DISSOCIATIVE RECOMBINATION of ELECTRONS with MOLECULAR CATIONS: APPLICACTION to NO^+, CO^+, H_2^+ and ISOTOPES

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

Ioan F. SCHNEIDER

Equipe "Instabilités, Turbulence, Plasmas"
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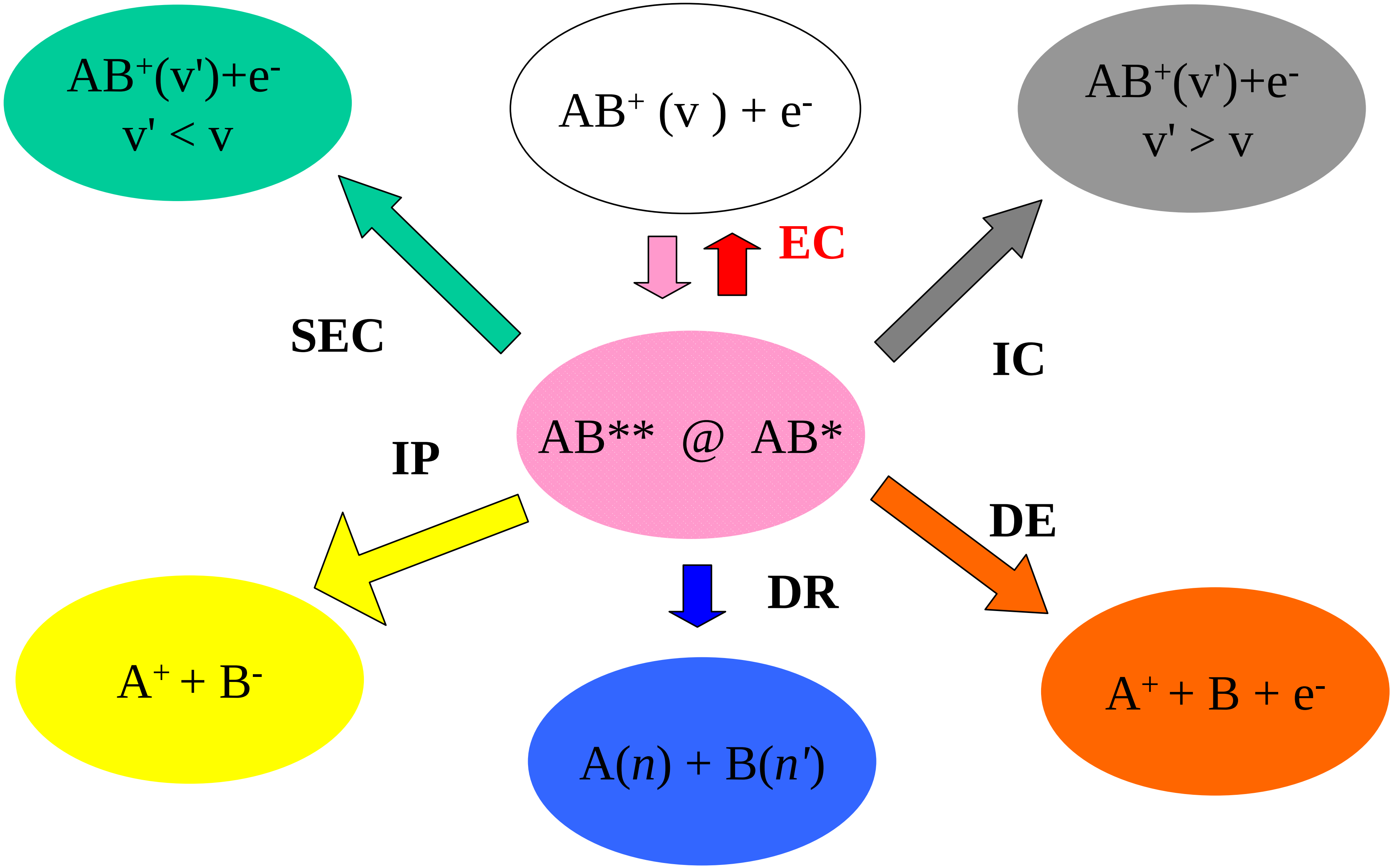
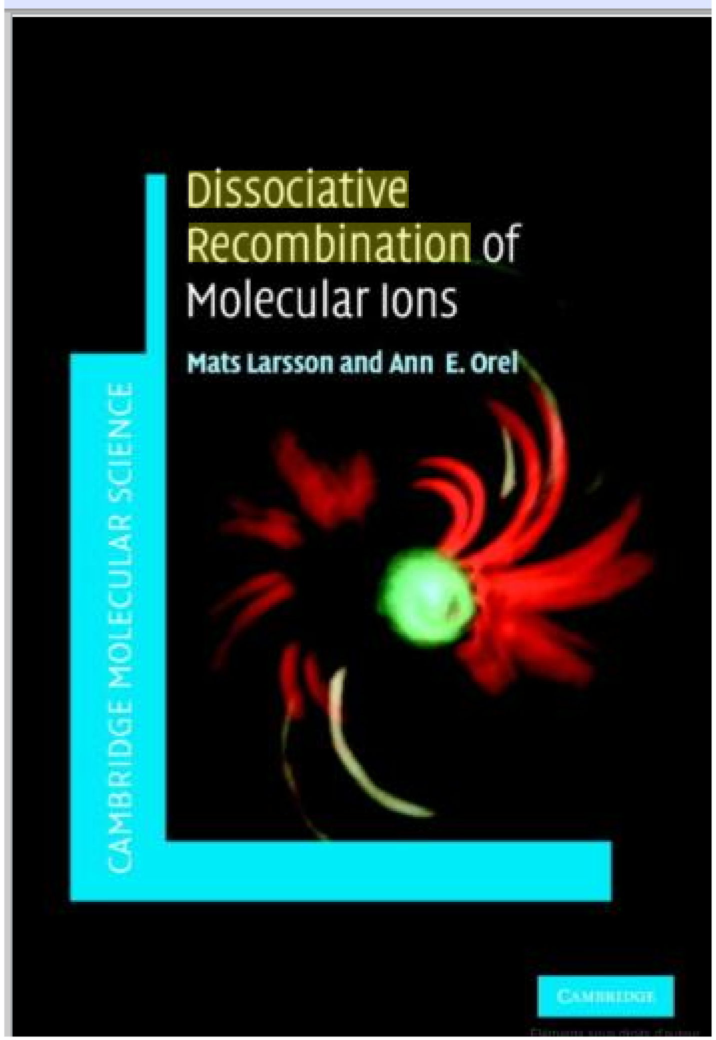
Université du Havre

2009/10/05, ADAS meeting

REACTIVE COLLISIONS:





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),
7) Ameland, Netherlands (2007).

Previous International Conferences

8) Kalamazoo, USA (2010)
9) Le Havre, France (? 2012)

ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 1202–1205

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Unified analytic representation of hydrocarbon impurity collision cross-sections

R.K. Janev [a,b], D. Reiter [a,*]

[a] Institut für Plasmaphysik, Forschungszentrum-Jülich GmbH, EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany

[b] Macedonian Academy of Sciences and Arts, P.O. Box 428, 1000 Skopje, Macedonia

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

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

(4) Dissociative recombination (DR):

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

PHYSICS OF PLASMAS VOLUME 7, NUMBER 11 NOVEMBER 2000

Catalytic mechanism of divertor plasma recombination provided by hydrocarbon impurities

R. K. Janev
National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu 509-5292, Japan and Macedonian Academy of Sciences and Arts, Skopje, Macedonia

T. Kato
National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu 509-5292, Japan

J. G. Wang
National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu 509-5292, Japan and Institute for Applied Physics and Computational Mathematics, Beijing, People's Republic of China

(ii) ion-conversion (IC) recombination mechanism[13,14]

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

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

Report 4105, Juelich, 2006

Collision Processes in Low-Temperature Hydrogen Plasmas

R.K. Janev[1,2], D. Reiter[1], U. Samm[1]

$$H(1s) + H(n) \rightarrow \quad H_2^+(v) + e, \quad n \geq 2 \tag{51a}$$

$$\rightarrow H(1s) + H^+ + e, n \geq 2 \tag{51b}$$

and the associative detachment reaction

$$H^+ + H^- \rightarrow H_2^+(v) + e \tag{65}$$

7.1.1 Vibrational excitation

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

$$e + H_2^+(v) \rightarrow e + H_2^+(v') \tag{174}$$

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 H_2, H_2^+ Behavior

- Lower temperatures ⇒ H_2 lifetime extended ⇒ undergo additional processes,
  - Including vibrational excitation & de-excitation,
  - ⇒ ion conversion: $H_2(v) + H^+ \rightarrow H_2^+ + H$,
  - Also brings in other species: H_3^+, 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 H_2, 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.

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

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

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*

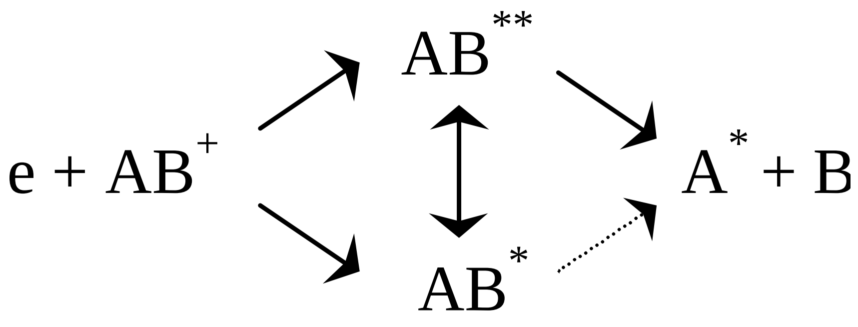
Kinetics

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

Multichannel Quantum Defect Theory: Seaton, Fano, Jungen, Green, Suzor-Weiner, …

DIRECT

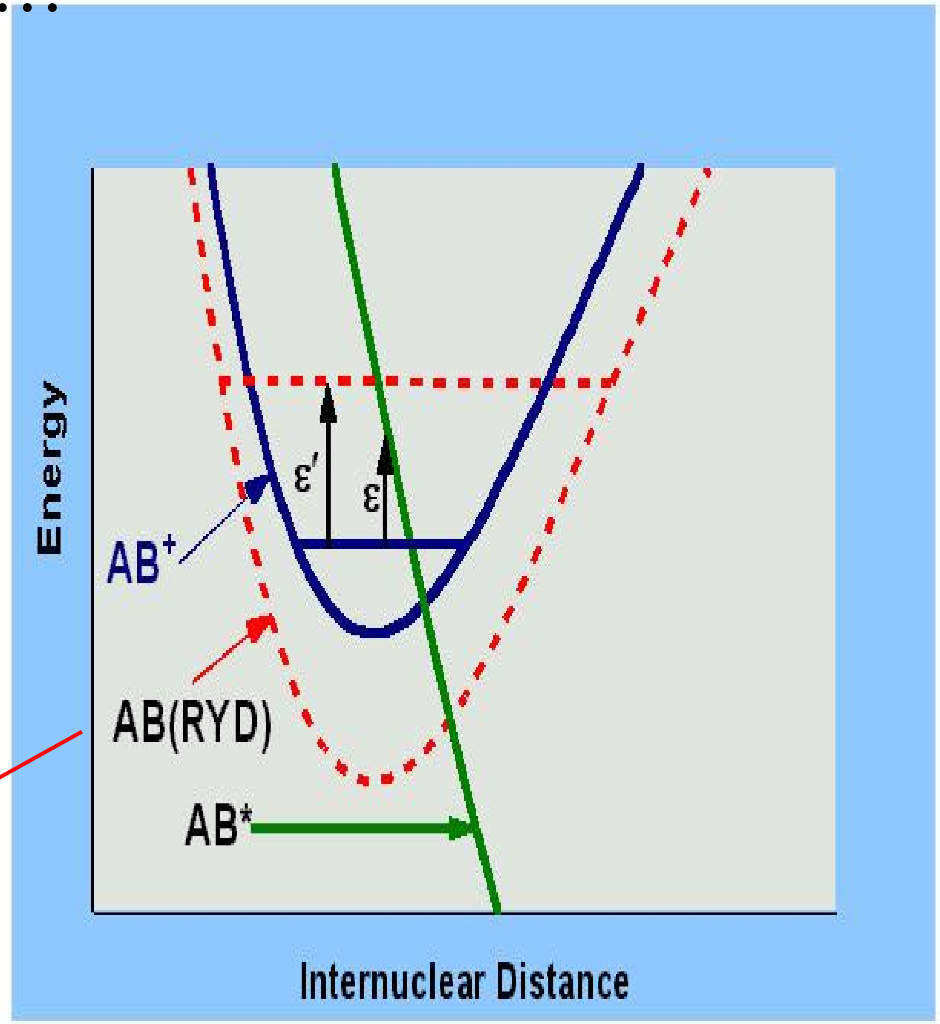
dissociative state



bound state

INDIRECT

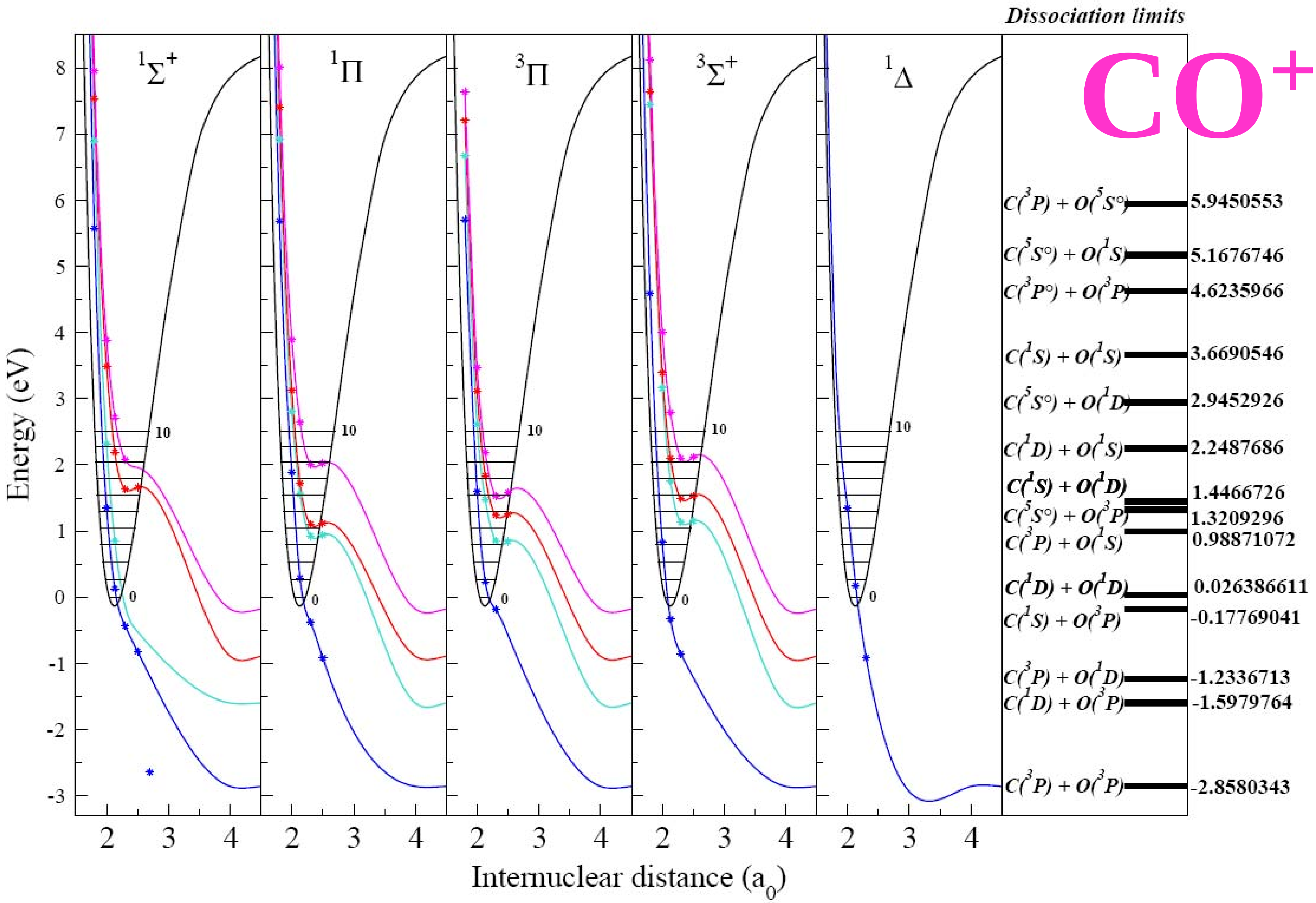
$$U_{nl\lambda}(R) = U^{+}(R) - \frac{Ryd}{[n - \mu_{nl\lambda}(R)]^2}$$



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

TARGET in its **GROUND** STATE

2009/10/05, ADAS meeting


Dissociation limits
CO+
$^1\Sigma^+$
$^1\Pi$
$^3\Pi$
$^3\Sigma^+$
$^1\Delta$
Energy (eV)
Internuclear distance (a_0)
C(3P) + O(5S°) 5.9450553
C(5S°) + O(1S) 5.1676746
C(3P°) + O(3P) 4.6235966
C(1S) + O(1S) 3.6690546
C(5S°) + O(1D) 2.9452926
C(1D) + O(1S) 2.2487686
C(1S) + O(1D) 1.4466726
C(5S°) + O(3P) 1.3209296
C(3P) + O(1S) 0.98871072
C(1D) + O(1D) 0.026386611
C(1S) + O(3P) -0.17769041
C(3P) + O(1D) -1.2336713
C(1D) + O(3P) -1.5979764
C(3P) + O(3P) -2.8580343

CO^+

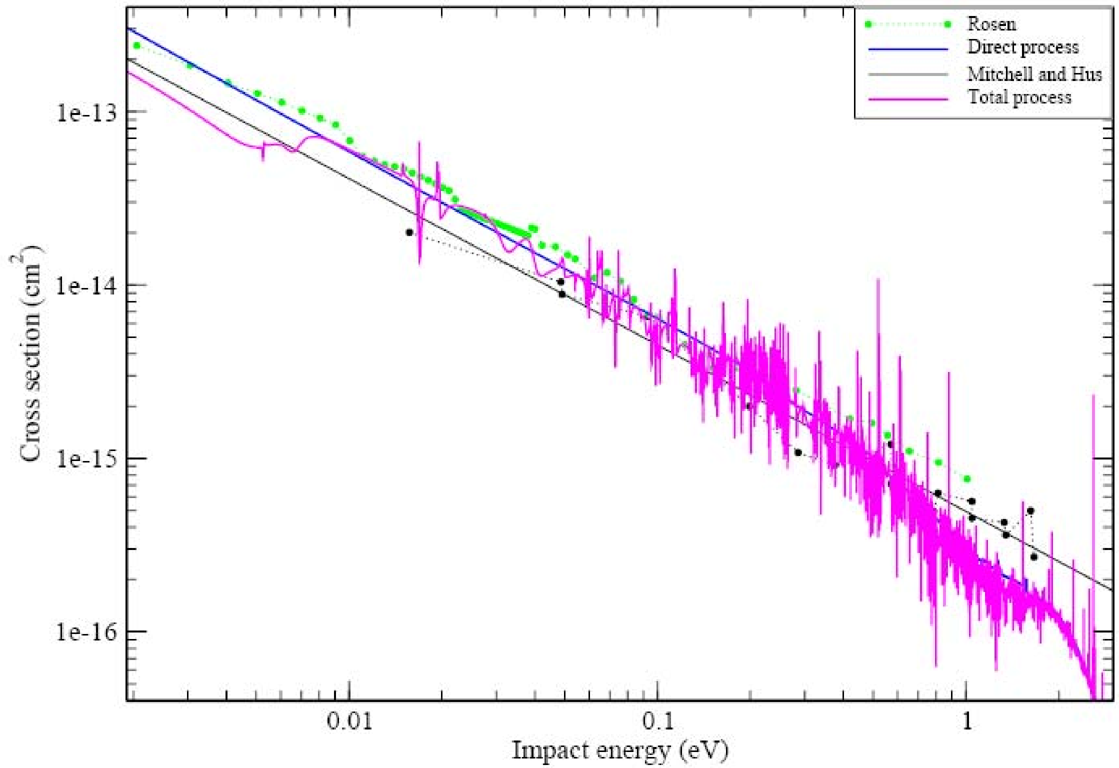


Figure 5: *CO^+ DR cross sections: Direct process in blue and, total process in magenta in which we can see the manifestation of Rydberg series as resonances. In black and green, the experiment results of Mitchell and Rosen respectively.*

CO^+

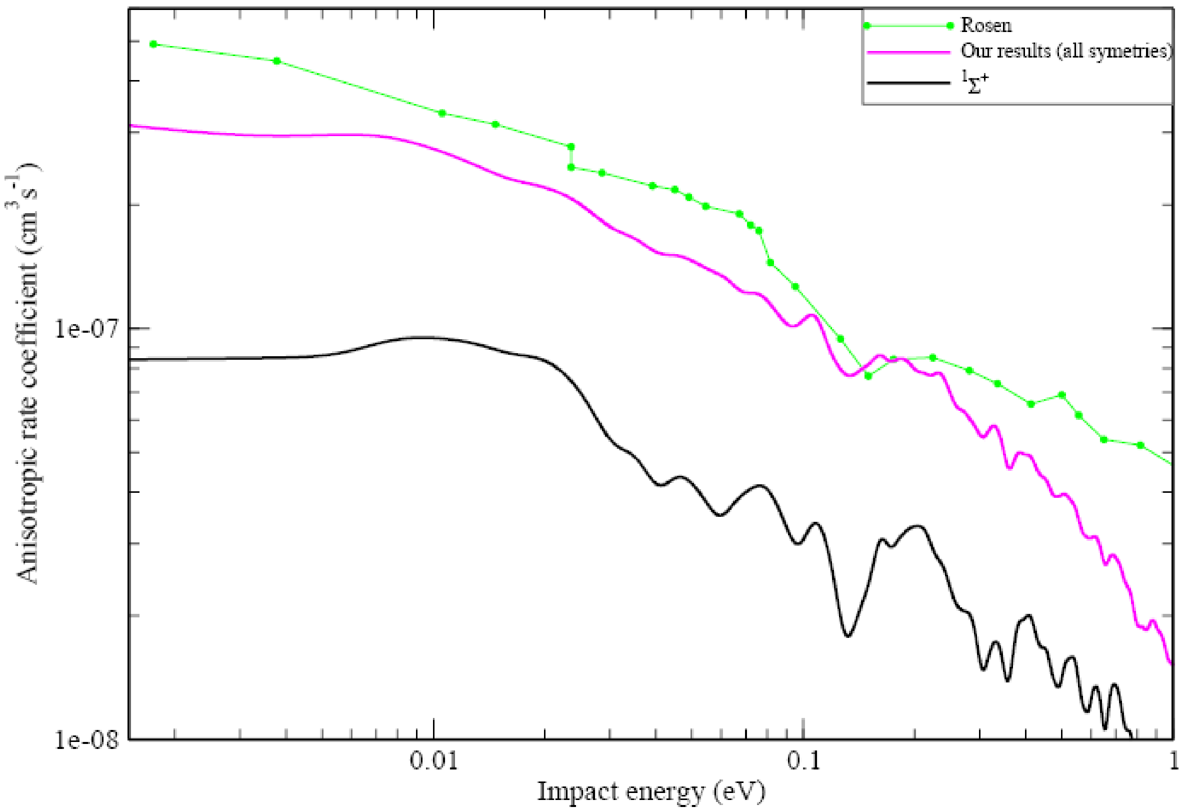


Figure 7: *Anisotropic rate coefficients. Rosen experiment results are in green. Our theoretical results are in magenta for all symetries and in black for the $^1\Sigma^+$ CO symetrie which represents very well the shape of expériment results.*

HD^+

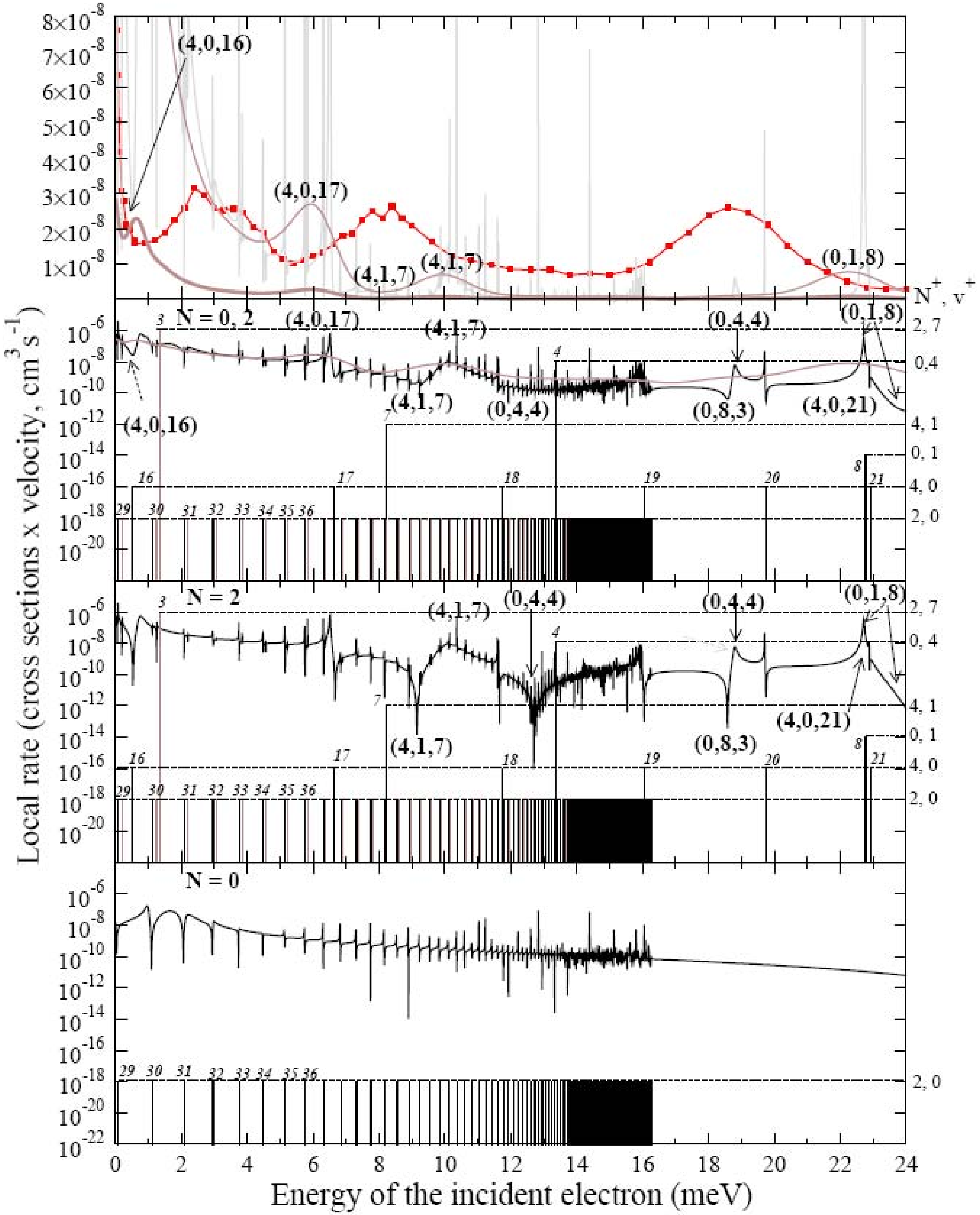
Waffeu Tamo, Buhr et al 2004-2008

$N_i^+=0, v_i^+=0$

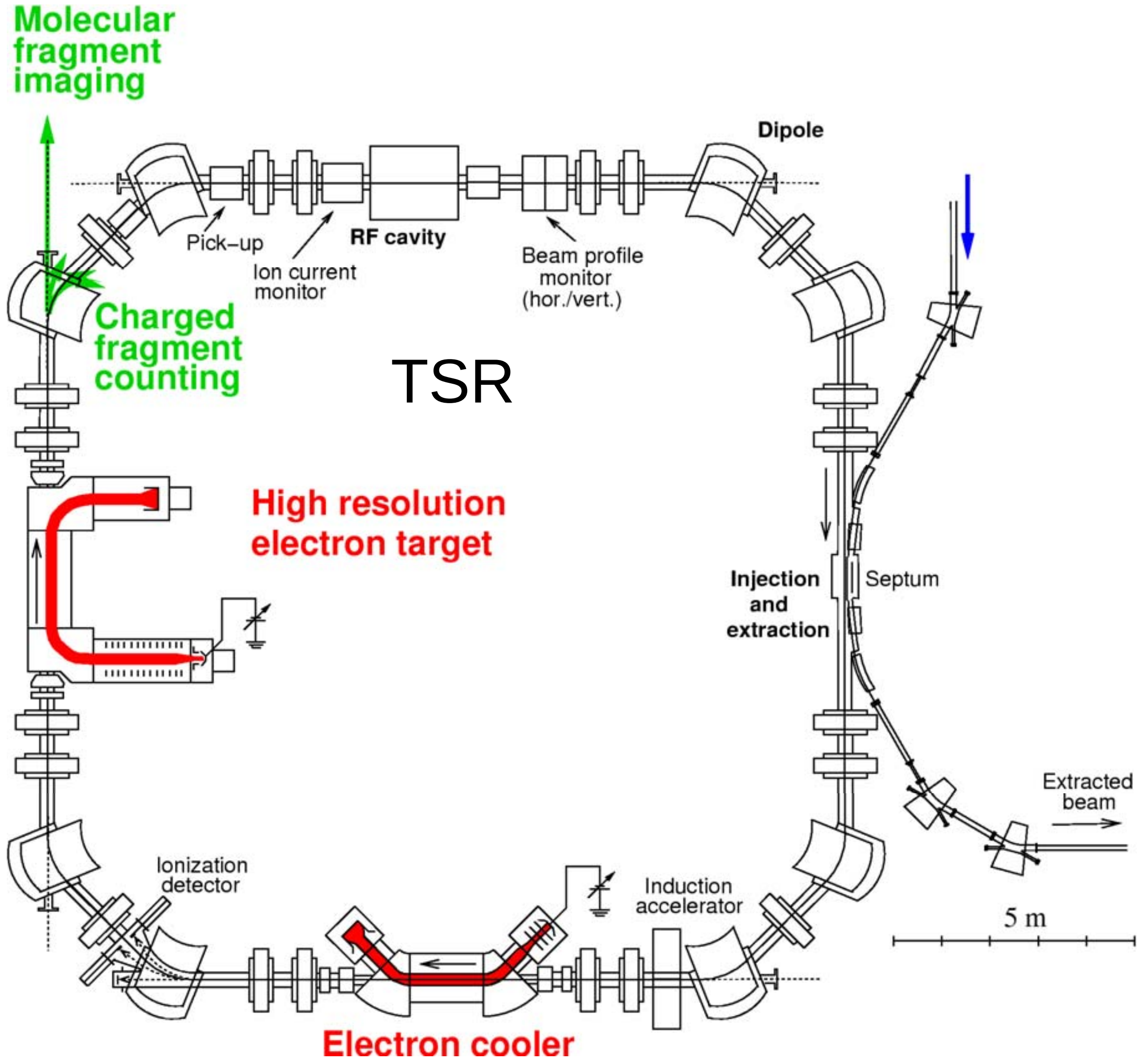
Hyperfine Interact (2006) 172:111–124
DOI 10.1007/s10751-007-9575-7

Progress in stored ion beam experiments on atomic and molecular processes

Andreas Wolf · Henrik Buhr · Manfred Grieser · Robert von Hahn · Michael Lestinsky · Eva Lindroth · Dmitry A. Orlov · Stefan Schippers · Ioan F. Schneider



Collision experiments at TSR



CROSS SECTION DEPENDENCIE on ROTATIONAL EXCITATION of the TARGET

2009/10/05, ADAS meeting

HD^+ DR, vibrationally relaxed

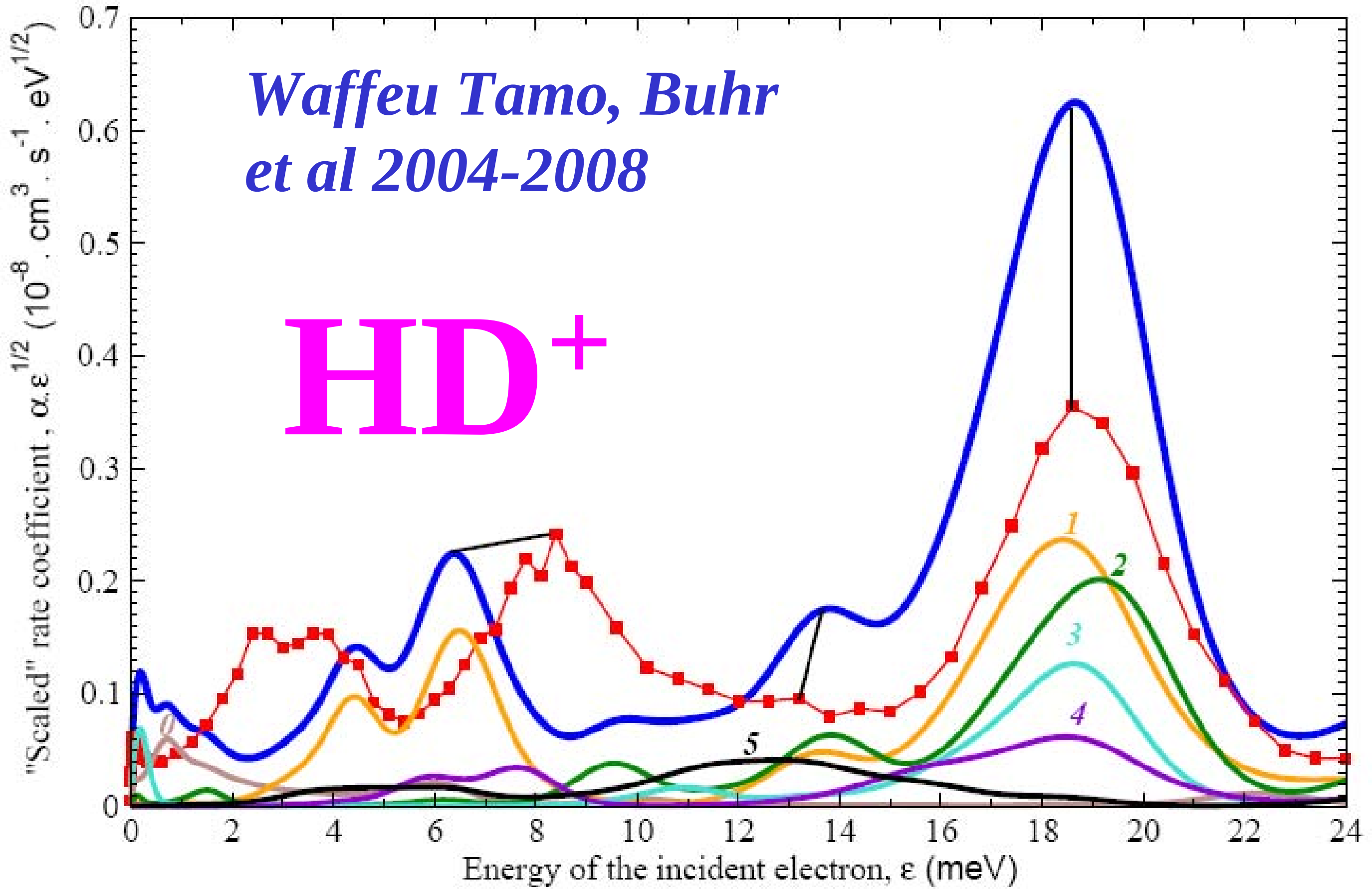


FIG. 5.3: *Contribution des états rotationnels* $N_i^+ = 0, 1, 2, 3, 4, 5$ *(brun, orange, vert, turquoise, violet, noir, respectivement) au taux de recombinaison dissociative des ions* HD^+ *(calculs MQDT (bleu) et expérience(rouge)).*

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. Rubinstein,[1] I.F. Schneider,[5] D. Schwalm,[1,2] J. Tennyson,[4] A. Wolf,[2] and D. Zajfman[1]

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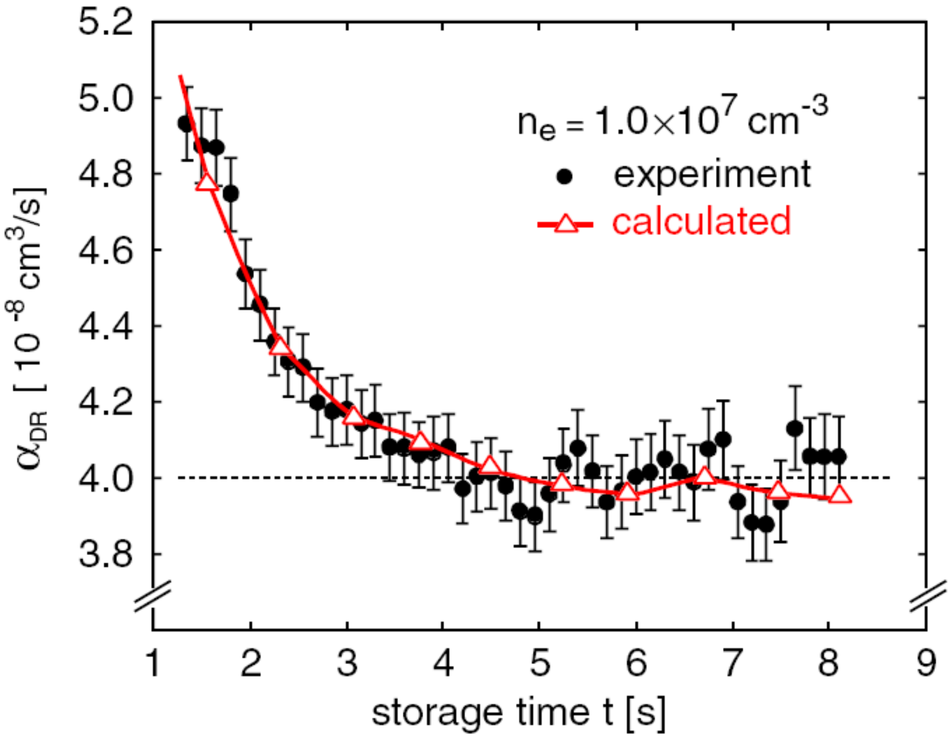
[3]*Laboratoire d'Astrophysique de Grenoble, Université Joseph Fourier, UMR 5571 CNRS, Grenoble, France*
[4]*Department of Physics and Astronomy, University College London, London WC1E6BT, United Kingdom*
[5]*Laboratory of Waves and Complex Media, FRE-CNRS-3102, University of Le Havre, France*

HD^+



$\tilde{\alpha}_0 = 3.8 \pm 0.1, \quad \tilde{\alpha}_3 = 4.0 \pm 0.2, \quad \text{and} \quad \tilde{\alpha}_6 = 9.0 \pm 1.3$

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^+

H_2^+

PHYSICAL REVIEW A **77**, 052711 (2008)

Decisive role of rotational couplings in the dissociative recombination and superelastic collisions of H_2^+ with low-energy electrons

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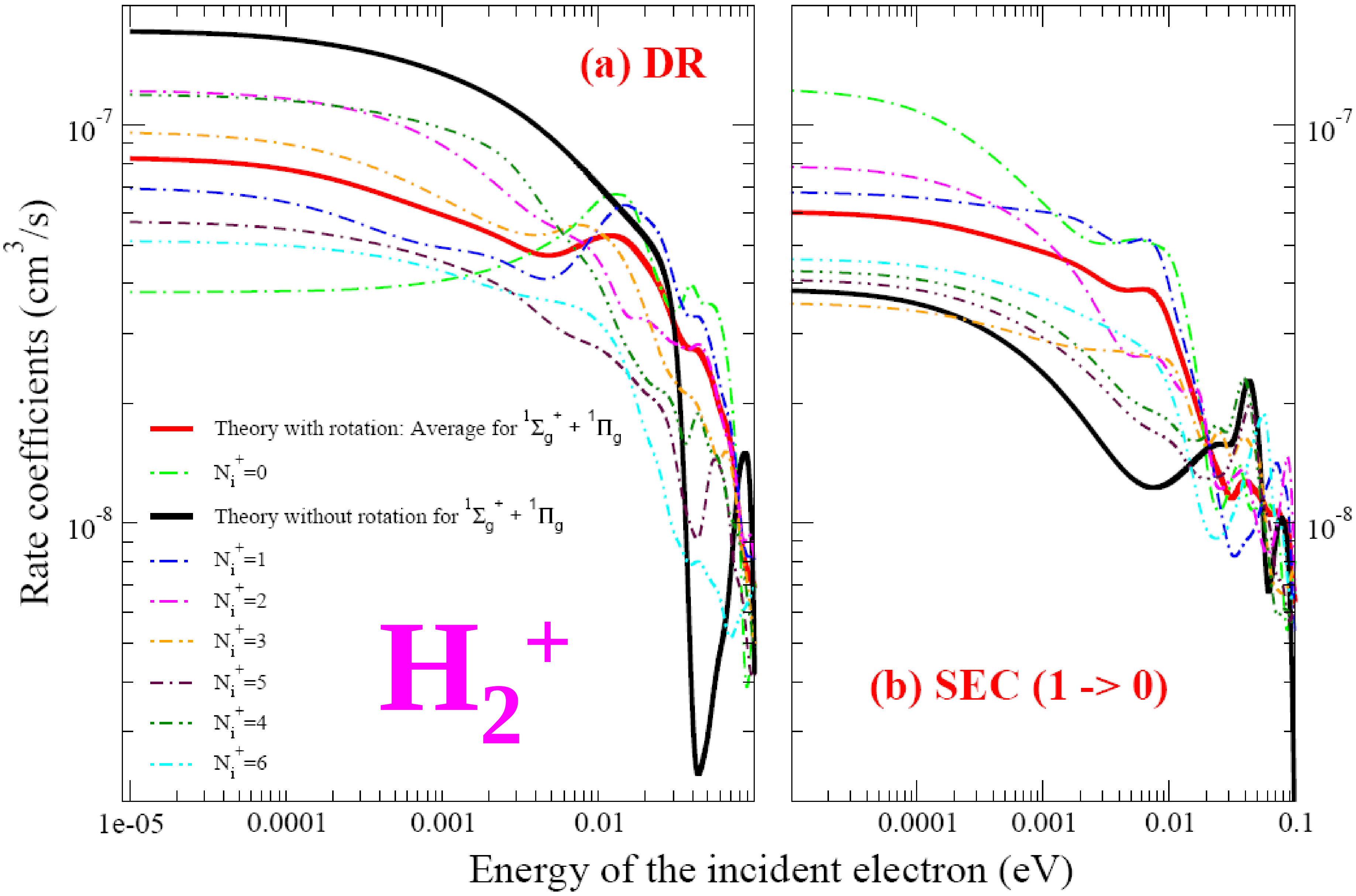
(Received 28 December 2007; published 20 May 2008)

2009/10/05, ADAS meeting

Partial and average rate coefficients for $v_i^+=1$



H_2^+

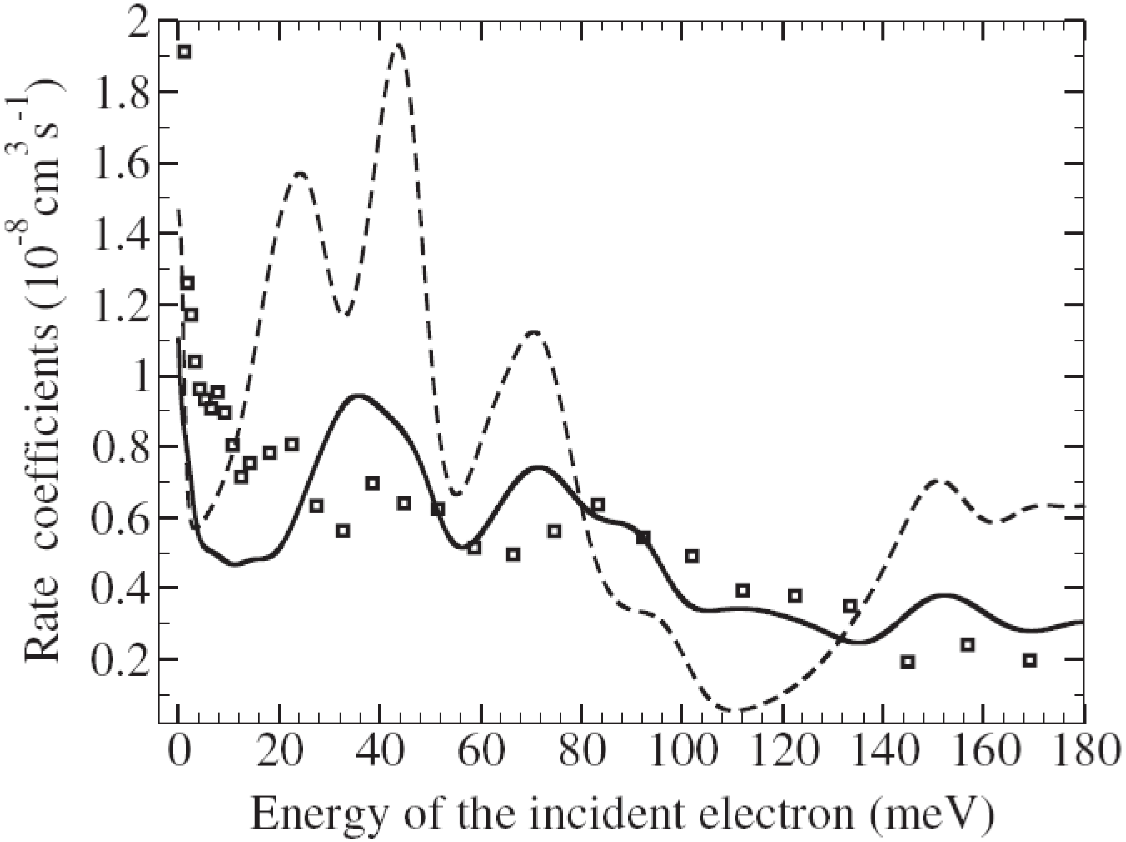


FIG. 1. Rate coefficients for dissociative recombination from $v_i^+ = 0$. Dashed line, theory without rotation [22]; full line, theory with rotation; squares, experiment [24]. Better agreement with experiment is found in the rotational case. Also a sensitivity with respect to the quantum defect is observed.

CROSS SECTION DEPENDENCIE on VIBRATIONAL EXCITATION of the TARGET

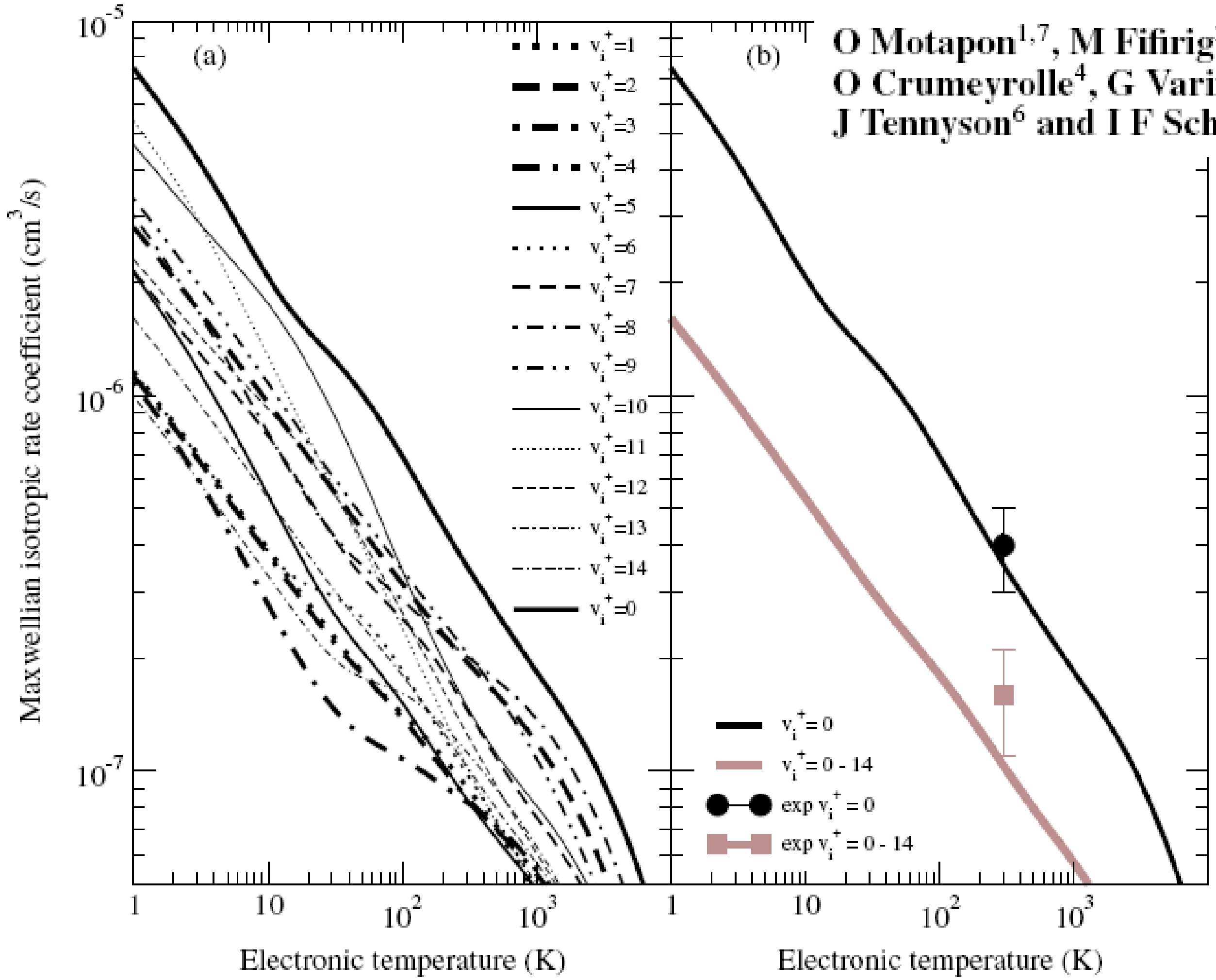
2009/10/05, ADAS meeting

INSTITUTE OF PHYSICS PUBLISHING PLASMA SOURCES SCIENCE AND TECHNOLOGY

Plasma Sources Sci. Technol. 15 (2006) 23–32 doi:10.1088/0963-0252/15/1/004

Reactive collisions between electrons and NO^+ ions: rate coefficient computations and relevance for the air plasma kinetics

O Motapon[1,7], M Fifirig[2], A Florescu[3,8], F O Waffeu Tamo[1,4], O Crumeyrolle[4], G Varin-Bréant[4], A Bultel[5], P Vervisch[5], J Tennyson[6] and I F Schneider[4]



NO^+

H_2^+

TABLE I. Rate coefficients for dissociative recombination of H_2^+ with electrons of near-zero kinetic energy.

v_i^+	Theory [22] (10^{-8} cm^3/s)	Theory (this work) (10^{-8} cm^3/s)	Experiment [24] (10^{-8} cm^3/s)
0	1.47	1.12	1.87 ± 0.15
1	17.16	8.31	18.7 ± 11.2
2	5.16	5.37	15.3 ± 9.5
3	9.61	16.46	18.0 ± 11.5
4	9.17	14.90	9.9 ± 6.3

H_2^+

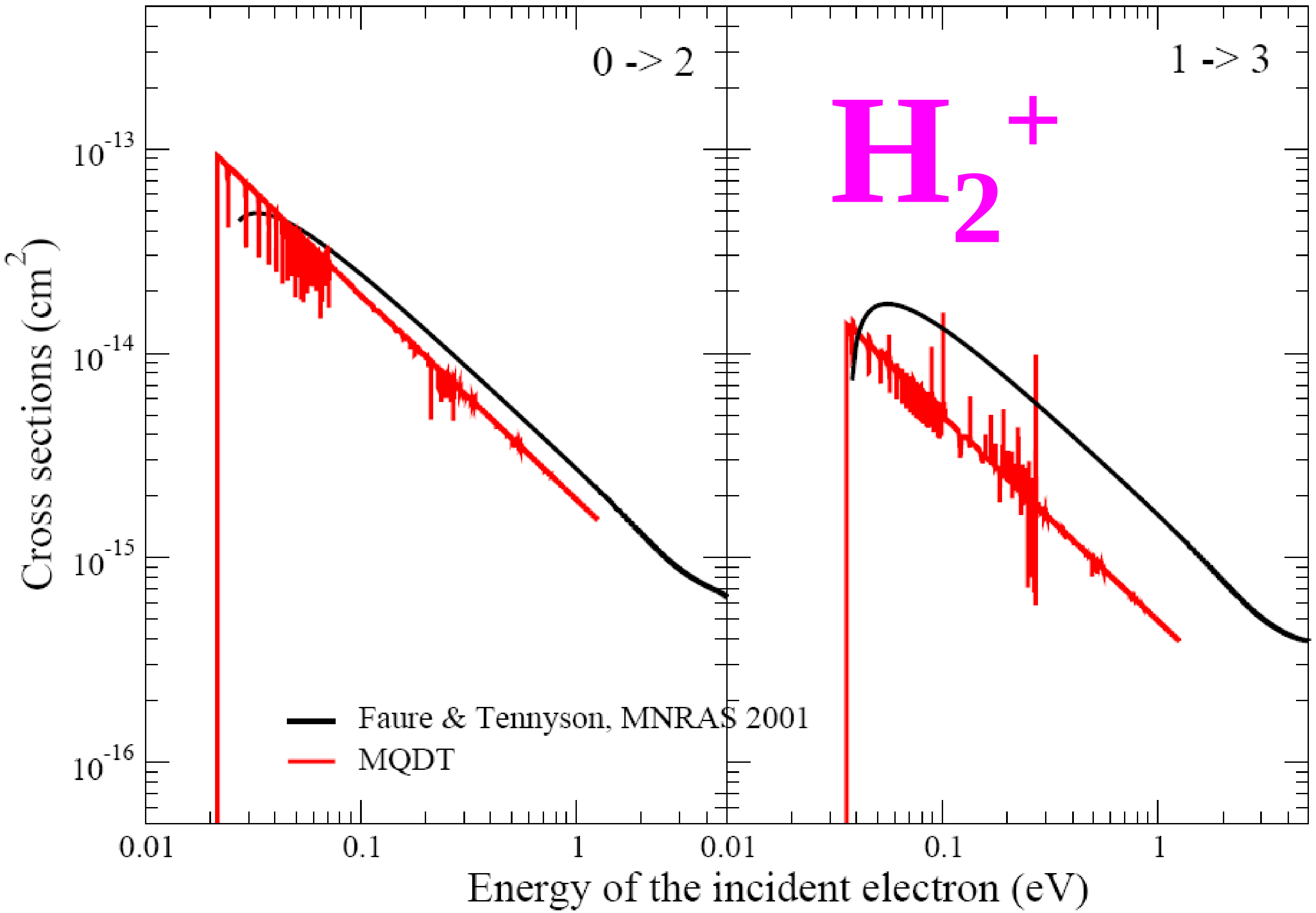
TABLE II. Rate coefficients for superelastic collisions of H_2^+ with electrons of near-zero kinetic energy.

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

Work in PROGRESS

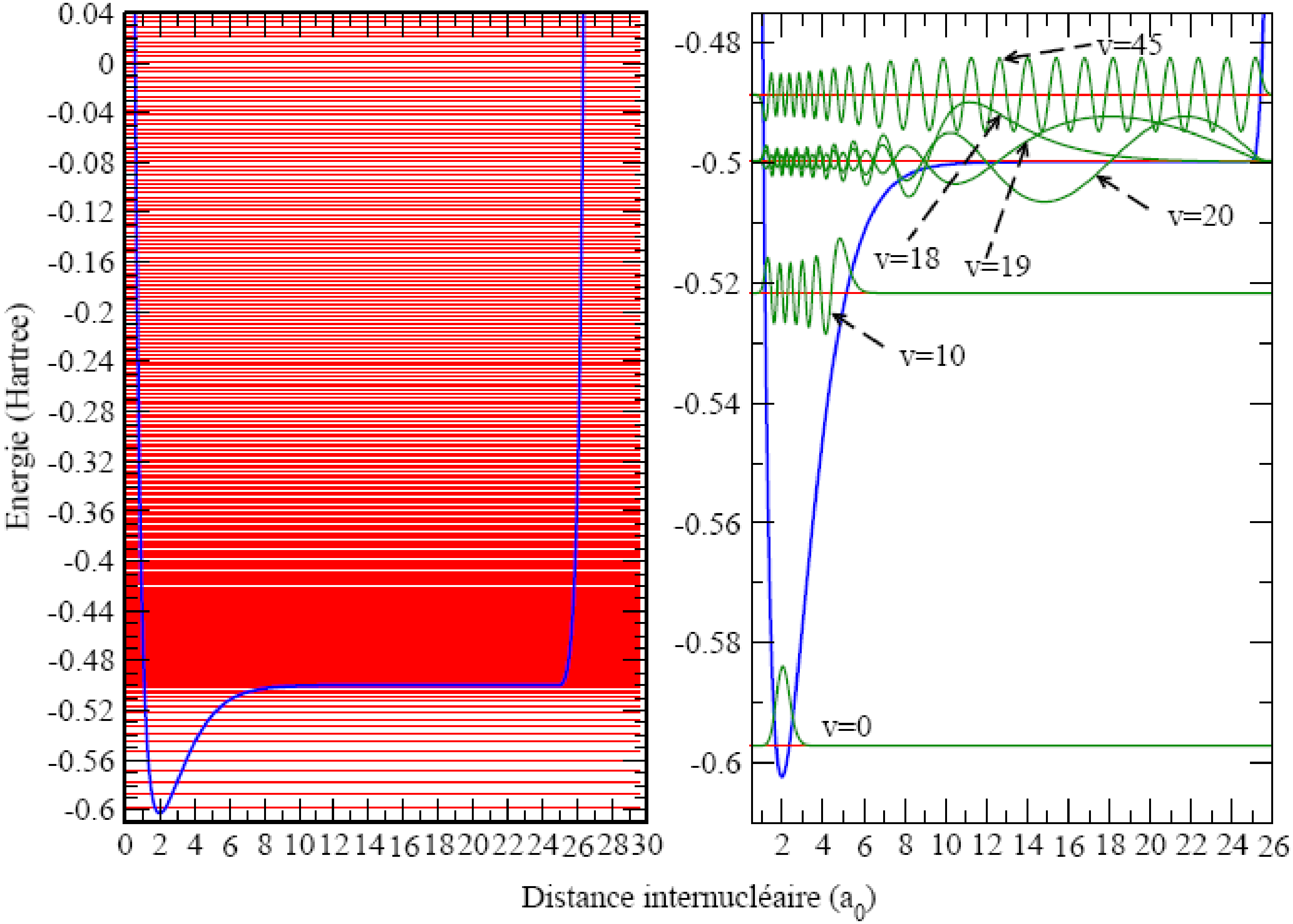
(since ADAS/2008 @ Juelich)

Rotational (DE-)EXCITATION



LABORATOIRE ONDES et MILIEUX COMPLEXES

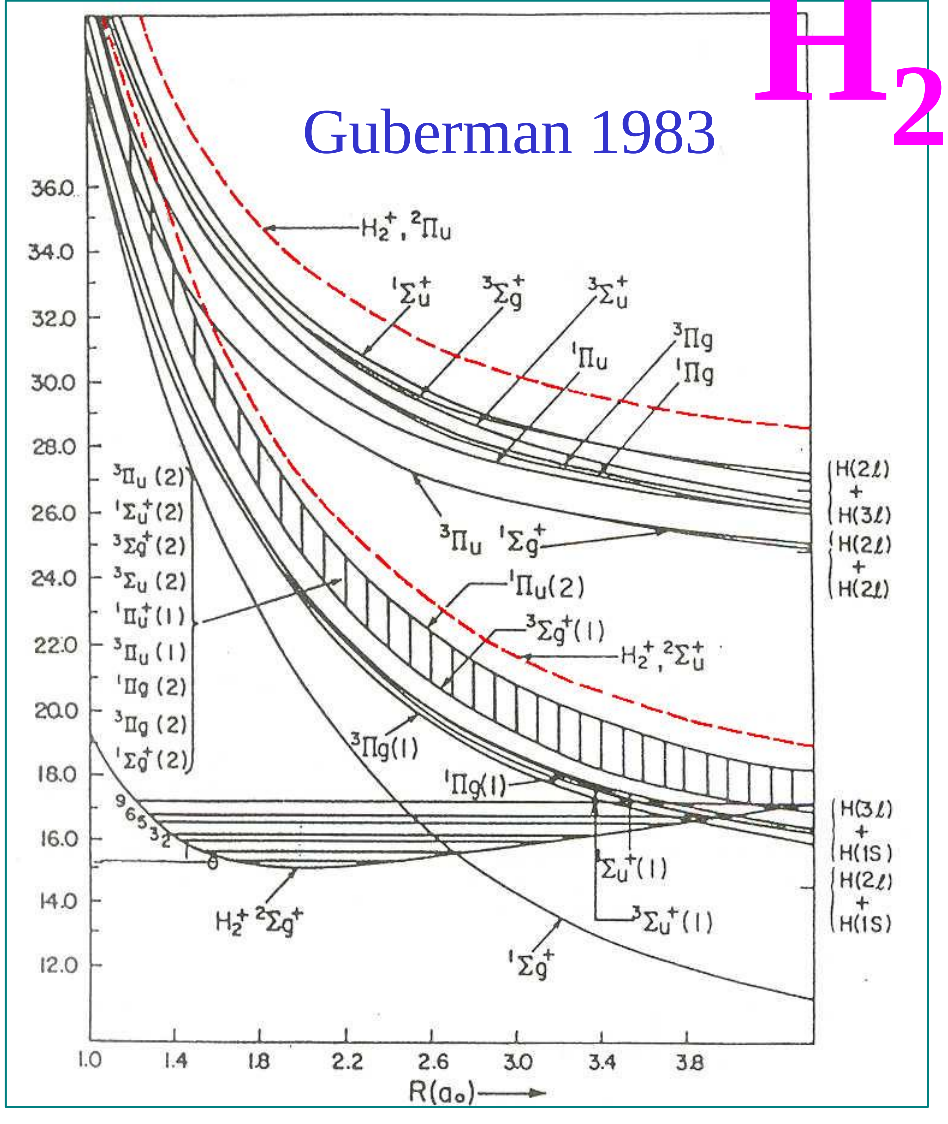
H_2^+ Dissociative Excitation



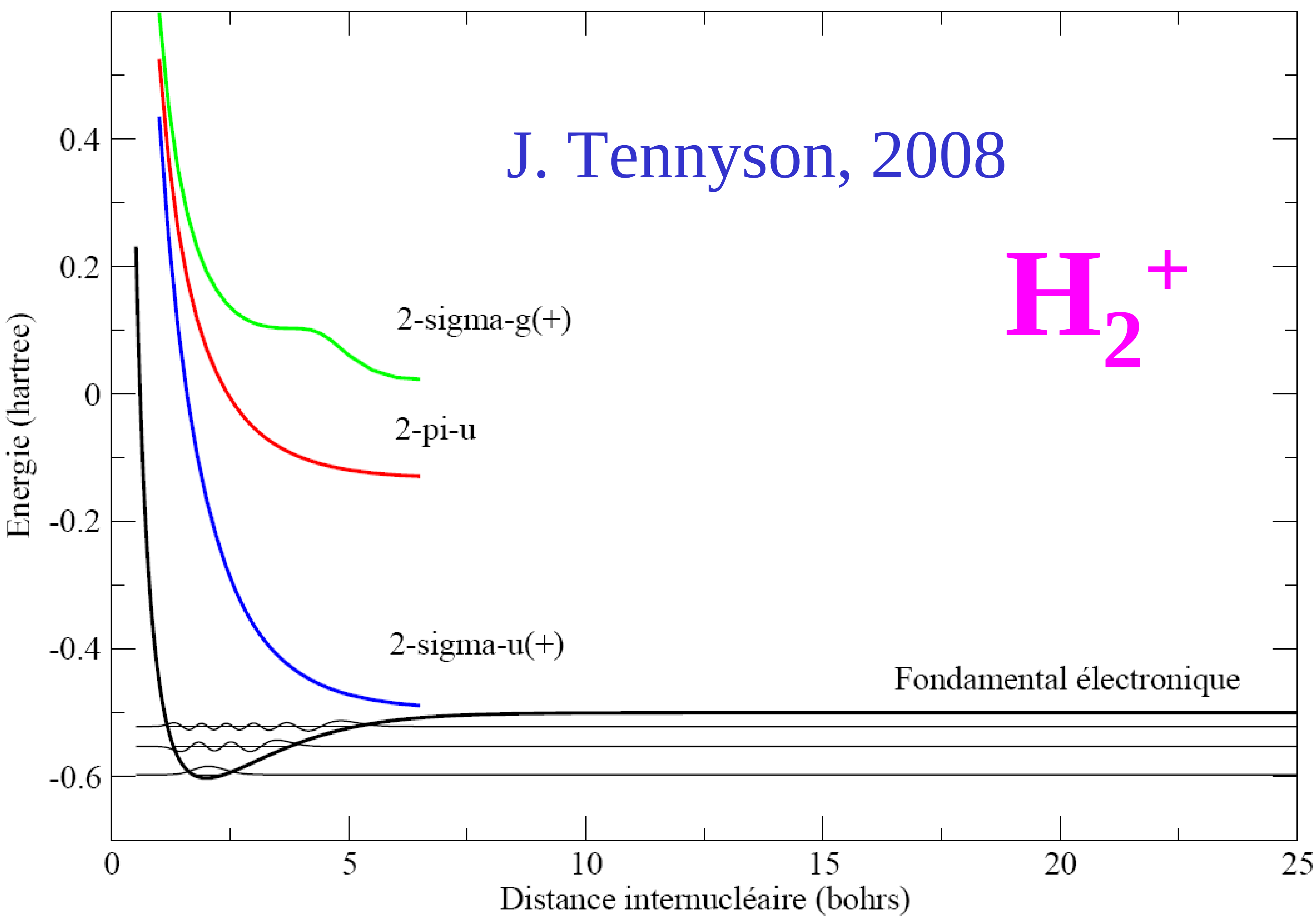
2009/10/05, ADAS meeting

D. BACKODISSA (2008)

H_2^+ / H_2



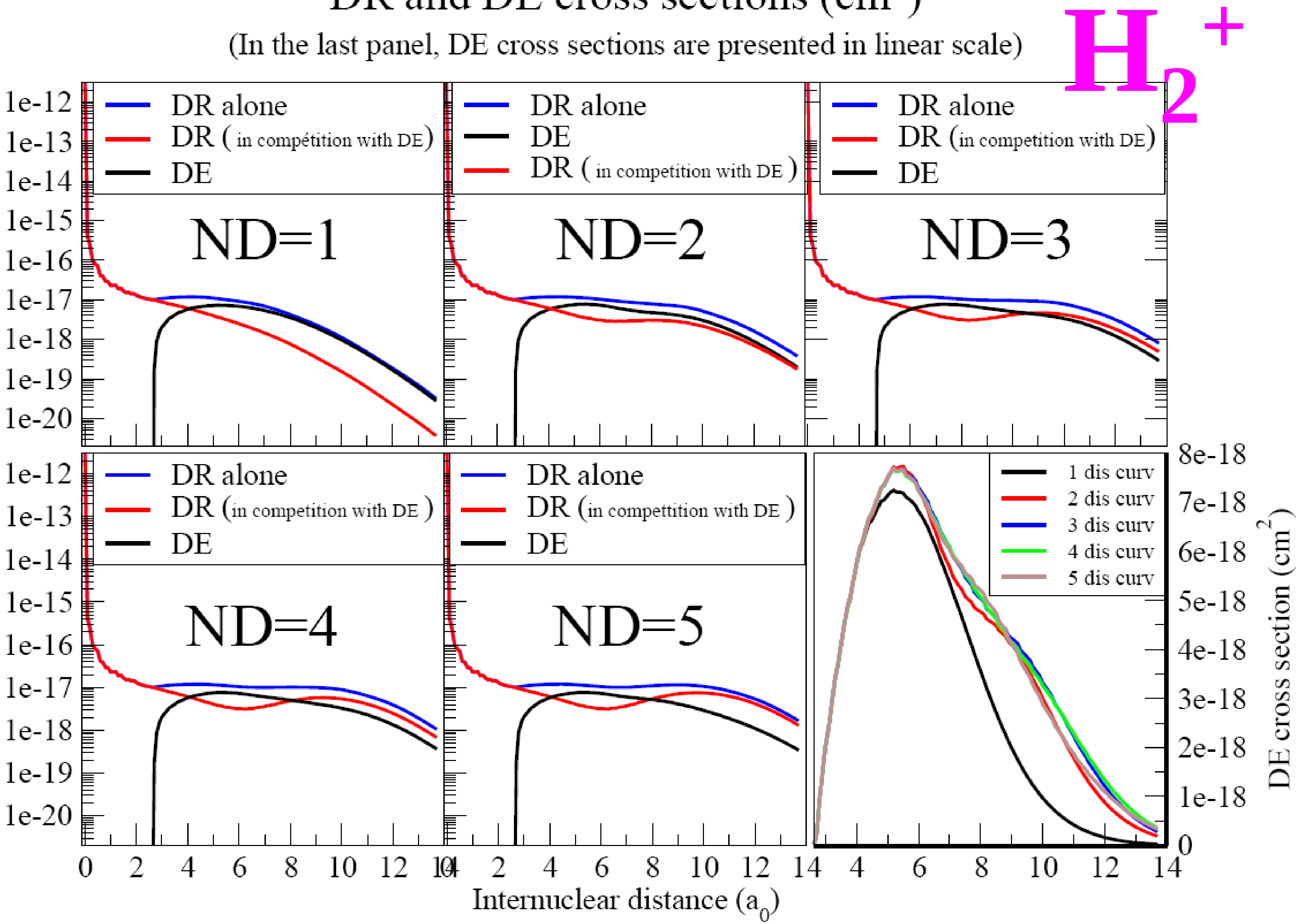
Guberman 1983
36.0
34.0
32.0
30.0
28.0
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
R(a₀)
H(2ℓ) + H(3ℓ)
H(2ℓ) + H(2ℓ)
H(3ℓ) + H(1S)
H(2ℓ) + H(1S)



J. Tennyson, 2008
H_2^+
2-sigma-g(+)
2-pi-u
2-sigma-u(+)
Fondamental électronique
Energie (hartree)
0.4
0.2
0
-0.2
-0.4
-0.6
0
5
10
15
20
25
Distance internucléaire (bohrs)

DR and DE cross sections (cm^2)

(In the last panel, DE cross sections are presented in linear scale)



Anisotropic fragmentation in low-energy dissociative recombination

S. Novotny[1], H. Rubinstein[2], H. Buhr[1,2], O. Novotný[1], J. Hoffmann[1], M.B. Mendes[1], D.A. Orlov[1], M.H. Berg[1], M. Froese[1], A.S. Jaroshevich[1,3], B. Jordon-Thaden[1], C. Krantz[1], M. Lange[1], M. Lestinsky[1], A. Petrignani[1], I.F. Schneider[4], D. Shafir[2], F.O. Waffeu Tamo[4], D. Zajfman[2], D. Schwalm[1,2] and A. Wolf[1]

[1]Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany
[2]Weizmann Institute of Science, Rehovot 76100, Israel
[3]Institute of Semiconductor Physics, 630090 Novosibirsk, Russia
[4]University of Le Havre, 76058 Le Havre, France

In press, 2009

HD^+

HD$^+$ @ LOW energy: theory vs experiment

ANGULAR distribution of the dissociation products

Guberman 2004: CI simple model

HD$^+$

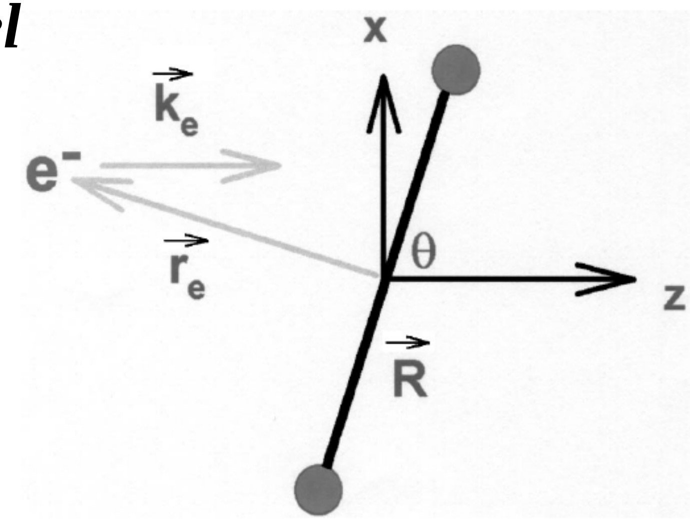


FIG. 1. Coordinates for electron (e^-) capture by a diatomic ion. The internuclear axis, $\vec{R}$, is oriented at an angle ϑ from the z axis and lies in the xz plane. The incoming electron at position $\vec{r}_e$, relative to the center of charge of the ion, has wave vector $\vec{k}_e$ and is moving parallel to the z axis.

Novotny et al 2006: TSR, imaging

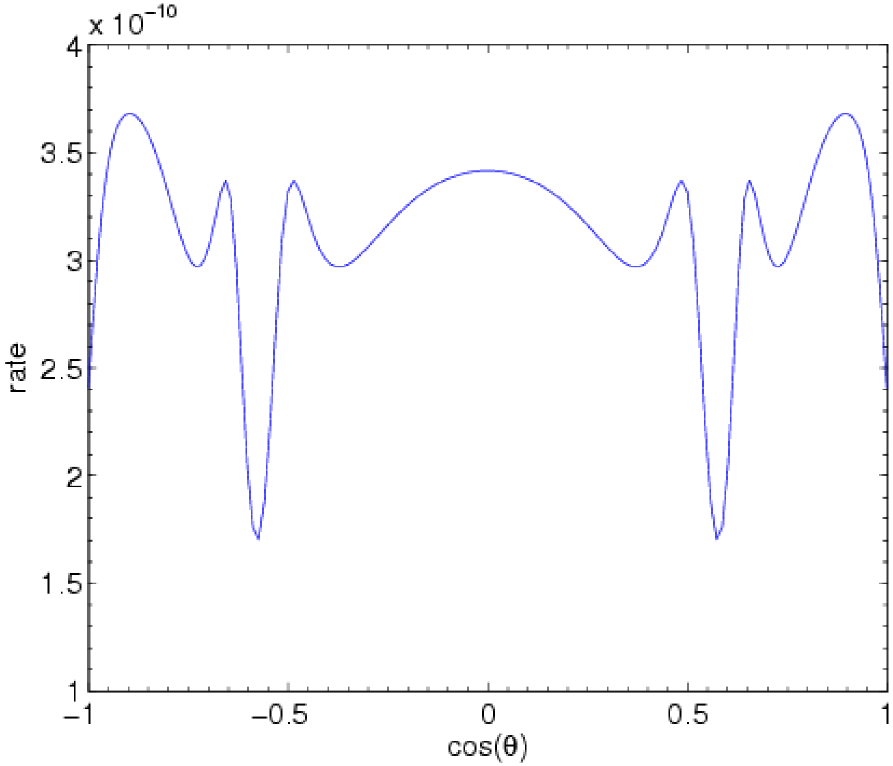
Waffeu Tamo & Schneider 2006-2007: MQDT modelling →

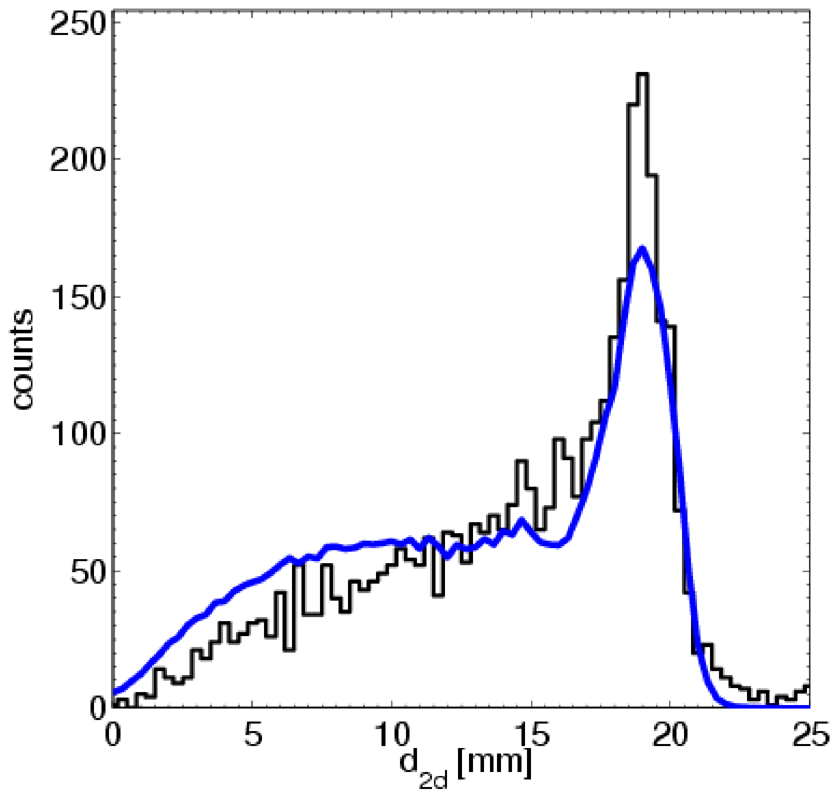
$$V_{\mathrm{el}}^{m}(k_e,\vec{\mathrm{R}})=\sum_{\ell=|m|}^{\infty} V_{\ell|m|}(k_e,R)\,Y_{\ell m}(\hat{R}), \qquad (11)$$

Compare latest MQDT results on angular distribution with 2D data
(July 2006)

E_e= 75.10 meV; T_{rot}=360 K

HD^+





data
with MQDT calculation

Dissociative recombination of CF^+: experiment and theory

O Novotný[1], O Motapon[2], M H Berg[1], D Bing[1], H Buhr[1,3], H Fadil[1], J Hoffmann[1], A S Jaroshevich[4], B Jordon-Thaden[1], C Krantz[1], M Lange[1], M Lestinsky[1], M Mendes[1], S Novotny[1], A Petrignani[1], D A Orlov[1], I F Schneider[5], A E Orel[6] and A Wolf[1]

[1] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany
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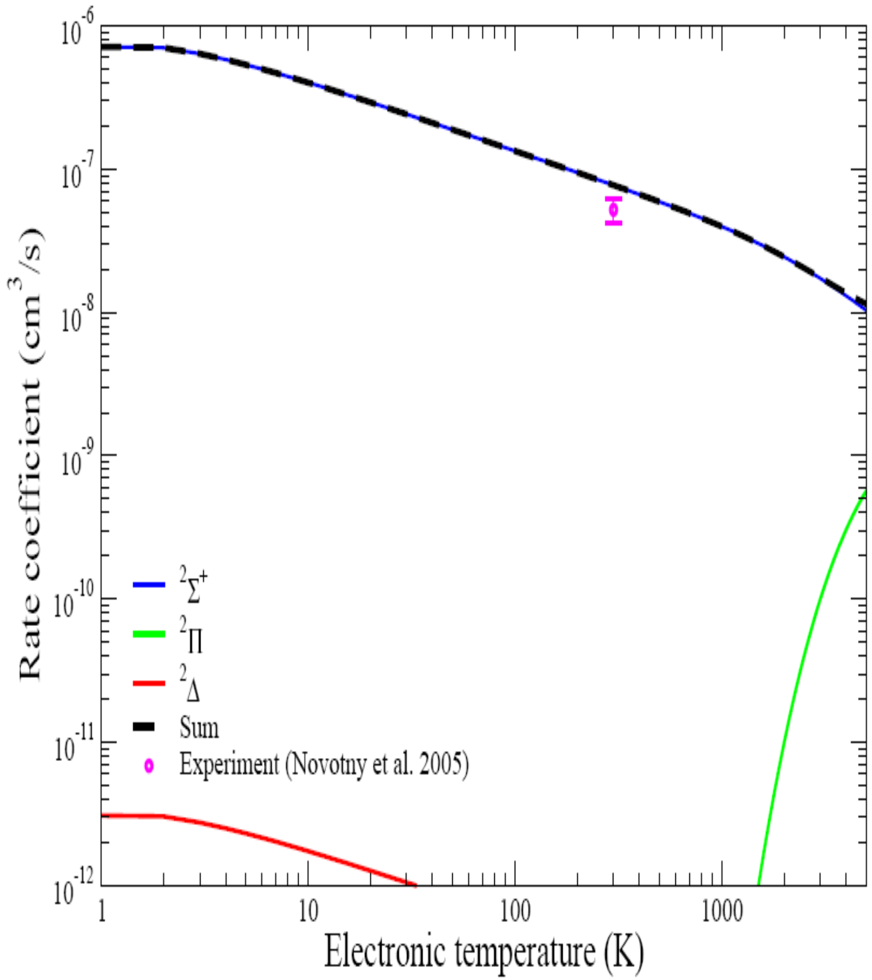
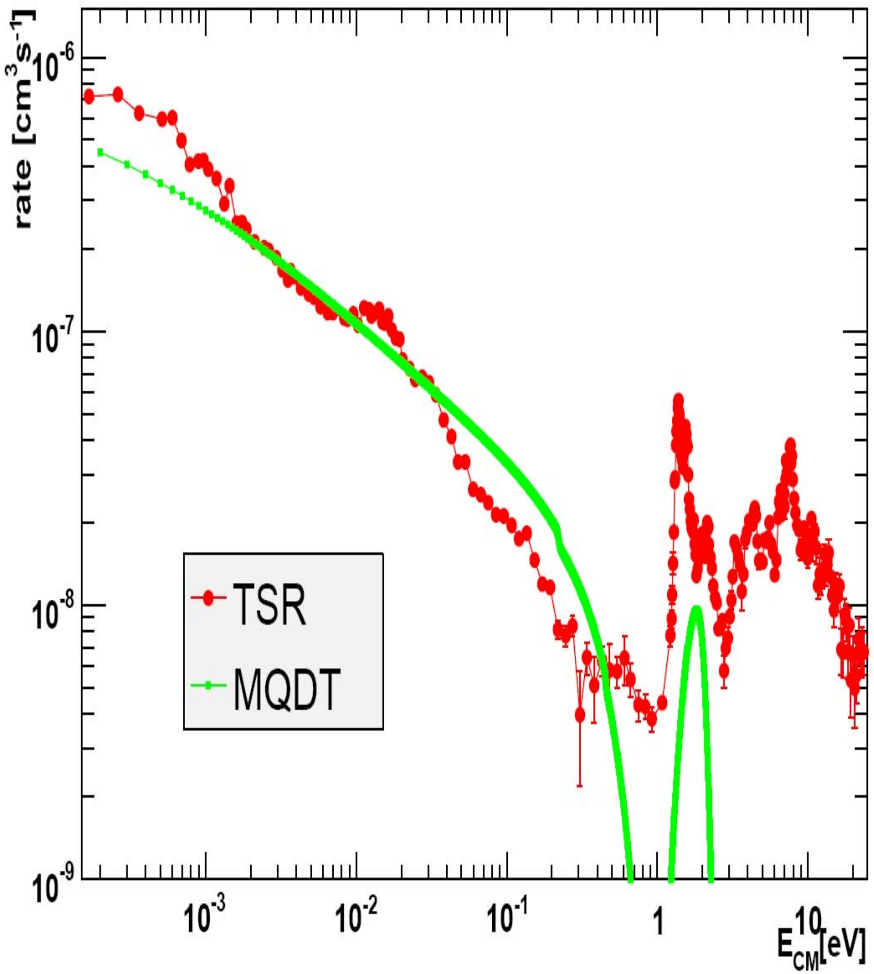
[4] Institute of Semiconductor Physics, 630090 Novosibirsk, Russia
[5] Laboratoire de Mécanique, Physique et Géosciences, Université du Havre, 25, rue Philippe Lebon, P.O. Box 540, 76058 Le Havre Cedex, France
[6] Department of Applied Science, University of California at Davis, Davis CA 95616 USA

In press, 2009

CF^+

RESULTS vs EXPERIMENTS





Maxwell ISOTROPIC rate coefficients

Maxwell ANISOTROPIC rate coefficients

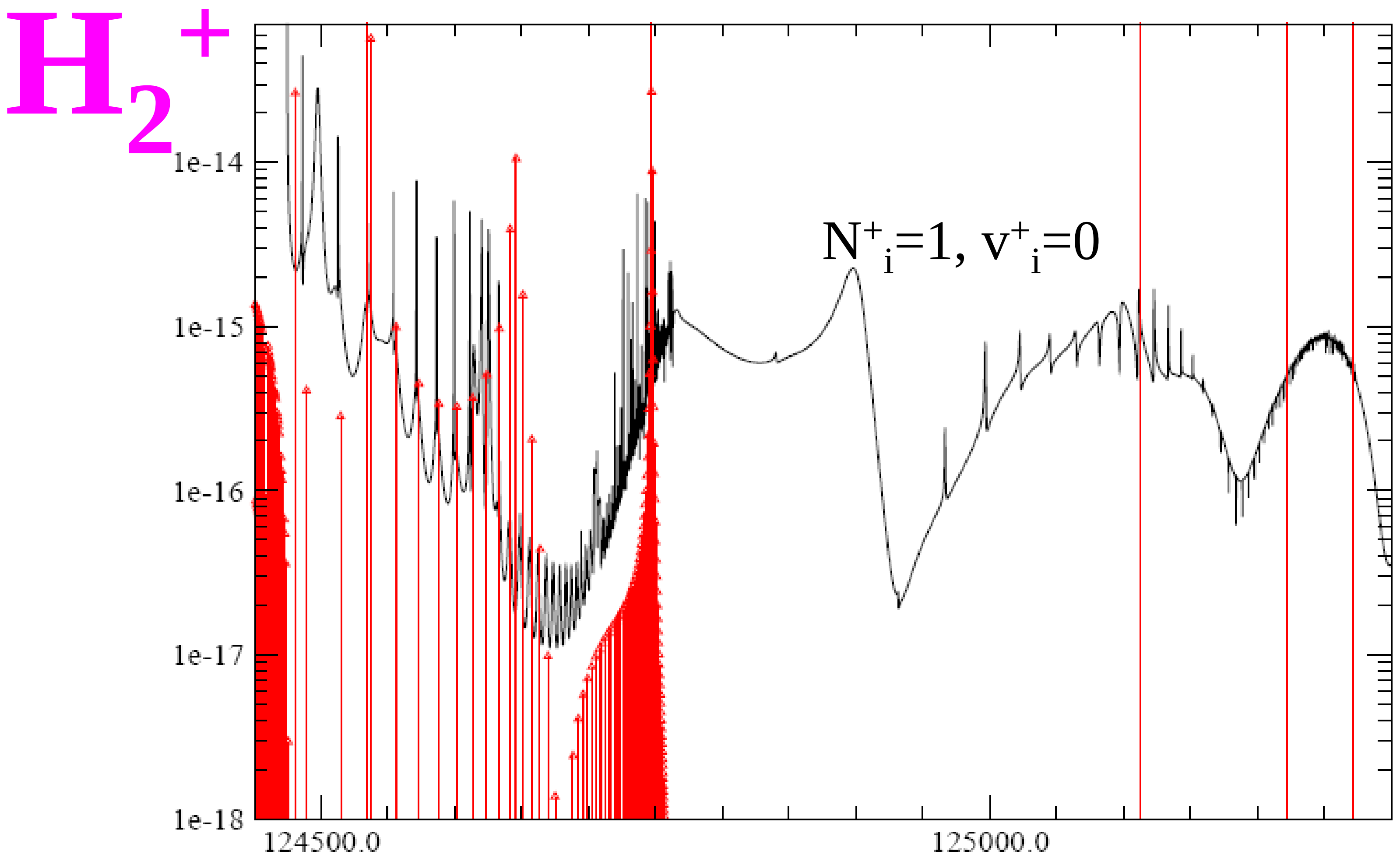
The « H_2^+ DR project»

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

LABORATOIRE ONDES et MILIEUX COMPLEXES

Comparaison with the photo-dissociation calculations of Christian JUNGEN



« 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[2], 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[1]

[1] Laboratoire de Mécanique, Physique et Géosciences, Université du Havre, F-76058 Le Havre, France
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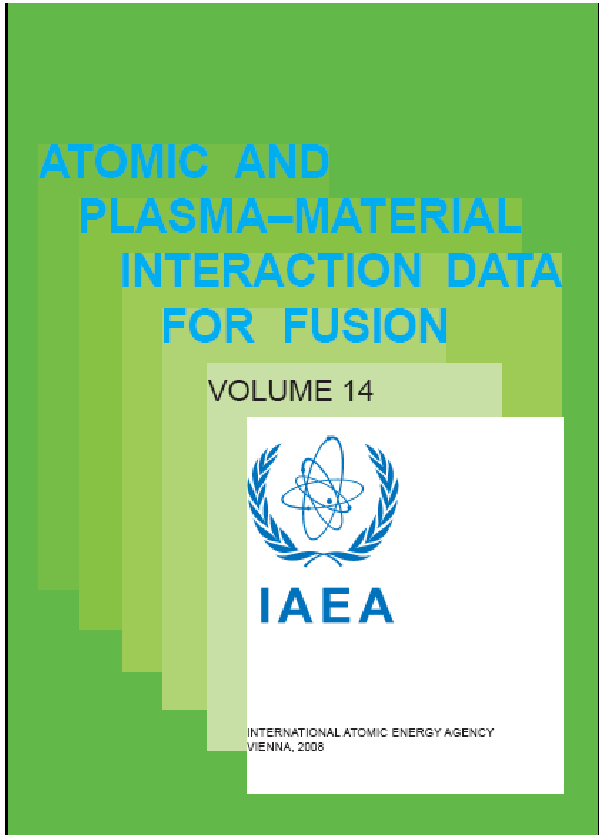


2009/10/05, ADAS meeting

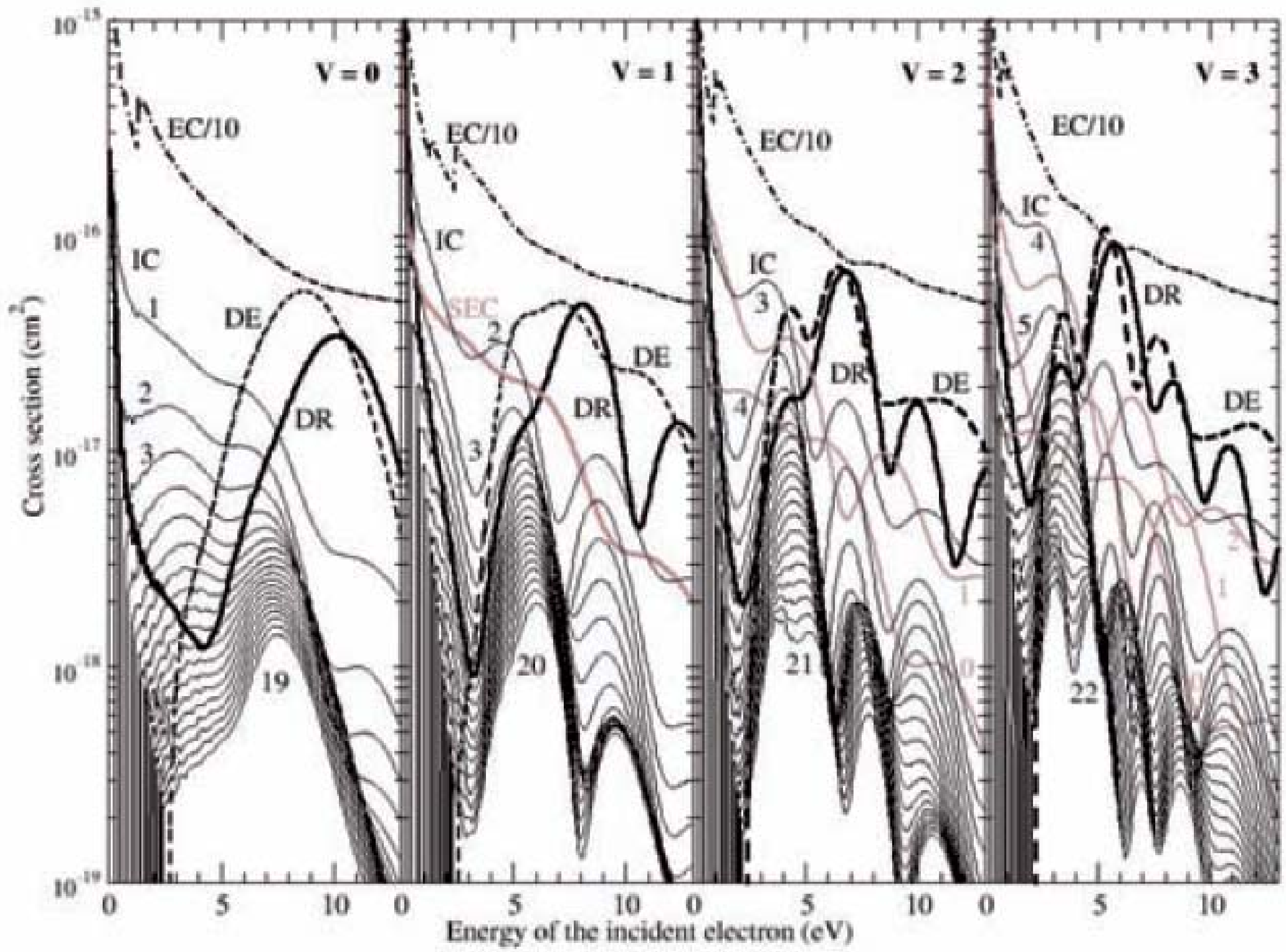
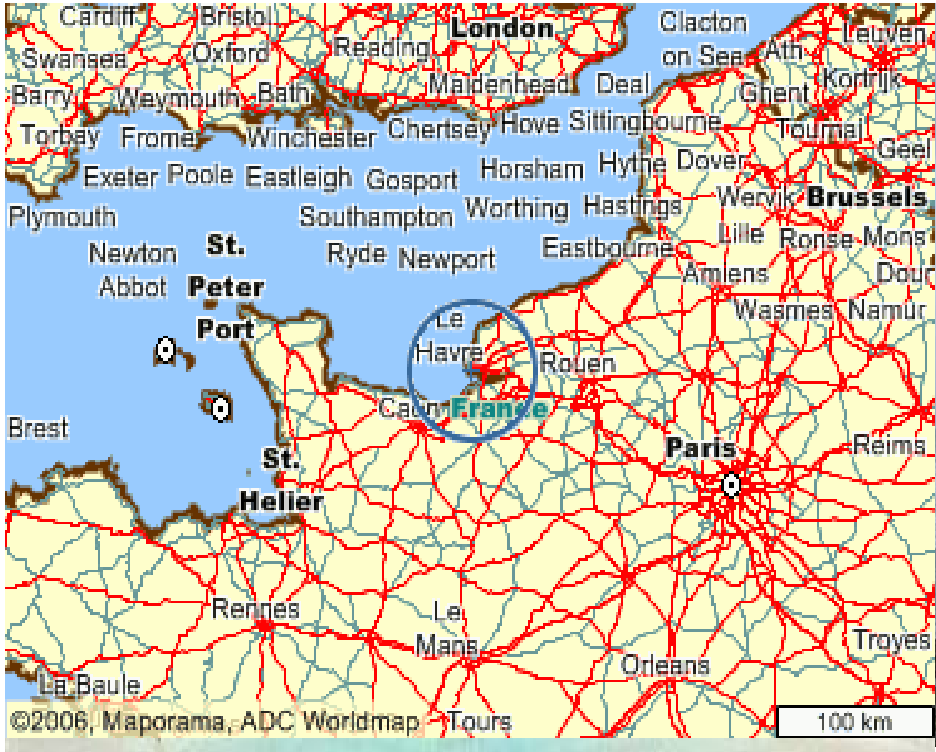
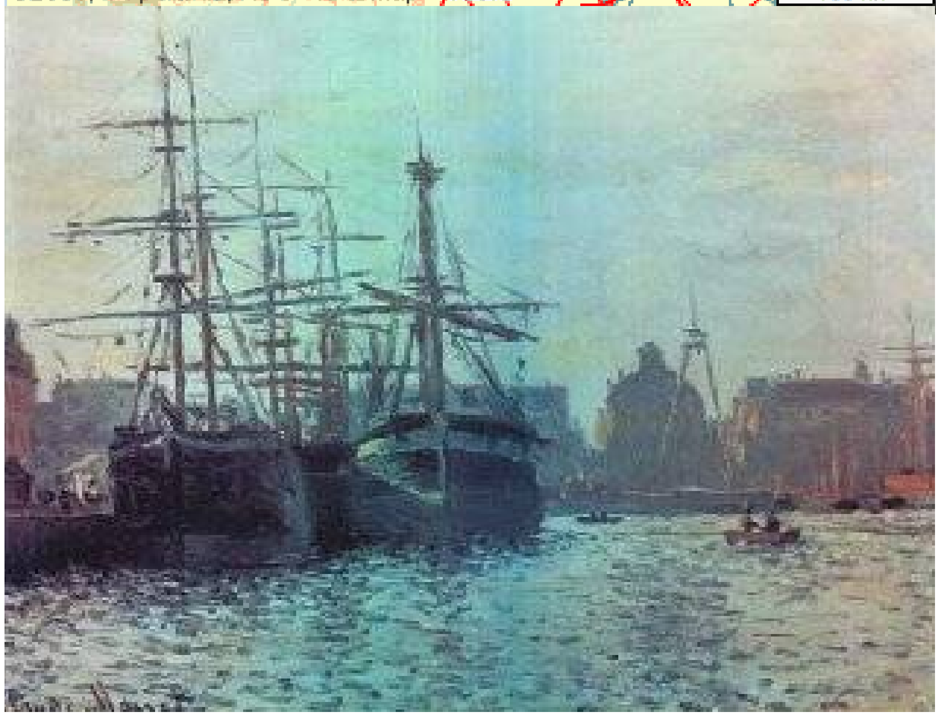


Figure 6. Reactive collisions of DT^+ molecular ion in a given vibrational state **v** with electrons (cross-sections): bold line — DR, broken line — DE, dashed dotted line — elastic collisions (EC), grey line — superelastic collisions (SEC) and thin line — inelastic collisions (IC). The numbers attached to the IC and SEC curves stand for the final vibrational states.





Thanks for your attention !

ADAS meeting

Why storage rings ?

T_{long} = 20 µeV= 0,23 K=0,16 cm^{-1}
T_{trans} = 500 µeV= 5,80 K=4,03 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,[3] H Takagi,[4] E B Starikov[5] and M Tateno[6,7]

Institute of Physics Publishing | Journal of Physics: Conference Series **4** (2005) 239–244
doi:10.1088/1742-6596/4/1/035 | Sixth International Conference on Dissociative Recombination

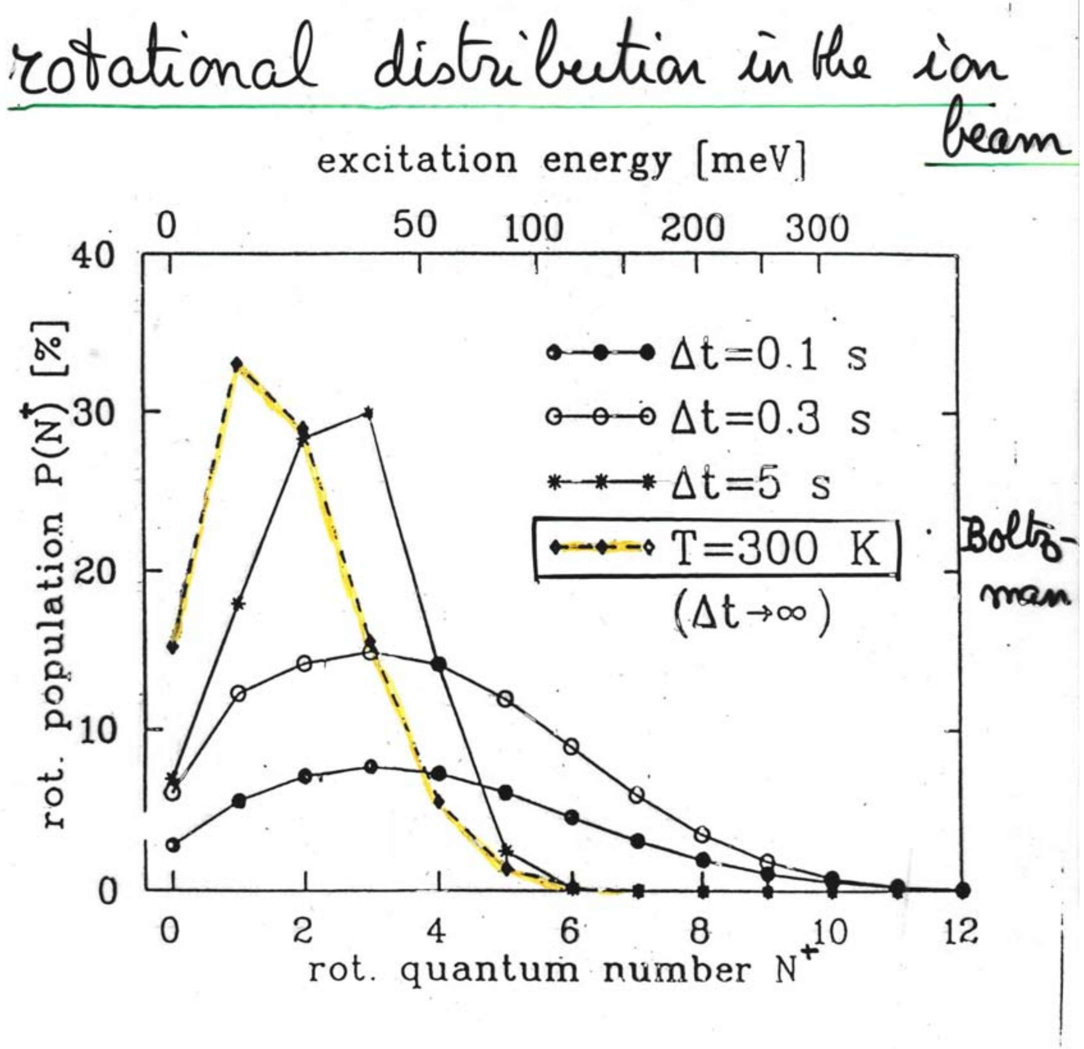
Experiments:**MULTIPLE pass/MERGED beams-STORAGE RINGS**

The ANISOTROPIC Maxwell distribution function

$$\alpha =< \mathrm{v}\sigma >= \int\int\int \sigma(\mathrm{v})\mathrm{v} f(\mathrm{v}_d, \mathbf{v}) d\mathbf{v} \tag{1}$$

$$f(\mathrm{v}_d, \mathbf{v}) = \frac{m}{2\pi k T_{e\perp}} exp(-\frac{m\mathrm{v}_\perp^2}{2kT_{e\perp}}) \sqrt{\frac{m}{2\pi k T_{e\|}}} exp(-\frac{m(\mathrm{v}_\| - \mathrm{v}_d)^2}{2kT_{e\|}}) \tag{2}$$

Experiments:**MULTIPLE pass/MERGED beams-STORAGE RINGS**



P. Forck (thesis), 1994, Heidelberg

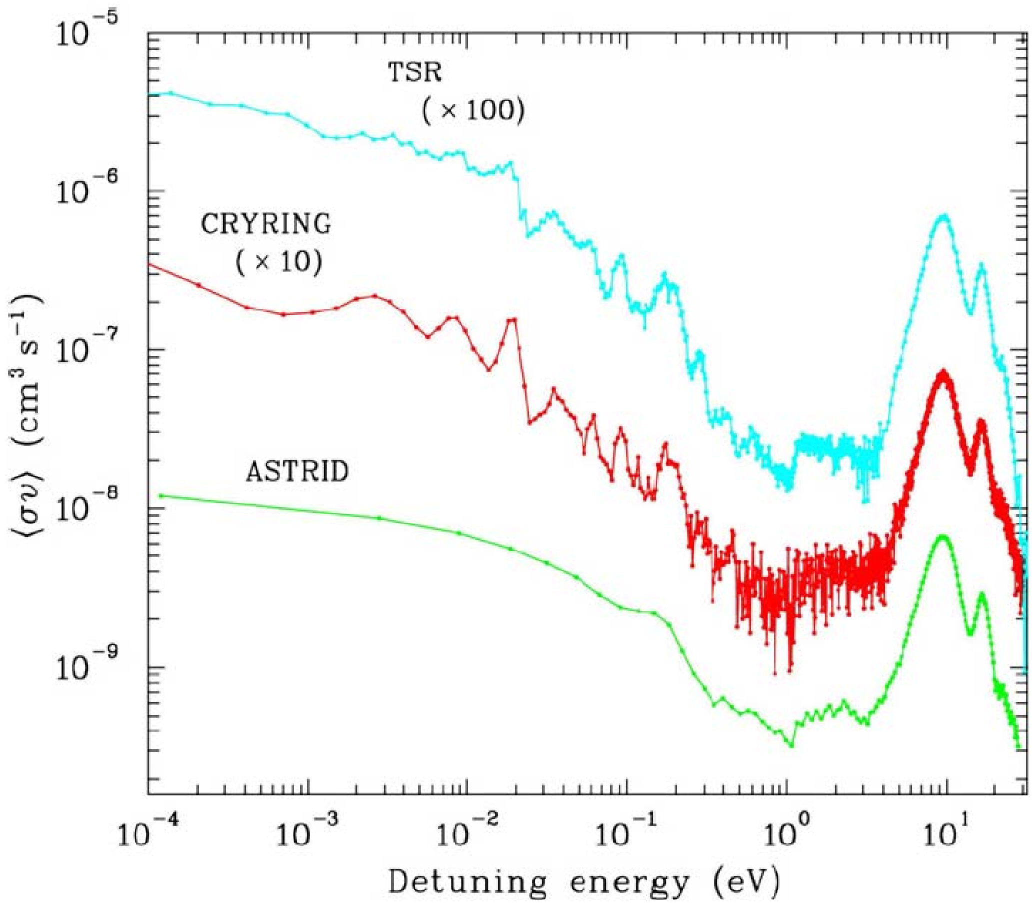
Experiments:**MULTIPLE pass/MERGED beams-STORAGE RINGS**

Ion Storage Rings

ESR

TARN (TOKYO) ----->

Experiments:**MULTIPLE pass/MERGED beams-STORAGE RINGS**



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).

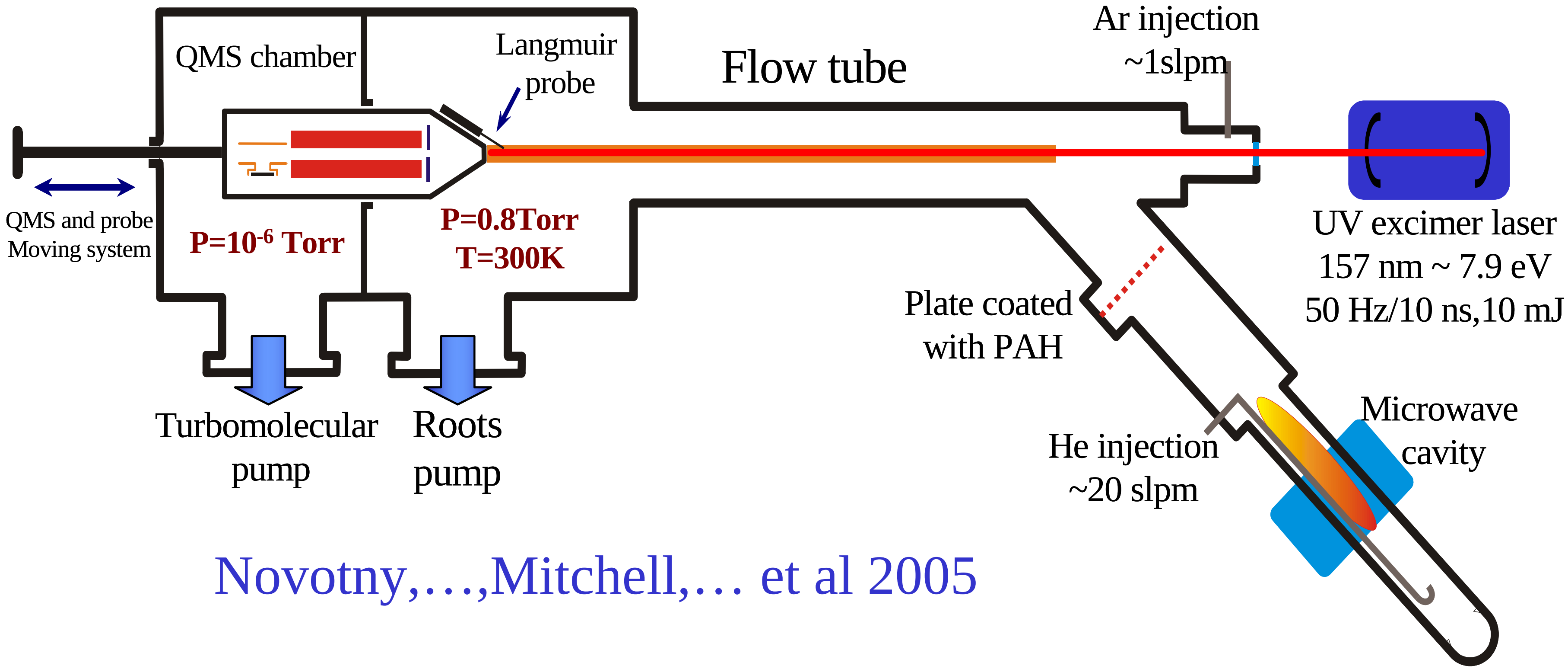
Molecular ion recombination in merged beams: experimental results on small systems and future perspectives

M Larsson

Institute of Physics Publishing
Journal of Physics: Conference Series **4** (2005) 50–57
doi:10.1088/1742-6596/4/1/007
Sixth International Conference on Dissociative Recombination

Experiments: FALP

Rennes



Novotny,…,Mitchell,… et al 2005

7.4.2 Associative and non-associative detachment

The associative detachment (AD) reaction

$$H_2^+(v_i) + H^- \to (H_3^*) \to H_3^+(v_3) + e \tag{222}$$

8.1 Collision processes of H_3^+ with electrons

8.1.1 Vibrational excitation

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

$$e + H_3^+(v_3) \to e + H_3^+(v_3') \tag{225}$$

$$e + H_3^+(v_3) \to e + H_3^{+*}\left(N^{1,3}\Lambda_\sigma; \epsilon\right) \to e + H^+ + H(1s) + H(n \geq 1) \tag{227a}$$

$$\to e + H^+ + H_2\left(N^{1,3}\Lambda_\sigma; v_0\right) \tag{227b}$$

$$\to e + H_2^+(v_i) + H(n \geq 1) \tag{227c}$$

$$e + H_3^+ (v_3) \rightarrow \left(H_3^{**}, H_3^{*Ryd} \right) \rightarrow H_2 \left(X^1\Sigma_g^+; v_0 \right) + H\,(n \geq 1) \quad (229a)$$

$$\rightarrow \quad 3H\,(1s) \quad (229b)$$

$$e + H_3^+(v_3) \rightarrow (H_3^{**}) \rightarrow H_2^+(v_i) + H^-. \quad (234)$$

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With 210 Figures

Example of data needs For H_2^+ & isotopomers:

...

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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

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

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

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

$$e + H_2^+(X; v) \rightarrow e + H^+ + H + e \qquad (19.56)$$

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 $(2p\pi_u;^2\Pi_u)$,

$$e + H_2^+(v) \to e + H_2^+(2p\sigma_u) \to e + H^+ + H(1s), \quad (177)$$

$$e + H_2^+(v) \to e + H_2^+(2p\pi_u) \to e + H^+ + H(n=2). \quad (178)$$

7.1.3 Dissociative recombination

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

$$e + H_2^+(v) \to \{H_2^{**}(\epsilon); H_2^{*Ryd}(N^{1,3}\Lambda_\sigma; \epsilon)\} \to H(1s) + H(n \geq 2) \quad (184)$$

CO^+

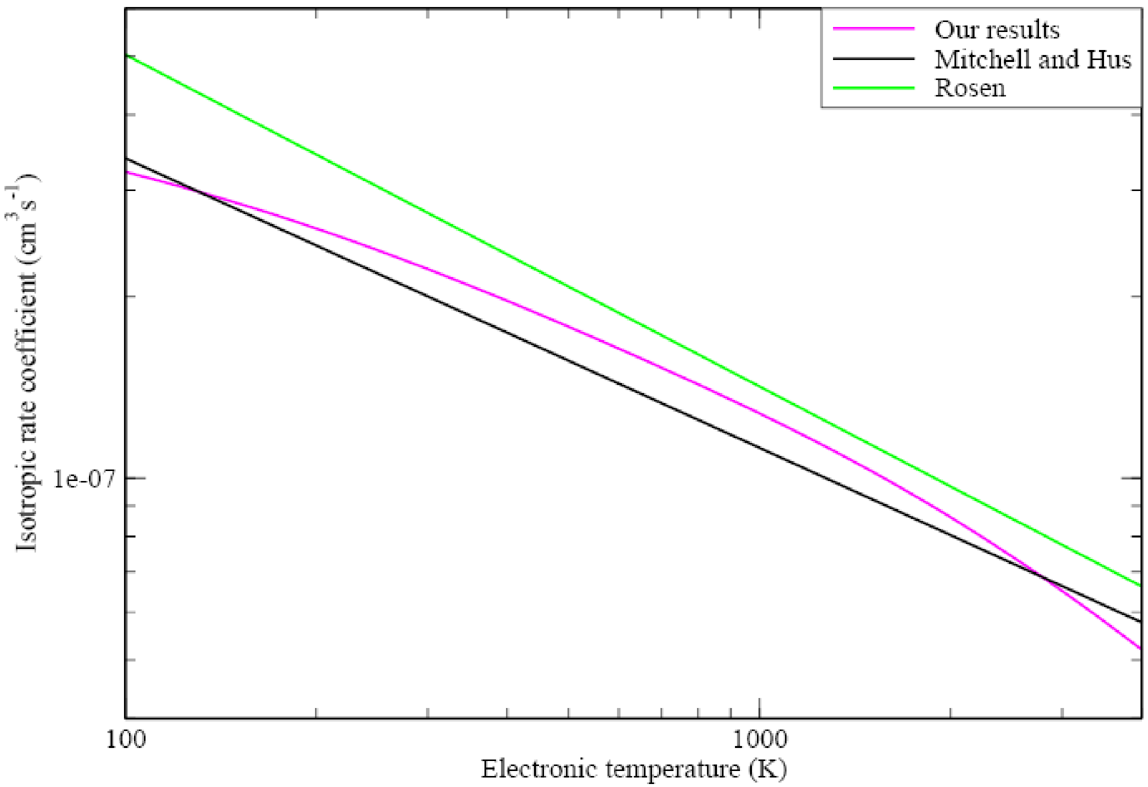

Figure 6: *Isotropic rate coefficients. Our theoretical results are represented in magenta. In black and green, the experiment results of Mitchell and Rosen respectively.*

H_2^+

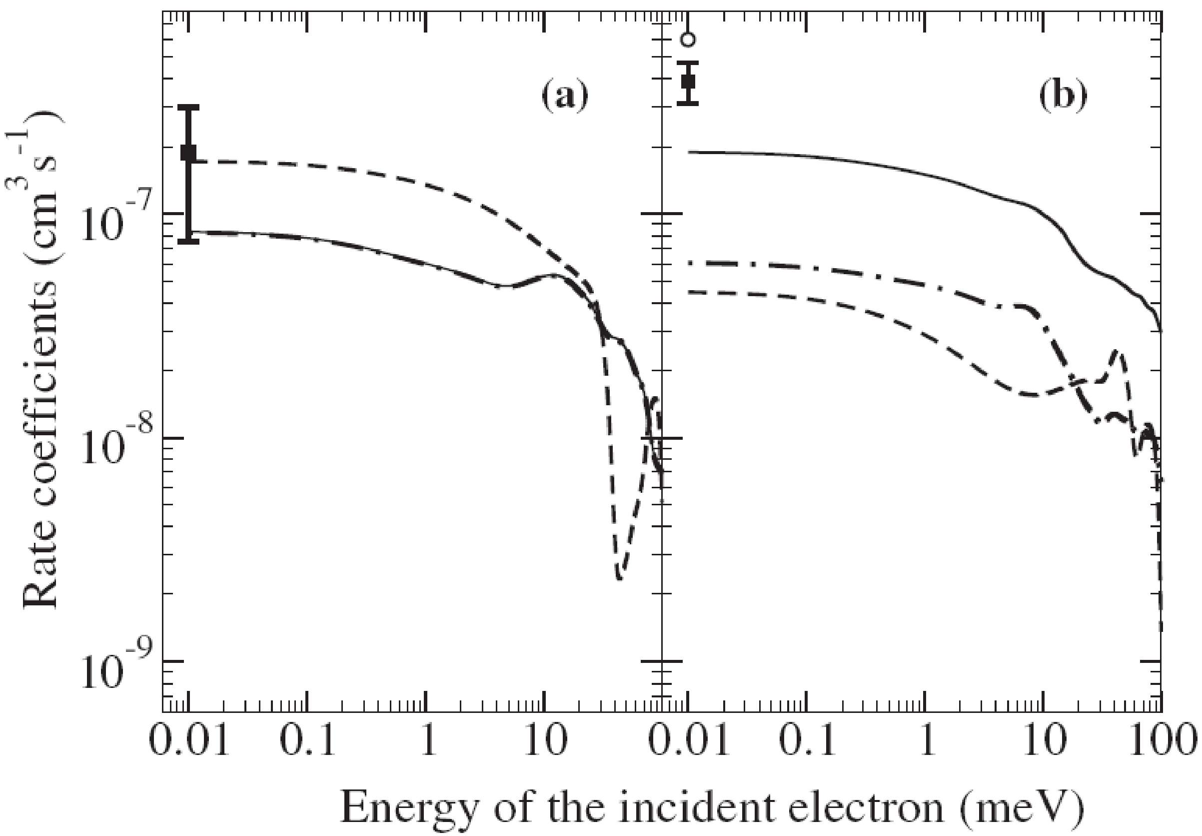

FIG. 2. Rate coefficients for (a) dissociative recombination and (b) superelastic collisions from $v_i^+=1$. Dashed lines, theory without rotation [22]; dash-dotted lines, theory with rotation for $^1\Sigma_g^+ + {}^1\Pi_g$; full black lines, theory with rotation for all symmetries; squares, experiment [24]; circle, experiment [23].