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Flow tube studies of the C($^3$P) reactions with ethylene and propylene

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**ABSTRACT**

Product detection studies of C($^3$P) atom reactions with ethylene, C$_2$H$_4$(X$^1$A$_g$) and propylene, C$_3$H$_6$(X$^1$A') are carried out in a flow tube reactor at 332 K and 4 torr (553.3 Pa) under multiple collision conditions. Ground state carbon atoms are generated by 193-nm laser photolysis of carbon suboxide, C$_3$O$_2$ in a buffer of helium. Thermalized reaction products are detected using tunable VUV photoionization and time of flight mass spectrometry. For C($^3$P) + ethylene, propargyl (C$_3$H$_3$) is detected as the only molecular product in agreement with previous studies on this reaction. The temporal profiles of the detected ions are used to discriminate C($^3$P) reaction products from side reaction products. For C($^3$P) + propylene, two reaction channels are identified through the detection of methyl (CH$_3$) and propargyl (C$_3$H$_3$) radicals for the first channel and C$_4$H$_5$ for the second one. Franck-Condon Factor simulations are employed to infer the C$_4$H$_5$-isomer distribution. The measured 1:4 ratio for the $i$-C$_4$H$_5$ isomer relative to the methylpropargyl isomers is similar to the C$_4$H$_5$ isomer distribution observed in low-pressure flames and differs from crossed molecular beams data. The accuracy of these isomer distributions is discussed in view of large uncertainties on the photoionization spectra of the pure C$_4$H$_5$ isomers.
Introduction

The chemistry of carbon atoms is involved in a wide variety of environments, from combustion reactors to astrophysical objects. Atomic carbon, the fourth most abundant element in the Universe, is ubiquitous in the interstellar medium and has been observed in various astronomical objects.\textsuperscript{1-3} In combustion flames, although their detection is experimentally very challenging,\textsuperscript{4} their reaction was proposed to be responsible for C\textsubscript{2} formation and chemiluminescence.\textsuperscript{5} Carbon atoms have been detected in discharge plasmas,\textsuperscript{6} chemical vapor deposition processes,\textsuperscript{7} and are also abundant in thermal plasmas.\textsuperscript{8} In all these environments the reactions of carbon atoms with small hydrocarbons are believed to initiate complex radical chemical schemes leading to the formation of larger molecules.\textsuperscript{6,9} Reactions of ground-state atomic carbon C(\textsuperscript{3}P) with unsaturated hydrocarbons and free radicals are therefore important in order to better understand and predict the growth of carbon containing molecules, including the formation of polycyclic aromatic hydrocarbons (PAHs).

Pioneering kinetic measurements performed by Husain and Haider\textsuperscript{10,11} demonstrated that C(\textsuperscript{3}P) reactions with hydrocarbons are very fast at room temperature. Very low temperature kinetic experiments (down to 20 K) also showed that these reactions remain rapid at low collision energies, indicating the absence of a barrier in the entrance channel.\textsuperscript{12-14} Even in cold environments such as interstellar clouds or planetary atmospheres, C(\textsuperscript{3}P) atoms will significantly contribute to the chemistry by fast barrierless reactions with the abundant hydrocarbons.\textsuperscript{12,15}

Reactions of ground state carbon atoms with small hydrocarbons are predicted to proceed by addition of the carbon atom onto carbon double or triple bonds to form an energy-rich reaction adduct.\textsuperscript{15} Large uncertainties still remain regarding the fate of the so-formed intermediate. One of the proposed exit channels used in chemical models is the loss of a hydrogen atom to form larger open-shell hydrocarbons. The overall reaction can be written as C + C\textsubscript{n}H\textsubscript{m} \rightarrow C\textsubscript{n+1}H\textsubscript{m-1} + H. H-atom branching ratios for C(\textsuperscript{3}P) reactions with unsaturated hydrocarbons have been studied by Bergeat and Loison.\textsuperscript{16,17} In most cases, the
H-loss accounts for no more than half of the reaction products. This result may be explained by competitive C-H and C-C cleavage as well as by the transition of the reaction intermediate from the triplet surface to the singlet surface by intersystem crossing (ISC).\textsuperscript{18} The accuracy of the models reproducing the chemistry of carbon-rich environments strongly depends on the identification of all the reaction products.

In addition to H-atom detection in flow reactors,\textsuperscript{16,17} crossed molecular-beams experiments combined with theoretical calculations have been widely used to investigate the dynamics of carbon atoms with a variety of hydrocarbons. The product formation of the reaction C(\textsuperscript{3}P) + ethylene (C\textsubscript{2}H\textsubscript{4}) was successively studied by R. Kaiser and co-workers at 7.1 and 38.1 kJ mol\textsuperscript{-1} collision energies,\textsuperscript{19} by M. Costes, P. Casavecchia and co-workers at collision energies ranging from 0.49 to 30.8 kJ mol\textsuperscript{-1}\textsuperscript{14} and more recently by S.-H. Lee and co-workers at 14.6 kJ mol\textsuperscript{-1}\textsuperscript{20} In these crossed beams experiments the products are detected by laser induced fluorescence of H-atoms,\textsuperscript{14} or quadrupole mass spectrometry coupled to electron impact ionization\textsuperscript{14,19} or synchrotron radiation photoionization.\textsuperscript{20} \textit{Ab initio} calculations by Mebel and co-workers\textsuperscript{21} indicate that the C(\textsuperscript{3}P) + C\textsubscript{2}H\textsubscript{4} reaction proceeds without an entrance barrier, as confirmed by the low temperature experimental kinetic study of Chastaing et al.\textsuperscript{12} Theoretical investigations of the C\textsubscript{3}H\textsubscript{4} potential energy surface have shown the presence of many minima on the potential energy surface leading to various isomers with a large number of energetically allowed dissociation routes.\textsuperscript{22,23} Mebel and co-workers performed Rice-Ramsperger-Kassel-Marcus (RRKM) calculations for collision energies lower than 38.5 kJ mol\textsuperscript{-1} resulting in branching ratios of 98-99% for the H\textsubscript{2}CCCH + H channel, 1-2% for the CH\textsubscript{2} + C\textsubscript{2}H\textsubscript{2} channel, and negligible contributions from other channels.\textsuperscript{22} These single collision branching ratios are consistent with the kinetic study of Bergeat et al.\textsuperscript{16} performed at room temperature (ca. 4 kJ mol\textsuperscript{-1}) and 2 Torr in a flow reactor showing an absolute H-branching ratio of 0.92 ± 0.04 under multiple collision conditions. The works of Kaiser and co-workers and Casavecchia and co-workers also led to the conclusion that C\textsubscript{3}H\textsubscript{3} (propargyl) + H was the main channel of the C(\textsuperscript{3}P) + C\textsubscript{2}H\textsubscript{4} reaction. However, at collision energies greater than 6 kJ mol\textsuperscript{-1}, Casavecchia and co-workers claimed the presence of at least one other H-atom elimination channel forming a less
stable C₃H₃ isomer(s). In the most recent study, Chin et al.²⁰ investigated the velocity distribution of C₃H₃ radicals produced by the C(^3P) + C₂H₄ reaction, at 14.6 kJ mol⁻¹ collision energy, using two different photoionization energies: 9.5 and 11.6 eV. For both ionization energies, the time of flight remains unchanged, indicating that only one isomer contributed to the C₃H₃ isomer channel, which was identified as propargyl (H₂CCCH) based on its photoionization spectrum.

The product formation of the C(^3P) + propylene (C₃H₆) reaction was first studied by Kaiser and co-workers²⁴ who recorded product angular and velocity distributions of C₄H₅ radical at m/z=53 at average collision energies of 23.3 and 45.0 kJ mol⁻¹. Similar to the C(^3P) + ethylene reaction, low temperature experimental kinetic studies²⁵ and ab initio calculations performed by Mebel and co-workers²¹ demonstrated that the carbon atom is likely to add to the π-orbitals of propylene without an entrance barrier. More recently, Lee and co-workers²⁶ identified C₄H₅ + H, C₄H₄ + 2H and C₃H₃ + CH₃ as exit channels in C(^3P) + propylene in their crossed molecular beams experiment coupled to synchrotron radiation mass spectrometry. Quantum calculations were used to calculate the C₄H₆ potential energy surface and infer the most likely reaction mechanisms.²¹,²⁴-²⁶ The accepted mechanism is the addition of the triplet carbon onto the reactant double bond to form a cyclic intermediate with no activation energy. The reaction adduct then isomerizes via ring opening to give the triplet Z- and E-CH₃CHCCH₂ stereoisomers.²⁴,²⁶ These triplet C₄H₆ adducts are found to isomerize through H-atom transfer and to decompose through H-loss to form H₂CCCHCH₂ (i-C₄H₅), HCCCCHCH₃ and H₂CCCCH₃, two methylpropargyl isomers. The CH₃ + C₃H₃ (propargyl) channel is also found to be energetically accessible. All the transition states are found to be below the energy of the reactants.

RRKM calculations on these surfaces predict branching ratios for HCCCCHCH₃/H₂CCCCH₃/i-C₄H₅ + H and H₂CCCH + CH₃ of 7:5:10:78 respectively at 17 kJ mol⁻¹, while experimental evaluations based on ionization efficiencies give a ratio of 17:8:75 for the C₄H₅ (sum of all isomers):C₄H₄:C₃H₃ products.²⁶ The same authors used photoionization spectroscopy of C₄H₅ (m/z=53) at photon energies ranging from 7
to 12 eV to assign HCCCHCH$_3$, H$_2$CCCCH$_3$ and $i$-C$_4$H$_5$ as the main formed isomers at 16 kJ mol$^{-1}$
collision energy. They determined the yield of the sum of the HCCCHCH$_3$ and H$_2$CCCCH$_3$ relatively to
the $i$-C$_4$H$_5$ contributions to be $\sim$1.4 by fitting calculated photoionization spectra to the experimental data
assuming all isomers have identical photoionization cross sections.

A better understanding of the role of C(3P) chemistry in interstellar chemistry, combustion and
plasma environments requires probing its reaction mechanisms with hydrocarbons over a very wide range
of experimental conditions, including multiple collision environments. In this study, we present the
detection of the products formed by the reactions of carbon atoms with ethylene and propylene under
multiple collision conditions at 332 K and 4 Torr and compare the results to recent crossed molecular-beams data. Flow tube and crossed beams experiments differ significantly by the energy range and the
collisional conditions. Crossed beam experiments look at the formation and dissociation of reaction
intermediates following a single collision of the reactants with no effect from the surrounding
environment. In flow tube experiments the large number of collisions leads to the thermalization of the
products to the temperature of the flow and may induce, in some cases, stabilization of reaction adducts
and intermediates. Flow tube experiments have been applied to a wide variety of reactions, and are
complementary to crossed molecular beam experiments; each approach has its advantages and
disadvantages. For example, crossed beam experiments can be quite sensitive to heavy/light product
channels (when probing the heavy product that is confined to a small Newton sphere), but much less
sensitive to highly exothermic bimolecular channels with more even mass pairs. This bias doesn’t exist in
a collisional experiment. Angular distributions can be easily extracted from crossed molecular beam
experiments, and generally not possible to extract from collisional environments. Photoionization spectra
are less often acquired in crossed beam environments because the signal levels can make this challenging,
whereas such spectra for identifying isomers are routine in flow tube experiments. Numerous studies have
been performed using flow tube$^{27-32}$ and crossed molecular beams,$^{14,33-38}$ the combination of which has
provided very valuable information for the understanding of the chemistry of gas phase environments
ranging from the interstellar medium to combustion flames. However, it is important to note that flow tube experiments are able to provide information about bimolecular processes only if one can discriminate between primary and secondary processes as well as demonstrate that the relevant products are formed by the studied reactions. Previous studies for highly reactive radicals (C₂H, CH, CN) have demonstrated that the time-, mass-, and energy-resolved detection of the products makes such identification possible.²⁷,²⁸,³⁹-⁴³ Goulay et al.³⁹ have demonstrated that multiplex photoionization mass spectrometry can directly rule out multiple collision effects when they do not happen.

In the present study, carbon atoms are created from photodissociation of carbon suboxide, C₃O₂, at 193 nm, and are shown to be formed essentially in their ground electronic state, C(³P), eliminating the effect of C(¹D) reactions. The products of both reactions are detected using time-resolved mass spectrometry combined with synchrotron photoionization spectroscopy. The effect of secondary reactions and pressure on the product distribution is discussed as well as the relevance of the experimental data for carbon-rich gas phase environments.

**Experimental section**

The reactions are performed in a slow flow reactor coupled to a time-resolved photoionization time of flight mass spectrometer at the Advanced Light Source (ALS) synchrotron at the Lawrence Berkeley National Laboratory. A description of the apparatus has been given elsewhere³²,⁴⁴ and only a brief overview is presented here. The flow tube is a 62-cm long quartz tube with 1.05 cm inner diameter. The gas pressure within the reaction tube is typically 4 Torr (533.3 Pa) with a total gas flow of 250 sccm (standard cubic centimetres per second). All the experiments are performed at 332 K corresponding to a gas flow velocity of 11 m s⁻¹ and total number density of 1.16×10¹⁷ cm⁻³. The helium buffer gas, carbon atom precursor (C₃O₂, 1.40×10¹⁴ cm⁻³) and reaction gases (ethylene, 2.55×10¹⁴ cm⁻³, and propylene 2.32×10¹⁴ cm⁻³) are supplied to the reaction flow via separate mass-flow controllers. The pressure within the reaction flow-tube is maintained constant using a butterfly valve that throttles a roots pump. Carbon
atom reactions are initiated by 193 nm photolysis of carbon suboxide, C$_3$O$_2$, using a pulsed excimer (ArF) laser operating at 10 Hz.

C$_3$O$_2$ is synthesized prior to the experiments via the dehydration of bis(trimethylsilyl) malonate (BTSM, Aldrich, 98% purity) using variations to the procedure reported by Birkoger and Sommer (with a 54% C$_3$O$_2$ yield). The system consists of a 3-neck flask (250 mL) connected to a nitrogen purge, two glass traps in series and a mechanical pump. The pressure in the entire system is measured using an absolute pressure gauge. The system is flushed with dry nitrogen at atmospheric pressure for at least 3 hours to remove any residual water. About 40 g phosphorous pentoxide (P$_2$O$_5$, Aldrich, 98.5% purity) is mixed with 20 g sand and placed in the flask. The phosphorous pentoxide is flushed with dry nitrogen to remove water. The system (flask and traps) is then evacuated to a pressure below 10 torr using a mechanical pump. About 20 mL of BTSM is measured with a syringe and injected at once through a rubber septum into the 3-neck flask. The reaction occurs spontaneously leading to a dark-red coloration of the solid and production of gas. The mixture of gaseous products is collected at 77 K in a large glass bubbler. After complete stop of gas production (formation of gas bubbles in the reactant flask) (~40 min) the liquid nitrogen is replaced by an acetone-liquid nitrogen slush at 179 K and the bubbler is evacuated. At this temperature, C$_3$O$_2$ has a negligible vapor pressure while CO$_2$ sublimes rapidly, leaving behind only C$_3$O$_2$ in the trap. Up to 110 Torr of C$_3$O$_2$ is then collected and buffered with 1100 Torr of helium in a 3.79 L stainless steel cylinder. The photoionization spectra of the gas mixture at m/z=68 confirmed the formation of carbon suboxide (Ionization Energy, IE=10.6 eV).

The 193-nm laser fluence inside the reaction flow tube ranges from 20 to 50 mJ/cm$^2$. Initial carbon atom number density in the flow tube is estimated to be approximately $2\times10^{11}$ cm$^{-3}$. At ~30 cm along the flow tube, a 650 µm diameter pinhole allows a small portion of the gas mixture to escape into a vacuum chamber. This gas is sampled by a skimmer creating a beam of molecules that is subsequently intersected by the quasi-continuous vacuum-ultraviolet (VUV) synchrotron radiation. Ions formed in this region are
detected as a function of their mass-to-charge (m/z) ratio using a 50 kHz pulsed orthogonal-acceleration time-of-flight mass spectrometer. All detected ions are time-tagged relative to the excimer laser pulse (at \( t = 0 \)) and accumulated in a multichannel scaler. In this way, complete mass spectra are collected as a function of reaction time. The excimer laser is operated at 10 Hz, allowing sufficient time between laser pulses to completely refresh the gas mixture before the next laser pulse. The total ion detection time-window is 50 ms, beginning 10 ms before the laser pulse.

Reagent gases were used without further purification: ethylene (99.9%, Aldrich), propylene (>99%, Aldrich).

**Computational methods**

\( \text{C}_4\text{H}_5 \) photoionization spectra are simulated within the Franck–Condon (FC) approximation. Electronic structure calculations of the neutral \( \text{C}_4\text{H}_5 \) species and their cations are carried out using the Gaussian09 package\(^47\) using the B3LYP/CBSB7 method to obtain optimized geometries and Cartesian force constants. All the vibrational frequencies are real, indicating that the optimized geometries represent minima on the potential energy surface. The FC factors are calculated at 298 K using the G09 package within the Franck–Condon approximation.\(^48\) The simulated factors are convolved with a 40 meV (FWHM) Gaussian response function and integrated to simulate photoionization spectra. The spectra are shifted such that the energy difference between the neutral and ion ground states matches the ionization energy calculated by Hansen et al. using B3LYP/6–311++G(d,p) level of theory.\(^49\)

**Results and discussion**

At 4 Torr and 332 K the collision frequency of the products (for example \( \text{C}_3\text{H}_5 \)) with the He buffer gas is of the order of \( 17 \times 10^6 \) s\(^{-1}\) (or 1 collision every 59 ns). Under these conditions, the products are rapidly thermalized to the flow temperature. These collisions may also stabilize reactive intermediates if the unimolecular decay of such chemically activated intermediates occurs on the same timescales (0.1 – 200
microseconds) as collisional energy transfer. For unimolecular decay rates faster than \( \sim 17 \times 10^6 \text{ s}^{-1} \), stabilization cannot compete with dissociation, and chemically activated intermediates will decay in the same way as in crossed molecular beams experiments. Therefore, when a reactive intermediates decays with a lifetime shorter than the collision frequency, and it decays to a stable molecule with a lifetime much longer than the collision frequency, the product branching observed via crossed molecular beams and collisional experiments should be identical if the proper weighting is given to the range of collision energies.

Successive reactions of the formed products with other radicals present in the reaction flow may also occur over a short time scale (<1 ms). These reactions will lead to secondary products at higher molecular masses than that of the \( \text{C}(^3\text{P}) + \) hydrocarbons products. At 193 nm, hydrocarbon photodissociation cross sections are relatively high leading to a large number of side reactions. Because \( \text{C}(^3\text{P}) \) reactions are very fast, under the experimental conditions, they will occur within few hundreds of microseconds after the laser pulse. It is therefore possible to discriminate between \( \text{C}(^3\text{P}) \) reaction and slower reactions by inspecting the product time traces. In the following sections, the contribution from slow reactions \( (k_{2\text{nd}}<5 \times 10^{-12} \text{ cm}^3 \text{ molec}^{-1} \text{ s}^{-1} \text{ or } k_{1\text{st}}<500 \text{ s}^{-1}) \) or subsequent reactions is minimized by integrating mass spectra only over the 0–1ms time range.

Time- and energy-resolved mass spectra are obtained by averaging at least 500 laser shots at each photon energy. In the present study the ionizing photon energy is scanned from 7.4 to 10.6 eV in steps of 0.025 eV. Kr or Ar is used in a gas filter to absorb higher energy photons at harmonics of the undulator energy. All data are normalized to account for the variations in ALS photocurrent using a NIST-calibrated photodiode (SXUV-100, International Radiation Detectors, Inc.). At each mass-to-charge (m/z) ratio, the average signal present before the laser pulse is subtracted from the time dependent data. Mass spectra of the buffer gas with the reactants and/or \( \text{C}(^3\text{P}) \) precursor were recorded at the beginning of each run with and without the laser pulse. No ion signals were detected at m/z=39 and 53, the masses of the expected
$C(^3P) +$ hydrocarbon products. The photoionization spectra at a given m/z ratio are obtained by integrating the data set over the desired mass and time windows. Three independent datasets are recorded for each reaction and averaged. The error bars for a given data point of a photoionization spectrum are twice the standard deviation around the mean value. The photon energy resolution is determined to be of the order of 40 meV by measuring an atomic resonance of Xe.

In the present experiments, carbon suboxide was used as the precursor of ground state carbon atoms, $C(^3P)$, and was chosen to avoid any contribution from the $C(^1D)$ state. The photodissociation of $C_3O_2$ has been studied by several authors.$^{50-55}$ The absorption cross section of carbon suboxide at 193 nm is ca. $10^{-18}$ cm$^2$ and the energetically accessible primary product channels are CO + $C_2$O and $C(^3P) + 2CO$.\textsuperscript{54} The first experimental measurement of the relative yield of carbon atoms to $C_2$O following the photolysis of $C_3O_2$ at 193 nm was performed in 1989 by McFarlane et al.\textsuperscript{53} Dissociation to CO + $C_2$O was shown to be the dominant pathway, with a ratio of ground state carbon atoms, $C(^3P)$, to $C_2$O of $0.06 \pm 0.03$. Carbon suboxide photolysis at 193 nm has been used by several authors to generate carbon atoms in their ground state. Chastaing et al.$^{12,13,57}$ performed kinetics experiments of $C(^3P)$ atom reactions at low temperatures using carbon suboxide as a precursor and monitoring ground state carbon atoms by VUV LIF at ca. 166 nm.

The 193-nm $C_3O_2$ photodissociation spin allowed exit channel leads to the formation of the singlet $C_2O(\tilde{a}^1\Delta)$ and CO($X^1\Sigma^+$).\textsuperscript{51,58} Figure 1 shows (a) the mass spectrum and (b) the kinetic trace of $C_2$O at m/z=40 recorded at 11.3 eV upon irradiation of $C_3O_2$ in helium. A positive peak represents species production following laser irradiation; a negative peak represents laser-induced destruction. Negative signals at m/z=43 and 60 are likely due to photolysis and dissociative ionization of impurities. The positive signal at m/z=52 could be due to reaction of $C_2$O with impurities. In the absence of any other reactants, loss on the reactor walls of singlet $C_2$O, along with its reaction with $C_3O_2$, is likely to account for the fast signal decay. The most thermodynamically favorable $C_2$O + $C_3O_2$ exit channel is the formation
of C₂ and 3CO. In the presence of ethylene and propylene, C₂O is likely to react with the unsaturated molecules via addition followed by CO-loss. C₂O may also react with atomic hydrogen with a rate of \(3 \times 10^{11} \text{ cm}^3 \text{ s}^{-1}\), leading to the formation of CH + CO. In our reaction flow, H atoms are formed from photolysis of the hydrocarbons as well as from their reactions with carbon atoms. Because C₂O is the most abundant radical in the reaction flow, a non-negligible amount of CH radicals will be formed. A list of the main reactions expected to occur upon irradiation of a C₃O₂ in the presence of hydrocarbon reactants at 193 nm is presented in supplementary information.

In the following section, we analyze mass spectra and photoionization spectra obtained upon irradiation of a mixture of carbon suboxide with ethylene and propylene. The formation of C₃H₃, upon photolysis of C₃O₂ in the presence of C₂H₄ is used to demonstrate the formation of atomic carbon. Energy- and time-resolved mass spectra for the C + C₂H₄ reaction with and without adding a large quantity of molecular hydrogen are used to rule out the formation of the excited singlet state, C(^1D). The time behavior of the ion signal after the laser pulse is used to discriminate between C(^3P) reaction products and products from side reactions. For the C(^3P) + C₃H₆ reaction, the isomeric structures of the reaction products are identified by comparing their photoionization spectra to flame data or to the integrated Franck–Condon factors.

**C(^3P) + ethylene**

Figure 2 displays the background subtracted photoionization mass spectrum obtained following photolysis of a mixture of C₃O₂ and ethylene in helium. The negative signals at m/z=28, 43 and 58 are due to imperfect subtraction of ion signal from ethylene and acetone impurity. At 193 nm, the absorption cross section of ethylene is of the order of 1×10^{-20} \text{ cm}^2 and its photodissociation may also contribute to the negative signal at m/z=28. \(^{60}\) The data are recorded at 10.7 eV photon energy and integrated over the 0–1 ms reaction time window. Over this short reaction window, the main ion signals are detected at m/z=39,
If C(\textsuperscript{1}D) were produced, its quenching by the helium buffer gas is likely to be very slow. In order to address the possible formation of C(\textsuperscript{1}D) in our experiments, a time- and energy-resolved mass spectrum was recorded adding at least 10 times more molecular hydrogen in the reaction flow than ethylene reactant. The C(\textsuperscript{1}D) + H\textsubscript{2} reaction rate coefficient has been measured to be $2.0(\pm 0.6) \times 10^{-10}$ cm\textsuperscript{3} molec\textsuperscript{-1} s\textsuperscript{-1} at room temperature\textsuperscript{61} while the C(\textsuperscript{3}P) + H\textsubscript{2} $\rightarrow$ CH + H reaction is endothermic by 96 kJ mol\textsuperscript{-1}.\textsuperscript{62} An upper limit of the termolecular rate coefficient for C(\textsuperscript{3}P) + H\textsubscript{2} + He at 300 K was derived by Husain and Young to be $6.9(\pm 1.2) \times 10^{-32}$ cm\textsuperscript{6} molec\textsuperscript{-2} s\textsuperscript{-1}.\textsuperscript{63} Under our experimental conditions the expected pseudo first order rate constants are of the order of 53,550 s\textsuperscript{-1} and 510,550 s\textsuperscript{-1} for C(\textsuperscript{3}P) + C\textsubscript{2}H\textsubscript{4} and C(\textsuperscript{1}D) + H\textsubscript{2}, respectively.\textsuperscript{25,64} Therefore, even if the C(\textsuperscript{1}D) + C\textsubscript{2}H\textsubscript{4} reaction has a gas-kinetic rate coefficient, any C(\textsuperscript{1}D) that might be formed via photolysis of C\textsubscript{3}O\textsubscript{2} will be consumed predominantly by reaction with molecular hydrogen. The C(\textsuperscript{1}D) + H\textsubscript{2} reaction produces the CH radical in its electronic ground state, which upon reacting with C\textsubscript{2}H\textsubscript{4} forms C\textsubscript{3}H\textsubscript{4} isomers.\textsuperscript{65,66} If C(\textsuperscript{1}D) were present in our experiment, adding a large amount of molecular hydrogen in the flow tube would lead to an increase of the C\textsubscript{3}H\textsubscript{4} ion signal. Furthermore, C(\textsuperscript{1}D) + C\textsubscript{2}H\textsubscript{4} is likely to be a source of C\textsubscript{3}H\textsubscript{3} and the competitive reaction with H\textsubscript{2} should greatly decrease the amount of C\textsubscript{3}H\textsubscript{3} formed by the C(\textsuperscript{1}D) + ethylene reaction. However, the absolute intensities of m/z=39 and m/z=40 are found to be unchanged upon addition of a large amount of molecular hydrogen. Together with the previous studies on the photodissociation of C\textsubscript{3}O\textsubscript{2} at 193 nm this strongly suggests that C(\textsuperscript{1}D) atoms are not produced in a significant amount. To be cautious, all the experiments were conducted with a large excess of molecular hydrogen. In the following discussion reactions between C(\textsuperscript{1}D) and the hydrocarbon reactants are neglected.

Figure 3 shows the photoionization spectrum measured at m/z=39. The solid red line is the photoionization spectrum of the propargyl radical (C\textsubscript{3}H\textsubscript{3}) obtained by Savee et al.\textsuperscript{67} The very good match between the two spectra shows that propargyl is formed upon C\textsubscript{3}O\textsubscript{2} photodissociation in the presence of ethylene. As indicated by previous H-atom branching ratio measurements and cross molecular beams
experiments, the $C(3^P) + C_2H_4$ reaction is expected to solely produce the propargyl radical through an addition-elimination mechanism. Table S1 (see supplementary information) displays the predominant reactions resulting from the reaction system. Under these multiple collision conditions, the propargyl radical may be formed by the $C(3^P) + C_2H_4$ reaction as well as by the $C_2O + C_2H_3$ reaction. The $C_2H_3$ radical has an ionization energy of 8.25 eV and has been previously detected in similar experiments. In Figure 2 the small signal at $m/z=27$ suggests that the vinyl radical is not formed in significant amount. In addition the rate coefficient for the $C_2O + C_2H_3$ is likely to be one order of magnitude slower than $C(3^P) + C_2H_4$ reaction (based on expected radical–radical kinetics of reactions with no barrier) and is therefore unlikely to contribute to the fast $m/z=39$ signal rise observed in Figure 5.

Figure 4 displays photoionization spectra of $m/z=40$. The red line is a fit to the spectrum using the experimental absolute spectra of allene and methylacetylene. The best fit is within the 2-σ error bars and corresponds to branching fraction of 49% allene and 51% methylacetylene. The formation of $C_3H_4$ isomers ($m/z = 40$) upon irradiation of a $C_3O_2/C_2H_4$ gas mixture at 193 nm was also previously reported by Bayes et al. As discussed by Kaiser et al. the formation of the reaction adduct at $m/z=40$ upon attack of the triplet carbon atom onto the ethylene double bond does not lead to formation of the singlet $C_3H_4$ final products. The lifetime of the triplet $C_3H_4$ intermediate is expected to be on the order of, or shorter than, the rotational period of the molecules (0.5 ps along the C axis). During this lifetime there will be a negligible number of collisions ($<<1$) between the triplet adduct and the He buffer gas. Crossing to the singlet surface is also predicted to be negligible. The triplet adduct is therefore expected to rapidly dissociate to form the propargyl radical by H-loss with negligible contribution from stabilization of the triplet or singlet intermediate. The $C_3H_4$ isomers observed in Figures 1 and 2 are therefore likely to come from side reactions in the reaction flow.

Figure 5 shows the temporal trace of the $C_3H_4$-isomers (red squares) and the propargyl radical (blue circles) signals. The decay of the $m/z=39$ ion signal after the initial radical formation is due to the
propargyl self-reaction and reaction with the reactor tube walls. In the case of the closed-shell C₃H₄ products, the signal is stable after its formation, with a slight linear rise due to slight changes in laser fluence along the reactor tube. Within the experimental time resolution, both products are formed rapidly after irradiation of the gas mixture. The formation of propargyl radicals is likely to come from the C(³P) + C₂H₄ reaction whereas that of C₃H₄ isomers may be explained by either the C₂O + C₂H₄, or CH + C₂H₄ reaction (see Table S1). The C₂O radical is formed by photodissociation of the C₃O₂ precursor while the CH radical is formed by the C₂O + H reaction. At room temperature, the later reaction has a rate coefficient of 3×10⁻¹¹ cm³ molec⁻¹ s⁻¹ while CH + C₂H₄ has a rate coefficient of 2.84×10⁻¹⁰ cm³ molec⁻¹ s⁻¹. Using these rate coefficients, and estimating the C₂O + C₃O₂ rate coefficient at 1×10⁻¹⁰ cm³ molec⁻¹ s⁻¹, a simple kinetic model including C₂O + C₃O₂, C₂O + H, C + C₂H₄ and CH + C₂H₄ predicts a characteristic time for the rise of the C₃H₄ products of the order of 200 µs in agreement with the fast kinetic rise of m/z=40 in Figure 5. The C₃H₄ time-trace can be reproduced without including effects from the stabilization of the reaction adduct. This agrees with the short adduct lifetime discussed above.

Upon irradiation of the C₃O₂/ethylene mixture, signals at m/z=52 and m/z=42 are also observed when integrating the mass spectra over 40 ms of reaction time. Photoionization spectra of m/z=52 and m/z=42 identify them as vinylacetylene (C₄H₄) and ketene (H₂CCO, IE=9.6 eV)⁷², respectively. Their formation kinetics is slower than that of the C₃H₄ isomers. Vinylacetylene is unlikely to come from the reaction of CH radicals with the C₃H₄ products as most CH radicals will be completely consumed by reactions with more abundant molecules such as C₂H₄ and C₃O₂ (see Table S1). The reaction of the CH radicals with the abundant C₃O₂ is expected to give C₂H radicals and two CO molecules.⁶¹ The ethynyl radical can then react with ethylene to give vinylacetylene.⁷³ Alternatively the C₂O + C₃H₄ reaction may also lead to the formation of C₄H₄ by CO-loss. It is important to note that these products are the results of secondary and tertiary reactions and do not significantly contribute to the detected products at short
reaction time (see Figure 2). Ketene is likely formed by successive C₂O reactions with hydrocarbons and/or atomic hydrogen.

\textbf{C}(^3P) + \textit{propylene}

According to the recent theoretical investigation of the C(^3P) reaction with propylene by Chin et al.\textsuperscript{26} the main exothermic product channels are the following:

\[
\begin{align*}
\text{C}(^3\text{P}) + \text{C}_3\text{H}_6(X^1\text{A'}) &\rightarrow \text{CH}_3 + \text{C}_3\text{H}_3 & \Delta H = -228.2 \text{ kJ mol}^{-1} \\
&\rightarrow \text{H} + \text{C}_4\text{H}_5(\text{H}_2\text{C}≡\text{C}–\text{CH}_3) & \Delta H = -198.1 \text{ kJ mol}^{-1} \\
&\rightarrow \text{H} + \text{C}_4\text{H}_5(\text{H}_2\text{C}≡\text{C}–\text{CH}≡\text{CH}_2) & \Delta H = -188.1 \text{ kJ mol}^{-1} \\
&\rightarrow \text{H} + \text{C}_4\text{H}_5(\text{HC}≡\text{C}–\text{C}–\text{CH}_3) & \Delta H = -186.8 \text{ kJ mol}^{-1} \\
&\rightarrow 2\text{H} + \text{C}_4\text{H}_4(\text{HC}≡\text{C}–\text{C}–\text{CH}_2) & \Delta H = -8.4 \text{ kJ mol}^{-1}
\end{align*}
\]

Figure 6 displays the mass spectra obtained by photolysis of (a) propylene and (b) a mixture of C₃O₂ and propylene in helium. The data are recorded at 10 eV photon energy and integrated over the 0–1 ms reaction time window. By irradiating a mixture of propylene and helium in the absence of carbon suboxide, CH₃ (m/z=15), C₂H₃ (m/z=27), C₃H₃ (m/z=39) and C₃H₅ (m/z=41) are identified as products of propylene photolysis. At 193 nm, the absorption cross section of propylene is of the order of 3×10⁻¹⁹ cm² and its photodissociation also contributes to the negative signal at m/z=42.\textsuperscript{74} Upon addition of carbon suboxide to the gas mixture the signal at m/z=39 increases significantly and signals at m/z=52 (C₄H₄), m/z=53 (C₄H₅) and m/z=54 (C₄H₆) appear. The main ion signals are detected at m/z=15, 27, 39, 41, 52, 53 and 54. Additional smaller signals are observed at m/z=51, 55, 56, 65, 66. Ion signal at m/z=40 is observed upon irradiation of propylene with no significant effect of C₃O₂ addition. In this case the C₃H₄ isomers may be formed by reaction of the propylene photoproducts such as C₃H₅ + H.\textsuperscript{75}
Figure 7 presents the normalized time traces of some of the (a) odd and (b) even masses over the first 5 ms, integrated over the 8.5–10.5 eV energy range. The thick solid lines are (a) double exponential and (b) single exponential fits to the signals at m/z=53 and 40, respectively. In Figure 7 (a), the slower time constant in the double exponential is fixed to the value obtained by fitting the same data from 1 ms to 40 ms using a single exponential decay. Because the long time signal has contribution from dissociative ionization of an higher mass (see further) an ion offset is added to the fit and fixed to the signal value at 40 ms. The best fits return a pseudo first order rise of $2400 \text{ s}^{-1}$ for m/z=40 and $5145 \text{ s}^{-1}$ for m/z=53. Table S2 (see supplementary information) displays the main reactions expected to occur in the reaction flow upon irradiation of a C$_3$O$_2$/C$_3$H$_6$ mixture at 193 nm. The slower rise of the m/z=40 and 54 displayed in Figure 7 (b) compared to that of m/z=15, 39, and 53 suggests that they are formed by slower reactions than the C($^3$P) + propylene reaction or secondary processes such as C$_2$O, CH and C$_2$H reactions. The signal at m/z=52 is identified based on its photoionization spectrum as vinylacetylene (C$_4$H$_4$) likely formed by reaction of the C$_2$H radical with C$_3$H$_6$ (CH$_3$-loss channel).$^{73,76}$ Because the lifetime of the reaction adduct is expected to be very short,$^{24}$ products at m/z=54 are likely to be formed by the CH + C$_3$H$_6$ reaction.$^{43}$

According to Table S2, C$_4$H$_5$ at m/z=53 may be formed by C($^3$P) + C$_3$H$_6$ or the unwanted C$_2$O + C$_3$H$_5$ reaction. We use the kinetic traces to distinguish between the two potential sources. Both the C$_2$O and C$_3$H$_5$ radicals are detected and are formed by 193 nm photolysis of C$_3$O$_2$ and C$_3$H$_6$, respectively. The C$_2$O + C$_3$H$_5$ reaction rate can be estimated to be of the order of $4 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ based on barrierless radical–radical reactions. According to the C$_3$O$_2$ and C$_3$H$_6$ number densities and 193-nm absorption cross sections, both radicals are expected to be formed with similar number densities, on the order of $5 \times 10^{12} \text{ cm}^{-3}$. The characteristic rise time of any reaction products is therefore expected to be 5 ms, which is much slower than the rise time of m/z=53 observed in Figure 7 (<500 µs). Based on this analysis, C$_4$H$_5$ + H are assigned as products of the C($^3$P) + C$_3$H$_6$ reaction.
The measurement of the C₄H₅/C₃H₃ branching ratio in the flow tube experiment is made difficult due to the high C₃H₆ 193 nm-absorption cross section and high C₃H₃ formation quantum yield. In addition, the propargyl and methyl radicals may also be formed by the C₂O + C₂H₃ and C₂H + C₃H₆ reactions, respectively (Table S2). Based on similar kinetic arguments as for the C₄H₅ products, it is unlikely that these reaction contribute to the fast m/z=39 and m/z=15 rise displayed in Figure 7 (a). From Figure 7(a), propargyl and the C₄H₅ isomers have a very similar temporal profile. The product ratio can therefore be estimated directly from the ratio of the signal corrected by the relative ionization cross sections. Because the absolute ionization cross sections for the C₄H₅ isomers are unknown the ratio of the ion signals gives only an estimate of the H vs. CH₃ loss branching. The ratio of the m/z=39 and 53 signals from Figure 6 subtracted from the photodissociation spectrum acquired with only propylene and helium, and assuming similar ionization cross sections, suggest a 1:1 branching fraction.

Figure 8 displays the m/z=53 photoionization spectrum obtained by irradiating a C₃O₂ and propylene mixture a 193 nm. The data are integrated over the 0–40 ms time range and displayed from (a) 7.4 to 10.5 eV and (b) 7.4 to 8.25 eV. In panel (a) the vertical lines indicate the ionization energies of i-C₄H₅ (IE=7.55 eV), and the methylpropargyl isomers (IE=7.94 eV for H₂CCCCH₃ and IE=7.95 eV for HCCCHCH₃), all to their singlet ion state, as well as the ionization to the triplet ion state of H₂CCCCH₃ (IE=9.74 eV). The ion signal observed above 7.5 eV and the ion onset at 7.9 eV suggest the presence i-C₄H₅ as well as one or two of the methylpropargyl isomers. Within the experimental photon energy resolution (40 meV) it is not possible to differentiate between the ionization of H₂CCCCH₃ or HCCCHCH₃. Additional ion signal onsets are observed at 8.25 eV and 9.5 eV. According to the calculated ionization energies of all the possible C₄H₅ isomers to their singlet or triplet ion states, the transition from the ground neutral state to the triplet ion state of H₂CCCCH₃ has the closest energy (9.74 eV) to that of the observed feature at 9.5 eV. The poor Franck–Condon overlaps calculated for transition to H₂CCCCH₃ triplet state suggest that the observed ion signal about 9.5 eV is not due to H₂CCCCH₃
ionization. Alternatively the ionization signal above 9.6 eV could be due to the dissociative ionization of a higher mass, leading to a charged ion at m/z=53 and a neutral fragment. In this case the time profile of the daughter ion is that of the parent molecule. Figure 9 displays the temporal profile of m/z=53 integrated from 8.5 to 9.4 eV and from 9.5 to 10.5 eV. The difference between the temporal traces is constant with time, suggesting contribution from a stable species other than the C₄H₅ radical isomers. The photoion spectrum of m/z=54 can be reproduced with contributions from only two isomers: 1,3-butadiene and 1-butyne; there is no evidence for cyclic C₄H₆ isomers. Neither 1,3-butadiene nor 1-butyne will dissociate to give C₄H₅ over the experimental energy range. The signal at photon energy higher than 9.5 eV is therefore likely to be mostly due to the dissociative ionization of a closed shell neutral whose parent ion corresponds to either 56 or 68. There is not enough information about the dissociative ionization of these molecules to conclusively assign the origin of the m/z=53 signal above 9.5 eV.

Figure 8b displays the m/z=53 photoionization spectrum over the 7.4–8.25 eV photon energy range together with the integrated Franck-Condon factor simulations for the i-C₄H₅ (dashed line) and the two methylpropargyl (dotted and dotted-dashed lines) isomers. The spectra for all the isomers are normalized to unity above 8.8 eV, where the simulated spectra are constant with photon energy. The thick red line is a fit to the experimental data up to 8.25 eV resulting in relative fractions of 1:4 for the i-C₄H₅ and methylpropargyl isomers, respectively, assuming equal ionization cross sections for all isomers. Because of the similarity of the methylpropargyl isomer spectra the fit is performed using only contribution from CH₃CCCH₂.

Figure 10 displays the m/z=53 photoionization spectra from the present experiments (circles) together with m/z=53 photoionization spectrum recorded in a low pressure (40 Torr) benzene flame (red line). Similar photoionization spectra were recorded in cyclopentene, propyne, and allene flames. Despite the large temperature difference, the very good overlap between the benzene flame spectrum and the present data strongly suggests that the C₄H₅ isomer distributions in the flow tube and in the flame are
similar. Hansen et al.\textsuperscript{77} identified $i$-$\text{C}_4\text{H}_5$ and the methylpropargyl isomers as the main contributors to m/z=53 ion signal. The authors were not able to explain the ion threshold at 8.25 eV based on simulated photoionization spectra and detailed combustion modeling. Using the same fitting procedure as that described above, they infer an isomer distribution of 1:3, which is similar to that expected under thermal equilibrium at 1700 K (using computed enthalpies of formation).\textsuperscript{49} At this temperature, the $\text{H}_2\text{CCCCH}_3$ isomer is twice as abundant as the HCCCHCH$_3$ isomer. At lower temperature, the equilibrium will shift toward the formation of the lowest energy isomer, $\text{H}_2\text{CCCCH}_3$. Close to room temperature under equilibrium conditions the contributions from $i$-$\text{C}_4\text{H}_5$ and HCCCHCH$_3$ are expected to be negligible. The detection of $i$-$\text{C}_4\text{H}_5$ in the flow tube experiment suggests that the measured m/z=53 ion spectrum in Figure 10 is not representative of a thermal equilibrium isomer distribution at 330 K.

Chin et al.\textsuperscript{26} identified m/z=15, 39, 52, and 53 as the main products of the C($^3\text{P}$) + propylene reaction under single collision conditions. They report a H:CH$_3$-loss channel ratio of 1:4 and a ratio of the sum of the methylpropargyl isomer densities over that of $i$-$\text{C}_4\text{H}_5$ of 1.4. The 1:4 branching ratio for H:CH$_3$-loss channels measured in crossed beams experiments differs from the 0.5 H-elimination branching ratio measured by Bergeat and Loison\textsuperscript{17} under multiple collision conditions. The 1:1 normalized signal ratio between the m/z=39 and m/z=53 from Figure 6 agrees with the results from Bergeat and Loison at room temperature, with the caveat that we assume equal photoionization cross sections for these radicals. Assuming that the m/z=53 and m/z=39 are primary products from the C($^3\text{P}$) + $\text{C}_3\text{H}_6$ reaction, the high collision energy in the crossed molecule beam experiments could account for the difference of H:CH$_3$.

Using RRKM calculations at about 16.7 kJ mol$^{-1}$ collision energy,\textsuperscript{26} Chin et al. predict a ratio of the sum of the methylpropargyl isomer densities over that of $i$-$\text{C}_4\text{H}_5$ of 1.2, which is close to their 1.4 experimental values. The difference from the ratio of 4 we measure in a flow tube close to room temperature is unlikely to come from pressure effects because the reaction adduct is expected to
decompose to the final products on a timescale much shorter than the collision rate.\textsuperscript{24} This difference could suggest that the formation of the methylpropargyl isomers is favored at lower temperature. This dependence could come from the fact that the decomposition channels of the initial intermediates to methylpropargyl isomers have low or no barriers relatively to the formation of \textit{i-C}_4\textit{H}_5. However, such large changes in isomer distribution with temperature are usually not observed for very exothermic reactions where the average thermal energy represents only a very small fraction of the internal energy of the reaction intermediates. In addition, despite the multiple collision conditions, the short predicted lifetimes of the intermediates implies that these branching ratios results are unaffected by collisional energy transfer. The difference in isomer fraction between the two experiments could also be due to uncertainties when fitting the m/z=53 ion signal. In the case of the crossed beams experiments the $\Delta E/E=4\%$ (compared to $\Delta E/E<1\%$ for the present experiments) energy resolution does not allow the observation of the methylpropargyl isomers’ ionization threshold.

The data displayed in Figures 8 allow the unambiguous identification of \textit{i-C}_4\textit{H}_5 and methylpropargyl isomers in the flow tube experiments. Large uncertainties still remain about the C\textsubscript{4}H\textsubscript{5} isomer distribution mostly due to the unattributed signal above 8.2 eV in both the flame and flow tube experiments. Based on the previous identification this signal is likely to come from the ionization of either the \textit{i-C}_4\textit{H}_5 or the methylpropargyl isomers, although the Franck–Condon simulations do not predict it. Previous studies have shown that Franck–Condon overlap calculations fail at reproducing experimental ion spectra in the case of shape resonances.\textsuperscript{78,79} The onset at 8.2 eV as well as the following structures (up to 9.4 eV) could therefore be due to auto-ionizing states of the neutral species at these energies. To our knowledge it is not possible to easily predict such features or to attribute them to one of the three considered isomers. If the ion signal at 8.2 eV is due to ionization of the methylpropargyl isomers, the relative branching ratios for the C\textsubscript{4}H\textsubscript{5} isomers would be unchanged. However, if this feature were due to the ionization of \textit{i-C}_4\textit{H}_5, the isomer branching ratios would be greatly affected toward a much higher ratio.
for \( i-C_4H_5 \). Such effect would affect the measured branching ratios in the flame, flow tube and crossed beams experiments the same way.

The detection of both \( i-C_4H_5 \) and methylpropargyl isomers from the \( C(^3P) + C_3H_6 \) reaction close to room temperature qualitatively agree with the previously accepted mechanisms inferred from single collision experiments and potential energy surfaces.\(^{19,22,24}\) Once formed, the final products will rapidly be thermalized to the flow temperature by collisional quenching with the buffer gas. The reaction of the so formed \( C_4H_5 \) isomers with a H-atom present in the flow is barrier-less only in the case of the \( HCCCHCH_3 \) isomer. The reaction proceeds via the formation of the \( Z- \) or \( E-\)CH\(_3\)CHCCH\(_2\) stereoisomers with no exit channels presenting energy barriers below the energy of the initial \( HCCCHCH_3 + H \). The lowest energy product channel is the formation of \( C_3H_3 \) and \( CH_3 \) radicals. Such reaction would deplete the \( HCCCHCH_3 \) contribution toward formation of the propargyl and methyl radicals. H-assisted isomerization is therefore unlikely to contribute to the difference of isomer fraction between the crossed beams experiments and the flow tube experiments.

**Astrophysical and combustion implications**

**Titan and the interstellar medium.** The kinetics of ground state carbon atoms, \( C(^3P) \), with ethylene and propylene has been shown to be fast down to very low temperature,\(^{25}\) making these reactions of interest for the photochemical modeling of cold astrophysical environments rich in hydrocarbons. Titan, a satellite of Saturn, has been the subject of many studies in the last decade due to the successful Cassini mission, which revealed a far more complex chemistry than predicted\(^{18,48,65,79,80}\) with neutral chemistry playing a central role.\(^{45,49,62,79,80}\) Zhang et al.\(^3\) identified the atomic neutral carbon emission CI line feature at 1657 Å (\( 2s^22p^33s^1\ 3P_J - 2s^22p^2\ 3P_J \)) in the upper atmosphere of Titan using the Cassini Ultra-violet Imaging Spectrograph. \( CH + H^{50} \) and \( CN + N^{81} \) are the major sources of atomic carbon on Titan, while the reactions with \( C_2H_x \) hydrocarbons, mainly \( C_2H_2 \) and \( C_2H_4 \), are their most important loss processes, at least above 600 km\(^3\). Recently, Hébrard et al.,\(^{49}\) pointing out that only a small fraction of all possible reactions
producing or involving C₃-compounds was included in previous photochemical models, reported an update of the photochemistry of C₃Hₓ in the stratosphere of Titan. Their study suggests that C(^3P) + C₂H₂ leads to the formation of C₃ and C₃H, while, C(^3P) + C₂H₄ forms essentially C₃H₃ + H, as inferred by Bergeat et al.,¹⁶ and confirmed by the present study. The reaction of C(^3P) with C₃H₆ however, plays a minor role in the formation of larger hydrocarbons on Titan due to the much lower molar fraction of propylene compared to acetylene in the atmosphere of Titan.⁴⁹ The situation is quite different for propylene in the interstellar medium. Due to its small dipole moment, it has been discovered only recently by Marcelino et al.⁸² using the IRAM 30 m telescope in the giant Taurus Molecular Cloud 1 (TMC-1). An abundance relative to H₂ of 4×10⁻⁹, comparable to other abundant hydrocarbons in this cloud was derived from these observations, indicating the potential importance of propylene in the chemistry of the interstellar medium. The reactions involving propylene with abundant species such as atomic carbon, for instance, are therefore of importance in the chemical reaction network aiming to determine the abundance of molecular species in the interstellar medium.⁸³-⁸⁵ The present study shows that even near room temperature, and likely below, the reaction of C(^3P) atoms with propylene can form larger species such as C₄H₅ and may contribute to the formation of complex molecules in the interstellar medium.

**Combustion environments:** The detection of carbon atoms in flames is made very difficult due to the large absorption cross section of hydrocarbons at the VUV wavelengths used for laser induced fluorescence detection of C(^3P). Ground state carbon has been detected in simple diffusion flames but the possible contribution from hydrocarbon photolysis by the excitation light has not been fully addressed.⁴ In flames, carbon atoms could be formed by the CH + H reaction as suggested for cold environments. Although the reaction is thermodynamically favorable and occurs at fractions of the collision rate over the combustion temperature range,⁴⁶ this channel will remain minor because CH will preferentially react with more abundant fuel molecules. If formed, the carbon atoms will immediately react with the most abundant hydrocarbon molecules in the flame. Nevertheless, even a small amount of carbon atom self reaction could
also be responsible for part of the observed C$_2$ chemiluminescence.\textsuperscript{5} The reaction of C$^3\text{P}$ with acetylene, ethylene and propylene would contribute to the formation of radicals such as C$_3$H, C$_3$H$_3$, CH$_3$ as well as C$_4$H$_5$, therefore participating in the propagation of the radical chemistry. The good match between the flame and flow tube C$_4$H$_5$ ion spectra could support a possible contribution from the C$^3\text{P}$ + C$_3$H$_6$ reaction in combustion.

With the advent of interest in plasma assisted combustion, there is an important need to better understand the chemistry of the reactive species formed in such energy and carbon rich environments.\textsuperscript{86} The neutral and ion chemical scheme initiated by plasma discharge in engines has been demonstrated to facilitate rapid combustion, thereby making it possible to use leaner mixtures, decreasing temperatures and hence NO$_x$ production.\textsuperscript{86} The carbon chemistry of these environments will be governed by fast ion and neutral reactions with the most abundant species. Carbon reactions may be able to compete with ion chemistry as long as carbon atoms are formed with a sufficiently high number density. Mass spectrometry experiments were able to detect carbon atoms in glow discharge plasmas\textsuperscript{6} suggesting much higher concentrations than in combustion environments. The reaction of carbon atoms with the hydrocarbons present in high concentration will contribute to the neutral radical chemistry propagation and ultimately to the overall combustion process. More advanced computational models on the role of ion and neutral chemistry is required in order to better understand plasma assisted combustion phenomena.

\textbf{Conclusions}

We investigated the reaction of the ground state C$^3\text{P}$ with ethylene and propylene under multiple collision conditions at 332 K and 4 torr. Despite these multiple collision conditions, as long as reaction intermediates have short lifetimes relatively to the collision frequency, the observed product distribution is unaffected by collisional energy transfer. Carbon atoms are generated by 193 nm photodissociation of carbon suboxide in a large excess of molecular hydrogen in order to minimize any potential contributions
from C(\(^1\)D) reactions. Time- and energy-dependent photoionization spectra recorded with and without hydrogen as a C(\(^1\)D) scavenger indicate that only C(\(^3\)P) atoms are formed in the reaction flow. Time traces of the observed products were used to differentiate between primary and secondary reaction products and reaction kinetics considerations were used to discuss the origin of the detected products. In the case of C(\(^3\)P) + ethylene, the propargyl (C\(_3\)H\(_3\)) radical is detected as the major molecular reaction products in agreement with previous H-atom branching ratios and molecular beam experiments.

In the case of the C(\(^3\)P) + propylene reaction, the observed reaction channels are C\(_4\)H\(_5\) + H and C\(_3\)H\(_3\) + CH\(_3\). The measured C\(_4\)H\(_5\):C\(_3\)H\(_3\) signal ratio from the present flow data is in agreement with the 1:1 H:CH\(_3\)-loss ratio from fast flow reactor H-atom detection results.\(^{16,17}\) Photoionization spectra recorded at the mass of the C\(_4\)H\(_5\) isomers show possible contamination from dissociative ionization of higher masses at energy above 9.5 eV. At lower energies, the C\(_4\)H\(_5\) spectra are found to be almost identical to that recorded in a low pressure benzene flame.\(^77\) The fit of the experimental data with integrated Franck–Condon factors gives a 1:4 relative distribution for the \(i\)-C\(_4\)H\(_5\) isomer relatively to the sum of both methylpropargyl isomers. The resemblance between the flame and flow tube data could indicate that the photoionization spectrum of the \(i\)-C\(_4\)H\(_5\) isomer displays a strong shape resonance features above its ionization threshold and eventually around the ionization energy of the methylpropargyl isomers. If true, the contribution from the methylpropargyl isomers to the overall isomer distribution would be overestimated in the flow tube, flame and cross-molecular beam experiments.

The good match between the flow tube and the flame spectra at m/z=53 suggests that C\(_4\)H\(_5\) isomers are likely to play a significant role in combustion chemistry. Carbon atoms are also present in plasmas where they will contribute to the molecular growth. For these reasons the C(\(^3\)P) + C\(_3\)H\(_6\) reaction needs to be studied over a wide range of experimental conditions, included collisional environments. The branching ratios measured in crossed beam experiments were so far the only available experimental data for the C(\(^3\)P) + C\(_3\)H\(_6\) reaction. The flow tube data extend the previous results to a much wider range of
experimental conditions more relevant for combustion and plasma chemistry. Under multiple collision conditions, the present experiments suggest the formation methyl and propargyl radicals in non-negligible amounts alongside both \textit{i}-C\textsubscript{4}H\textsubscript{5} and methylpropargyl isomers. Suggested branching ratios for computational model are 1:4 for the \textit{i}-C\textsubscript{4}H\textsubscript{5}:methylpropargyl isomers. Further computational studies are required in order to determine the effect of these branching ratios on the outcome of chemical models.

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References


Figure 1: (a) Mass spectrum integrated over the 0–1 ms time range and (b) m/z=40 kinetic trace recorded at 11.3 eV photon energy upon irradiation of C$_3$O$_2$ in helium.
Figure 2: Mass spectrum obtained by photolysis of a C$_3$O$_2$ and ethylene mixture in helium, at 10.7 eV photon energy, integrated over the 0–1 ms time range.
Figure 3: Photoion signal at m/z 39 ion (open circles) integrated over the 0–40 ms time range obtained by photolysis of a C₃O₂ and ethylene mixture in helium together with the absolute spectrum (solid red line) of the propargyl radical (C₃H₃) obtained by Savee et al.⁵¹
Figure 4: Photoion signal at m/z = 40 (open circles) obtained by photolysis of a C$_3$O$_2$ and ethylene mixture in helium. The red solid line is a fit to the data using the absolute photoion spectra of allene (green dashed line) from Yang et al.$^{52}$ and methylacetylene (blue point line) from Cool et al.$^{53}$ The best fit to the data is obtained for 49% allene and 51% methylacetylene.
Figure 5: Kinetic traces of C$_3$H$_4$ isomers (red squares) and propargyl radical C$_3$H$_3$ (blue circles) integrated over the 8.6-10.6 eV photon energy range obtained by photolysis of a C$_3$O$_2$ and ethylene mixture in helium. Error bars are derived from Poisson counting statistics.
Figure 6: Mass spectra obtained by 193-nm photolysis of (a) propylene in helium and (b) a mixture of propylene and C$_3$O$_2$ in helium, recorded at 10 eV photon energy and integrated over the 0–1 ms time range.
**Figure 7:** Normalized kinetic traces obtained by photolysis of a C$_3$O$_2$ and propylene mixture in helium of (a) mass 15 (red circles), 27 (blue triangles), 39 (brown stars), 41 (green squares) and 53 (purple diamonds) and (b) mass 40 (green squares), 52 (orange circles) and 54 (brown triangles) integrated over the 8.5–10.5 eV energy photon range. The thick pink line in (a) is a double exponential fit to m/z=53. The thick green line in (b) is a single exponential fit to m/z=40.
**Figure 8:** Photoionization spectrum of m/z=53 obtained by photolysis of a C₃O₂ and propylene mixture in helium integrated over the 0–40 ms time range and displayed from (a) 7.4 to 10.5 eV and (b) 7.4 to 8.25 eV photon energy. The vertical dashed lines in panel (a) correspond to the photoionization of i-C₄H₅, methylpropargyl isomers to their singlet ion state and to the triplet ion state of H₂CCCCH₃. The lines in panel (b) are the integrated Franck-Condon factor simulations for i-C₄H₅ (green dashed line) and the two methylpropargyl (blue
dotted and brown dashed dotted lines) isomers. The thick red line is a fit to the experimental data up to 8.25 eV yielding a 1:4 ratio of $i$-C$_4$H$_5$: methylpropargyl isomers.
Figure 9: Kinetic traces of m/z=53 integrated from 8.5 to 9.4 eV photon energy (red circles) and from 9.5 to 10.5 eV (blue squares).
Figure 10: Photoionization spectrum of m/z=53 from the C(3P) + C₃H₆ reaction integrated over 40 ms after lasher shot and displayed from 7.4 to 9.2 eV photon energy. The red line is m/z=53 photoionization spectrum recorded in a low pressure (40 Torr) benzene flame.⁶⁰