Collisional excitation of CH$_2$ rotational/fine-structure levels by helium

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ABSTRACT

Accurate determination of the abundance of CH$_2$ in interstellar media relies on both radiative and collisional rate coefficients. We investigate here the rotational/fine-structure excitation of CH$_2$ induced by collisions with He. We employ a recoupling technique to generate fine-structure-resolved cross-sections and rate coefficients from close coupling spin-free scattering calculations. The calculations are based on a recent, high-accuracy CH$_2$–He potential energy surface computed at the coupled clusters level of theory. The collisional cross-section calculations are performed for all fine-structure transitions among the first 22 and 24 energy levels of ortho- and para-CH$_2$, respectively, and for temperatures up to 300 K. As a first application, we simulate the excitation of CH$_2$ in typical molecular clouds. The excitation temperatures of the CH$_2$ lines are found to be small at typical densities of molecular clouds, showing that the non-local thermodynamic equilibrium approach has to be used to analyse interstellar spectra. We also found that the fine-structure lines connected with the $4_{04}$ level, which lies $\sim$215 K above the ground level, are small at typical densities of molecular clouds, showing that the non-local thermodynamic equilibrium approach has to be used to analyse interstellar spectra. These calculations show that CH$_2$ may have to be detected mainly through absorption spectra.

Key words: molecular data – molecular processes – ISM: abundances.

1 INTRODUCTION

Methylene (CH$_2$) shares the same chemistry as the widely detected methyldiene (CH) radical (Gerin, Neufeld & Goicoechea 2016). Yet, there have been only several astronomical observations of this species in the interstellar medium (ISM). Using the Hubble Space Telescope, Lys, Smith & Brüheiler (2001) reported the tentative detection of CH$_2$ in the UV absorption spectrum towards two stars.

The first unambiguous observation of CH$_2$ in the ISM was made by Hollis, Jewell & Lovas (1995), who identified the $4_{04} - 3_{13}$ rotational transition with observation of the fine-structure transitions associated with this transition in the spectral range 68–71 GHz. These transitions were detected in emission towards Orion KL and W51, which are dense ‘hot core’ sources that provide excitation to the $4_{04}$ level, which lies $\sim$215 K above the ground level.

Transitions involving low rotational levels of CH$_2$ occur in the far-infrared (FIR) spectral region. Polehampton et al. (2005) reported detection of several rotational transitions involving low rotational levels of CH$_2$ in absorption towards the FIR-emitting molecular cloud complexes Sagittarius B2 and W49N using the ISO Long Wavelength Spectrometer (Clegg et al. 1996). They observed transitions out of the lowest rotational levels of both ortho- and para-CH$_2$.

These observations were compared with predictions from chemical models. This work was facilitated by the availability of high-accuracy spectroscopic data on methylene transitions and hence energies of the rotational/fine-structure levels (Sears et al. 1984; Michael et al. 2003; Brüken et al. 2004).

Further interpretation of these and future observations would benefit from comparison with the results of radiative transfer calculations. Unfortunately, rate coefficients for state-to-state transitions of collisions of CH$_2$(X$^1$B$_1$) with the dominant neutral interstellar species have not been available. In the laboratory, state-resolved collisional transfer involving the low lying excited CH$_2$(a$^3$A$_1$) electronic state has been experimentally investigated through transient frequency modulation spectroscopy (Komissarov et al. 2006), and rate constants for removal of selected rotational levels of ortho-CH$_2$(a$^3$A$_1$) in collisions with helium and other collision partners have been measured (Hall & Sears, private communication).

From a theoretical viewpoint, treatment of collisions of CH$_2$ with helium is much simpler than for CH$_2$–He/H collisions. Potential energy surfaces (PESs) for the interaction of helium with CH$_2$(a$^3$A$_1$) electronic state have been computed (Ma, Dagdigian & Alexander 2011, 2012) and employed in theoretical investigations of rotationally inelastic CH$_2$(X$^1$B$_1$)–He and CH$_2$(a$^3$A$_1$)–He collisions. Cross-sections for rotational transitions were significantly smaller for the former system, since this PES is much less anisotropic than for the latter.

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Computed rate coefficients for removal of selected ortho-CH\(_2\)(\(^{3}\)A\(_1\)) rotational levels in collisions with helium agree well with the experimental measurements.

In the published theoretical work on CH\(_2\)(\(^{3}\)B\(_1\))–He collisions (Ma et al. 2012), cross-sections were computed only between spin-free rotational levels \(n_{kk'}\). Here, \(n\) is the total rotational angular momentum exclusive of electron spin of the molecule, and \(k\) and \(k'\) are the projections of \(n\) on the body-frame \(z\) axis in the prolate and oblate limits, respectively. Radiative transfer calculations on this collision pair require spin-resolved cross-sections and rate coefficients between pairs of rotational/fine-structure levels since the fine-structure splittings are readily resolved in the pure rotational spectrum (Polehampton et al. 2005). The hyperfine splittings are much smaller and are only partially resolved in the observational spectra (Polehampton et al. 2005). Hyperfine-resolved cross-sections and rate coefficients will not be presented in this work.\(^1\)

In this work, we employ the recoupling scheme (Corey & Alexander 1988) to compute spin-resolved cross-sections and rate coefficients from spin-free scattering calculations. This approach has been extensively employed to compute rate coefficients for hyperfine-resolved transitions (Offer, van Hemert & van Dishoeck 1994; Chen, Zhang & Zhou 1998; Lique 2011; Spiefiedel et al. 2012; Kalugina & Lique 2015; Lique, Bulut & Roncerio 2016; Marinakis, Kalugina & Lique 2016).

Section 2 describes the recoupling scheme and the approximations this scheme invokes. Section 3 presents the resulting spin-resolved cross-sections and rate coefficients for transitions between CH\(_2\)(\(^{3}\)B\(_1\)) rotational/fine-structure levels induced by collisions with helium. In Section 4, we present a simple astrophysical application of these rate coefficients. A conclusion section follows in Section 5.

2 THEORETICAL APPROACH

In the calculation of hyperfine-resolved cross-sections and rate coefficients, one can assume that the energies of hyperfine levels associated with a particular rotational level are degenerate since these splittings are usually very small (typically \(10^{-3}\) cm\(^{-1}\)). In this case, the scattering calculations do not have to explicitly include the hyperfine levels, and the dynamical problem is reduced to the collision of a molecule without nuclear spin. This is advantageous since the calculations scale non-linearly with the number of scattering basis functions.

The fine-structure splittings in CH\(_2\)(\(^{3}\)B\(_1\)) are larger (\(\leq 0.5\) cm\(^{-1}\)) than typical hyperfine splittings but are still significantly smaller than the spacings between rotational energy levels and the range of collision energies required to compute rate coefficients. Hence, we will apply the recoupling method to obtain cross-sections between CH\(_2\)(\(^{3}\)B\(_1\)) rotational/fine-structure levels \(n_{kk'}\), where \(j\) is the total molecular angular momentum and equals the vector sum of \(n\) and the electron spin \(s = 1\).

When electron spin \(s\) is included, the total angular momentum \(J_T\) of the collision pair equals
\[
J_T = J + s
\]
where \(J\) is the total angular momentum of the collision pair excluding the electron spin. The \(T\)-matrix elements of the colliding system including electron spin can be obtained from the nuclear-spin-free \(T\)-matrix elements (Corey & Alexander 1988):
\[
T_{n'j',l',s',j''l''}^{n,j,l,s,j} = (-1)^{J+J'+j+j'} e^{-2iJ}\times [(2J+1)(2J'+1)]^{1/2} \sum_{j} (2J + 1) \\
\times \left\{ n s j \right\} \left\{ n' s j' \right\} \left\{ J T J' l' l'' \right\} \\
\times T_{n'j',l',s',j''l''}^{n,j,l,s,j} \tag{2}
\]
In equation (2), \(J\) and \(l\) denote the initial and final orbital angular momentum, respectively, of the collision complex.

The cross-sections for transitions between the CH\(_2\)(\(^{3}\)B\(_1\)) rotational/fine-structure levels can be computed with the following equation:
\[
\sigma_{n'j',l',s',j''l''} = \frac{\pi}{k_{kk'}^{2j}(2J+1)} \sum_{J_T} (2J_T + 1) \\
\times \left| T_{n'j',l',s',j''l''}^{n,j,l,s,j} \right|^2 \tag{3}
\]
where \(k_{kk'}\) denotes the initial wavevector.

The PES describing the interaction of CH\(_2\)(\(^{3}\)B\(_1\)) with helium was computed (Ma et al. 2012) through spin-restricted coupled cluster calculations with inclusion of single, double, and (perturbatively) triple excitations [RCCSD(T)]. The molecule has a bent equilibrium structure, but the barrier to linearity is small. Hence, it was treated as semirigid with fixed bond lengths, but a varying bond angle.

The interaction energy was first computed as a function of the relative orientation and separation of the collision pair, as well as of the CH\(_2\) bond angle. The bending wavefunction for the ground \((0, 0, 0)\) vibrational level was computed with a rigid bender model (Hougen, Bunker & Johns 1970). The CH\(_2\)(\(^{3}\)B\(_1\), 000)–He interaction energies were then obtained by averaging over the bending vibrational probability distribution to obtain the PES.

3 CROSS SECTIONS AND RATE COEFFICIENTS

Fig. 1 displays the low-lying rotational levels of ortho- and para-CH\(_2\) and the frequencies of the allowed spectroscopic transitions between these levels. As discussed above, each of the rotational levels (except for the \(0_00\) level) is split into three fine-structure levels whose energy separations are too small to be visible in Fig. 1. The radiative rotational transitions are governed by type-\(b\) selection rules, namely \(\Delta k = \pm 1\), \(\Delta s = \pm 1\), with \(\Delta n = 0, \pm 1\). Transitions between fine-structure levels are governed by the selection rule \(\Delta J = 0, \pm 1\) (except \(J' = 0 \leftrightarrow J = 0\)).

State-to-state integral cross-sections were computed as a function of energy for de-excitation transitions between the 22 and 24 lowest rotational/fine-structure levels, displayed in Fig. 1, of ortho- and para-CH\(_2\)(\(^{3}\)B\(_1\)), respectively, in collisions with helium. These include the levels whose energies lie below 280 cm\(^{-1}\). The calculations were carried out up to a total energy of 2000 cm\(^{-1}\), with an energy spacing of 0.5 cm\(^{-1}\) for energies less than 400 cm\(^{-1}\), 1 cm\(^{-1}\) for energies between 400 and 500 cm\(^{-1}\), 2 cm\(^{-1}\) for energies between 500 and 1000 cm\(^{-1}\), 20 cm\(^{-1}\) for energies between 1000 and 1500 cm\(^{-1}\), and 50 cm\(^{-1}\) for energies greater than 1500 cm\(^{-1}\). The differing magnitudes and collision energy dependence of de-excitation cross-sections for several ortho and para rotational/
Figure 1. Energies of the low-lying rotational levels of CH$_2$(X$^3B_1$) and the approximate frequencies (in GHz) of the allowed transitions between these levels. The ortho 2$_{20}$ level is connected to the 2$_{11}$ and 1$_{11}$ levels by transitions at 4925 and 5934 GHz (labelled A and B), respectively, and the para 2$_{21}$ level is connected to the 2$_{12}$ and 1$_{10}$ levels by transitions at 5022 and 5895 GHz (labelled C and D), respectively. The fine-structure splittings are too small to be visible in the figure.

Figure 2. Integral cross-sections as a function of collision energy for de-excitation transitions from the ortho-CH$_2$ 1$_{11}$ level to the 0$_{00}$ $j=1$ and 2$_{02}$ $j=1, 2, 3$ rotational/fine-structure levels in collisions with helium. The cross-section for the 1$_{11}$ $j=0$ to 2$_{02}$ $j=2$ transition is too small to be visible in the upper right-hand panel.

Figure 3. Integral cross-sections as a function of collision energy for de-excitation transitions from the para-CH$_2$ 1$_{10}$ $j=1$ and 2$_{12}$ $j=1, 2, 3$ fine-structure levels to the 1$_{01}$ $j=0, 1, 2$ and 3$_{03}$ $j=2, 3, 4$ rotational/fine-structure levels, respectively, in collisions with helium.

Figure 4. The largest cross-sections are seen to involve $j \rightarrow j'$ transitions differ considerably. For high-$j$ levels, the fine-structure-resolved cross-sections follow the propensity rule $\Delta j = \Delta n$. This is analogous to the corresponding propensity rule for hyperfine resolved radiative transitions. This is illustrated in Fig. 4 with the 5$_{05}$–4$_{14}$ collisional transition. The largest cross-sections are seen to involve $\Delta j = \Delta n = -1$. The corresponding rate coefficients were computed for the temperature range from 15 to 300 K as an average over the collision energy ($E_c$):

$$k_{\alpha \rightarrow \beta}(T) = \left( \frac{8}{\pi \mu k_B T^3} \right)^{1/2} \times \int_0^\infty \sigma_{\alpha \rightarrow \beta} E_c \exp \left( -\frac{E_c}{k_B T} \right) dE_c \quad (4)$$

where $\sigma_{\alpha \rightarrow \beta}$ is the cross-section from initial state $\alpha$ to final state $\beta$, $\mu$ is the CH$_2$–He reduced mass and $k_B$ is Boltzmann’s constant.

The complete set of (de-)excitation rate coefficients will be made available through the LAMDA (Schöier et al. 2005) and BASECOL (Dubernet et al. 2013) data bases. Temperature-dependent rate coefficients corresponding to the energy-dependent cross-sections displayed in Figs 2–4 are presented in Figs 5–7, respectively. The differing dependence of the rate coefficients upon temperature reflects differences in the energy dependence of the cross-sections upon collision energy. As with the cross-sections, we observe the

fine-structure levels are illustrated in Figs 2–4. The sharp features in the energy-dependent cross-sections are due to Feshbach or shape resonances associated with the opening of a rotational channel. Fig. 2 presents cross-sections for de-excitation transitions out of the ortho-CH$_2$ 1$_{11}$ level to the 0$_{00}$ $j=1$ and 2$_{02}$ $j=1, 2, 3$ rotational/fine-structure levels in collisions with helium. The cross-section for the 1$_{11}$ $j=0$ to 2$_{02}$ $j=2$ transition is too small to be visible in the upper right-hand panel.

The 2$_{02}$ $j=3$ fine-structure level are larger than for transitions to the $j=1$ and 2 fine-structure levels. The magnitude of the cross-sections is also governed, in part, by the degeneracy of the final level.

Fig. 3 presents integral cross-sections for transitions involving low-lying para-CH$_2$ rotational/fine-structure levels, namely cross-sections for transitions out of the 1$_{10}$ $j=1$ rotational/fine-structure level to the 1$_{01}$ $j=0, 1, 2$ and 3$_{03}$ $j=2, 3, 4$ rotational/fine-structure levels. These cross-sections are seen to have a small magnitude at low collision energy and increase to a maximum value at $\sim$750 cm$^{-1}$ collision energy. The magnitudes of the individual $j \rightarrow j'$ transitions differ considerably.
Collisional excitation of CH$_2$

4 THE EXCITATION OF CH$_2$ IN THE ISM

As the first application and in order to test the impact of these new rate coefficients, we have carried out radiative transfer calculations to simulate the excitation of methylene in interstellar molecular clouds. While it is beyond the scope of this work to model quantitatively the observations of methylene (Hollis et al. 1995; Polehampton et al. 2005), it will nevertheless be interesting to connect these calculations with observations of specific rotational/fine-structure levels.

Non-local thermodynamic equilibrium (non-LTE) radiative transfer calculations were performed with the RADEX code (van der Tak et al. 2007) using the escape probability formalism approximation for an expanding sphere. Both radiative and collisional processes were taken into account. We consider only the H$_2$ collisional partner. In order to estimate CH$_2$–H$_2$ rate coefficients, the main collisional partner in ISM, we apply a scaling factor of 1.4 to the CH$_2$–He rate coefficients (Lique et al. 2008). Such an approach can
be unsuccessful for light hydride molecules (Roueff & Lique 2013). However, in the absence of proper data with the H2 collisional partner, it is the most accurate prediction that can be made. In addition, He and H2 rate coefficients usually share the same propensity rules so that we do not expect major differences when simulating the excitation of CH2 with actual CH3–H2 collisional data.

We have performed radiative transfer calculations for typical physical conditions from where CH2 emission and absorption spectra were detected. In all the calculations, the kinetic temperature was fixed at 100 K and a line width of 5 km s−1 was taken into account (e.g. Hollis et al. 1995; Polehampton et al. 2005). The cosmic microwave background radiation was set at 2.73 K. The column density of CH2 is fixed at $3 \times 10^{14}$ cm$^{-2}$, which is the typical column density derived from the available observations. We included all the energy levels for which both radiative and collisional data are available. Ortho-CH2 and para-CH2 were treated as two separate species since they are neither radiatively nor collisionally connected. Tables 1 and 2 show the possible radiative transitions of ortho-CH2 and para-CH2, respectively, between the levels displayed in Fig. 1. The Einstein coefficients were obtained from the data presented by Sears et al. (1984) and Polehampton et al. (2005).

Fig. 8 shows the excitation temperatures ($T_{ex}$) and brightness temperatures ($T_{b}$) of the fine-structure resolved CH2 lines connected with the rotational $1_{11} - 0_{10}$, $2_{12} - 1_{01}$ and $4_{04} - 3_{13}$ transitions that were detected in the ISM, as a function of molecular hydrogen volume density for a temperature of 100 K. The $1_{11} - 0_{10}$ lines of ortho-CH2 and the $2_{12} - 1_{01}$ lines of para-CH2 have been seen in absorption (Polehampton et al. 2005) whereas the $4_{04} - 3_{13}$ lines of ortho-CH2 have been seen in emission (Hollis et al. 1995).

The behaviour of the fine-structure resolved lines connected with the $1_{11} - 0_{10}$ and $2_{12} - 1_{01}$ rotational lines is extremely classic. The excitation temperatures tend to be equal to the adopted value of the background radiation field (2.73 K) at very low volume densities of molecular hydrogen. The excitation temperatures rise to higher values as collisional excitation becomes more important. At volume densities above a critical value, the excitation temperature approaches the kinetic temperature, at which point the LTE approximation may be used. For both sets of lines, the critical density lies at $\approx 10^6$–$10^{10}$ cm$^{-3}$, which could have been anticipated from the
Figure 8. Excitation temperature \( T_{\text{ex}} \) and brightness temperature \( T_B \) for the fine-structure lines connected to the \( 1_{11} - 0_{00} \), \( 2_{12} - 1_{01} \) and \( 4_{04} - 3_{13} \) rotational transitions. The lines are denoted by their frequency. The H\(_2\) volume density varies between \( 10^5 \) and \( 10^{12} \) cm\(^{-3}\) and the CH\(_2\) column density is fixed at \( 3 \times 10^{14} \) cm\(^{-2}\). The inset in the plot of \( T_{\text{ex}} \) for the \( 4_{04} - 3_{13} \) transition in the upper right-hand panel shows an expanded plot of the \( T_{\text{ex}} \) for this transition.

The computed critical densities\(^2\) owing to the relatively small magnitude of the rate coefficients compared to the magnitude of the Einstein coefficients. As the temperature variation of the rate coefficients is weak, the determined critical densities are almost independent of the temperature.

Such critical densities are well above the typical densities of molecular clouds in the ISM. Hence, we can conclude that these CH\(_2\) lines are not thermalized and that non-LTE analysis is required even for the analysis of absorption spectra, as was recently demonstrated for the analysis of NH absorption lines in the pre-stellar core L1629E in L1689N (Bacmann et al. 2016). In addition, assuming LTE conditions in low-density media would lead the CH\(_2\) abundance to be underestimated relative to the non-LTE assumption. We can thus expect that the use of the new theoretical rate coefficients may increase the abundance of CH\(_2\) derived from the observations.

It is also interesting to note that the excitation temperatures of these CH\(_2\) lines are very small so that the lines can be easily seen in absorption even in high-density media, as was the case in the observations by Polehampton et al. (2005). Indeed, for densities below \( 10^5 \)–\( 10^6 \) cm\(^{-3}\), the excitation temperatures of lines from excited states to the ground state of both ortho- and para-CH\(_2\) are below \( \sim 10 \) K so that these lines can be easily seen in absorption versus a background source.

Fig. 8 also displays the brightness temperatures of these lines as a function of hydrogen density. As the optical depth is small for these lines (\( \tau < 1 \)), \( T_B \) is proportional to the column densities. \( T_B \) increases gradually with the density before becoming constant at around \( n(H_2) = 10^6 - 10^{10} \) cm\(^{-3}\), when LTE conditions are reached. All the fine-structure resolved lines connected with a rotational transition display the same variation with the \( H_2 \) volume density, and the order of magnitude of the brightness temperatures is the same for all these fine-structure lines. Hence, there are no anomalies linked with the intensities of the emission lines as happens sometimes for hyperfine-resolved transitions (Loughnane et al. 2012).

The case of the fine-structure resolved lines connected with the \( 4_{04} - 3_{13} \) rotational transition is much more intriguing. Indeed, it is at first surprising that these lines have been seen in emission towards hot cores because these transitions imply highly excited levels that are supposed to be weakly populated at the typical temperatures of hot cores. Radiative transfer calculations may help to understand such observations.

As one can see in Fig. 8, the excitation temperatures of these lines are almost independent of the density for densities up to \( 10^9 \) cm\(^{-3}\) and, especially, are negative. This means that there are population inversions for these lines that can lead to maser emission. Such an effect certainly explains the detection of these lines and can be attributed to the peculiar radiative and collisional propensity rules so that the populations of the \( 4_{04} \) states are enhanced. This provides an explanation to the detection of CH\(_2\) in emission, and CH\(_2\) may join the list of molecules showing maser emission.

As a consequence, the corresponding brightness temperatures are relatively high (\( T_B > 0.1 \)) even at moderate densities \( n(H_2) \sim 10^6 \) cm\(^{-3}\), so that this clearly explains the fact that these specific lines have been observed. Maser emission occurs for all three fine-structure lines. We also note that the brightness temperatures associated with the \( 4_{04} - 3_{13} \) fine-structure transitions increase rapidly with the \( H_2 \) volume density and then reach a constant value for densities larger than \( \sim 10^4 - 10^5 \) cm\(^{-3}\). Such densities correspond to the expected critical density for these specific lines.

Finally, it is interesting to predict what other lines can be detected in absorption or emission in molecular clouds. Table 3 shows the intensity of the lines of ortho-CH\(_2\) and para-CH\(_2\) lines with brightness temperatures greater than \( 10^{-3} \), computed for an \( H_2 \) volume density of \( 10^9 \) cm\(^{-3}\). First, we see that the lines involving low rotational levels that were detected in absorption by Polehampton et al. (2005) have the highest computed brightness temperatures. These

\(^2\) The critical density is the gas density at which photon de-excitation and collisional de-excitation are equal.
of para-CH$_2$ is predicted to have a brightness temperature slightly below 0.1 K, so that the lines will be observable by an NH line. We also see from Table 3 that the 2783.067 line at 2783.067 GHz for para-CH$_2$. We also see that the 1954.330 GHz line, the 592.425 1.97 GHz associated with the 313 transition of ortho-CH$_2$, discussed above, the lines at 593.122, 605.509 and 592.425 GHz associated with the 414 rotational transition were already detected (Hollis et al. 1995), and the present calculations explain this surprising detection of highly excited levels. The predicted maser emission for the fine-structure lines connected with the $5_{05} - 4_{14}$ rotational transition should be confirmed by a search in an astronomical survey.

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**5 CONCLUSION**

We have presented the first set of collisional rate coefficients for the CH$_2$ molecules using a recoupling technique to generate fine-structure-resolved rate coefficients from close coupling spin-free scattering calculations. The calculations were based on a recent, high-accuracy CH$_2$–He PES of Ma et al. (2012). Rate coefficients were obtained for all fine-structure transitions among the first 22 and 24 energy levels of ortho- and para-CH$_2$, respectively, and for temperatures up to 300 K. Propensity rule in favour of transitions with $\Delta j = \Delta n$ was found for higher rotational levels.

The rate coefficients were then used in radiative transfer calculations to simulate the excitation of CH$_2$ in molecular clouds. The excitation temperatures of both ortho- and para-CH$_2$ lines were found to be very small so that it is expected that CH$_2$ lines are not thermalized and that non-LTE analysis (using radiative and collisional rate coefficients) is required. The use of non-LTE analysis for deriving the abundance of CH$_2$ in molecular clouds may lead to an increase of the CH$_2$/CH abundance ratio compared to available analyses and as expected for pure astrochemical considerations.

Finally, we found that maser emissions occur for the fine-structure lines connected with the $4_{04} - 3_{13}$ and $5_{05} - 4_{14}$ rotational transitions. The fine-structure lines connected with the $4_{04} - 3_{13}$ rotational transition were already detected (Hollis et al. 1995), and the present calculations explain this surprising detection of highly excited levels. The predicted maser emission for the fine-structure lines connected with the $5_{05} - 4_{14}$ rotational transition should be confirmed by a search in an astronomical survey.

<table>
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