DISSOCIATIVE RECOMBINATION of ELECTRONS with MOLECULAR CATIONS: APPLICATION to NO$^+$, CO$^+$, H$_2^+$ and ISOTOPES

$e^- + AB^+ \rightarrow A + B$, $e^- + AB^+$, $e^- + A^+ + B$

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2009/10/05, ADAS meeting
REACTIVE COLLISIONS:

$\text{AB}^+(v') + e^- \quad v' < v$

$\text{AB}^+(v) + e^-$

$\text{AB}^+(v') + e^- \quad v' > v$

$\text{A}^+(n) + \text{B}(n')$

$\text{AB}** @ \text{AB}^*$

$\text{A}^+ + \text{B}^-$

$\text{A}^+ + \text{B} + e^-$

2009/10/05, ADAS meeting
Previous International Conferences
1) Lake Louise, Alberta, Canada (1988),
2) Saint Jacut, Brittany, France (1992),
3) Ein Gedi, Israel (1995),
4) Nässlingen, Stockholm Archipelago, Sweden (1999),
5) Chicago, USA (2001),
6) Mosbach, Germany (2004),

Previous International Conferences
8) Kalamazoo, USA (2010)
9) Le Havre, France (? 2012)
Unified analytic representation of hydrocarbon impurity collision cross-sections

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(3) Dissociative excitation (DE) of $C_xH_y^+$ ions:

$$e + C_xH_y^+ \rightarrow C_{x-k}H_{y-l}^+ + \sum_{\kappa,\lambda} C_{\kappa}H_{\lambda} + e$$

(4) Dissociative recombination (DR):

$$e + C_xH_y^+ \rightarrow \sum_{\kappa,\lambda} C_{\kappa}H_{\lambda}$$
Catalytic mechanism of divertor plasma recombination provided by hydrocarbon impurities

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(ii) ion-conversion (IC) recombination mechanism$^{13,14}$

$$H^+ + H_2(v) \rightarrow H + H_2^+$$

$$e + H_2^+ \rightarrow H + H(n), \quad n \geq 2,$$

2009/10/05, ADAS meeting
Collision Processes in Low-Temperature Hydrogen Plasmas

R.K. Janev\textsuperscript{1,2}, D. Reiter\textsuperscript{1}, U. Samm\textsuperscript{1}

\begin{align*}
H(1s) + H(n) &\rightarrow H_2^+(v) + e, \quad n \geq 2 \quad (51a) \\
&\rightarrow H(1s) + H^+ + e, \quad n \geq 2 \quad (51b)
\end{align*}

and the associative detachment reaction

\[ H^+ + H^- \rightarrow H_2^+(v) + e \] \quad (65)

7.1.1 Vibrational excitation

Since $H_2^+(1s\sigma_g)$ ion is a non-polar system, its electron-impact vibrational excitation

\[ e + H_2^+(v) \rightarrow e + H_2^+(v') \] \quad (174)
Atomic Physics in ITER
The Foundation for the Next Step to Fusion Power

Daren Stotler
Princeton Plasma Physics Lab

The 5th International Conference on Atomic and Molecular Data and Their Applications
Meudon, France, October 15-19, 2006
More Complex $\text{H}_2, \text{H}_2^+$ Behavior

- Lower temperatures $\Rightarrow$ $\text{H}_2$ lifetime extended $\Rightarrow$ undergo additional processes,
  - Including vibrational excitation & de-excitation,
  - $\Rightarrow$ ion conversion: $\text{H}_2(v) + \text{H}^+ \rightarrow \text{H}_2^+ + \text{H}$,
  - Also brings in other species: $\text{H}_3^+, \text{H}^-$.
- Initial predictions were for “Molecule Assisted Recombination” [Krasheninnikov 1997],
  - But, ASDEX-U modeling [Fantz 2001], showed instead “Molecule Assisted Dissociation”!
  - Explicitly modeled transport of vibrationally excited molecules!
- Attempts to fold effects into effective “collisional radiative” rates for $\text{H}_2, \text{H}_2^+$: [Sawada 1995, Greenland 2001, Pigarov 2002].
- [Janev 2003] reviews & assesses current data,
  - More data still needed:
    - State-selective processes involving vibrationally excited states,
    - Impact of rotational excitation on plasma kinetics,
    - Isotope specific data.
  - Sawada has more complete model on the way.
  - Still need to be integrated into comprehensive, simplified model for simulations.
Available cross sections for H$_2^+$ and OTHER cations, BUT:

• Few or not exhaustive (energy, ro-vibrational excitation of the target)
• Permanent update of input molecular data (PEC’s & couplings)
• Need of data for further species/isotopomers
• Need of « new » reactions study:
  * inelastic & superelastic collisions
  * ion-pair production
My coleagues

O. Motapon, *Douala*,

F. O. Waffeu Tamo*, *Le Havre & Douala*

D. R. Backodissa-Kiminou,
*Le Havre*

F. Lique, *Le Havre*

C. Laville,
*Le Havre & Montréal*

2009/10/05, ADAS meeting
COLLABORATIONS

Theory

A. Suzor-Weiner, Ch. Jungen, O. Dulieu, Paris-South University

L. Tchang-Brillet, Paris VI University & Obs. de Paris @ Meudon

A. E. Orel, University of California @ Davis

L. Pichl, International Christian University, Tokyo

J. Tennyson, University College London,

D. Tudorache, Ecole Centrale de Paris

Experiment

A. Wolf, D. Zajfman, D. Schwalm & team, MPIK & Weizmann Inst.

X. Urbain, Louvain la Neuve Catholic University

M. Larsson & team, Stockholm University

Kinetics

A. Bultel, P. Vervisch, B. Chéron, CORIA, Rouen University

2009/10/05, ADAS meeting
**Multichannel Quantum Defect Theory:** Seaton, Fano, Jungen, Green, Suzor-Weiner, ...

**DIRECT**

dissociative state

\[ e + AB^+ \rightarrow AB^{**} \rightarrow A^* + B \]

**BOUND STATE**

**INDIRECT**

\[ U_{nl\lambda}(R) = U^+(R) - \frac{Ryd}{[n - \mu_{nl\lambda}(R)]^2} \]

*If* \( n \geq n_0, \mu_{nl\lambda} \approx \mu_{l\lambda} \) (energy independent) **ALMOST...!?**

2009/10/05, ADAS meeting
TARGET in its GROUND STATE
Figure 5: $CO^+$ DR cross sections: Direct process in blue and, total process in magenta in which we can see the manifestation of Rydberg series as resonances. In black and green, the experiment results of Mitchell and Rosen respectively.
Figure 7: Anisotropic rate coefficients. Rosen experiment results are in green. Our theoretical results are in magenta for all symetries and in black for the $^1\Sigma^+$ CO symetrie which represents very well the shape of expériment results.

2009/10/05, ADAS meeting
HD$^+$

Waffeu Tamo, Buhr et al 2004-2008

$N_i^++v_i^+=0$
Collision experiments at TSR

2009/10/05, ADAS meeting
CROSS SECTION DEPENDENCY on ROTATIONAL EXCITATION of the TARGET

2009/10/05, ADAS meeting
**HD⁺ DR, vibrationally relaxed**

*Waffeu Tamo, Buhr et al 2004-2008*

**HD⁺**

**Fig. 5.3:** *Contribution des états rotationnels \( N_i^+ = 0, 1, 2, 3, 4, 5 \) (brun, orange, vert, turquoise, violet, noir, respectivement) au taux de recombinaison dissociative des ions HD⁺ (calculs MQDT (bleu) et expérience(rouge)).*
Rotational Cooling of HD$^+$ Molecular Ions by Superelastic Collisions with Electrons

D. Shafir,¹  S. Novotny,²  H. Buhr,²  S. Altevogt,²  A. Faure,³  M. Grieser,²  A. G. Harvey,⁴  O. Heber,¹  J. Hoffmann,²  H. Kreckel,²  L. Lammich,²  I. Nevo,¹  H. B. Pedersen,²  H. Rubenstein,¹  I. F. Schneider,⁵  D. Schwalm,¹,²  J. Tennyson,⁴  A. Wolf,²  and D. Zajfman¹

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HD$^+$

\[
\begin{align*}
\text{Experimental results} & \quad n_e = 1.0 \times 10^7 \text{ cm}^{-3} \\
\text{Calculated results} & \\
\end{align*}
\]
\[ \tilde{\alpha}_0 = 3.8 \pm 0.1 \quad \tilde{\alpha}_3 = 4.0 \pm 0.2, \quad \text{and} \quad \tilde{\alpha}_6 = 9.0 \pm 1.3 \]

in units of \(10^{-8}\) cm\(^3\)/s. The total DR rate coefficients

Fig. 2. Note that this result constitutes another example for the \(J\) dependence of the DR cross section of molecular hydrogen ions [5], and that these values compare favorably, in particular, when taking the error of the absolute DR scale of 20\% into account, to the corresponding averaged values of \(5.3\), \(4.0\), and \(10.3 \times 10^{-8}\) cm\(^3\)/s, respectively, derived within the MQDT approach [16].

**HD\(^+\)**

2009/10/05, ADAS meeting
Decisive role of rotational couplings in the dissociative recombination and superelastic collisions of $\text{H}_2^+$ with low-energy electrons

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Boîte Postale 540, 76058, Le Havre, France
(Received 28 December 2007; published 20 May 2008)
Partial and average rate coefficients for $v_i^+=1$

(a) DR

(b) SEC (1 $\rightarrow$ 0)
FIG. 1. Rate coefficients for dissociative recombination from $v_i^+ = 0$. Dashed line, theory without rotation [22]; full line, theory with rotation; squares, experiment [24]. Better agreement with experiment is found in the rotational case. Also a sensitivity with respect to the quantum defect is observed.
CROSS SECTION DEPENDENCE on VIBRATIONAL EXCITATION of the TARGET

2009/10/05, ADAS meeting
Reactive collisions between electrons and NO$^+$ ions: rate coefficient computations and relevance for the air plasma kinetics
\[ \text{H}_2^+ \]

**TABLE I.** Rate coefficients for dissociative recombination of \( \text{H}_2^+ \) with electrons of near-zero kinetic energy.

<table>
<thead>
<tr>
<th>( v_i^+ )</th>
<th>Theory [22] ( (10^{-8} \text{ cm}^3/\text{s}) )</th>
<th>Theory (this work) ( (10^{-8} \text{ cm}^3/\text{s}) )</th>
<th>Experiment [24] ( (10^{-8} \text{ cm}^3/\text{s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.47</td>
<td>1.12</td>
<td>1.87 ( \pm ) 0.15</td>
</tr>
<tr>
<td>1</td>
<td>17.16</td>
<td>8.31</td>
<td>18.7 ( \pm ) 11.2</td>
</tr>
<tr>
<td>2</td>
<td>5.16</td>
<td>5.37</td>
<td>15.3 ( \pm ) 9.5</td>
</tr>
<tr>
<td>3</td>
<td>9.61</td>
<td>16.46</td>
<td>18.0 ( \pm ) 11.5</td>
</tr>
<tr>
<td>4</td>
<td>9.17</td>
<td>14.90</td>
<td>9.9 ( \pm ) 6.3</td>
</tr>
</tbody>
</table>
\( \text{H}_2^+ \)

**TABLE II.** Rate coefficients for superelastic collisions of \( \text{H}_2^+ \) with electrons of near-zero kinetic energy.

<table>
<thead>
<tr>
<th>( v \rightarrow v' )</th>
<th>Experiment [23] (10^{-8} \text{ cm}^3/\text{s})</th>
<th>Theory [22] (10^{-8} \text{ cm}^3/\text{s})</th>
<th>Theory (this work) (10^{-8} \text{ cm}^3/\text{s})</th>
<th>Experiment [24] (10^{-8} \text{ cm}^3/\text{s})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ( \rightarrow ) 0</td>
<td>60</td>
<td>4.47</td>
<td>18.82</td>
<td>39 ± 8</td>
</tr>
<tr>
<td>2 ( \rightarrow ) 1</td>
<td>120</td>
<td>16.95</td>
<td>38.48</td>
<td>76 ± 16</td>
</tr>
<tr>
<td>2 ( \rightarrow ) 0</td>
<td></td>
<td>3.15</td>
<td>3.48</td>
<td></td>
</tr>
<tr>
<td>3 ( \rightarrow ) 2</td>
<td>220</td>
<td>9.61</td>
<td>52.16</td>
<td>121 ± 26</td>
</tr>
<tr>
<td>3 ( \rightarrow ) 1</td>
<td></td>
<td>6.73</td>
<td>11.42</td>
<td></td>
</tr>
<tr>
<td>3 ( \rightarrow ) 0</td>
<td></td>
<td>1.70</td>
<td>1.67</td>
<td></td>
</tr>
<tr>
<td>4 ( \rightarrow ) 3</td>
<td>240</td>
<td>27.20</td>
<td>94.03</td>
<td>146 ± 30</td>
</tr>
<tr>
<td>4 ( \rightarrow ) 2</td>
<td></td>
<td>2.61</td>
<td>16.31</td>
<td></td>
</tr>
<tr>
<td>4 ( \rightarrow ) 1</td>
<td></td>
<td>3.78</td>
<td>5.26</td>
<td></td>
</tr>
<tr>
<td>4 ( \rightarrow ) 0</td>
<td></td>
<td>1.07</td>
<td>1.18</td>
<td></td>
</tr>
</tbody>
</table>

2009/10/05, ADAS meeting
Work in PROGRESS

(since ADAS/2008 @ Juelich)
Rotational (DE-)EXCITATION

\[ \text{Cross sections (cm}^2\text{)} \]

\[ \begin{align*}
0 \rightarrow 2 & \quad 10^{-13} \\
1 \rightarrow 3 & \quad 10^{-14}
\end{align*} \]

\[ \text{Energy of the incident electron (eV)} \]

- Faure & Tennyson, MNRAS 2001
- MQDT

\[ \text{H}_2^+ \]
H$_2^+$ Dissociative Excitation

D. BACKODISSA (2008)

2009/10/05, ADAS meeting
Energie (hartree) vs Distance internucléaire (bohrs)

- 2-sigma-g(+)
- 2-pi-u
- 2-sigma-u(+)

Fondamental électronique

J. Tennyson, 2008
DR and DE cross sections (cm$^2$)
(In the last panel, DE cross sections are presented in linear scale)

\[ \text{H}_2^+ \]
Anisotropic fragmentation in low-energy dissociative recombination

S. Novotny¹, H. Rubinstein², H. Buhr¹,², O. Novotný¹, J. Hoffmann¹, M.B. Mendes¹, D.A. Orlov¹, M.H. Berg¹, M. Froese¹, A.S. Jaroshevich¹,³, B. Jordon-Thaden¹, C. Krantz¹, M. Lange¹, M. Lestinsky¹, A. Petrignani¹, I.F. Schneider⁴, D. Shafir², F.O. Waffeu Tamo⁴, D. Zajfman², D. Schwalm¹,² and A. Wolf¹

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³Institute of Semiconductor Physics, 630090 Novosibirsk, Russia
⁴University of Le Havre, 76058 Le Havre, France

In press, 2009
HD$^+$ @ LOW energy: theory vs experiment

ANGULAR distribution of the dissociation products

**Novotny et al 2006: TSR, imaging**

**Waffeu Tamo & Schneider 2006-2007: MQDT modelling**

\[ V_{el}^m(k_e, \hat{R}) = \sum_{\ell = |m|}^{\infty} V_{\ell m}(k_e, R) Y_{\ell m}(\hat{R}), \quad (11) \]
Compare latest MQDT results on angular distribution with 2D data
(July 2006)

\[ E_e = 75.10 \text{ meV}; \ T_{\text{rot}} = 360 \text{ K} \]

2009/10/05, ADAS meeting
Dissociative recombination of CF⁺:
experiment and theory

O Novotný¹, O Motapon², M H Berg¹, D Bing¹, H Buhr¹,³, H Fadil¹,
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⁶ Department of Applied Science, University of California at Davis, Davis CA 95616 USA

In press, 2009  CF⁺

2009/10/05, ADAS meeting
RESULTS vs EXPERIMENTS

Maxwell ISOTROPIC rate coefficients

Maxwell ANISOTROPIC rate coefficients
The « H$_2^+$ DR project »

Collaboration with Ch. Jungen, C. H. Greene, J. Tennyson

- MQDT « global » treatment
  - States and couplings from self-consistent computations
  - Energy dependence of couplings and quantum defects
- « Total » rotational treatment (including SPIN)
- Angular distribution
Comparaison with the photo-dissociation calculations of Christian JUNGEN

$H_2^+$

$N_{i}^+=1$, $v_{i}^+=0$
« Ultimate » aim:

to provide MORE & BETTER data than this:…
Reactive collisions between electrons and molecular hydrogen cation isotopomers: Cross-sections and rate coefficients for HD$^+$ and DT$^+$

M.C. Stroe$^1,2$, M. Fifirig$^3$, F.O. Waffeu Tamo$^1,3$, O. Motapon$^3$, O. Crumeyrolle$^1$, G. Varin-Breant$^1$, A. Bultel$^4$, P. Vervisch$^4$, A. Suzor-Weiner$^5$, I.F. Schneider$^4$

1 Laboratoire de Mécanique, Physique et Géosciences, Université du Havre, F-76058 Le Havre, France
2 Department of Physics, Faculty of Chemistry, University of Bucharest, RO-70346 Bucharest, Romania
3 Center for Atomic, Molecular Physics and Quantum Optics, University of Douala, 00237 Douala, Cameroon
4 Laboratoire CORIA, Université de Rouen, F-76801 Saint-Étienne du Rouvray, France
5 Laboratoire de Photophysique Moléculaire, Université Paris-Sud, 91405 Orsay, France
Figure 6. Reactive collisions of DT\textsuperscript{+} molecular ion in a given vibrational state $v$ with electrons (cross-sections): bold line — DR, broken line — DE, dashed dotted line — elastic collisions (EC), grey line — superelastic collisions (SEC) and thin line — inelastic collisions (IC). The numbers attached to the IC and SEC curves stand for the final vibrational states.
Thanks for your attention!

ADAS meeting
Why storage rings?

\[ T_{\text{long}} = 20 \ \mu\text{eV} = 0.23 \ \text{K} = 0.16 \ \text{cm}^{-1} \]
\[ T_{\text{trans}} = 500 \ \mu\text{eV} = 5.80 \ \text{K} = 4.03 \ \text{cm}^{-1} \]

1) high luminosity, 2) high resolution, 3) variable relative energy, 4) low background
...... 5) quenching of vibrationally excited states for molecular ions.

Neutral-particle emission in collisions of electrons with biomolecular ions in an electrostatic storage ring

T Tanabe,1 K Noda,2 M Saito,1 H Takagi,1 E B Starikov1 and M Tateno2

Institute of Physics Publishing
doi:10.1088/1742-6596/4/1/035


Sixth International Conference on Dissociative Recombination

2009/10/05, ADAS meeting
The ANISOTROPIC Maxwell distribution function

\[ \alpha = \left< v\sigma \right> = \int \int \sigma(v) v f(v_d, v) dv \] (1)

\[ f(v_d, v) = \frac{m}{2\pi k T_{e\perp}} \exp\left(-\frac{mv^2_{\perp}}{2k T_{e\perp}}\right) \sqrt{\frac{m}{2\pi k T_{e\parallel}}} \exp\left(-\frac{m(v_{\parallel} - v_d)^2}{2k T_{e\parallel}}\right) \] (2)
Experiments: MULTIPLE pass/MERGED beams- STORAGE RINGS

Rotational distribution in the ion beam

Excitation energy [meV]

rot. population $P(N)$ [%]

rot. quantum number $N^*$

$\Delta t=0.1\ s$
$\Delta t=0.3\ s$
$\Delta t=5\ s$

$T=300\ K$

(\(\Delta t \rightarrow \infty\))

P. Forsk (Thesis), 1994, Heidelberg
Molecular ion recombination in merged beams: experimental results on small systems and future perspectives

M Larsson
Institute of Physics Publishing
doi:10.1088/1742-6596/4/1/007

Dissociative recombination rate coefficient for HD$^+$ ($v = 0$) ions measured at the three storage ring facilities ASTRID, CRYRING and TSR. The electron coolers used have different transverse electron temperatures amounting to 20 meV (ASTRID), 4.5 meV (TSR) and 2 meV (CRYRING).
Experiments: FALP

- QMS chamber
- Langmuir probe
- P=0.8 Torr
- T=300 K
- QMS and probe
- Moving system
- Flow tube
- Ar injection ~1 slpm
- He injection ~20 slpm
- Microwave cavity
- UV excimer laser
  157 nm ~ 7.9 eV
  50 Hz/10 ns, 10 mJ
- Plate coated with PAH
- P=10^-6 Torr
- T=300 K
- Turbomolecular pump
- Roots pump

Rennes

Experiments: FALP

- Novotny,…,Mitchell,… et al 2005

2009/10/05, ADAS meeting
7.4.2 Associative and non-associative detachment

The associative detachment (AD) reaction

$$H_2^+ (v_i) + H^- \rightarrow (H_3^*) \rightarrow H_3^+ (v_3) + e$$  \hfill (222)

8.1 Collision processes of $H_3^+$ with electrons

8.1.1 Vibrational excitation

The electron impact vibrational excitation of $H_3^+ (v_3)$

$$e + H_3^+ (v_3) \rightarrow e + H_3^+ (v'_3)$$  \hfill (225)

$$e + H_3^+ (v_3) \rightarrow e + H_3^{+ \ast} (N^{1,3} \Lambda \sigma; \epsilon) \rightarrow e + H^+ + H (1s) + H (n \geq 1)$$  \hfill (227a)

$$\rightarrow e + H^+ + H_2 (N^{1,3} \Lambda \sigma; v_0)$$  \hfill (227b)

$$\rightarrow e + H_2^+ (v_i) + H (n \geq 1)$$  \hfill (227c)
\[ e + H_3^+ (v_3) \rightarrow (H_3^{**}, H_3^{* Ryd}) \rightarrow H_2 (X^1\Sigma_g^+; v_0) + H (n \geq 1) \quad (229a) \]
\[ \rightarrow \quad 3H (1s) \quad (229b) \]
\[ e + H_3^+ (v_3) \rightarrow (H_3^{**}) \rightarrow H_2^+ (v_i) + H^- . \quad (234) \]
Example of data needs
For H$_2^+$ & isotopomers: ...
Janev, Fantz, Reiter 2005

The chain of reactions, which played the key role in these arguments, was, firstly, a vibrational excitation of molecules by electron impact (through resonant $H_2^-$ levels), then, secondly, an ion conversion: $p + H_2(v) \rightarrow H + H_2^+$, followed by, thirdly, an immediate dissociative recombination: $e + H_2^+ \rightarrow H + H^*$. The excited atom decays by spontaneous emission. At the end of

The dominant electron-impact process at low collision energies is the dissociative recombination

$$e + H_2^+(X, v) \rightarrow H_2^{**}(2p\sigma_u^2) \rightarrow H(1s) + H(n \geq 2) \quad (19.52)$$

which has been subject to many experimental [78] and theoretical [79, 80] studies. The most detailed cross-section calculations of reactions (19.52) have been performed in [80] by using the multi-channel quantum defect theory (MQDT). The $n$-distribution of excited products from reaction (19.52) obtained in MQDT calculations support the earlier semi-empirical assessment [14], at least for the lower $v$-states.

At higher collision energies, the most important electron-impact processes of $H_2^+(X; v)$ are

$$e + H_2^+(X^2\Sigma_g^+, v) \rightarrow e + H_2^+(N^2\Lambda)^{\text{diss}} \rightarrow e + H^+ + H(n), \quad N \geq 2, \ n \geq 1 \quad (19.55)$$

$$e + H_2^+(X; v) \rightarrow e + H^+ + H + e \quad (19.56)$$
7.1.2 Dissociative excitation

The simplest mechanism of dissociative excitation (DE) of \( H_2^+ (X^2\Sigma_g^+; v) \) ion by electron impact is its excitation to the two lowest dissociative excited states, \((2p\sigma_u,^2\Sigma_u^+)\) and \((2p\pi_u,^2\Pi_u)\),

\[
e + H_2^+ (v) \rightarrow e + H_2^+ (2p\sigma_u) \rightarrow e + H^+ + H(1s),
\]

\[
e + H_2^+ (v) \rightarrow e + H_2^+ (2p\pi_u) \rightarrow e + H^+ + H(n = 2).
\]

7.1.3 Dissociative recombination

In view of its importance for the recombination of low-temperature plasmas, dissociative recombination (DR) process

\[
e + H_2^+ (v) \rightarrow \{H_2^{**}(\epsilon); H_2^{*\text{Ryd}}(N^{1,3}\Lambda_{\sigma}; \epsilon)\} \rightarrow H(1s) + H(n \geq 2)
\]
Figure 6: Isotropic rate coefficients. Our theoretical results are represented in magenta. In black and green, the experiment results of Mitchell and Rosen respectively.
FIG. 2. Rate coefficients for (a) dissociative recombination and (b) superelastic collisions from $v_i^+ = 1$. Dashed lines, theory without rotation [22]; dash-dotted lines, theory with rotation for $^1\Sigma_g^+ + ^1\Pi_g$; full black lines, theory with rotation for all symmetries; squares, experiment [24]; circle, experiment [23].