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Product channels in the 193-nm photodissociation of HCNO (fulminic acid)

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ABSTRACT

IR diode laser spectroscopy was used to detect the products of HCNO (fulminic acid) photolysis at 193 nm. Six product channels are energetically possible at this photolysis wavelength: O + HCN, H + NCO/CNO, CN + OH, CO + NH, NO + CH and HNCO. In some experiments, isotopically labeled ¹⁵N¹⁸O, C₂D₆ or C₆H₁₂ reagents were included into the photolysis mixture in order to suppress and/or redirect possible secondary reactions. HCN, $OC^{18}O$, ¹⁵N¹⁵NO, CO, DCN and HNCO molecules were detected upon laser photolysis of HCNO/reagents/buffer gas mixtures. Analysis of the yields of product molecules leads to the following photolysis quantum yields: $\phi_{1a} (O + HCN) = 0.38 \pm 0.04$, $\phi_{1b} (H + (NCO)) = 0.07 \pm 0.02$, $\phi_{1c} (CN + OH) = 0.24 \pm 0.03$, $\phi_{1d} (CO + NH(a^1\Delta)) < 0.22 \pm 0.1$, $\phi_{1e} (HNCO) = 0.02 \pm 0.01$ and $\phi_{1f} (CH + NO) = 0.21 \pm 0.1$, respectively.

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1. Introduction

Fulminic acid (HCNO) and isocyanic acid (HNCO) are important intermediates in NO-reburning processes for reduction of NO_x pollutants from fossil-fuel combustion emission [1] and have also been found existing in a large variety of environments in the interstellar medium [2]. HCNO (fulminic acid) is the less stable isomer of isocyanic acid; the kinetics of several reactions involving HCNO has only recently been studied [3–7]. There is only one previous study of the photochemistry of HCNO, an infrared laser spectroscopic study from our laboratory that identified five separate photolysis channels in the 248 nm photodissociation of this molecule [8].

In this paper, we extend the previous study to include photolysis at 193 nm. At this wavelength, an additional channel (1f) becomes energetically accessible, resulting in six possible channels:

$$HCNO + hv (193 \text{ nm}) \longrightarrow O + HCN$$
(1a)

$$\longrightarrow H + (NCO) \tag{1b}$$

$$\rightarrow OH + CN$$
 (1c)

$$\longrightarrow CO + NH(a^{1}\Delta)$$
(1d)

$$\longrightarrow$$
 HNCO (1e)

$$\rightarrow$$
 CH + NO (1f)

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NCO is written as (NCO) to indicate that we cannot distinguish between NCO and CNO isomers in this study, because we detect secondary products of NCO (or CNO) reactions, rather than the NCO radical itself. Fig. 1 shows the energetics of these species. The thermochemical information has been obtained from standard tables [9] as well as other literature for the heats of formation of NCO [10] and NH ($a^{1}\Delta$) [11]. Formation of ground state NH (X ${}^{3}\Sigma^{-}$) is also possible, but is less likely as it is a spin-forbidden process.

2. Experimental section

The experimental apparatus was described in our previous study [8]. Briefly, HCNO was photolyzed by 193 nm light from an excimer laser (Coherent, Compex-pro). Reaction products were detected by transient infrared diode laser absorption spectroscopy using lead salts diode lasers (Laser Components) operating in the 80–110 K temperature range. Transient infrared absorption signals were recorded on a digital oscilloscope (Lecroy, Wavesurfer 422) and transferred to a computer for analysis. All experiments were performed at 298 K.

HCNO samples were synthesized as previously described [8,12–14] by flash vacuum pyrolysis of 3-phenyl-4-oximino-isoxazol-5(4H)-one. Sample purity was characterized by FT-IR spectroscopy via a strong HCNO absorption band at 2195 cm⁻¹ [15], and a strong HNCO band at 2168 cm⁻¹ [16]. The sample purity was estimated at 95% or better, with only small CO₂ and









Fig. 1. Relative energy levels of possible photolysis products of HCNO photolysis. Thresholds (kJ/mol) compared to HCNO: -291.2 (HNCO), 95.1 (CO + NH (X $^{3}\Sigma^{-}$)), 174.5 (H + NCO), 213.3 (O + HCN), 261.9 (CO + NH ($a^{1}\Delta$)), 303.1 (OH + CN), 436.6 (H + CNO), 516.1(CH + NO), 620 (193 nm photon) and 482.6 (248 nm photo).

HNCO impurities. Samples were kept at 77 K except when filling the reaction cell.

 CF_4 and SF_6 (Matheson) was purified by repeated freezepump-thaw cycles at 77 K and by passing through an Ascarite II column to remove traces of CO_2 . ¹⁵N¹⁸O (Isotec) was purified by repeated freeze-pump-thaw cycles at 153 K. The following molecules were probed using infrared diode laser absorption spectroscopy:

The HITRAN molecular database was used to locate and identify the spectral lines of $OC^{18}O$ and HCN product molecules [17]. Other published spectral data were used to locate and identify DCN [18], $^{15}N_2O$ [19] and HNCO [16] lines.

Typical experimental conditions were P(HCNO) = 0.1 Torr, $P(^{15}N^{18}O) = P(^{15}N^{16}O) = 1.0$ Torr, $P(SF_6) = P(CF_4) = 1.50$ Torr, $P(C_2D_6) = 0.5-7.0$ Torr, $P(C_6H_{12}, \text{ cyclohexane}) = 0.5-3.0$ Torr and 193 nm laser pulse energies of 8.5 mJ (fluence of ~30 mJ/cm²). In order to minimize waste of HCNO samples, all experiments were performed using static gas fills. Typical transient signals were signal averaged over only four photolysis laser shots, after which the gas cell was evacuated and refilled for further experiments. This procedure minimizes any buildup of photolysis products, and therefore minimizes effects of secondary photolysis laser shots was observed.

3. Results

Infrared diode laser absorption was used to detect product molecules (or products of secondary chemistry) from channel (1a)-(1f) upon 248 nm laser photolysis of HCNO/ buffer gas. In order to modify and/or suppress potential secondary chemistry, additional reagents were sometimes included in the reaction mixture, as described below. Fig. 2 shows two typical signals for detection of HCN and CO₂ molecules. The purpose of the isotopic labeling will be discussed in Section 3.2, below. Typically, transient



Fig. 2. Transient signals of HCN and ¹⁶OC¹⁸O detected upon laser photolysis of HCNO (0.1 Torr)/¹⁵N¹⁸O (1 Torr)/SF₆ (1.5 Torr) mixture.

signals show a fast (~10–100 µs) rise, followed by a slow (~1 ms) decay. The rise is attributed to formation of the detected product by either direct photolysis and/or subsequent secondary chemistry, as described below. The decay is attributed to diffusion of molecules out of the probed volume. The rate of the rise is primarily determined by the rate of collisional relaxation of a nascent vibrational distribution to a Boltzmann distribution. The buffer gas (CF₄ or SF₆) was used to maximize this relaxation rate. Our product yield measurements assume that the detected products have reached a Boltzmann distribution of internal states on the 10–100 µs timescale of the transient signals.

In order to estimate the yields, the slow decay portion of each transient signal was fit to a single exponential decay function. Transient signal amplitudes were obtained by extrapolation to t = 0 (this extrapolated amplitude was typically a small (~5–15%) increase compared to the peak–peak amplitudes). Because the correction vs. the peak–peak amplitude is small, and about the same for different detected molecules, errors in this procedure due to the fact that diffusion out of a cylindrical volume is not strictly exponential are insignificant.

The resulting amplitudes were converted into absolute concentrations using HITRAN line strengths for all of the detected molecules except for DCN molecules, which were calibrated. Table 1 shows the resulting yields of the detected molecules.

Our previous studies [2–6] show that HCNO is a highly reactive molecule. Many secondary reactions following the photolysis can therefore occur. Most but not all of this secondary chemistry is identical to that considered in our previous study [8]:

Table 1

Raw product yields.^a

Product	Yield (in units of 10^{12} molecule cm ⁻³)
HCN OC ¹⁸ O	17.9 ± 1.8
DCN	1.0 ± 0.1 11.1 ± 1.2
CO HNCO	<10.3 ± 2.0 1 0 + 0 2
¹⁵ N ₂ O	9.3 ± 0.7

^a Experimental conditions: P(HCNO) = 0.1 Torr, P(¹⁵N¹⁸O) = P(¹⁵N¹⁶O) = 1.0 Torr, P(SF₆) = 1.5 Torr (for HCN, NCO and DCN detection), P(CF₄) = 1.5 Torr (for CO detection only), 193 nm photolysis laser pulse energy ~8.5 mJ. Uncertainties represent one standard deviation.

 $0 + HCNO \longrightarrow H + CO + NO$ (2)

 $CN + HCNO \longrightarrow NO + HCCN$ (3)

 $NCO + HCNO \longrightarrow HCN + CO + NO$ (4)

 $OH + HCNO \longrightarrow CO + H_2NO$ (5a)

$$\longrightarrow$$
 HCO + HNO (5b)

$$\rightarrow NO + H_2CO$$
 (5c)

$$\mathbf{NH} + \mathbf{HCNO} \longrightarrow \mathbf{products} \tag{6}$$

$$H + HCNO \longrightarrow products \tag{7}$$

Reactions (2)–(6) have been studied previously in our lab [2–6], resulting in the following rate constants: $k_2 = (5.32 \pm 0.4) \times 10^{-12} - \text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$, $k_3 = (1.04 \pm 0.1) \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$, $k_4 = (1.58 \pm 0.2) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$, $k_5 = (3.4 \pm 0.3) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ and $k_6 \leq 2.1 \times 10^{-13} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ at 298 K. While the rate of H + HCNO, reaction (7), is not experimentally known, our previous study [8] showed that it was too slow to affect the results of HCNO photolysis experiments. Reactions (2)–(5) are fast and may produce some of the same product molecules as those probed in these experiments, potentially complicating the interpretation of product yields. The approach used here is similar to that used previously [8], in which we include additional reagents in the reaction mixture in order to suppress or redirect these secondary reactions, as described in detail below.

Some additional secondary chemistry, potentially present in this study but not relevant to our previous study, is due to the possible presence of channel (1f), forming CH + NO photoproducts. This channel was not energetically accessible at 248 nm, but is at 193 nm. If this channel is active, the following reaction must be considered:

$$CH + HCNO \longrightarrow products$$
 (8)

The rate constant of reaction (8) is unknown, but CH is a highly reactive species, so it is likely that this reaction is fast. Products are also unknown, but likely include many of the same molecules probed in these experiments.

3.1. Product channel (1f), CH + NO

The most obvious approach to quantifying this channel would be to directly detect and quantify the yield of NO products. This approach is complicated, however, by secondary sources of NO, including reaction (2)–(4), (5c), etc. We therefore used an alternative approach to detect this channel: we included an excess of $^{15}N^{16}O$ in the reaction mixture: HCNO (0.1 Torr)/ $^{15}N^{16}O$ (1.0 Torr)/SF₆ (1.5 Torr). Under these conditions, any CH radicals produced in (1f) will react with $^{15}N^{16}O$ as follows:

$$CH + {}^{15}NO \longrightarrow {}^{15}NCO + H \tag{9a}$$

$$\longrightarrow HC^{15}N + 0 \tag{9b}$$

The product branching ratio of reaction has been estimated to be $\varphi_{9a} = 0.21 \pm 0.1$; $\varphi_{9b} = 0.72 \pm 0.1$ [20]. A subsequent secondary reaction then produces ¹⁵N¹⁵NO:

$${}^{5}\mathrm{NCO} + {}^{15}\mathrm{NO} \longrightarrow {}^{15}\mathrm{N}{}^{15}\mathrm{NO} + \mathrm{CO}$$
(10a)

$$\longrightarrow {}^{15}\mathrm{N}{}^{15}\mathrm{N} + \mathrm{CO}_2 \tag{10b}$$

(Product branching ratios at 296 K: $\varphi_{10a} = 0.44 \pm 0.07$; $\varphi_{10b} = 0.56 \pm 0.07$) [21,22].

We then detected the double labeled ${}^{15}N^{15}NO$ molecule, using spectral line positions reported previously [19]. Although the branching ratio into (9a) is modest, N₂O is a very strong infrared absorber, so this experiment has a reasonably low detection limit. We found a small transient signal attributable to ${}^{15}N^{15}NO$, shown in Fig. 3.

3.2. Product channel (1a), O + HCN

The procedure for quantification of channel (1a) is similar to that described previously [8]. We directly detect the HCN photolysis product by transient absorption, as shown in Fig. 2 (top panel). The HCN yield from photolysis of HCNO could arise from channel (1a), but also may have contributions from reaction (4) if channel (1b) is significant. By including an excess of isotopically labeled ¹⁵N¹⁸O reagent, however, reaction (4) is suppressed:

$$NCO + {}^{15}N^{18}O \longrightarrow N^{15}N^{18}O + CO$$
 (10a)

$$\longrightarrow N^{15}N + OC^{18}O \tag{10b}$$

where $\varphi_{10a} = 0.44$ and $\varphi_{10b} = 0.56$ [21,22], and $k_{10} = (4.3 \pm 0.4) \times 10^{-11}$ cm³ molecule⁻¹ s⁻¹ [6]. Based on the rate constant of (4) and (10), we estimate that a 10:1 ratio of ${}^{15}N^{18}O$ to HCNO is sufficient to ensure that nearly all NCO radicals react by (10) rather than (4), and therefore do not result in HCN production. Reaction (10) will not suppress reaction (3), CN + HCNO, because the CN + NO reaction is slow at the low pressures used in these experiments. Reaction (3) produces HCCN radicals [4,7] which then react with ${}^{15}N^{18}O$, producing labeled HC¹⁵N molecules:

$$CN + HCNO \longrightarrow NO + HCCN$$
 (3)

$$\mathrm{HCCN} + {}^{15}\mathrm{N}{}^{18}\mathrm{O} \longrightarrow \mathrm{HC}{}^{15}\mathrm{N} + \mathrm{NC}{}^{18}\mathrm{O} \tag{11}$$

In these experiments, however, we detect the non-labeled HC¹⁴N isotope, which is not affected by this secondary chemistry. The nitrogen-15 labeling is therefore important for this experiment

Fig. 3. The $^{15}\rm N^{15}NO$ transient IR absorption signal detected upon photolysis of HCNO (0.1 Torr)/ $^{15}\rm N^{16}O$ (1.0 Torr)/SF₆ (1.5 Torr).

60

(the oxygen-18 labeling is not). We also note that any CH formed from channel (1f) will react with ¹⁵N¹⁸O, effectively suppressing reaction (8). Although CH + NO produces HCN as a product, CH + $^{15}N^{18}O$ would make HC¹⁵N, not the detected HC¹⁴N molecule.

Other potential secondary reactions, such as O + HCNO, OH + HCNO, NH + NO, and NH + HCNO do not produce significant amounts of HCN. Therefore, we can confidently attribute the HCN signal obtained upon photolysis of a HCNO $(0.1 \text{ Torr})/^{15}\text{N}^{18}\text{O}$ (1.0 Torr)/SF₆ (1.5 Torr) mixture, as shown in Fig. 2, to photolysis channel (1a).

3.3. Product channel (1b), H + (NCO)

We assume here, as in our previous study [8] that if the high energy CNO isomer is formed, it quickly converts to the more stable NCO; as a result we do not distinguish between NCO and CNO. In order to quantify the yield of this channel, we added isotopically labeled ¹⁵N¹⁸O reagent in the photolysis mixture as described above (Section 3.2), resulting in reaction (10), to produce $OC^{18}O$. A transient signal is shown in Fig. 2 (bottom panel). (In this experiment, the oxygen-18 labeling is crucial, while the nitrogen-15 labeling is not). Assuming an excess of ¹⁵N¹⁸O, resulting in most NCO radicals reacting via (10), and knowing the branching ratio of $\varphi_{10b} = 0.56$, we quantify the yield of NCO molecules originally produced in photolysis channel (1b):

 $[NCO]_{1b} = [OC^{18}O]/0.56$

Additional secondary chemistry that can also produce $\mbox{\rm CO}_2$ includes

$$CN + HCNO \longrightarrow NO + HCCN$$
 (3)

 $HCCN + {}^{15}N^{18}O \longrightarrow HC^{15}N + NC^{18}O$ (11)

$$NC^{18}O + {}^{15}N^{18}O \longrightarrow N^{15}N + {}^{18}OC^{18}O$$
(10b*)

The notation (10b*) is used to identify an isotopic variant of reaction (10b). CO_2 molecules in reaction (10b*) are double labeled ($^{18}OC^{18}O$) and do not contribute to the yield of the detected $OC^{18}O$. A similar argument can be made for secondary chemistry involving CH radicals: reactions (9a) and (10b), when using $^{15}N^{18}O$, would also produce $^{18}OC^{18}O$, not the detected $OC^{18}O$.

3.4. Product channel (1c), CN + OH

In our previous publication [8], several approaches were used to quantify the CN + OH channel. The most effective method proved to be the addition of deuterated ethane, C₂D₆, resulting production of DCN:

$$CN + C_2 D_6 \longrightarrow C_2 D_5 + DCN$$
 (12)

This approach was used in the present experiments. Fig. 4 shows the resulting transient signal for DCN. We measured these DCN signals as a function of C_2D_6 pressure upon photolysis of HCNO (0.1 Torr)/ C_2D_6 (variable: 0.5–7.0 Torr)/SF₆ (1.5 Torr) mixtures. These data, after calibration by a procedure described previously [8], which includes a modest correction for pressure broadening effects, are shown in Fig. 5.

As shown in Fig. 5, the DCN yield has not become completely constant even at the highest C_2D_6 pressures used. As discussed previously [8], this is roughly consistent with the relevant kinetics; $k_{12} \sim 1.2 \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ [8], and $k_3 = (1.04 \pm 0.1) \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ [4]. Based on the rate constants involved, we estimate that about 30 Torr of C_2D_6 is needed for reaction (12) to suppress most of reaction (3). The data was therefore fit to an



Fig. 4. Transient signal of DCN detected upon photolysis of HCNO (0.1 Torr)/ C_2D_6 (5.0 Torr)/ SF_6 (1.5 Torr) mixture.



Fig. 5. The yields of DCN as the function C_2D_6 pressures. DCN was detected upon photolysis of HCNO (0.1 Torr)/ C_2D_6 (variable: 0–7.0 Torr)/SF₆ (1.5 Torr) mixture; 193 nm photolysis laser pulse energy ~8.5 mJ. The experimental data were simulated by an function: $y = 34.1 - 28.5e^{-(x+3.0)/152.8} - 840.2e^{-(x+3.0)/0.6} - 908.1e^{-(x+3.0)/0.6}$.

empirical three parameter exponential equation, as shown in Fig. 5. Extrapolating this equation, we estimate $[DCN] = (1.11 \pm 0.12) \times 10^{13}$ molecule cm⁻³ at $[C_2D_6] = 30$ Torr. This result is shown in Table 2.

Table 2Yields of product channels of HCNO photolysis.^a

Product	Yield (in units of 10^{12} molecule cm ⁻³)	
HCN	17.9 ± 1.8	
NCO	3.2 ± 0.2	
CN	10.1 ± 1.2	
СО	<10.3 ± 2.0	
HNCO	1.0 ± 0.2	
СН	9.8 ± 0.8	
Total	43.0	

^a Experimental conditions are same as in Table 1.

3.5. Product channel (1d), CO + NH

We investigated the channel by direct detection of CO. If an excess of a hydrocarbon molecule such as C_6H_{12} (cyclohexane) is included, most of the secondary chemistry of radicals reacting with HCNO is suppressed, as follows:

$$O + C_6 H_{12} \longrightarrow OH + C_6 H_{11} \tag{13}$$

$$\mathbf{OH} + \mathbf{C}_6 \mathbf{H}_{12} \longrightarrow \mathbf{H}_2 \mathbf{O} + \mathbf{C}_6 \mathbf{H}_{11} \tag{14}$$

$$CN + C_6 H_{12} \longrightarrow HCN + C_6 H_{11}$$
(15)

$$NCO + C_6 H_{12} \longrightarrow HNCO + C_6 H_{11}$$
(16)

Fig. 6 shows the CO yield obtained upon 193-nm photolysis of HCNO is the presence of C_6H_{12} . As shown, the yield drops as the C_6H_{12} pressure is increased, indicating that reactions (13)–(16) do in fact suppress much of the secondary chemistry, reactions (2)–(5). At about 2–3 Torr of C_6H_{12} , the CO yield has reached an approximately constant value. By comparing the rate constants of (13)–(16) with those of (2)–(5), we estimate that this cyclohexane pressure is sufficient to suppress most of reactions (2), (3) and (5), but probably only partially suppressed reaction (4), because reaction (16) is relatively slow. We therefore must interpret the limiting CO yield in Fig. 6 as an estimate of the upper limit to the yield of channel (1d).

3.6. Product channel (1e), HNCO

As shown in Fig. 7, a small absorption transient was detected for HNCO, the result of photoisomerization. This signal (peak amplitudes) was converted to an absolute concentration using the calibration procedure described previously [8]. This measurement is subject to significant uncertainties that are described in detail in our previous study [8], but we do estimate a very small yield of channel (1e).

3.7. Summary of quantum yields

Table 1, as described above, shows the raw yields of the detected molecules. Table 2 shows the resulting yields of the six HCNO photolysis channels after the above analysis to account for secondary chemistry. The sum of the channels gives a total product yield of 4.3×10^{13} molecule cm⁻³. We then converted the product



Fig. 6. The CO yield as the function of the added C_6H_{12} concentration. Transient signal of CO radical detected upon photolysis of HCNO (0.1 Torr)/ C_6H_{12} (cyclohexane, variable pressure)/ CF_4 (1.5 Torr) mixture.



Fig. 7. The HNCO transient IR absorption signal detected upon photolysis of HCNO (0.1 Torr)/SF₆ (1.5 Torr) using the R(10) line of HNCO. The brief negative spike at t = 0 is an artifact due to a small HNCO impurity present in the mixture.

Table 3
Quantum yields of HCNO photolysis products at 248 and 193 nm.

Product channel	$\phi (248 \text{ nm})^{a}$	$\phi (193 \text{ nm})^{b}$
O + HCN	0.39 ± 0.07	0.38 ± 0.04
H + (NCO)	0.21 ± 0.04	0.07 ± 0.02
CN + OH	0.16 ± 0.04	0.24 ± 0.03
NH + CO	0.19 ± 0.03	<0.22 ± 0.04
HNCO	0.05 ± 0.02	0.02 ± 0.01
CH + NO	0.00	0.21 ± 0.06
Total	1.00 ± 0.15	0.92-1.11

^a Results from Ref. [8].

^b Results from this study.

yields into photolysis quantum yields, using a measured value of the UV absorption coefficient of HCNO at 193 nm: $\alpha_{193} =$ $(1.83 \pm 0.16) \times 10^{-2}$ Torr⁻¹ cm⁻¹, equivalent to a cross section of $\sigma_{193} = (5.65 \pm 0.48) \times 10^{-19}$ cm² molecule⁻¹. Under the experimental conditions of Table 2, we estimate the number density of absorbed photons to be 4.69×10^{13} molecule cm⁻³. We then determined the quantum yields, as shown in Table 3. The sum of the quantum yields is 0.92–1.14, depending on the value used for the NH + CO channel. The uncertainties quoted in Table 3 include random errors (1 σ) inherent in the measurements as well as consideration of systematic errors, primarily due to estimated uncertainties in the infrared linestrengths and HCNO UV absorption coefficient. The yield of NH + CO is expressed as an upper limit, as described above.

It is worthwhile to compare our current results at 193-nm with the previously obtained 248-nm photolysis yields. As shown in Table 3, multiple channels are present at both photolysis wavelengths, although channel (1e) is sufficiently minor to be considered negligible. At both wavelengths, O + HCN is the most important photolysis channel. The primary difference between the two wavelengths is that channel (1b), H + (NCO), is much less prevalent at 193 nm than at 248 nm, while channel (1f), which is not energetically accessible at 248 nm but is accessible and is a significant minor channel at 193 nm.

4. Conclusions

Infrared diode laser spectroscopy was used to study the photolysis products of fulminic acid (HCNO). The results show that six product channels have a measurable yield, and that O + HCN (1a) is the major but not dominant product channel. Photolysis quantum yields ϕ_{1a} (0 + HCN) = 0.38 ± 0.04, ϕ_{1b} (H + (NCO)) = 0.07 ± 0.02, ϕ_{1c} (CN + OH) = 0.24 ± 0.03, ϕ_{1d} (CO + NH(a¹ Δ)) < 0.22, ϕ_{1e} (HNCO) = 0.02 ± 0.01, ϕ_{1f} (CH + NO) = 0.21 ± 0.06, respectively.

Conflict of interest

The authors declare no conflict of interest.

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