Isotopic Enrichment Resulting from Differential Condensation of Methane Isotopologues Involving Non-equilibrium Gas–Surface Collisions Modeled with Molecular Dynamics Simulations

Michelle R. Brann, Xinyou Ma, and S. J. Sibener*

**ABSTRACT:** We employ molecular dynamics simulations to understand the energy transfer processes involved during the collisions of CH₄ and CD₄ with CH₄ layered surfaces at 20 K in order to explain our experimental finding of preferential adsorption of CD₄ compared to CH₄. There is good agreement between our MD simulations and our experimental results. We find that gas–surface collisional energy accommodation is dominated by exchange involving the translational degrees of freedom of the incident molecule and intermolecular vibrations of the interface. This observation allows us to understand that the cause of CD₄ preferential sticking arises from its propensity to lose more energy during its first impact with the surface, inducing longer residence times and leading to increased probability of becoming trapped and condensed onto the surface. Systematic trends are seen for sticking probabilities and energy transfer when we explore the behavior of the other H/D-substituted isotopologues of methane. These molecular insights provide context into the adsorption behavior occurring on icy dust grains in our solar system. Because sticking probabilities and energy transfer when we explore the behavior of the other H/D-substituted isotopologues of methane. These molecular insights provide context into the adsorption behavior occurring on icy dust grains in our solar system.

**INTRODUCTION**

Understanding energy-transfer dynamics at the gas–surface interface helps to accurately model a variety of chemical and physical phenomena.¹,² The energy transfer that occurs when a gas molecule collides with a condensed surface is complicated and a result of many factors such as the gas–surface potential, translational energy and incident kinematics of the projectile, gas–surface mass ratio, density of states of the interface’s degrees of freedom, surface morphology, and surface temperature. We present detailed molecular dynamics simulations to explicitly calculate energy transfer with the surface in order to understand our experimental observation³ that preferential adsorption occurs for CD₄ when striking the CH₄ surface compared to CH₄ under non-equilibrium gas–surface collision conditions.

In general, adsorption is a key process in both astrophysical and terrestrial environments because it is the first step in many gas–surface interactions.⁴–⁶ In extraterrestrial environments where chemical species are scarce, adsorption onto an interstellar grain, planetesimal, or other larger body dictates whether more complex organic molecules can form.⁷–¹² In order to accurately model chemical abundances, we previously examined isotopologues to understand how differences in mass between the projectile and the surface influence the ability of the species to adsorb and thus lead to observed relative isotopic abundances.¹³,¹⁴ We studied methane and its isotopologue deuterated methane due to methane’s interstellar abundance in both the gaseous and solid forms¹⁵–²¹ and its ability to form larger hydrocarbon species through addition reactions.²² We determined, through two independent experimental methods (monitoring reflected species as well as those species adsorbed on the surface), that preferential sticking and condensation occurred for CD₄ compared CH₄ under specific non-equilibrium gas–surface collision conditions.³

Molecular dynamics simulations of gas–surface collisions provide fundamental details of reaction dynamics, energy...
transfer, and product states for gas–surface reactions at the atomic level, where the gas–surface interaction is described by a multidimensional potential energy surface.\textsuperscript{1,23–31} For isotopologues, the gas–surface potentials are intrinsically identical; hence, any difference in sticking probabilities is directly correlated to the dynamics of the gas–surface collision. Here, we refine our computational parameters and perform molecular dynamics (MD) simulations using VENUS\textsuperscript{23} to fully investigate this energy transfer during the collision of \( \text{CH}_4 \) and \( \text{CD}_4 \) with \( \text{CH}_4 \) layered surfaces that results in these differing trapping efficiencies. We conclude that the dominant energy exchange occurs between the incident translational degrees of freedom and intermolecular lattice surface vibrations. Because \( \text{CD}_4 \) loses more translational energy upon impact compared to \( \text{CH}_4 \), the \( \text{CD}_4 \) projectiles interact with the surface longer and are therefore more likely to be trapped on the surface.

Understanding the refined details of intermolecular energy exchange responsible for gaseous condensation is in itself quite important as it has a direct linkage to many technological applications. One such avenue pertains to water condensation on windmill blades for power generation operating in cold environments.

Additionally, these findings can be incorporated into the development of novel heterogeneous isotopic enrichment and separation techniques. More broadly, this work is also critical to understanding the nature of methane adsorption within astrophysical environments. Trapping efficiency differences and energy exchange mechanisms can be incorporated into astrophysical models to explain molecular abundances and increased deuterium abundance in cometary ices and outer solar system planets. Moreover, aside from astrophysical environments, adsorption has implications into fields such as heterogeneous catalysis or thin film growth where the adsorption process serves as the first step in film formation.\textsuperscript{32}

\section*{COMPUTATIONAL DETAILS}

\subsection*{Potential Energy Surface.}

As detailed in our earlier publication and summarized here,\textsuperscript{3} the potential energy function for the \( \text{(CH}_4\text{)}_{\text{beam}} \) and \( \text{(CH}_4\text{)}_{\text{surface}} \) on top of a \( \text{Au}(111) \) crystal is given by

\begin{equation}
V = V_{\text{beam}} + V_{\text{surface}} + V_{\text{beam+surface}}
\end{equation}

where \( V_{\text{beam}} \) is the beam \( \text{CH}_4 \) intramolecular potential, \( V_{\text{surface}} \) is composed of intramolecular \( \text{CH}_4 \) potentials (same as \( V_{\text{beam}} \)) as well as the intermolecular \( \text{CH}_4–\text{CH}_4 \) and \( \text{Au–CH}_4 \) potentials using the 6–12 Lennard-Jones formulation, and \( V_{\text{beam+surface}} \) is the intermolecular \( \text{CH}_4–\text{CH}_4 \) potential. Each intramolecular \( \text{CH}_4 \) potential is expressed as a sum of Morse potentials for the \( \text{C}–\text{H} \) stretches and quadratic potentials for the \( \text{H}–\text{C}–\text{H} \) bends: the Morse parameters are \( D = 4.878 \text{ eV}, \beta = 1.86 \text{ Å}^{-1} \), and \( r_0 = 1.086 \text{ Å} \),\textsuperscript{38} and each HCH quadratic bend has \( f = 0.585 \text{ mdyn Å/rad}^2 \) and \( \theta = 109.47^\circ \).\textsuperscript{28,34} These parameters were also used for the \( \text{CD}_4 \) beam. The methane harmonic frequencies are 3193, 3021, 1583, and 1413 cm\(^{-1}\).

The surface model consists of 6 methane layers stacked in an AB sequence on top of a layer of gold to form a cubic close-packed structure (Figure 1).\textsuperscript{35} There are 789 \( \text{CH}_4 \) molecules in alternating layers of 120/143 molecules to prepare a methane surface area of 1600 Å\(^2\). The surface height of all of the stacked layers is 18 Å including the gold layer on the bottom. All intermolecular potentials are written as sums of 6–12 Lennard-Jones two-body potentials with a cutoff distance of 10 Å and are summarized in Table 1.\textsuperscript{35,36} For the \( \text{Au}(111) \) base, \( \epsilon_0 = 0.229 \text{ eV} \) and \( \sigma_0 = 2.951 \text{ Å} \).

\begin{table}[h]
\begin{center}
\caption{Parameters of the Lennard-Jones 12–6 Atom–Atom Interactions}
\begin{tabular}{lcc}
\hline
 & \( \epsilon_0 \) (eV) & \( \sigma_0 \) (Å) \\
\hline
\text{Au–Au} & 0.2294 & 2.951 \\
\text{C–C} & 0.0044 & 3.35 \\
\text{C–H} & 0.0021 & 2.99 \\
\text{H–H} & 0.0004 & 2.61 \\
\text{Au–C} & 0.0318 & 2.99 \\
\text{Au–H} & 0.0 & 0.0 \\
\hline
\end{tabular}
\end{center}
\end{table}

Prior to trajectory simulations, the surface configuration was fully relaxed to a potential energy minimum after a geometry optimization step and a thermal equilibration step at 20 K. The surface configuration at 20 K is similar to a flat crystalline surface, which is a model representation of a local section of the experimental methane surface prepared from beam deposition of methane on a \( \text{Au}(111) \) substrate, which in reality may contain domains of small, imperfect crystallites. However, even with this difference, there is qualitatively similar energy-transfer dynamics and thus appropriate to use for our study.\textsuperscript{29}

Although the surface retains a layered crystalline configuration of methane molecules in the \( z \)-direction at 20 K, the orientations of the hydrogens of a particular methane molecule within a layer are randomized. Thus, as the surface relaxes into its configuration, there may be some regions that can adsorb incident projectiles more efficiently.

The easiest test to determine a small radial area acceptable for gas–surface collision simulations is to calculate the methane binding enthalpy with different impact parameters (BMAX, Å) where BMAX is the radial distance in angstroms in the \( X–Y \) plane from a head on collision to a methane on the surface. A microcanonical ensemble averaged intermolecular potential curve for \( \text{CH}_4 \) approaching the surface is obtained by

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Schematic model of the optimized methane surface comprised of methane layers on top of a layer of gold. The methane surface area is 1600 Å\(^2\) and is in a cubic close-packed structure.}
\end{figure}
averaging the potential energies of over 1000 randomly oriented CH₄ molecules as a function of CH₄-surface distance.⁵¹ Comparing the interfacial potential energy curves evaluated at several BMAX impact parameters (Figure 2), we find that the potential minimum decreases as the impact parameter traverses the unit cell. The potential energy curve at 4 Å is close to the curve at 0 Å, but not identical because our average C–C distance is 3.8 Å. We then decided to use a BMAX impact parameter of 8 Å to sample the equivalence of two unit cells for a representative sampling of the surface.

Procedure for the Molecular Dynamics Simulations. Molecular dynamics simulations were performed using the VENUS general chemical dynamics computer program.²³,⁴² Classical trajectories were used to simulate collisions of a beam of CH₄ or CD₄ with the CH₄ surface. Initial conditions for the trajectories were selected to sample the beam’s translational and vibrational energy at the experimental conditions; rotations were frozen at 0 K given the supersonic expansion of the incident beam. The selection of initial conditions follows from previous VENUS studies.³⁰,⁴³ For each simulation, a beam of colliding molecules was aimed at a circular area. Each trajectory was initialized with a separation of 10 Å between the center-of-mass of the beam molecule and the surface aiming point. Unless otherwise specified (in the simulations with an angle of 45° between the beam and the surface), the beam molecule collides perpendicularly to the surface to match the predominant configuration of the experimental apparatus. For each beam, the initial vibrational levels were sampled from Boltzmann distributions at 300, 700, 900, or 1100 K including the vibrational zero-point energy. Our experimental studies employ essentially monoenergetic seeded supersonic beams so that the CH₄ and CD₄ have the same incident velocity but different kinetic energies and momenta (0.49, 1.16, 1.48, and 1.79 eV for CH₄ and 0.67, 1.41, 1.74, and 2.19 eV for CD₄).

We also ran classical trajectories to simulate collisions of a beam of CH₃D, CH₂D₂, and CD₂H with the CH₄ surface. These trajectories were compared to those of the 1.79 eV CH₄ and 2.19 eV CD₄ beam (the highest initial velocity, 4613 m/s). Thus, the initial vibrational levels were sampled from a Boltzmann distribution at 1100 K, and the rotational levels were frozen at 0 K. The kinetic energies were 1.93, 2.02, and 2.1 eV for CH₃D, CH₂D₂, and CD₂H, respectively.

For each trajectory, the gold and bottom three layers were held rigid and acted as anchor layers. Additionally, the mass of carbon atoms in rim CH₄ molecules was artificially increased by 10000 to truncate the surface. Initial conditions for this surface were selected by assigning velocities to the carbon atoms of these layers, sampled from a Maxwell–Boltzmann distribution at 20 K. The surface was equilibrated by a 50 ps molecular dynamics simulation with velocity scaling every 1000 steps and another equilibration without velocity scaling. The trajectories were propagated with a Velocity-Verlet integrator with a time step of 0.01 fs. Trajectories were terminated either when the distance between the central methane molecule and the outgoing product exceeded 30 Å or when the total integration exceeded 50 ps. Typically, 1900–2000 trajectories were calculated for each ensemble of initial conditions, including the surface composition and beam conditions.

Figure 3. Sticking probabilities (a) calculated from the number of CH₄ and CD₄ direct and physisorption scattering trajectories (open circles) on a CH₄ surface at 20 K. Error bars represent the standard error of a binomial distribution of at least 1900 trajectories for each velocity. The experimental sticking probabilities (solid circles)⁷ are from at least three King and Wells measurements on at least three different days. The differential sticking probability (b) is the ratio of the CH₄/CD₄ sticking probability at the CD₄ initial velocity. The experimental and VENUS CH₄ sticking probabilities are extrapolated using the linear fit in (a), so that the ratio is taken at the same initial condition. Excellent agreement between experiment and theory is readily seen in (b).
RESULTS AND DISCUSSION

Sticking Probability. First, the theoretical predictions of the sticking probabilities from the trajectory simulations agree well with the experimentally determined sticking probabilities. Computationally, the sticking probability is the fraction of trajectories with CH$_4$ or CD$_4$ remaining on the surface after 50 ps. Our VENUS calculations demonstrate (1) a decrease in sticking probability with increasing incident velocity as well as (2) a significant isotopic effect as seen in the difference between CH$_4$ and CD$_4$ sticking probabilities on the CH$_4$ surface (Figure 3) as a function of incident velocity. In general, we find that the CD$_4$ and CH$_4$ sticking probabilities are identical for the lowest velocity beam before diverging for the higher velocity beams as more CD$_4$ trajectories become preferentially trapped on the surface. For comparison, the VENUS calculations are overlaid with our experimental King and Wells sticking probability measurements (solid circles). Although the theoretical sticking probabilities are slightly lower than the experimental values, the trend and differential sticking between CH$_4$ and CD$_4$ at each initial condition are in excellent agreement (Figure 3b). This offset could result from structural differences between our disordered experimental surface and our layered flat theoretical surface. Additionally, Lennard-Jones potentials are not fully optimized for the repulsive region.

Regardless, there is qualitatively similar energy-transfer dynamics between crystalline and domains of small, imperfect crystallites so that we can use our theoretical system to explain how the two isotopologues are differentially condensed.

Direct/Indirect Scattering. The trajectories that eventually scatter off the surface can experience different dynamics on the surface. In particular, these trajectories are categorized as two types: (1) direct scattering with only 1 inner turning point (ITP) and (2) physisorption/desorption with multiple ITPs, where an ITP occurs when the CH$_4$/CH$_4$ center-of-mass height changes from decreasing to increasing. Representative CH$_4$ trajectories of both types at an incident velocity of 4613 m/s are shown in Figure 4a as well as a comparison to a sticking/trapped trajectory, where the center-of-mass height from the layered surface is plotted as a function of time. The direct scattering trajectory bounces on the surface with a shorter residence time near the surface, while the physisorption/desorption trajectory can experience multiple hops on the surface until a successful escape from the surface. The trapped trajectory remains about 3.5 Å above the surface, in agreement with the CH$_4$—CH$_4$ intermolecular Lennard-Jones potentials and surface spacing. At our selected incident velocities, we do not find any CH$_4$ or CD$_4$ projectiles contain enough incident energy to penetrate into the bulk film.

Separating the scattered trajectories into direct and physisorption/desorption trajectories, we find that with increasing incident velocity, the percentage of direct trajectories and physisorption/desorption trajectories both increase as fewer projectiles are trapped on the surface. Additionally, the relative percentage of direct trajectories compared to physisorption/desorption trajectories decreases. This difference is particularly stark for the highest velocity (4613 m/s) beam where among the scattered trajectories there is a larger percentage of direct trajectories for CH$_4$ than for CD$_4$. This provides mechanistic support for why trapping efficiencies differ between these two isotopologues and how energy loss to the surface plays an important role.

Scattered Trajectory Energy Distributions. For each trajectory that does not stick on the surface, we conducted additional analyses to determine the post-collision velocity distributions, translational and internal energy lost to the surface, residence time on the surface, and angle scattered from the surface. When CH$_4$ and CD$_4$ collide with the CH$_4$ surface, in order for trapping to occur, the CH$_4$ or CD$_4$ molecule must lose enough of its initial energy to avoid bouncing back. To align with our experimental setup employing monoenergetic seeded supersonic beams, the molecular dynamics simulations consider CH$_4$ and CD$_4$ molecules with identical incident velocities but different kinetic energies and momenta. Thus, we
The sum of two Maxwell velocity distributions are well described by either one or the molecules scatter with a larger final velocity (Figure 5b). The essentially no difference between CH$_3$ and CD$_4$ molecules, there is translational energy exchange to the surface. First, we examined the final velocity distributions for the projectiles scatter off with an average faster final velocity; CH$_4$ scatters off with a higher velocity. For the CH and CD scatters off of a CH$_4$ surface at 20 K. The average final velocity is plotted in (c). As the incident velocity increases, the projectiles scatter off with an average faster final velocity; CH$_4$ scatters off with a higher velocity. As expected, with increasing incident velocity, the scattered molecules leave the surface with a higher final velocity. For the lowest incident velocity (2483 m/s) molecules, there is essentially no difference between CH$_4$ and CD$_4$. However, when the incident velocity is increased to 4613 m/s, the CH$_4$ molecules scatter with a larger final velocity (Figure 5b). The velocity distributions are well described by either one or the sum of two Maxwell–Boltzmann distributions. We see that there is an inelastic collision with the surface, but the molecules are not thermally equilibrated with the surface, as the fitting temperature is greater than 20 K (Figure 5b).

We next examine the translational, vibrational, and rotational energy transfer upon impact with the CH$_4$ surface because trapping only occurs when a molecule loses enough energy to the surface (Figure 6). The incident projectiles contain no rotational energy (to be consistent with our supersonic beam expansion conditions) so we calculated the rotational energy gain due to collisions with the surface; the vibrational and translational energy losses are calculated by taking the initial — final energy (in electronvolts) for each scattered trajectory. With increasing initial incident velocity, more energy (translational and vibrational) is lost to the surface while nevertheless still leading to the overall decrease in sticking probability (Figure 3). For the translational energy at the faster incident velocity (Figure 6a), we see the largest divergence; CD$_4$ loses 2.07 eV to the surface compared to 1.67 eV for CH$_4$. The larger translational energy loss for CD$_4$ is what enables it to be trapped on the surface with a greater relative probability. Additionally, even at the highest velocity with 1100 K initial rotational energy and 0 K initial rotational energy, both CH$_4$ and CD$_4$ lose less than 0.25 eV vibrational energy to the surface and gain less than 0.05 eV rotational energy (Figure 6b,c). We find that the vibrational energy lost and rotational energy gained are all at least an order of magnitude smaller than the translational energy lost to the surface. This indicates that it is the translational energy exchange that dominates the condensation behavior between incident CH$_4$ and CD$_4$ and the CH$_4$ surface, leading to trapping of these molecules rather than rotational and vibrational energy exchange.

As a comparison and to further generalize our energy exchange occurring for CH$_4$ and CD$_4$, we also ran additional trajectories for CH$_3$D, CH$_2$D$_2$, and CD$_3$H impinging on the 20 K CH$_4$ surface. These trajectories were for the highest initial velocity (4613 m/s), corresponding to kinetic energies of 1.93 2.02, and 2.10 eV for CH$_3$D, CH$_2$D$_2$, and CD$_3$H, respectively. The trajectories contained vibrational energies sampled from a Boltzmann distribution at 1100 K and 0 K rotational energy to directly compare to CH$_4$ and CD$_4$. First, we examined the sticking probability (Figure 7) and found that the increased
condensation is directly proportional to the number of deuterated atoms in the methane molecule. Thus, CD₂ has the highest sticking probability as compared to CH₄ and the other isotopologues (CH₃D, CH₂D₂, and CD₃H).

Next, we examine the translational energy loss (Figure 8a), vibrational energy loss (Figure 8b), and rotational gain (Figure 8c) for these five beams (CH₄, CH₂D, CH₃D, CD₂H, and CD₃H) with the same initial velocity but increasing initial kinetic energies. We confirm that translational energy exchange dominates and is an order of magnitude higher than vibrational and rotational energy exchange. Additionally, the translational energy loss increases monotonically to preferentially trap the deuterated methane molecules.

Residence Time Distributions. To further understand how this translational energy loss is dissipated to trap the methane isotopologues, we examine their time on the surface (residence time). For all scattered trajectories, the residence time is the duration of time that an incident CH₄ or CD₂ has its center-of-mass (COM) height within 10 Å of the surface. The residence time distributions for the lowest velocity (2483 m/s) and highest velocity (4613 m/s) of CH₄/CD₄ molecules are shown in Figure 9a,b. These distributions are fit to an exponentially modified Gaussian (EMG) function which is a convolution of an exponential and a Gaussian distribution probability distribution:

\[ h(t) = \frac{a}{\sqrt{\pi}} \exp\left(\frac{kS - t}{2}\right) \left(1 - \text{erf}\left(\frac{S - t + k\sigma^2}{\sqrt{2}\sigma}\right)\right) \]

where the complementary error function is defined as

\[ \text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} \, dt \]

In eq 2a, \( a \) is the amplitude, \( \sigma \) is the Gaussian width, \( S \) is the skew or shift in the time from a normal Gaussian distribution, and \( k \) is the exponential decay. For the lowest velocity beams (Figure 9a), the CH₄ and CD₄ distributions are quite similar to Gaussian peak widths of ~0.3 ps, a relaxation time (1/k) of 0.77 ps, and an amplitude of 0.2. For the higher velocity beams, although both Gaussian widths are ~0.17 ps, there are some clear differences between the CH₄ and CD₄ results (Figure 9b). First, when considering the Gaussian component of the fit, CH₄ has a much higher amplitude (0.064) compared to CD₄ (0.048). Second, when considering the exponential decay component, the relaxation time is longer for CD₄ (1.31 ps) compared to CH₄ (0.98 ps). This supports the finding that CH₄ molecules spend less time interacting with the surface (1.5 vs 1.7 ps at the highest initial velocity).

Thus, we can clearly see in Figure 9c that with increasing initial velocity, on average, the molecules spend less time on the surface. To avoid convolution between different mechanisms, the average residence time on the surface (Figure 9c) considers only direct scattering trajectories. For these direct scattering trajectories, the translational energy loss during one bounce with the surface directly impacts the residence time.

We find that because CD₄ projectiles lose more translational energy to the surface during collision (particularly for the highest velocity beam), they end up interacting with the methane surface longer than the CH₄ projectiles and are therefore more likely to be trapped.

Scattering Angle Distributions and 45° Incident Angle Trajectories. The final scattering angle (\( \theta_f \)) is defined as the angle between the final velocity vector of CH₄ or CD₄ and the surface normal. With increasing incident velocity, the average scattered angle decreases for both CH₄ and CD₄, but it decreases more for CD₄. The final average angles are 48° and
44° for CH₄ at the lowest and highest incident velocity, respectively, and 47° and 40° for CD₄. For all incident conditions, we find that the emitted trajectories do not scatter with a cosine distribution, indicating dominance of direct scattering and the lack of reemitted thermalized trajectories.

We also ran an additional set of simulations with trajectories that approach the surface from 45° instead of normal. The initial conditions for these trajectories were $v_i = 2483$ m/s and $v_i = 4613$ m/s with vibrational energy sampled from Boltzmann distributions at 300 and 1100 K, respectively, to match the experimental conditions and the trajectories impinging upon the surface at normal. We also included CH₄ and CD₄ trajectories with an initial velocity of 6579 m/s and vibrational energy sampled from a Boltzmann distribution at 1100 K so that the normal velocity component was 4613 m/s. In general, we find a lower overall sticking probability for trajectories incident at 45° versus normal. Therefore, our mechanism involving direct translational energy exchange with the intermolecular vibrations of the surface lattice upon one impact with the surface is broadly applicable regardless of the incident angle. Because the sticking probabilities are much lower for the 45° trajectories, we propose that perpendicular components of the incident momentum are especially important in this translational energy transfer to the surface lattice.

In general, our increased understanding of this gas–surface energy exchange under non-equilibrium conditions at cold substrate temperatures from these numerical simulations has important astrophysical and technological implications. Two such technological applications are water condensation in high-velocity gas flows as experienced by aircraft in low-temperature situations and condensation on windmill blades for power generation operating in cold environments.

Importantly, these results offer a novel route for isotope enrichment and separation via the preferential condensation of heavier isotopes during gas–surface collisions under carefully selected substrate, gas mixture, kinematic, and incident velocity conditions.

These novel trapping efficiency differences and energy exchange mechanisms can also be incorporated into astrophysical models. Adsorption is often the first step for many cold temperature reactions occurring on dust grains, with trapping efficiency differences having notable implications for allowed reaction probabilities and subsequent events, leading to increased molecular complexity. Our investigations of gas–surface collisional energy transfer processes can help to not only explain increased abundance of deuterium in solar system planets, but these mechanisms can be incorporated into astrophysical models of the icy dust grain processes including those in the interstellar region.

### CONCLUSION

In conclusion, we performed detailed molecular dynamics simulations to understand our experimental result of differential condensation between CH₄ isotopologues impinging onto a CH₄ surface at 20 K. First, we have good agreement between our MD simulations and our experimental results, where there was increased adsorption of CD₄ compared to CH₄, particularly for the highest velocity beam. Second, we find that gas–surface collisional energy accommodation is dominated translational energy exchange with intermolecular vibrations of the methane surface lattice. CD₄ preferential sticking arises from its propensity to lose more energy during its first impact with the surface, inducing longer residence times and leading to increased probability of becoming trapped and condensed onto the surface. Systematic trends are seen for sticking probabilities and energy transfer when we explore the behavior of the other H/D substituted isotopologues of methane.

In general, our increased understanding of this gas–surface energy exchange under non-equilibrium conditions at cold substrate temperatures from these numerical simulations has important astrophysical and technological implications. Two such technological applications are water condensation in high-velocity gas flows as experienced by aircraft in low-temperature situations and condensation on windmill blades for power generation operating in cold environments.

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### AUTHOR INFORMATION

**Corresponding Author**

S. J. Sibener — The James Franck Institute and Department of Chemistry, The University of Chicago, Chicago, Illinois 60637, United States; orcid.org/0000-0002-5298-5484; Email: s-sibener@uchicago.edu

**Authors**

Michelle R. Brann — The James Franck Institute and Department of Chemistry, The University of Chicago, Chicago, Illinois 60637, United States; orcid.org/0000-0002-9889-3921

Xinyou Ma — The James Franck Institute and Department of Chemistry, The University of Chicago, Chicago, Illinois 60637, United States; orcid.org/0000-0002-0923-8758

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jpcc.3c02386

**Notes**

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