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Dianailys Nuñez-Reyes, Jean-Christophe Loison, Kevin Hickson, Michel Dobrijevic. A low temperature investigation of the N(2 D) + CH 4 , C 2 H 6 and C 3 H 8 reactions. Physical Chemistry Chemical Physics, 2019, 21 (12), pp.6574-6581. 10.1039/C9CP00798A . hal-02322302

HAL Id: hal-02322302 https://hal.science/hal-02322302

Submitted on 11 Jan2021

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A low temperature investigation of the N(²D) + CH₄, C₂H₆ and C₃H₈ reactions

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Abstract

The gas-phase reactions between metastable nitrogen atoms, $N(^2D)$ and saturated hydrocarbons CH₄, C_2H_6 and C_3H_8 have been investigated using a supersonic flow reactor over the 296 - 75 K temperature range. $N(^2D)$ was generated as a product of the $C(^3P) + NO$ $\rightarrow N(^2D) + CO$ reaction, with $C(^3P)$ atoms created in-situ by pulsed laser photolysis of CBr₄. The kinetics of $N(^2D)$ loss were followed by vacuum ultraviolet laser induced fluorescence. The measured rate constants for the $N(^2D) + CH_4$ reaction are in good agreement with earlier work and extend the available kinetic data for this process down to 127 K. The measured rate constants for the $N(^2D) + C_2H_6$ and $N(^2D) + C_3H_6$ reactions are in reasonable agreement with previous work at room temperature and extend the available kinetic data for these processes down to 75 K. The rate constants for all three reactions decrease as the temperature falls, indicating the presence of activation barriers for all three processes. While the recommended values for the low temperature rate constants of the $N(^2D) + CH_4$ reaction are close to those reported here, the previous recommendations for the other saturated hydrocarbon reactions significantly overestimate the rate constants for these processes. The effects of the new rate constants on a coupled ion-neutral photochemical model of Titan's atmosphere are discussed.

1 Introduction

Nitrogen is the fifth most abundant element in the Universe behind hydrogen, helium, carbon and oxygen.¹ The reactions of atomic nitrogen are important processes in a wide range of astrochemical environments. In the interstellar medium, N-atoms in their ground electronic ⁴S state participate in a series of reactions with other nitrogen containing radicals, effectively controlling the transformation from N to N₂ in dense interstellar clouds.^{2, 3} In these regions, the specific form of the major elemental nitrogen reservoir (N or N₂) is critically important for the overall complexity of the molecules present, considering the highly unreactive nature of molecular nitrogen. Excited electronic states of atomic nitrogen, N(²D) and N(²P), play little or no role in the chemistry of the gas-phase interstellar medium as the timescale for radiative relaxation is shorter than the collision timescale. Nevertheless, in contrast to cold interstellar environments, excited state nitrogen atoms participate in the gas-phase chemistry of planetary atmospheres, where large fluxes of energetic photons and high densities lead to numerous collisions with the various atmospheric components. In the Earth's atmosphere, atomic nitrogen is produced through the short wavelength photodissociation of N₂ and through N₂ collisions with photoelectrons in the upper atmosphere.⁴ Indeed, the reactions of N(⁴S) and $N(^{2}D)$ with O_{2} are both thought to be major sources of NO in the thermosphere, while subsequent reactions of N(4S) and N(2D) with NO5, 6 limit the overall odd nitrogen concentration at these altitudes. In Titan's upper atmosphere, both N(⁴S) and N(²D) atoms are considered to be important reactive species for the formation of nitrogen-bearing compounds. While N(⁴S) atoms react with radicals such as CH₃,⁷ to form nitrogen containing hydrocarbon molecules such as H₂CN (and ultimately HCN),⁸ these ground state atoms are largely unreactive with the most abundant closed-shell hydrocarbon molecules present in Titan's atmosphere, CH₄, C_2H_2 , C_2H_4 and C_2H_6 . Instead, the more reactive metastable N(²D) atoms react with these molecules to form a range of amines, imines and nitriles⁹ (N(²P) is much less reactive than N(²D),¹⁰ so that the fate of these atoms is quenching to the ²D state through collisions with N₂, rather than reaction). Although the major reaction channels for the $N(^{2}D) +$ $CH_{4,11-15} N(^{2}D) + C_{2}H_{6,16} N(^{2}D) + C_{2}H_{4}^{-17, 18}$ and $N(^{2}D) + C_{2}H_{2}^{19-21}$ reactions have been identified theoretically and through crossed molecular beam experiments, there are few kinetics measurements of these processes and none at temperatures pertinent to Titan's atmosphere. For the $N(^{2}D) + CH_{4}$ reaction, the derived room temperature rate constants²²⁻²⁵ fall in the range $(3.0 - 5.4) \times 10^{-12}$ cm³ s⁻¹. Black et al.²² generated N(²D) atoms in their reactor through N₂O photolysis at 147 nm and 123.6 nm. N(²D) removal in the presence of coreagent CH₄ was followed using the chemiluminescent emission from NO(B² $\Pi \rightarrow X^2\Pi$)

produced by the $N(^{2}D) + N_{2}O$ reaction. In their study, Fell et al.²³ used a fast flow system where $N(^{2}D)$ atoms were produced through the microwave discharge of N_{2} diluted in He. The N(²D) concentration was monitored through electron spin resonance spectroscopy. They measured rate constants for N(²D) removal for numerous coreagent species including CH₄, C₂H₆ and C₃H₈. Umemoto et al.²⁴ created N(²D) atoms in their experiments through the multiphoton dissociation of NO at 275.3 nm. These authors detected N(²D) through twophoton excitation around 269 nm via the $2p^{3} {}^{2}D_{5/2}$ - $2p^{2}3p {}^{2}S$ transition. Rapid relaxation to the 2p²3s ²P state followed by VUV fluorescence at 149 nm allowed these authors to determine rate constants for the reactions of N(²D) with various species at room temperature including CH₄, C₂H₆ and C₃H₈. Takayanagi et al.²⁵ used the pulsed radiolysis – resonance absorption method to perform kinetic measurements over the 292 K- 223 K range, reporting a positive temperature dependence for the $N(^{2}D) + CH_{4}$ reaction, with the rate constant decreasing to a value of $(2.3 \pm 0.2) \times 10^{-12}$ cm³ s⁻¹ at 223 K. The Arrhenius parameters of A = 4.8×10^{-12} cm³ s⁻¹ and E/R = 750 recommended by Herron¹⁰ were based on the temperature dependence of the Takayanagi et al.²⁵ study and the earlier room temperature work (with a correction factor applied to the Fell et al. rate constants - see Herron¹⁰ for further justification). For the N(²D) + C₂H₆ and N(²D) + C₃H₈ reactions, kinetic studies have only been performed at room temperature. Fell et al.23 and Umemoto et al.24 obtained rate constants of 2.7×10^{-11} cm³ s⁻¹ and 2.1×10^{-11} cm³ s⁻¹ for the N(²D) + C₂H₆ reaction and 4.6 \times 10⁻¹¹ cm³ s⁻¹ and 3.1 \times 10⁻¹¹ cm³ s⁻¹ for the N(²D) + C₃H₈ reaction respectively. The recommended rate constants¹⁰ for these two reactions are 1.9×10^{-11} cm³ s⁻¹ (N(²D) + C₂H₆) and 2.9 \times 10⁻¹¹ cm³ s⁻¹ (N(²D) + C₃H₈) at 298 K, considering the correction factor of 0.6 that was systematically applied to the Fell et al. results. Given the lack of temperature dependent data, current models of Titan's atmosphere^{26, 27} consider temperature independent rate constants for these two processes, equal to the recommended room temperature values.

This study presents kinetic measurements for the $N(^2D) + CH_4$, C_2H_6 and C_3H_8 reactions down to 75 K using a Laval nozzle supersonic flow reactor. In this work, $N(^2D)$ atoms were generated by chemical reaction, employing the technique described by Nuñez-Reyes & Hickson⁶ during their investigation of the $N(^2D) + NO$ reaction. These atoms were detected through on-resonance pulsed laser induced fluorescence in the vacuum ultraviolet wavelength range. The experimental methods are presented in section 2 of the paper. The results are presented and discussed within the context of earlier work in Section 3. Section 4 discusses the astrophysical implications of the present work through an updated photochemical model of Titan's atmosphere. The conclusions are outlined in Section 5.

2 Experimental methods

The experiments performed in this study employed an existing continuous supersonic flow reactor whose main features have been described previously.²⁸⁻³⁰

Further modifications to the apparatus allowing the generation of narrowband tunable radiation in the vacuum ultraviolet wavelength range for the detection of atomic radicals in ground and excited electronic states are reported in later work $(C({}^{3}P),{}^{31-33} H({}^{2}S){}^{31, 33-41}$ and $D({}^{2}S), {}^{33, 42} O({}^{1}D),{}^{38, 41, 43-47}$ and $N({}^{2}D)).^{6}$ During this work, both Ar and N₂ were used as carrier gases as they result in only slow quenching of $N({}^{2}D)$ atoms.^{48, 49} The properties of the Laval nozzles employed in this work are summarized in Table 1.

1			
Mach number	1.83 ± 0.02^{a}	1.99 ± 0.03	2.97 ± 0.06
Carrier gas	N ₂	Ar	Ar
Density (× 10^{16} cm ⁻³)	9.4 ± 0.2	12.6 ± 0.3	14.7 ± 0.6
Impact pressure (Torr)	8.2 ± 0.1	10.5 ± 0.2	15.3 ± 0.5
Stagnation pressure (Torr)	10.3	13.9	34.9
Temperature (K)	177 ± 2	127 ± 2	75 ± 2
Mean flow velocity (ms ⁻¹)	496 ± 4	419 ± 3	479 ± 3
Chamber pressure (Torr)	1.4	1.5	1.2

 Table 1 Supersonic flow characteristics

^a The errors on the Mach number, density, temperature and mean flow velocity (1σ) are calculated from separate measurements of the impact pressure using a Pitot tube as a function of distance from the Laval nozzle and the stagnation pressure within the reservoir.

Room temperature measurements were also performed during the present investigation. These experiments were conducted at reduced flow velocities without a Laval nozzle, to ensure that no pressure gradients existed within the reactor. In a similar manner to the study of Nuñez-Reyes & Hickson,⁶ $N(^{2}D)$ atoms were generated chemically, through the reaction of ground state $C(^{3}P)$ atoms with nitric oxide

$$C(^{3}P) + NO \rightarrow N(^{2}D, ^{4}S) + CO \quad (1a)$$
$$\rightarrow O(^{3}P) + CN \quad (1b)$$

The ratio $[N(^{2}D) + N(^{4}S)]/[O(^{3}P)]$ has been estimated as 1.5 ± 0.3 at room temperature⁵⁰ while previous theoretical work predicts that the branching ratio for channel (1a) should decrease by

approximately 50 % between 300 K and 50 K.⁵¹ Ground state C(³P) atoms were produced by the pulsed multiphoton dissociation of carbon tetrabromide, CBr₄, at 266 nm with pulse energies around 26 mJ. C(¹D) atoms were also produced during the photolysis process.³¹ Possible interferences from secondary reactions are discussed below. To introduce these molecules into the system, a small flow of the carrier gas was diverted into a vessel containing solid CBr₄ at a known fixed (room) temperature and pressure before rejoining the main flow upstream of the Laval nozzle reservoir. The CBr₄ concentration in the flow was estimated to be less than 3.2×10^{13} cm⁻³ as determined by the product of the ratio of the CBr₄ vapour pressure and the total pressure and the flow rate through the vessel (P_{CBr_A}/P_{vessel}) × F_{vessel} . The method employed to follow N(²D) atoms in the present work was on-resonance pulsed laser induced fluorescence in the vacuum ultraviolet range (VUV LIF) via the 2s²2p³ ²D° - 2s²2p²(³P)3d ²F transition at 116.745 nm. Tunable radiation at and around this wavelength was produced in an identical manner to study of Nuñez-Reyes & Hickson⁶ where a more detailed description of the procedure for its generation can be found. The VUV radiation was collimated by a MgF₂ lens at the exit of the tripling cell and steered into the reactor through a 75 cm long sidearm containing baffles to reduce the flux of divergent residual UV radiation. The VUV beam overlapped with the cold supersonic flow at right angles. As the coreagents CH₄, C₂H₆ and C₃H₈ all absorb strongly in the VUV region, this zone was continuously flushed with either N₂ or Ar to minimize the attenuation of the probe beam. The solar blind photomultiplier tube detector (PMT) was placed at right angles to both the probe beam and the supersonic flow, collecting fluorescence from unreacted $N(^{2}D)$ atoms. The PMT was protected from reactive gases within the chamber by a LiF window while the zone separating the PMT from the reactor (containing a LiF lens to focus the VUV light onto the photocathode) was continuously evacuated by a dry pump. As signal levels were small compared with our earlier studies of atomic carbon and oxygen reactions, spurious light sources (residual UV light, scattered VUV light and window fluorescence) were reduced to a minimum, while it was also necessary to connect a preamplifier module to the output of the PMT before signal processing and integration by a boxcar system. Although this provided a substantial improvement in signal-to-noise levels, scattered light and/or window fluorescence from the photolysis laser which could not be entirely removed was also detected. This resulted in saturation of amplified signal for the first 15 microseconds following the photolysis pulse, preventing us from recording VUV LIF signals in this time period throughout the experiments. A delay generator was used to scan the time between photolysis and probe lasers to obtain the temporal profile of N(²D) atoms. 30 points were recorded at each time point with at least 70 time points recorded for each kinetic profile. Points recorded at negative time delays (that is with the probe laser pulse occurring before the photolysis laser one) allowed the baseline level to be established. Gases (Linde Ar 99.999%, Xe 99.999%, CH4 99.9995%, C₂H₆ 99.5%, C₃H₈ 99.5%, Air Liquide N₂ 99.999%, NO 99.9%) were used without further purification. Gas cylinders were attached to calibrated mass-flow controllers, allowing the various carrier gas and reagent flows to be regulated precisely.

Potential secondary chemistry

Although several secondary reactions could be occurring in the reactor during these experiments, these are not expected to interfere with the present measurements to any significant extent considering that N(²D) atoms are detected directly. A discussion of the influence of potential secondary reactions has already been provided by Nuñez-Reyes & Hickson⁶ for the simpler case of the $N(^{2}D) + NO$ reaction. In the present case, additional secondary processes arising from the reactions of photolysis products $C(^{3}P)$ and $C(^{1}D)$, quenching product N(⁴S), as well as reaction products CN and O(¹D) with the saturated hydrocarbon reagents also need to be considered. Both C(³P) and N(⁴S) atoms are unreactive with CH₄, C₂H₆ and C₃H₈ at room temperature and below, so that these reactions do not need to be considered further. Although $C(^{1}D)$ will react with all three of these reagents, leading to atomic products such as H(2S) and hydrocarbon radicals such as CH and CH₃,^{39, 52} these species will be present in low concentrations and none will yield N(²D) as a product through reaction with NO, the only nitrogen containing excess reagent present in the chamber. Similarly, although the CN and $O(^{1}D)$ products of the C + NO reaction react readily with saturated hydrocarbon molecules,^{38, 41, 53} none of these processes are thought to lead to the formation of $N(^2D)$ atoms.

3 Results and Discussion

The pseudo-first-order approximation was applied in these experiments, by maintaining both NO and the hydrocarbon reagent C_xH_{2x+2} in excess with respect to both C(³P) and N(²D). Under these conditions, the temporal profile of N(²D) atoms, $I_{N(^2D)}$, can be described by the following expression

$$I_{N(^{2}D)} = C(\exp(-k'_{a}t) - \exp(-k'_{b}t))$$
(2)

where C is a constant, k'_a is the pseudo-first-order rate constant for N(²D) removal, k'_b is the pseudo-first-order rate constant for N(²D) production and t is time. The term k'_a comprises

several contributions including the pseudo-first-order losses of N(²D) with NO $(k_{N(^2D)+NO}[NO])$, C_xH_{2x+2} $(k_{N(^2D)+C_xH_{2x+2}}[C_xH_{2x+2}])$, any other excess reagent (such as CBr₄ for example $(k_{N(^2D)+CBr_4}[CBr_4])$ and through diffusion $(k_{N(^2D),diff})$. As C(³P) atoms do not react with C_xH_{2x+2} , $k'_b = k_{C(^3P)+NO}[NO] + k_{C(^3P),diff}$. Nevertheless, as the first 15 microseconds of the N(²D) temporal profiles were not exploitable, it was more convenient to use a function of the form

$$I_{\rm N(^2D)} = \operatorname{Cexp}(-k'_{\rm a}t) \tag{3}$$

to describe the $N(^{2}D)$ signal as a function of time. In this respect, the starting points of individual fits were carefully chosen to avoid the rising part of the temporal profile. Figure 1 shows two profiles of the $N(^{2}D)$ fluorescence intensity as a function of time recorded at 296 K in the presence and absence of $C_{3}H_{8}$.



Figure 1 N(²D) VUV LIF intensity as a function time recorded at 296 K. (Red solid circles) without C₃H₈; (blue-solid circles) $[C_3H_8] = 2.3 \times 10^{15} \text{ cm}^{-3}$. The signal recorded in the presence of C₃H₈ has been multiplied by an arbitrary factor to allow a comparison of the two traces on the same intensity scale.

Decays similar to those displayed in Figure 1 were recorded at several values of $[C_xH_{2x+2}]$ whilst maintaining a fixed value for [NO]. In this way, any change in the observed decay rate of N(²D) atoms was entirely due to the change in $[C_xH_{2x+2}]$. Plots of the measured pseudo-first-order rate constant versus $[C_xH_{2x+2}]$ thus yielded the second-order rate constant from weighted linear least-squares fits to the data. The decay curves recorded at high $[C_xH_{2x+2}]$ were always considerably more scattered than the data recorded at low $[C_xH_{2x+2}]$ due to absorption of the N(²D) VUV LIF emission by residual saturated hydrocarbon present in the reactor. Two example second-order plots are shown in Figure 2, for the reactions of N(²D) with CH₄ (purple triangles) and C₂H₆ (red squares) at 177 K.



Figure 2 Pseudo-first-order rate constant as a function of saturated hydrocarbon concentration recorded at 177 K. (Red solid squares) the N(²D) + C₂H₆ reaction; (purple solid triangles) the N(²D) + CH₄ reaction. [NO] = 2.7×10^{14} cm⁻³. Solid lines represent weighted linear least-squares fits to the data. The error bars on individual data points (1 σ) are derived from exponential fits to temporal profiles such as those displayed in Figure 1.

The y-axis intercept values here correspond to the pseudo-first-order losses of N(²D) through reaction with NO and through diffusion. In these examples, $[NO] = 2.7 \times 10^{14} \text{ cm}^{-3}$ with $k_{N(^2D)+NO}(177 \text{ K}) = 8.0 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$, leading to a theoretical contribution of

approximately 22000 s⁻¹ from the N(²D) + NO reaction and therefore only a minor contribution to the intercept value from diffusional loss of N(²D) atoms. It is clear from Figure 2 that the rate constant for the N(²D) + C₂H₆ reaction is substantially faster than the one for the N(²D) + CH₄ reaction which displays almost no variation over the entire range of [CH₄]. The measured rate constants for the N(²D) + C_xH_{2x+2} reactions are summarized in Table 2 and are displayed in Figure 3 as a function of temperature.

Reaction	T / K	N^a	$[C_xH_{2x+2}]$	[NO]	$k_{\mathrm{N}(^{2}\mathrm{D})+\mathrm{C_{x}H_{2x+2}}}/$
			$/ 10^{14} \text{ cm}^{-3}$	$/ 10^{14} \text{ cm}^{-3}$	$10^{-13} \text{ cm}^3 \text{ s}^{-1}$
$N(^{2}D) + CH_{4}$	296	44	0 - 46.4	4.3	(24.8 ± 5.4)
	296	24	0 - 45.8	2.2	(21.0 ± 4.3)
	177	34	0 - 55.5	2.6	(4.7 ± 2.4)
	127	20	0 - 61.9	1.6	(1.7 ± 1.5)
$N(^{2}D) + C_{2}H_{6}$	296	28	0 - 23.6	4.4	(122.0 ± 28.7)
	296	18	0 - 24.4	6.3	(126.4 ± 25.7)
	177	39	0 - 37.6	2.7	(25.2 ± 5.8)
	127	38	0 - 43.2	3.1	(16.8 ± 3.7)
	127	18	0 - 43.1	4.6	(17.6 ± 4.6)
	75	19	0 - 21.3	2.7	(11.1 ± 3.5)
$N(^{2}D) + C_{3}H_{8}$	296	21	0 - 24.9	6.3	(173.3 ± 37.9)
	177	38	0 - 26.7	2.7	(56.1 ± 12.0)
	127	36	0 - 30.9	3.2	(42.8 ± 9.0)
	127	18	0 - 31.0	4.7	(45.5 ± 9.8)
	75	30	0 - 10.5	2.7	(32.5 ± 8.8)

Table 2 Measured rate constants for the $N(^{2}D) + C_{x}H_{2x+2}$ reactions

^a Number of individual kinetic profiles recorded for each experiment to derive the secondorder rate constant.



Figure 3. Second order rate constants for the $N(^{2}D) + C_{x}H_{2x+2}$ reactions as a function of temperature. The $N(^{2}D) + CH_{4}$ reaction: (Blue solid circles) this work; (purple open circles) (solid black circle) Black et al.²²; (open red circle) Fell et al.²³; (solid purple circle) Umemoto et al.²⁴; Takayanagi et al.²⁵ The solid blue lines represent best fits to the present experimental data. The $N(^{2}D) + C_{2}H_{6}$ reaction: (Green solid squares) this work; (black solid square) Fell et al.²³; (blue open square) Umemoto et al.²⁴ The $N(^{2}D) + C_{3}H_{8}$ reaction: (Cyan solid triangles) this work; (red solid triangle) Fell et al.²³; (black solid triangle) Umemoto et al.²⁴ The dashed lines represent the previously recommended values for these reactions. Error bars on the present data represent the combined statistical (1 σ) and systematic errors (estimated to be 20 % of the nominal value of the rate constant except for measurements of the $N(^{2}D) + CH_{4}$ reaction at 177 K where it was estimated to be 50 %).

The N(²D) + CH₄ reaction At room temperature, experiments were performed with two different NO concentrations (2.2 × 10¹⁴ cm⁻³ and 4.3 × 10¹⁴ cm⁻³) to test for the influence of potential secondary reactions, yielding similar values for $k_{N(^2D)+CH_4}(296 \text{ K}) = (2.1 \pm 0.4) \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ and (2.5 ± 0.5) × 10⁻¹² cm³ s⁻¹. These values are slightly lower than those obtained by previous studies²²⁻²⁵ with values in the range (3.0 – 5.4) × 10⁻¹² cm³ s⁻¹. The measured rate constants for the N(²D) + CH₄ reaction below room temperature are slower

than 10⁻¹² cm⁻³ s⁻¹; a value which is normally considered as the lower limit for rate constant measurements through the Laval nozzle method (assuming that the minor reagent decay can be followed over at least two half-lives). If we consider the measurements performed at 177 K as an example, the nozzle used has a characteristic hydrodynamic time of ~250 microseconds (that is, the time over which the nominal characteristics of the supersonic flow are valid). In this case, the maximum [CH4] used in these experiments was 5.6 \times $10^{15}~{\rm cm}^{-3}$ which constitutes approximately 6 % of the total flow, and therefore approaching the upper limit for the added coreagent concentration before significant deviations from the nominal flow conditions occur (N₂ carrier gas density = 9.4×10^{16} cm⁻³). The measured rate constant for the $N(^{2}D)$ + CH₄ reaction at 177 K is 4.7 × 10⁻¹³ cm³ s⁻¹ allowing us to calculate a half-life time, $t_{1/2} = (\ln(2)/k') = 260$ microseconds. Consequently, the loss of N(²D) due to the N(²D) + CH₄ reaction alone over the entire duration of the flow at 177 K is significantly less than the loss due to the competing N(²D) + NO reaction ($t_{1/2} = 29$ microseconds). Although a clear progression of the pseudo-first-order rate constant as a function of [CH₄] is obtained in these experiments (see Figure 2), it is important to realize that the derived second-order rate constants at 177 K and at 127 K are characterized by substantially larger uncertainties than usually associated with this type of measurement. In this respect, we have increased our estimate of the systematic errors on these two measurements to 50 % of the nominal value, although an upper limit value of 3.2×10^{-13} cm³ s⁻¹ could also be considered as appropriate for the measured rate constant at 127 K. Nevertheless, the measured rate constants are in reasonably good agreement with the recommended ones.¹⁰ Indeed, the recommended Arrhenius parameters A = 4.8 × 10⁻¹¹ cm³ s⁻¹ and (Ea/R) = 750 K yield $k_{N(^2D)+CH_4}(177 \text{ K}) =$ $6.9 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ and $k_{N(^2D)+CH_4}(127 \text{ K}) = 1.3 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ which are close to the values obtained in this work $(k_{N(^2D)+CH_4}(177 \text{ K}) = (4.7 \pm 2.4) \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ and $k_{N(^2D)+CH_4}(127 \text{ K})$ = $(1.7 \pm 1.5) \times 10^{-13}$ cm³ s⁻¹). An Arrhenius fit to the present data yields the following Arrhenius parameters; $A = 1.93 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ and (Ea/R) = 638 K. Given the slow rate constants at 177 K and 127 K, no attempt was made to measure rate constants at lower temperature.

The N(²D) + C₂H₆ reaction In a similar manner to the N(²D) + CH₄ reaction, experiments were performed with two different NO concentrations (4.4 × 10¹⁴ cm⁻³ and 6.6 × 10¹⁴ cm⁻³) to test for the influence of potential secondary reactions, yielding similar values for $k_{N(^2D)+C_2H_6}(296 \text{ K}) = (1.2 \pm 0.3) \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ and $(1.3 \pm 0.3) \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$. These values are slightly lower than previous work by Fell et al.²³ and Umemoto et al.²⁴ which yielded values of $(1.6 \pm 0.6) \times 10^{-11}$ cm³ s⁻¹ (corrected value – see Herron¹⁰ for more detail) and (2.1 \pm 0.2) \times 10⁻¹¹ cm³ s⁻¹ respectively. The rate constant is seen to decrease as the temperature falls, reaching a value of $(1.1 \pm 0.3) \times 10^{-12}$ cm³ s⁻¹ at 75 K. An Arrhenius fit to the present data does not provide an adequate description of the rate constant over the entire temperature range, so we choose instead to use a modified Arrhenius type expression $(k = A \times (T/300)^n \times$ exp(-Ea/RT)) where A = 3.58×10^{-12} cm³ s⁻¹, n = 4.45 and (Ea/R) = -379 K. These parameters are valid over the 75 – 296 K temperature range. The deviation from Arrhenius behavior at low temperature might be an indication that H atom tunneling plays a small but non-negligible role in the $N(^{2}D) + C_{2}H_{6}$ reaction. Interestingly, photochemical models of Titan's atmosphere^{26, 27} use the recommended room temperature rate constant¹⁰ $k_{N(^2D)+C_2H_6} =$ 1.9×10^{-11} cm³ s⁻¹ as a temperature independent value to describe the reactivity of the N(²D) $+ C_2H_6$ reaction at lower temperature. At temperatures relevant to Titan's atmosphere (taking 150 K as a representative temperature) the fit to the present data yields a rate constant of 2.1 \times 10⁻¹² cm³ s⁻¹; almost an order of magnitude lower than the currently recommended value. Following the joint experimental and theoretical study of this reaction by Balucani et al.¹⁶ the major products are expected to be methanimine (CH₂NH) and CH₃ with small contributions from ethanimine (CH₃CH₂NH) and H atoms, NH and C₂H₅, as well as other products at the 1 % level or less.

The N(²D) + C₃H₈ reaction The measured rate constants at 296 K were found to be lower than the values obtained previously by Fell et al.²³ and Umemoto et al.²⁴ of $(2.8 \pm 0.8) \times 10^{-11}$ cm³ s⁻¹ (corrected value) and $(3.1 \pm 0.3) \times 10^{-11}$ cm³ s⁻¹ respectively. Given the discrepancy between the present and previous studies, further tests were performed to check for potential errors in the current work. In particular, as N(²D) atoms are formed through reaction (1a) rather than prompt formation through direct photolysis, it is possible that N(²D) formation and N(²D) loss through the N(²D) + C₃H₈ reaction were occurring over the same time period. Indeed, such an effect is expected to lead to slower pseudo-first-order rate constants for the target reaction. During these test experiments, pseudo-first-order rate constants for the N(²D) + C₃H₈ reaction were measured with three different fixed NO concentrations (2.2, 4.2 and 6.3 × 10¹⁴ cm⁻³) at room temperature. Assuming a rate constant of 1.5 × 10⁻¹⁰ cm³ s⁻¹ for reaction (1),⁵⁴ we obtain pseudo-first-order rate constants of 3.4, 6.3, 9.4 × 10⁴ s⁻¹ respectively thus allowing us to calculate the half-life times for N(²D) formation under these conditions. The delay times when only 13 % of the initial C(³P) remains to be converted to N(²D) (corresponding to three half-lives) are 64, 33 and 22 µs, indicating that data acquired at delays

shorter than these values may not accurately reflect the kinetics of the $N(^{2}D) + C_{3}H_{8}$ reaction. For the lowest NO concentration, the data acquired after 64 µs was difficult to analyse given the weak signal levels, with a measured rate constant of $(1.2 \pm 0.2) \times 10^{-11}$ cm³ s⁻¹. With the intermediate NO concentration, a similar measured rate constant of $(1.2 \pm 0.2) \times 10^{-11}$ cm³ s⁻¹ was obtained. Only the rate constant value obtained for the $N(^{2}D) + C_{3}H_{8}$ reaction with [NO] = $6.3 \times 10^{14} \text{ cm}^{-3}$ (yielding $k_{N(^2D)+C_3H_8}(296 \text{ K}) = (1.7 \pm 0.4) \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ respectively) was retained to derive the temperature dependent fitting parameters. The rate constant decreases as the temperature falls reaching a value of $(3.2 \pm 0.9) \times 10^{-12}$ cm³ s⁻¹ at 75 K. As the Arrhenius expression does not yield a good fit to the data over the entire temperature range, the modified Arrhenius type expression described above is used instead, where $A = 7.36 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$, n = 2.99 and (Ea/R) = -252 K. These parameters are valid over the 75 - 296 K temperature range. Current photochemical models of Titan's atmosphere^{26, 27} use the recommended room temperature rate constant¹⁰ $k_{N(^2D)+C_3H_8} = 2.9 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ as a temperature independent value to describe the reactivity of the $N(^{2}D) + C_{3}H_{8}$ reaction. At 150 K, the fit to the present data predicts a rate constant of 5.0×10^{-12} cm³ s⁻¹; six times smaller than the currently recommended value.

4 Influence of the new rate constants on Titan's atmospheric chemistry

We wanted to test the effect of the new rate constants on current models of Titan's atmosphere. To do this, we employed the 1D-photochemical model described by Dobrijevic et al.²⁶ with more recent updates related to the chemistry of aromatic compounds,⁵⁵ although a detailed description is not provided here (see Dobrijevic et al.²⁶). This model treats the coupled chemistry of neutral and ionic species (both cations and anions) to provide an accurate description of the chemistry occurring from the lower atmosphere all the way up to the ionosphere, including high resolution absorption cross-sections for an improved description of N₂ photodissociation. Earlier models by these authors which did not include ions already updated the neutral chemistry of nitrogen bearing molecules.⁸, ⁹, ⁵⁶ Indeed, an uncertainty propagation study by Loison et al.⁹ focusing on the chemistry of nitriles, amines and imines clearly identified the N(²D) + CH₄ and N(²D) + C₂H₆ reactions as key reactions for future study in order to improve the accuracy of model predictions.

Here, we ran two different simulations to examine the effects of the measured rate constants on the species mole fractions as a function of altitude. The first employed the previously recommended rate constants and branching ratios for the $N(^2D) + CH_4$, C_2H_6 and C_3H_8

reactions to yield the standard profiles. The second used the new values as described by the Arrhenius parameters for the respective reactions as presented in section 3. As we do not measure the various product channels for these processes, the relative branching ratios remain unchanged. The differences produced by the two models for various species at 1000 km are summarized in Table 3.

Species	Mole fraction	Difference (with respect to the
	(New Model)	standard model) / %
C ₂ H ₆	2.3×10^{-5}	+9.3
C_3H_8	3.45×10^{-7}	+9.4
C4N2	8.3×10^{-7}	+9.4
NH ₂	8.7×10^{-7}	-10.8
NH ₃	8.6×10^{-7}	-10.6
CH ₂ NH	1.75×10^{-5}	-11.1
CH ₃ NH ₂	9.35×10^{-10}	-10.6

Table 3 Mole fractions at 1000 km produced by the two model runs.

Due to the low mole fraction of C_3H_8 in Titan's atmosphere, the reaction of N(²D) with C_3H_8 has a negligible influence on the chemistry in both models. For the other two reactions, the new rate constants lead to only small differences in the mole fraction profiles for all species at altitudes which correspond to the peak of the N(²D) mole fraction profile. Taking CH₂NH as an example, this species is a major product of the $N(^{2}D) + CH_{4}$ reaction with the channel leading to CH₂NH + H considered to represent 80 % of the total, while the products CH₃ + CH₂NH are considered to be the sole products of the $N(^{2}D) + C_{2}H_{6}$ reaction in current models. By examining the integrated column rates, we note that the N(²D) + CH₄ reaction represents the major source of CH₂NH in the standard model (47 %), followed by the NH + $CH_3 \rightarrow CH_2NH + H (30 \%)$ and $CH_2NH_2^+ + e^-$ reactions (although $CH_2NH_2^+$ is almost entirely formed by proton transfer reactions with CH₂NH, so this mostly just recycles between CH_2NH and $CH_2NH_2^+$ with only a minor loss channel to form $NH_2 + {}^{3}CH_2$). This result also holds for the new model given the very minor change in the rate constant values for the N(²D) + CH₄ reaction between the two simulations. In the standard model, the $N(^2D)$ + C_2H_6 reaction represents the third largest source of CH₂NH in Titan's atmosphere, albeit with a contribution of only 2.5 % due to the relatively low mole fraction of C₂H₆ with respect to CH₄

(and despite the much larger rate constant). After the new rate constant is included, the $N(^{2}D)$ + $C_{2}H_{6}$ reaction becomes an entirely negligible source of CH₂NH (0.3 %), with a decrease of the integrated rate by a factor of 8 between the two models.

As CH_3NH_2 is formed through the $NH_2 + CH_3$ reaction, this species also decreases slightly in the new model due to the less efficient $CH_2NH_2^+ + e^-$ dissociative recombination reaction where NH_2 is a minor reaction product as described above. Similarly, the NH_3 mole fraction also decreases as it forms mostly from reactions of NH_2 .

The N(²D) + CH₄ reaction remains the major loss process for N(²D) atoms in the atmosphere of Titan representing approximately 28 % of the total N(²D) removal, followed by the N(²D) + HCN (22 %) and N(²D) + C₂H₂ (13 %) reactions. Whereas the N(²D) + C₂H₆ reaction was the 9th most important loss process for N(²D) (representing approximately 1% of its total removal), with the new rate constants it now represents only 0.1 % of N(²D) loss.

While the new model results are similar to those of the standard model, it will be interesting to test the effects of the new and more realistic error bars for these reactions on the mole fraction profiles of a range of atmospheric species obtained through uncertainty propagation studies. Previous models (see Loison et al.⁵⁵ for example) employed values for the uncertainty factor, F = 1.5 for the N(²D) + C₂H₆, C₃H₈ reactions. In light of the present experimental results, it is clear that these uncertainties were severely underestimated. While these findings illustrate the difficulty of attributing realistic uncertainties to reactions that have only been investigated at temperatures far from the relevant range, they also reinforce the need for kinetic measurements at appropriate temperatures. Indeed, even though the measured rate constants for the N(²D) + CH₄ reaction are close to the previously recommended ones, the new uncertainties associated to this process might lead to an entirely different set of key reactions compared to earlier work. As further experimental studies of other important N(²D) reactions are currently underway, a more detailed uncertainty propagation study will be performed at a later date once their rate constants and associated uncertainties have been fully characterized.

5 Conclusions

Here we present a temperature dependent kinetic study of the reactions of metastable nitrogen atoms in the ²D state with the saturated hydrocarbons CH_4 , C_2H_6 and C_3H_8 . A supersonic flow (Laval nozzle) reactor was used to perform these measurements at temperatures as low as 75 K. As N(²D) atoms are difficult to generate photolytically, a chemical source of these atoms was employed, through the reaction of C(³P) atoms with NO molecules as first described by Nuñez-Reyes & Hickson.⁶ C(³P) atoms themselves were produced by the multiphoton dissociation of CBr₄ molecules, while N(²D) atoms were detected directly through vacuum ultraviolet laser induced fluorescence. While the measured rate constants for the N(²D) + CH₄ reaction are in good agreement with earlier work at higher temperature, the values derived for the N(²D) + C₂H₆ and N(²D) + C₃H₈ reactions are significantly smaller at low temperature than previous estimates based on earlier room temperature results. The effects of the new rate constants are tested on a coupled ion-neutral photochemical model of Titan's atmosphere. These simulations confirm that the N(²D) + CH₄ reaction is the main loss process for N(²D) atoms in Titan's atmosphere in addition to being the major source of CH₂NH. In contrast, the N(²D) + C₂H₆ and N(²D) + C₃H₈ reactions are shown to be negligibly important processes in the overall photochemistry of Titan's atmosphere. The need for uncertainty propagation studies to test the effects of the new rate constant uncertainties, alongside those of future measurements, is highlighted.

Acknowledgements

K.M.H. and D.N.R acknowledge support from the French program "Physique et Chimie du Milieu Interstellaire" (PCMI) of the CNRS/INSU with the INC/INP co-funded by the CEA and CNES as well as preliminary funding from the "Program National de Planétologie" (PNP) of the CNRS/INSU.

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One sentence summary for TOC entry:

Low temperature rate constants for the $N(^{2}D) + C_{2}H_{6}$, $C_{3}H_{8}$ reactions are shown to be much smaller than previously thought.