab initio MP2/6-311++G(df,pd) calculations:

$$P_i = \frac{\exp(-\Delta G_i / kT)}{\sum_i \exp(-\Delta G_i / kT)} \quad (2)$$

where $\Delta G_i = G_i - G_0$ – the difference between the Gibbs Free Energy of i^{th} conformer and the Gibbs Free Energy of the most stable conformer a_1 . Results of these calculations are presented in Supporting Information section (Tables 2S, 3S). The profiles of the majority of bands of heavy tops registered in low temperature inert solvent are close to the Lorentz [28, 29]. Thus, the bands of each conformer were modeled by the Lorentz profile:

$$L_j(\nu - \nu_{0j}) = \frac{\Gamma_j}{\pi} \cdot \frac{1}{(\nu - \nu_{0j})^2 + \Gamma_j^2} \quad (3a)$$

$$I_i(\nu) = \sum_j I_j L_j(\nu - \nu_{0j}) \quad (3b)$$

where j is the number of a band, Γ_j – is the half width at the half maximum, ν_{0j} – is the origin of the band, I_j – is IR intensity A_j (km/mol) or Raman activity S_j ($\text{\AA}^4/\text{amu}$). Then, taking into account all the conformers the whole spectrum can be obtained as:

$$I(\nu) = \sum_i P_i \cdot I_i(\nu) \quad (4)$$

Because of very small barrier between conformers 1 and 2 ($\leq 10 \text{ cm}^{-1}$, see Fig. 7), it is reasonable to simplify the consideration. As a rough approximation, we use the mean weighted spectrum of these forms, including their populations. Together with experimental frequencies, the results of such evaluations are given in Tables 4, 5, 6 and 7. The final spectra are reproduced on bottom panels of Figures 1, 2, 3 and 4. They are obtained with the following values of width (Γ): 5 cm^{-1} for CH stretch, 2 cm^{-1} for other bands at $T = 120 \text{ K}$, and 10 cm^{-1} for CH stretch, 5 cm^{-1} for other bands at $T = 295 \text{ K}$. So that, the widths of particular bands in the simulated IR and Raman spectra and the widths of respective bands in the experimental spectra are comparable. Temperature measurements performed in liquid Kr at $T \sim 120 - 160 \text{ K}$ did not reveal qualitative changes in IR spectrum of enflurane, except for quite observable broadening of all the bands registered.

Assignment of experimental bands has been performed with the help of comparison the measured and calculated spectra. The vibrational bands are numbered, as commonly accepted from high frequency CH stretch to low frequency ones (see Figures 1, 2, 3, and 4). It should be recognized that the majority of the bands which belong to different conformers are strongly overlapped. However, there are few regions, where the bands ascribed to conformers a , b , c can be resolved. These are: ν_{13} , ν_{15} (Figure 1), ν_{15} , ν_{16} (Figure 3) for enflurane HH, and ν_{14} (Figure 2), ν_{14} , ν_{16} (Figure 4) for enflurane HD.

Finally, probe experiments performed for two component solutions of enflurane and acetone in liquid Kr have confirmed the possible participation of atoms H of both CHFCl and CHF₂ groups in hydrogen bond formation recently suggested [17]. The characteristic example is presented in Figure 8. Complex formation results in the blue shift effect, which is stronger in the case of atom H of CHF₂ group. Namely $\Delta\nu_1^{c-m} \sim +22 \text{ cm}^{-1}$, $\Delta\nu_2^{c-m} \sim +11 \text{ cm}^{-1}$. However the intensity of respective CH stretch band ν_2 is noticeably larger in the case of more “acidic” hydrogen of CHFCl group. The effect is compatible with the feature of the dipole moment function [18, 19]. In the case of high frequency CH stretch ν_1 the dominative component of the first derivative of the dipole moment is directed along the CH bond and is negative. It is worth noting incomplete cancellation of ν_1^m band after subtraction procedure (bottom band on Figure 8). This is due to slight change of the frequency of this band in the case of interaction of acetone with more “acidic” atom H of CHFCl group. Ab initio calculations confirm this experimental result.

5. Conclusions

The IR spectrum of diluted solutions (10^{17} – 10^{18} molecules/cm³) of enflurane HH (CHFCl–CF₂–O–CHF₂) and enflurane HD (CDFCl–CF₂–O–CHF₂) in liquefied Kr is obtained and analyzed in the range c.a. 800 – 4000 cm⁻¹. Additionally the Raman spectrum of liquid enflurane is measured at room temperature.

The ab initio calculations, performed at MP2/6-311++G(df,pd) level predict 6 most stable conformers of enflurane. They differ by two dihedral angles: χ_1 (Cl₂ – C₁ – C₅ – O₈) and χ_2 (H₁₀ – C₉ – O₈ – C₅). The barrier between pairs of conformers, differing by dihedral angle χ_2 is very small ($\leq 10 \text{ cm}^{-1}$). This result suggests that only three conformers might be experimentally detected, as it was done in the work on gas electron diffraction studies [15].

The vibrational frequencies are calculated at the same level using “anharm” option in Gaussian. Infrared intensity and Raman scattering activity are also obtained for all the conformers found. PED is calculated for the most stable conformer of enflurane. The results obtained for normal vibrations of enflurane HH are similar to the data obtained earlier at noticeably lower level of theory [16]. The exception concerns the ν_4 and ν_5 vibrations for which the serious disagreement has been revealed.

The majority of vibrational bands of different conformers are strongly overlapped. However, there are few characteristic regions in IR and Raman spectra of H/D substituted enflurane, where the bands ascribed to three conformers can be resolved.

Both atoms H of CHFCl and CHF₂ groups of enflurane can participate in H bond formation characterized by blue shifting effect in the case of interactions with acetone.

Acknowledgements

The work was supported by the RFBR N° 14-03-00716, National Science Centre for research funding N° 2012/05/B/ST/02029 and Saint-Petersburg State University (grant 11.38.265.2014). The calculations have been performed using the computer resources of the Resource Center of SPbGU (<http://cc.spbu.ru>) and of the Wrocław Center for Networking and Supercomputing (<http://www.wcss.wroc.pl>). The spectroscopic measurements were partly performed on the apparatus of the Resource Center Geomodel of SPbGU.

References

- [1] B.J. van der Veken, W.A. Herrebout, R. Szostak, D.N. Shchepkin, Z. Havlas, P. Hobza, J. Am. Chem. Soc. 123 (2001) 12290-12293.
- [2] Y. Gu, T. Kar, S. Scheiner, J. Am. Chem. Soc. 121 (1999) 9411-9422.
- [3] W. Qian, S. Krimm, J. Phys. Chem. A 106 (2002) 11663-11671.
- [4] K. Hermansson, J. Phys. Chem. A 106 (2002) 4695-4702.
- [5] S.M. Melikova, K.S. Rutkowski, P. Rodziewicz, A. Koll, Chem. Phys. Lett. 352 (2002), 301-310.
- [6] A. Karpfen, E.S. Kryachko, J. Phys. Chem. A 107 (2003) 9724-9789.
- [7] E.S. Kryachko, A. Karpfen, Chem. Phys. 329 (2006) 313-328.
- [8] S. Scheiner, T. Kar, J. Phys. Chem. A 112 (2008) 11854-11860.
- [9] S.A. McDowell, Chem. Phys. Lett. 424 (2006) 239-242.
- [10] P. Rodziewicz, K.S. Rutkowski, S.M. Melikova, A. Koll, ChemPhysChem 6 (2005) 1282-1292.
- [11] K.S. Rutkowski, S.M. Melikova, P. Rodziewicz, W.A. Herrebout, B.J. Van der Veken, A. Koll, J. Mol. Struct. 880 (2008) 64-68.
- [12] B. Czarnik-Matusewicz, D. Michalska, C. Sandorfy, Th. Zeegers-Huyskens, Chem. Phys. 322 (2006) 331-342.
- [13] B. Michelsen, W.A. Herrebout, B.J. van der Veken, ChemPhysChem. 9 (2008) 1693-1701.
- [14] B. Michelsen, J.J.J. Dom, B.J. van der Veken, S. Hesse, Z. Xue, M.A. Suhm, W.A. Herrebout, Phys. Chem. Chem. Phys. 12 (2010) 14034-14044.
- [15] A. Pfeiffer, H.G. Mack, H. Oberhammer, J. Am. Chem. Soc. 120 (1998) 6384-6388.
- [16] D. Michalska, D.C. Bienko, B. Czarnik-Matusewicz, M. Wierzejewska, C. Sandorfy, Th. Zeegers-Huyskens, J. Phys. Chem. B 111 (2007) 12228-12238.
- [17] W. Zierkiewicz, B. Czarnik-Matusewicz, D. Michalska, J. Phys. Chem. A 115 (2011) 11362-11368.
- [18] W. Zierkiewicz, R. Zalesny, P. Hobza, Phys. Chem. Chem. Phys. 15 (2013) 6001-6007.
- [19] S.M. Melikova, K.S. Rutkowski, B. Czarnik-Matusewicz, M. Rospenk, Chem. Phys. Lett. 604 (2014) 68-71.
- [20] T.R. Burke Jr., L.R. Pohl, Journal of Labeled Compound and Radiopharmaceuticals. 18 (1981) 663-670.
- [21] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, and D. J. Fox, Gaussian 09, Revision C.01. Gaussian, Inc., Wallingford CT, 2010.
- [22] C. Møller and M.S. Plesset, Phys. Rev. 46 (1934) 618-622.
- [23] M.H. Jamróz, Spectrochimica Acta 114 (2013) 220-230.

- [24] M.J. Nowak, L. Lopinski, D.C. Bienko, D. Michalska, *Spectrochimica Acta A* 53 (1997) 855-865.
- [25] A.V.Cherevatova, T.D.Kolomiitsova, D.N.Shchepkin, K.G.Tokhadze, Z.Mielke, S.Coussan, P.Roubin, *J. Mol. Spectrosc.* 238 (2006) 64-71.
- [26] G. Placzek. Rayleigh Streuung und Raman - Effekt / *Handbuch der Radiologie* / Ed. by E. Marx. - Leipzig: Akademische Verlagsgesellschaft M.B.H., 1934. - Bd.6, T.2. - P.205-374.
- [27] D. Michalska, R. Wysokinski, *Chem. Phys. Lett.* 403 (2005) 211-217.
- [28] V.A. Kondaurov, S.M. Melikova, D.N. Shchepkin, *Opt. Spectrosc.* 56 (1984) 1020-1025 (Rus).
- [29] K.S Rutkowski., S.M. Melikova, D.N. Shchepkin, *Vibr. Spectrosc.* 24 (2000) 277-286.

Table 1. MP2/6-311++G(df,pd) predicted geometric parameters of the most stable conformers of enflurane.

	a_1	a_2	b_1	b_2	c_1	c_2
χ_1 (Cl ₂ -C ₁ -C ₅ -O ₈), deg	-62.25	-63.86	-178.08	-179.10	-298.72	-299.69
χ_2 , (H ₁₀ -C ₉ -O ₈ -C ₅), deg	-16.47	17.54	-16.69	12.99	-19.85	17.89
χ_3 , (C ₁ -C ₅ -O ₈ -C ₉), deg	186.14	175.57	185.45	176.84	184.17	173.10
r (C ₁ -H ₄), Å	1.0905	1.0906	1.0906	1.0906	1.0913	1.0914
r (C ₁ -Cl ₂), Å	1.7460	1.7457	1.7483	1.7483	1.7461	1.7462
r (C ₁ -F ₃), Å	1.3482	1.3484	1.3458	1.3459	1.3464	1.3461
r (C ₉ -H ₁₀), Å	1.0904	1.0906	1.0907	1.0904	1.0908	1.0908
r (C ₉ -F ₁₂), Å	1.3280	1.3288	1.3290	1.3283	1.3275	1.3281
r (C ₉ -F ₁₁), Å	1.3338	1.3325	1.3321	1.3337	1.3337	1.3328
ΔE_{el} , cm ⁻¹	0	-6.6	93.8	106.6	39.1	45

Table 2. Calculated (MP2/6-311++G(df,pd)) harmonic (ω), anharmonic (ν) frequencies, IR intensities (A), Raman activities (S) and potential energy distribution (PED) for a_1 conformer of enflurane-HH.

N ^o	ω , cm ⁻¹	ν , cm ⁻¹	A , km/mol	S , Å ⁴ /amu	PED
1	3172	3075	14	45	$\nu_{C_9H_{10}}$ (100)
2	3162	3045	5.4	64	$\nu_{C_1H_4}$ (100)
3	1472	1436	39	2.4	$\beta_{H_{10}C_9O_8}$ (83)
4	1427	1393	78	2.5	$\beta_{H_4C_1C_5}$ (33), $\nu_{C_1C_5}$ (26), $\beta_{H_{10}C_9O_8}$ (10)
5	1413	1385	53	2.1	$\gamma_{H_{10}C_9O_8}$ (87)
6	1349	1323	24	2.9	$\gamma_{H_4C_1C_5}$ (82)
7	1327	1297	122	3.0	$\beta_{H_4C_1C_5}$ (38), $\nu_{C_5F_7}$ (22), $\nu_{C_1C_5}$ (10)
8	1269	1238	234	1.1	$\nu_{C_5O_8}$ (54), $\nu_{C_5F_6}$ (11)
9	1226	1200	330	1.9	$\nu_{C_9F_{12}}$ (62), $\gamma_{F_{12}C_9O_8}$ (10)
10	1188	1163	531	2.5	$\nu_{C_9F_{11}}$ (57), $\gamma_{F_{12}C_9O_8}$ (10)
11	1183	1156	150	2.7	$\nu_{C_1F_3}$ (29), $\nu_{C_5F_6}$ (17), $\nu_{C_9O_8}$ (11)
12	1168	1143	117	2.5	$\nu_{C_1F_3}$ (43), $\nu_{asC_5F_6F_7}$ (28), $\beta_{H_4C_1C_5}$ (10)
13	1100	1075	124	3.8	$\nu_{C_9O_8}$ (58), $\nu_{C_1F_3}$ (11)
14	932	914	63	1.5	$\nu_{sC_5F_6F_7}$ (34), $\nu_{C_1Cl_2}$ (29), $\nu_{C_1C_5}$ (11)
15	876	861	59	7.2	$\nu_{C_1Cl_2}$ (30), $\nu_{C_5F_7}$ (15), $\beta_{F_6C_5C_1}$ (12)
16	797	786	53	2.4	$\beta_{C_1C_5F_7}$, $\gamma_{F_3C_1C_5}$ (13), $\beta_{F_3C_1C_5}$ (12)
17	670	662	0.9	2.5	$\gamma_{F_{12}C_9O_8}$ (17), $\beta_{F_7C_5O_8}$ (16), $\beta_{O_8C_9F_{11}}$ (13)
18	596	590	9.8	0.5	$\gamma_{F_{12}C_9O_8}$ (30), $\beta_{F_7C_5O_8}$ (22), $\beta_{O_8C_9F_{11}}$ (19)
19	586	582	8.8	0.6	$\beta_{C_5F_6F_7}$ (33), $\beta_{O_8C_9F_{12}}$ (25), $\beta_{F_6C_5C_1}$ (10)
20	507	499	4.5	2.0	$\beta_{F_7C_5O_8}$ (16), $\beta_{O_8C_9F_{11}}$ (13), $\beta_{C_1C_5O_8}$ (12)
21	450	443	4.5	2.3	$\beta_{O_8C_9F_{12}}$ (27), $\beta_{C_5F_6F_7}$ (21), $\nu_{C_1Cl_2}$ (17)
22	428	424	2.9	0.6	$\gamma_{F_3C_1C_5}$ (33), $\beta_{O_8C_9F_{11}}$ (24), $\beta_{F_7C_5O_8}$ (12)
23	350	345	0.6	1.9	$\beta_{O_8C_9F_{12}}$ (14), $\beta_{F_3C_1C_5}$ (13), $\beta_{F_6C_5C_1}$ (11)
24	314	309	1.7	1.0	$\beta_{F_3C_1C_5}$ (39), $\beta_{F_6C_5C_1}$ (23), $\nu_{C_1C_5}$ (16)
25	261	257	1.3	0.4	$\beta_{C_1C_5F_7}$ (43), $\beta_{C_5O_8C_9}$ (25), $\gamma_{F_3C_1C_5}$ (10)
26	211	205	3.0	0.4	$\beta_{C_5C_1Cl_2}$ (46), $\beta_{C_5O_8C_9}$ (22), $\beta_{C_1C_5F_7}$ (10)
27	123	116	2.1	0.2	$\beta_{C_1C_5O_8}$ (45), $\beta_{C_5O_8C_9}$ (26), $\beta_{C_5C_1Cl_2}$ (12)
28	79	76	0.07	0.2	$\tau_{O_8C_5C_1Cl_2}$ (91)
29	59	52	0.6	0.1	$\tau_{C_1C_5O_8C_9}$ (89)
30	30	20	1.9	0.05	$\tau_{C_5O_8C_9F_{11}}$ (88)

Table 3. Calculated (MP2/6-311++G(df,pd)) harmonic (ω), anharmonic (ν) frequencies, IR intensities (A), Raman activities (S) and potential energy distribution (PED) for a_1 conformer of enflurane-HD.

N ^o	ω , cm ⁻¹	ν , cm ⁻¹	A , km/mol	S , Å ⁴ /amu	PED
1	3172	3076	14	46	$\nu\text{C}_9\text{H}_{10}$ (100)
2	2330	2266	6.0	31	$\nu\text{C}_1\text{D}_4$ (100)
3	1472	1436	44	2.6	$\beta\text{H}_{10}\text{C}_9\text{O}_8$ (83)
4	1413	1385	62	2.3	$\gamma\text{H}_{10}\text{C}_9\text{O}_8$ (85)
5	1393	1362	127	1.9	$\nu\text{C}_1\text{C}_5$ (38)
6	1277	1246	230	1.0	$\nu\text{C}_5\text{O}_8$ (48), $\nu\text{C}_5\text{F}_6\text{F}_7$ (16)
7	1231	1203	450	0.8	$\nu_{\text{as}}\text{C}_5\text{F}_6\text{F}_7$ (43), $\nu_{\text{as}}\text{C}_9\text{F}_{11}\text{F}_{12}$ (27), $\beta\text{C}_5\text{O}_8\text{C}_9$ (10)
8	1223	1199	20	4.9	$\nu\text{C}_9\text{F}_{12}$ (48), $\nu\text{C}_1\text{F}_3$ (16), $\beta\text{F}_{12}\text{C}_9\text{F}_{11}$ (12)
9	1192	1165	382	1.8	$\nu\text{C}_1\text{F}_3$ (34), $\nu_{\text{as}}\text{F}_{12}\text{C}_9\text{O}_8$ (26), $\nu\text{C}_5\text{F}_6$ (12)
10	1185	1158	248	2.3	$\nu\text{C}_9\text{F}_{11}$ (67)
11	1109	1082	209	3.5	$\nu\text{C}_9\text{O}_8$ (50), $\nu\text{C}_1\text{F}_3$ (15)
12	1048	1029	84	0.7	$\gamma\text{D}_4\text{C}_1\text{Cl}_2$ (40), $\nu\text{C}_5\text{F}_6$ (18), $\nu\text{C}_1\text{Cl}_2$ (12)
13	997	982	10	3.9	$\gamma\text{D}_4\text{C}_1\text{C}_5$ (53), $\beta\text{F}_3\text{C}_1\text{C}_5$ (18), $\nu\text{C}_1\text{F}_3$ (14)
14	878	864	35	2.0	$\nu\text{C}_5\text{F}_6\text{F}_7$ (34), $\beta\text{C}_1\text{C}_5\text{F}_6$ (11)
15	816	804	30	5.3	$\nu\text{C}_1\text{Cl}_2$ (46), $\gamma\text{D}_4\text{C}_1\text{Cl}_2$ (39)
16	772	761	40	2.8	$\nu\text{C}_5\text{F}_7$ (14), $\nu\text{C}_5\text{C}_1$ (10), $\beta\text{F}_7\text{C}_5\text{C}_1$ (10)
17	666	6595	1.1	2.6	$\beta\text{C}_5\text{O}_8\text{C}_9$ (19), $\beta\text{F}_{12}\text{C}_9\text{F}_{11}$ (15), $\beta\text{F}_{11}\text{C}_9\text{O}_8$ (13)
18	595	588	9.8	0.5	$\beta\text{F}_{12}\text{C}_9\text{F}_{11}$ (33), $\beta\text{C}_5\text{O}_8\text{C}_9$ (19), $\beta\text{F}_{11}\text{C}_9\text{O}_8$ (18)
19	580	574	9.9	0.4	$\beta\text{C}_5\text{F}_6\text{F}_7$ (32), $\gamma\text{O}_8\text{C}_9\text{F}_{12}$ (23)
20	505	496	4.5	1.9	$\beta\text{F}_7\text{C}_5\text{O}_8$ (16), $\beta\text{O}_8\text{C}_9\text{F}_{11}$ (13), $\beta\text{C}_1\text{C}_5\text{O}_8$ (12)
21	447	440	4.2	2.3	$\beta\text{O}_8\text{C}_9\text{F}_{12}$ (27), $\beta\text{C}_5\text{F}_6\text{F}_7$ (21), $\nu\text{C}_1\text{Cl}_2$ (17)
22	427	422	3.0	0.7	$\gamma\text{F}_3\text{C}_1\text{C}_5$ (33), $\beta\text{O}_8\text{C}_9\text{F}_{11}$ (24), $\beta\text{F}_7\text{C}_5\text{O}_8$ (12)
23	349	344	0.6	1.8	$\beta\text{O}_8\text{C}_9\text{F}_{12}$ (14), $\beta\text{F}_3\text{C}_1\text{C}_5$ (13), $\beta\text{F}_6\text{C}_5\text{C}_1$ (11)
24	314	309	1.7	1.0	$\beta\text{F}_3\text{C}_1\text{C}_5$ (39), $\beta\text{F}_6\text{C}_5\text{C}_1$ (23), $\nu\text{C}_1\text{C}_5$ (16)
25	260	256	1.3	0.4	$\beta\text{C}_1\text{C}_5\text{F}_7$ (43), $\beta\text{C}_5\text{O}_8\text{C}_9$ (25), $\gamma\text{F}_3\text{C}_1\text{C}_5$ (10)
26	210	205	3.0	0.4	$\beta\text{C}_5\text{C}_1\text{Cl}_2$ (46), $\beta\text{C}_5\text{O}_8\text{C}_9$ (22), $\beta\text{C}_1\text{C}_5\text{F}_7$ (10)
27	123	114	2.1	0.2	$\beta\text{C}_1\text{C}_5\text{O}_8$ (45), $\beta\text{C}_5\text{O}_8\text{C}_9$ (26), $\beta\text{C}_5\text{C}_1\text{Cl}_2$ (12)
28	76	75	0.06	0.2	$\tau\text{O}_8\text{C}_5\text{C}_1\text{Cl}_2$ (91)
29	59	52	0.7	0.1	$\tau\text{C}_1\text{C}_5\text{O}_8\text{C}_9$ (89)
30	29	21	1.8	0.05	$\tau\text{C}_5\text{O}_8\text{C}_9\text{F}_{11}$ (88)

Table 4. Measured frequencies ν (cm^{-1}); calculated (MP2/6-311++G(df,pd)) mean weighted frequencies $\langle \nu \rangle$ (cm^{-1}) and IR intensities $\langle A \rangle$ (km/mol) in the IR spectrum of enflurane HH at $T = 120$ K.

N	Calculation						Kr _{liq} , 120 K
	<i>a</i>		<i>b</i>		<i>c</i>		
	⟨ <i>ν</i> ⟩	⟨ <i>A</i> ⟩	⟨ <i>ν</i> ⟩	⟨ <i>A</i> ⟩	⟨ <i>ν</i> ⟩	⟨ <i>A</i> ⟩	<i>ν</i>
1	3075	7.80	3075	1.77	3071	4.89	3023
2	3045	3.05	3044	0.67	3037	1.70	2996
3	1436	21.4	1437	5.08	1438	11.69	1408
4	1393	41.7	1396	9.40	1399	14.94	1373
5	1386	31.6	1387	7.59	1385	17.06	1362
6	1323	18.5	1323	6.15	1326	15.08	(1304•), 1297
7	1300	68.5	1300	12.1	1324	51.71	(1282*), 1270
8	1238	130	1227	25.2	1209	121	1207(<i>a</i>), 1192(<i>c</i>)
9	1195	187	1197	50.7	1189	79.7	1172, 1162, 1152, 1130, 1112, 1102, 1098
10	1167	248	1182	25.3	1175	126	
11	1152	141	1158	55.4	1157	9.74	
12	1143	57	1144	10.1	1143	28.6	
13	1075	70.0	1090	30.7	1095	83.7	1068(<i>c</i>), 1063(<i>b</i>), 1045(<i>a</i>)
14	916	36.5	919	0.58	932	11.6	906(<i>c</i>), 886(<i>a</i>)
15	862	32.5	849	9.93	877	23.3	841(<i>c</i>), 831(<i>a</i>), 819(<i>b</i>)
16	787	30.2	772	8.25	717	6.72	-
17	656	0.97	664	0.12	660	2.82	-
18	595	4.70	594	1.00	612	0.99	-
19	581	4.79	576	1.70	560	5.98	-
20	493	3.40	501	0.34	498	2.67	-
21	446	2.57	467	1.24	459	3.76	-
22	424	1.20	414	0.20	441	0.61	-
23	340	0.45	362	0.22	357	0.17	-
24	311	0.91	270	0.06	320	0.20	-
25	259	0.71	243	0.11	239	1.45	-
26	207	1.76	237	0.65	198	0.41	-
27	118	1.14	113	0.15	119	0.06	-
28	78	0.08	80	0.04	81	0.14	-
29	51	0.40	55	0.11	49	0.31	-
30	23	0.95	27	0.16	28	0.17	-

Notes: •, * – see Fig. 1.

Table 5. Measured frequencies ν (cm^{-1}); calculated (MP2/6-311++G(df,pd)) mean weighted frequencies $\langle \nu \rangle$ (cm^{-1}) and IR intensities $\langle A \rangle$ (km/mol) in the IR spectrum of enflurane HD at $T = 120$ K.

N	Calculation						Kr _{liq} , 120 K
	<i>a</i>		<i>b</i>		<i>c</i>		
	⟨ <i>ν</i> ⟩	⟨ <i>A</i> ⟩	⟨ <i>ν</i> ⟩	⟨ <i>A</i> ⟩	⟨ <i>ν</i> ⟩	⟨ <i>A</i> ⟩	<i>ν</i>
1	3075	7.83	3075	1.86	3072	4.60	3024
2	2267	3.39	2263	0.79	2254	1.92	-
3	1436	24.6	1435	6.21	1436	11.0	1407
4	1386	35.4	1387	8.06	1387	18.7	1363
5	1362	72.8	1364	18.4	1365	45.4	1340
6	1249	135	1242	28.5	1262	59.1	1216(<i>c</i>), 1204(<i>a</i>)
7	1205	208	1208	44.2	1202	111	1162
8	1182	85.6	1191	31.7	1179	127	1141
9	1168	156	1175	18.5	1162	20.2	1123
10	1157	170	1158	31.5	1154	41.1	1115
11	1082	115	1107	62.4	1102	88.7	1075(<i>b,c</i>), 1049(<i>a</i>)
12	1029	51.5	1016	2.66	1030	35.0	994
13	983	5.98	986	0.48	982	0.61	965
14	864	19.4	861	5.69	899	6.33	880(<i>c</i>), 844(<i>a</i>)
15	804	17.1	799	4.09	805	9.54	-
16	762	22.7	746	6.43	704	3.26	-
17	646	1.40	659	0.15	646	2.55	-
18	594	4.74	591	1.21	612	0.89	-
19	574	5.15	574	1.71	552	5.70	-
20	491	3.57	494	0.41	494	2.75	-
21	443	2.43	465	1.22	457	3.90	-
22	422	1.20	413	0.21	440	0.57	-
23	339	0.44	361	0.24	356	0.17	-
24	311	0.92	269	0.06	320	0.19	-
25	257	0.71	243	0.12	239	1.40	-
26	207	1.79	236	0.68	198	0.39	-
27	117	1.13	113	0.15	117	0.06	-
28	77	0.08	79	0.04	79	0.14	-
29	50	0.38	55	0.13	49	0.30	-
30	23	0.96	26	0.17	28	0.17	-

Table 6. Measured frequencies ν (cm^{-1}); calculated (MP2/6-311++G(df,pd)) mean weighted frequencies $\langle \nu \rangle$ (cm^{-1}) and Raman activities $\langle S \rangle$ ($\text{\AA}^4/\text{amu}$) in the Raman spectrum of enflurane HH at $T=295$ K.

N	Calculation						Liquid, 295 K
	<i>a</i>		<i>b</i>		<i>c</i>		
	$\langle \nu \rangle$	$\langle S \rangle$	$\langle \nu \rangle$	$\langle S \rangle$	$\langle \nu \rangle$	$\langle S \rangle$	ν
1	3075	25.9	3075	9.26	3071	16.2	3035
2	3045	36.4	3044	13.8	3037	24.9	3006
3	1436	1.45	1437	0.62	1438	0.87	1406
4	1393	1.37	1396	0.57	1399	0.86	1368
5	1386	1.22	1387	0.45	1385	0.80	
6	1323	1.65	1323	0.48	1325	0.84	1298
7	1300	1.64	1300	0.82	1323	1.02	1271
8	1238	0.65	1227	0.24	1208	0.41	1200
9	1195	1.21	1197	0.45	1188	0.63	1140
10	1167	1.34	1172	0.54	1176	0.82	1100
11	1154	1.40	1157	0.34	1157	0.84	1070
12	1143	1.54	1144	0.47	1143	0.70	
13	1075	2.13	1090	1.39	1095	1.17	
14	916	0.84	919	0.36	932	0.33	904(<i>c</i>), 888(<i>a</i> , <i>b</i>)
15	862	4.12	849	1.97	877	2.50	838(<i>c</i>), 829(<i>a</i>), 819(<i>b</i>)
16	787	1.36	772	0.35	717	0.31	768(<i>a</i>), 754(<i>b</i>), 708(<i>c</i>)
17	660	1.14	666	0.43	660	1.71	645
18	600	0.48	602	0.15	614	0.51	600(<i>c</i>) 571(<i>a</i> , <i>b</i>)
19	581	0.40	576	0.10	560	0.25	555
20	498	0.77	497	0.42	497	0.26	490
21	447	1.53	464	0.25	459	0.42	432
22	423	0.44	414	0.21	441	0.63	403
23	341	1.05	363	0.44	356	0.57	356(<i>c</i>), 339(<i>a</i>)
24	312	0.60	270	0.30	320	0.32	316(<i>c</i>), 310(<i>a</i>), 269(<i>b</i>)
25	258	0.18	243	0.15	239	0.18	244
26	206	0.20	237	0.05	198	0.09	211
27	119	0.10	114	0.02	119	0.06	-
28	77	0.10	80	0.03	81	0.07	-
29	51	0.07	55	0.00	49	0.06	-
30	25	0.04	28	0.02	27	0.02	-

Table 7. Measured frequencies ν (cm^{-1}); calculated (MP2/6-311++G(df,pd)) mean weighted frequencies $\langle \nu \rangle$ (cm^{-1}) and Raman activities $\langle S \rangle$ ($\text{\AA}^4/\text{amu}$) in the Raman spectrum of enflurane HD at $T=295$ K.

N	Calculation						Liquid, 295 K
	<i>a</i>		<i>b</i>		<i>c</i>		
	$\langle \nu \rangle$	$\langle S \rangle$	$\langle \nu \rangle$	$\langle S \rangle$	$\langle \nu \rangle$	$\langle S \rangle$	ν
1	3075	21.0	3075	9.70	3072	15.3	3038
2	2267	14.1	2263	6.75	2254	12.1	2245
3	1436	1.18	1435	0.63	1436	0.87	1406
4	1386	1.00	1387	0.48	1387	0.68	1367
5	1362	0.95	1364	0.50	1365	0.78	1337
6	1249	0.41	1242	0.33	1262	0.50	
7	1205	0.69	1207	0.13	1201	0.48	
8	1182	1.74	1193	0.72	1179	0.65	
9	1168	1.01	1171	0.50	1162	0.74	1164
10	1157	0.99	1157	0.38	1154	0.65	1117
11	1082	1.56	1107	1.46	1102	1.22	1080
12	1029	0.32	1016	0.23	1030	0.26	
13	983	1.78	986	0.84	982	1.23	969
14	864	0.93	861	0.39	899	0.59	880(<i>c</i>), 844(<i>a</i>)
15	804	2.41	799	1.67	805	1.77	771
16	762	1.26	747	0.42	704	0.47	746(<i>a</i>), 729(<i>b</i>), 694(<i>c</i>)
17	646	0.97	665	0.44	646	1.31	630
18	594	0.38	598	0.14	613	0.51	563
19	574	0.26	573	0.09	552	0.30	543
20	491	0.56	494	0.34	492	0.26	486
21	443	1.25	464	0.35	458	0.41	427
22	422	0.37	413	0.21	440	0.63	405
23	339	0.84	362	0.45	355	0.55	358(<i>b, c</i>), 338(<i>a</i>)
24	311	0.48	269	0.32	320	0.31	268(<i>b</i>), 313(<i>a, c</i>)
25	257	0.15	243	0.15	239	0.17	244
26	207	0.15	236	0.04	198	0.09	209
27	117	0.08	113	0.02	118	0.06	-
28	77	0.08	79	0.03	79	0.06	-
29	50	0.06	55	0.00	49	0.06	-
30	23	0.03	26	0.03	28	0.02	-

Figure captions

Fig. 1 The IR spectrum of enflurane HH ($\text{CHFCl}-\text{CF}_2-\text{O}-\text{CHF}_2$). Top panel – experimental spectrum in liquid Kr at $T \sim 120\text{K}$, $n(\text{CHFCl}-\text{CF}_2-\text{O}-\text{CHF}_2) \sim 2 \cdot 10^{17}$ molecules/cm³; tentative assignment: $\bullet - \nu_{15} + \nu_{21} \sim \nu_6$, $* - \nu_{15} + \nu_{22} \sim \nu_7$. Bottom panel – calculated spectrum. Weak CH bands are scaled by a factor of 10 for convenience. a, b, c – the bands ascribed to conformers a, b, c .

Fig. 2 The IR spectrum of enflurane HD ($\text{CDFCl}-\text{CF}_2-\text{O}-\text{CHF}_2$). Top panel – experimental spectrum in liquid Kr at $T \sim 120\text{K}$, $n(\text{CDFCl}-\text{CF}_2-\text{O}-\text{CHF}_2) \sim 10^{17}$ molecules/cm³. Bottom panel – calculated spectrum. Weak CH bands are scaled by a factor of 10 for convenience. a, b, c – the bands ascribed to conformers a, b, c .

Fig. 3 The Raman spectrum of enflurane HH ($\text{CHFCl}-\text{CF}_2-\text{O}-\text{CHF}_2$). Top panel – experimental spectrum of liquid enflurane at $T \sim 295\text{K}$. Bottom panel – calculated spectrum. CH bands are scaled by a factor of 10 for convenience.

Fig. 4 The Raman spectrum of enflurane HD ($\text{CDFCl}-\text{CF}_2-\text{O}-\text{CHF}_2$). Top panel – experimental spectrum of liquid enflurane at $T \sim 295\text{K}$. Bottom panel – calculated spectrum. CH and CD bands are scaled by a factor of 10 for convenience.

Fig. 5 MP2/6-311++G(df,pd) optimized structures of the most stable conformers of enflurane.

Fig. 6 The relaxed PES scan over the dihedral angle $\chi_1=(\text{Cl}_2-\text{C}_1-\text{C}_5-\text{O}_8)$.

Fig. 7 The relaxed PES scan over the dihedral angle $\chi_2=(\text{H}_{10}-\text{C}_9-\text{O}_8-\text{C}_5)$.

Fig. 8 Region of CH stretch bands ν_1, ν_2 . Enflurane ($\sim 6 \cdot 10^{17}$ molecules/cm³) + $(\text{CD}_3)_2\text{CO}$ ($\sim 4 \cdot 10^{17}$ molecules/cm³) in liquid Kr at $T \sim 134\text{K}$.

Fig. 1

Fig.2.

Fig.3.

Fig.4.

Fig.5.

Fig.6.

Fig.7.

Fig.8.

Supporting information:

Table 1S. Calculated spectroscopic parameters of enflurane.

Con- former.	harm. ω , cm ⁻¹	anharm. ν , cm ⁻¹	A, Km/mol	S, Å ⁴ /amu	harm. ν , cm ⁻¹	anharm. ν , cm ⁻¹	A, Km/mol	S, Å ⁴ /amu
	CHFCl-CF ₂ -O-CHF ₂				CDFCl-CF ₂ -O-CHF ₂			
<i>a</i> ₁	3172	3075	14	45	3172	3075	14	46
<i>a</i> ₂	3170	3074	14	47	3170	3074	14	47
<i>b</i> ₁	3169	3073	14	44	3169	3073	14	44
<i>b</i> ₂	3172	3076	14	42	3173	3076	14	43
<i>c</i> ₁	3168	3072	16	49	3168	3071	15	48
<i>c</i> ₂	3167	3071	16	48	3168	3072	16	47
<i>a</i> ₁	3162	3045	5.4	64	2330	2266	6.0	31
<i>a</i> ₂	3161	3044	5.4	65	2329	2268	5.9	31
<i>b</i> ₁	3160	3043	5.3	64	2328	2264	5.8	31
<i>b</i> ₂	3161	3044	5.3	64	2329	2262	5.9	30
<i>c</i> ₁	3153	3037	5.6	75	2323	2254	6.5	37
<i>c</i> ₂	3153	3037	5.5	74	2323	2254	6.4	37
<i>a</i> ₁	1472	1436	27	1.6	1472	1436	44	2.6
<i>a</i> ₂	1471	1436	23	1.6	1471	1435	43	2.7
<i>b</i> ₁	1472	1436	40	3.0	1471	1435	46	2.9
<i>b</i> ₂	1473	1437	38	2.6	1472	1436	46	2.8
<i>c</i> ₁	1472	1437	38	2.6	1471	1434	37	2.7
<i>c</i> ₂	1474	1438	38	2.6	1472	1438	37	2.7
<i>a</i> ₁	1427	1393	77	2.5	1413	1385	62	2.3
<i>a</i> ₂	1426	1394	66	2.3	1414	1386	62	2.1
<i>b</i> ₁	1430	1395	56	1.9	1415	1387	65	2.1
<i>b</i> ₂	1430	1393	33	1.2	1413	1386	55	2.2
<i>c</i> ₁	1433	1399	37	2.6	1415	1387	58	2.1
<i>c</i> ₂	1433	1399	56	2.6	1414	1388	66	2.1
<i>a</i> ₁	1413	1385	53	2.1	1393	1362	127	2.0
<i>a</i> ₂	1414	1387	59	2.0	1392	1361	129	2.2
<i>b</i> ₁	1415	1388	63	2.1	1392	1364	139	2.4
<i>b</i> ₂	1413	1386	57	2.1	1393	1364	136	2.1
<i>c</i> ₁	1414	1386	67	2.4	1396	1365	152	2.4
<i>c</i> ₂	1414	1385	48	2.4	1396	1365	154	2.4
<i>a</i> ₁	1350	1323	25	2.9	1277	1246	230	1.0
<i>a</i> ₂	1349	1323	44	2.9	1281	1252	248	0.8
<i>b</i> ₁	1350	1323	60	2.2	1274	1245	229	1.4
<i>b</i> ₂	1350	1323	39	2.2	1269	1240	196	1.6
<i>c</i> ₁	1357	1325	102	1.9	1291	1263	200	1.5
<i>c</i> ₂	1358	1325	179	2.4	1291	1261	198	1.6
<i>a</i> ₁	1327	1297	100	2.5	1231	1203	450	0.8
<i>a</i> ₂	1334	1303	95	2.1	1237	1208	259	2.5
<i>b</i> ₁	1332	1303	94	3.6	1235	1206	227	0.9
<i>b</i> ₂	1327	1297	96	4.0	1235	1208	425	0.4
<i>c</i> ₁	1345	1322	66	1.4	1231	1204	442	1.6
<i>c</i> ₂	1346	1318	24	2.0	1226	1199	323	1.4
<i>a</i> ₁	1269	1238	230	0.8	1223	1199	21	4.9
<i>a</i> ₂	1268	1237	222	1.2	1207	1180	313	2.4
<i>b</i> ₁	1252	1225	161	1.3	1210	1186	303	2.8

b_2	1255	1228	229	1.0	1222	1198	174	3.6
c_1	1240	1214	424	1.2	1200	1174	376	1.7
c_2	1231	1205	373	1.2	1207	1182	469	2.2
a_1	1226	1200	312	1.8	1192	1165	382	1.8
a_2	1217	1189	333	2.6	1200	1175	140	2.8
b_1	1216	1191	412	2.1	1204	1177	239	2.6
b_2	1229	1202	388	2.0	1190	1162	43	2.0
c_1	1213	1185	169	2.7	1190	1164	50	2.0
c_2	1218	1191	317	1.4	1186	1160	82	2.5
a_1	1189	1163	507	2.6	1185	1158	248	2.3
a_2	1199	1175	296	1.8	1185	1157	362	2.0
b_1	1210	1186	336	2.4	1180	1155	147	1.5
b_2	1190	1161	60	2.4	1185	1159	316	1.9
c_1	1197	1171	455	1.4	1179	1153	138	2.6
c_2	1202	1178	378	3.25	1183	1155	138	1.5
a_1	1184	1156	173	2.6	1109	1082	209	3.5
a_2	1178	1150	359	2.3	1109	1082	192	3.3
b_1	1179	1152	253	1.3	1135	1107	462	6.6
b_2	1189	1160	566	1.7	1135	1107	467	6.5
c_1	1183	1157	28	2.7	1128	1102	291	3.6
c_2	1183	1157	34	2.4	1128	1102	304	3.9
a_1	1168	1143	116	2.5	1048	1029	84	0.7
a_2	1167	1143	80	3.0	1047	1029	99	0.7
b_1	1169	1145	72	2.3	1036	1016	20	1.1
b_2	1169	1144	85	2.1	1036	1017	19	1.0
c_1	1168	1141	104	2.4	1050	1029	127	0.8
c_2	1170	1144	86	1.9	1050	1030	110	0.8
a_1	1100	1075	124	3.8	997	982	10	3.9
a_2	1100	1075	123	3.8	997	983	10	4.0
b_1	1115	1089	244	6.5	1000	985	3.1	3.8
b_2	1114	1090	240	6.4	1001	986	3.9	3.8
c_1	1125	1096	269	3.4	997	982	3.0	3.8
c_2	1124	1094	274	3.6	997	982	1.2	3.8
a_1	932	915	63	1.5	878	864	35	2.0
a_2	933	917	62	1.3	878	864	33	2.1
b_1	936	920	3.4	1.6	874	861	41	1.8
b_2	936	918	3.9	1.2	874	860	44	1.7
c_1	949	932	42	1.0	914	900	21	1.9
c_2	949	932	30	0.9	915	898	22	1.8
a_1	876	861	36	4.4	816	804	30	5.3
a_2	876	862	54	7.3	817	803	29	5.3
b_1	862	849	77	9.0	811	799	30	7.4
b_2	862	849	79	9.2	810	799	31	7.6
c_1	891	875	50	5.3	818	805	31	5.5
c_2	891	875	61	5.8	818	805	33	5.5
a_1	797	786	53	2.4	772	761	40	2.8
a_2	799	787	33	1.5	775	764	40	2.8
b_1	783	773	66	1.7	758	748	49	2.0
b_2	782	771	64	1.6	756	745	47	1.8
c_1	728	718	20	0.9	715	707	9.7	1.4
c_2	725	717	23	0.9	712	702	12	1.5
a_1	670	662	0.9	2.5	666	659	1.1	2.6

a_2	657	653	2.5	1.2	649	642	4.1	1.5
b_1	668	662	1.6	1.7	664	658	2.0	1.7
b_2	678	669	0.4	2.2	677	669	0.2	2.2
c_1	667	659	9.4	4.7	654	645	8.1	3.7
c_2	666	660	9	5.4	655	647	9.0	4.3
a_1	596	590	9.7	0.5	595	588	9.8	0.5
a_2	615	606	6.3	1.3	614	605	6.5	1.2
b_1	622	613	4	0.9	619	610	4.7	0.7
b_2	595	590	7	0.4	591	584	13	0.6
c_1	616	609	5.1	1.7	616	610	5.0	1.7
c_2	627	618	2	1.4	624	616	1.5	1.5
a_1	586	582	8.8	0.6	580	574	9.9	0.4
a_2	586	580	8	0.9	581	574	7.9	0.7
b_1	579	574	15	0.7	577	572	15	0.6
b_2	584	579	12	0.3	582	576	11	0.2
c_1	569	563	17	0.8	559	554	17	1.0
c_2	562	558	21	0.7	555	550	21	0.9
a_1	507	499	4.5	2	505	496	4.5	1.9
a_2	496	488	8.2	0.4	495	487	8.4	0.4
b_1	493	485	1.2	1.5	488	480	2.3	1.2
b_2	516	507	3.6	1.9	511	503	3.7	1.7
c_1	507	501	13	0.9	505	499	13	0.8
c_2	499	494	5.9	0.7	494	487	6.2	0.8
a_1	450	443	4.5	2.3	447	440	4.2	2.3
a_2	457	451	4.6	3.3	452	446	4.4	3.3
b_1	482	473	12	0.8	479	471	11	1.5
b_2	471	460	8	1.4	467	458	7.4	1.6
c_1	468	458	11	0.9	464	454	12	1.0
c_2	473	459	13	1.5	471	459	14	1.5
a_1	424	424	2.2	0.5	427	422	3.0	0.7
a_2	429	423	1	1.0	428	423	1.0	1.0
b_1	420	414	0.7	1.3	419	414	0.7	1.2
b_2	420	414	2.3	0.7	418	413	2.4	0.7
c_1	447	440	1	2.2	445	439	0.9	2.3
c_2	447	441	2.6	1.7	445	440	2.7	1.7
a_1	350	345	0.6	1.9	349	344	0.6	1.8
a_2	341	336	1.1	1.8	340	335	1.0	1.8
b_1	366	363	1.8	1.4	365	360	2.6	1.9
b_2	367	364	1.1	2.1	366	363	1.1	2.1
c_1	360	354	0.2	1.6	359	354	0.2	1.7
c_2	362	357	0.8	1.8	361	356	0.8	1.8
a_1	314	309	1.7	1.0	314	309	1.7	1.0
a_2	318	315	1.2	0.9	318	313	1.6	1.1
b_1	276	272	0.4	1.4	274	270	0.4	1.4
b_2	272	268	0.5	1.4	271	267	0.5	1.4
c_1	323	318	0.6	1.03	323	318	0.6	1.0
c_2	325	321	0.7	0.9	325	321	0.7	0.9
a_1	261	257	1.3	0.4	260	256	1.3	0.4
a_2	264	261	1.2	0.3	263	259	1.2	0.3
b_1	246	243	0.8	0.7	245	243	0.8	0.6
b_2	247	243	0.9	0.7	246	243	0.9	0.7
c_1	245	240	4.7	0.5	244	240	4.7	0.5

c_2	244	238	4.7	0.5	244	238	4.7	0.5
a_1	211	205	3	0.4	210	205	3.0	0.4
a_2	214	209	3.3	0.3	213	208	3.3	0.3
b_1	242	239	5.2	0.2	242	237	5.2	0.2
b_2	240	235	5	0.2	240	235	5	0.2
c_1	203	200	1.5	0.2	203	200	1.4	0.2
c_2	201	197	1.2	0.3	201	197	1.2	0.3
a_1	123	116	1.8	0.1	123	114	2.1	0.2
a_2	125	122	1.9	0.2	124	121	1.8	0.2
b_1	121	118	1.1	0.1	120	116	1.1	0.09
b_2	120	110	1.2	0.1	120	110	1.2	0.1
c_1	124	122	0.2	0.2	123	120	0.2	0.2
c_2	124	117	0.2	0.2	123	116	0.2	0.2
a_1	79	76	0.1	0.2	79	75	0.06	0.2
a_2	80	79	0.2	0.2	80	77	0.2	0.1
b_1	81	79	0.3	0.1	80	78	0.3	0.1
b_2	80	80	0.3	0.1	80	80	0.2	0.1
c_1	86	84	0.4	0.2	86	80	0.4	0.2
c_2	84	79	0.5	0.2	84	78	0.5	0.2
a_1	59	52	0.7	0.1	59	52	0.7	0.1
a_2	56	50	0.7	0.1	56	48	0.7	0.1
b_1	61	54	0.9	0.01	60	55	0.9	0.01
b_2	61	55	0.9	0.01	61	55	0.9	0.01
c_1	56	50	1	0.2	56	48	1	0.2
c_2	59	49	1	0.2	58	49	1	0.2
a_1	29	20	1.8	0.05	29	21	1.8	0.05
a_2	32	28	1.5	0.1	32	26	1.5	0.1
b_1	31	30	1	0.1	30	29	1	0.1
b_2	16	25	1.4	0.1	21	23	1.4	0.1
c_1	34	31	0.8	0.08	34	31	0.8	0.08
c_2	31	23	0.4	0.06	32	24	0.4	0.05

Table 2S. Relative populations of six conformers of enflurane - HH.

conformer		a_1	a_2	b_1	b_2	c_1	c_2
E_{el} , Hartree (-1148.)		562048	562078	5616205	561562	561870	561843
ΔE_{el} , cm^{-1}		0	-6.6	93.8	106.6	39.1	45
120 K	S_{anharm} , cal/K	80.92	80.15	79.88	80.34	79.91	80.79
	G , cm^{-1}	10747	10785	10800	10772	10793	10751
	ΔG , cm^{-1}	0	37.8	52.9	24.9	46.3	3.7
	$\Delta G + \Delta E$, cm^{-1}	0	31.2	146.7	131.5	85.4	48.7
	P_{rel}	0.33	0.23	0.057	0.070	0.12	0.19
295 K	S_{anharm} , cal/K	101.44	100.66	100.38	100.86	100.42	101.30
	G , cm^{-1}	5256	5340	5373	5318	5363	5267
	ΔG , cm^{-1}	0	84.3	117.3	61.8	107.4	11.4
	$\Delta G + \Delta E$, cm^{-1}	0	77.7	211.1	168.4	146.5	56.4
	P_{rel}	0.27	0.18	0.096	0.12	0.13	0.20

Notes: $P_{\text{rel}} = \frac{P_i}{\sum_{j=1}^6 P_j}$, where P_i is relative population of i^{th} conformer (see eq. (2)).

Table 3S. Relative populations of six conformers of enflurane-HD.

conformer		a_1	a_2	b_1	b_2	c_1	c_2
E_{el} , Hartree (-1148.)		562048	562078	5616205	561562	561870	561843
ΔE_{el} , cm^{-1}		0	-6.6	93.8	106.6	39.1	45
120 K	S_{anharm} , cal/K	85.31	84.83	84.48	84.90	84.46	85.06
	G , cm^{-1}	9816	9841	9854	9834	9851	9823
	ΔG , cm^{-1}	0	25.0	38.1	18.1	35.0	7.3
	$\Delta G + \Delta E$, cm^{-1}	0	18.4	131.9	124.7	74.1	52.3
	P_{rel}	0.32	0.25	0.065	0.069	0.13	0.17
295 K	S_{anharm} , cal/K	102.84	102.36	101.88	102.43	101.38	102.59
	G , cm^{-1}	4317	4371	4420	4361	4403	4339
	ΔG , cm^{-1}	0	53.6	102.6	43.6	85.5	21.9
	$\Delta G + \Delta E$, cm^{-1}	0	47.0	196.4	150.2	124.6	66.9
	P_{rel}	0.25	0.20	0.10	0.12	0.14	0.18

Notes: $P_{\text{rel}} = \frac{P_i}{\sum_{j=1}^6 P_j}$, where P_i is relative population of i^{th} conformer (see eq. (2)).

IR spectra of two H/D derivatives of enflurane were registered in liquid Kr.

Raman spectra of liquid enflurane were also measured and analyzed.

A set of MP2/6-311++G(df,pd) calculations was performed.

3 conformers of enflurane were identified in few regions of IR and Raman spectra.

IR spectra of enflurane + acetone in liquid Kr show blue shifting H bond formation.

ACCEPTED MANUSCRIPT