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Vacuum-UV negative photoion spectroscopy of CH$_3$F, CH$_3$Cl and CH$_3$Br

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Using tunable vacuum-UV radiation from a synchrotron, negative ions are detected by quadrupolar mass spectrometry following photoexcitation of three gaseous halogenated methanes CH$_3$X (X = F,Cl,Br). The anions X$^-$, H$^-$, CX$^-$, CHX$^-$ and CH$_2$X$^-$ are observed, and their ion yields recorded in the range 8–35 eV. The anions show a linear dependence of signal with pressure, showing that they arise from unimolecular ion-pair dissociation, generically described as AB + h$\nu$ → A$^-$ + B$^+$ (+ neutrals). Absolute cross sections for ion-pair formation are obtained by calibrating the signal intensities with those of F$^-$ from both SF$_6$ and CF$_4$. The cross sections for formation of X$^-$ + CH$_3$ are much greater than for formation of CH$_2$X$^-$ + H$^+$. In common with many quadrupoles, the spectra of m/z 1 (H$^-$) anions show contributions from all anions, and only for CH$_3$Br is it possible to perform the necessary subtraction to obtain the true H$^-$ spectrum. The anion cross sections are normalised to vacuum-UV absorption cross sections to obtain quantum yields for their production. The appearance energies of X$^-$ and CH$_2$X$^-$ are used to calculate upper limits to 298 K bond dissociation energies for $D^o$ (H$_2$C–X) and $D^o$ (XH$_2$C–H) which are consistent with literature values. The spectra suggest that most of the anions are formed indirectly by crossing of Rydberg states of the parent molecule onto an ion-pair continuum. The one exception is the lowest-energy peak of F$^-$ from CH$_3$F at 13.4 eV, where its width and lack of structure suggest it may correspond to a direct ion-pair transition.
1. Introduction

Ion-pair formation from an isolated gas-phase polyatomic molecule is a unimolecular dissociative process in which an anion-cation pair is formed following photoexcitation, i.e. \( AB + h\nu \rightarrow A^- + B^+ (+ \text{ neutrals}) \). Vacuum-UV photons with energy in excess of \( \text{ca.} \ 10 \text{ eV} \) are typically needed. Ion-pair production can either occur directly into the ion-pair continuum, or indirectly following predissociation of an initially-excited Rydberg state into the continuum. In both cases, the appearance energy of the anion \( A^- \), \( \text{AE}(A^-) \), is constrained to the following energetics:

\[
\text{AE}(A^-) \geq D'(A-B) + \text{IE}(B) - \text{EA}(A) \quad (I)
\]

where \( D' \) is a dissociation energy, \( \text{IE} \) an ionisation energy and \( \text{EA} \) an electron affinity. On Franck-Condon grounds the latter process of predissociation is more common,\(^1\) so the detection of ion pairs provides information on the electronic structure of a molecule and the decay dynamics of its excited states. An alternative way to express the inequality of eq. (I) is to write \(^2\)

\[
\text{AE}(A^-) \geq \text{IE}(AB) + D'(A-B^+) - \text{EA}(A) \quad (II)
\]

For the three titled molecules, the threshold for ion-pair formation lies below that of molecular photoionisation since the electron affinity of the halogen atom \( X \) (X = F, Cl or Br) exceeds \( D'(\text{CH}_3X^+ \rightarrow \text{CH}_3^+ + X) \). Detection of anions therefore at low energies is relatively facile because there is no overlapping electron signal.

Our interest in the \( \text{CH}_3X \) series of halo-substituted methanes, where \( X = \text{F, Cl or Br} \), is primarily fundamental – to compare data and see the trends in changing the substituent \( X \). \( \text{CH}_3\text{Cl} \) and \( \text{CH}_3\text{Br} \) are anthropogenic sources of Cl and Br atoms in the marine boundary layer.\(^3\) Although nearly all solar VUV radiation is absorbed in the mesosphere, it is important to understand the effects of VUV radiation interacting with these important constituents of the earth’s atmosphere. \( \text{CH}_3\text{I} \) was not studied because previous work has shown that the cross sections are too small to produce measurable quantities of ion pairs in the VUV region.\(^1\)

All three \( \text{CH}_3\text{X} \) molecules studied have \( C_{3v} \) symmetry, and the main effect of changing \( X \) is to lengthen and subsequently weaken the C–X bond. The valence molecular orbitals can be labelled \( \ldots (2a_1)^2(1e)^4(3a_1)^2(2e)^4, \) where the \( 2e \) orbital is essentially non-bonding \( X np \pi \) orbitals and the three lower orbitals arise from the \( \sigma \)-bonding framework formed from overlap of the \( C 2s \) \((a_1)\), \( C 2p \) \((a_1+e)\) with 3H \((a_1+e)\) and \( X np \) \((a_1)\) atomic orbitals. For \( \text{CH}_3\text{Cl} \) and \( \text{CH}_3\text{Br} \), the \( 3p / 4p \pi \)-orbitals of Cl / Br show little mixing with the \( \text{CH}_3\text{X} \) \( \sigma \)-orbitals where the evidence is best provided from HeI, HeII or threshold
photoelectron spectroscopy. Both molecules show the effects of spin-orbit splitting, but limited vibrational structure in the \((2e)^{-1}\) first band with a strong \(v^+=0\) transition, showing that the electron has been removed from an orbital that is essentially non-bonding in character. By contrast, the first photoelectron band of CH$_3$F shows no measurable spin-orbit splitting, but an extended vibrational progression. Indeed, molecular orbital calculations show that the 2e orbital in this molecule has a degree of anti-bonding character, probably due to the ability of the fluorine 2p$_\pi$ atomic orbitals to interact with other orbitals of equivalent symmetry, inducing secondary mixing. This effect is not observed with CH$_3$Cl and CH$_3$Br because p$_\pi$-bonding is dependent on internuclear distance. Electron removal from the lower-energy 3a$_1$, 1e and 2a$_1$ valence orbitals of CH$_3$F, CH$_3$Cl and CH$_3$Br show very similar features in the photoelectron spectra, as these orbitals are based on the CH$_3$ σ–bonding framework with only the 3a$_1$ orbital showing a minor contribution from the X np orbitals. The ionisation energies of the \((3a_1)^{-1}\) and \((1e)^{-1}\) bands in CH$_3$F are close together, and it has been speculated that their order might be reversed, relative to the equivalent bands in the heavier halides.

In this paper, we report the formation of anions from CH$_3$X following photoexcitation with tunable VUV radiation in the range 10-35 eV from a synchrotron. An earlier study by Suzuki \textit{et al.} observed the X$^-$ anion from these molecules, and cross sections of anion formation were estimated to be between $10^{-21}$ and $10^{-20}$ cm$^2$. We extend this work and report the formation of X$^-$, H$^-$, CH$_2$X$^-$ and CHX$^-$. Apart from H$^-$, absolute cross sections for formation of all anions are also reported. Our work also extends that of Shaw \textit{et al.} on CH$_3$Cl and CH$_3$Br where the use of a double ion chamber with no mass selection meant that the identity of the ions produced was not known. Ion-pair imaging studies have been performed following laser photoexcitation at ca. 10.5 eV for CH$_3$Cl and CH$_3$Br, looking at the CH$_3^+/X^-$ pair. Anisotropy in the ion distributions was observed, and analysed to gain information on the dissociation dynamics of the initially-excited Rydberg state. Ion-pair dissociation from CH$_3$F $\rightarrow$ CH$_3^+$ + F$^-$ has also been studied by imaging techniques at the higher energy of 21.3 eV. Finally, we note that high-resolution absorption studies have recently been performed on CH$_3$F, CH$_3$Cl and CH$_3$Br by Locht \textit{et al.}, and since most anion formation is attributed to the predissociation of Rydberg states these studies are useful for comparison.

\section*{2. Experimental and Procedure}

The ion-pair apparatus has been described in detail elsewhere. Briefly, an effusive jet of the gas under investigation is injected from a needle and intersects orthogonally the incident photon beam. The crossing point is positioned between two grids along the third orthogonal axis. A potential difference applied across these grids attracts negative ions towards a three-element electrostatic lens for focussing, and into a Hiden Analytical HAL IV triple quadrupole mass spectrometer (QMS) for mass selection and
detection by a channeltron electron multiplier. The apparatus and QMS are connected via a 1 mm
diameter aperture, and pumped by separate turbomolecular pumps which are backed by a common rotary
pump. Differential pumping enhances sensitivity by reducing the number of free electrons and secondary
collisions in the QMS. Tunable radiation in the range 10-35 eV was provided by beamline 3.1 (equipped
with a 1 m focal length Wadsworth monochromator) from the UK Daresbury Synchrotron Radiation
Source.\textsuperscript{19} Two gratings, mounted back-to-back in the monochromator, cover this range of energies,
although the majority of these studies used the higher-energy grating ($h\nu > 12$ eV). The optimum
resolution of the beamline is 0.05 nm, corresponding to ca. 0.01 eV at 15 eV. However, to enhance
sensitivity, the spectra reported in this paper were recorded at a degraded resolution. A capillary light
guide connects the beamline to the experimental apparatus, providing the necessary differential pumping.

The base pressure of the apparatus was ca. $10^{-7}$ mbar. The pressure was measured in the main chamber
using an ionisation gauge, and the introduction of the sample gas to the system raised the pressure to ca.
$10^{-5}$ mbar. The sensitivity of the ionisation gauge to CH$_3$X ($X = F, Cl, Br$), SF$_6$ and CF$_4$, which is essential
for determination of absolute cross sections of anion formation, was calibrated in a separate experiment
relative to N$_2$ using a capacitance manometer.\textsuperscript{20} Gas samples were supplied by Apollo Scientific or
Aldrich Chemical Company, and were used without further purification.

Following exposure to white light with the grating set to zero order, mass spectra were recorded to
observe all the anions produced by photoabsorption of the sample gas. The mass-to-charge ratio ($m/z$) of
each peak in the mass spectrum was then defined, and the ion yield recorded as a function of photon
energy. Once the peak positions were determined, the anion signal was recorded as a function of gas
pressure over a typical range of ca. ($0.5–5.0$) $\times 10^{-5}$ mbar. Anions displaying a linear dependence with
pressure can be attributed to ion-pair formation, defined in Section 1, whereas those showing a non-linear
pressure dependence cannot. The latter are likely to result from the two-step kinetic process of
dissociative electron attachment (\textit{i.e.} $AB + h\nu \rightarrow AB^+ + e^-$; $AB + e^- \rightarrow A^- + B$), in which the rate of
formation of $A^-$ is proportional to the square of the pressure of $AB$.\textsuperscript{21} With the exception of CHBr$^-$ from
CH$_3$Br in which time constraints at the beamline precluded the measurement, the signals of all anions
observed from CH$_3$F, CH$_3$Cl and CH$_3$Br showed a linear dependence with pressure. Since the
CHF$^-$/CH$_3$F signal is first order with respect to pressure, we have analysed the CHBr$^-$/CH$_3$Br signal
assuming that it is also formed by ion-pair formation.

To determine absolute cross sections of the anions from ion-pair formation, the anion signal must be
normalised to the photon flux, the ring current, the gas pressure, the ionisation gauge sensitivity, and the
relative mass sensitivity of the QMS to detection of the different anions. As in our previous studies on
SF$_3$CF$_3$,\textsuperscript{21} the CF$_3$X series ($X = Cl, Br, I$),\textsuperscript{22} and CH$_4$,\textsuperscript{23} we can write that:
\[
\sigma (h \nu) = k \left( \frac{SM}{frpl} \right)
\]  

where \( S \) is the detected signal normalised to unit time, \( f \) is the relative photon flux which effectively is a measure of the grating efficiency, \( r \) is the storage ring current, \( p \) is the sample gas pressure corrected for ionisation gauge sensitivity (see above), \( I \) is the isotope correction factor which is only pertinent for anions containing one Cl or Br atom, and \( M \) is the relative mass sensitivity of the QMS. \( k \) is the constant of normalisation. In detecting chlorine-containing anions from CH\(_3\)Cl, only the \(^{35}\)Cl isotopomer was detected. Likewise, for bromine-containing anions from CH\(_3\)Br, only the \(^{79}\)Br isotopomer was detected. Therefore, for these anions \( I \) takes the value 0.758 and 0.507 to account for the experiment only detecting 75.8% and 50.7%, respectively, of the true signal. Normalisation to \( I \), but also to \( f, r \) and \( p \), is therefore facile, but the process is slightly more complicated for \( M \). An extensive set of experiments was performed to determine \( M \) as a function of \((m/z)\), described elsewhere.\(^{23}\) As \( m/z \) increases, the detection efficiency of the QMS decreases, and a higher value of \( M \) is needed to correct this effect; thus, \( M \) rises from 0.27 for \( m/z \) 19 (\( F^- \)) non-linearly to 1.86 for \( m/z \) 93 (\( \text{CH}_2^{35}\text{Br}^- \)), the heaviest anion detected, with \( m/z \) 69 (\( \text{CF}_3^- \)) arbitrarily being given the value \( M = 1 \). Finally, the zero-blast artefact,\(^ {24}\) whereby all ions entering the quadrupole mass filter may be transmitted when the applied potentials are set to detect \( m/z \) 1 (\( i.e. \) \( \text{H}^- \)), is an important factor in this study because \( \text{H}^- \) from all three CH\(_3\)X molecules, whilst observed in all cases, is not the dominant anion. The \( \text{H}^- \) yield from CH\(_3\)X therefore appears on top of a background scan that mimics that of \( \text{X}^- \), the dominant anion. To determine the true \( \text{H}^- \) yield, it was necessary to subtract a scaled \( \text{X}^- \) spectrum from the normalised \( \text{H}^- \) spectrum. The determination of an absolute cross section for \( \text{H}^- \) production was therefore not possible. This is different from the formation of \( \text{H}^- \) from CH\(_4\) where this anion is dominant, so an absolute value for \( \sigma \) can be determined.\(^ {23}\)

The normalised signals are then put onto an absolute scale by determining the \( \text{F}^- \) signal strengths in our experiment from SF\(_6\) and CF\(_4\), and calibrating them to values of the cross section determined by Mitsuke \textit{et al.} for SF\(_6\) ((7 \pm 2) \times 10^{-21} \text{ cm}^2 \text{ at 14.3 eV})\(^ {25}\) and CF\(_4\) ((1.25\pm0.25) \times 10^{-21} \text{ cm}^2 \text{ at 13.9 eV}).\(^ {26}\) (We note that these cross sections are not strictly absolute, but obtained indirectly from the signal of \( \text{O}^- \) produced from O\(_2\) at 17.3 eV for which the absolute cross section is known.\(^ {27}\) Future experiments will probably calibrate the signals directly with \( \text{O}^- \) from O\(_2\).) The values of the normalisation constants, \( k (\text{F}^-/\text{SF}_6) \) and \( k (\text{F}^-/\text{CF}_4) \), should be equivalent, but in fact they differ by a factor of 1.5. Given the number of corrections made to the anion signals in the two experiments, this discrepancy falls within a reasonable expected experimental uncertainty. The average value of \( k \) was then used in Equation (1) to determine the absolute cross sections, \( \sigma \), in units of cm\(^2\), for production of \( \text{X}^- \), CH\(_2\)\( \text{X}^- \) and CH\( \text{X}^- \) from CH\(_3\)X. We
estimate that these cross sections are accurate to a factor of $ca.$ 2. Due to the zero-blast artefact, only the relative cross sections for production of $H^-$ from CH$_3$X are reported (see earlier).

3. Thermochemistry

Our work determines appearance energies at 298 K ($AE_{298}$) for fragment anions from CH$_3$F, CH$_3$Cl and CH$_3$Br, and they are compared with calculated thermochemical values. Berkowitz noted that for many polyatomic molecules, when suitable assumptions are made about the nature of the accompanying cation and neutral fragment(s), a calculated threshold energy is a lower limit to the experimental $AE_{298}$ of an anion.\textsuperscript{1} Furthermore, in comparing experimental $AE_{298}$ values of anions with calculated enthalpies of appropriate dissociation reactions, $\Delta H^o_{298}$, we are making two assumptions which are justified at the relatively modest resolution of the experiment, $ca.$ 0.1–0.2 eV. First, although it is not accurate to equate an $AE_{298}$ to $\Delta H^o_{298}$ because of thermal effects,\textsuperscript{28} however the corrections needed to the $AE_{298}$ values are typically only 0.05–0.15 eV, and we feel justified in ignoring them. Second, the effects of entropy are disregarded, even though all unimolecular reactions involve $\Delta n > 0$, where $\Delta n$ is the stoichiometric number of product species minus the number of reactant species. Thus $\Delta S^o_{298}$ will be positive, and $\Delta G^o_{298}$ for the unimolecular reactions will be more negative than the calculated $\Delta H^o_{298}$ values.

Values for $\Delta H^o_{298}$ of relevant ion-pair reactions were calculated using literature values for enthalpies of formation ($\Delta H^o_{298}$ in kJ mol$^{-1}$): CH$_3$F = $-234.3$, CH$_3$Cl = $-83.7$, CH$_3$Br = $-34.3$; CH$_2$F$^-$ = $-53$, CH$_2$Cl$^-$ = 45, CH$_2$Br$^-$ = 75; CHF$^-$ = 109, CHBr$^-$ = 231; CF$^-$ = $-63$; F$^-$ = $-249$, Cl$^-$ = $-227$, Br$^-$ = $-213$; H$^-$ = 145; H$^+$ = 1530, H$_2^+$ = 1488; CH$_3^+$ = 1098.\textsuperscript{29,30}

4. Results

4.1 CH$_3$F

The ion yields and absolute cross sections for formation of F$^-$, CF$^-$, CHF$^-$ and CH$_2$F$^-$ from CH$_3$F in the range 12–35 eV are shown in Figures 1(a)–1(d), respectively. The data are collected in Table 1. The spectra were recorded on the high-energy grating with a resolution of 0.6 nm, corresponding to 0.07 eV at 12 eV and 0.28 eV at 24 eV. The F$^-$ signal is the most intense. Scans at $m/z$ 1 and 15 ($H^-$ and CH$_3^-$) both mimic the F$^-$ spectrum, but are artefacts for different reasons. The $H^-$ normalised signal, whilst being only $ca.$ 10% of the normalised F$^-$ signal, has an identical relative ion yield to that of F$^-$ over the range 12–16 eV due to the zero-blast effect, the contribution of all anions to the $m/z$ 1 signal in many quadrupole mass spectrometers.\textsuperscript{24} A subtracted spectrum could therefore not be trusted. The CH$_3^-$ signal at $m/z$ 15 is too close in mass to the very strong $m/z$ 19 signal, and thus any CH$_3^-$ signal lies in the tail of
the much stronger $\text{F}^-$ signal. The same problem inhibited possible detection of $\text{HF}^-$ ($m/z$ 20). There is no similarity between any of the four anion yields and the photoelectron spectrum of $\text{CH}_3\text{F}$ over this energy range. For example, the strong $\text{F}^-$ signal shows an onset at $12.28 \pm 0.02$ eV and a maximum at 13.4 eV, whilst the first photoelectron band has adiabatic and vertical ionisation energies of 12.53 and 13.04 eV, respectively. $^4$ In addition to the linearity of the anion signal vs. pressure tests, these provide evidence that all four anions are not formed by dissociative electron attachment but by ion-pair dissociation.

The arrows in Figure 1 show the calculated $\Delta_h H^\circ_{298}$ values for possible ion-pair dissociation reactions (1)–(8). As described earlier, we do not distinguish a reaction \textit{enthalpy} from a reaction \textit{energy} at the relatively low resolution of this experiment. They take the values 11.18, 16.47, 21.15, 19.46, 22.15, 18.98, 21.67 and 17.73 eV, respectively.

\[
\begin{align*}
\text{CH}_3\text{F} & \rightarrow \text{F}^- + \text{CH}_3^+ & (1) \\
\text{CH}_3\text{F} & \rightarrow \text{F}^- + \text{CH}_2^+ + \text{H} & (2) \\
\text{CH}_3\text{F} & \rightarrow \text{F}^- + \text{CH}^+ + 2\text{H} & (3) \\
\text{CH}_3\text{F} & \rightarrow \text{CF}^- + \text{H}_2^+ + \text{H} & (4) \\
\text{CH}_3\text{F} & \rightarrow \text{CF}^- + \text{H}^+ + 2\text{H} & (5) \\
\text{CH}_3\text{F} & \rightarrow \text{CHF}^- + \text{H}_2^+ & (6) \\
\text{CH}_3\text{F} & \rightarrow \text{CHF}^- + \text{H}^+ + \text{H} & (7) \\
\text{CH}_3\text{F} & \rightarrow \text{CH}_2\text{F}^- + \text{H}^+ & (8)
\end{align*}
\]

4.2 \text{CH}_3\text{Cl}

The ion yields and absolute cross sections for the formation of $\text{Cl}^-$ and $\text{CH}_2\text{Cl}^-$ from $\text{CH}_3\text{Cl}$ in the range 8–35 at a resolution of 0.6 nm are shown in Figures 2(a)–2(b), respectively. The spectrum of the strongest anion, $\text{Cl}^-$, was run on both gratings from 8–18 eV (low energy) and 12–35 eV (high energy), and the spectra merged. The $\text{CH}_2\text{Cl}^-$ spectrum was obtained on the high-energy grating. Only these two anions could conclusively be detected, because resolving $m/z$ values of fragments differing by 1 u is very difficult in chlorine-containing moieties; a spectrum recorded with $m/z$ 48 (\textit{i.e.} $\text{CHCl}^-$) was identical to that of $m/z$ 49, but thermochemistry shows that the signal, with a threshold of $17.2 \pm 0.2$ eV, can only be due to $\text{CH}_2\text{Cl}^-$ (Section 5.3). An $\text{H}^-$ spectrum was recorded, but its shape and resolved features were identical to those of $\text{Cl}^-$, although a factor of \textit{ca.} 40 weaker. A subtracted spectrum, to yield the true $\text{H}^-$ spectrum, could not therefore be obtained reliably. An $\text{HCl}^-$ spectrum with $m/z$ 36 was recorded, but its mass lies in between the two isotopes of chlorine, so the presence of this anion is deemed uncertain. A spectrum of $\text{CH}_2\text{Cl}^-$ was also run with the low-energy grating and a LiF window only transmitting $h\nu < 11.8$ eV. No peaks were detected. The apparent rise in the signal of this anion for $h\nu < 14$ eV on the
high-energy grating (Figure 2(b)) is probably an artefact due to inaccurate flux normalisation at these
energies, where the flux is low.

The arrows in Figure 2 show the calculated $\Delta_{r} H_{298}^{\circ}$ values for possible ion-pair dissociation reactions
(9)–(12). They take values 9.85, 15.14, 19.85 and 17.19 eV, respectively.

$$\text{CH}_3\text{Cl} \rightarrow \text{Cl}^- + \text{CH}_3^+ \quad (9)$$
$$\text{CH}_3\text{Cl} \rightarrow \text{Cl}^- + \text{CH}_2^+ + \text{H} \quad (10)$$
$$\text{CH}_3\text{Cl} \rightarrow \text{Cl}^- + \text{CH}^+ + 2\text{H} \quad (11)$$
$$\text{CH}_3\text{Cl} \rightarrow \text{CH}_2\text{Cl}^- + \text{H}^+ \quad (12)$$

4.3 CH₃Br

The ion yields for formation of $\text{H}^-$, $\text{Br}^-$, $\text{CHBr}^-$ and $\text{CH}_2\text{Br}^-$ from CH₃Br in the range 9–35 eV at a
resolution of 0.6 nm are shown in Figures 3(a)–3(d), respectively. As with CH₃Cl, both gratings were
needed to record the spectrum of the strongest anion, $\text{Br}^-$, since the threshold energy is observed at 9.46 ±
0.02 eV. The $\text{H}^-$ spectrum was also recorded on both gratings. Over the range 9.5–12.0 eV the spectrum
was identical to that of $\text{Br}^-$, and it was not possible to obtain a subtracted ‘true $\text{H}^-$’ spectrum. Above 12
eV on the high-energy grating, however, the $\text{Br}^-$ is much weaker, the two spectra were significantly
different, and it was possible to perform a Br⁻ subtraction to obtain the true $\text{H}^-$ spectrum (Figure 3(a)).
Thus the cross sections in Figures 3(b)–3(d) are accurate to the usual error of a factor of two, but only
relative cross sections for production of $\text{H}^-$ are shown in Figure 3(a). For reasons outlined in Section 4.2
above, the very weak CHBr⁻ spectrum ($m/z$ 92) may contain a component of the CH₂Br⁻ spectrum ($m/z$
93). It was analysed, however, assuming that it is a clean $m/z$ 92 signal and, as explained in Section 2,
that it is formed by ion-pair dissociation in conjunction with a cation ($\text{H}_2^+$ or $\text{H}^+$).

The arrows in Figure 3 show the calculated $\Delta_{r} H_{298}^{\circ}$ values for possible ion-pair dissociation reactions
(13)–(21). They take values 11.57, 17.38, 22.09, 9.53, 14.77, 19.48, 18.17, 20.86 and 16.99 eV,
respectively.

$$\text{CH}_3\text{Br} \rightarrow \text{H}^- + \text{CH}_2\text{Br}^+ \quad (13)$$
$$\text{CH}_3\text{Br} \rightarrow \text{H}^- + \text{CH}_2^+ + \text{Br} \quad (14)$$
$$\text{CH}_3\text{Br} \rightarrow \text{H}^- + \text{CH}^+ + \text{H} + \text{Br} \quad (15)$$
$$\text{CH}_3\text{Br} \rightarrow \text{Br}^- + \text{CH}_3^+ \quad (16)$$
$$\text{CH}_3\text{Br} \rightarrow \text{Br}^- + \text{CH}_2^+ + \text{H} \quad (17)$$
$$\text{CH}_3\text{Br} \rightarrow \text{Br}^- + \text{CH}^+ + 2\text{H} \quad (18)$$
\[
\begin{align*}
\text{CH}_3\text{Br} & \rightarrow \text{CHBr}^- + \text{H}_2^+ \quad (19) \\
\text{CH}_3\text{Br} & \rightarrow \text{CHBr}^- + \text{H}^+ + \text{H} \quad (20) \\
\text{CH}_3\text{Br} & \rightarrow \text{CH}_2\text{Br}^- + \text{H}^+ \quad (21)
\end{align*}
\]

### 4.4 Higher resolution studies

The \( X^- / \text{CH}_3\text{X} \) ion curves for the strong first peak are shown at a higher resolution of 0.2 nm in Figure 4. The \( \text{F}^- \) curve shows a gradual onset and no apparent structure at this resolution, with most of the intensity appearing at higher energy than the adiabatic ionisation energy of \( \text{CH}_3\text{F} \) \( (i.e. \) to the \( \tilde{X} \ 2\text{E} \) ground state of \( \text{CH}_3\text{F}^+ \)). By contrast, for \( \text{Cl}^- \) and \( \text{Br}^- \) much of the signal lies below the energy of the lower spin-orbit resolved \( \tilde{X} \ 2\text{E}_{3/2} \) state of \( \text{CH}_3\text{Cl}^+ \) and \( \text{CH}_3\text{Br}^+ \). The spectra, discussed in Section 5, show discrete resolved structure, and they are very similar to photoabsorption spectra of \( \text{CH}_3\text{Cl} \) and \( \text{CH}_3\text{Br} \) over this energy range.\(^{16,17} \) They correspond to Rydberg states of \( \text{CH}_3\text{Cl} \) or \( \text{CH}_3\text{Br} \) converging on the \( \tilde{X} \ 2\text{E} \) state of the parent ion which are crossed by predissociating ion-pair states to form \( \text{Cl}^- \) or \( \text{Br}^- + \text{CH}_3^+ \). The \( X^- / \text{CH}_3\text{X} \) ion curves for the weaker peaks between 16–24 eV are expanded in Figure 5. Suzuki et al. have commented that these peaks lie between the \( \tilde{B} \ 2\text{E} \) and \( \tilde{C} \ 2\text{A}_1 \) states of \( \text{CH}_3\text{X}^+ \), and therefore probably correspond to Rydberg states of \( \text{CH}_3\text{X} \) converging on the \( \tilde{C} \ 2\text{A}_1 \) state of the ion.\(^{10} \) As above, they cross with (different) predissociating ion-pair states to form \( X^- + \text{CH}_3^+ \). Their assignments are discussed in Section 5.

### 5. Discussion

#### 5.1 \( X^- \) from \( \text{CH}_3\text{X} \) at threshold

On thermochemical grounds, the \( X^- \) anion can only form with \( \text{CH}_3^+ \) at the first peak of each \( X^- / \text{CH}_3\text{X} \) spectrum in the 9–15 eV range (see Figures 1–4). The \( \text{F}^- / \text{CH}_3\text{F} \) and \( \text{Cl}^- / \text{CH}_3\text{Cl} \) spectra in Figures 4(a) and 4(b) correspond well to data published by Suzuki et al.,\(^{10} \) but they could not detect a \( \text{Br}^- / \text{CH}_3\text{Br} \) spectrum at low energy due to the poor flux from the monochromator used below 10 eV. Apart from a brief report in the review article by Berkowitz,\(^1 \) this is the first detailed observation of \( \text{Br}^- \) from \( \text{CH}_3\text{Br} \). We determine \( \text{AE}_{298} \) values for \( \text{F}^- \), \( \text{Cl}^- \) and \( \text{Br}^- \) of 12.28 ± 0.02, 10.04 ± 0.02 and 9.46 ± 0.02 eV (Table 1). These values lie below the respective ionisation energies to the \( \tilde{X} \ 2\text{E}_{3/2} \) state of \( \text{CH}_3\text{X}^+ \) of 12.53, 11.29 and 10.54 eV (see eq. (II)), and exceed the respective thermochemical values for the appearance energy, given by \( D^0(\text{CH}_3^- - \text{X}) + \text{IE(}\text{CH}_3\text{)} - \text{EA(}\text{X}) \), of 11.21, 9.85 and 9.52 eV for \( \text{X} = \text{F}, \text{Cl} \) and \( \text{Br} \). The inequality of eq. (I) is therefore obeyed in all three cases. The \( \text{F}^- \) yield shows no structure, whereas discrete transitions can be identified in the \( \text{Cl}^- \) and \( \text{Br}^- \) yields.
We consider first the structure in CH₃Cl and CH₃Br. As described in Section 1, the ground-state photoelectron band of these molecules, removal of an electron from the 2e HOMO, has only limited vibrational structure, with the strongest transitions occurring to \( v^+ = 0 \).⁴,⁶,⁷ Thus, electronic transitions in CH₃Cl and CH₃Br from the 2e HOMO to a Rydberg state converging on the \( \tilde{X}^2\text{E} \) state of the parent ion would not be expected to exhibit extensive vibrational progressions, but rather sharp Rydberg peaks. Assuming that ion-pair production is indirect, structured features should therefore be observed in the Cl⁻ and Br⁻ yields following crossing of the Rydberg potential surface to an ion-pair surface. This is indeed what is observed. The fine structure is complicated by the number of Rydberg series that are allowed, each converging on two spin-orbit-split ionisation thresholds, \( \tilde{X}^2\text{E}_{3/2} \) and \( \tilde{X}^2\text{E}_{1/2} \). These splittings take values of 27 and 305 meV for CH₃Cl⁺ and CH₃Br⁺ respectively,⁴,⁶,⁷ and Suzuki et al. have assigned the peaks in the Cl⁻/CH₃Cl spectrum to members of \( s, p \) and \( d \) Rydberg series converging on both ion thresholds.¹⁰ Furthermore, at these energies below the adiabatic IE, in studies of CH₃Cl and CH₃Br by Locht et al., the CH₃⁺ ion yield duplicates exactly our Cl⁻ and Br⁻ yields of Figures 4(b) and 4(c).⁶,³¹ This is to be expected, since the ion-pair dissociation reaction \( \text{CH}_3\text{X} \rightarrow \text{CH}_3^+ + \text{X}^- \) is the only ionic channel that is energetically open. We note, however, that the earlier photoabsorption studies by the same group at a resolution of \( \text{ca.} \) 0.01 eV suggest that there is generally good, but not perfect agreement between the absorption spectrum and the Cl⁻ or Br⁻ ion yield spectrum below the ionisation energy of CH₃Cl and CH₃Br,¹⁶,¹⁷ suggesting that there are competing dissociation channels such as neutral photodissociation.

For CH₃Cl, the Rydberg peak assignments given by Locht et al. are in good agreement with those reported by Suzuki et al.¹⁰ For CH₃Br, Rydberg assignments, again involving \( s, p \) and \( d \) Rydberg series, are given by Locht et al.¹⁷ Neither set of assignments is repeated here.

By contrast, the ground-state photoelectron band of CH₃F, removal of an electron from the 2e HOMO, has extended vibrational structure.⁴ The origin of the F⁻ signal from CH₃F is more uncertain, as its first maximum just exceeds the adiabatic ionisation energy, and thus cannot correspond to Rydberg states converging on \( v^+ = 0 \) of CH₃F⁺ \( \tilde{X}^2\text{E} \). Given the large width of the peak and its lack of structure, it is possible that it corresponds to a direct ion-pair transition. Alternatively, Suzuki et al. have suggested that this peak consists of unresolved Rydberg states converging to a number of vibrationally-excited levels of CH₃F⁺ \( \tilde{X}^2\text{E} \).¹⁰

### 5.2 \( \text{X}^- \) from CH₃X between 16–24 eV

The peaks observed in all the X⁻/CH₃X scans between 16 and 24 eV are shown on an expanded scale in Figure 5. These peaks all lie between the \( \tilde{B}^2\text{E} \) and \( \tilde{C}^2\text{A}_1 \) ionisation thresholds of CH₃X⁺; the vertical IE for the \( \tilde{B}^2\text{E} \) (\( \tilde{C}^2\text{A}_1 \)) state of CH₃F⁺, CH₃Cl⁺ and CH₃Br⁺ is 17.2 (23.2),⁴,⁵ 16.0 (21.56),⁴,⁷ and 15.0 (21.3) eV,⁵,⁶ respectively. Two peaks are observed in the F⁻/CH₃F spectrum (labelled F2 and F3) and
three peaks are present in both the Cl/CH3Cl and Br/CH3Br spectra (labelled F1, F2 and F3). Suzuki et al. have assigned most of these peaks to Rydberg states of CH3X converging on the $C\tilde{2}A_1$ state of the ion,\textsuperscript{10} using the well-established Rydberg formula for the energy levels, $E_n$, of Rydberg series,

$$E_n = IE - \frac{R_H}{(n-\delta)^2}$$  \hspace{1cm} (IV)

The quantum defect, $\delta$, and assignment of the peaks are given in Table 2. Two points should be noted. First, there has been inconsistency in the literature regarding the use of the adiabatic or vertical IE in such calculations, and this choice can significantly affect the Rydberg assignments for high values of $n$, near the convergence limit. In spectra that consist of many unresolved vibrational modes such as here, it is more appropriate to use the vertical IE because, assuming little change in geometry between Rydberg state and cation, both the vertical Rydberg and vertical ionisation transitions will occur from $v'' = 0$ of CH3X $\tilde{X}^1A_1$ to the same value of $v'$. Second, difficulties can arise in comparing Rydberg assignments because different choices in Rydberg-state nomenclature exist. Suzuki et al. treat the MOs as an extension of halogen atomic orbitals (AO), with $n = 3/4/5$ for the lowest $ns$ and $np$ Rydberg orbitals of CH3F/Cl/Br, respectively.\textsuperscript{10} Alternatively, an extension of the carbon AOs can be considered, which is our chosen nomenclature. This renders $n = 3$ for the lowest $ns$ and $np$ Rydberg orbitals of all three methyl halides. We believe this to be particularly useful as it emphasises that $(n-\delta)$ is approximately equal for corresponding Rydberg transitions in a series of related molecules, i.e. CH3X.\textsuperscript{32} A further reason to choose this nomenclature lies with the nature of the Rydberg electron, which is being removed from the $2a_1$ MO. This MO is based on C–H $\sigma$ bonds,\textsuperscript{4,5,6,8} and it seems more sensible to use carbon-type Rydberg labels. The quantum defects we determine should then be comparable to those values for atomic C; $\delta = 0.98$ (s), 0.58 (p), 0.01 (d), 0.00 (f).\textsuperscript{33} The assignments of Suzuki et al. give quantum defects that are more comparable to values for the atomic halogen atom in question. Unassignable $n^*$ values for the F1 transition in CH3Cl and CH3Br have been attributed to valence states both by us and by Suzuki et al. (Table 1). Finally, we should note that assignments of isolated term values are not conclusive, as different but sensible values of $n$ and $\delta$ could correspond to a particular value of $E_n$. Detailed Rydberg assignments can only be made unambiguously by fitting a whole series of states to the Rydberg formula, usually from absorption spectra.

We note the broad nature of all the peaks in Fig. 5 for production of X$/CH_3$X above ca. 16 eV. Furthermore, feature F3 of the Cl$/CH_3$Cl spectrum at 20 eV, assigned to the $(2a_1)^{-1}4s$ Rydberg state, has partially-resolved structure, with ‘peaks’ observed at 20.13, 20.39, 20.66 and 20.93 eV. This structure was first observed in absorption by Wu et al.,\textsuperscript{34} and the spacing of ca. 0.27 eV or 2180 cm$^{-1}$ is most likely to be vibrational structure in the totally symmetric $v_1$ ($a_1$) mode, since the fourth photoelectron band at
21.56 eV, ionisation to CH$_3$Cl$^+$ $\tilde{C} \, ^2$A$_1$, also shows discrete vibrational structure with peaks at 21.56, 21.83 and 22.09 eV yielding the same vibrational spacing. This reduced value from the $\nu_1$ frequency of 2966 cm$^{-1}$ in the ground state of CH$_3$Cl is consistent with the 2a$_1$ molecular orbital having strong C–H $\sigma$-bonding character. Locht et al. also observe partially resolved peaks in the $\tilde{C}$-state photoelectron band, with peaks at 21.60, 21.82, 21.98 and 22.14 eV.\textsuperscript{31}

In order to explain the linear response of X$^-$ signal with pressure, X$^-$ must form with a cation (+ neutral(s)). It is possible that X$^-$ forms with CH$_3^+$, just like the X$^-$ signal formed near threshold at ca. 10 eV (Section 5.1). However, since the thresholds for Cl$^-$ and Br$^-$ signal in this energy region correspond closely to the enthalpies of reactions (10) and (17) (see Figures 2a and 3b, respectively), it seems likely that X$^-$ is formed with CH$_2^+$ + H. The enthalpy of reaction (2) is also not inconsistent with this interpretation for F$^-$/CH$_3$F. In all three halide molecules, the highest-energy peak, F3, for X$^-$ production has its maximum at an energy slightly above the enthalpy of reactions (3), (11) and (18) for F$^-$, Cl$^-$ and Br$^-$, respectively. It is possible, therefore, that these Rydberg states of CF$_3$X are crossed by ion-pair surfaces which dissociate to X$^-$ + CH$^+$ + 2H. A coincidence experiment between mass-selected anions and cations, similar to that reported for CO$_2$ + h$\nu$ $\rightarrow$ O$^-$ + CO$^+$, is needed to take this interpretation further.\textsuperscript{35}

5.3 H$^+$, CH$_2$X$^-$, CHX$^-$ and CX$^-$ from CH$_3$X
As explained in Sections 4.1–4.3, due to the zero-blast effect the H$^-$ yield from CH$_3$Br (Figure 3(a)) was the only one of the three H$^-$ spectra where an ‘X$^-$-subtracted’ spectrum was reliable and genuine. The experimental onset for H$^-$/CH$_3$Br of 12.1 ± 0.2 eV, leading to the first peak at 14.0 eV, is compatible with a calculated enthalpy for reaction (13), production of H$^-$ with CH$_2$Br$^+$, of 11.57 eV. A second peak at 20.5 eV with a threshold at ca. 17 eV is compatible with formation of H$^-$ with CH$_2^+$ + Br (reaction (14)), calculated threshold 17.38 eV. If there is a third peak present at 23 eV, it correlates reasonably well with the calculated threshold for reaction (15), production of H$^-$ with CH$^+$ + H + Br. The observation of H$^-$ experimental thresholds close to the calculated thresholds for reactions (13)–(15) suggests that H$^-$ forms either with CH$_2$Br$^+$ or with fragments of CH$_2$Br$^+$ that do not involve the formation of a new bond.

The anions CH$_2$X$^-$ (X = F,Cl,Br) can only form in an ion-pair reaction in combination with H$^+$. The appearance energies of these three ions are 18.2 ± 0.2, 17.2 ± 0.2 and 17.1 ± 0.2 eV (Table 1) respectively, in excellent agreement with the enthalpies for reactions (8), (12) and (21) of 17.73, 17.19 and 16.99 eV. Thus, these ions are being formed at threshold, as would be expected in the absence of an exit-channel barrier. The cross sections for forming CH$_2$X$^-$ + H$^+$ are ca. two to four orders of magnitude smaller than for formation of X$^-$ + CH$_3^+$ (Table 1 and Figures 1–3), the difference being the greatest
where $X=F$. This observation indicates that there is preferential $C-X$ bond cleavage over $C-H$ cleavage for all three molecules. This effect is presumably due to the greater electronegativity value of the fluorine atom compared to the other halogen atoms, polarising significantly the $C^{\delta+}-F^{\delta-}$ bond in the neutral molecule. The $C-H$ bonds in all three molecules are much less polarised, making formation of $CH_2X^- + H^+$ a weaker process with lower cross section.

The $CHF^-$ and $CHBr^-$ anions show experimental thresholds at 21.5 and ca. 20 eV respectively, although the spectrum of the latter anions shows a poor signal-to-noise ratio. These thresholds compare reasonably with calculated enthalpies of reactions (7) and (20) of 21.67 and 20.86 eV, suggesting that the accompanying products are probably $H^+ + H$, and not $H_2^+$. As explained earlier, the ion yield of $CHCl^-$ could not be determined with certainty due to mass resolution effects. The $CF^-$ spectrum (Figure 1(b)) shows a weak peak at 22.5 eV with an onset of 21.4 eV. The latter energy slightly precedes the thermochemical onset of reaction (5), 22.1 eV. This part of the $CF^-$ signal is therefore more likely to result from the overlap of signal from $CHF^-$ (Figure 1(c)), and the true AE($CF^-$) is deemed to be at the higher energy of $24.4 \pm 0.2$ eV. The cross sections for production of $CCl^-$ and $CBr^-$ were too weak for the yields of these anions to be measured.

The peaks in all the $X^-/CH_3X$ spectra from 16–24 eV have been assigned to predissociating Rydberg states converging on the $\tilde{C}^2A_1$ state of $CH_3X^+$ which dissociate into ion-pair continua (Section 5.2). We note that feature F2 of Fig. 5 of the $F^-/CH_3F$ spectrum occurs at the same energy, ca. 19.8 eV, as the peak in the $CH_2F^-$ spectrum (Fig. 1). This suggests that both the $F^- + CH_3^+$ and $CH_2F^- + H^+$ ion-pair states cross the $(2a_1)^{-1}3s$ Rydberg states of $CH_3F$, and the different intensities of the two peaks reflect the different coupling of the ion-pair states to this particular Rydberg state. Similarly, features F2 and F3 of the $Cl^-/CH_3Cl$ spectrum of Fig. 5 at 18.2 and 20.1 eV match the positions of both peaks in the $CH_2Cl^-/CH_3Cl$ spectrum (Fig. 2), and feature F2 of the $Br^-/CH_3Br$ spectrum of Fig. 5 has approximately the same energy, 17.9 eV, as the peak in the $CH_2Br^-/CH_3Br$ spectrum (Fig. 3). What is somewhat surprising is that in all these cases, the cross section for $X^-$ formation is much greater than for $CH_2X^-$ formation, suggesting preferential $C-X$ over $C-H$ bond cleavage. Yet these ion-pair states are crossing Rydberg states converging on the $\tilde{C}^2A_1$ state of $CH_3X^+$ where an electron has been excited from the $2a_1$ molecular orbital which has more $C-H$ than $C-X \sigma$-character.\textsuperscript{4,5,6,8} Thus excitation of this electron might be expected to weaken the $C-H \sigma$-bond to a greater extent.

The peak at ca. 22 eV in the $CHF^-/CH_3F$ spectrum (Fig. 1) matches the energy of feature F3 of the $F^-/CH_3F$ spectrum (Fig. 5), so both anions at this energy are probably formed by predissociation of the $(2a_1)^{-1}4p$ Rydberg state of $CH_3F$. Similarly, there is a very weak peak in the $CHBr^-/CH_3Br$ spectrum at
ca. 18 eV (Fig. 3), but this precedes the thermochemical onset of reactions (19) and (20) and is more likely to be an artefact of CH₂Br⁻ detection at this energy.

5.4 Absolute cross sections for anion production from CH₃X
The absolute cross sections for anion formation from CH₃X (X = F, Cl and Br) are presented in Table 1. Those for X⁻ formation are slightly larger than the estimated range of 10⁻²⁰ to 10⁻²¹ cm² quoted by Suzuki et al., but are a factor of ca. six smaller than the absolute cross sections determined by Shaw et al. for total ion-pair formation from ion detection below the ionisation threshold of the parent molecule. We have noted before the difficulty of interpreting the cross sections determined in the experiments of Suzuki et al., and in particular whether they have allowed for mass discrimination effects. Our values should, however, be comparable with those of Shaw et al., as X⁻ is by far the dominant anion produced in the three molecules and, based on thermochemical grounds, is the only species that can form below the first ionisation energy of each molecule. Using our cross section values together with total photoabsorption cross sections, the absolute quantum yields for the peak cross section of each anion formed have been calculated (Table 1). They take values in the range (0.4–2.3) x 10⁻³ for X⁻ formation, and values in the range 10⁻⁷ to 10⁻⁴ for the other anions. The X⁻ quantum yields are quite high compared to those obtained in earlier studies of CF₃X, CH₄ and SF₅CF₃, whereas the quantum yields for the other anions formed are of the same order of magnitude.

5.5 Bond dissociation energies
Using the inequality of Equation (1), the experimental AE values for anion formation determined in this work can be used to calculate upper limits to bond dissociation energies, D₀²⁹⁸, when the AE correlates to single-bond breaking ion-pair dissociation. The AE values of X⁻ formation presented in Table 1 and Figure 4 are used with the IE of the CH₃ radical (9.84 ± 0.01 eV) and the EA of the respective halogen atom (F (3.401 eV); Cl (3.613 eV); Br (3.364 eV)) for the C–X bond cleavage, and with the IE of H (13.606 eV) and the EA of the respective counter radical (CH₂F (0.25 ± 0.18 eV), CH₂Cl (0.74 ± 0.16), CH₂Br (0.79 ± 0.14) for the C–H bond cleavage. The resulting upper limits to bond dissociation energies are presented in Table 3, and are compared to literature values. An alternative way to present the data for XH₂C–H bond cleavage is to use literature values for the bond dissociation energies, and calculate a lower limit to the electron affinity of the CH₂X radical. We then obtain EA(CH₂F) ≥ −0.20 ± 0.2 eV, EA(CH₂Cl) ≥ 0.75 ± 0.2 eV, and EA(CH₂Br) ≥ 0.93 ± 0.2 eV, all consistent within error limits of literature values.

With the possible exception of the H₃C–Br data where the values for D₀²⁹⁸ are within error limits, there is excellent consistency between the upper-limit values for D₀²⁹⁸ (H₃C–X) and for D₀²⁹⁸ (XH₂C–H) obtained indirectly from this ion-pair work and the accepted literature values. Furthermore, the
significant difference between the upper limit for $D^0(\text{CH}_3\text{--F})$ from this work and the literature value is in excellent agreement with the large kinetic energy of over 1 eV measured by Locht et al. for reaction (1) by ion kinetic energy analysis in photoionisation mass spectrometry. It is also interesting to note that the upper-limit value tends toward the accurate value as the size of the halogen atom increases from F to Br. This trend has also been observed in our ion-pair work on CF$_3$X molecules (X = F,Cl,Br,I). As the size of X increases, the density of Rydberg states increases, increasing the likelihood of a Rydberg state crossing with an ion-pair state at as low an energy as thermochemically possible, thereby reducing the inequality presented in Equation (I) ultimately to an equality.

6. Conclusions

Absolute cross sections and quantum yields for production of X$^-$, CH$_2$X$^-$, CHX$^-$ and CX$^-$ from CH$_3$X (X = F,Cl,Br) over the energy range 8–35 eV have been determined. The relative ion yield spectrum of H$^-$ from CH$_3$Br has also been measured. The signals of all the ions display a linear dependence with pressure, showing that they arise from an ion-pair mechanism and not from the multi-step process of dissociative electron attachment. The CH$_2$X$^-$, CHX$^-$, CX$^-$ and H$^-$ spectra are observed for the first time, the X$^-$ spectra are very similar to those reported by Suzuki et al. The X$^-$ cross sections are somewhat larger than the approximate range of $10^{-21}$ to $10^{-20}$ cm$^2$ quoted by Suzuki et al., but a factor of ca. six smaller than the cross sections determined by Shaw et al. for total ion-pair formation. The discrete structure in the spectra suggests that most of the anions form indirectly by predissociative crossing of an initially-excited Rydberg state of the parent molecule into an ion-pair continuum; the one exception is the lowest-energy peak of F$^-$ from CH$_3$F at 13.4 eV, where its width and lack of structure suggest it may correspond to a direct ion-pair transition. The cross sections for formation of X$^-$ + CH$_3^+$ (cleavage of the C–X bond) greatly exceed those for formation of CH$_2$X$^-$ + H$^+$ (cleavage of a C–H bond), suggesting a very different coupling strength of these two ion-pair states to the molecular Rydberg states. By comparing the appearance energy of the X$^-$, H$^-$, CHX$^-$ and CX$^-$ anions with thermochemical thresholds, it is possible to make sensible assignments of what the partner cation (+ neutral species) are; CH$_2$X$^-$ can only form with H$^+$. Appearance energies of X$^-$ and CH$_2$X$^-$ can be used to calculate upper limits to 298 K bond dissociation energies for $D^0$ (H$_3$C–X) and $D^0$ (XH$_2$C–H). The data are consistent with literature values.

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and Belfast was partially funded by EPSRC Network Grant No. GR/N26234/01. The Science and Technology Facilities Council is thanked for the provision of beamtime

References


[19] K. F. Dunn, 2009 *private communication*


Table 1: Appearance energies, cross sections and quantum yields for anions observed from photoexcitation of CH$_3$F, CH$_3$Cl and CH$_3$Br.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Anion</th>
<th>AE$_{298}$ / eV</th>
<th>Cross section / cm$^2$</th>
<th>Energy of cross section maximum / eV</th>
<th>Quantum Yield$^h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_3$F</td>
<td>F$^-$</td>
<td>12.28 ± 0.02$^a$</td>
<td>1.2 x 10$^{-19}$</td>
<td>13.4</td>
<td>2.3 x 10$^{-3}$</td>
</tr>
<tr>
<td>CH$_3$F</td>
<td>CF$^-$</td>
<td>24.4 ± 0.2$^b,c$</td>
<td>4.2 x 10$^{-23}$</td>
<td>27.2</td>
<td>1.5 x 10$^{-6}$</td>
</tr>
<tr>
<td>CH$_3$F</td>
<td>CHF$^-$</td>
<td>21.5 ± 0.2$^b$</td>
<td>8.8 x 10$^{-23}$</td>
<td>22.4</td>
<td>2.2 x 10$^{-6}$</td>
</tr>
<tr>
<td>CH$_3$F</td>
<td>CH$_2$F$^-$</td>
<td>18.2 ± 0.2$^b$</td>
<td>4.1 x 10$^{-23}$</td>
<td>19.7</td>
<td>8.9 x 10$^{-7}$</td>
</tr>
<tr>
<td>CH$_3$Cl</td>
<td>Cl$^-$</td>
<td>10.04 ± 0.02$^a$</td>
<td>1.2 x 10$^{-19}$</td>
<td>11.3</td>
<td>2.3 x 10$^{-3}$</td>
</tr>
<tr>
<td>CH$_3$Cl</td>
<td>CH$_2$Cl$^-$</td>
<td>17.2 ± 0.2$^b$</td>
<td>7.6 x 10$^{-21}$</td>
<td>18.2</td>
<td>1.0 x 10$^{-4}$</td>
</tr>
<tr>
<td>CH$_3$Br</td>
<td>H$^-$</td>
<td>12.1 ± 0.2$^d$</td>
<td>-</td>
<td>14.0</td>
<td>-</td>
</tr>
<tr>
<td>CH$_3$Br</td>
<td>Br$^-$</td>
<td>9.46 ± 0.02$^a$</td>
<td>2.5 x 10$^{-20}$</td>
<td>10.0</td>
<td>4.1 x 10$^{-4}$</td>
</tr>
<tr>
<td>CH$_3$Br</td>
<td>CHBr$^-$</td>
<td>ca. 20$^e$</td>
<td>1.3 x 10$^{-22}$$^g$</td>
<td>22.4</td>
<td>3.3 x 10$^{-6}$</td>
</tr>
<tr>
<td>CH$_3$Br</td>
<td>CH$_2$Br$^-$</td>
<td>17.1 ± 0.2$^b$</td>
<td>5.6 x 10$^{-22}$</td>
<td>17.8</td>
<td>8.1 x 10$^{-6}$</td>
</tr>
</tbody>
</table>

$^a$ Appearance energy (AE) observed from this work, from the high resolution spectra shown in Figure 4.

$^b$ Appearance energy (AE) observed from this work, from the spectra shown in Figure 1-3.

$^c$ The AE(F$^-$) given here assumes that the peak at 22.5 eV in Figure 1(b)) is overlap of CHF$^-$ signal.

$^d$ AE is difficult to determine, as scan starts as 12 eV and the subtraction method discussed in Section 2 has been implemented.

$^e$ Cannot determine AE with confidence due to poor signal to noise. The signal may have contributions from CH$_3$Br$^-$.

$^f$ Cross section cannot be determined due to the zero-blast effect, discussed in Section 2.

$^g$ Cross sections are determined for the CHBr$^-$ anion, assuming that its signal varies linearly with pressure.

$^h$ Quantum yields for anion production are obtained by dividing cross sections for anion production (Column 4) by the total absorption cross sections. The latter values are taken from data for CH$_3$F, CH$_3$Cl and CH$_3$Br respectively.$^{15,16,17,34}$
Table 2: Energies, assignments and quantum defects of the X−/CH3X peaks between 16 and 24 eV converging on the $^2A_1$ state of CH3X*.

<table>
<thead>
<tr>
<th>Peak (^a)</th>
<th>$E_n$ (^b) / eV</th>
<th>Term value (^c) / eV</th>
<th>$n^*$ (^d, f)</th>
<th>$\delta$ (^e, f)</th>
<th>Rydberg state</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH3F (F2)</td>
<td>19.9</td>
<td>3.3 (^g)</td>
<td>2.03</td>
<td>0.97</td>
<td>3s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>([1.97])</td>
<td>([1.03])</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH3F (F3)</td>
<td>22.0</td>
<td>1.2 (^g)</td>
<td>3.37</td>
<td>0.63</td>
<td>4p</td>
</tr>
<tr>
<td></td>
<td></td>
<td>([3.24])</td>
<td>([-0.24])</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH3Cl (F1)</td>
<td>17.3</td>
<td>4.3 (^h)</td>
<td>1.78</td>
<td>-</td>
<td>$\sigma^*$</td>
</tr>
<tr>
<td>CH3Cl (F2)</td>
<td>18.3</td>
<td>3.3 (^h)</td>
<td>2.03</td>
<td>0.97</td>
<td>3s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>([2.03])</td>
<td>([1.97])</td>
<td></td>
<td>([4s])</td>
</tr>
<tr>
<td>CH3Cl (F3)</td>
<td>20.1</td>
<td>1.5 (^h)</td>
<td>3.01</td>
<td>0.99</td>
<td>4s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>([3.24])</td>
<td>([-0.24])</td>
<td></td>
<td>([3d])</td>
</tr>
<tr>
<td>CH3Br (F1)</td>
<td>16.2</td>
<td>5.1 (^i)</td>
<td>1.63</td>
<td>-</td>
<td>$\sigma^*$</td>
</tr>
<tr>
<td>CH3Br (F2)</td>
<td>17.7</td>
<td>3.6 (^i)</td>
<td>1.94</td>
<td>1.06</td>
<td>3s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>([1.92])</td>
<td>([3.08])</td>
<td></td>
<td>([5s])</td>
</tr>
<tr>
<td>CH3Br (F3)</td>
<td>19.6</td>
<td>1.7 (^i)</td>
<td>2.83</td>
<td>0.17</td>
<td>3d</td>
</tr>
<tr>
<td></td>
<td></td>
<td>([2.92])</td>
<td>([1.08])</td>
<td></td>
<td>([4d])</td>
</tr>
</tbody>
</table>

\(^a\) Peaks displayed in the ion-pair spectrum of the X−/CH3X spectrum shown in Figure 5.

\(^b\) $E_n$ is the peak energy of the Rydberg state.

\(^c\) Term value is the ionisation energy to which the Rydberg state converges minus the energy of the Rydberg state.

\(^d\) $n^*$ is the effective principle quantum number, i.e. $(n - \delta)$

\(^e\) $\delta$ is the quantum defect.

\(^f\) Alternative assignments and data from Suzuki et al. are shown in squared brackets.\(^{10}\)

\(^g\) Calculated using the VIE to $^2A_1$ state of CH3F+ of 23.2 eV.\(^5\)

\(^h\) Calculated using the VIE to $^2A_1$ state of CH3Cl+ of 21.56 eV.\(^7\)

\(^i\) Calculated using the VIE to $^2A_1$ state of CH3Br+ of 21.3 eV.\(^5\)
**Table 3**: Upper limits to bond dissociation energies and comparisons with literature values.

<table>
<thead>
<tr>
<th>Bond</th>
<th>This work $D^\text{298}_{\text{0}}$ / eV</th>
<th>Literature value $^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_3\text{C}--\text{F}$</td>
<td>$\leq 5.84 \pm 0.02\text{ }^a$</td>
<td>4.770 ± 0.087</td>
</tr>
<tr>
<td>$\text{H}_3\text{C}--\text{Cl}$</td>
<td>$\leq 3.81 \pm 0.02\text{ }^a$</td>
<td>3.630 ± 0.018</td>
</tr>
<tr>
<td>$\text{H}_3\text{C}--\text{Br}$</td>
<td>$\leq 2.98 \pm 0.02\text{ }^a$</td>
<td>3.048 ± 0.025</td>
</tr>
<tr>
<td>$\text{FH}_2$--$\text{H}$</td>
<td>$\leq 4.84 \pm 0.27\text{ }^b$</td>
<td>4.392 ± 0.044</td>
</tr>
<tr>
<td>$\text{ClH}_2$--$\text{H}$</td>
<td>$\leq 4.33 \pm 0.26\text{ }^b$</td>
<td>4.343 ± 0.024</td>
</tr>
<tr>
<td>$\text{BrH}_2$--$\text{H}$</td>
<td>$\leq 4.28 \pm 0.24\text{ }^b$</td>
<td>4.428 ± 0.025</td>
</tr>
</tbody>
</table>

$^a$ Calculated from the AE of $\text{X}^-$ formation from $\text{CH}_3\text{X}$, in Figure 4. The compound errors have contributions from the errors in AE ($\text{X}^-$), typically 0.02 eV, and the error in IE ($\text{CH}_3$), 0.01 eV.

$^b$ Calculated from the AE of $\text{CH}_2\text{X}^-$ formation from $\text{CH}_3\text{X}$, in Figures 1–3. The errors are dominated by errors in AE ($\text{CH}_2\text{X}^-$), typically 0.2 eV.

$^c$ Reference [41].
**Figure Captions**

**Figure 1**: Absolute cross sections for $F^-$, $CF^-$, $CHF^-$ and $CH_2F^-$ production following vacuum-UV photoexcitation of CH$_3$F. Ion yields were measured between 12 and 32 eV at a wavelength resolution of 0.6 nm. Solid arrows show the energies of the thermochemical thresholds calculated for reactions (1) – (8) (Section 4.1).

**Figure 2**: Absolute cross sections for $Cl^-$ and $CH_2Cl^-$ production following vacuum-UV photoexcitation of CH$_3$Cl. Ion yields were measured between 8 and 34 eV at a wavelength resolution of 0.6 nm. Solid arrows show the energies of the thermochemical thresholds calculated for reactions (9) – (12) (Section 4.2).

**Figure 3**: Relative ($H^-$) and absolute ($Br^-$, $CHBr^-$, $CH_2Br^-$) cross sections for anion production following vacuum-UV photoexcitation of CH$_3$Br. Ion yields were measured between 8 and 34 eV at a wavelength resolution of 0.6 nm. Solid arrows show the energies of the thermochemical thresholds calculated for reactions (13) – (21) (Section 4.3). The cross section for CHBr$^-$ is determined, assuming that this anion is formed by ion-pair dissociation (Sections 2 and 4.3).

**Figure 4**: The threshold region for production of $X^-$ from CH$_3$X recorded with a stepsize of 0.005 eV and a wavelength resolution of 0.2 nm, corresponding to ca. 0.02 eV at 12 eV. Absolute cross sections are not shown because the calibration signals of $F^-$ from CF$_4$ and SF$_6$ were not measured at this resolution. (i) and (ii) show the energies of the adiabatic and vertical ionisation energy of the first photoelectron band of CH$_3$F. (iii) shows the energy of the adiabatic or vertical ionisation energy of the first band of CH$_3$Cl, ionisation to CH$_3$Cl$^+$ $\tilde{X}$ 2$E$ where the spin-orbit splitting is very small, 0.027 eV. (iv) and (v) show the energies of the adiabatic ionisation energy of the two spin-orbit components of CH$_3$Br$^+$ $\tilde{X}$ 2$E_{3/2}$ and 2$E_{1/2}$ where the spin-orbit splitting is much larger, 0.320 eV.

**Figure 5**: Relative cross sections for production of $X^-$ from CH$_3$X between 14 and 28 eV recorded at a resolution of 0.6 nm. Features F1, F2 and F3 are described in the text, and assigned in Table 2. The arrows show the vertical ionisation energies of the fourth photoelectron band, ionisation to $\tilde{C}$ 2$A_1$. A progression with approximate spacing of 0.27 eV is observed in F3 of the Cl$^-$ / CH$_3$Cl spectrum, probably corresponding to vibrational structure in the $(2a_1)^{-1}4s$ Rydberg state of CH$_3$Cl (see text).
Figure 1:
Figure 2:
Figure 3:
Figure 5:

(a) $F^- / \text{CH}_3\text{F}$

(b) $\text{Cl}^- / \text{CH}_3\text{Cl}$

(c) $\text{Br}^- / \text{CH}_3\text{Br}$

Relative Cross Section / Arbitrary Units

Photon Energy / eV