Oxime rearrangements: *ab initio* calculations and reactions in the solid state †

Vesna Šimunić-Mežnarić, Zlatko Mihalić * and Hrvoj Vančik *

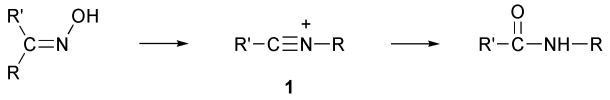
University of Zagreb, Faculty of Science, Department of Chemistry, Strossmayerov trg 14,
10000 Zagreb, Croatia. E-mail: vancik@rudjer.irb.hr

Received (in Cambridge, UK) 4th July 2001, Accepted 21st October 2002
First published as an Advance Article on the web 7th November 2002

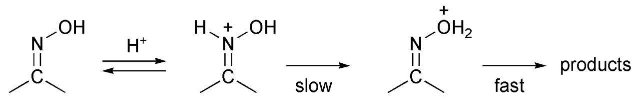
Rearrangements of oximes in reactions with strong Lewis acids may include Beckmann alkyl group shift or hydride migration. These reaction mechanisms were studied by FT-IR spectroscopy in solid superacid cryogenic matrices and supported by *ab initio* calculations. It was found that cyclic oximes with smaller rings (cyclobutanone oxime and cyclopentanone oxime) undergo hydride migration rather than alkyl group shift. Resulting aminoallyl cations were isolated in superacid cryogenic matrix and characterized spectroscopically. Cyclohexanone oxime rearranges by a classical Beckmann mechanism to a cyclic seven-membered nitrylium cation, which was also observed in the matrix. The ion is found to be persistent in solid superacid medium despite the highly strained non-linear carbon–nitrogen triple bond. It seems that hydrogen bonds with halogens formed in the Lewis acid–oxime complex could play an important role in the hydrogen migrations.

Introduction

Although the Beckmann rearrangement[1a] is a classical reaction in organic synthesis, its mechanism is still a topic of investigation.[1b–e] The overall accepted mechanism includes a rate determining step in which the departure of the OH group is concerted with the migration of a *trans* substituent[1a] from carbon to nitrogen and formation of a nitrylium cation **1** (Scheme 1). In recently published papers[1b,c,e] it has been calculated that the rate determining step includes proton migration from nitrogen to oxygen (Scheme 2). The *N*-protonated oxime is the the most stable intermediate in this process.



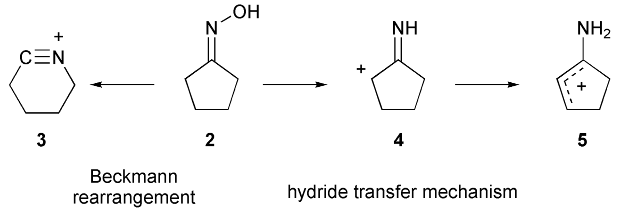
Scheme 1



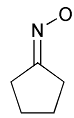
Scheme 2

In this work we examine how the reaction proceeds if the proton as an electrophile is replaced with a superacid molecule. What would be the role of the *N*-coordinated complex in such a reaction? Can the reaction follow mechanisms other than Beckmann alkyl migration? For instance, **2** (Scheme 3) can be rearranged either by ring expansion to nitrylium cation **3** (Beckmann rearrangement) or to cations **4** and **5**. Oxime **2** can be transformed into **4** and/or to **5** either by concerted *intra*-molecular or by an *inter*molecular hydride transfer mechanism.

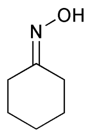
Here we investigate the structures and stabilities of the proposed intermediates with the intention of providing an explanation of the mechanism of the reaction of oximes with superacids in the solid state. The structures and vibrational spectra of nitrylium, nitrenium, imino and aminoallyl cations, which could be intermediates in the reactions of cyclic oximes **2**, **6**, **7** and **8** with superacids (SbF_5 and/or $SbCl_5$), were calculated at correlated *ab initio* levels of theory. The problem of N *versus* O coordination of electrophiles on the oxime molecule[1a–e] was studied by investigation of complexes of oximes with SbF_5 and $SbCl_5$. Predicted vibrational frequencies and intensities were compared with the experimental FT-IR spectra. The reactive intermediates were prepared[2] by reactions of the corresponding oximes with an excess of SbF_5 or $SbCl_5$ under cryogenic matrix conditions.



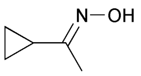
Scheme 3



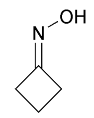
2



6



7



8

Results and discussion

Cyclohexanone oxime (6)

When oxime **6** was codeposited with SbF_5 at 77 K, new signal at 2304 cm^{-1} started to grow upon warming the matrix to 180 K (Fig. 1). Its frequency can be assigned to the carbon–nitrogen stretching vibration which implies the formation of the cyclic nitrylium ion **9**. Typical $C{\equiv}N^+$ stretching frequencies of nitrylium cations in the 2300 cm^{-1} spectral region are already known from the literature.[3] Moreover, the higher cyclic homologue, eight-membered cation **10**, has previously been characterized in solution[4] and its CN stretching frequency was found to be 2330 cm^{-1}.

---

† Electronic supplementary information (ESI) available: Cartesian coordinates, frequencies and intensities for structures **3**–**5**,**7**,**9** and **11**–**20**. See http://www.rsc.org/suppdata/p2/b1/b105923h/

DOI: 10.1039/b105923h

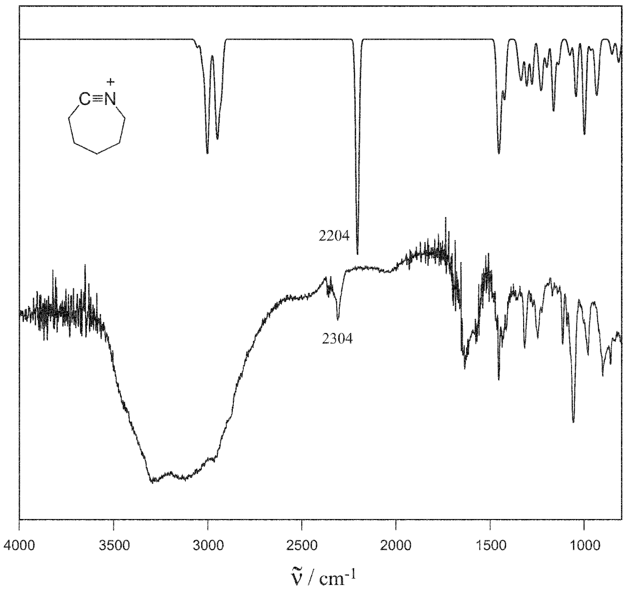
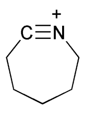
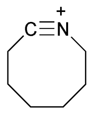


Fig. 1 FT-IR spectrum of the product mixture obtained by reaction of **6** in SbF_5 matrix at 150 K. The signal at 2304 cm^{-1} is assigned to the CN str. mode of **9**.



9

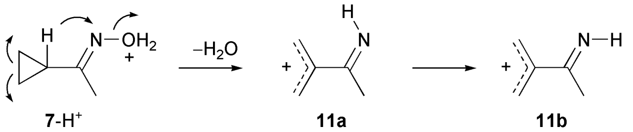


10

The C≡N stretching frequency of **9** (2304 cm^{-1}) is in good agreement with the scaled (see the Computational methods section) *ab initio* calculated value (2204 cm^{-1}). The appearance of **9** indicates that under superacid conditions Beckmann rearrangement proceeds through formation of the seven-membered cyclic nitrylium ion intermediate. The ion is, as yet, the smallest cyclic molecule with a carbon–nitrogen triple bond isolated.

1-Cyclopropylethanone oxime (7)

The precursor **7** was chosen as a good model compound for study of the hydride shift. Namely, the cyclopropyl ring can attain a conformation in which the hydrogen atom on the tertiary carbon is coplanar with the C=NOH group, *i.e.* in an ideal position for migration to nitrogen (Scheme 4).



Scheme 4

At both MP2(fc)/6-31G(d) and B3LYP/6-31G(d) levels of theory the movement of the hydrogen to the N-atom is concerted with the disrotatory cyclopropyl ring opening to the allyl cation **11a** *via* a single transition structure 7H$^+$–TS (Fig. 2). Since 7H$^+$–TS has a plane of symmetry, and **11a** does not, there is a bifurcation point along the path between them. The calculations showed that the likely candidate for the reaction intermediate, the cyclopropyl cation, does not exist as a minimum on the potential energy surfaces examined. The intially formed ion **11a** is 9.3 kcal mol^{-1} less stable than its planar isomer **11b**, which has the N–H bond *anti* to the allyl group (Fig. 3, Table 1).

The IR frequencies and intensities of **11a** and **11b** were calculated and compared with the IR spectrum obtained after the reaction of **7** with $SbCl_5$. Since the simulated spectra of **11a** and **11b** are very similar (Fig. 4), the agreement between the spectral patterns of both structures and those of the experimental spectrum is satisfactory. Absorbances at 1629 cm^{-1} and 1583 cm^{-1} are assigned to the C=N stretching and to the allyl CCC$^+$ asymmetric stretching vibrations, respectively. Scaled calculated values for **11b** are 1621 cm^{-1} and 1558 cm^{-1}. Signals of the allyl CCC$^+$ group stretching appear in the spectral region where other open-chain allyl cations have absorptions, such as the parent allyl cation (1578 cm^{-1}), and other simple substituted cations.[5,6]

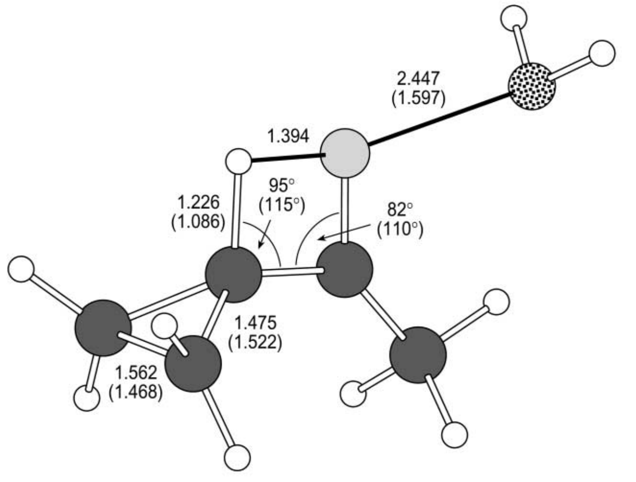
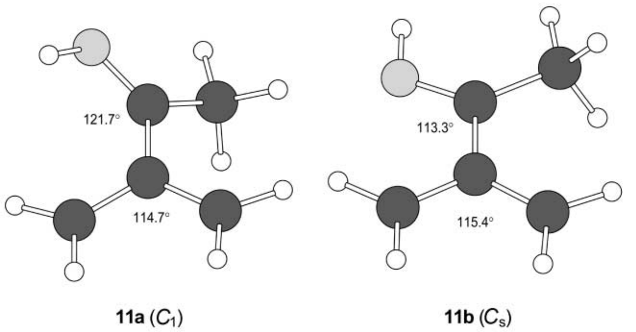
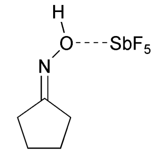


Fig. 2 The transition structure for the reaction **7**-H$^+$ ⟶ **11a** (distances in Å), calculated at the MP2(fc)/6-31G(d) level of theory. In parenthesis are given the corresponding values for the precursor, protonated oxime **7**, calculated at the same level of theory.

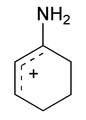


11a (C_1)   **11b** (C_s)

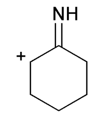
Fig. 3 Structure of allyl cations **11a** and **11b** (distances in Å), calculated at the MP2(fc)/6-31G(d) level of theory. In **11a**, the CH_3–C=NH plane is twisted about 40° relative to the allyl group plane.



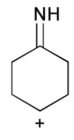
13



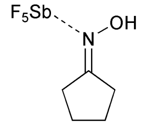
14



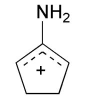
15



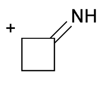
16



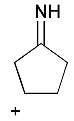
17



18



19



20

Cyclobutanone oxime (8)

The spectrum obtained starting for **8** in $SbCl_5$ matrix, under almost identical conditions as in the previous experiment, is represented in Fig. 5. The signals in the NH2 and CCC$^+$

Table 1 Total energies (E_{tot}), corresponding zero-point vibrational corrections (E_{ZPV}) (in hartree/particle) and relative energies E_{rel} (in kcal mol^{-1}) calculated at the MP2(fc)/6-31G(d) level of theory

Intermediate	E_{tot}	E_{ZPV}	$E_{tot} + E_{ZPV}$	E_{rel}
7H$^+$	−325.086361	0.150528	−324.935833	0.00
7H$^+$–TS	−325.039777	0.141511	−324.898266	23.6 ($E^{\neq}$)
11a	−248.876513	0.120263	−248.756250	9.30
11b	−248.891671	0.120608	−248.771063	0.00
19	−209.685668	0.090979	−209.594689	59.6
12	−209.785277	0.095650	−209.689627	0.00
3	−248.939806	0.125051	−248.814755	43.4
4	−248.905320	0.122505	−248.782815	63.5
5	−249.010112	0.126145	−248.883967	0.0
18	−248.954769	0.122437	−248.832332	32.4
20	−248.906018	0.120449	−248.785569	61.7
9	−288.132428	0.155396	−287.977032	31.0
14	−288.183110	0.156727	−288.026383	0.00
15	−288.085313	0.152810	−287.932503	58.9
16	−288.081288	0.151164	−287.930124	60.4
13	−7106.485294			16.3
17	−7106.511261			0.00

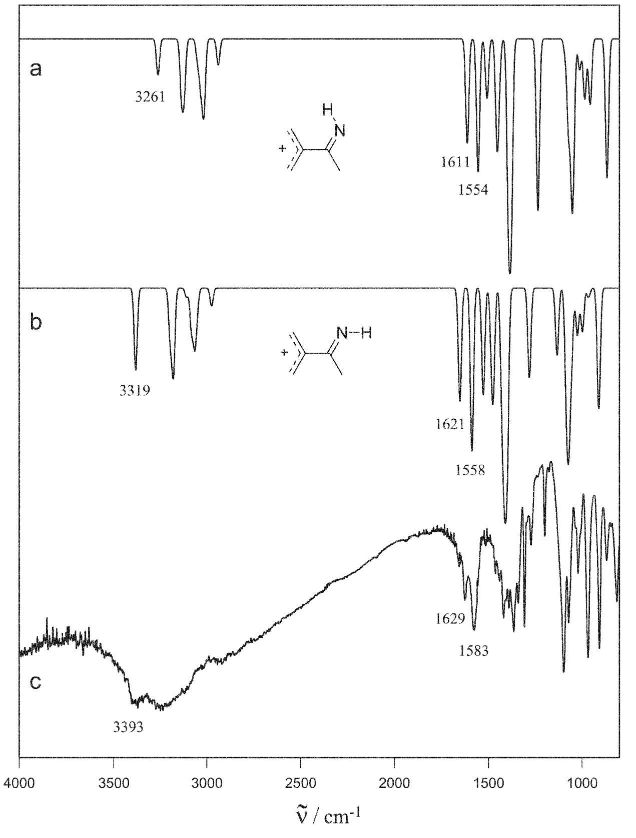
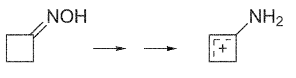


Fig. 4 (a),(b) Scaled MP2(fc)/6-31G(d) IR spectrum of **11**. (c) FT-IR spectrum of the product mixture obtained by reaction of **7** in $SbCl_5$ matrix at 150 K.

stretching regions of the experimental spectrum agree with the frequencies and intensities calculated for aminocyclobutenyl cation **12** (Fig. 5), which also suggests the hydride migration mechanism:



8 **12**

The frequency of the asymmetric CCC$^+$ stretching of the allyl group in **12** at 1386 cm^{-1} (the scaled calculated value is 1336 cm^{-1}) is close to values previously measured for other cyclobutenyl cation analogs.[7] The absorption of the amino group vibration at 3504 cm^{-1} is almost at the same position as in the spectrum obtained from the reaction of **2** with SbF_5.

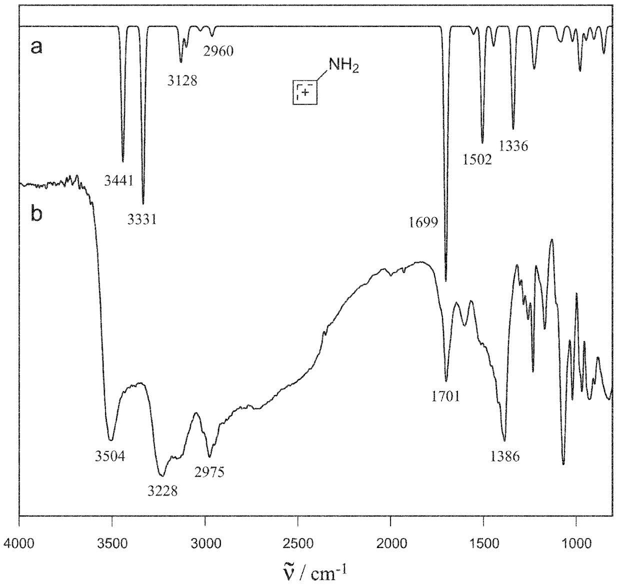


Fig. 5 (a) Scaled MP2(fc)/6-31G(d) IR spectrum of **12**. (b) FT-IR spectrum of the product mixture obtained by reaction of **8** in $SbCl_5$ matrix at 150 K.

Cyclopentanone oxime (2)

Possible structures of the reactive intermediates that could be formed by reaction of **2** with superacids are proposed in Scheme 3. From results of calculations at different levels of theory, **5** is found to be the global minimum on this $C_5H_8N^+$ potential energy surface (Table 1). Its stability is a result of additional stabilization of the allyl cation sub-structure by back donation of n-electrons from the nitrogen atom. Consequently, if the reaction of **2** proceeds through any kind of the hydride migration, ion **5** is the most probable candidate to be isolable. The cyclic nitrylium cation **3**, which could be the intermediate in classical Beckmann rearrangement is more stable than **4**, but less stable than **5**. It is difficult to believe in the persistence of such a six-membered ring molecule with such a highly strained

CN triple bond. However, none of the calculated spectra of possible intermediates containing a five-membered ring completely agree with the experimental spectrum obtained by reaction of **2** with SbF_5. It is likely that the reaction yields a mixture of cationic reaction intermediates. The calculated spectra of the most probable structures as well as the experimental spectrum are shown in Fig. 6.

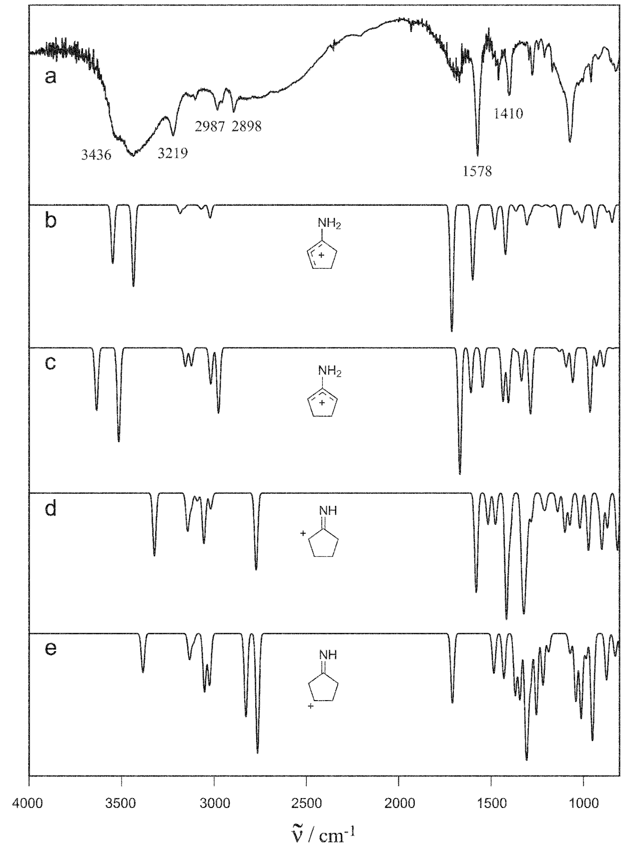


Fig. 6 (a) FT-IR spectrum of the product mixture obtained by reaction of **2** in $SbCl_5$ matrix at 150 K. (b)–(e) Scaled MP2(fc)/6-31G(d) IR spectra of possible reaction intermediates.

Complexes of cyclopentanone oxime (2) with SbF_5

Geometries of the **2**–SbF_5 complexes (**13** and **17**) were calculated at the MP2(fc)/6-31G(d) level of theory and shown are in Fig. 7. The most stable structure corresponds to the *N*-coordinated complex (**17**). It should be pointed out that the smallest distances between fluorine atoms on SbF_5 and the α-hydrogens in both complexes range from 2.0 Å to 2.5 Å, which implies the formation of hydrogen bonds. Such an effect might play an important role in the hydrogen migration process in the reactions of small ring cyclic oximes.

Conclusions

The mechanism of the Beckmann rearrangement of cyclic oximes depends on the ring size of the starting oxime and on external conditions such as phase or acidity. Because the ring expansion of four- and five-membered oximes leads to highly strained cyclic nitrylium cations (such as **3**), the favored reaction pathway in solid superacid is hydride migration. Such a shift was confirmed by investigation of the reaction of cyclopropylethanone oxime **7**, which rearranges by a [1,3] hydride shift to the stable allyl cation **11**. Other reactive intermediates observed in the matrix include aminoallyl cations **12** and possibly **5**. Ion **12** is the simplest cyclobutenyl cation observed and was characterized in the condensed phase. Hydrogen bonds formed between halogen atoms in the superacid molecule and the α-hydrogens of the oxime can play a role in the hydride transfer either by *inter*- or by *intra*molecular processes. This follows from the calculated structure of the complex of cyclopentanone oxime with SbF_5.

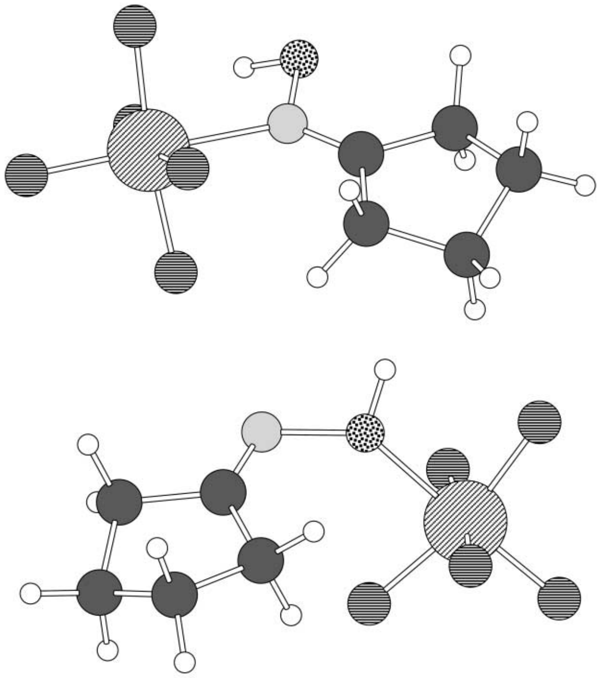


Fig. 7 The structure of the complexes **2**–SbF_5 (**17** and **13**) calculated at the MP2(fc)/6-31G(d) level of theory.

Ionization of **6** in solid superacid yields the nitrylium ion **9** as a stable reactive intermediate. Consequently, in contrast with cyclobutanone oxime and cyclopentanone oxime, six-membered and higher cyclic oxime homologues preferentially undergo classical Beckmann-type rearrangement to a nitrilium cation. The ion **9** is the most strained cyclic nitrylium ion characterized in the condensed phase to date. Its C–N–C angle deviates 47.2° from linearity.

Experimental

General

All reagents and solvents were *pa* grade materials purchased from commercial sources and were used without further purification. Infrared spectra were recorded on a Perkin-Elmer 1725x FT-IR spectrometer with 2 cm^{-1} resolution. The ^{13}C NMR spectra were recorded on a Varian Gemini 300 spectrometer operating at 75 MHz, with TMS as an internal standard and CDCl3 as the solvent.

Synthetic procedures

Preparation of oximes. All the compounds were prepared by using the following procedure.

The ketone and hydroxylamine hydrochloride were placed in a 100 ml flask equipped with stirrer. The pH of the solution was held at 7–8 by adding saturated aq. sodium carbonate (5 ml). The resulting solution was stirred at 40 °C. After extraction with ether, the solution was dried over Na_2SO_4 and evaporated.

Cyclobutanone oxime[8]. The product (97%) was a white solid; mp 75–78 °C. IR (KBr) ν/cm^{-1}: 976 (N=O), 1701 (C=N), 3100–3300 (O–H); ^{13}C NMR δ/ppm: 14.17, 30.24, 31.18, 159.82.

Cyclopentanone oxime[8]. The product (81%) was a white solid, mp 55–57 °C. IR (KBr) ν/cm^{-1}: 980 (N–O), 1693 (C=N), 2900–3200 (O–H); ^{13}C NMR δ/ppm: 22.52, 23.43, 25.23, 163.5.

Cyclohexanone oxime[8]. The product (70%) was a white solid, mp 87–89 °C. IR (KBr) ν/cm^{-1}: 911 (N–O), 1617 (C=N), 2900–3200 (O–H); ^{13}C NMR δ/ppm: 24.22, 25.35, 26.57, 31.78, 160.5.

1-Cyclopropylethanone oxime[8]. The product (86%) was a white solid, mp 38–40 °C. IR (KBr) ν/cm^{-1}: 961 (N–O), 1656 (C=N), 2900–3200 (O–H); ^{13}C NMR δ/ppm: 4.2, 4.7, 10.4, 15.0, 159.4.

Matrix experiment

All the matrices were prepared on a CsI window cooled by a closed cycle cryostat ROK 10-300 Leybold Heraeus connected to vacuum line equipped with an oil diffusion pump. During the deposition, the temperature was held at 70 K and vacuum at 10^{-5} Torr. The flow of the sample was regulated by a Teflon valve. The deposition times were 5 min in all experiments. The matrix material (SbF_5 or $SbCl_5$) to sample ratio was estimated to be 500:1.

Computational methods

All of the calculations were conducted with the program GAMESS (R3 version of 26th October 2000),[9a] using the MP2 method with a frozen-core approximation and standard 6-31G(d) split valence basis set with added polarization functions on non-hydrogen atoms. It was unnecessary to use larger basis sets like 6-311G(d,p) since they gave essentially the same final geometries and frequencies. For the calculations of the SbF_5 complex we used the 6-31G(d) basis set for the oxime part, and the 3-21G(*) basis set for the SbF_5 part of the complex (*i.e.* 3-21G with the additional d-functions on antimony). The geometries of all of the structures studied were fully optimized, using any existing molecular symmetry. Then, at the same level of theory, harmonic vibrational frequencies were calculated, both for the comparison with the experimental spectra and for the confirmation that the optimized structure is indeed a minimum at the chosen potential energy surface. Vibrational frequencies were scaled down with the literature scaling factor 0.9434.[10] Vibrational normal modes were visualized and analyzed with the help of the program MacMolPlot.[9b]

Acknowledgements

This work was supported by Ministry of Science and Technology of the Republic of Croatia (Grants 0119611 and 0119612).

References

1 (*a*) E. Beckmann, *Chem.Ber.*, 1886, **89**, 988; (*b*) M. O. Glocker, P. B. Shrestha-Davadi, J. Küchler-Krischun, J. Hofmann, H. Fischer and J. C. Jochims, *Chem. Ber.*, 1993, **126**, 1859; (*c*) M. T. Nguyen and L. G. Vanquickenborne, *J. Chem. Soc., Perkin Trans. 2*, 1993, 1969; (*d*) P. A. Hunt and H. S. Rzepa, *J. Chem. Soc., Chem. Commun.*, 1989, 623; (*e*) M. T. Nguyen, G. Raspoet and L. G. Vanquickenborne, *J. Am. Chem. Soc.*, 1997, **119**, 2552 and references therein.

2 (*a*) H. Vančik and D. E. Sunko, *J. Am. Chem. Soc.*, 1989, **111**, 2742; (*b*) H. Vančik, *Pure Appl. Chem.*, 1995, **67**, 761.

3 (*a*) G. Olah and A. Kiovsky, *J. Am. Chem. Soc.*, 1968, **90**, 4666; (*b*) R. Hoti, Z. Mihalić and H. Vančik, *Croat. Chem. Acta*, 1995, **68**, 359.

4 M. Hitzler, M. Lutz, P. B. Shrestha-Davadi and J. C. Jochims, *Liebigs Ann. Chem.*, 1996, 247.

5 (*a*) P. Buzek, P. v. R. Schleyer, H. Vančik, Z. Mihalić and J. Gauss, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 448 and references therein; (*b*) R. W. Moncrieff and D. P. Young, *Br. Pat.*, 563–783 (*Chem. Abstr.*, 1946, **40**, 3143(3)).

6 (*a*) D. Kiđemet, Z. Mihalić, I. Novak and H. Vančik, *J. Org. Chem.*, 1999, **63**, 4931; (*b*) H. Vanćik, Z. Mihalić and D. Kiđemet, *Croat. Chem. Acta*, 1996, **69**, 1511; (*c*) H. Vančik, V. Gabelica, D. E. Sunko, P. Buzek and P. v. R. Schleyer, *J. Phys. Org. Chem.*, 1993, **6**, 427; (*d*) H. Vancik, *Croat. Chem. Acta*, 2000, **73**, 595.

7 T. J. Katz and E. H. Gold, *J. Am. Chem. Soc.*, 1964, **86**, 1600.

8 P. Fournar, P. Cointet and E. Laviron, *Bull. Soc. Chim. Fr.*, 1968, **6**, 2438.

9 (*a*) M. W. Schmidt, K. K. Baldridge, J. A. Boatz, S. T. Elbert, M. S. Gordon, J. H. Jensen, S. Koseki, N. Matsunaga, K. A. Nguyen, S. J. Su, T. L. Windus, M. Dupuis and J. A. Montgomery, *J. Comput. Chem.*, 1993, **14**, 1347; (*b*) B. M. Bode and M. S. Gordon, *J. Mol. Graphics Model.*, 1999, **16**, 133.

10 A. P. Scott and L. Radom, *J. Phys. Chem.*, 1996, **33**, 16502.