Theoretical study of the $\text{H}_3^+$ ion
dissociative recombination process

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Abstract. We report recent developments in the theory of dissociative recombination of the $\text{H}_3^+$ ion. The
theory is able to explain the surprisingly large dissociative recombination rate observed in storage-ring
experiments. We have found that the high rate is caused by Jahn-Teller coupling between the electronic
and vibrational degrees of freedom. We compare two theoretical models: A simplified model and an
improved one. The two models each produce a theoretical rate that is consistent with the storage-ring
observations. The final theoretical dissociative recombination rate presented here accounts for several
experimental details that are often not considered.

1. Introduction
Despite extensive experimental and theoretical effort, there remains considerable interest in the process
of $\text{H}_3^+$ dissociative recombination (DR). This process is fundamental as a prototype for theory, with
considerable practical importance for understanding the chemistry of interstellar clouds as well.

Two different kinds of laboratory experiments measure the rate of $\text{H}_3^+$ dissociative recombination:
Storage ring experiments [1–6] and stationary or flowing afterglow experiments performed in several
laboratories [7–12] (see also the references cited in [11]). After more than a decade of investigation, the
storage ring experiments seem to have converged to approximately the same DR rate. At 300 K the rate
obtained from the most recent experiment [6] is $6.8 \times 10^{-8}$ cm$^3$/s. The most important difference between
the newest experiment and the earlier storage ring experiments appears to be the fact that the molecular
ion source is orders of magnitude cooler in the rotational temperature of the target ions that are injected
into the storage ring. The afterglow experiments have produced results that are somewhat controversial
and difficult to interpret. Some of the results are in agreement with the storage ring experiments, while
others give far lower apparent DR rates. Moreover, a very recent stationary afterglow experiment [11]
suggests that the DR rate depends strongly on the density of the background $\text{H}_2$ gas.

A previous theoretical description [13] was successful in explaining the DR rate for high energy ($5 \text{ eV} < E < 15 \text{ eV}$)
electron-ion collisions in the storage ring-experiments. However the lower energy region ($10^{-5} \text{ eV} < E < 2 \text{ eV}$) was challenging to understand even qualitatively: Theory [14, 15] produced a DR
rate that was smaller than the experimental one by three orders of magnitude.
Our recent study [16–19] showed that the high DR rate at low energies can be explained by the Jahn-Teller effect. In that study we used two different theoretical models to calculate the $H_3^+$ rate. In this article we briefly discuss the two different theoretical models [16, 18] and present the results obtained. We also discuss the DR rates calculated for individual symmetries of the $H_3^+$ ion. Such rates may be of interest for future experiments.

The article is organized as follows. In section 2 we present the main elements of our theoretical approach. The underlying elements are the same in the two theoretical models. Sections 3 and 4 present the two models: The simplified and the improved model. In section 5 we discuss experimental conditions that must be taken into account when theory and experiment are compared. Section 6 summarizes briefly the main results on the total $H_3^+$ DR rate. In section 7 we present the $H_3^+$ DR rates calculated for individual symmetries of the $H_3^+$ ion. Finally, section 8 discusses our conclusions.

2. The main theoretical ingredients

The two theoretical models discussed in this work share three main ingredients: Jahn-Teller coupling physics, multi-channel quantum defect theory (MQDT) and hyperspherical coordinates.

The key effect responsible for the relatively fast DR rate is the Jahn-Teller coupling: A strong non-adiabatic coupling between electronic and vibrational degrees of freedom in the $H_3^++e^-$ system. The non-adiabatic coupling is strong only if the outer electron is in one of the $np(\pi)$ states. This type of coupling was first recognized by Landau and then formulated as a theorem by Jahn and Teller, who proved that any symmetric configuration of the nuclei is unstable in a degenerate electronic state [20]. For $H_3^+$ the relevant degenerate states are any of the $np(\pi)$ states. In principle, the $nd(\pi)$ and $nd(\delta)$ states can play a similar role. However, our estimates suggest that their contributions to the DR rate are far smaller than the $np(\pi)$ contributions.

The idea that the Jahn-Teller effect could play an important role in the $H_3^+$ DR process grew out of an earlier study by Stephens and Greene [21, 22], which dealt with an interpretation of the $H_3^+$ photoabsorption spectrum [23]. In that study [21,22] several features were identified in the experimental spectrum that were apparently caused by the Jahn-Teller effect. The Jahn-Teller coupling was included in that treatment by using a reaction matrix $K$ that describes the scattering of a Rydberg electron by the $H_3^+$ target. (The reaction matrix $K$ is an alternative way of expressing the information contained in the scattering matrix $S$. The two descriptions are equivalent [24].) The description of the Jahn-Teller coupling in terms of a scattering matrix was developed somewhat earlier by Staib, Domcke, and Sobolewski [25,26].

The details of our approach to describe the DR process can be found in our previous work [16–18]. Very briefly, the Jahn-Teller effect is included in the following manner. We take the reaction matrix $K$ in the form developed by [25,26] and transform it to get the scattering matrix $S_{AA'}(Q)$ [24]. The matrix $S_{AA'}(Q)$ describes the scattering of an electron by the $H_3^+$ target at a fixed nuclear geometry $Q$, where $Q$ means three internuclear coordinates and $\Lambda$ means the projection of the orbital momentum of the electron on the molecular axis of symmetry. Non-diagonal elements $S_{AA'}(Q)$ give the amplitude that the electronic orbital momentum changes its projection from $\Lambda'$ to $\Lambda$ after the collision. Non-diagonal elements $S_{1-1}(Q)$ and $S_{-1,1}(Q)$ are not zero exclusively due to the Jahn-Teller coupling. The passage from the $S$-matrix for fixed nuclei to the one $S_{i,f}^{(\text{vib})}$ that allows vibration is performed using the frame transformation techniques developed in multi-channel quantum defect theory [24,27–29]. In order to obtain the matrix $S_{i,f}^{(\text{vib})}$ from $S_{AA'}(Q)$, we need vibrational wavefunctions $(Q|\nu')$ of the $H_3^+$ ion. The matrix elements $S_{i,f}^{(\text{vib})}$ obtained after such a procedure – the vibrational frame transformation – represent amplitudes of scattering of the electron on the vibrating $H_3^+$ ion. However, since the initial matrix $S_{AA'}(Q)$ is determined with respect to the coordinate system fixed with the molecule, we need one more transformation to get the scattering matrix in the laboratory coordinate system. This transformation involves a change of the rotational basis. In the language of MQDT the second procedure is called
the rotational frame transformation. To perform this second frame transformation, we need to have rotational eigenfunctions of the $\text{H}_3^+$ ion and the neutral molecule (symmetric top rotational states) and the eigenfunctions of the electron (spherical harmonics). After the two frame transformations the resulting matrix $S_{i,j'}$ represents the scattering of the electron on the rotating and vibrating $\text{H}_3^+$ ion. The indices $i'$ and $i$ specify an initial and a final state of the ion, namely, the vibrational quantum number $V$ and two rotational numbers $N^+$ and $K^+$: The ionic rotational momentum and its projection on the molecular axis. These quantum numbers could change during the collision. There are few conserved quantum numbers [18]. The resulting $S_{i,j'}$ contains information about the Jahn-Teller coupling, which produces an appreciable amplitude for transitions between different states $i$.

The energies of interest in our studies are the comparatively low range within 2 eV of the lowest ionization threshold. In that range, the matrix $S_{i,j'}$ is approximately energy-independent. It is also important to understand that it is only immediately applicable to describe collision processes when the total energy is higher than the energy $E_i$ of the highest rovibrational state $i$. In order to obtain the physical scattering matrix $S'_i\text{phys}$ applicable at lower energies, we employ the familiar approach of MQDT channel elimination. For more details, see our theoretical formulation [18], or available reviews of MQDT [24, 28, 29].

The preceding discussion shows that the second key ingredient of our treatment is the description of an electron-ion scattering process by a scattering matrix, which utilizes two MQDT techniques: The rovibrational frame transformation and the closed-channel elimination procedure to enforce exponential decay in all channels for which electron escape is energetically forbidden at large distances.

The adiabatic representation in hyperspherical coordinates is a third key ingredient adopted in both of the theoretical models discussed here. The vibrational wavefunctions of $\text{H}_3^+$ needed to perform a vibrational frame transformation are obtained by diagonalizing the vibrational Hamiltonian of $\text{H}_3^+$. The three vibrational coordinates of the triatomic system are represented in terms of hyperspherical coordinates – the hyper-radius $R$ and two hyperangles $\theta$ and $\phi$ [16–18]. The hyperspherical coordinates are particularly well-suited for the treatment of dissociative processes like DR, since the hyper-radius represents a natural dissociation coordinate: Large $R$ corresponds to a situation where at least one H atom is far from the two others. In addition, it becomes necessary to distinguish between two-body (H+H$_2$) and three-body (H+H+H) dissociation, the relative strengths of competing fragmentation pathways can be discerned by investigating the vibrational wavefunctions at large $R$. In our present treatment we do not separate the branching ratios into the two-body (H+H$_2$) and three-body (H+H+H) pathways.

3. Simplified theoretical model for $\text{H}_3^+$ DR

In our first attempt [16] to interpret the large experimental DR rate [4, 5] we adopted a simplified theoretical model, which is described in the following.

First of all, we diagonalize the ionic vibrational Hamiltonian adiabatically as a function of the hyper-radius. In doing so, we diagonalize it only in the space of the two hyperangles, and only for the states with zero angular momentum $J = 0$. The resulting vibrational eigenenergies $U_i^\text{v}(R)$ depend parametrically on the hyper-radius $R$ and can be viewed as potential curves depending on $R$. The corresponding vibrational eigenfunctions are $\Phi_j(R; \theta, \phi)$ where $\theta, \phi$ are variables and $R$ is considered as a parameter. This approach is called the adiabatic hyperspherical approach. Technically, it is equivalent to the Born-Oppenheimer approach in diatomic molecules, where the internuclear coordinate is treated as a parameter when the electronic part of the total Hamiltonian is diagonalized. Using such an analogy we treat the $\text{H}_3^+$ DR in a fashion similar to the well-developed strategies for diatomic ions, except that we replace the internuclear coordinate by the hyper-radius.

To apply the theoretical methods used to describe DR in diatomic molecules, we need the scattering matrix $S_{j,j'}(R)$ or the reaction matrix $K_{j,j'}(R)$. In [16] we deal with the reaction matrix $K_{j,j'}(R)$ rather than with $S_{j,j'}(R)$. We start with the reaction matrix $K_{\Lambda,N'}(Q)$ for fixed nuclei and apply a reduced
vibrational frame transformation

\[ K_{j,j'}(R) = \langle \Phi_i(R; \theta, \phi) | K_{\Lambda,\Lambda'} | \Phi_j(R; \theta, \phi) \rangle_{\theta,\phi}, \]  

where each index \( j \) consists of the pair \( i \) and \( \Lambda \). The reduced vibrational frame transformation means that we integrate only over the two hyperangles \( \theta, \phi \) but not over \( R \) when we perform the frame transformation procedure. As a result, we obtain a reaction matrix \( K_{j,j'}(R) \) that depends parametrically on \( R \). Rotational states of the ion were not included at all in that study [16], and the rotational frame transformation was not performed.

The calculated reaction matrix \( K_{j,j'}(R) \) is then used to obtain a set of resonances \( U_\beta(R) (\beta = 1, 2, \ldots) \) at every given hyper-radius \( R \). These resonances are autoionizing electronic states of the neutral \( \text{H}_3^+ \) molecule. Every resonance is characterized by the energy \( U_\beta(R) \) and the autoionization width \( \Gamma_\beta(R) \).

The autoionization width gives the information needed about the initial capture probability. In other words, \( U_\beta(R) \) form a set of autoionizing potential curves for \( \text{H}_3^+ \). Using these potential curves and knowing the initial wavefunction of the ion \( \Psi(R) \) we can calculate (1) the probability of recombination of the ion and (2) the rate of the subsequent dissociation of the neutral molecule. To do this, we employ the method of O’Malley (see his original paper [30] and our study [16]). We describe the theoretical method as an “upper bound” estimate, because it has been assumed that every capture leads to dissociation, whereas in the real molecule, there is some branching ratio between ionization and dissociation. It appears as though \( \text{H}_3^+ \) is dominated by dissociation, once the initial capture has occurred, so the true rate is reasonably close to our calculated “upper bound” rate.

The theoretical DR rate is calculated as a function of the \( \text{H}_3^+ + e^- \) collision energy. To compare with experimental data we have to average over the experimental energy distribution. The resulting theoretical DR rate was lower than the experimental rate [4, 5] by a factor of about 10. After our first work [16] of \( \text{H}_3^+ \) DR had been published, we found that the Jahn-Teller \( K_{\Lambda,\Lambda'}(Q) \) matrix that we extracted from [22], must be multiplied by \( -\pi \). (This correction factor of \( -\pi \) was already missing in [22]), owing to an error in correctly transcribing the reaction matrix of Staib and Domcke to our conventions.) As a result the correct theoretical rate should be approximately \( \pi^2 \) times larger than the one reported in [16]. (However, it should be remembered that this simple scaling of the final cross section by \( \pi^2 \) is only valid in the perturbative limit.) In figure 1 we compare the the experimental DR data [5] with the two theoretical curves – the one published in [16] and the corrected one.
4. The advanced theoretical model

The simplified model does not account for the situation when the neutral H3 molecule can autoionize back to the free ion and the electron. The model implies that every electron capture will eventually result in a molecular dissociation. In other words, the theoretical rate in the simplified model should be considered as an upper limit for the DR rate. In order to account for the competition between autoionization and dissociation, we have included into the treatment vibrational states (Siegert states) of H3+ that permit the neutral molecule H3 to dissociate. The detailed description of the improved approach is given in [17,18].

We only point out here that the DR rate is calculated using the matrix \( S_{ij} \) that represents H3+ + e− scattering. The matrix is constructed using the dissociating vibrational states of H3+ and thus it contains the information about the dissociation. The dissociating vibrational (Siegert) states make the electronic matrix non-unitary. This is because not all of the incident electron flux that collides with the molecular target ion will emerge in outgoing waves of the scattered electron. A part of the flux is lost due to the events that lead to dissociation. Therefore, the defect from unitarity of the \( S \)-matrix can be used to calculate the probability of dissociation and the rate of DR.

To construct the total scattering matrix \( S_{ij} \), we employ the full rotational and vibrational frame transformations [17,18] as discussed above. To perform the vibrational frame transformation, we use the vibrational functions \( \langle \mathcal{Q} | \mathcal{V} \rangle \) that are calculated in the adiabatic hyperspherical approximation. Although these functions are not exact, the adiabatic approximation is good enough for the accuracy of the present calculation. A comparison of exact and approximate adiabatic vibrational energies is given in [18].

Although the adiabatic approximation works well enough for the vibrational states of H3+ and D3+, we have found that it is not a good approximation for the H2D+ and HD2+ isotopomers. The non-adiabatic coupling between different adiabatic states \( \Phi(R; \theta, \phi) \) is much stronger in H2D+ and HD2+ and this produces considerable error in the vibrational states \( |\mathcal{V}\rangle \), their energies, as well as the DR rate. We have solved this problem using the slow variable discretization (SVD) suggested by Tolstikhin et al. [31]. Essentially, the SVD method gives vibrational states and their energies with the same accuracy as the direct diagonalization of the 3-dimensional vibrational Hamiltonian. Indeed, our calculation shows that vibrational energies obtained with SVD are in close agreement with exact energies available in the literature. On the other hand the use of hyperspherical coordinates along with SVD allows us to retain the idea of considering the hyper-radius as a dissociation coordinate. Correspondingly, we are able to include the dissociating vibrational states into the H3+ + e− scattering matrix. Details of this approach will be discussed in a future publication. The main result of this calculation is that the resulting theoretical DR rate for H2D+ is in good agreement with the available experimental results.

5. Modeling the experimental conditions

The theoretical H3+ DR rate \( \alpha(E) \) calculated as described above exhibits a forest of resonances associated with autoionizing states of H3. The data from most storage ring experiments [4, 5] does not exhibit any resonances for collision energies below 5 eV. We attribute the absence of resonances in the experimental data in part to the wide experimental spread in the collision energy, and in part to the higher rotational target temperatures of the earlier storage ring experiments that tend to smear out resonance effects. A recent experiment with a rotationally colder target [6] does exhibit some resonances. In any case, it is clearly necessary to average the theoretical DR rate \( \alpha^{\text{raw}}(E) \) over the experimental energy distribution and ionic target temperature.

There are three distributions that must be considered: (1) the collision energy distribution, (2) the rotational energy distribution and (3) the toroidal correction.

5.1. Convolution over the distribution of collision energies

One distribution \( f(E_x, E_y, E_z) \) is over the relative energy \( E = E_x + E_y + E_z \) of the colliding H3+ and e−. In the storage ring experiments [4–6], \( f(E_x, E_y, E_z) \) is not isotropic: The width of the distribution along one spatial direction (let it be the x-component \( E_x = E_{||} \)) differs from the widths along the two other
directions ($E_x$ and $E_z$). The widths along $y$ and $z$ are the same. For the sum $E_y + E_z$ we will use the symbol $E_{||}$. Let the corresponding widths be $\Delta E_{||}$ and $\Delta E_{\perp}$. Note that experimental measurements in this field are typically reported as a DR rate measured as a function of $E_{||}$, the parallel energy component. We need to consider velocities $v_i$ as well as energies $E_i$, $i = x, y, z$. The total velocity of the electron relative to the ion is $\vec{v} = \vec{v}_|| + \vec{u}$, where $v_||$ is the velocity measured in the experiment. This velocity is the center of the velocity distribution. $\vec{u}$ is the velocity that describes the distribution; it represents the deviation of the total velocity from the center of the distribution. We also represent $\vec{u}$ as a sum of two contributions $\vec{u} = \vec{u}_{\perp} + \vec{u}_{||}$. Then the averaging over the non-isotropic distribution \( f(E_x, E_y, E_z) \) is carried out through the following integral:

\[
\langle \alpha(v_||) \rangle = \frac{1}{(2\pi)^{1/2} \Delta E_{||}} \int_{-\infty}^{\infty} du_|| \exp \left( -\frac{u_||^2}{2\Delta E_{||}} \right) \int_0^\infty dE_\perp \exp \left( -\frac{E_\perp}{\Delta E_{\perp}} \right) \alpha \left( (v_|| + u_||)^2/2 + E_\perp \right).
\]

\[ (2) \]

5.2. Rotational energy averaging

In addition to the relative velocity distribution, in the experiment there is a non-negligible population of different rotational energy levels associated with the rotation of the ion. It is reasonable to assume that such a distribution obeys Boltzmann statistics. Therefore, the DR rate calculated for different initial rotational states of $H_3^+$ should be weighted with the factor $\exp \left( -\frac{E_{\text{rot}}}{kT_{\text{rot}}} \right)$, where $E_{\text{rot}}$ is the energy of a given state above the lowest rotational state. The additional averaging takes the form

\[
\frac{\sum_{\text{rot}} (2I + 1)(2N^+ + 1) \exp \left( -\frac{E_{\text{rot}}}{kT_{\text{rot}}} \right) \alpha_{\text{rot}}}{\sum_{\text{rot}} (2I + 1)(2N^+ + 1) \exp \left( -\frac{E_{\text{rot}}}{kT_{\text{rot}}} \right)}.
\]

\[ (3) \]

In the above formula we include the statistical factor $(2I + 1)(2N^+ + 1)$ that accounts for the $(2I + 1)$ degenerate projections of the nuclear spin ($I = 1/2$ or $3/2$ for $H_3^+$) and the $(2N^+ + 1)$ projections of the ionic angular momentum on a laboratory fixed axis.

5.3. Toroidal correction

There is one more experimental factor that was not accounted for in the comparisons between theory and experiment that were shown in [17, 18]. This is the so-called toroidal correction.

The electron-ion interaction region in a storage ring experiment actually consists of two different regions (see figure 2): The region $p$ of length $L$, where the electron and ion beams are parallel, and two symmetric regions of length $l_{\text{bend}}$ each, where the electrons are bent into and out of the ion beam (region $b$).

![Figure 2. Geometry of the toroidal effect in storage-ring experiments, showing how the ion and electron beams are not parallel at the interaction region edges.](image)
Electron energy, $E_{\parallel}(eV)$

Theory without the toroidal and $E_{\parallel}$ averagings
Theory with the toroidal and $E_{\parallel}$ averagings
Experimental data (raw data)

Figure 3. Experimental [6] (triangles) and theoretical (two solid lines) $H_3^+$ DR rates. The thin thick line represents the theoretical rate averaged according to 2 and 3. The thin line represents the result published in our previous work [17, 18], where the averaging over $E_{\parallel}$ was not performed. Clearly, the $E_{\parallel}$ averaging and the toroidal correction are both very important. The main effect of the toroidal correction is to significantly increase the measured rate, above about 0.6 eV and also near the deep dip near 0.1 eV. On the other hand, the effect of including the averaging over $E_{\parallel}$ is to smooth out the sharper resonance features.

Experimentally, the dissociative recombination rate $\alpha_{\text{meas}}(E)$ is determined from the measured number of dissociative recombination events that occur per unit time interval. Since the relative velocity of electrons with respect to ions is not exactly uniform along the interaction region, especially at its edges, $\alpha_{\text{meas}}(E)$ represents an average of the actual DR rate $\alpha(E)$ over a range of relative electron-ion energies $E$. The measured rate $\alpha_{\text{meas}}(E)$ is linked to the raw DR rate $\alpha(E)$ by the following expression (we will give a detailed description in a future work):

$$\alpha_{\text{meas}}(E) = \frac{1}{L} \int_{\text{int.region}} \alpha(E(x)) \, dx$$  \hspace{1cm} (4)

where the notation $E(x)$ reflects the fact that the relative kinetic energy $E$ depends on the position $x$ in the bending region $b$. The relative energy $E(x)$ can be calculated from $E$ and from the known dependence of the angle $\theta(x)$ between ionic and electron velocities as a function of $x$.

To introduce the toroidal correction into the theoretical DR rate, we took our calculated DR rate and convolved it with the experimental rotational $E_{\text{rot}}$, transverse $E_\perp$ and parallel $E_{\parallel}$ energy distributions. In order to include the toroidal correction properly, we need the higher-energy DR rate above 2 eV, where we have not performed calculations. To this end, we have smoothly joined our theoretical curve below 2 eV with the experimental data above 3.8 eV. We use this dependence as $\alpha(E)$ in (4). The result of this calculation is the effective experimental DR rate coefficient, shown in figure 3.

In the bending region $b$, the contribution from $E_\perp$ is considerably increasing the total collision energy $E$ and this effect can influence the final result for $\alpha_{\text{meas}}(E)$. This effect has not been previously accounted for in our theoretical analysis (except in [19]), although in the experiment an attempted iterative deconvolution was carried out. Such deconvolutions may produce results with large error bars in energy ranges where the DR rate is small, if the full, energy-dependent DR rate is not known in advance.

6. Results

The comparison with the recent experimental data [6] is given in figure 3. The agreement between theory and experiment is quite good and it is significantly better than in [17, 18], where the averaging over $E_{\parallel}$ was not performed and where the toroidal correction was not included. For comparison, we show both theoretical curves in figure 3 to demonstrate the importance of the $E_{\parallel}$ averaging.

The toroidal correction improves considerably the agreement between theory and experiment in the energy region above 0.3 eV. (The theoretical rate is calculated only up to 2 eV). The averaging over $E_{\parallel}$...
significantly smears out sharp resonances present in the theoretical rate. The resulting theoretical curve agrees much better with the experimental one. Therefore, the two additional averagings appear to explain some of the most prominent differences between our original raw theoretical DR rates and those reported in storage-ring experiments.

7. DR rate for individual symmetries

In order to properly perform the rotational frame transformation and to include the Jahn-Teller coupling between vibrational modes and the electron motion, we have to consider the total symmetry of the system. This forced us to account in a consistent manner for the nuclear spin statistics. Because the Jahn-Teller coupling depends strongly on the electronic and vibrational symmetry, the DR rate is quite different for different symmetries of the ion. Figure 4 shows DR rates calculated separately for different symmetries of the ion. The DR rates for individual symmetries could be deserving of study by more detailed experiments, and potentially of interest for astronomers.

8. Conclusion

In this article we have briefly summarized the results of our recent theoretical study [16–19] of H$^+_3$ dissociative recombination. The main results are the following:

- The non-adiabatic coupling between vibrational and electronic degrees of freedom in H$_3$, the Jahn-Teller effect, plays a decisive and even controlling role in determining the DR rate in the $10^{-5}$ eV–2 eV energy range for e$^-$+$\text{H}_3^+$ collisions.
- We have developed two different theoretical approaches that describe the DR process. One approach based on an O’Malley-style resonance model is far simpler than the other one which treats quantum mechanically every degree of freedom in the problem. In principle, both approaches can be used in the DR treatment of other triatomic ions, depending on the degree of sophistication that is desirable for the application at hand.
- The two approaches both predict the DR rate as a function of the collision energy. The results from the two theoretical approaches are in good agreement with the storage ring experiments, although the detailed model predicts a much richer structure of fine resonances that can in principle be observable in high resolution experiments.
• We have accounted for several experimental effects that were not considered previously. Without introducing any unknown quantities into the modeling, we find that proper incorporation of these effects has produced a considerably improved agreement between theory and experiment.

• Finally, we have presented the DR rates calculated individually for all four different symmetries relevant for the target $H_3^+$ ion at low temperatures, which constitutes a prediction that could in principle be tested experimentally one day.

Despite the good agreement that has emerged between theory and the storage ring experiments, the case of $H_3^+$ DR is far from closed. The recent experiments employing the techniques of afterglow plasmas [7–12] still appear to contradict the results from storage ring experiments and our theoretical calculations. This contradiction should be addressed in future studies.

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