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Collision dynamics of symmetric top molecules: A comparison of the rotationally inelastic scattering of CD$_3$ and ND$_3$ with He

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We compare rotationally inelastic scattering of deuterated methyl radicals (CD$_3$) and ammonia (ND$_3$) in collisions with helium using close-coupling quantum-mechanical scattering calculations performed with \textit{ab initio} potential energy surfaces (PESs). The theoretical methods have been rigorously tested against angle-resolved experimental measurements obtained using crossed molecular beam apparatuses in combination with velocity map imaging [O. Tkáč, A. G. Sage, S. J. Greaves, A. J. Orr-Ewing, P. J. Dagdigian, Q. Ma, and M. H. Alexander, Chem. Sci. \textbf{4}, 4199 (2013); O. Tkáč, A. K. Saha, J. Onvlee, C.-H. Yang, G. Sarma, C. K. Bishwakarma, S. Y. T. van de Meerkker, A. van der Avoird, D. H. Parker, and A. J. Orr-Ewing, Phys. Chem. Chem. Phys. \textbf{16}, 477 (2014)]. Common features of the scattering dynamics of these two symmetric top molecules, one closed-shell and the other an open-shell radical, are identified and discussed. Two types of anisotropies in the PES influence the interaction of an atom with a nonlinear polyatomic molecule. The effects of these anisotropies can be clearly seen in the state-to-state integral cross sections out of the lowest CD$_3$ rotational levels.

I. INTRODUCTION

In recent experiments from our laboratories, the rotationally inelastic scattering dynamics of symmetric top molecules in collisions with rare gas atoms were examined using crossed molecular beam and velocity map imaging (VMI) methods and compared with quantum scattering calculations. The bulk of experimental and theoretical studies of the dynamics of rotational energy transfer involved studies of collisions of diatomic molecules, as exemplified by a number of recent studies. Some attention has also been paid to experimental and theoretical studies of inelastic collisions of nonlinear polyatomic molecules. Collisions of nonlinear polyatomic molecules, such as the symmetric tops under study here, display a richer dynamics because the potential energy surface (PES) depends upon two angular coordinates, rather than just one as for diatomics, and the energy level structure is more complicated. In particular, there are two types of anisotropies for the interaction of a symmetric top molecule with a structureless collision partner, involving approach of the perturber along and perpendicular to the molecular symmetry axis. By contrast, the anisotropy in an atom-diatom interaction only involves differences between end-on vs. side-on approach. In a recent review article, Dagdigian discussed the effect of the two types of anisotropies in the PES for inelastic collisions of small hydrocarbon reactive intermediates.

The particular symmetric tops selected for investigation here are deuterated methyl (CD$_3$) and ammonia (ND$_3$) molecules, and we will focus on collisions with helium. In our experimental studies of these molecules, resonance-enhanced multi-photon ionization detection (REMPI) allowed acquisition of VMI for methyl radicals in levels corresponding to a single rotational angular momentum quantum number $n'$, but averaged over a subset of the projection quantum number $k'$, whereas for ND$_3$, images were acquired for molecules scattered into individual $n_n^k$ levels. Product rotational level resolved angular scattering distributions for the CD$_3$–He and ND$_3$–He systems were extracted from the experimental images and were compared with the results of close-coupling quantum-mechanical scattering calculations that used recently developed \textit{ab initio} PESs. The experimental measurements provided rigorous tests of the accuracy of the PESs and computed quantum scattering dynamics, and agreement between experiment and theory was found to be excellent for both the CD$_3$–He and ND$_3$–He systems.

The aim of the current paper is to compare the rotationally inelastic scattering dynamics of these two symmetric top molecules, one a closed-shell molecule (ND$_3$) and the other an open-shell radical (CD$_3$) and to relate any differences to
specific features of the PESs for the two systems. Although our VMI study of ND₃–He scattering was fully resolved in the pre- and post-collision rotational levels of the ND₃, precise comparisons with CD₃–He scattering based solely on experimental results are difficult because the REMPI detection scheme for CD₃ was not fully k’ level specific for a given n’. Moreover, the initial population of n and k levels in the photolytically generated and supersonically cooled beam of CD₃ radicals was distributed over some rotational levels. However, our detailed comparison of experimental and theoretical scattering dynamics demonstrated that the quantum scattering calculations provided an accurate description of the collision dynamics for both ND₃–He and CD₃–He. Therefore, we focus here on a comparison between the computational results for these two systems, but recognize that these comparisons are underpinned by the validation provided by our experimental measurements.

This paper is organized as follows. In Sec. II we review the rotational level structures of the two symmetric tops of interest, with consideration of the effects of deuterium nuclear spin, discuss the ND₃–He and CD₃–He PESs, and describe briefly the quantum scattering calculations. Section III presents the calculated integral and differential cross sections (DCSs) for the two systems and discusses the observed propensities for certain types of transitions in terms of the anisotropies of the PESs. A Conclusion follows.

II. METHOD

A. Rotational levels of ND₃ and CD₃

The three-fold rotational symmetry of the symmetric top molecules, the symmetry/asymmetry of their vibrational wave functions associated with umbrella inversion, and the nuclear spin symmetry types of the three equivalent deuterium atoms all influence the inelastic scattering dynamics in collisions with a rare gas atom. In this subsection, we briefly describe the rotational levels of the CD₃ and ND₃ molecules and their nuclear spin symmetries. Rotational level diagrams for CD₃ and ND₃ are shown in Fig. 1 for the ground vibrational level of their X electronic states. Both molecules are symmetric tops, and we label the rotational levels by n_A, where n and k (taken to be nonnegative) designate, respectively, the rotational quantum number and its body-frame projection. Rotational levels with k > 0 are doubly degenerate.

Ammonia in the ground electronic state has a pyramidal (C₃v) equilibrium geometry. The double-minimum potential along the inversion coordinate associated with the v₂ “umbrella” vibrational mode of ammonia gives rise to a splitting of all rotational levels into levels that are symmetric and antisymmetric (denoted by + and −, respectively) with respect to the umbrella coordinate. The ground state inversion tunnelling splitting for n_A = 0 in ND₃ is 0.0530 cm⁻¹. The ground electronic state of methyl has a planar (D₃h) equilibrium geometry, and there is no inversion splitting in this radical.

Because the three D atoms, with nuclear spin I = 1, are equivalent, the ground vibronic states of CD₃ and ND₃ have three nuclear spin modifications. CD₃ rotational levels have the following nuclear spin symmetries: the A₁ nuclear spin functions are those with rotational levels with k = 0 and odd n and levels for which k is a multiple of 3; the A₂ nuclear spin functions correspond to rotational levels with even n and k = 0 and levels for which k is a multiple of 3; and the E nuclear spin functions include all levels for which k is not a multiple of 3. Thus, CD₃ rotational levels with k = 3, 6, . . . have two components, A₁ and A₂. Because of the inversion doubling, there are ND₃ levels of both A₁ and A₂ symmetry for each value of n in the k = 0 manifold. For this manifold, the + inversion levels for even and odd n have A₁ and A₂ symmetry, respectively, while the − inversion levels for odd and even n have A₁ and A₂ symmetry. There are both A₁ and A₂ levels for levels when k is a multiple of 3. As with CD₃, the ND₃ E nuclear spin functions include all levels for which k is not a multiple of 3. The CD₃ and ND₃ nuclear spin modifications do not interconvert during collisions.

B. Potential energy surfaces for CD₃–He and ND₃–He

The PESs employed in the scattering calculations were computed with coupled-cluster methods. Details of these quantum mechanical calculations can be found in the literature. A CH₃–He PES was computed with CH₃ fixed at its equilibrium geometry. Since the center-of-mass of methyl is located at the carbon atom, this PES could be used without modification for the CD₃ isotopologue. In subsequent work, we computed a PES for which the CD₃ geometry was...
averaged over the probability distribution for the \( v_2 \) umbrella coordinate.\(^{29} \) The interaction was expanded in terms of spherical harmonics as\(^{30} \)

\[
V(R, \theta, \phi) = \sum_{\lambda, \mu \geq 0} V_{\lambda\mu}(R)(1 + \delta_{\mu0})^{-1}[Y_{\lambda\mu}(\theta, \phi) + (-1)^\mu Y_{\lambda,-\mu}(\theta, \phi)]. \tag{1}
\]

The potential energy depends on the atom-molecule separation \( R \) and the orientation of the perturber, given by the angles \( \theta \) (polar angle from the \( C_3 \) symmetry axis) and \( \phi \) (azimuthal angle from a \( C-D \) bond) of the He atom with respect to the center-of-mass of the molecule [see Fig. 1 of Ref. 27].

The ND\(_3\)-He PES was obtained from the PES computed by Gubbels et al.\(^{28} \) for NH\(_3\)-He. This PES was computed as a function of four coordinates: \( R, \theta, \phi, \) and \( \rho \). Here, \( \rho \) is the umbrella or inversion angle, defined as the angle between the \( C_3 \) axis and a vector pointing from the N atom to one of the H atoms, so \( \rho = \pi/2 \) corresponds to a planar ND\(_3 \) geometry. Also, \( \theta = 0^\circ \) corresponds to approach of the He atom toward the lone pair on ammonia. The ND\(_3\) and NH\(_3\) isotopologues have the same electronic structure, and we assume also the same bond lengths; hence, the NH\(_3\)-He and ND\(_3\)-He interaction potentials are identical. However, the monomer center-of-mass shifts along the \( C_3 \) axis of the molecule, and the \( R \) and \( \theta \) Jacobi coordinates are shifted (the azimuthal angle \( \phi \) and the \( \rho \) inversion coordinate are unaffected by isotopic substitution). Hence, a new angular expansion of the PES was carried out for the ND\(_3\)-He system.\(^2 \) The ND\(_3\)-He PES was expanded slightly differently from the angular expansion for the CD\(_3\)-He PES. In particular, the former was expanded in terms of tesseral spherical harmonics \( S_{\lambda\mu}(\theta, \phi) \),\(^{28,31} \) and the origin of the azimuthal angle \( \phi \) was chosen to lie between two N–D bonds and so was 60° different from that for the CD\(_3\)-He PES. Therefore, the expansion coefficients for ND\(_3\)-He were rescaled for comparison with corresponding CD\(_3\)-He coefficients.

The ammonia inversion motion in the ND\(_3\)-He scattering calculations was included by the use of a two-state model\(^{11,28} \) In this model the \( v_2 = 0 \) inversion tunnelling levels of ammonia are approximated as an even and odd combination of the two rigid equilibrium structures. The \( \rho \) dependence of the intermolecular potential is not employed in this method, only the potential for the equilibrium umbrella angle \( \rho_\theta \).

Contour plots of the CD\(_3\)-He and ND\(_3\)-He PESs as a function of the angular coordinates \( \theta \) and \( \phi \) for two atom-molecule separations \( R \) are presented in Fig. 2. At the smaller values of \( R \) the interaction energies span the collision energies of the molecular beam experiments,\(^1,2 \) while the larger \( R \) values are close to those of the respective global minima. At the global minimum of the PESs the He atom is located at \( \theta = 90^\circ \) (in the molecular plane in case of CD\(_3 \)) and bisecting the \( D-C/N-D \) angle. The atom-molecule separations at the global minima are 6.52 and 6.095 bohr, and the dissociation energies are 27 and 35 cm\(^{-1} \) for the CD\(_3\)-He and ND\(_3\)-He PES, respectively.\(^{27,28} \) The \( \phi \) angle for the ND\(_3\)-He PES has been shifted by 60° from that defined by Gubbels et al.\(^{28} \) so that the coordinate systems defining the two PESs are the same; the angular coordinates for both PESs are defined as those described below Eq. (1).

We see for both PESs that there is a strong 3-fold corrugation with respect to the azimuthal angle \( \phi \) (vertical direction in Fig. 2), corresponding to approach of the atom in a direction perpendicular to the \( C_3 \) axis, due to repulsion of the He atom by the D atoms. Since CD\(_3 \) is planar, the atom experiences the same interaction for both from above and below the molecular plane (\( \theta < 90^\circ \) and \( \theta > 90^\circ \), respectively). We see from Figs. 2(c) and 2(d) that approach of the atom toward the ND\(_3 \) lone pair (\( \theta = 0^\circ \)) is more repulsive than approach on the side containing the D atoms (\( \theta = 180^\circ \)). While the equilibrium geometry of ND\(_3 \) is nonplanar and hence the potential for approach of the atom from above and below the molecule is different, both the \( \pm \) inversion vibrational wave functions have equal probability for the D atoms to be pointing up and down. We discuss below the parts of the ND\(_3\)-He PES responsible for collisions that conserve and change the \( \pm \) inversion level.

The angular expansion of the PES given in Eq. (1) simplifies the calculation of matrix elements of the interaction potential between channel basis functions. We expect that the transitions with the largest cross sections will be those for which there is direct coupling through the larger angular expansion coefficients \( V_{\lambda\mu} \). Since CD\(_3 \) is planar and has a \( C_3 \) rotational symmetry axis, the only nonzero \( V_{\lambda\mu} \) terms are those for which \( \lambda + \mu \) is even and \( \mu \) is a multiple of 3. In the two-state model describing the ND\(_3 \) inversion motion, the even \( \lambda + \mu \) terms enable inelastic transitions conserving the \( \pm \) inversion quantum number, while odd \( \lambda + \mu \) terms control inversion-changing transitions.\(^{11} \) As with CD\(_3\)-He, the nonzero \( V_{\lambda\mu} \) terms for ND\(_3\)-He must have \( \mu \) a multiple of 3.

Since we are comparing inelastic scattering dynamics of noninverting CD\(_3 \) and inverting ND\(_3 \), we will concentrate below on collision-induced transitions in ND\(_3 \) that...
conserves the ± inversion inversion quantum number. Figure 3 compares
the larger angular expansion coefficients \( V_{\lambda\mu}(R) \) for CD\(_3\)-He and
ND\(_3\)-He for which \( \lambda + \mu \) is even. The isotropic \( V_{00} \) term
is comparable in magnitude for both systems. We also see
that the largest anisotropic terms for both systems are \( V_{33} \) and
then \( V_{20} \), and that these are comparable in magnitude or larger
than the isotropic term for values of \( R \) smaller than that of the
global minima. The sign of the \( V_{20} \) term is different for the
two systems for \( R \) between 4.6 and 6.4 bohr; this is discussed
below.

As we discussed in the Introduction, there are two types
of anisotropies in the PES for the interaction of an atom with
a nonlinear polyatomic molecule. To visualize the anisotropy
upon approach of the atom around the molecular \( C_3 \) symmetry axis, we plot in Figs. 4(a) and 4(c), respectively the depen-
dence of the interaction energy upon the azimuthal angle \( \phi \) for
\( \theta = 90^\circ \) of the CD\(_3\)-He PES and the part of the ND\(_3\)-He PES
that governs ± inversion conserving transitions (even \( \lambda + \mu \)
terms) for several values of \( R \). We see that the corrugation for
small \( R \) is greater for CD\(_3\)-He than for ND\(_3\)-He, consistent
with the larger equilibrium atom-molecule separation for the
former. For both systems, the maximum repulsion occurs at \( \phi = 0^\circ, 120^\circ, \) and \( 240^\circ \) for \( \theta = 90^\circ \). This \( \phi \) dependence arises largely
from the \( V_{33} \) term. From Eq. (1), the term multiplying
\( V_{33} \) is proportional to \( -\sin^3 \theta \cos 3\phi \). The product of this term and a negative \( V_{33} \) has maxima at the same values of \( \phi \).

To visualize the dependence of the interaction energy for
approach of the atom along vs. perpendicular to the symmetry
axis, we plot in Figs. 4(b) and 4(d) the dependence of the
CD\(_3\)-He PES and the even \( \lambda + \mu \) part of the ND\(_3\)-He PES
upon \( \theta \) for several values of \( R \) and the azimuthal angle \( \phi \). For
both systems the repulsion depends strongly upon \( \phi \) at small
\( R \); for the smallest value of \( R \) in both plots the interaction energy
is plotted for \( \phi = 0^\circ-60^\circ \) (which correspond to approach of
He along a C/N–D bond and between two bonds, respectively)
in \( 10^\circ \) increments. For the smallest value of \( R \) the repul-
sion in the CD\(_3\)-He system is seen to be greater at \( \theta = 90^\circ \)
than at \( \theta = 0^\circ/180^\circ \) for most values of \( \phi \), while the opposite
is true for ND\(_3\)-He.

For both systems, the \( \theta \) dependence is well described
by the \( V_{20} \) term (with positive and negative values for
CD\(_3\)-He and ND\(_3\)-He, respectively). The angular dependence
of this term is \((3\cos^2 \theta - 1)/2\) from Eq. (1). The difference
in sign arises because the repulsion due to the doubly filled
nitrogen lone pair on ND\(_3\) is greater than that due to the
singly occupied out-of-plane \( 2p \) orbital on CD\(_3\). We see from
Fig. 4 that for both systems the anisotropy for approach of
the atom around the symmetry axis (e.g., through the \( V_{33} \) term)
is greater than the anisotropy for approach of the atom along
or perpendicular to the symmetry axis (e.g., through the \( V_{20} \)
term).

The \( V_{\lambda\mu} \) terms with \( \mu \neq 0 \) for both CD\(_3\)-He and
ND\(_3\)-He directly couple rotational levels differing by a multi-
ple of 3 in the body-frame projection quantum number. Hence,
the \( V_{33} \) term couples levels with \( k \) differing by \( \pm 3 \).

Since rotational wave functions of definite symmetry have ±
signed-\( k \) components [see Eq. (12) of Ref. 30 or Eq. (4) of
Ref. 27], the signed \( k = \pm 1 \) components of \( k = 1 \) levels of \( E \)
the nuclear symmetry are directly coupled to the signed \( k = \mp 2 \)
components of \( k = 2 \) levels by the \( V_{33} \) term. We also note that a
\( V_{\lambda\mu} \) term can directly couple rotational levels for which
the change \( \Delta n \) of the rotational angular momentum is less than
or equal to \( \lambda \). The \( \mu = 0 \) terms (e.g., the \( V_{20} \) term) enable \( \Delta n \)
transitions within a given \( k \) manifold.

C. Quantum scattering calculations

The HIBRIDON suite of programs \(^{32}\) and a separate scat-
tering code written in Nijmegen were used to carry out quan-
tum close-coupled scattering calculations to compute state-
resolved integral and differential cross sections for collisions
of CD\(_3\) and ND\(_3\) with He, respectively. Rotational energies
were computed with a rigid rotor symmetric top Hamilton-
ian using spectroscopic parameters from Sears et al. \(^{33}\) for
CD\(_3\). The methyl radical is an open-shell species, with doublet
spin multiplicity, so that each rotational level, with rotational
angular momentum $n$, is split into spin doublets, with total angular momentum $j = n \pm 1/2$. We have ignored spin in our scattering calculations since the spin-rotation and hyperfine splittings are small and not resolved in our REMPI spectra. In the two-state model for ND₃, rotational energies were computed with a rigid rotor symmetric top Hamiltonian using experimental values for the rotational constants and the inversion splitting. Separate calculations were carried out for each of the three nuclear spin modifications of CD₃ and ND₃ since they are not interconverted in collisions with closed-shell species without nuclear spin.

Convergence of the differential cross sections was checked with respect to the size of the rotational basis and the number of partial waves in the calculation. Rotational levels whose energies were less than 1100 cm⁻¹ were included in the channel basis for the CD₃–He system, and the calculations included total angular momenta $J \leq 130 \hbar$. For ND₃, all rotational levels up to $n = 10$ (560 cm⁻¹) were included in the channel basis and all partial wave contributions up to $J = 100 \hbar$ were taken into account.

III. RESULTS AND DISCUSSION

A. Integral cross sections

The effect of the two types of anisotropy in the CD₃–He PES can be clearly seen in the state-to-state integral cross sections (ICSs) out of the lowest CD₃ rotational levels of each nuclear spin symmetry at a collision energy of 440 cm⁻¹, corresponding to the collision energy in the molecular beam experiment. Figure 5 presents computed integral cross sections for transitions out of the 0₀ (A₂ nuclear spin symmetry), 1₀ (A₁ symmetry), and 1₁ (E symmetry) levels. For the 0₀ and 1₀ initial levels, the largest cross section is found for the transition to the 3₄ final level. These initial and final levels are coupled by the large $V_{33}$ term. In addition, the transitions to the 6₀ final level also have substantial cross sections; these are enabled either by direct coupling of the $V_{16}$ term, or second-order transitions involving the $V_{33}$ term. We see that the cross sections for transitions within the $k = 0$ manifold, which are enabled by the $V_{20}$ and other $\mu = 0$ terms, are significantly smaller. This is consistent with the smaller magnitude of the $V_{20}$ term as compared with the $V_{33}$ term (see Fig. 3).

For the CD₃ 1₁ initial level, the largest cross sections involve transitions to the 2₂ and 4₄ levels. Both of these final levels are directly coupled to the initial level by the $V_{33}$ term, as discussed at the end of Sec. II B. Other reasonably strong $k \neq 0$ transitions access the 5₅ and 7₇ final levels. These levels can be directly coupled to the initial level through the $V_{66}$ term, or second-order transitions involving the $V_{33}$ term. Propensities in state-to-state integral cross sections for collisions of higher CH₃ rotational levels of E symmetry with helium are discussed in Ref. 27.

The lowest-energy ND₃ rotational levels of A₁, A₂, and E nuclear spin symmetry are the 0₀⁺, 0₀⁻, and 1₁⁺ levels, respectively. The cross sections for transitions out of the 0₀⁺ and 0₀⁻ levels conserving the ± inversion level are virtually identical, and likewise for transitions changing the inversion level, since the coupling matrix elements are the same but the energies of inversion levels are slightly different. We hence present in Fig. 6 state-to-state integral cross sections for inversion conserving transitions out of the ND₃ rotational 0₀⁺ and 1₁⁺ levels at a collision energy of 430 cm⁻¹, corresponding to the collision energy in the molecular beam experiment. We note in passing that the sum of the ICSs for the inversion changing transitions is ∼28% of the sum of ICSs for the inversion conserving transitions for these initial levels. For both initial levels, the largest cross sections plotted in Fig. 6 are for $\Delta k = +3$ transitions, namely, the 0₀⁺ → 3₅⁺ and 1₁⁺ → 4₄⁺ transitions, connected mainly through the $V_{33}$ term. In con-
Contrast to the CD$_3$–He system, the largest cross sections for $\Delta k = 0$ transitions are comparable in magnitude to those for the CD$_3$–He system, because the CD$_3$ REMPI lines are not resolved in the $k$ projection quantum number. The only measured $k$-resolved line for CD$_3$ corresponds to detection of the 2$_1$ final level. The experimental DCSs for inelastic scattering of CD$_3$ into $n'_k = 2_1$ and ND$_3$ into 2$_1^-$ and 2$_1^+$ levels from the 1$_1$ and 1$_1^-$ levels, respectively, in collision with He are compared in Fig. 8. The DCS for CD$_3$ is normalized to match the value at $\theta = 30^\circ$ with that for ND$_3$ (2$_1^-$), whereas the DCS for ND$_3$ (2$_1^-$) is normalized to match the DCS for ND$_3$ (2$_1^+$) at $\theta = 150^\circ$. In the experiments, the ND$_3$ was prepared in a single initial state 1$_1^-$, whereas the CD$_3$ initially populated several levels, the most significant of which is 1$_1$. The DCS for CD$_3$ scattering agrees well with that for ND$_3$ (2$_1^-$), whereas the inversion-symmetry changing DCS for ND$_3$ (2$_1^+$) differs from both.

Figure 9 shows a comparison of calculated DCSs for the ND$_3$–He and CD$_3$–He systems for the $E$ nuclear spin modification for transitions to several final levels (see Fig. 1). The DCSs for CD$_3$–He were calculated for the $n_k = 1_1$ initial level, whereas the DCSs for ND$_3$–He are plotted for both 1$_1^-$ and 1$_1^+$ initial levels and $n'_k$ final levels. We note that for the ND$_3$–He system the $n_k^-$ to $n_k^-$ and $n_k^+$ to $n_k^+$ transitions have essentially identical DCSs, and therefore we show only DCSs for $-\Delta k$ transitions. The DCSs were calculated at a collision energy of 440 cm$^{-1}$ for CD$_3$–He and 430 cm$^{-1}$ for ND$_3$–He, which correspond to the experimental collision energies. The small difference in collision energies will have a negligible effect on the DCSs, as shown in the supplementary material.
FIG. 8. Comparison of the experimental DCSs for inelastic scattering of CD$_3$ into the $n_k' = 2_1$ level and ND$_3$ into the $2_{1,3}$ levels from the $1_1$ and $1_{1'}$ initial levels, respectively, in collisions with He. The methods of normalization of the data are described in the main text.

of the recent ND$_3$–He paper. In this section, we show only a representative sample of DCSs for both systems. Further comparisons of computed DCSs for transitions out of the lowest rotational levels of each nuclear spin modification can be found in the supplementary material.

The DCSs for scattering into these final levels for CD$_3$–He resemble the DCSs for ND$_3$–He that conserve the $\pm$ inversion symmetry in the collision, whereas the scattering dynamics for $\pm$ symmetry changing collisions differ. The $\pm$ symmetry conserving transitions in ND$_3$ are enabled by the same expansion coefficients $V_{\lambda\mu}$ as in CD$_3$ scattering dynamics (with $\lambda + \mu$ even, in contrast to $\pm$ symmetry changing transitions where $\lambda + \mu$ is odd). This differing behaviour for $\pm$ symmetry conserving vs. changing transitions is especially evident for the $3_2$ and $4_1$ final levels of ND$_3$ [see Figs. 9(c) and 9(e)]. The magnitudes (and hence integral cross sections) for $\pm$ symmetry changing collisions are much lower, and these DCSs were therefore multiplied by a constant scaling factor to be visible in Fig. 9.

Although there are many similarities between the DCSs for ND$_3$–He and CD$_3$–He scattering, observed differences can be linked to $V_{\lambda\mu}$ terms which directly couple given transitions. The transitions directly coupled by terms other than the large $V_{20}$ and $V_{33}$ terms could be enabled by higher-order transitions involving these large terms. For example, transitions directly coupled by the $V_{60}$ or $V_{53}$ terms can also be enabled by transitions involving the $V_{33}$ term twice or a combination of $V_{33}$ and $V_{20}$ terms, respectively.

We see that the DCSs for scattering of CD$_3$ into the $2_{2,3}, 3_2$, and $4_4$ final levels and the corresponding ND$_3$ transitions conserving the inversion symmetry have a similar shape. These transitions, which are coupled directly by the $V_{33}$ term, all display broad DCSs, starting from zero intensity at $\theta = 0^\circ$ and extending over the entire angular range, with oscillations at small angles ($\theta \leq 45^\circ$). The DCS for CD$_3$ is always more forward scattered than the corresponding DCS for ND$_3$ for transitions dominated by the $V_{33}$ term in the potential. The similarity in DCSs for transitions directly coupled by the $V_{33}$ term for the two systems reflects the similarity of $V_{33}$ in both the radial dependence and magnitude [see Figs. 3, 4(a), and 4(c)]. The partial cross sections for CD$_3$–He and ND$_3$–He collisions involving the $1_1 \rightarrow 3_2$ transition conserving and changing the inversion symmetry are shown in Fig. 10. The scattering occurs over similar ranges of total angular momentum (classically over similar impact parameters) for CD$_3$ and ND$_3$ conserving inversion symmetry, whereas the scattering leading to a change of the inversion symmetry occurs on average at smaller impact parameters, and these collisions result in a backward peaking DCS.

By contrast, there are significant differences in the CD$_3$ and ND$_3$ (conserving inversion symmetry) DCSs for FIG. 9. Comparison of the theoretical DCSs for inelastic scattering of CD$_3$ ($1_1$ to $n_k'$ transitions) with He at a collision energy of 440 cm$^{-1}$ (black lines) and ND$_3$ with He ($1_1'$ to $n_k'$ or $1_{1'}$ to $n_k'$ transitions, which are identical) at a collision energy of 430 cm$^{-1}$ (red lines). The DCSs for ND$_3$ scattering with He for the $1_{1'}$ to $n_k'$ transition (blue lines) are also plotted, and have been vertically scaled as indicated for ease of comparison.

FIG. 10. Partial cross sections for CD$_3$–He and ND$_3$–He systems at a collision energy 440 cm$^{-1}$ for scattering from the $1_1$ and $1_{1'}$ initial levels into (a) $3_2$ and (b) $2_1$ final levels (with both inversion symmetries for ND$_3$).
transitions into the $2_1$ and $3_1$ levels plotted in Fig. 9, which are enabled by direct coupling through the $V_{20}$ term. The DCSs for the CD$_3$–He system exhibit a dip in the forward hemisphere around $\theta = 25^\circ$, whereas for ND$_3$–He the DCSs continuously rise and peak in the forward hemisphere. The partial cross sections for the $1_1 \rightarrow 2_1$ transition for CD$_3$–He and ND$_3$–He collisions conserving and changing the inversion symmetry are shown in Fig. 10(b). We see a dip in the CD$_3$–He partial cross sections around $\theta = 27 ($b = 5.8 bohr), while the ND$_3$–He partial cross section decreases monotonically with increasing $J$ from its maximum value.

The $\Delta \kappa = 0$ transitions, which are directly coupled by the expansion coefficients with $\mu = 0$ ($V_{10}$), are shown in panels (b), (d), and (f) of Fig. 9. These expansion coefficients with $\mu = 0$ describe the anisotropy in the $\theta$ coordinate. The differences in the DCSs for small $\Delta n$ transitions [in Figs. 9(b) and 9(d)] are a manifestation of the difference in the $V_{20}$ terms for the systems of interest [see Figs. 3, 4(b), and 4(d)]. On the other hand, the ND$_3$–He and CD$_3$–He DCSs for $\Delta k = 0$ transitions for large $\Delta n$ are very similar except for the absolute value, as can be seen in Fig. 9(f).

The DCSs for transitions directly coupled by the $V_{66}$ term are completely backward scattered for ND$_3$ with maxima at $\theta = 180^\circ$, whereas they exhibit maxima at intermediate scattering angles ($\theta = 110^\circ$–135$^\circ$) for CD$_3$. Examples of DCSs enabled by the $V_{66}$ term are shown for CD$_3$ and ND$_3$ in Fig. 11(a) for the $1_1$ to $5_2$ transition. The maxima of the DCSs for CD$_3$ shift to larger scattering angles as the amount of transferred energy associated with the transition increases.

The transitions directly coupled by the $V_{53}$ term exhibit completely backward scattered DCSs with maxima at $\theta = 180^\circ$ for CD$_3$, and DCSs dominated by sideways scattering for ND$_3$ with maxima typically at intermediate scattering angles. This behaviour is opposite to that seen for the transitions directly coupled by the $V_{66}$ term. Examples of DCSs for both systems directly coupled by the $V_{53}$ term are shown in Fig. 11(b) for the $1_0$ to $5_1$ transition. The maxima of the DCSs for ND$_3$ move to larger scattering angles as the internal energy change in a collision increases. Whereas the transitions in CD$_3$ directly coupled by the $V_{73}$ term are associated with backward scattering, the DCSs for ND$_3$ exhibit oscillatory behaviour as illustrated in Fig. 11(c) for the $0_0$ to $7_3$ transition. The $V_{73}$ term is very weak in comparison with other expansion coefficients and therefore not shown in Fig. 3. The transitions directly coupled by this term will be enabled mainly by a combination of larger expansion coefficients through multiple quantum transitions. These transitions for ND$_3$ are very weak and the example DCS had to be multiplied by 10 to be visible. For the transitions controlled by the $V_{53}$ and $V_{73}$ terms, and associated with the largest internal energy changes ($1_0 \rightarrow 6_3$ and $1_1 \rightarrow 6_3$), the scattering maxima shift to $\theta = 180^\circ$.

Some transitions (e.g., $0_0 \rightarrow 4_3$, $6_3$, $7_6$) are not directly coupled by any of the large expansion coefficients, and they are enabled only by a combination of the expansion coefficients through the higher-order transitions. By way of example, Fig. 11(d) shows DCSs for ND$_3$ and CD$_3$ for the $0_0 \rightarrow 6_1$ transition. The DCSs are similar for both systems and the ICSs are much smaller than for directly coupled transitions. Note that the DCSs are dominated by diffraction oscillations at small angles, even though the DCSs for transitions associated with approximately the same amount of energy transfer, but directly coupled by expansion coefficients of the potential, do not exhibit such oscillations. For the systems of interest, they are present only for transitions into final levels with $n^\prime \leq 4$.

The initial to final rotational level transitions can also be directly coupled by more than one of the expansion coefficients. For example, $1_1 \rightarrow 4_2$ are both directly coupled by the $V_{53}$ and $V_{73}$ terms. These DCSs are shown in Fig. 12 for CD$_3$ as well as for ND$_3$. The $1_1 \rightarrow 4_2$ transition has a broad peak characteristic of DCSs enabled solely by the $V_{53}$ term, whereas the DCSs for the $1_1 \rightarrow 4_2$ transition resemble those expected for transitions enabled solely by the $V_{53}$ term.

**IV. CONCLUSIONS**

We have presented a comparison of the scattering dynamics of two deuterated symmetric top molecules, one closed-shell (ND$_3$) and the other an open-shell radical (CD$_3$) in collisions with He. The scattering dynamics are compared on the basis of close-coupling quantum-mechanical scattering...
calculations that used ab initio PESs. These theoretical studies were carefully validated by comparison to experimental measurements of rotationally resolved differential cross sections, as described in two recent publications. The comparisons drawn here are between the inelastic scattering dynamics of non-inverting CD$_3$ and umbrella-motion inverting ND$_3$, and so concentrate on collision-induced transitions in ND$_3$ that conserve the ± inversion symmetry.

The transitions with the largest ICSs are those for which there is direct coupling through the larger angular expansion coefficients $V_{3\mu}$ of the PES. For the interaction of an atom with a nonlinear polyatomic molecule, two types of anisotropy influence the scattering dynamics. For both systems the anisotropy in the $\phi$ coordinate (described predominantly by the $V_{33}$ term in an expansion of the potential in angular functions) is greater than the anisotropy in the $\theta$ coordinate (described by the $V_{20}$ term). The isotropic $V_{00}$ term is comparable in magnitude for both systems. The largest anisotropic terms for both systems are $V_{33}$ and $V_{20}$, and these are comparable in magnitude or larger than the isotropic contribution to the potential for values of $R$ smaller than those of the global minima. However, the signs of the $V_{20}$ terms are different (at intermediate values of $R$) for the two scattering systems. The differences in integral and state-resolved differential cross sections for rotationally inelastic scattering of CD$_3$ and ND$_3$ with He reflect the differences in magnitude and effect of individual expansion coefficients of the potential. The effect of the two anisotropies is clearly seen in the state-to-state integral cross sections out of the lowest CD$_3$ rotational levels of each nuclear spin symmetry at a collision energy of 440 cm$^{-1}$: the ICSs coupled by the $V_{33}$ term are larger than ICSs enabled by the $V_{20}$ term. The $\Delta k = 0$ transitions are the only transitions that have systematically larger ICSs for the ND$_3$–He system conserving $\pm$ symmetry than for the CD$_3$–He system (with the exception of the 00 $\rightarrow$ 43 and 70 transitions, which are not directly coupled by any of the expansion coefficients). The larger ICSs for the ND$_3$–He system for transitions enabled by $V_{20}$ terms are caused by the stronger anisotropy in the $\theta$ coordinate.

There are many similarities between the DCSs for ND$_3$–He (conserving $\pm$ symmetry) and CD$_3$–He scattering, nevertheless observed differences can be linked to $V_{3\mu}$ terms which directly couple given transitions. The transitions directly coupled by the $V_{33}$ term display broad DCSs starting from zero intensity at $\theta = 0^\circ$ and extending over the entire angular range for both systems. In this case, the DCS for CD$_3$ is always more forward scattered than the corresponding DCS for ND$_3$. The similarity in DCSs for transitions directly coupled by the $V_{20}$ term for the two systems reflects the similarity of $V_{33}$ in both the radial dependence and magnitude. In addition the scattering occurs over similar ranges of total angular momentum (classically over similar impact parameters) for CD$_3$ and ND$_3$ (conserving inversion symmetry). The $\Delta k = 0$ transitions directly coupled by the $V_{20}$ expansion coefficients exhibit differences in the DCSs for small $\Delta n$ transitions, which reflects the difference in the $V_{20}$ terms for the systems. On the other hand, the DCSs for large $\Delta n$ transitions are very similar. These expansion coefficients with $\mu = 0$ describe the anisotropy in the $\theta$ coordinate.

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32. HI1RIDON is a package of programs for the time-independent quantum treatment of inelastic collisions and photodissociation written by
M. H. Alexander, D. E. Manolopoulos, H.-J. Werner, B. Follmeg, P. J. Dagdigian, Q. Ma, and others. More information and/or a copy of the code can be obtained from the website http://www2.chem.umd.edu/groups/physical/hibridon/hib43.


38 See supplementary material at http://dx.doi.org/10.1063/1.4869596 for computed DCSs of transitions out of the lowest rotational levels of each nuclear spin modification.