Methane activation by gold-doped titanium oxide cluster anions with closed-shell electronic structures †

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The reactivity of closed-shell gas phase cluster anions AuTi3O7− and AuTi3O8− with methane under thermal collision conditions was studied by mass spectrometric experiments and quantum chemical calculations. Methane activation was observed with the formation of AuCH3 in both cases, while the formation of formaldehyde was also identified in the reaction system of AuTi3O8−. The cooperative effect of the separated Au+ and O2− ions on the clusters induces the cleavage of the first C–H bond of methane. Further activation of the second C–H bond by a peroxide ion O2− leads to the formation of formaldehyde. This study shows that closed-shell species on metal oxides can be reactive enough to facilitate thermal H–CH3 bond cleavage and the subsequent conversion.

Introduction

Methane, the major component of natural gas and shale gas, represents an important feedstock for the production of value-added chemicals.1–6 However, the direct conversion of methane poses a serious challenge in contemporary catalysis owing to the significant energy required for C–H bond cleavage.7–9 Many heterogeneous and homogeneous catalytic systems have been studied to transform methane, while it is challenging to uncover the elementary reactions and molecular level (ML) mechanisms associated with methane activation and conversion.10–13 In the last decades, model investigations of the elementary reactions between methane and gas phase atomic clusters with state-of-the-art mass spectrometric experiments and quantum chemistry calculations have been serving as an important approach to discovering the ML mechanisms of methane activation and transformation.14–16 The identified mechanisms can be very useful for catalyst design and optimization.17–20

Many atomic clusters including oxides,21–23 carbides,24 noble metals,25–29 and so on have been identified to be able to activate methane under thermal collision conditions. Investigations of these cluster systems have revealed three types of mechanism to activate the C–H bond of methane:

\[
\begin{align*}
[\text{MO}^-] + \text{CH}_4 & \rightarrow [\text{M(O-H)}^-] + \text{CH}_3 \quad (1) \\
[\text{M}] + \text{CH}_4 & \rightarrow [\text{H-M-CH}_3] \quad (2) \\
[\text{M}] + \text{CH}_4 & \rightarrow [\text{M-CH}_3] + \text{H-L} \quad (3)
\end{align*}
\]

where M is usually a metal atom and L is a ligand bonded with M. The atomic oxygen radical anions (O−) were extensively identified to activate methane through hydrogen atom abstraction (Reaction (1)).15,21,22 on many oxide clusters such as V2O106+,23 Al3O125+,24 and AuNbO75+25. The coordinatively unsaturated metal atoms in naked and ligated metal species such as Au3+,16 Pt5+,16 PtCH3+,26 and TaC6+,27 (ref. 21) can activate methane through oxidative addition (Reaction (2)).15,22,27 The mechanism of σ-bond metathesis (Reaction (3))22 was reported for a few simple mononuclear systems such as NiF+ (ref. 28) and HTiO+ (ref. 29) in which the σ-bonded ligand can be replaced through a reaction with the σ-bond of the incoming CH4. Herein, we report a new mechanism of methane activation by gas phase atomic clusters (Reaction (4)):

\[
[\text{M}^+\cdots\text{O}^2-] + \text{CH}_4 \rightarrow [\text{CH}_3\cdots\text{M}^+\cdots\text{O}^-] \quad (4)
\]

where the metal cation M+ is separated from the oxygen anion O2− on polynuclear metal oxide clusters and the cooperation of the two ions with counter polarity cleaves the C–H bond of methane.

The ability of two atoms with different polarity to promote chemical activity of atomic clusters in reactions with small molecules has been previously identified in the literature.
Castleman, Khanna, and their co-workers have reported that a complementary active site composed of a pair of adjacent Al atoms that respectively act as a Lewis acid and Lewis base can activate a variety of polar molecules such as water, alcohols, aldehydes, and thiols.\textsuperscript{26,29} Recently, we have found that a pair of non-adjacent ions Au\textsuperscript{−}\textsubscript{s}\textsuperscript{−}\textsuperscript{−}\textsuperscript{−} on AuCeO\textsubscript{2}\textsuperscript{−} and AuCeO\textsubscript{2}\textsuperscript{−} ions on gold-doped titanium oxide clusters AuTi\textsubscript{s}O\textsubscript{7} can bring about methane activation at thermal energies. Subsequent conversion of methane to a stable organic compound, formaldehyde, has also been identified. It is noteworthy that for the thermal activation of methane, most of the reactive clusters reported have open-shell electronic structures and the very few reactive species with closed-shell electronic structures are all mononuclear cations.\textsuperscript{26,29} The cluster anions were generally found to be much less reactive than the corresponding cations in the reactions with methane.\textsuperscript{10,13,16} For the first time, we report thermal methane activation by cluster anions with closed-shell electronic structures.

**Results**

**Reactivity of AuTi\textsubscript{3}O\textsubscript{7}− and AuTi\textsubscript{3}O\textsubscript{8}− with methane**

The AuTi\textsubscript{3}O\textsubscript{7}− and AuTi\textsubscript{3}O\textsubscript{8}− cluster anions were prepared by a reaction of O\textsubscript{2} with metal plasmas generated by laser vaporization of a solid disk compressed with Au and 48Ti powders. The clusters of interest were mass-selected by a quadrupole mass filter and entered into a linear ion trap reactor, where they were thermalized by collisions with a pulse of He gas (maximal instantaneous pressure around 2–4 Pa) and then interacted with a pulse of CH\textsubscript{4}, CD\textsubscript{4}, or CH\textsubscript{2}D\textsubscript{2} for a period of time.\textsuperscript{13} Upon the interaction of AuTi\textsubscript{3}O\textsubscript{7}− with 50 mPa CH\textsubscript{4} for about 1.07 ms (Fig. 1b), a strong product peak that can be assigned to Ti\textsubscript{3}O\textsubscript{7}H\textsuperscript{−} was observed, suggesting the following reaction channel:

\[
\text{AuTi}_3\text{O}_7^− + \text{CH}_4 \rightarrow \text{Ti}_3\text{O}_7\text{H}^− + \text{AuCH}_3
\]

(CID, such as AuTi\textsubscript{3}O\textsubscript{8}− + CH\textsubscript{4} → AuTi\textsubscript{3}O\textsubscript{8}− + O\textsubscript{2} + CH\textsubscript{4}). In addition to molecular association, the following four reaction channels are suggested by the experiments:

\[
\begin{align*}
\text{AuTi}_3\text{O}_7^− + \text{CH}_4 & \rightarrow \text{Ti}_3\text{O}_7\text{H}^− + \text{AuCH}_3 \quad (6) \\
\text{AuTi}_3\text{O}_8^− + \text{CH}_4 & \rightarrow \text{Ti}_3\text{O}_7\text{H}^− + \text{AuCH}_3 \quad (7) \\
\text{AuTi}_3\text{O}_8^− + \text{CH}_4 & \rightarrow \text{Ti}_3\text{O}_7\text{H}^− + \text{AuCH}_3 \quad (8) \\
\text{AuTi}_3\text{O}_8^− + \text{CH}_4 & \rightarrow \text{AuTi}_3\text{O}_6^− + \text{CH}_2\text{O} \quad (9)
\end{align*}
\]

The branching ratios of generating AuTi\textsubscript{3}O\textsubscript{8}−CH\textsubscript{4} (41%), Ti\textsubscript{3}O\textsubscript{7}H\textsuperscript{−} (35%), and AuTi\textsubscript{3}O\textsubscript{8}− (15%) are much larger than those of AuTi\textsubscript{3}O\textsubscript{7}H\textsubscript{2} (6%) and Ti\textsubscript{3}O\textsubscript{7}O\textsuperscript{−} (3%) (Fig. 1f). An atomic cluster often has different structural isomers with very different reactivities.\textsuperscript{29} The analysis of the methane-pressure dependent reactivity indicated that (87 ± 1)% of the experimentally generated AuTi\textsubscript{3}O\textsubscript{7}− ions (Fig. S2†) and only (37 ± 4)% of the AuTi\textsubscript{3}O\textsubscript{8}− ions (Fig. S3†) were reactive with CH\textsubscript{4}. For the reactive component of AuTi\textsubscript{3}O\textsubscript{7}−, the pseudo first-order rate constant (k\textsubscript{1}) of Reaction (5) is (7.7 ± 2.3) × 10\textsuperscript{−11} cm\textsuperscript{3} per molecule per second, corresponding to a reaction efficiency (θ)\textsuperscript{29} of (7.7 ± 2.3)%.

![Fig. 1](image-url)
per molecule per second [\(\Phi = (0.1 \pm 0.03)\%\)]. The inter-molecular KIE amounts to 4.0 ± 1.3.

**Reaction mechanisms of \(\text{AuTi}_3\text{O}_7^-\) and \(\text{AuTi}_3\text{O}_8^-\) with \(\text{CH}_4\)**

Density functional theory (DFT) calculations at the TPSS level, which shows the overall best performance in calculating several critical bond energies among the 18 tested methods (Table S1, ESIf), have been conducted to explore the detailed reaction mechanisms. A Fortran code based on the genetic algorithm was used to search the global minimum structures of \(\text{AuTi}_3\text{O}_7^-\) as well as \(\text{AuTi}_3\text{O}_8^-\) clusters with different spin multiplicities.\(^\dag\)

To determine the lowest-energy isomers of \(\text{AuTi}_3\text{O}_7^-\) and \(\text{AuTi}_3\text{O}_8^-\), further single-point energy calculations with a high-level quantum chemistry method of a restricted coupled-cluster method with single, double, and perturbative triple excitations [\(\text{RCCSD}(\text{T})\)] have also been performed for the TPSS optimized structures. In the reaction pathway of \(\text{AuTi}_3\text{O}_8^- + \text{CH}_4\), concomitant cleavage and formation of several chemical bonds are involved in important transition states. It is known that commonly used density functionals do not correctly describe the long- and mid-range dispersion interactions, which can influence the chemical reaction energies.\(^\ddag\) Thus, TPSS functional calculated energies with dispersion corrections\(^*\) are given throughout the reaction pathways.

The lowest-lying isomer of \(\text{AuTi}_3\text{O}_8^-\) (Fig. 2 and S5\(^\dag\)) has two terminally-bonded oxygen anions (\(\text{O}_2^2^-\), \(-0.62e\)) and a one-fold coordinated gold anion (\(\text{Au}_{1f}^2\), \(+0.42e\)). It is noteworthy that the superscripts “\(-2\)” of \(\text{O}_2^2^-\) and “\(+n\)” of \(\text{Au}^\ddagger\) denote the formal oxidation states rather than the net charges on the atoms. As marked in Fig. 2, the \(\text{Au}_{1f}^2\) cation is separated from the \(\text{O}_2^2^-\) anions. The Au-side of \(\text{AuTi}_3\text{O}_7^-\) is the least negatively charged, so it is expected that the \(\text{Au}_{1f}^2\) atom traps \(\text{CH}_4\) to form the encounter complex I1 with a significant binding energy (54 kJ mol\(^{-1}\)). Then the \(\text{CH}_4\) is delivered to be close to a \(\text{O}_2^2^-\) ion (TS1) so that the cleavage of one C-H bond and the concomitant formation of one Au-CH\(_3\) bond and one O-H bond can take place. Such a process (I1 \(\rightarrow\) TS1 \(\rightarrow\) I2) is subject to an energy barrier of 13 kJ mol\(^{-1}\) which is surmountable by the binding energy of I1. The formation of I2 can release a high energy of 198 kJ mol\(^{-1}\), which is enough to evaporate the AuCH\(_3\) species rather than Au + CH\(_3\) (endothermic by 244 kJ mol\(^{-1}\)) from the reaction complex to form the experimentally observed \(\text{Ti}_3\text{O}_7\text{H}^-\) cluster (Fig. 1b).

The gold atom in the lowest-lying isomer of \(\text{AuTi}_3\text{O}_7^-\) is one-fold coordinated (Fig. 2). In a low-lying isomer of \(\text{AuTi}_3\text{O}_7^-\) (Fig. S5\(^\dag\)), the \(\text{Au}^\ddagger\) ion can be two-fold coordinated (\(\text{Au}_{2f}^2\)). Such a cluster anion with \(\text{Au}_{2f}^2\) can hardly trap (binding energy is only 8 kJ mol\(^{-1}\)) the reactant molecule \(\text{CH}_4\). The activation of \(\text{CH}_4\) by \(\text{AuTi}_3\text{O}_7^-\) with the \(\text{Au}_{2f}^2\) is subject to an additional transformation so that the \(\text{Au}_{2f}^2\) ion becomes \(\text{Au}_{1f}^2\) (as in I1 of Fig. 2). The \(\text{Au}_{1f}^2 \rightarrow \text{Au}_{1f}^1\) transformation has an overall positive barrier (3 kJ mol\(^{-1}\)) which hinders subsequent methane activation, suggesting that the \(\text{AuTi}_3\text{O}_7^-\) isomer with \(\text{Au}_{1f}^2\) corresponds to the un-reactive component (13%) of \(\text{AuTi}_3\text{O}_7^-\) in the experiments.

When one of the \(\text{O}_2^2^-\) ions in the lowest-lying isomer of \(\text{AuTi}_3\text{O}_7^-\) is replaced by a peroxide unit (\(\text{O}_2^2-\)), a low-lying isomer of \(\text{AuTi}_3\text{O}_8^-\) with \(\text{Au}_{1f}^2\) and \(\text{O}_2^2^-\) ions can be formed (see I3 of Fig. 3). However, this isomer with \(\text{Au}_{1f}^2\) is less stable by 24 kJ mol\(^{-1}\) than the lowest-lying isomer of \(\text{AuTi}_3\text{O}_8^-\) that contains an \(\text{Au}_{2f}^2\) ion (Fig. S6\(^\dag\)). The activation of \(\text{CH}_4\) by the lowest-lying isomer of \(\text{AuTi}_3\text{O}_8^-\) also involves the \(\text{Au}_{1f}^2 \rightarrow \text{Au}_{1f}^1\) conversion which is hindered by an overall positive reaction barrier (1 kJ mol\(^{-1}\)). As a result, this lowest-lying isomer with \(\text{Au}_{1f}^2\) accounts for the 63% un-reactive component of the experimentally generated \(\text{AuTi}_3\text{O}_8^-\) ions. The 37% reactive ions can then be assigned to the low-lying isomer with \(\text{Au}_{1f}^2\) and the reaction mechanism is shown in Fig. 3.

Similarly to \(\text{AuTi}_3\text{O}_7^- + \text{CH}_4\) in Fig. 2, the \(\text{Au}_{1f}^2\) on \(\text{AuTi}_3\text{O}_8^-\) traps \(\text{CH}_4\) and delivers CH\(_4\) to be close to the \(\text{O}_2^2^-\) ion for C-H bond cleavage (I4 \(\rightarrow\) TS3 \(\rightarrow\) I5, Fig. 3). The large amount of

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**Fig. 2** TPSS functional calculated potential energy profile for \(\text{AuTi}_3\text{O}_7^- + \text{CH}_4 \rightarrow \text{Ti}_3\text{O}_7\text{H}^- + \text{AuCH}_3\). All of the species are in a singlet spin state. The dispersion corrected energies of the reaction intermediates (I1 and I2), transition state (TS1), and products (P1) with respect to the separated reactants (R1) are given in kJ mol\(^{-1}\). Bond lengths are given in pm.

**Fig. 3** TPSS functional calculated potential energy profile for \(\text{AuTi}_3\text{O}_8^- + \text{CH}_4\) to generate the products \(\text{Ti}_3\text{O}_7\text{H}^- + \text{AuCH}_3\) (P2), \(\text{AuTi}_3^-\), \(\text{O}_2^2- + \text{CH}_2\text{O}\) (P3), \(\text{Ti}_3\text{O}_7\text{H}^- + \text{CH}_2\text{O} + \text{AuH}\) (P4), and \(\text{AuTi}_3\text{O}_6^- + \text{CH}_2\text{O} + \text{H}_2\text{O}\) (P5). All of the species are in a singlet spin state. The dispersion corrected energies of the reaction intermediates (I3–I8), transition states (TS2–TS6), and products (P2–P5) with respect to the separated reactants (R2) are given in kJ mol\(^{-1}\). Bond lengths are given in pm.
exothermic energy released (191 kJ mol\(^{-1}\)) can evaporate the AuCH\(_3\) unit to produce Ti\(_3\)O\(_7\)H (I5 → P2, Reaction [6]). Alternatively, I5 can overcome the energy barrier (122 kJ mol\(^{-1}\), I5 → TS4) involving the activation of a second C–H bond by the O\(^{2-}\) unit (I5 → TS4 → I6) to produce a neutral CH\(_3\)O molecule and AuTi\(_2\)O\(_3\)H\(_2\) ions (I6 → TS5 → I7 → TS6 → I8 → P3, Reaction [7]). The formation of AuTi\(_3\)O\(_7\)H\(_2\) and CH\(_3\)O is highly exothermic (\(\Delta H_a = -261\) kJ mol\(^{-1}\)), so the resulting AuTi\(_3\)O\(_7\)H\(_2\) has enough internal energy to evaporate AuH and H\(_2\)O (Fig. S7f) to form the product ions Ti\(_3\)O\(_7\)H (Reaction [8]) and AuTi\(_3\)O\(_4\) (Reaction [9]), respectively. It can be seen that Reactions (7)–(9) all involve the generation of formaldehyde (CH\(_2\)O) and the DFT calculations correctly predict that Reactions (6)–(9) are all kinetically and thermodynamically favorable. Furthermore, the lower energy of TS4 (−69 kJ mol\(^{-1}\)) than that of P2 (−46 kJ mol\(^{-1}\)) can well rationalize the experimental branching ratios that show Reaction (6) as a minor channel.

In the reaction of AuTi\(_3\)O\(_8\) with CH\(_4\), the Au\(_{t}^+\) cation can also deliver CH\(_4\) to be close to the O\(^{2-}\) anion to activate the first C–H bond of methane (Fig. S9f). Subsequent transformation to form the intermediate I5 is kinetically less favorable than the reaction path of Fig. 3. A reaction path to form I7 (Fig. S10f) is slightly more favorable than the path of Fig. 3 kinetically (−45 kJ mol\(^{-1}\) versus −38 kJ mol\(^{-1}\) for the critical transition states). This alternative path has a very deep potential well (209 kJ mol\(^{-1}\)) which can hinder the further transformation of the reaction complex into separate products and leads to the formation of the association species AuTi\(_3\)O\(_8\)CH\(_4\). This result is consistent with the experimental observation that molecular association is a major reaction channel (41%) for AuTi\(_3\)O\(_8\) + CH\(_4\) (Fig. 1f).

Discussion

Many metal oxide clusters including homo-nuclear (M\(_{x}\)O\(_{y}\)) and hetero-nuclear oxide clusters [M\(^{+}\)\(_{x}\)M\(^{2+}\)\(_{y}\)O\(_{z}\)] have been found to react with methane under thermal collision conditions.\(^{4,11,23-25}\) All of the reactive oxide clusters were open-shell systems with oxygen radical centers and methane activation primarily followed Reaction (1). Recently, it has been demonstrated that the Pd\(_4\)O\(_{6}\) cluster can activate CH\(_4\) through Reaction (2) and then the oxygen radical accepts the transferred H atom.\(^{39}\) Herein, the AuTi\(_2\)O\(_{2}\) and AuTi\(_3\)O\(_{4}\) clusters are closed-shell systems (without radical oxygen species) and they activate methane through the new mechanism, Reaction (4). Previously, a few positively charged mononuclear species\(^{28-29}\) with closed-shell electronic structures were shown to activate methane through Reactions (2) and (3).

The observed reactivity of AuTi\(_3\)O\(_{2}\) and AuTi\(_3\)O\(_{4}\) with methane (Reactions (5)–(9)) can be closely related to the extraordinary properties of gold, and results from the strong relativistic effect on this element.\(^{40}\) The high electron-electrostatic energy of gold leads to a rather weak Au–O chemical bond (bond energy of 219 kJ mol\(^{-1}\))\(^{41}\) so that the O–Au\(_{t}^+\) bond can be flexible for the delivery of CH\(_4\) to be close to O\(^{2-}\) (Fig. 2 and 3) or O\(^{2-}\) (Fig. S9f) for C–H activation. Moreover, the analogous Au/H\(_{2}\) results in relatively strong Au–CH\(_3\) (232 kJ mol\(^{-1}\)) by the TPSS functional) and Au–H (292 kJ mol\(^{-1}\)) by the TPSS functional) bonds so that the evaporation of AuCH\(_{3}\) (Reactions (5) and (6)) and AuH (Reaction [8]) from the reaction complex is possible. Upon generation of the CH\(_2\)O moiety in AuTi\(_3\)O\(_8\) + CH\(_4\), the Au atom is bonded with the metal atom Ti (I8 of Fig. 3) and the gold atom becomes negatively charged (−0.20e), which is also a result of the relativistic effect.\(^{40,41,44}\)

In addition to the extraordinary properties of gold, the co-participation of both Au\(_{t}^+\) and O\(^{2-}\) ions is very important for the activation of methane (Fig. 2 and 3). The reaction paths for the C–H bond cleavage of CH\(_4\) by the single Au\(_{t}^+\) cation and a single O\(^{2-}\) anion of AuTi\(_3\)O\(_4\) have been also followed. These processes are subject to very high energy barriers (Fig. S11f). In addition, the reaction of AuTi\(_3\)O\(_{2}\) with CH\(_4\) on the triplet potential energy surface has also been calculated. It turned out that all of the triplet reactants, intermediates, and transition states are much higher (>100 kJ mol\(^{-1}\)) in energy than the corresponding singlet counterparts. As a result, the cooperative activation by the Au\(_{t}^+\) and O\(^{2-}\) ions, as shown in Fig. 2, is the only mechanism of methane activation by AuTi\(_3\)O\(_{2}\).

To explore the excellent ability of the cooperative Au\(_{t}^+\) and O\(^{2-}\) ions to promote methane activation by the closed-shell cluster anions of AuTi\(_2\)O\(_{2}\) and AuTi\(_3\)O\(_{4}\) under thermal collision conditions, variation of the geometrical structures of the reaction intermediates and the change of natural charge (Table S2\(^{+}\) as well as the Wiberg bond order (Table S3\(^{+}\) of critical atoms and chemical bonds have been analyzed for the reaction system of AuTi\(_3\)O\(_{2}\) + CH\(_4\) (Fig. 2). During the course of C–H bond cleavage (I1 → TS1 → I2), the electron population on the CH\(_3\) group and Au atom increases (−0.11e → −0.41e for CH\(_3\) and +0.44e → +0.28e for Au) and that on the transferring H decreases (+0.18e → +0.47e), indicating that the C–H bond may be cleaved in a heterolytic manner and the reaction may follow a Lewis acid–base pair mechanism taking into account that the separated Au\(_{t}^+\) and O\(^{2-}\) ions in AuTi\(_3\)O\(_{2}\) can be considered as a Lewis acid and Lewis base, respectively. However, the change in the natural charges of the CH\(_3\) moiety and H is not very large (around 0.3e), additionally, the charge increase on the H is normal for a bond conversion of C–H → O–H. In contrast to the Lewis acid–base mechanism, another mechanism of the flexible switch of the roles of the two O\(_{t}\) atoms in [Ti\(_3\)O\(_{2}\)]\(^{2-}\) which enables the favorable C–H activation is proposed from a bonding point of view. The reactant of AuTi\(_3\)O\(_{2}\) can be viewed as Au\(_{t}^+\) [Ti\(_3\)O\(_{2}\)]\(^{2-}\), in which Au\(_{t}^+\) (+0.42e) is attached to one of the O\(_{t}\) in [Ti\(_3\)O\(_{2}\)]\(^{2-}\) (−1.42e) with a bond strength of 1058 kJ mol\(^{-1}\) and the O\(_{t}\) becomes a bridging-bonded oxygen (Ob, as marked in Fig. 2). During the C–H activation, such Ob releases gold to form CH\(_3\) (Fig. 2). Thus, the overall increased bond strengths in the products drive the C–H activation thermodynamically. The switch of the roles of the two O\(_{t}\) in [Ti\(_3\)O\(_{2}\)]\(^{2-}\) can also be evidenced by the change of the Wiberg bond order of Ti–O\(_{t}\) (Table S3\(^{+}\)). The Ti1–O\(_{t}\) and Ti2–O\(_{t}\) bonds (Fig. 2) gradually switch from single/double bonds (187/167 pm) in the reactant to double/single bonds (166/187 pm) in the product. This mechanism suggests that the C–H
bond may be cleaved in a homolytic manner, namely, hydrogen atom transfer (HAT).

The identification of the Lewis acid–base mechanism or HAT for \( \text{AuTi}_3\text{O}_7^- + \text{CH}_4 \) relies on the transfer mode of one electron (\( e^- \)) and one proton (\( \text{H}^+ \)) of a H atom. HAT is characterized by the transfer of the electron and proton to a single site. In contrast, a Lewis acid–base mechanism corresponds to the transfer of the electron and proton to different acceptor sites. Such a transfer mode can be called an electron–proton transfer (EPT).\(^{41}\) It was proposed that a key element in the theoretical characterization of the mechanisms of proton and electron transfer is the formulation of their localized diabatic states.\(^{46}\) However, the electron and proton described by standard quantum mechanical methods tend to be delocalized, and the analysis of the electron or proton acceptors such as a molecular orbital or a chemical bond depends on the adopted computational level of theory.\(^{46}\) Consequently, it is hard to distinguish exactly the two proposed mechanisms of \( \text{AuTi}_3\text{O}_7^- + \text{CH}_4 \) at the present level of theory. More advanced methods such as multistate DFT, in which the electron and proton localized diabatic configurations can be constructed through block-localization of Kohn–Sham orbitals, should be employed to study the potential energy surfaces of the HAT and EPT, which may provide clues to recognize the mechanistic details of our reaction systems.

Conclusions

The reactions of methane with negatively charged titanium oxide clusters doped with single gold atoms, \( \text{AuTi}_3\text{O}_7^- \) and \( \text{AuTi}_3\text{O}_8^- \), have been identified by mass spectrometry and quantum chemistry calculations. To the best of our knowledge, this is the first example of the thermal activation and transformation of methane by atomic cluster anions with closed-shell electronic structures. Unlike the previously reported three general mechanisms including hydrogen atom abstraction, oxidative addition, and \( \sigma \)-bond metathesis for methane activation by atomic clusters, the cooperation of the separated Au\(^+\) and O\(^2^-\) induces the cleavage of the first C–H bond of methane for \( \text{AuTi}_3\text{O}_7^- \) and \( \text{AuTi}_3\text{O}_8^- \) clusters. Further activation of the second C–H bond of methane on the oxygen-rich system of \( \text{AuTi}_3\text{O}_8^- \) leads to the formation of the stable organic compound formaldehyde (\( \text{CH}_2\text{O}\)). The observed unique reactivity of \( \text{AuTi}_3\text{O}_7^- \) and \( \text{AuTi}_3\text{O}_8^- \) toward methane results from the strong relativistic effect on the gold element. This study not only serves as an important step in understanding that closed-shell species on metal oxides can be reactive enough to facilitate thermal H–CH\(_3\) bond cleavage, but also provides molecular-level insights into the design of active sites on metal oxide supported gold catalysts to activate and transform methane.

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Notes and references