# H-Atom Yields from the Photolysis of Acetylene and from the Reaction of $C_2H$ with $H_2$ , $C_2H_2$ , and $C_2H_4^{\dagger}$

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The photolysis of acetylene at 193 nm has been investigated as a source of the ethynyl radical, C<sub>2</sub>H, for product branching ratio studies, particularly the formation of H atom product as the photolysis, producing a 1:1 ratio of C<sub>2</sub>H and H, provides an internal calibration. Previous literature had suggested that C<sub>2</sub>H and H may only be a minor component of acetylene photolysis at 193 nm. Acetylene was photolyzed at low laser energy densities ( $<7 \text{ mJ cm}^{-2}$ ), with H atoms being observed as a function of time by VUV laser induced fluorescence. When C<sub>2</sub>H was reacted with C<sub>2</sub>H<sub>2</sub>, a reaction that is known to produce H atoms with unit yield, the ratio of photolytic H atom production to chemical production was 0.96 ± 0.03. The rate coefficient for the reaction of C<sub>2</sub>H with C<sub>2</sub>H<sub>2</sub> could accurately be retrieved from the time evolution of the H atom signal. The results suggest that acetylene photolysis at low laser energies is a good source of C<sub>2</sub>H for product branching studies, and the technique has been applied to the reactions of C<sub>2</sub>H with ethene and propene. For the reaction with ethene between 23 and 81 Torr, the yield of H is 0.94 ± 0.06, suggesting that an addition elimination mechanism dominates with the formation of vinylacetylene and H atoms. For the reaction of C<sub>2</sub>H with propene, no H atom product was observed, putting a lower limit of <5% for H atom production. Possible explanations for the low H atom yield are discussed. The implications of these results in combustion and planetary atmospheres are briefly considered.

### Introduction

The ethynyl radical,  $C_2H$ , plays an important role in the production of soot during combustion<sup>1</sup> and in the production of polyenes in the reducing atmospheres of the outer planets<sup>2,3</sup> and in the interstellar medium.<sup>3</sup> The radical can undergo two main types of reaction; a direct abstraction typified by the reaction with H<sub>2</sub> or saturated alkanes

$$C_2H + H_2 \rightarrow C_2H_2 + H \tag{R1}$$

$$C_2H + CH_4 \rightarrow C_2H_2 + CH_3 \tag{R2}$$

Alternatively, for reactions with unsaturated hydrocarbons or radical species such as O<sub>2</sub>, the reaction proceeds via the formation of a complex that can either break up to yield products or be stabilized by collisions with a bath gas. The high heat of formation of the ethynyl radical ( $\Delta_f H C_2 H = 567 \pm 1$  kJ mol<sup>-1 4,5</sup>) means that in many cases a variety of product channels are thermodynamically accessible, including the production of electronically excited products.

The reaction of  $C_2H$  with acetylene is typical of the complexforming mechanism; in this case, only one product is thermodynamically accessible from the dissociation of the complex

$$C_2H + C_2H_2 \rightarrow C_4H_3^* \rightarrow C_4H_2 + H$$
(R3)

However, for the reaction of  $C_2H$  with  $O_2$ , an important reaction in combustion, a large number of product channels are accessible with the different products having a potentially significant effect on subsequent chemistry

$$C_{2}H + O_{2} \rightarrow HCO + CO \quad \Delta_{r}H = -620 \text{ kJ mol}^{-1}$$
(R4a)  

$$\rightarrow H + 2CO \quad \Delta_{r}H = -547 \text{ kJ mol}^{-1}$$
(R4b)  

$$\rightarrow CH + CO_{2} \quad \Delta_{r}H = -363 \text{ kJ mol}^{-1}$$
(R4c)  

$$\rightarrow C_{2}O + OH \quad \Delta_{r}H = -154 \text{ kJ mol}^{-1}$$
(R4d)  

$$\rightarrow HCCO + O \quad \Delta_{r}H = -73 \text{ kJ mol}^{-1}$$
(R4e)

For the reaction of  $C_2H$  with ethene, there are two thermodynamically accessible channels

$$C_{2}H + C_{2}H_{4} \rightarrow C_{2}H_{2} + C_{2}H_{3} \quad \Delta_{r}H = -90.4 \text{ kJ mol}^{-1}$$
(R5a)  

$$\rightarrow C_{4}H_{4} + H \quad \Delta_{r}H = -95.4 \text{ kJ mol}^{-1}$$
(R5b)

Reaction R5a could potentially take place via either a direct abstraction or an addition elimination mechanism.

The kinetics of  $C_2H$  have received considerable attention, particularly in the studies led by Leone and coworkers,<sup>6–8</sup> Curl, Glass, and coworkers,<sup>9,10</sup> and Peeters and coworkers.<sup>11,12</sup> Sims

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and coworkers have made measurements at very low temperatures using a continuous-flow Laval system,<sup>13</sup> and Leone and coworkers have more recently measured C<sub>2</sub>H kinetics around 100 K using a pulsed Laval system.<sup>14</sup> C<sub>2</sub>H has predominantly been generated by the excimer laser photolysis of C<sub>2</sub>H<sub>2</sub> or CF<sub>3</sub>C<sub>2</sub>H at 193 nm and monitored by IR absorption. Additional studies have been performed by Laufer and Fahr, who have authored a review on the reactions of C<sub>2</sub>H and other unsaturated radicals.<sup>5</sup>

In contrast with the kinetics, much less is known about the products of  $C_2H$  radical reactions. Quantitative product studies of radical reactions are challenging experiments because many of the spectroscopic techniques used to monitor radical concentrations do not provide absolute concentrations. The calculation of radical concentrations from photolysis fluence measurements is subject to many uncertainties. An alternative approach is to use a calibration reaction, a reaction of the radical that produces the target product with a well-defined, ideally 100%, product yield. Issues around quantitative product determinations have recently been reviewed.<sup>15</sup>

For C<sub>2</sub>H studies, reactions R1 and R3 provide a suitable calibration reaction for H atoms because  $H + C_2H_2$  and  $H + C_4H_2$ , respectively, are the only possible products under our experimental conditions. C<sub>4</sub>H<sub>3</sub> can be produced from reaction R1 at high pressures; however, previous calculations<sup>11</sup> have shown that stabilization should not occur under our conditions, a prediction verified in the current study. Uncertainties exist over the yield of C<sub>2</sub>H from the 193 nm photolysis of acetylene, the most convenient source of C<sub>2</sub>H. Early studies suggested that triplet acetylene or vinylidene (H<sub>2</sub>CC) was the dominant product,<sup>16</sup> secondary reactions of such species could distort the kinetics of H atom formation. The photolysis of acetylene is particularly appealing for H atom studies because C<sub>2</sub>H and H are formed in identical amounts from the primary photodissociation

$$C_2H_2 + h\nu(193 \text{ nm}) \rightarrow C_2H + H$$
 (R6)

potentially providing an internal calibration<sup>17</sup> of  $C_2H$  and H. However, alternative multiphoton dissociations that yield H atoms or secondary chemistry will negate this advantage.

More recently Lauter et al.<sup>18</sup> have demonstrated that reaction R6 is the dominant channel for acetylene dissociation at 193 nm with a quantum yield of  $0.94 \pm 0.12$ , suggesting that, in contrast with the earlier studies, acetylene photolysis should be a clean source of C<sub>2</sub>H. The objective of this article is to confirm the suitability of acetylene photolysis as a source of C<sub>2</sub>H for H-atom product studies and to see whether the potential advantages of an internal calibration can be realized. We subsequently apply this technique to determine the H-atom yield from the reaction of C<sub>2</sub>H with ethene (R5a,R5b) and propene

$$C_2H + C_3H_6 \rightarrow \text{products}$$
 (R7)

### **Experimental Section**

Reactions were carried out in a slow flow excimer laser flash photolysis apparatus with H-atom detection by VUV laserinduced fluorescence. The  $C_2H$  precursor, acetylene, reagent (if appropriate), and bath gas were metered using calibrated mass flow controllers and premixed before being flowed into the stainless steel reaction vessel. The reaction vessel was a stainless steel six-way cross with the photolysis, probe laser, and fluorescence detection axis mutually perpendicular to each other. The pressure within the cell was controlled by a needle valve located between the exit of the cell and the vacuum pump. The pressure in the cell was measured by a baratron-type pressure gauge, and all reactions were carried out at room temperature (295  $\pm$  2 K).

C<sub>2</sub>H radicals were generated by the photolysis of acetylene using a GAM EX5 excimer laser operating at 193 nm. H atoms were monitored by VUV laser-induced fluorescence at the Lyman-α transition at 121.56 nm. The technique has been used before in this laboratory to monitor H atom yields from CH,<sup>19</sup> CN,<sup>20,21</sup> and CH<sub>2</sub><sup>22</sup> reactions. A 308 nm excimer laser (Lambda Physik LPX 100) pumped dye laser (Lambda Physik FL2002) was used for probing. Radiation (364.68 nm, ~5–7 mJ pulse<sup>-1</sup>) was produced from a DMQ dye and was frequency tripled in krypton–argon mixture (Kr/Ar 1:2.5). Light (364.68 nm) was focused by a quartz lens (focal length = 15 cm) into a glass cell attached directly to the cell containing ~1000 Torr of Kr/ Ar; the exact mixture varied depending on the laser energy. Lyman-α radiation was coupled to the cell perpendicularly to the photolysis beam through a MgF<sub>2</sub> window.

Fluorescence was detected perpendicularly to both laser beams by a solar blind photomultiplier tube (PMT, Perkin-Elmer CPM-18). The power of the VUV radiation was monitored by a second solar blind PMT (Thorn EMI Gencom, RFI/B-214 FV model) with exactly the same path length in the cell. Some of the probe light was reflected using quartz flat at 45° through a VUV interference filter and onto the second PMT. This resulting signal was used directly as the absorption signal and also to normalize the VUV LIF signal taking into account any temporal power fluctuations of the probe laser and attenuation by absorption.

By varying the time delay between the photolysis and probe beams, a time profile of the H atom concentration was recorded. The time between photolysis and probing was varied by a digital delay generator type DG 535 (Stanford Research Systems). The PMT outputs were converted by an AD converter and recorded and stored on a PC. In typical, the time profiles consisted of 200 points, where each time point was the average of 10-20shots and the time interval between the points was  $0.1 \ \mu$ s. Photolysis laser powers were measured by a Gentec energy type power meter.

The power dependence of the acetylene photodissociation was investigated in detail. By varying the applied voltage to the excimer or by focusing or defocusing the photolysis laser beam (using either metal mesh filters or cylindrical lens), the light energy densities could be varied from  $5 \times 10^{15}$  to  $3 \times 10^{18}$ photon cm<sup>-2</sup>. To investigate the yield of H atoms from both the photolysis of acetylene and the reaction of C<sub>2</sub>H with calibrant and test molecules, the photolysis of N<sub>2</sub>O at 193 nm in the presence of hydrogen was used as a well-characterized H-atom source. Photolysis of N<sub>2</sub>O at 193 nm leads exclusively to the production of N<sub>2</sub> and excited oxygen atoms, O(<sup>1</sup>D)

$$N_2O + h\nu(193 \text{ nm}) \rightarrow N_2 + O(^{1}D)$$
 (R8)

Sufficient hydrogen (typically  $3.3 \times 10^{17}$  molecule cm<sup>-3</sup>) is added to ensure that all oxygen atoms produced react rapidly with H<sub>2</sub> to generate an essentially instantaneous H atom signal. The H atom concentration can be calculated from the welldetermined N<sub>2</sub>O absorption cross section at 193 nm (8.95 ×  $10^{-20}$  cm<sup>2 23</sup>), unit quantum yield, and the measured laser photon density.



**Figure 1.** Typical experimental H atom profiles following the photolysis of acetylene (pressure 42 Torr Ar,  $[C_2H_2] = 1.6 \times 10^{14}$  molecule cm<sup>-3</sup>, laser fluence = 7 mJ cm<sup>-2</sup>). The solid line is a fit to reaction R1.

Argon (BOC Pureshield) and helium (BOC VP grade, 99.9999%) were admitted directly from cylinders without purification, whereas acetylene (Aldrich, 99.9+%, HPLC grade), ethylene (Aldrich, 99.9+%, HPLC grade), and propylene (Aldrich, 99.9+%, HPLC grade) were stored diluted in helium in glass bulbs following freeze-pump-thaw purifications.

#### **Results and Discussion**

a. Reaction with Acetylene at Low Photolysis Powers. Figure 1 shows an experimental profile of the H atom signal following the photolysis of an acetylene and argon mixture at low excimer fluences (7 mJ cm<sup>-2</sup>). A prompt rise in H atom signal is seen to be consistent with the photolysis process

$$C_2H_2 + h\nu(193 \text{ nm}) \rightarrow C_2H + H \tag{R6}$$

followed by a slower exponential rise in the signal associated with the reaction of C<sub>2</sub>H with acetylene. Under these conditions, where  $[C_2H_2] \gg [C_2H]$  ( $[C_2H]_0 = 1.4 \times 10^{11}$  molecules cm<sup>-3</sup> and ~1/1000th  $[C_2H_2]$ ), the production of H atoms should be controlled by pseudo-first-order kinetics. Traces such as Figure 1 were fit with eq E1, which accounts for both prompt photolytic production and the chemical production of H atoms and subsequent slow removal due to diffusion and reaction with acetylene.

$$I_{\rm f,H} = \frac{S_{\rm H,R}k'_3}{k_{\rm d} - k'_3} (e^{-k'_3 t} - e^{-k_{\rm d} t}) + S_{\rm H,P} e^{-k_{\rm d} t}$$
(E1)

where  $I_{f,H}$  is the observed H atom fluorescence,  $S_{H,R}$  is the signal associated with H atoms produced in reaction R3,  $k'_3$  is the pseudo-first-order rate coefficient for the removal of C<sub>2</sub>H ( $k'_3 = k_3[C_2H_2] + c$ ),  $k_d$  is the rate coefficient for H atom loss (mainly via diffusion), and  $S_{H,P}$  is the signal associated with prompt H production from acetylene photolysis.

The ratio of  $S_{\rm H,R}/S_{\rm H,P}$  was 0.96  $\pm$  0.03 for 48 experiments carried out at low photolysis laser fluences (<7 mJ cm<sup>-2</sup>) and with acetylene concentrations from (1.5 to 2.3)  $\times$  10<sup>14</sup> molecule cm<sup>-3</sup> and total pressures (23–98 Torr). Under these conditions,



**Figure 2.** Bimolecular plot ( $k'_3$  vs [C<sub>2</sub>H<sub>2</sub>]) for reaction R3 at 298 K and 23 Torr. The bimolecular rate coefficient obtained as the gradient is (1.16  $\pm$  0.06)  $\times$  10<sup>-10</sup> cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup>, where the errors are statistical only at the 1 sigma level.

TABLE	1:	Summary	of	298	K	Rate	Coefficients	for	the
Reaction	$\mathbf{C}_2$	$_{2}H + C_{2}H_{2}$	2						

author	date	$10^{10} \times k_{298}/\text{cm}^3$ molecule <sup>-1</sup> s <sup>-1</sup>	comments
this work	2009	$1.2 \pm 0.2$	monitoring H atom
Ceursters et al. <sup>11</sup>	2000	$1.3 \pm 0.1$	monitoring chemiluminescence via
Farhat et al. <sup>10</sup>	1993	$1.6 \pm 0.3$	reaction of $C_2H + O_2$ monitoring $C_2H$ by IR absorption
Pederson et al.6	1993	1.2	monitoring $C_2H$ by IR absorption
Koshi et al. <sup>24</sup>	1992	$1.5 \pm 0.3$	monitoring C <sub>4</sub> H <sub>2</sub> by mass spectrometry or H atoms by VUV absorption
Shin and Michael <sup>43</sup>	1991	1.4	monitoring H atom production by VUV
Stephens et al.9	1987	1.5	monitoring $C_2H$ by IR absorption

the expected 1:1 relationship is observed on the bais of  $C_2H + H$  being the sole products of acetylene photolysis at low powers and  $C_4H_2 + H$  being the sole products of reaction R3 at these pressures (20–300 Torr argon).

Further evidence of the sole production of C<sub>2</sub>H and H at low laser fluences comes from the good agreement obtained when we compare our observed H atom signal from acetylene photolysis with that from N<sub>2</sub>O photolysis in the presence of H<sub>2</sub>, for which the cross section and yield of H (via O<sup>1</sup>D + H<sub>2</sub>) are known. The calculated quantum yield of H at 193 nm with a laser photon fluence of  $8.2 \times 10^{15}$  photons cm<sup>-2</sup> is  $1.02 \pm$ 0.05.

The rise in the concentration of H atoms from reaction R3 can clearly be seen, and by carrying out measurements over a range of acetylene concentrations, it is possible to extract the bimolecular rate coefficient for reaction R3. Figure 2 shows an example of a bimolecular plot (pseudo-first-order rate coefficient for H production vs  $[C_2H_2]$ ), and the resultant bimolecular rate coefficient (the gradient of plot) is compared with literature values in Table 1.

Our determination,  $(1.2 \pm 0.2) \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ , where the error includes both statistical uncertainties and



Figure 3. Variation of the ratio of prompt to reactive H with photon fluence.

estimates of systematic errors (flow controller and pressure calibrations), is in excellent agreement with literature values of  $k_{3,298}$ , which have been measured using a wide variety of techniques including monitoring both reagents and products. This excellent agreement suggests that there are no unexpected sources of H in our system. Koshi et al.<sup>24</sup> measured identical values for  $k_{3,298}$  by monitoring H atom production by VUV absorption and  $C_4H_2$  by mass spectrometry. They argued that this precluded significant involvement of vinylidene, which would produce  $C_4H_2 + H_2$  on reaction with acetylene, distorting the kinetics of  $C_4H_2$  versus H production. Interestingly Koshi et al. do show a figure for H-atom production; the figure shows equal concentrations of photolytic and reactive H, but Koshi et al. did not exploit this for product studies.

The invariance of the H atom yield with pressure (20-300 Torr argon) shows that stabilization of the C<sub>4</sub>H<sub>3</sub> radical is not significant up to 300 Torr. This is to be expected from the potential energy surface (PES) of reaction R3. Ceusters et al.<sup>11</sup> have calculated the PES using B3LYP or CCSD(T) calculations at the 6-311++G(d,p) level. The formation of C<sub>4</sub>H<sub>3</sub> (-239 kJ mol<sup>-1</sup> relative to entrance channel) is barrierless, and the loose barrier for production of H + C<sub>4</sub>H<sub>2</sub> is ~73 kJ mol<sup>-1</sup> below the entrance channel. Alternatively, the initial C<sub>4</sub>H<sub>3</sub>\* radical can isomerize via a 1,2 H-atom shift with a barrier of ~173 kJ mol<sup>-1</sup> to produce the more stable HC=C-C•=CH<sub>2</sub> radical (-285 kJ mol<sup>-1</sup>) with respect to entrance channel. The only calculated fate of this radical is also H atom elimination with a barrier of ~187 kJ mol<sup>-1</sup>.

**b.** Acetylene Photolysis at High Laser Fluences. As the excimer laser pulse energy density is increased above 10 mJ cm<sup>-2</sup>, the ratio of prompt to reactive H increases above unity. The prompt photolysis signal increases with laser pulse energy in a nonlinear fashion indicating that multiphoton processes are involved. The reactive H atom signal decreases in comparison with the prompt signal, and the relationships of the two signals are shown in Figure 3. The symmetry of the plot suggests that the source of the additional photolytic H comes at the expense of the reactive H, that is, that it is the photolysis of C<sub>2</sub>H to give C<sub>2</sub> + H that is the source of the photolytic H.

The coproduct of  $C_2H$  photolysis,  $C_2$ , can be formed in either the ground singlet state  $X^1\Sigma_g^+$ , the first excited triplet state  $a^3\Pi_u$ , or possibly higher states.<sup>25</sup> Previous studies indicate that predominantly ground-state  $C_2$  (6.6:1) is formed from 193 nm photolysis of acetylene.<sup>26</sup> However both forms of  $C_2$  are reactive with rate coefficients for  ${}^{1}C_{2} + C_{2}H_{2}$  of  $(4.1 \pm 0.4)^{27}$  or  $(3.5 \pm 1.0)^{28} \times 10^{-10}$  cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup> and for  ${}^{3}C_{2} + C_{2}H_{2}$  of  $(1.1 \pm 0.1) \times 10^{-10}$  cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup>.<sup>27,28</sup> The reaction proceeds via the formation of the diacetylene complex, and the expected products of diacetylene dissociation are C<sub>4</sub>H + H.<sup>29</sup> However, these molecular beam studies<sup>29</sup> also show that the lifetime of the diacetylene, which is in a deep well with barriers to dissociation of 577 and 544 kJ mol<sup>-1</sup> to reagents and products, respectively, is long compared with the rotational period, even at a collision energy of 29 kJ mol<sup>-1</sup>. Under our room-temperature thermal conditions, the complex lifetime is expected to be much longer, and hence it is likely that the diacetylene complex is collisionally stabilized under our experimental conditions, explaining the reduction of reactive H-atom signal on the formation of C<sub>2</sub>.

Adding oxygen to the system provides a sensitive diagnostic for the presence of  $C_2$ . In the presence of oxygen, a very strong VUV emission could be observed at photolysis laser powers where there was significant deviation from the 1:1 photolytic/ reactive H atom ratio. Photolysis laser powers were reduced until the chemiluminescence disappeared. The origin of the chemiluminescence will be discussed in a future paper on the  $C_2H/O_2$  system.

Lauter et al.<sup>18</sup> found that C<sub>2</sub>H photolysis becomes important only at fluences above 100 mJ cm<sup>-2</sup>. They typically used 2-45 mJ cm<sup>-2</sup> photolysis fluence, and single photon absorption was reported under these conditions. Our results suggest that there may be  $\sim 10\%$  C<sub>2</sub>H photolysis at the upper end of their linear photolysis region, which may have been within their error limits for detection. Low powers of 121.6 nm probe radiation  $(\langle 25 \, \mu J \, cm^{-2})$  were enough to generate additional H atom signal, presumably from C<sub>2</sub>H photolysis, followed by H detection in the same laser pulse.<sup>18</sup> The low concentrations of  $C_2H$  and low probe energies negate this process under our experimental conditions, but some effects from the high intensities of the 364.8 nm light in combination with the VUV radiation were observed. These could be avoided by adjusting the lens focusing the light into the tripling cell such that the intensity in the reaction cell was reduced.

c. H Atom Yields from the Reaction of  $C_2H$  and  $H_2$ . The reaction of  $C_2H$  with hydrogen

$$C_2H + H_2 \rightarrow C_2H_2 + H \tag{R1}$$

should show the same behavior as reaction R3, that is, a 1:1 relationship between the H produced from  $C_2H_2$  photolysis and the H produced from reaction R1, and Figure 4a shows that this indeed is the case. Low concentrations of acetylene (typically  $\sim 1 \times 10^{13}$  molecule cm<sup>-3</sup>) and high concentrations of hydrogen are used to ensure that a majority of the C<sub>2</sub>H reacts with hydrogen. In Figure 4a, the rise time now corresponds to the pseudo-first-order rate coefficient,  $k'_1$ , for reaction of C<sub>2</sub>H and H<sub>2</sub>, and Figure 4b shows the resultant bimolecular plot. The measured bimolecular rate coefficient is compared with previous literature values in Table 2.

As expected from a simple abstraction reaction, there was no dependence of the H-atom yield with total pressure (20–100 Torr Ar). The prompt and reactive H atom signal from the C<sub>2</sub>H/ H<sub>2</sub> system showed a very similar dependence with laser power as the earlier C<sub>2</sub>H/C<sub>2</sub>H<sub>2</sub> system. The increase in prompt H can again be explained by C<sub>2</sub>H photolysis, and the lack of reactive H atom signal is due to the very slow rate of reaction of either state of C<sub>2</sub> with H<sub>2</sub> (<3 × 10<sup>-16</sup> cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-130</sup>).



**Figure 4.** (a) H atom profile from reaction R1 (pressure 24 Torr He,  $[C_2H_2] = 7.9 \times 10^{14}$  molecule cm<sup>-3</sup>,  $[H_2] = 3.0 \times 10^{17}$  molecules cm<sup>-3</sup>). (b) Bimolecular plot for reaction R1 at 298 K and 24 Torr helium. The bimolecular rate coefficient is  $(5.15 \pm 0.42) \times 10^{-13}$  cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup>, where the errors are statistical at the 1 sigma level.

TABLE 2: Summary of 298 K Rate Coefficients for the Reaction  $C_2H\,+\,H_2$ 

author	date	$\frac{10^{13} \times k_{298}/\text{cm}^3}{\text{molecule}^{-1} \text{ s}^{-1}}$	comments
this work	2009	$5.2 \pm 0.8$	monitoring H atom production
Peeters et al. <sup>12</sup>	2002	5.6 ± 0.6	$C_2H$ monitored via chemiluminescence from $C_2H + O_2$
Opansky and Leone <sup>8</sup>	1996	$4.6\pm0.7$	C <sub>2</sub> H monitored via IR absorption
Farhat et al. <sup>10</sup>	1993	4.7	C <sub>2</sub> H monitored via IR absorption
Koshi et al. <sup>24</sup>	1992	4.6	decrease in $C_4H_2$ product measured with increasing $H_2$
Stephens et al.9	1987	4.8	$C_2$ H monitored via IR absorption

d. H-Atom Yield from the Reaction of  $C_2H + C_2H_4$  and  $C_3H_6$ . The studies of the H atom yield from ethene and propene were slightly complicated by the production of H atoms from substrate photolysis. Background traces in the absence of acetylene were recorded to take into account this source of H. Figure 5 shows the H atom yield from the reaction of  $C_2H$  with



**Figure 5.** Variation of H atom yield from the reaction of  $C_2H$  and  $C_2H_4$  as a function of argon bath gas pressure.



Figure 6. Schematic of the potential energy surface for  $C_2H + C_2H_4$ . All energies are in kilojoules per mole.

 $C_2H_4$  (reactions R5a and R5b). The average H atom yield is 0.94  $\pm$  0.06 (errors are 1 $\sigma$ ) over a total pressure of 23–81 Torr. Figure 5 also shows that there is no systematic variation of yield with pressure; therefore, stabilization of the  $C_4H_5^*$  intermediate does not appear to be occurring at these pressures. The only other thermodynamically accessible products are  $C_2H_2 + C_2H_3$ , which could be formed either from a direct abstraction or following a rearrangement of the energized  $C_4H_5$  intermediate; however, for the reasons outlined below, we would not expect reaction R5a to contribute significantly.

Opansky and Leone<sup>8</sup> have correlated activation energies of  $C_2H$  abstraction reactions with bond dissociation energies. Direct abstraction by  $C_2H$  from  $C_2H_4$  would be expected to have a positive activation energy; indeed, high-level calculations by Temelso et al.<sup>31</sup> do calculate barrier heights of 4–8 kJ mol<sup>-1</sup> for reaction R5a at various levels of theory. However, the overall reaction exhibits a negative temperature dependence<sup>8,13</sup> and a similar room temperature rate coefficient as reaction R3; the overall kinetics appear to be more compatible with an addition elimination mechanism.

Following addition, two different 1,2-H-atom migrations could occur with the resultant isomers fragmenting to form either vinylacetylene + H (reaction R5b) or acetylene + vinyl (reaction R5a). The enthalpy of formation of the initial vinyl radical has been calculated as  $\Delta_f H^0$  (0 K) 389 kJ mol<sup>-1</sup>,<sup>32</sup> and the enthalpies of the other two C<sub>4</sub>H<sub>5</sub> isomers have been calculated by both Hansen et al.<sup>32</sup> and Wheeler et al.<sup>33</sup> Figure 6 shows a schematic of the possible PES adapted from the above references. Some barrier heights are unknown, but by comparison with analogous systems, we do expect these to be below the energy of the entrance channel.

Although the formation of vinyl and acetylene is likely to be possible via isomerizations with barriers below the entrance channel, the observation of near-unity H-atom yield suggests that these isomerizations, which would occur via relatively tight transition states, cannot compete with the looser transition states for H-atom elimination either from the initially formed adduct  $HC \equiv CCH_2CH_2 \cdot \text{ or from the more stable } HC \equiv CCH \cdot CH_3$ radical formed via a 1,2-H-atom migration (given the tight transition state for the 1,2 migration, the contribution from this channel is, however, likely to be limited). The isoelectronic reaction of CN with C<sub>2</sub>H<sub>4</sub> also produces essentially unity H-atom yield.<sup>20,34</sup>

No H-atom signal was observed from the reaction of  $C_2H +$ propene at 50 Torr total pressure. Uncertainties in the analysis put an upper limit of 5% on H-atom production. Various reasons can be postulated for the lack of H-atom production from reaction R7: (1) Under our experimental conditions, collisional stabilization of this system (which is larger than  $C_2H + C_2H_4$ ) is essentially complete. (2) 1,2-H migration from the initial adduct, forming the more stable (CH<sub>3</sub>)CH<sub>2</sub>-C•H-C=CH radical, is more rapid than H-atom elimination. Methyl radicals will be preferentially produced from the fragmentation of (CH<sub>3</sub>)CH<sub>2</sub>-C•H-C=CH. (3) Direct abstraction to form the resonantly stabilized allyl radical occurs.

Whereas it is not possible to be definitive with the current experimental measurements, some pointers to the products can be gained from comparison with the isoelectronic CN + propene reaction (R8a–R8d), which has recently been investigated experimentally and through theoretical calculations.<sup>21,35</sup>

$$CN + C_3H_6 \rightarrow H + C_4H_5N \qquad (R8a)$$

$$\rightarrow$$
 CH<sub>3</sub> + C<sub>3</sub>H<sub>3</sub>N (R8b)

$$\rightarrow C_4 H_6 N \qquad (R8c)$$

$$\rightarrow$$
 HCN + C<sub>3</sub>H<sub>5</sub> (R8d)

For this reaction (and the larger CN + iso-butene reaction), a pressure-dependent H-atom yield was observed<sup>21</sup> over the range of 2–200 Torr (i.e., both reactions R8a and R8c were occurring), suggesting that whereas the initial complex formed between C<sub>2</sub>H and propene might be collisionally stabilized, complete stabilization of the complex would not be expected under our experimental conditions.

Extrapolation of the H-atom yield from reaction R8a to zero pressure predicted an H-atom yield of ~50%.<sup>21</sup> This experimental yield was consistent with preferential, but not exclusive, formation of the secondary radical following CN addition and competition between 1,2-H atom migration, with subsequent methyl elimination, and H atom dissociation from the secondary radical. Broadly similar results were obtained in the more recent study of Trevitt et al.35 using photoionization mass spectrometry to observe cyanoethene  $(+CH_3)$  or  $C_4H_5N$  (+H) species. In the low-pressure study of Trevitt et al., H atom elimination was the minor channel (25  $\pm$  15%), but error bars of the zeropressure H-atom yields overlap. It is possible that the analogous C<sub>2</sub>H system behaves differently with a more facile 1,2-H-atom migration. Given the similarities in behavior between the C<sub>2</sub>H and CN + ethene systems, this seems unlikely, but either highlevel calculations or experimental observation of the CH<sub>3</sub> yield are needed to confirm the role of isomerizations following addition.

The final possibility is that direct abstraction to yield  $C_3H_5$ and  $C_2H_2$  is dominating. Calculations for H atom abstraction by C<sub>2</sub>H from isobutane predict a negative activation energy for this abstraction system with a relatively weak C–H tertiary bond (DH<sub>298</sub> = 403 kJ mol<sup>-1 36</sup>), and earlier measurements by Hoobler et al.<sup>37</sup> do indeed measure a slight negative temperature dependence for reaction R7 and a fast rate coefficient of  $9.6 \times 10^{-11}$  cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup> at room temperature. The C–H bond leading to allyl is significantly weaker (DH<sub>298</sub> = 369 kJ mol<sup>-1 38</sup>), and given the correlation between activation energies of abstraction reactions and bond dissociation energies observed by Opansky and Leone,<sup>8</sup> one would expect H-atom abstraction by C<sub>2</sub>H to form allyl and acetylene to be barrierless and possibly competitive with addition/elimination.

e. Implications. This work has demonstrated that the H-atom yield of  $C_2H$  reactions can be studied using the photolysis of acetylene at low laser energy densities at 193 nm as an internal calibration. This reaction can now be used as the basis for the study of H-atom yields from other  $C_2H$  reactions, and the H-atom yields from  $O_2$  and NO will be the subject of a future paper.

Internal calibration systems have the major advantage that the H-atom signal does not need to be corrected for the different detection efficiency in the presence of either the calibrant or test reagents. This is particularly important if  $H_2$  is used as the calibration reaction because  $H_2$  can quench Lyman- $\alpha$  fluorescence.<sup>20</sup> However, internal calibrations do introduce a significant alternative source of error in that the signal directly following photolysis, at zero time, needs to be accurately determined. For normal calibration reactions, this is a straightforward process for exponential growth, which starts at zero signal at zero time. However, for internal calibrations, this approach is not possible, introducing additional random errors and limiting the concentration of substrate that can be introduced.

The reaction of C<sub>2</sub>H with C<sub>2</sub>H<sub>4</sub> (R5a and R5b) is of potential importance in both combustion chemistry and in the reducing atmospheres of the outer planets and their satellites. C<sub>4</sub>H<sub>5</sub> species can be formed either by stabilization at high pressures of the C<sub>4</sub>H<sub>5</sub>\* intermediate formed in reactions R5aand R5b or from the addition of H atoms to vinylacetylene. The reactions of C<sub>4</sub>H<sub>5</sub> isomers with acetylene have been implicated in the first steps of soot formation.<sup>39,40</sup> In planetary atmospheres, the formation of vinylacetylene is one example of the growth of larger functionalized compounds. Such molecules are important in the synthesis of yet larger compounds and hazes, but also, because they photolyze at longer wavelengths than simple alkenes or alkynes,<sup>41</sup> they can be a source of radicals lower in the atmosphere.

A recent model for haze formation in Titan's atmosphere<sup>42</sup> includes only the  $C_4H_4 + H$  channel from reactions R5a and R5b, and this work confirms that this will be the only important reaction under such conditions. The same model has H + unidentified coproducts for reaction of  $C_2H$  with  $C_3H_6$  (reaction R7). In this case, the current studies suggest that this is incorrect and that for alkenes with allylic hydrogens, the efficiency of  $C_2H$  reactions in promoting molecular growth may need to be adjusted.

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