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Formation of Na containing complex molecules in the gas phase in dense molecular clouds: Quantum study of the Na$^+\text{H}_2$ and Na$^+\text{D}_2$ radiative association step

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ABSTRACT

The Na$^+\text{H}_2$ radiative association (RA) is the first and limiting step in the models of formation of NaH in the gas phase. Also the accurate evaluation of the RA rate is required to be included in chemical models of dense molecular clouds. In this work a quantum study of the formation of the Na$^+\text{H}_2$ and Na$^+\text{D}_2$ complexes by radiative association is presented. We use a 3D potential energy surface published recently and a quantum dynamical method based on the driven equation formalism. The values obtained for the radiative association rates are compared with previous evaluations based on approximate methods and the possible role played by these two processes in the gas phase chemistry of dense molecular clouds is discussed.


1 INTRODUCTION

Metals were for a long time considered not to play an important role in the gas-phase chemical processes of interstellar clouds. This assumption was motivated by the common belief that the metals mostly accumulated on dust-grain surfaces (Petrie & Dunbar 2000). Also, metals were only thought to participate in two types of processes: radiative recombination with free electrons and charge transfer reactions with neutrals. While the former is slow, the latter is improbable as the ionization energies of neutrals are often too high to allow charge transfer. The last motivation for neglecting metals in interstellar cloud reactions was that early studies involving Na$^+$ and Mg$^+$ reacting with some neutrals gave very low reaction rates.

Now the assumption that metals are unimportant in gas phase chemistry is for debate, mostly because several molecules containing metals like NaCl, AlF or KCl were observed in the envelope of IRC+1026 (Petrie & Dunbar 2000). NaH was also searched for by Plambeck & Erickson (1982) but unsuccessfully up to now. The authors of this later study conclude that the observed upper limit of the fractional abundance of NaH in Orion is at least two orders of magnitude smaller than what would be predicted if NaH were formed efficiently on grains. It is furthermore consistent with the upper limit expected from ion-molecule chemistry when using the estimation of Na$^+\text{H}_2$ RA by Smith et al. (1983) which was available at that time. In any case, the occurrence of association reactions of the abundant metal ions with interstellar molecules may have important implications for cloud chemical evolution, even if these reactions do not lead to significant abundances of any metal-containing molecules.

The gas phase mechanism of formation of such molecules within the Smith et al. (1983) model involves two steps: first the radiative association of the cationic form of the metal M$^+$ with H$_2$:

\[ M^+ + H_2 \rightarrow M^+ - H_2 + h\nu \]

followed by the following channel of the dissociative recombination process with electron:

\[ M^+ - H_2 + e^- \rightarrow MH + H^+ \]

This mode of depletion of M$^+$ is in competition with the radiative recombination with an electron. In the case of Na$^+$ the rate coefficient of this process at 20 K was estimated by Prasad & Huntress (1980) to be $k_{RR}^{H_2} = 1.7 \times 10^{-11} \text{cm}^3\text{s}^{-1}$.

Knowing the fractional abundance $f_e$ of electrons relative to H$_2$ one can deduce the minimum value of the RA rate coefficient $k_{RA}$ with H$_2$ which would make this process important for the chemistry of the cloud:

\[ k_{RA}^{H_2} \gg k_{RR}^{H_2} \times f_e \]

Two evaluations of the Na$^+\text{H}_2$ RA rate coefficients were obtained using approximate methods. Herbst and
coworkers obtained the first evaluation of the RA rate coefficient in 1983 (Smith et al. 1983). They found a rate coefficient almost independent of temperature and equal to 4.0 \times 10^{-19}\text{cm}^3\text{molecule}^{-1}\text{s}^{-1}. This would lead to a fractional abundance of electron relative to H_2 lower than 2.6 \times 10^{-8} which is close to its usual estimate in dense molecular clouds. These authors then concluded that the Na^+ – H_2 RA process could play a role in the chemistry of dense molecular clouds and needed to be included in the chemical models of dense molecular clouds. More recently, Petrie & Dunbar (2000) performed calculations based on transition state theory and obtained a rate varying with temperature. The value at 30 K is 8.7 \times 10^{-23}\text{cm}^3\text{molecule}^{-1}\text{s}^{-1} which is four orders of magnitude smaller than the evaluation by Herbst and coworkers. These later results would exclude the Na^+ – H_2 RA process from the chemistry of dense molecular clouds.

This difference motivates the need for a more accurate study based on the close coupling approach in order to illustrate the role of this process in the chemistry of intermolecular clouds. We present a quantum study of the formation of the Na^+ – H_2 and Na^+ – D_2 complexes by radiative association (RA).

Recent investigations of the Na^+ – H_2 and Na^+ – D_2 complexes were performed by Poad et al. (2008, 2011). They performed experimental measurements and \textit{ab initio} calculations of the rotationally resolved rovibrational spectrum of these two complexes. In their studies very good agreement between theory and experiment was obtained, which demonstrated the high accuracy of their potential energy surface (PES). In the present work we use the 3D PES and dipole moment surfaces calculated by those authors to study the radiative association to form these two complexes. Close Coupling (CC) radiative association calculations are routinely performed for diatomics like CH, CH^+, NH, NO, CN, CO, C_2, OH (Julienne & Krauss 1973; Nyman et al. 2015), while available calculations for triatomic systems are limited to the five systems: H_2^+ + He (Mrugala et al. 2003), H^+ + H_2 (Ayouz et al. 2011), H^+ + N_2 (Stoecklin et al. 2013) and very recently H + CO (Stoecklin et al. 2018b) and H^+ + CO (Stoecklin et al. 2018a). The methods developed in the last three of the above mentioned studies are used in the present work as well.

The manuscript is organized as follows: In section II we briefly describe the main features of both the PES and the dipole moment surface calculated by Poad et al. (2008, 2011) and we summarize the main steps of the method used to calculate the RA rate coefficient. In section III we present and discuss the results. The possible importance of the RA process for these two systems in the chemistry of molecular clouds is discussed in section IV.

2 METHODS

Throughout this article the same Jacobi coordinates are used to describe the initial scattering state and the final bound state. These coordinates are illustrated in figure 1, where r is the distance between the atoms in the diatomic molecule (H_2 or D_2), R is the distance between the center of mass of the diatomic molecule and the sodium atom and \theta is the angle between R and r.

2.1 Potential energy surface and dipole moment

We use the 3D potential energy surface and dipole moment surface calculated by Poad et al. (2008, 2011). In summary, both are based on a large grid of 1850 spin-restricted coupled cluster calculations (RCCSDT) using a cc-pVQZ and an aug-cc-pVQZ basis set for the sodium and the hydrogen atoms respectively. The three lowest vibrational levels of H_2 are accurately described on this grid where the vibrational coordinate \textit{r} ranges from 1 to 3 Bohr in steps of 0.2 Bohr. The intermolecular coordinate \textit{R} varies from 3 up to 40 Bohr in order for the long range potential to be well represented. Poad et al. (2008) obtained an analytical representation of the 3D PES by using the Reproducing Kernel Hilbert Space method (RKHS) by Hollebeek et al. (1999). Outside the upper limit of the \textit{ab initio} grid the analytical RKHS long range potential varies as 1/R^4, as expected for a charge induced dipole potential. The minimum geometry of the complex is \textit{T} shaped and its energy is 1184 cm\(^{-1}\) below the zero point level of the reactants. The rovibrational calculations performed by Poad et al. (2008) predict that the ground state of the Na^+ – pH_2 (para hydrogen) complex lies \(D_0 = 842\text{ cm}^{-1}\) below the Na^+ – H_2 (j = 0) limit and that the ground state of the Na^+ – oH_2 (ortho hydrogen) complex lies 888 cm\(^{-1}\) below the Na^+ – H_2 (j = 1) limit. The corresponding calculated binding energies of Poad et al. (2011) for the Na^+ – D_2 complex are found to be 923 cm\(^{-1}\) and 949 cm\(^{-1}\) respectively for the ortho and para species. Due to its slightly lower vibrational zero point energy, Na^+ – oD_2 is then bound 81 cm\(^{-1}\) more strongly than Na^+ – pH_2.

From the above it is possible to conclude that the intermolecular potential is not strong enough to vibrationally excite H_2 or D_2. The equilibrium \textit{r} distance in the complex is furthermore very close to its free diatomic value, supporting the assumption that vibrational coupling is not very strong and suggesting that the rigid rotor approximation could be considered for performing both the Bound states and the dynamics calculations. We choose an intermediate solution by including in both types of calculations only the lowest vibrational state of the diatom and integrating over the vibrational coordinate. The associated 3D dipole moment function calculated by Poad et al. (2008, 2011) is a linear combination of Legendre polynomials and of powers of the intermolecular and vibrational coordinates. They found that accordingly to the model we used for the N_2H^+ and HCO^− systems, the intermolecular component of the dipole moment varies like \textit{R} and that the other components are negligible.
2.2 Bound states and Dynamics

The dynamics calculation are performed using the method that we developed in previous work dedicated to the N$_2$+H$^-$ radiative association (Stoecklin et al. 2013). A brief account of this procedure is given below. The interested reader may find more details in our original work (Stoecklin et al. 2013).

The method that we used is based on the driven equation formalism and is an adaptation of the method developed for photo-dissociation by Band et al. (1981), Balint-Kurti & Shapiro (1981) and Heather & Light (1983). The driven equation method connects the initial and the final wave functions of the colliding system through the matter-radiation interaction operator. We use the same Jacobi coordinates $(R,r,\theta)$ (see figure 1) and coupled angular basis sets for the expansion of the initial and final molecular wave functions in the space fixed frame:

$$Y^{JM}_{jl}(\hat{R},\hat{r}) = \sum_{m_jm_l} (jmjm_l|JM)\psi_l^{m_l}(\hat{r})\psi_j^{m_j}(\hat{R})$$

where $j$, $l$ and $J$ are respectively the quantum numbers associated with the rotational angular momentum of the diatom $j$, the orbital angular momentum $l$ and the total angular momentum $J = j + l$. In this basis set the initial $\Psi_i(R,r,\theta)$ and final $\Psi_f(R,r,\theta)$ wave functions of the system are respectively written like:

$$\Psi^{JM}_{jl}(R,r,\theta) = \frac{1}{R_l} \sum_{v,j,l} k^{JM}_{v,j,l}(R)\phi_{v,j}(r)Y^{JM}_{jl}(\hat{R},\hat{r})$$

(2)

$$\Psi^{J'M'}_{j'f'}(R,r,\theta) = \frac{1}{R_{j'f'}} \sum_{v',j',l'} \omega^{J'M'}_{v',j',l'}(R)\phi_{v',j'}(r)Y^{J'M'}_{j'f'}(\hat{R},\hat{r})$$

(3)

In this expression $a$ denotes bound states, $k^{JM}_{v,j,l}(R)$ and $\omega^{J'M'}_{v',j',l'}(R)$ are the radial parts in $R$ of the initial and final wave functions, while $\phi_{v,j}(r)$ and $\phi_{v',j'}(r)$ are the corresponding radial parts in $r$. We furthermore use the hydrogen exchange symmetry of the system and make separate calculations for the two spin isomers of H$_2$ and D$_2$.

2.2.1 Bound state calculations

In our previous work dedicated to N$_2$H$^-$ (Lique et al. 2012; Stoecklin et al. 2013) we used an adaptation of the CC method proposed by (Hutson 1994), which is also detailed in a previous study dedicated to Ar – NO$^+$ (Halvick et al. 2011). In this study we use the same variational approach (Ajili et al. 2016) as in our work dedicated to HCO$^-$ (Stoecklin et al. 2018a).

The computations are performed by using the analytical expansion (1) for the angular basis set. A Chebyshev DVR grid of 400 points in the range [3.0,80.0] $a_0$ is used to describe the $R$ radial part of the wave function and 18 Gauss-Hermite points in the range [0.725,2.09] $a_0$ are used for the vibrational coordinate $r$, along with 10 rotational basis functions for each spin isomer of H$_2$ and D$_2$.

2.2.2 Dynamics

The radial part of the total wave function describing the system before and after radiative association is a solution of the following equation:

$$\frac{d^2}{dR^2} - \frac{1}{R}(l+1)\frac{d}{dR} + k_{v, jl}^2(E) - U_{v, jl}^{v', j', l'}(R)\psi_{v, jl}(R) = \lambda_{v, jl}^{v', j', l'}(R)$$

(4)

where $k_{v,jl}$ are channel wave vectors and $U_{v, jl}^{v', j', l'}$ are the matrix elements of the intermolecular potential. The term appearing on the right hand side of the close coupled equations, $\lambda_{v,j,l,M}^{J',M'}(R)$, is called the driving term. It is real and results from the dipolar coupling of the initial scattering and final bound states within the dipolar approximation.

$$\lambda_{v,j,l,M}^{J',M'}(R) = -2\mu_{Na}^{-1}H_1 \int d\hat{R}d\hat{r}d\phi_{v,j}(r)\psi_{v,j}(R)Y^{JM}_{jl}(\hat{R},\hat{r})^* \times \mu(\hat{R},\hat{r})\psi_{v',j',l',l}(R)$$

(5)

For a charged atom interacting with a neutral diatom, the dipole moment of the system can safely be assumed to lie along the intermolecular axis $(R-direction)$. This is indeed confirmed by the ab initio dipole moment calculated by Poad et al. (2008, 2011). If we further neglect the diatomic vibrational dependence of the dipole and take it to be proportional to $R$, then equation 5 can be simplified to:

$$\lambda_{v,j,l,M}^{J',M'}(R) = -\frac{2\mu_{Na}^{-1}H_1}{m_{Na}^{-1}} \delta_{v,v'}\delta_{j,j'}\sum_{l,l'} \psi_{v,j,l}(R)R\omega_{v,j,l'}^{v',j',l'}(R)$$

(6)

In this expression $a$ denotes bound states, $k^{JM}_{v,j,l}(R)$ and $\omega^{J'M'}_{v',j',l'}(R)$ are the radial parts in $R$ of the initial and final wave functions, while $\phi_{v,j}(r)$ and $\phi_{v',j'}(r)$ are the corresponding radial parts in $r$. We furthermore use the hydrogen exchange symmetry of the system and make separate calculations for the two spin isomers of H$_2$ and D$_2$.

$$\sigma_{v,j}(E) = \frac{8\pi^2\omega_r^3}{3k_v c^3} \sum_{J',l',a} \left[M^{a,J',J}_{v,j,l}(E)\right]^2$$

(7)

where a summation is performed over all the possible values of the initial and final total angular momenta and over the possible bound states. $\omega_r$ is the frequency of the corresponding emitted photon and $M^{a,J',J}_{v,j,l}(E)$ are state selected driving terms integrated over $R$ as detailed in our previous work (Stoecklin et al. 2013).

3 RESULTS

A 3D contour plot in Jacobi coordinates of the PES developed by Poad et al. (2008) is presented in figure 3 where the
diatomic bond length \( r \) is fixed at 1.41 Bohr. The strong long range potential as well as the T shaped equilibrium geometry of the complex (for \( R=4.7 \) Bohr) appear both clearly on this figure.

As usual for complexes including homonuclear molecules, the two nuclear spin isomers of \( \text{H}_2 \) and \( \text{D}_2 \) were treated separately. We took into account the states with positive energy that are located above the \( j=0 \) state of \( \text{H}_2 \) or \( \text{D}_2 \) but are bound because they have no open channels for rotational predissociation. These are all the states with odd parity which are below the \( j=1 \) threshold as well as the states with even \( j \) parity below the \( j=2 \) threshold. This results in the need to include 457 para and 432 ortho bound states in the calculations of the RA of the \( \text{Na}^+\text{H}_2 \) complex. For the \( \text{Na}^+\text{D}_2 \) complex even more bound states need to be included - 1161 para and 1214 ortho states.

The rotational basis sets used for the initial and final states of the systems are each made up of ten rotational states with \( j \) ranging from 0 to 18 for para \( \text{H}_2 \) and ortho \( \text{D}_2 \) while \( j \) is taken to vary from 1 to 19 for ortho \( \text{H}_2 \) and para \( \text{D}_2 \). With these basis sets the highest values of the total angular momentum \( J \) giving bound states are 26 for \( \text{Na}^+\text{pH}_2 \) and 25 for \( \text{Na}^+\text{oH}_2 \) and 36 for both \( \text{Na}^+\text{pD}_2 \) and \( \text{Na}^+\text{oD}_2 \). These results are illustrated in figure 2 where the number of bound states of the \( \text{Na}^+\text{H}_2 \) and \( \text{Na}^+\text{D}_2 \) complexes as a function of the total angular momentum \( J \) are compared. As expected for such ionic systems, the density of bound states increases near the dissociation threshold of the complex (Munro et al. 2005) as a result of the strength of the long range part of the interaction potential. Also, one could be tempted to expect these states to give an important contribution to the RA cross section and to give a special attention to their accurate determination. However, the driving term components associated with these states can be large only at very low collision energy. This means that the corresponding frequency \( \omega_d \) of the emitted photon is also very small and is the associated RA cross section component which is proportional to \( \omega_d^2 \). This discussion is illustrated in figure 4 where is presented the variation of the driving terms associated with two different bound states as a function of the intermolecular coordinate for \( J=0 \) and a collision energy of 1 cm\(^{-1}\).

It can be seen that the driving term gives a very intuitive picture of the RA process. Clearly, the lower bound states which are localized in a narrower intermolecular distance interval give a localized driving term while the most excited bound states extend over a large intermolecular range and give rise to an extended domain of the driving term. As the cross section is directly proportional to the driving terms associated with two different bound states as illustrated in figure 3, it is clear that both \( \text{Na}^+\text{H}_2 \) and \( \text{Na}^+\text{D}_2 \) exhibit the same behavior when it comes to the difference in magnitude of cross sections corresponding to different values of \( j \) with also the \( j=2 \) cross section lying higher than the \( j=0 \) and \( j=4 \) cross sections.

The variation of the \( \text{Na}^+\text{H}_2 \) RA cross sections as a function of collision energy are shown for the para and ortho species of \( \text{H}_2 \) for various initial rotational states of the diatomic fragment respectively in the lower and upper panels of figure 5. It can be seen in this figure that the RA cross section of ortho \( \text{H}_2 \) with \( \text{Na}^+ \) decrease when the rotational excitation of \( \text{H}_2 \) increases while for para \( \text{H}_2 \) the \( j=2 \) gives larger RA cross sections than \( j=0 \) and \( j=4 \).

The dependence of the \( \text{Na}^+\text{D}_2 \) cross sections on the collision energy is depicted in figure 6. Comparing these results with the ones shown in figure 5, it can be observed that both \( \text{Na}^+\text{H}_2 \) and \( \text{Na}^+\text{D}_2 \) exhibit the same behavior when it comes to the difference in magnitude of cross sections corresponding to different values of \( j \) with also the \( j=2 \) cross section lying higher than the \( j=0 \) and \( j=4 \) cross sections.

Figure 2. Comparison between the number of bound states of the \( \text{Na}^+\text{H}_2 \) and \( \text{Na}^+\text{D}_2 \) complexes as a function of the total angular momentum of the system.

Figure 3. Potential energy surface for \( \text{Na}^+\text{H}_2 \) obtained by Poad et al.
cross sections. Mostly the Na\(^+\) D\(_2\) cross sections are larger than the Na\(^+\) H\(_2\) ones, which at least partly is due to the larger number of bound states for the Na\(^+\) D\(_2\) complex.

In figures 7 and 8 j-resolved rate coefficients are shown as a function of temperature for Na\(^+\) H\(_2\) and Na\(^+\) D\(_2\), respectively. The results of Boltzmann averaging are also shown in these two figures for each spin isomer. The large cross section of the j=2 state has a significantly larger effect on the Boltzmann averaged rate coefficients in the case of Na\(^+\) D\(_2\) than for Na\(^+\) H\(_2\) since the j = 2 level of D\(_2\) is thermally more accessible than it is for H\(_2\).

Figure 9 summarizes the rate coefficients for the Na\(^+\) + H\(_2\), lower panel, and Na\(^+\) + D\(_2\), upper panel, reactions. The panels show thermal rate coefficients obtained separately for ortho states and for para states and also the Boltzmann weighted average of these. When combining the o-D\(_2\) and p-D\(_2\) rate coefficients a ratio of 2:1, obtained from spin statistics is included. The same was done for Na\(^+\) + H\(_2\) using ratio of 3:1 between the ortho and para states.

Comparing the total rate coefficients of Na\(^+\) + D\(_2\) and Na\(^+\) + H\(_2\) we can see that both curves are smooth with a bump at higher temperatures after which the rates decrease monotonously. The Na\(^+\) + D\(_2\) complex shows a much bigger bump than the Na\(^+\) + H\(_2\) complex due to the thermal accessibility of the j = 2 state. The total rate coefficient is mostly larger for Na\(^+\) D\(_2\) than for Na\(^+\) H\(_2\).

4 CONCLUSIONS

We calculated the overall reaction rate coefficients for the radiative association of Na\(^+\) H\(_2\) and Na\(^+\) + D\(_2\) at the Close Coupling level using a recent 3D PES and dipole moment surface. We found that the total number of bound states of Na\(^+\) D\(_2\) is almost three times larger than for Na\(^+\) H\(_2\) due to the mass difference. Similarly, the maximum value of J supporting bound states is larger for the Na\(^+\) D\(_2\) complex, 36, while it is only 26 for Na\(^+\) H\(_2\). These differences result in an overall larger value of the RA rate constant for Na\(^+\) + D\(_2\) which reaches a maximum value of approximately \(5 \times 10^{-11}\) cm\(^3\) molecule\(^{-1}\) s\(^{-1}\) at 200 K while the maximum value of the Na\(^+\) H\(_2\) RA rate coefficient, \(7 \times 10^{-20}\) cm\(^3\) molecule\(^{-1}\) s\(^{-1}\), is reached at 100 K.

An interesting result in the present study is that the j=2 rotational states of H\(_2\) and D\(_2\) give notably larger cross sections than the other rotational states.

The reaction rate coefficients obtained in this study are the first Close Coupling RA values obtained for Na\(^+\)–H\(_2\) and are closer to the ones predicted by Smith et al. (1983) than...
to those of the later study of Petrie & Dunbar (2000). As a matter of fact the present Close Coupling Na$^+$–H$_2$ RA value is only 10 times smaller than the one of Smith et al. (1983). We therefore conclude in agreement with these authors that the Na$^+$–H$_2$ RA rate coefficients are large enough for this mode of production of NaH in the gas phase to need to be included in the chemistry models of dense molecular clouds.

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Figure 8. Dependence of the Na\textsuperscript{+} + D\textsubscript{2}(v = 0, j) RA rate coefficient as a function of rotational excitation illustrated for three values of the rotational quantum number of each of the two spin isomers of D\textsubscript{2}: The upper panel shows the results for the j = 1, 3, 5 states of para D\textsubscript{2} while the lower panel shows those for the j = 0, 2, 4 states of ortho D\textsubscript{2}. On each of these two panels the Boltzmann averaged rate coefficient is also shown for the para and ortho species of D\textsubscript{2}.

Figure 9. The lower and upper panels of this figure show respectively the temperature dependence of the Na\textsuperscript{+} + H\textsubscript{2} and Na\textsuperscript{+} + D\textsubscript{2} RA rate coefficients. For each molecule, the contributions of the two spin isomers are given as well as the result of total Boltzmann averaging.
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