olytechnic of Bari, Italy

Institute of Nanot
CNR - Bari, Ita

From elementary processes to plasma modeling

Roberto Celiberto

1st Research Coordination Meeting on
Atomic Data for Vapour Shielding in Fusion Devices
I.A.E.A. Vienna, March 2019

Non-equilibrium low-temperature plasmas

- Molecular plasmas
  - Non-Boltzmann population
  - Non-Maxwellian electron energy distributions function
- State-to-state vibrational kinetics
- Large sets of cross section data

Vibrational kinetics of electronically excited states in H_2 discharges

Colonna et al., Eur. Phys. J. D (2017)

- The evolution of atmospheric pressure hydrogen plasma under the action of repetitively ns electrical pulse

Input data

==========

$E_m/N = 200$ *Td*;

Pulse = 20 *ns*;

Gas temperature = 1000 K

Gas pressure = 1 bar.

Molar fractions:

$$\chi_e = \chi_{H_2^+} = 10^{-10}$$

$$\chi_H = 2 \cdot 10^{-9}$$

$$\chi_{H^+} = \chi_{H^-} = \chi_{H_3^+} = 0$$

==========

H_2/H STATE-TO-STATE KINETICS

Ground state vibrational kinetics

Ground state vibrational kinetics

$$
\begin{aligned}
\mathrm{H_2}(v) + \mathrm{H_2}(\omega - 1) &\rightleftharpoons \mathrm{H_2}(v-1) + \mathrm{H_2}(\omega) \\
\mathrm{H_2}(v) + \mathrm{H_2}(\omega) &\rightleftharpoons \mathrm{H_2}(v-1) + \mathrm{H_2}(\omega) \\
\mathrm{H_2}(v) + \mathrm{H} &\rightleftharpoons \mathrm{H_2}(v-\Delta v) + \mathrm{H} \\
\mathrm{H_2}(v) + \mathrm{H_2} &\rightleftharpoons 2\mathrm{H} + \mathrm{H_2} \\
\mathrm{H_2}(v) + \mathrm{H}(n=1) &\rightleftharpoons 3\mathrm{H}(n=1) \\
\mathrm{H_2}(v) + \mathrm{H}(n=2) &\rightleftharpoons 3\mathrm{H}(n=1)
\end{aligned}
$$

Atomic level kinetics

$$
\begin{aligned}
\mathrm{H}(m) + \mathrm{H}(n=1) &\rightleftharpoons \mathrm{H}(m') + \mathrm{H}(n=1) \\
\mathrm{H}(m) + \mathrm{H}(n=1) &\rightleftharpoons \mathrm{H^+} + \mathrm{e^-} + \mathrm{H}(n=1) \\
\mathrm{H}(m) + \mathrm{e^-} &\rightleftharpoons \mathrm{H}(m') + \mathrm{e^-} \\
\mathrm{H}(m) + \mathrm{e^-} &\rightleftharpoons \mathrm{H^+} + 2\mathrm{e^-} \\
\mathrm{H}(m) &\rightarrow \mathrm{H}(m') + h\nu \\
\mathrm{H^+} + \mathrm{e^-} &\rightarrow \mathrm{H}(m) + h\nu
\end{aligned}
$$

Electron impact induced processes

$$
\begin{aligned}
\mathrm{H_2}(v) + \mathrm{e^-} &\rightleftharpoons \mathrm{H_2}(\omega) + \mathrm{e^-} \\
\mathrm{H_2}(v) + \mathrm{e^-} &\rightleftharpoons \mathrm{H_2^+} + 2\mathrm{e^-} \\
\mathrm{H_2}(v) + \mathrm{e^-} &\rightleftharpoons \mathrm{H^+} + \mathrm{H}(n=1) + 2\mathrm{e^-} \\
\mathrm{H_2}(v) + \mathrm{e^-} &\rightleftharpoons \mathrm{H_2}(b, e^3\Sigma_u^+) + \mathrm{e^-} \rightleftharpoons \mathrm{H}(n=1) + \mathrm{H}(n=1) + \mathrm{e^-} \\
\mathrm{H_2}(v) + \mathrm{e^-} &\rightleftharpoons \mathrm{H_2}(^1Y^\star) + \mathrm{e^-} \rightleftharpoons \mathrm{H}(n=1) + \mathrm{H}(n=2,3,4) + \mathrm{e^-}
\end{aligned}
$$

Molecular ion kinetics

$$
\begin{aligned}
\mathrm{e^-} + \mathrm{H_2^+} &\rightleftharpoons \mathrm{H}(m') + \mathrm{H}(n=1) \\
\mathrm{e^-} + \mathrm{H_2^+} &\rightleftharpoons \mathrm{H^+} + \mathrm{H}(n=1) + \mathrm{e^-} \\
\mathrm{e^-} + \mathrm{H_2^+} &\rightleftharpoons 2\mathrm{H^+} + 2\mathrm{e^-} \\
\mathrm{H^+} + \mathrm{H_2}(v'') &\rightleftharpoons \mathrm{H} + \mathrm{H_2^+}
\end{aligned}
$$

H_2/H STATE-TO-STATE KINETICS

Updated model

Singlets vibrational kinetics

$$
\begin{aligned}
\mathrm{H_2}(X^1\Sigma_g^+, v'') + \mathrm{e^-} &\rightleftharpoons \mathrm{H_2}(^1Y^\star, v') + \mathrm{e^-} \\
\mathrm{H_2}(^1Y^\star, v') &\rightarrow \mathrm{H_2}(X^1\Sigma_g^+, v'') + h\nu \\
\mathrm{H_2}(^1Y^\star, v') &\rightarrow \mathrm{H_2}(X^1\Sigma_g^+, \varepsilon) + h\nu \rightarrow 2\mathrm{H}(n=1) \\
\mathrm{H_2}(^1Y^\star, v') + \mathrm{H_2/H} &\rightarrow 2\mathrm{H}(n=1) + \mathrm{H_2/H}
\end{aligned}
$$

$$
{}^1Y^* = \begin{cases} {}^1\Sigma_g^+ : B, B', B'' \\ {}^1\Pi_g : C, D, D' \end{cases}
$$

Triplets kinetics

$$
\begin{aligned}
\mathrm{e^-} + \mathrm{H_2}(X^1\Sigma_g^+, v) &\rightleftharpoons \mathrm{e^-} + \mathrm{H_2}(a^3\Sigma_g^+) \\
\mathrm{H_2}(a^3\Sigma_g^+) &\rightarrow \mathrm{H_2}(b^3\Sigma_u^+) + h\nu \rightarrow 2H(n=1) \\
\mathrm{H_2}(a^3\Sigma_g^+) + \mathrm{H_2/H} &\rightleftharpoons \mathrm{H_2}(c^3\Pi_u) + \mathrm{H_2/H} \\
\mathrm{H_2}(c^3\Pi_u) + \mathrm{H_2/H} &\rightleftharpoons 2\mathrm{H} + \mathrm{H_2/H}
\end{aligned}
$$

$$
b^3\Sigma_u^+, a^3\Sigma_g^+, c^3\Pi_
$$

Negative Ions kinetics

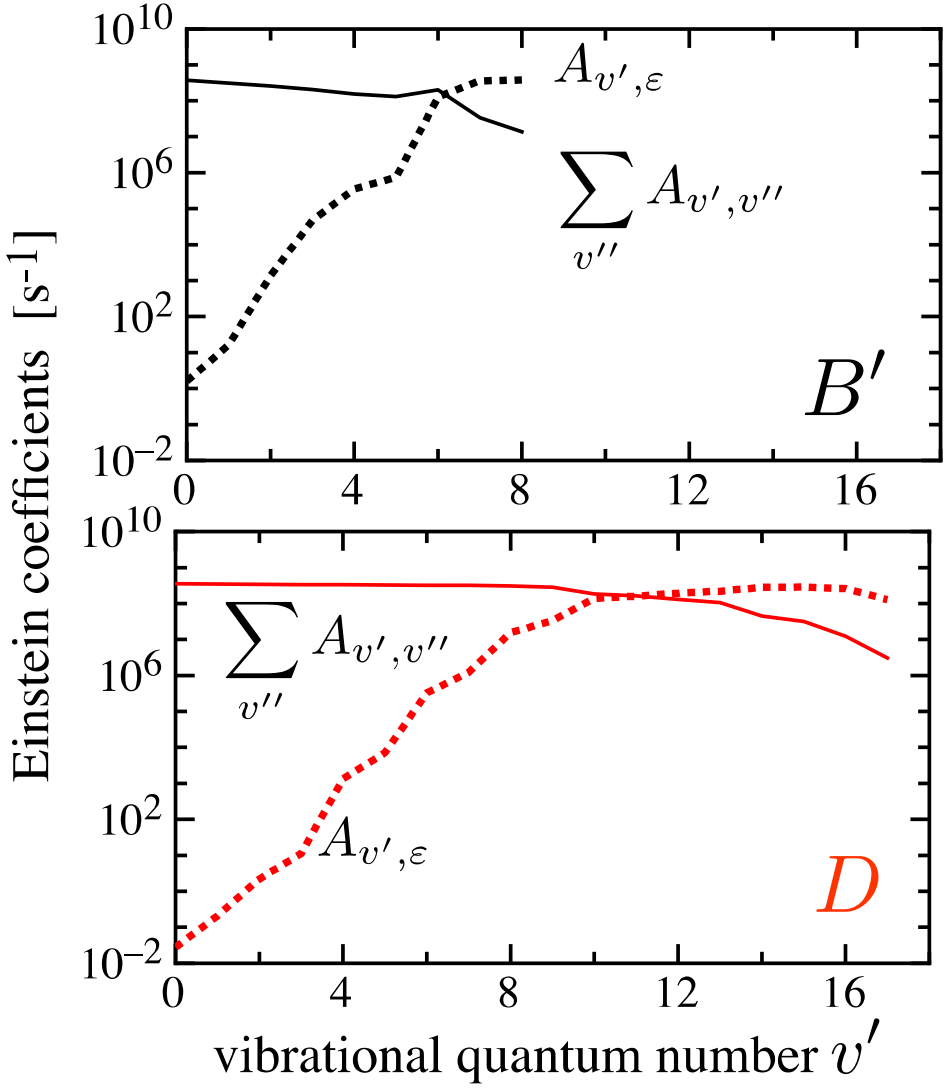
$$
\begin{aligned}
\mathrm{e^-} + \mathrm{H_2}(X^1\Sigma_g^+, v'') &\rightleftharpoons \mathrm{H^-} + \mathrm{H} \\
\mathrm{e^-} + \mathrm{H_2^+} &\rightleftharpoons \mathrm{H^-} + \mathrm{H^+} \\
\mathrm{H^-} + \mathrm{H^+} &\rightleftharpoons \mathrm{H}(n=1) + \mathrm{H}(n>1) \\
\mathrm{H^-} + \mathrm{H_2^+} &\rightleftharpoons \mathrm{H_2}(v''=0) + \mathrm{H}(n=1) \\
\mathrm{H^-} + \mathrm{H_3^+} &\rightleftharpoons \mathrm{H_2}(v''=0) + \mathrm{H_2}(v''=0)
\end{aligned}
$$

H_3^+ cation kinetics

$$
\begin{aligned}
\mathrm{H^+} + 2\mathrm{H_2}(v''=0) &\rightleftharpoons \mathrm{H_3^+} + \mathrm{H_2}(v''=0) \\
\mathrm{H_2^+} + \mathrm{H_2}(v''=0) &\rightleftharpoons \mathrm{H_3^+} + \mathrm{H}(n=1) \\
\mathrm{e^-} + \mathrm{H_3^+} &\rightleftharpoons \mathrm{e^-} + \mathrm{H^+} + 2\mathrm{H}(n=1) \\
\mathrm{e^-} + \mathrm{H_3^+} &\rightarrow \mathrm{H_2^+} + \mathrm{H^-} + h\nu \\
\mathrm{e^-} + \mathrm{H_3^+} &\rightarrow \mathrm{H_2}(v=0) + \mathrm{H}(n=1) \\
\mathrm{e^-} + \mathrm{H_3^+} &\rightarrow 3\mathrm{H}(n=1)
\end{aligned}
$$

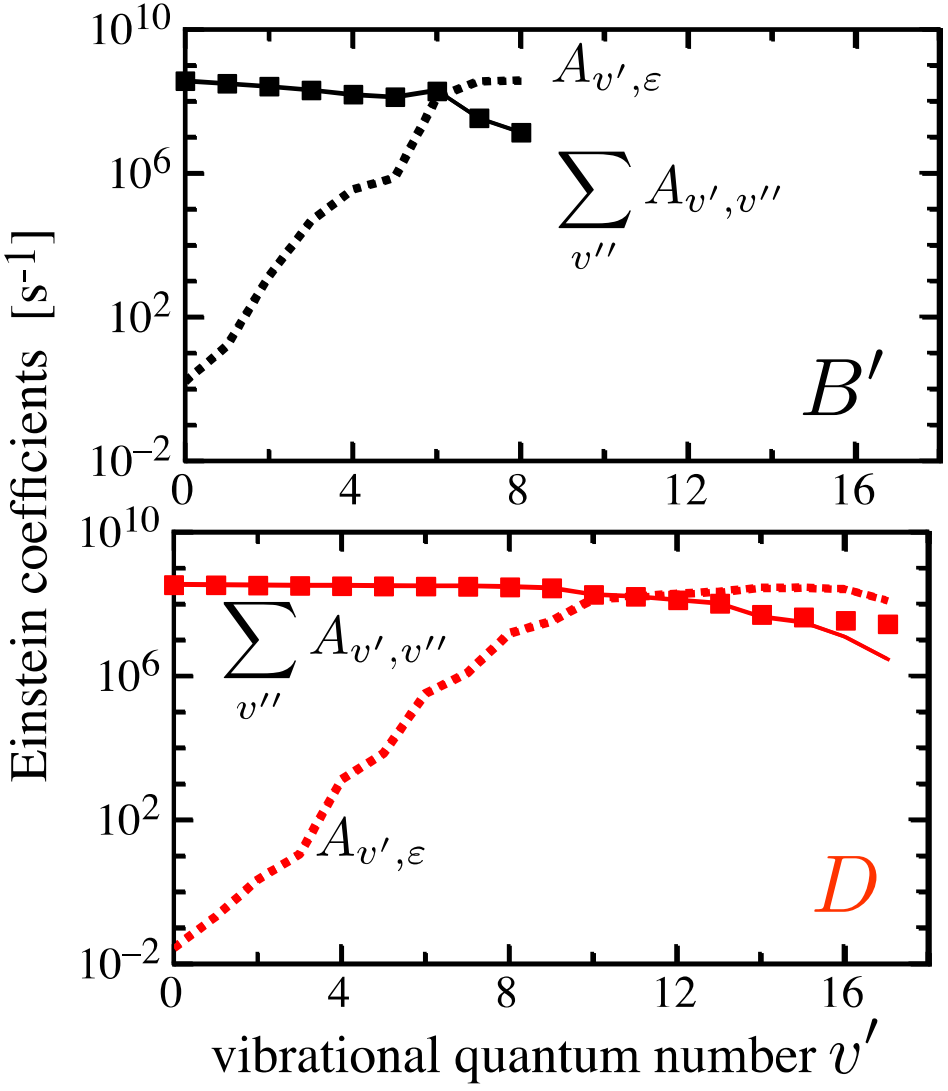
The European Physical Journal D (2017), *Vibrational kinetics of electronically excited states in H_2 discharges*
Colonna, G., Pietanza, L. D., D'Ammando, G., Celiberto, R., Capitelli, M., & Laricchiuta, A.

- ✓ state-to-state
- ✓ radiative processes



The European Physical Journal D (2017), *Vibrational kinetics of electronically excited states in H_2 discharges*
Colonna, G., Pietanza, L. D., D'Ammando, G., Celiberto, R., Capitelli, M., & Laricchiuta, A.

- ✓ state-to-state
- ✓ radiative processes

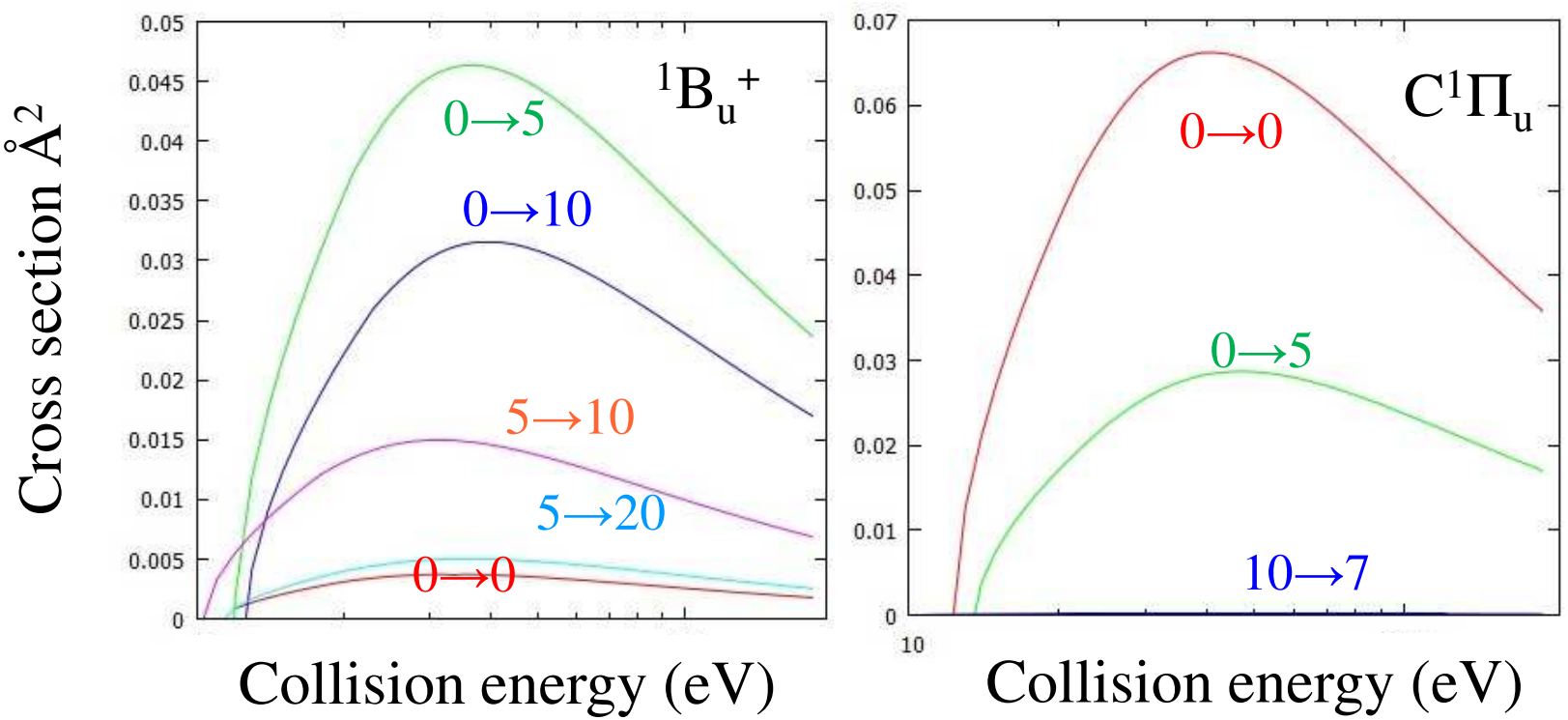


U. Fantz, D. Wünderlich, ADNDT (2006)

The European Physical Journal D (2017), *Vibrational kinetics of electronically excited states in H_2 discharges*
Colonna, G., Pietanza, L. D., D'Ammando, G., Celiberto, R., Capitelli, M., & Laricchiuta, A.

- ✓ state-to-state
- ✓ radiative processes
- ✓ energy profile cross section

$$H_2(X\,^1\Sigma_g^+, v) + e \rightarrow H_2(B\,^1\Sigma_u^+, C\,^1\Pi_u, v')$$



semiclassical IPM - R. Celiberto et al., ADNDT (2001)

The European Physical Journal D (2017), *Vibrational kinetics of electronically excited states in H_2 discharges*
Colonna, G., Pietanza, L. D., D'Ammando, G., Celiberto, R., Capitelli, M., & Laricchiuta, A.

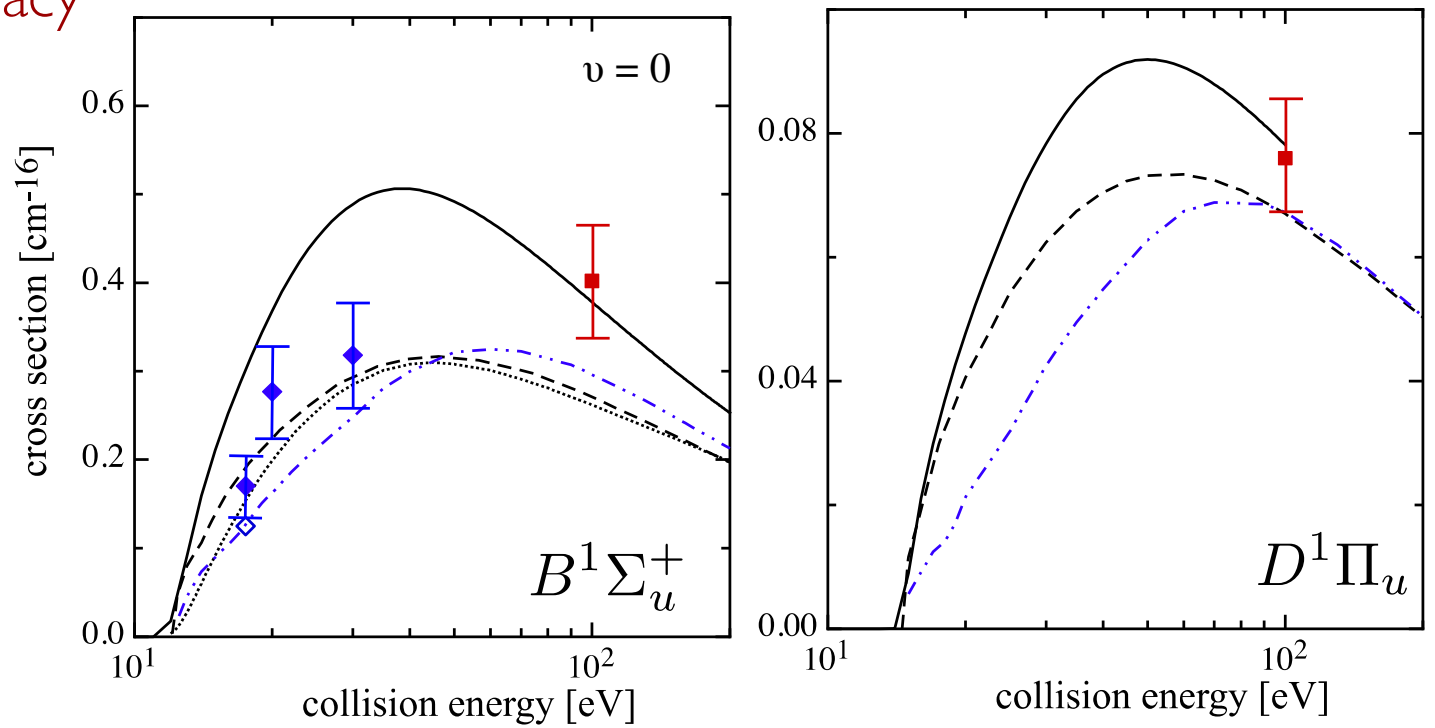
- ✓ state-to-state
- ✓ radiative processes
- ✓ energy profile cross sections
- ✓ accuracy

BE*f* scaling
Tanaka et al. Reviews of Modern Physics (2016)
Kim, J Chem Phys (2007)

CCC approach
M.C. Zammit et al., Physical Review Letters (2016)

Ajello et al., Physical Review A (1984)

Wrkich et al., Journal of Physics B (2002)

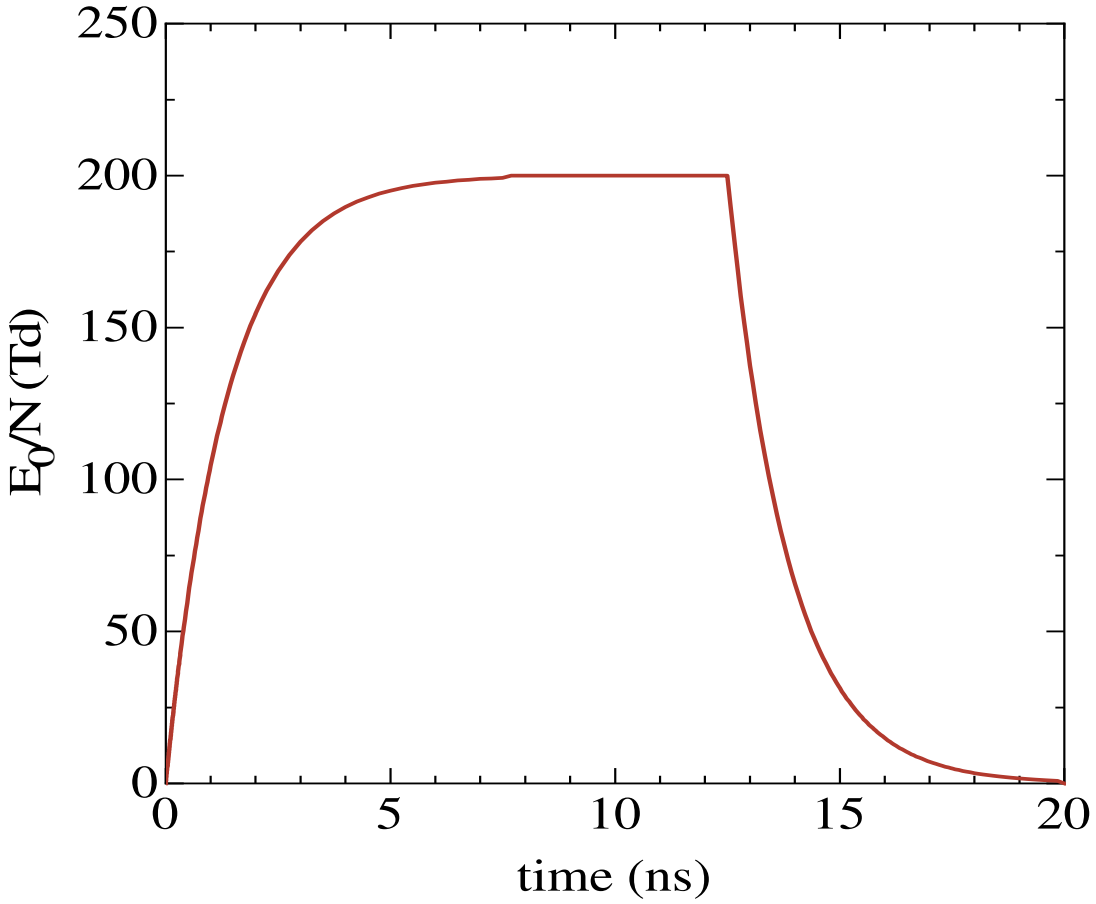


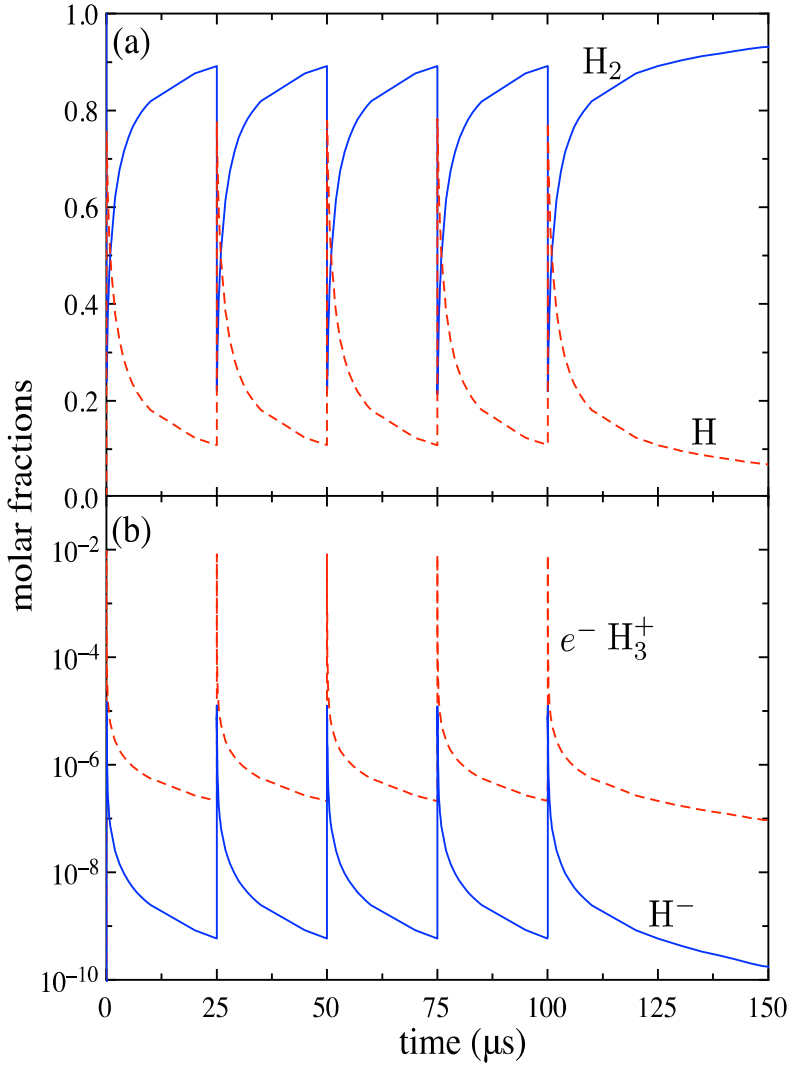
semiclassical IPM - R. Celiberto et al., ADNDT (2001)

The European Physical Journal D (2017), *Vibrational kinetics of electronically excited states in H_2 discharges*
Colonna, G., Pietanza, L. D., D'Ammando, G., Celiberto, R., Capitelli, M., & Laricchiuta, A.

Fast (ns-pulsed) discharges in hydrogen

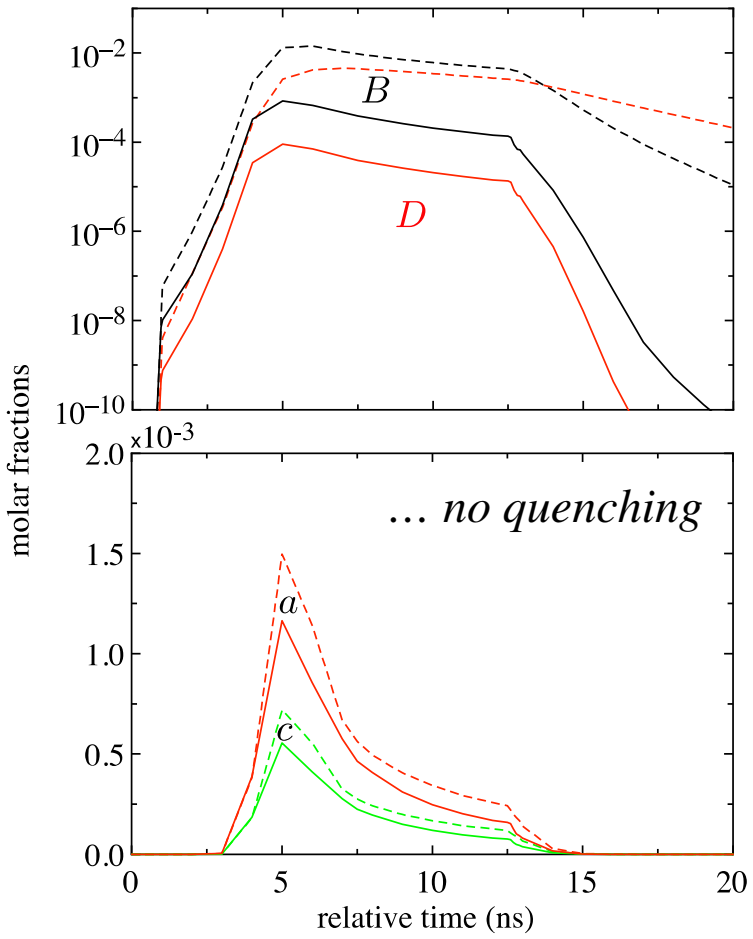
excited state concentration
& singlets vibrational distributions

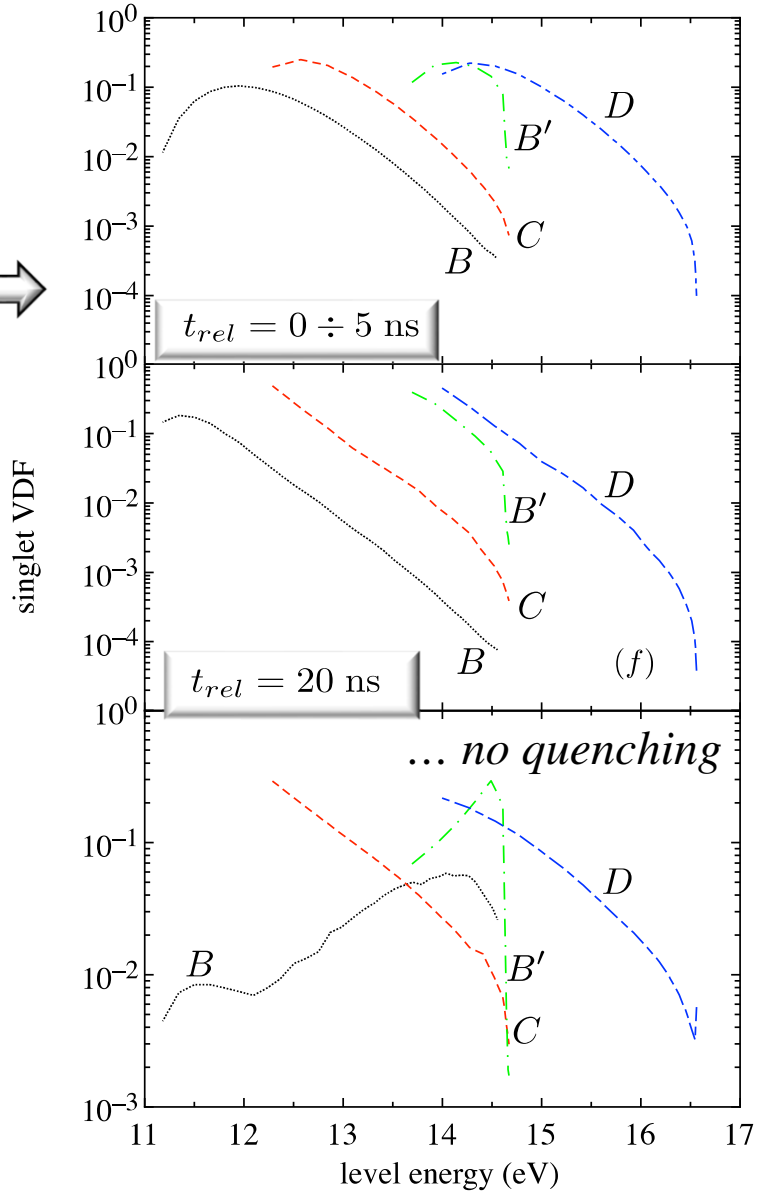




Fast (ns-pulsed) discharges in hydrogen

excited state concentration & singlets vibrational distributions

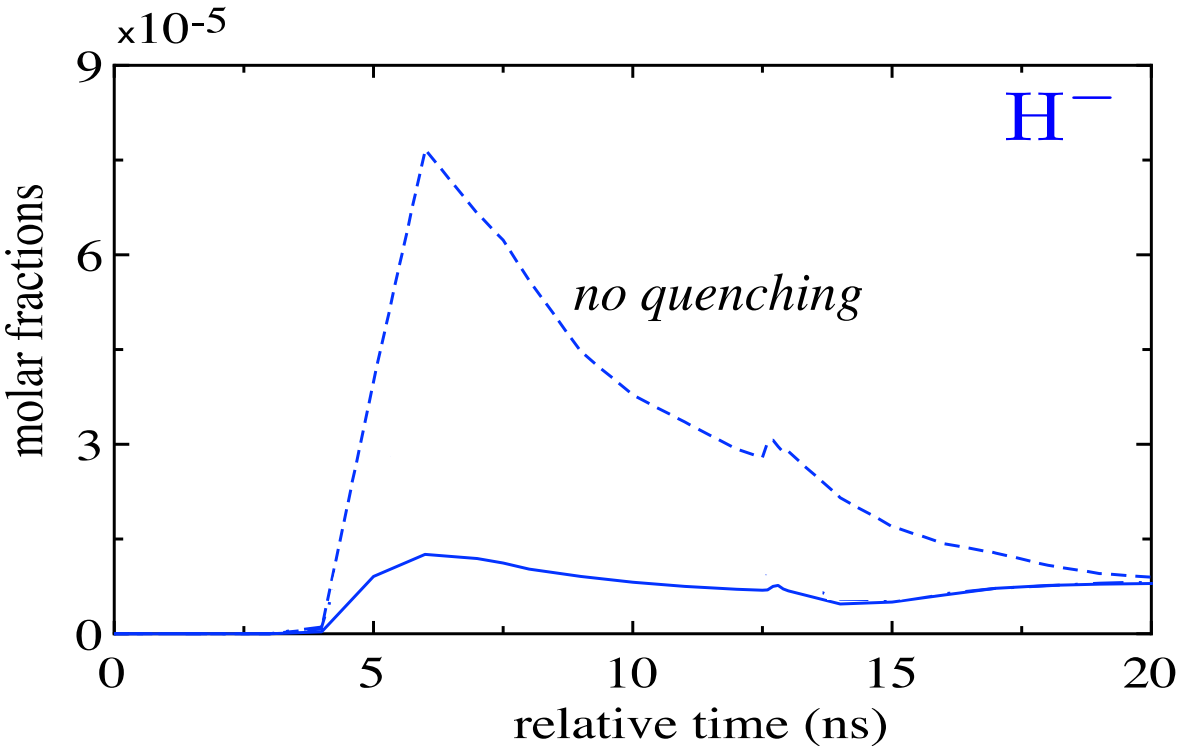




The European Physical Journal D (2017), *Vibrational kinetics of electronically excited states in H_2 discharges*
Colonna, G., Pietanza, L. D., D'Ammando, G., Celiberto, R., Capitelli, M., & Laricchiuta, A.

Fast (ns-pulsed) discharges in hydrogen

hydrogen negative ion concentration



The European Physical Journal D (2017), *Vibrational kinetics of electronically excited states in H_2 discharges*
Colonna, G., Pietanza, L. D., D'Ammando, G., Celiberto, R., Capitelli, M., & Laricchiuta, A.

Dense plasmas

$$U = -\frac{e^{-r/\lambda_D}}{r}$$

$\lambda_D = [k_B T_e/(4\pi n_e)]^{1/2}$ is the Debye leng

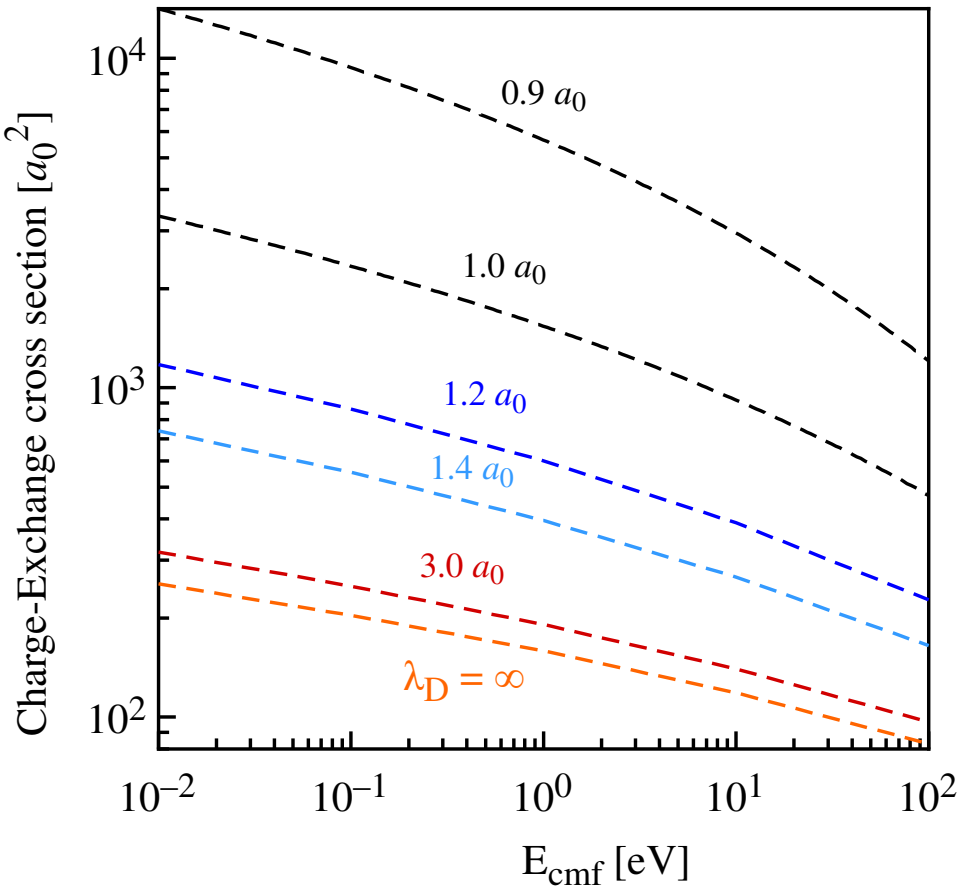
$$H + H^+ \rightarrow H^+ + H$$

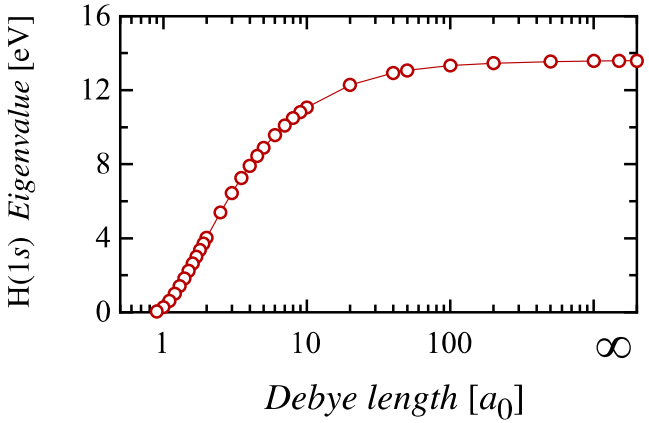
Resonant charge exchange for H-H+ in Debye plasmas
A. Laricchiuta, G. Colonna, M. Capitelli1, A. Kosarim, and B. M. Smirnov
Eur. Phys. J. D (2017)

H⁺/H RESONANT CHARGE EXCHANGE in DEBYE PLASMAS

$1s) + H^+$

ASYMPTOTIC APPROACH



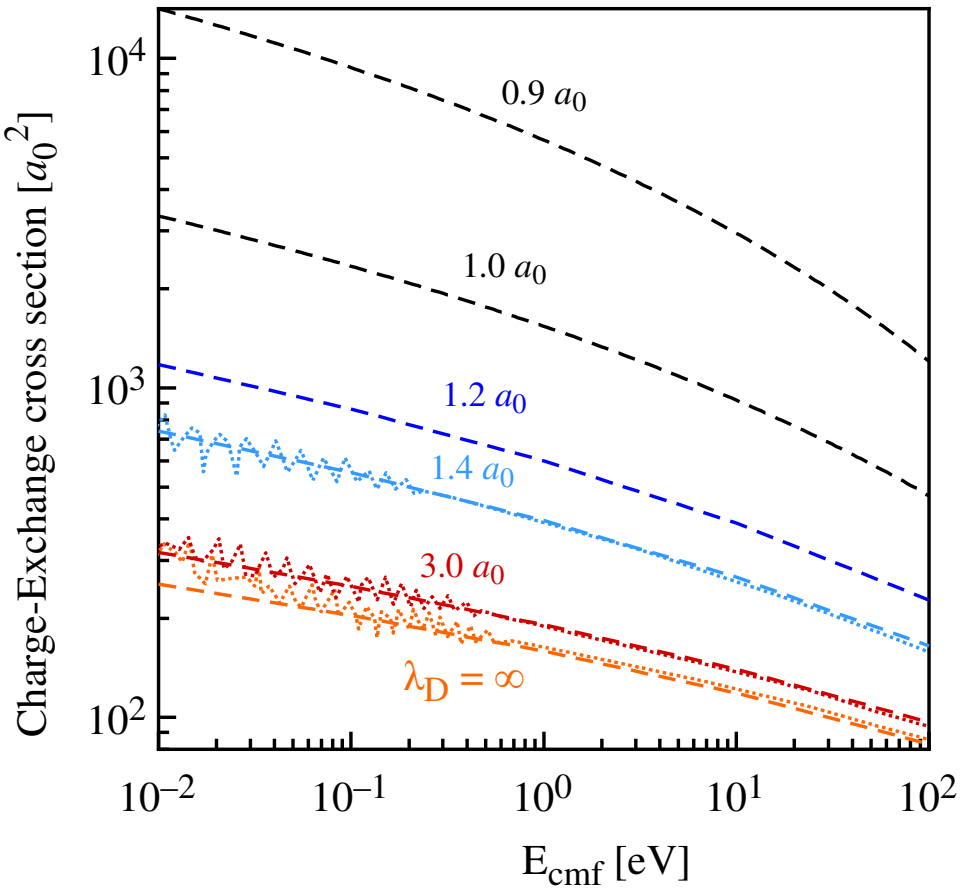


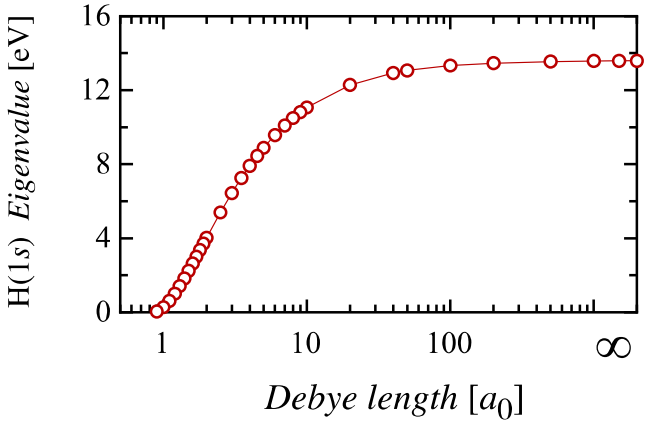
chiuta, A., Colonna, G., Capitelli, M., Kosarim, A., & Smirnov, B. M..
ant charge exchange for H–H⁺ in Debye plasmas
European Physical Journal D (2017).

H^+/H RESONANT CHARGE EXCHANGE in DEBYE PLASMAS

$s) + H^+$

ASYMPTOTIC APPROACH vs QUANTUM





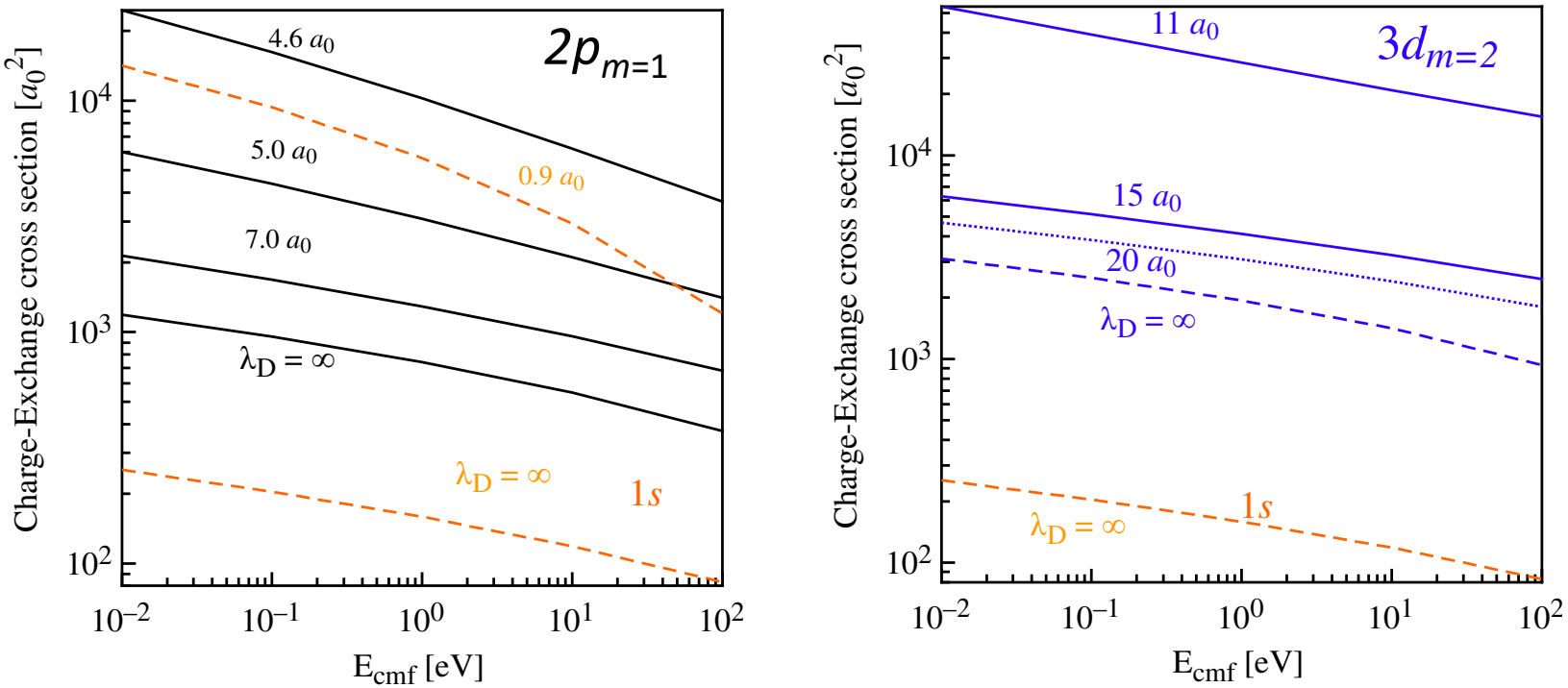
u, J.G. Wang, P.S. Krstic, R.K. Janev, J. Phys. B 43, (2010)

chiuta, A., Colonna, G., Capitelli, M., Kosarim, A., & Smirnov, B. M.
ant charge exchange for H–H⁺ in Debye plasmas
European Physical Journal D (2017).

H⁺/H RESONANT CHARGE EXCHANGE in DEBYE PLASMAS

$n = 2, 3) + H^+$

EXCITED STATES H*



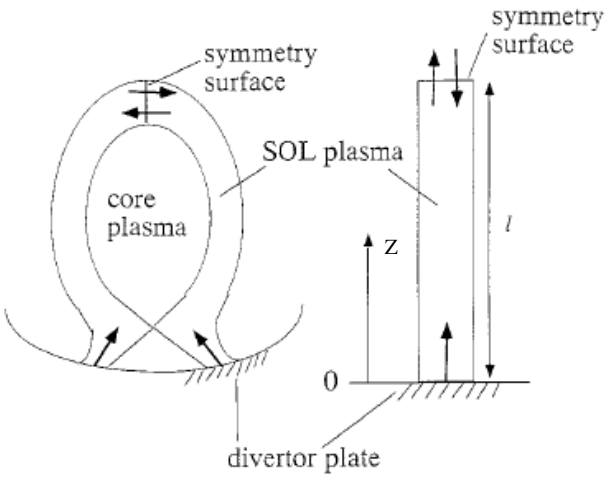
chiuta, A., Colonna, G., Capitelli, M., Kosarim, A., & Smirnov, B. M..
nant charge exchange for H–H⁺ in Debye plasmas
European Physical Journal D (2017).

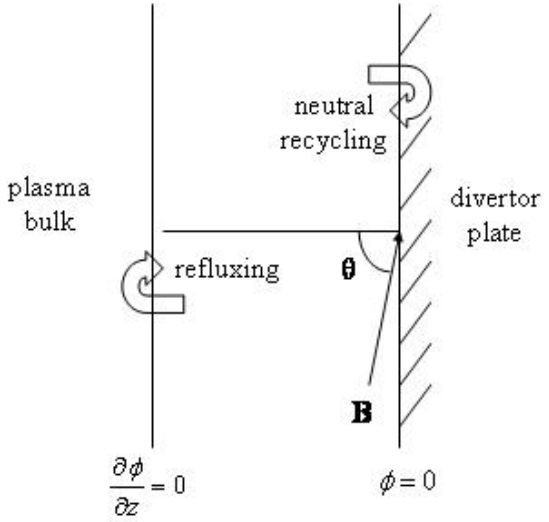
Kinetic and divertor modeling

F. Taccogna, P. Minelli, D. Bruno, S. Longo, R. Schneider
Chem. Phys. (2012)

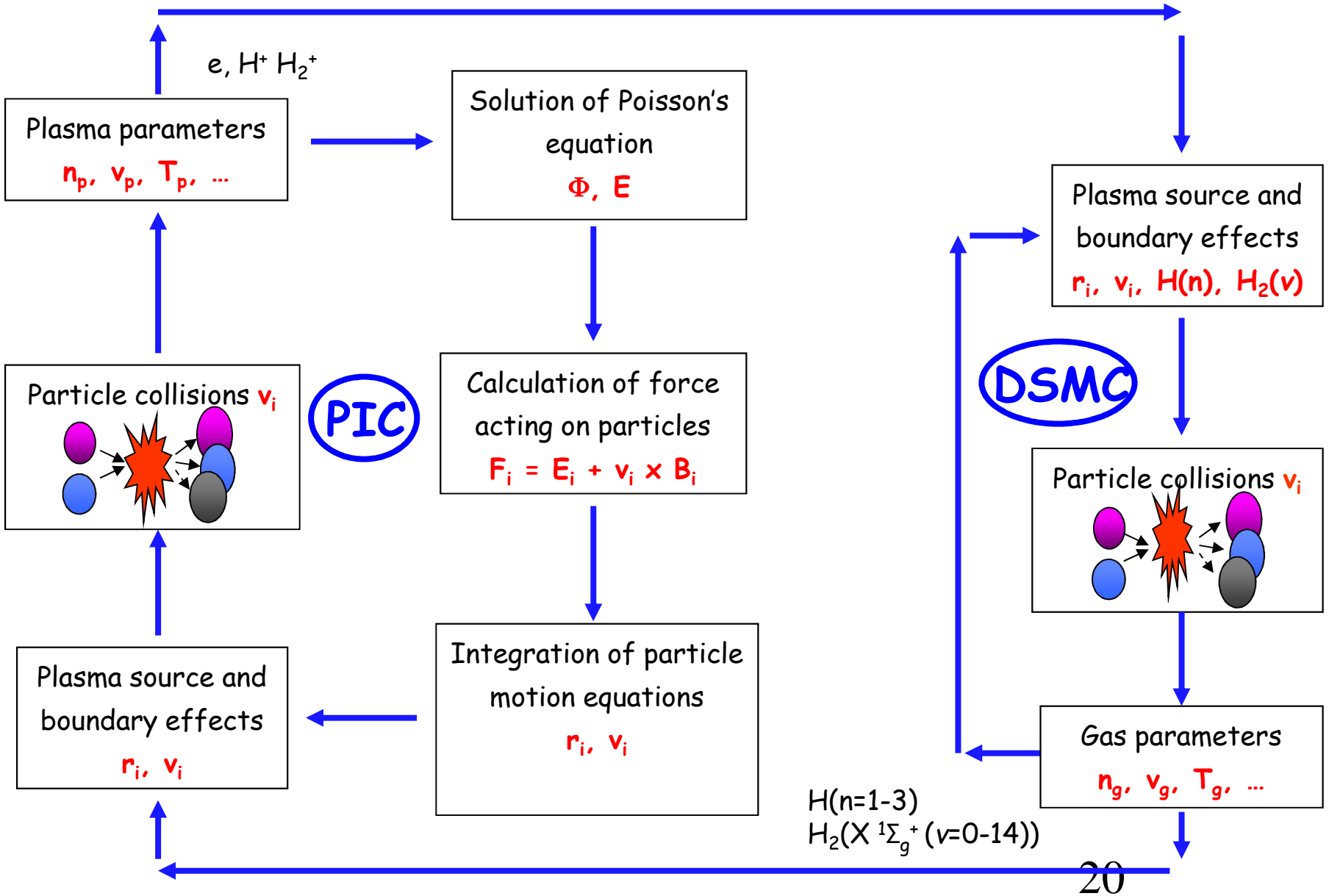
Reduction of the Divertor Region to 1 Dimension

- Input data: (detached divertor plasma condition)
  - e/H^+ density: $n_p=10^{21}$ m^{-3}
  - e/H^+ Temperature : T_p=5 eV
  - B=1 Tesla; θ=85 °
- Simulation domain: l=0.3 mm
- Every Particle carries: - species: e, H^+, H_2^+, H^-; H, $H_2(X^1\Sigma_g^+)$
  - axial position, velocities: (z, v_x, v_y, v_z)
  - quantities averaged over x,y (uniformity)
  - quantum energy levels: - electronic: n=1s-3s for H
  - vibrational: v=0-14 for H_2
- Collision Methodology: - Plasma-Plasma (e+H_2^+/H^-+H^+/H^-+e)
  - Plasma-Neutral
  - Neutral-Neutral relaxation (Vt/VT/VV)
- Boundary module:
  - $H_2(v)$ wall relaxation-dissociation
  - H wall recombinative desorption (ER/LH) -> $H_2(v)$ vibrational excitation (A-V)
  - H^+/H_2^+/ wall Auger neutralization -> $H_2(v)$ vibrational excitation (s-V)

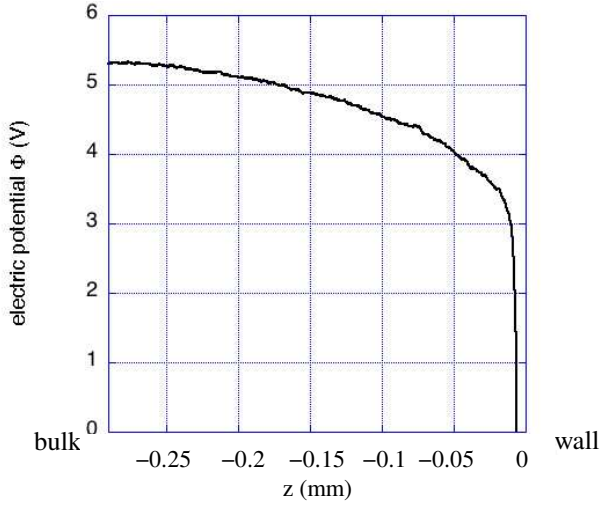


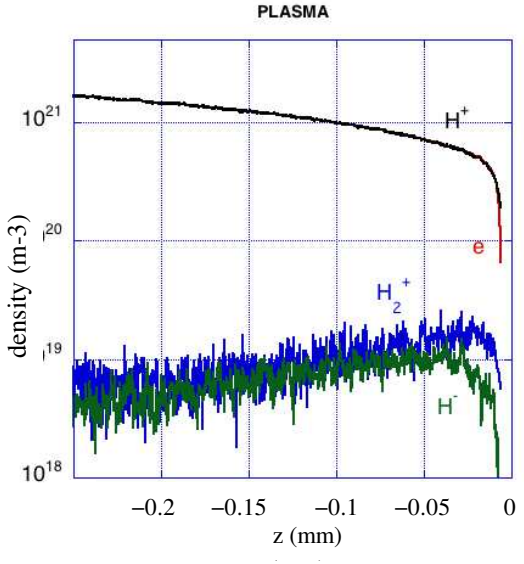


Particle-in-Cell / Direct Simulation Monte Carlo Model of Plasma-Gas Coupling in the Divertor Region (PIC-DSMC)

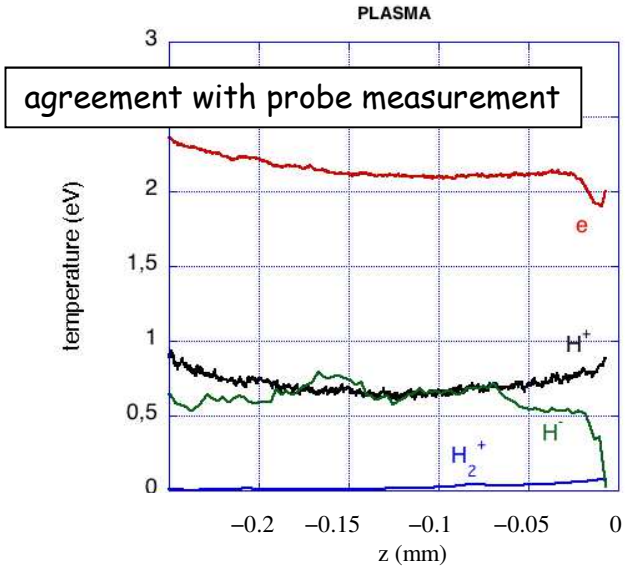


Results: Plasma

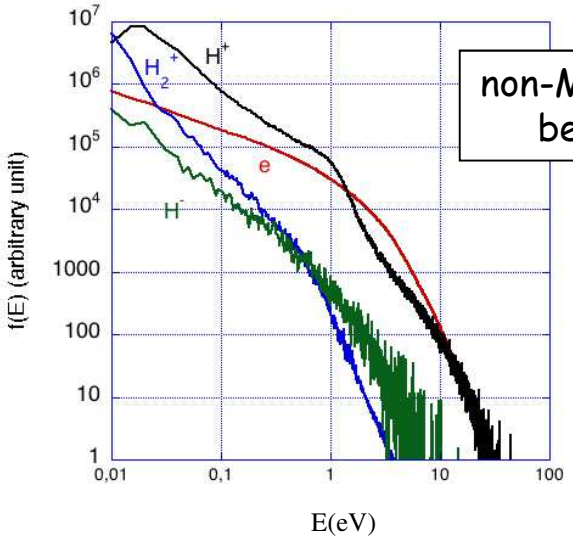




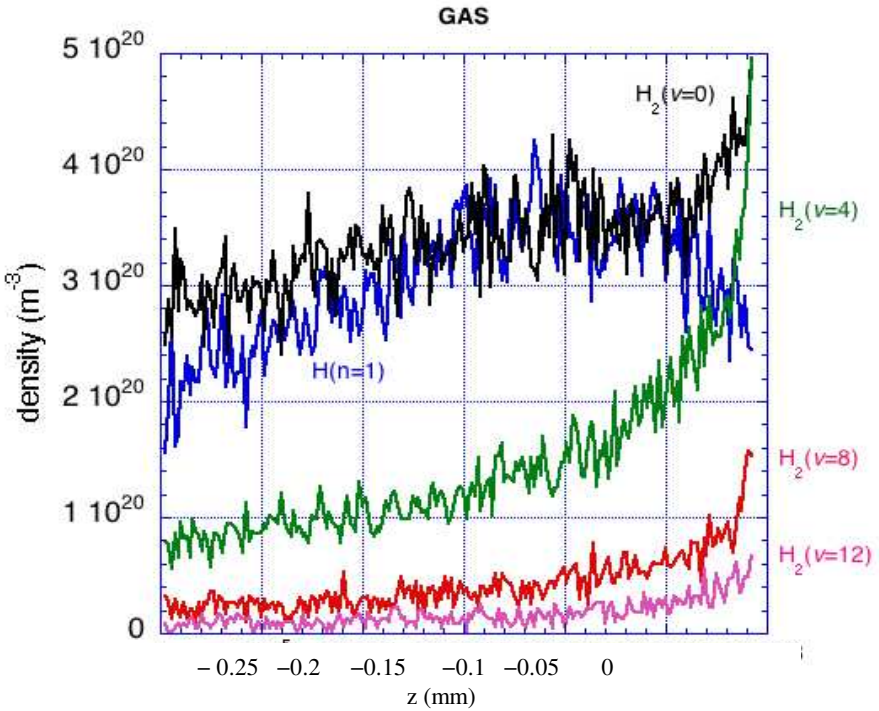
agreement with probe measurement



non-Maxwellian behavior

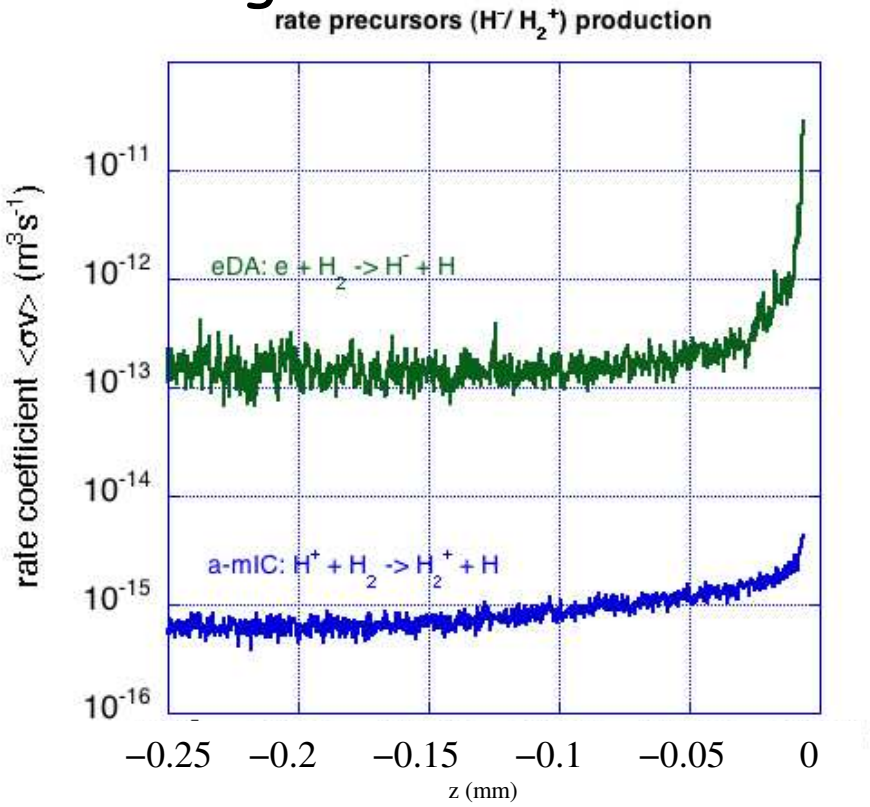


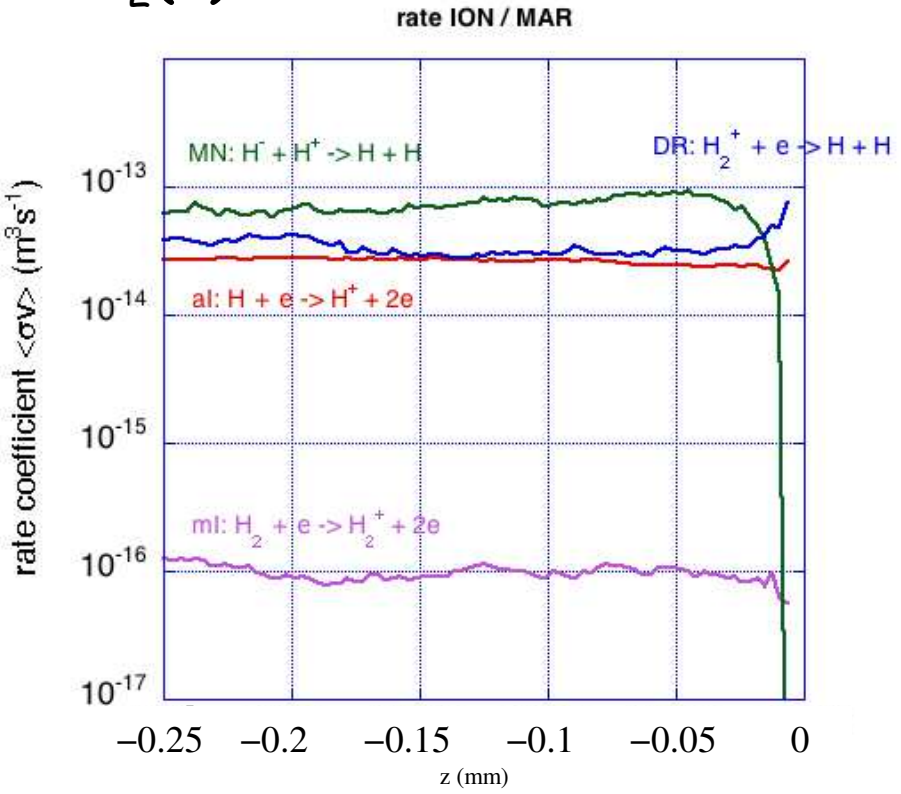
Results: Gas


GAS
5 10^20
4 10^20
3 10^20
2 10^20
1 10^20
0
density (m^-3)
H2(v=0)
H2(v=4)
H(n=1)
H2(v=8)
H2(v=12)
– 0.25
–0.2
–0.15
–0.1
–0.05
0
z (mm)

Results: MAR processes

production of precursors peaks close to the wall
due to high vibrational excitation $H_2(v)$

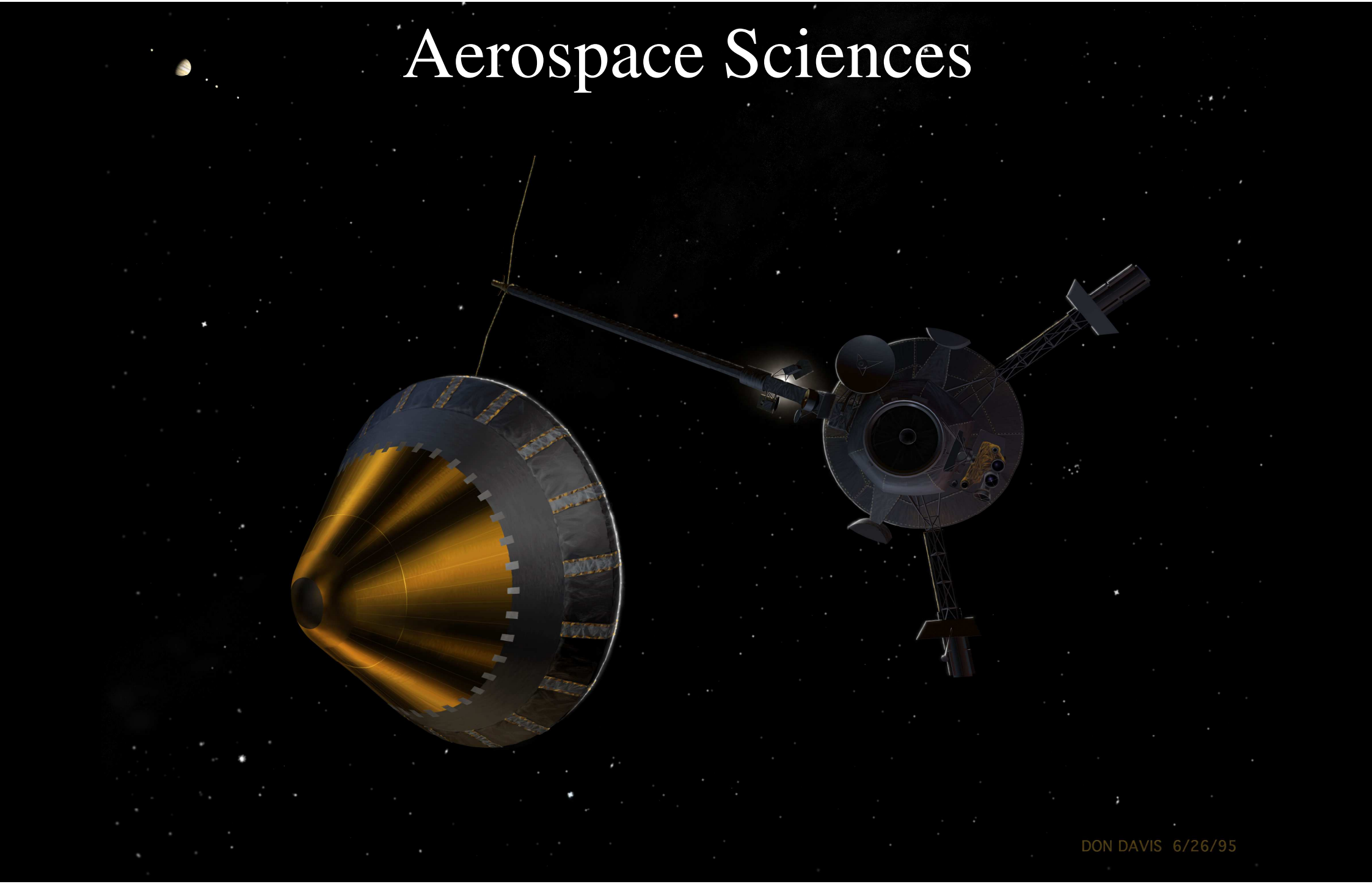




a) $e + H_2(v) \rightarrow H + H^-$, $\quad H^- + H^+ \rightarrow H + H$

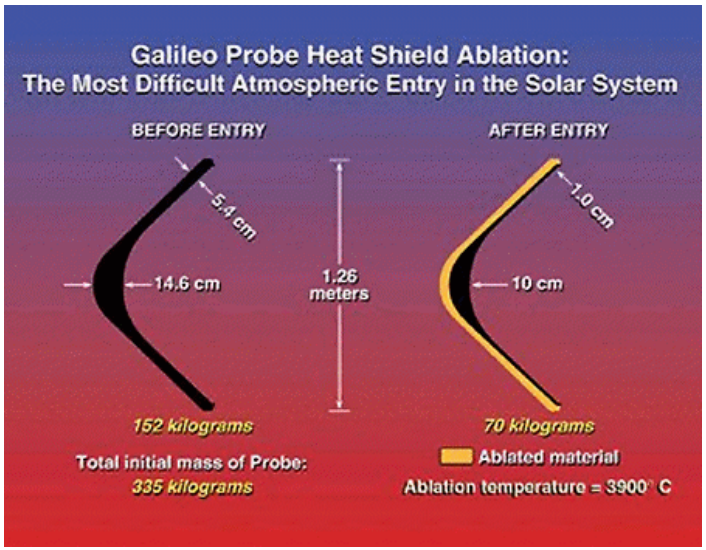
b) $H^+ + H_2(v) \rightarrow H + H_2^+$, $\quad H_2^+ + e \rightarrow H + H$

Aerospace Sciences



Motivation

Planet	Speed (km/s)	Heat flux (kW/cm2)	Enthalpy (kJ/cm2)	Acceleration (g)
Jupiter	47.4	30	300	250
Saturn	26.9	1.3	257	
Uranus	22.3	5.1	32.8	



Modelling chemical kinetics and convective heating in giant planet entries
P. Reynier, G. D'Ammando, D. Bruno,
Progress in Aerospace Sciences (2018)

The code couples the fluid-dynamics with the kinetic chemistry
(Jupiter atmosphere modeled: H_2/He)

Fluid-dynamics input data

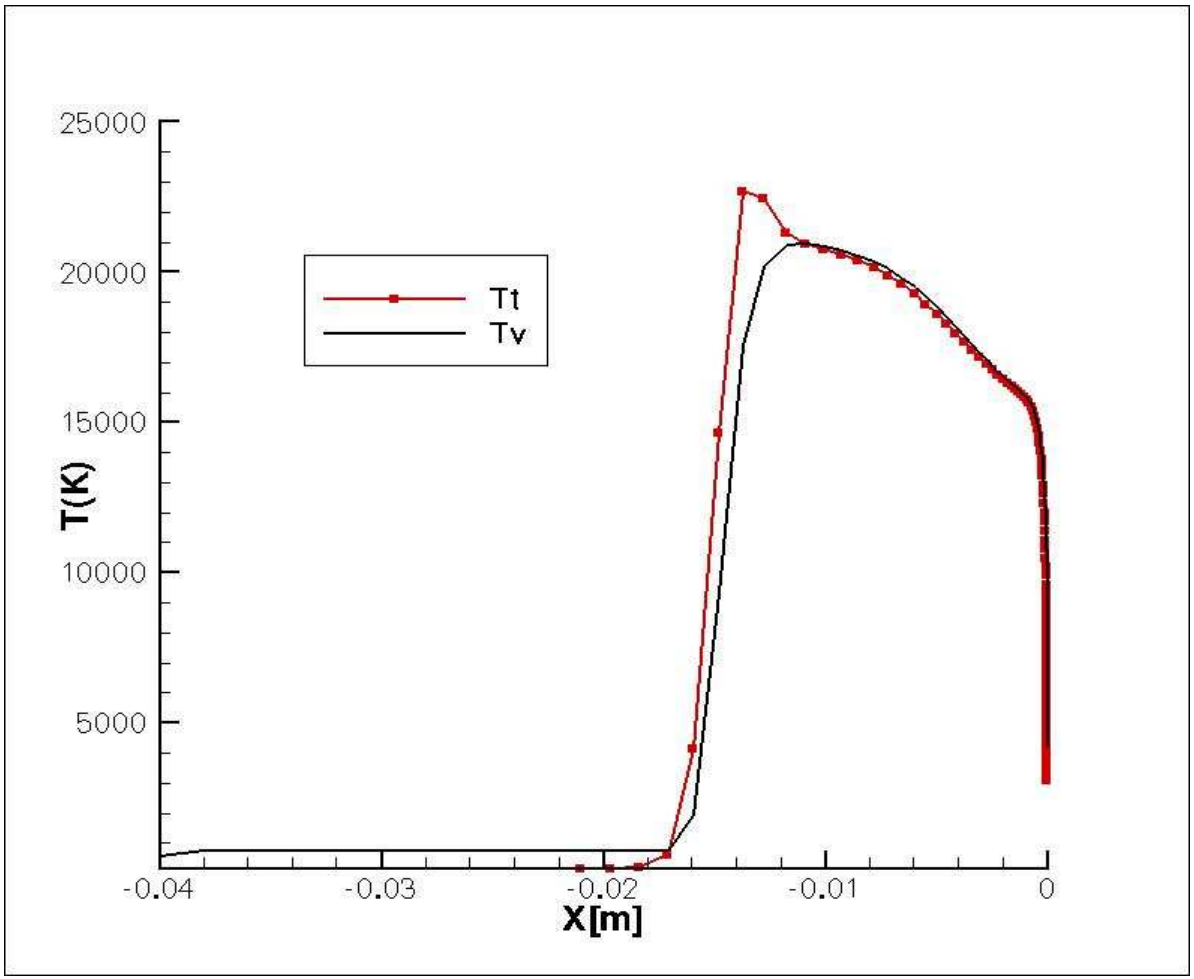
Flight data, i.e. probe velocity, gas density, gas temperature and pressure as a function of the altitude in the atmosphere.

Chemical input data

Cross sections for all the processes included in the model.

Kinetic scheme

Processes	
$H + e^- = H^+ + e^- + e^-$	$H_2 + e^- = 2H + e^-$
$He + e^- = He^+ + e^- + e^-$	$H_2 + e^- = H_2^+ + 2e^-$
$H + H = H^+ + e^- + H$	$H_2 + e^- = H + H^+ + 2e^-$
$H + He = H^+ + e^- + He$	$H_2^+ + e^- = 2H^+ + 2e^-$
$H_2 + He = H + H + He$	$H_2^+ + e^- = H + H^+ + e^-$
$H_2 + H_2 = H + H + H_2$	$H_2^+ + e^- = 2H$
$H_2 + H = H + H + H$	$H + e^- = H^+ + 2e^-$
$H_2 + H^+ = H + H + H^+$	$He + e^- = He^+ + 2e^-$
$H_2 + e^- = H + H + e^-$	$H + H = H + H^+ + e^-$
$H_2^+ + e^- = H + H$	$He + He = He + He^+ + e^-$
	$H_2 + H_2 = 2H + H_2$
	$H_2 + H = 3H$
	$H_2 + He = 2H + He$



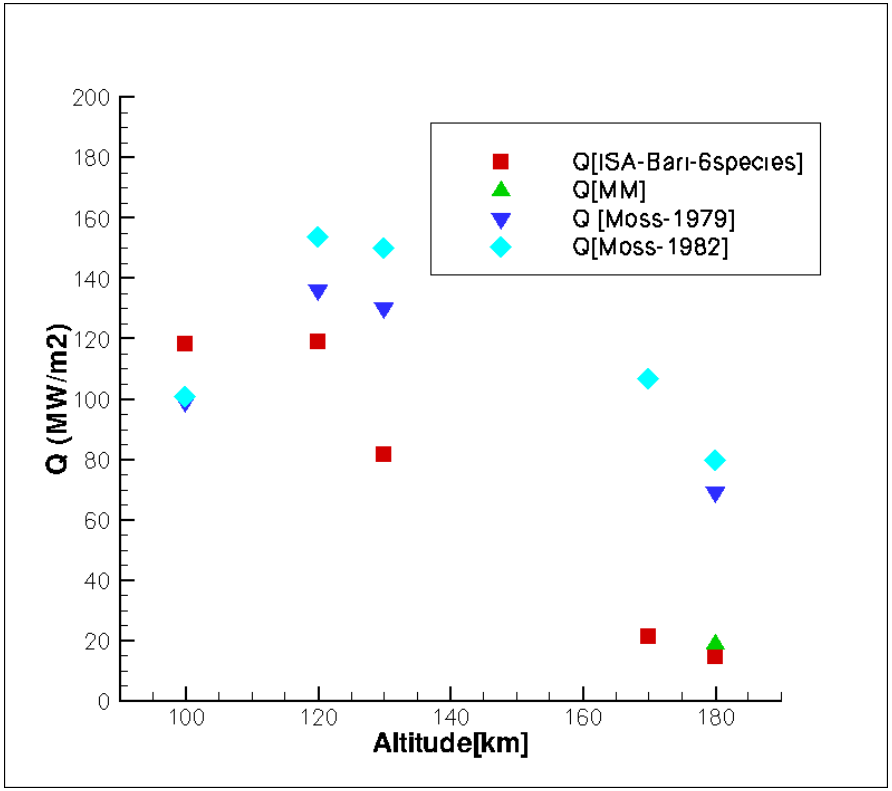
T_t(K) = translational temperature along the stagnation line at 18 km of altitude;

T_v(K) = vibrational temperapture;

X(m) = distance from the pr

[1] D. Bruno et al., Transport properties of high-temperature Jupiter atmosphere components, *Physics of Plasmas*, **17**(11) (2010) 112315.
[2] G. Palmer, D. Prabhu, B. A. Cruden, Aeroheating uncertainties in Uranus and Saturn entries by the Monte Carlo method, *Journal of Spacecraft and Rockets*, **51**(3) (2014) 801–814.

Convective Heat Flux



Ph. Reynier, G. D'Ammando, D. Bruno, Review: Modelling chemical kinetics and convective heating in giant planet entries, *Progress in Aerospace Sciences* **96** (2018) 1–22.

Elementary processes

- Heavy particle collisions
- Electron-molecule collisions

Collision processes of heavy particles

Inelastic processes

$$A+BC(v, j) \rightarrow A+BC(v', j')$$

Reactive processes

$$A+BC(v,j) \rightarrow B+AC(v', j'),\ C+AB(v', j')$$

Dissociation

$$A+BC(v, j) \rightarrow A+B+C$$

Collision processes of heavy particles

Inelastic processes

$$A+BC(v, j) \rightarrow A+BC(v', j')$$

Reactive processes

$$A+BC(v,j) \rightarrow B+AC(v', j'),\ C+AB(v', j')$$

Dissociation

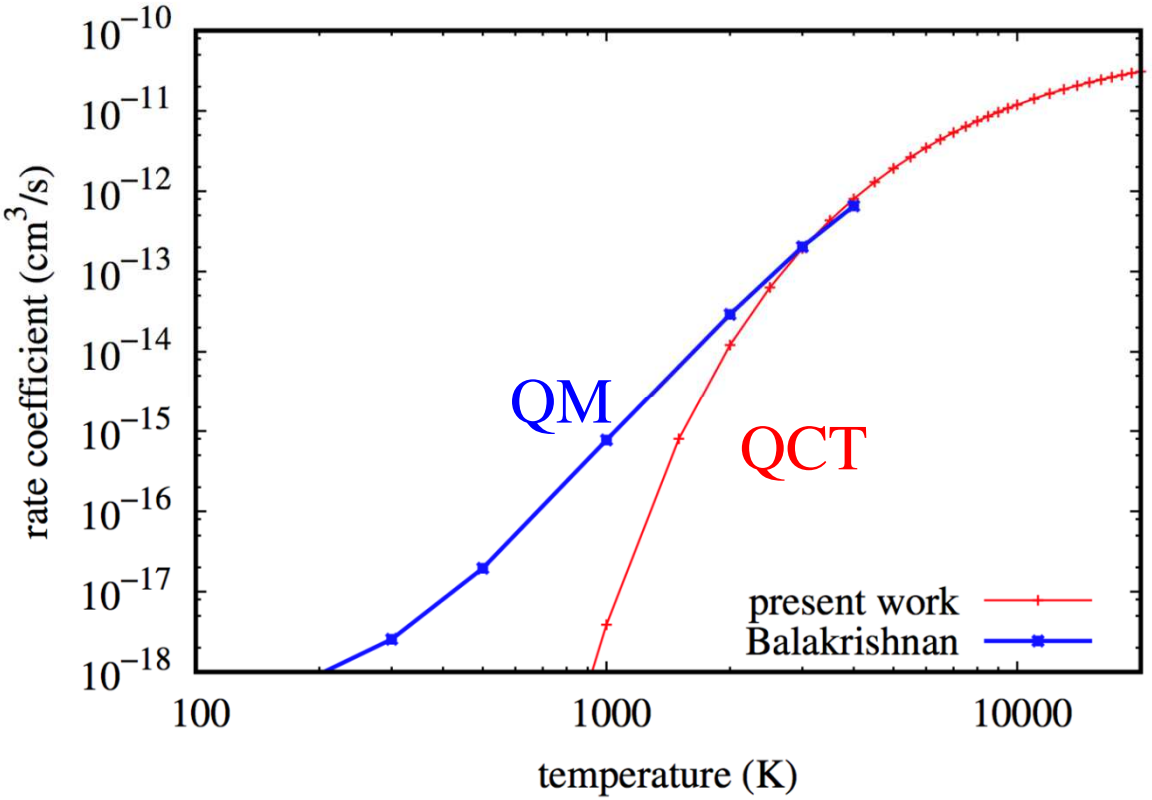
$$A+BC(v, j) \rightarrow A+B+C$$

The general philosophy is to use approximated methods for cross section calculations to reduce the computational load

Quasi-classical trajectory method

Relaxation of $He+H_2$

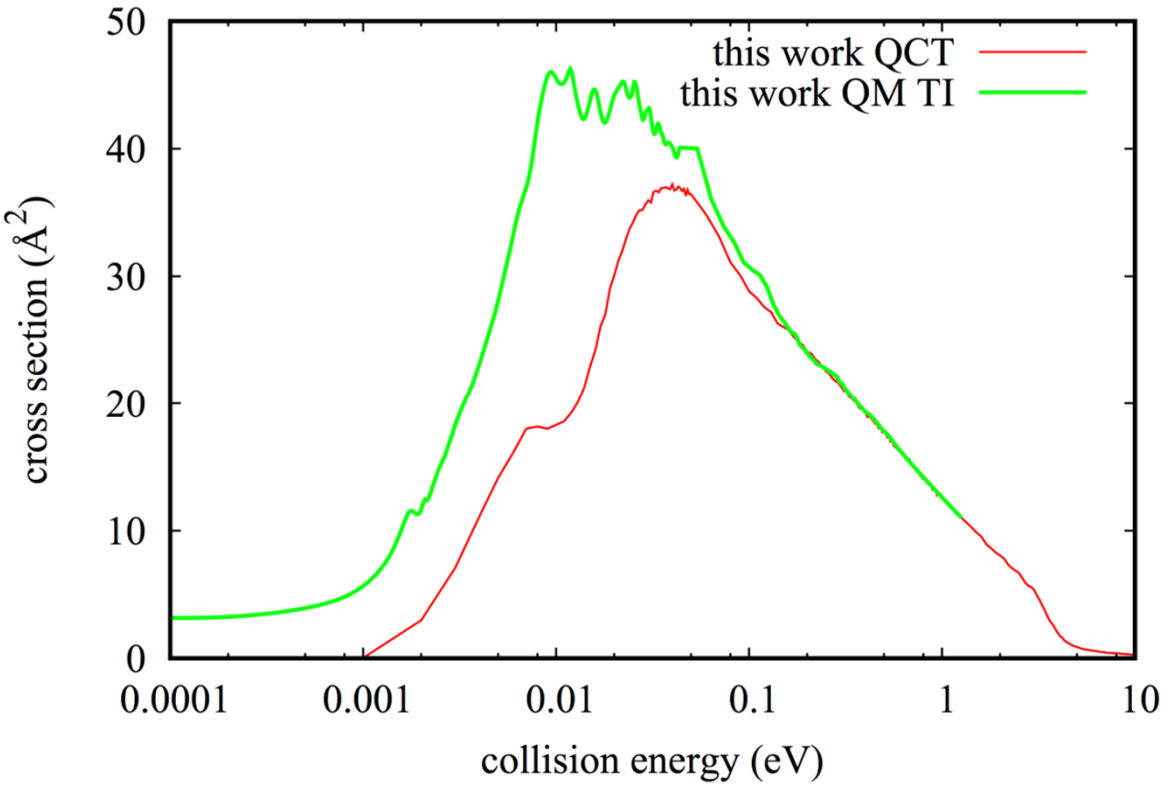
Comparison of QCT with QM Close Coupling calculations



R. Celiberto, M. Capitelli, G. Colonna, G. D'Ammando, F. Esposito,
R. Janev, V. Laporta, A. Laricchiuta, L. Pietanza, M. Rutigliano, and J. Wadehra, Atoms **5**, 18 (2017).
N. Balakrishnan, M. Vieira, J. Babb, A. Dalgarno, R. Forrey, and S. Lepp, ApJ **524**, 1122 (1999).

Reaction of $H+HeH^+ \rightarrow He+H_2^+$

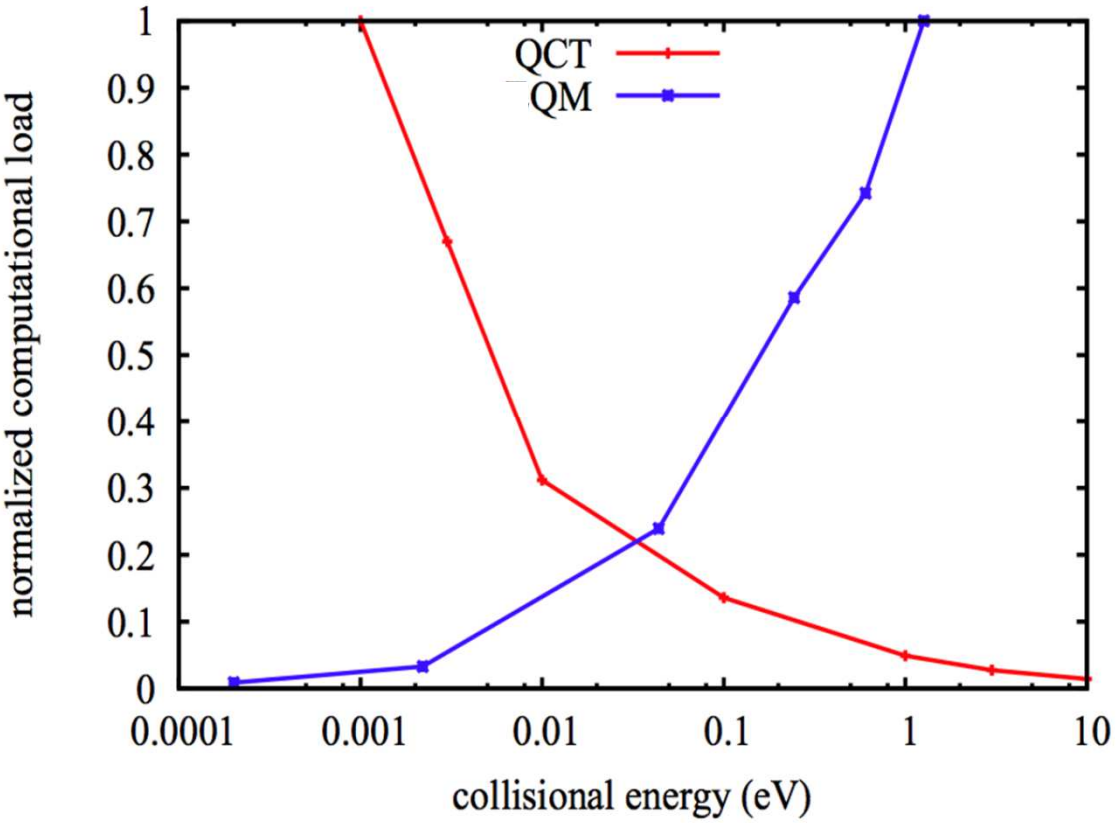
Comparison of QCT with accurate QM calculations



F. Esposito, C.M. Coppola, and D. De Fazio,
PCA **119,** 12615–12626 (2015).

Reaction of $H+HeH^+ \rightarrow He+H_2^+$

Normalized computational load in QCT and QM calculations

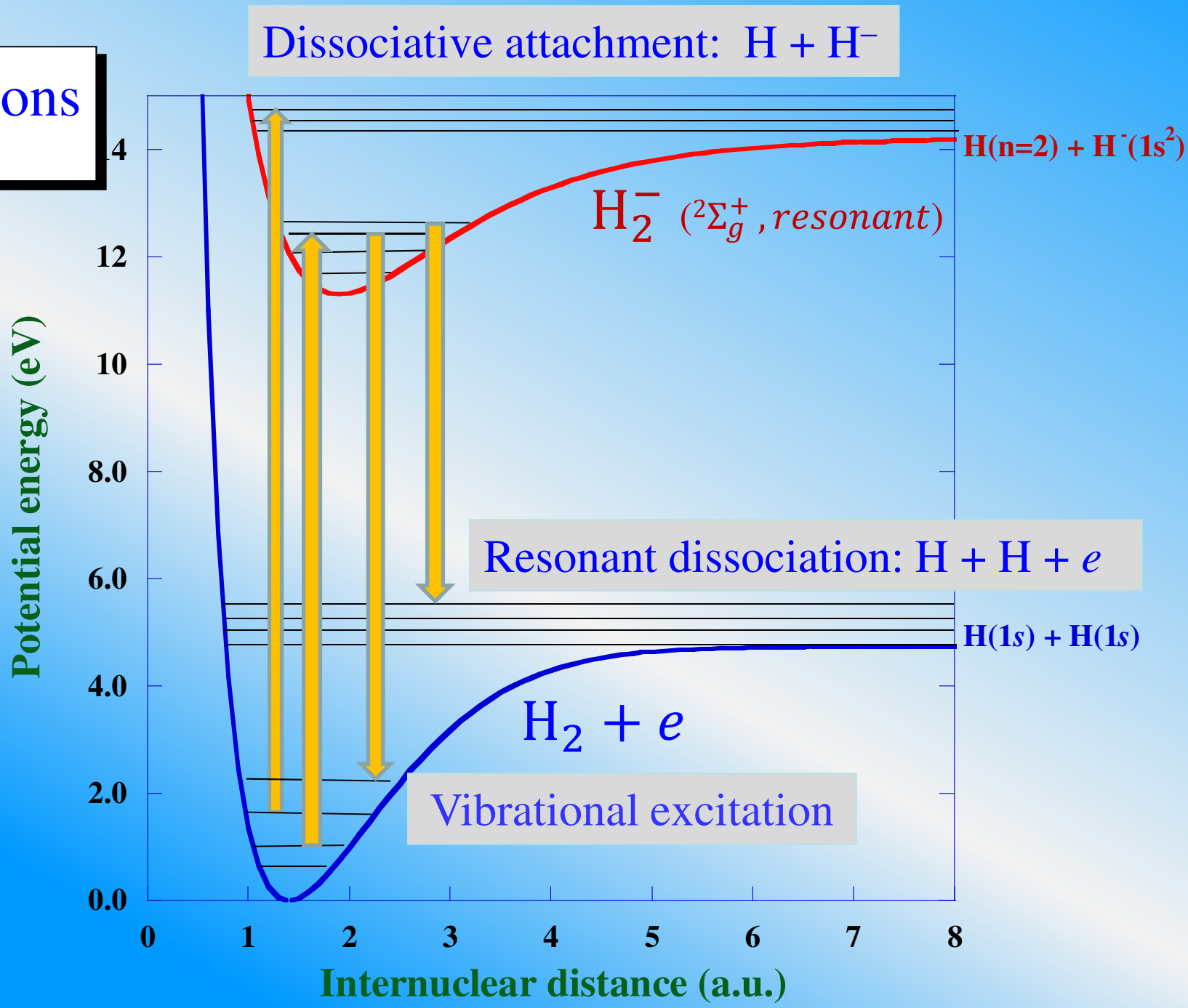


F. Esposito, C.M. Coppola, and D. De Fazio,
JPCA **119,** 12615−12626 (2015).

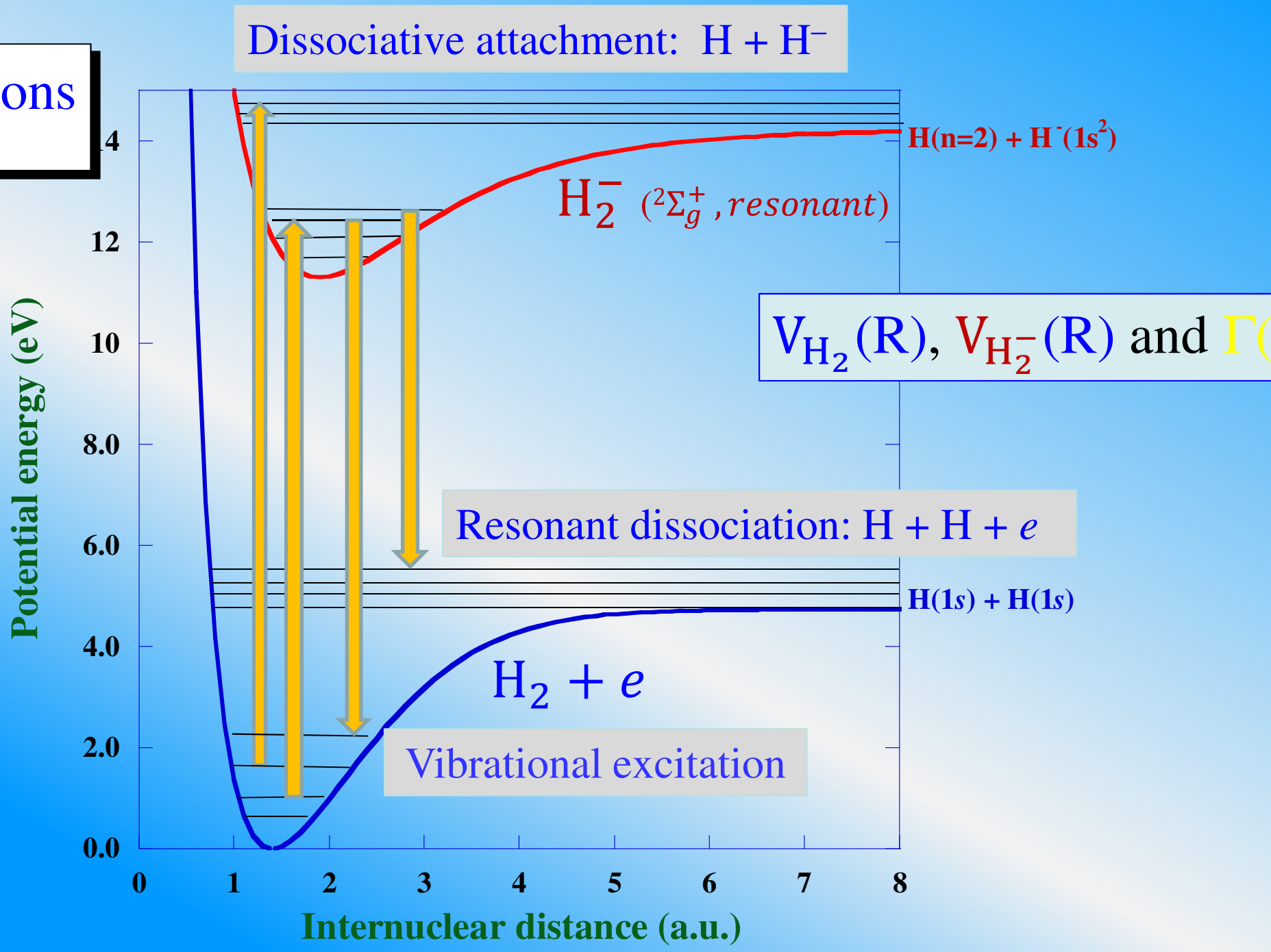
Electron-molecule collisions

- Resonant collisions
- Non-resonant collisions

onant collisions

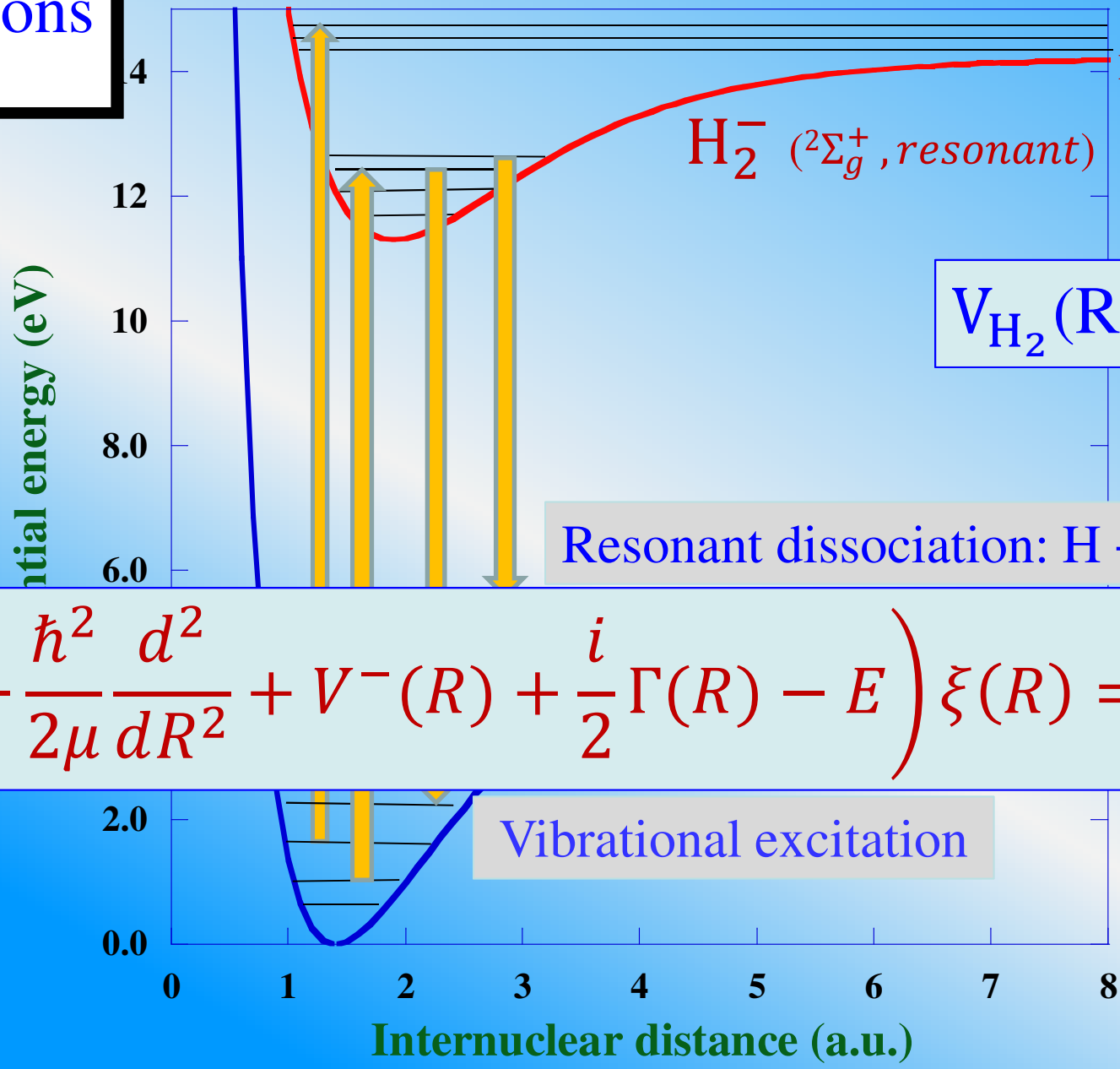


onant collisions



onant collisions

Dissociative attachment: H + H⁻



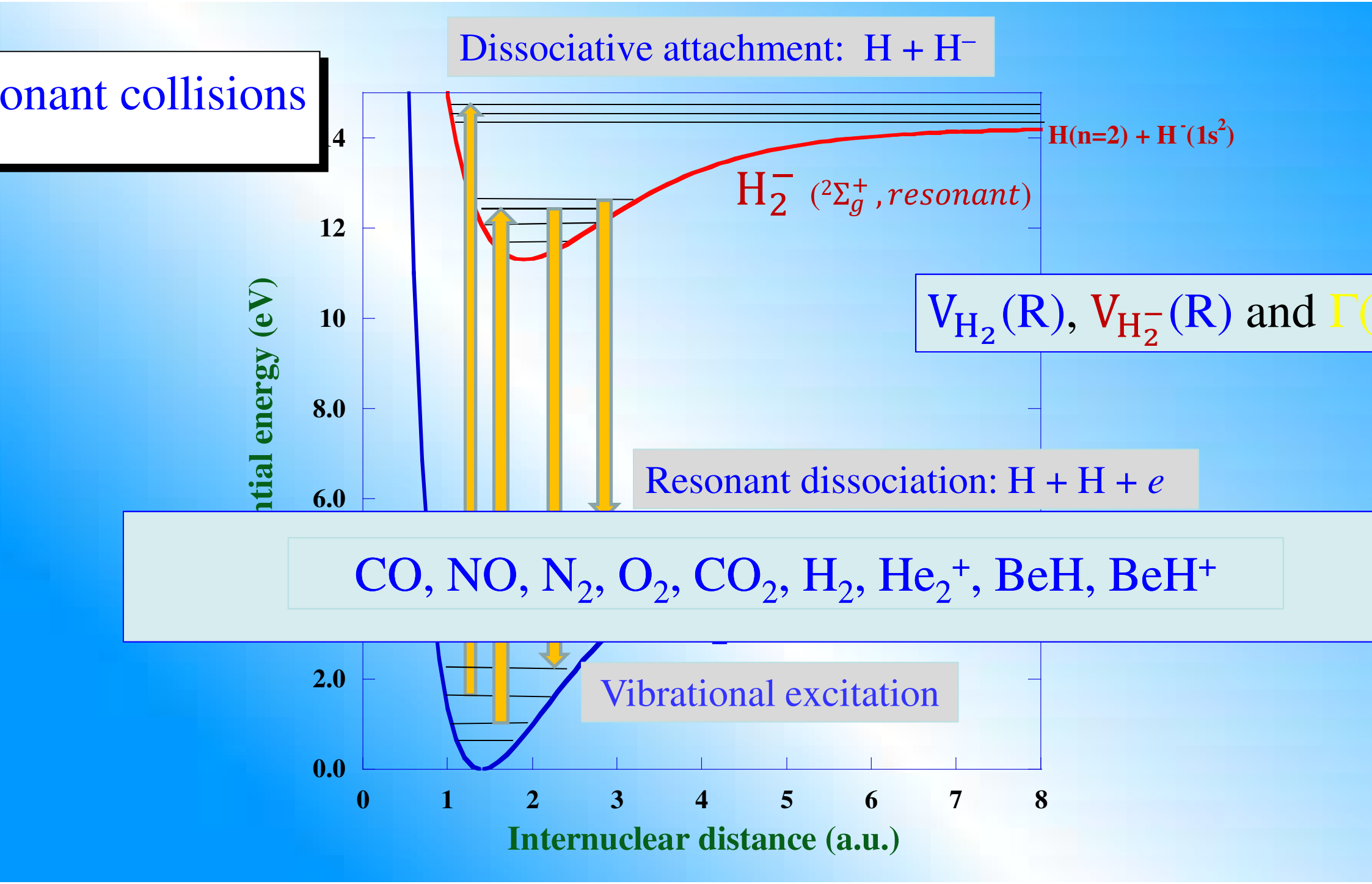
$V_{H_2}(R)$, $V_{H_2^-}(R)$ and $\Gamma($

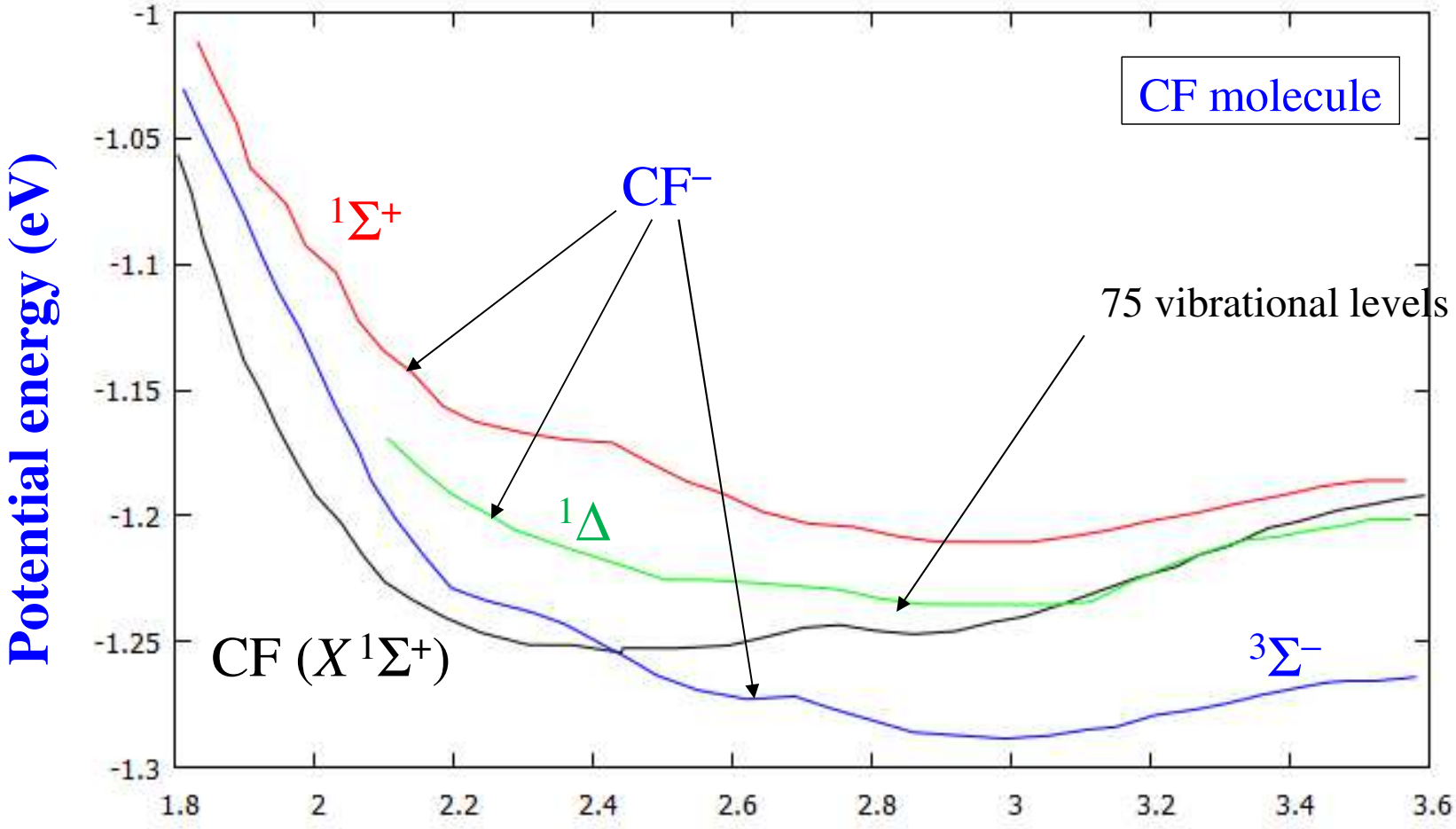
Resonant dissociation: H + H + e

$$\left(-\frac{\hbar^2}{2\mu}\frac{d^2}{dR^2} + V^-(R) + \frac{i}{2}\Gamma(R) - E\right)\xi(R) = -\mathcal{V}_{\epsilon_i}(R)\chi_{v_i}(R$$

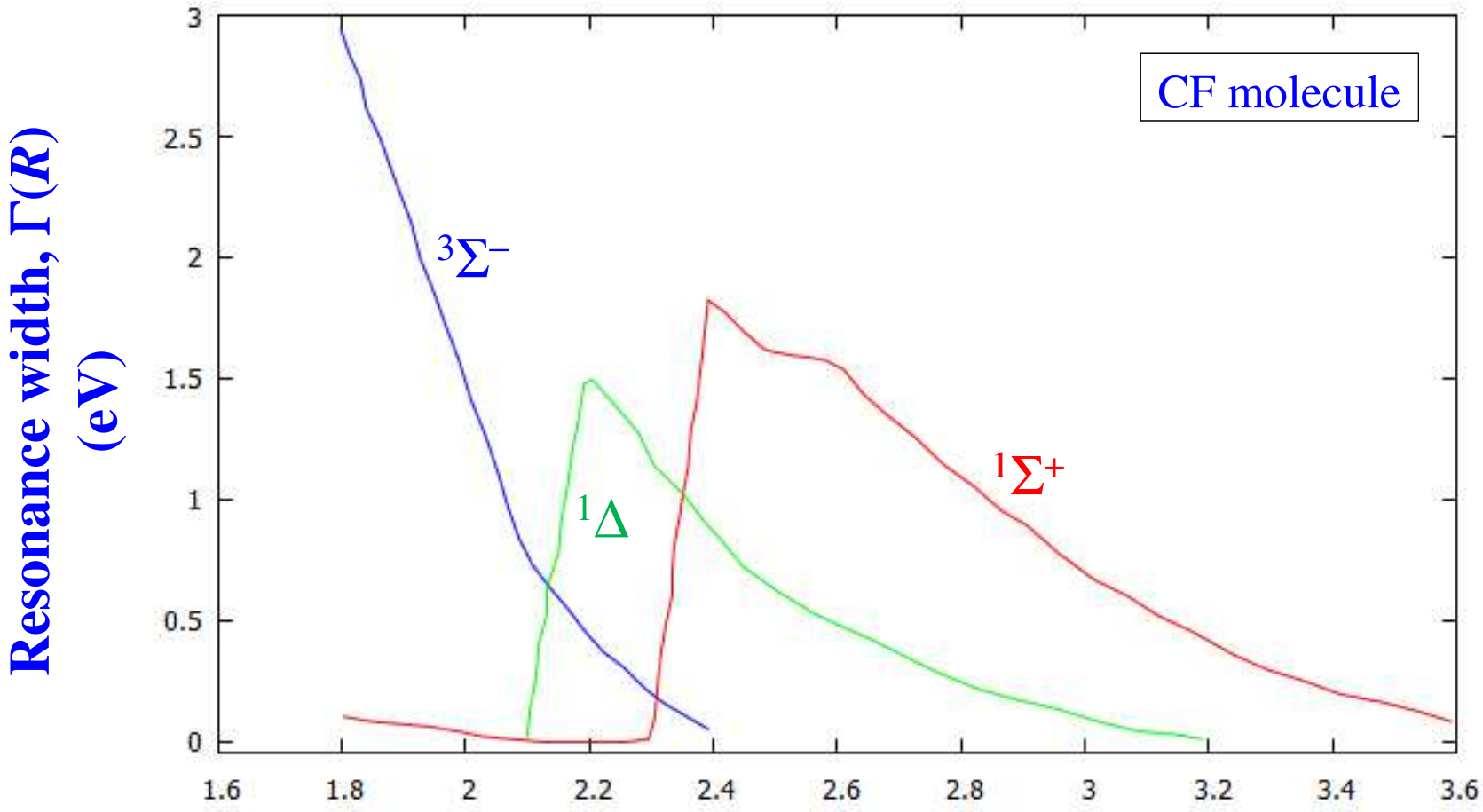
Vibrational excitation

onant collisions



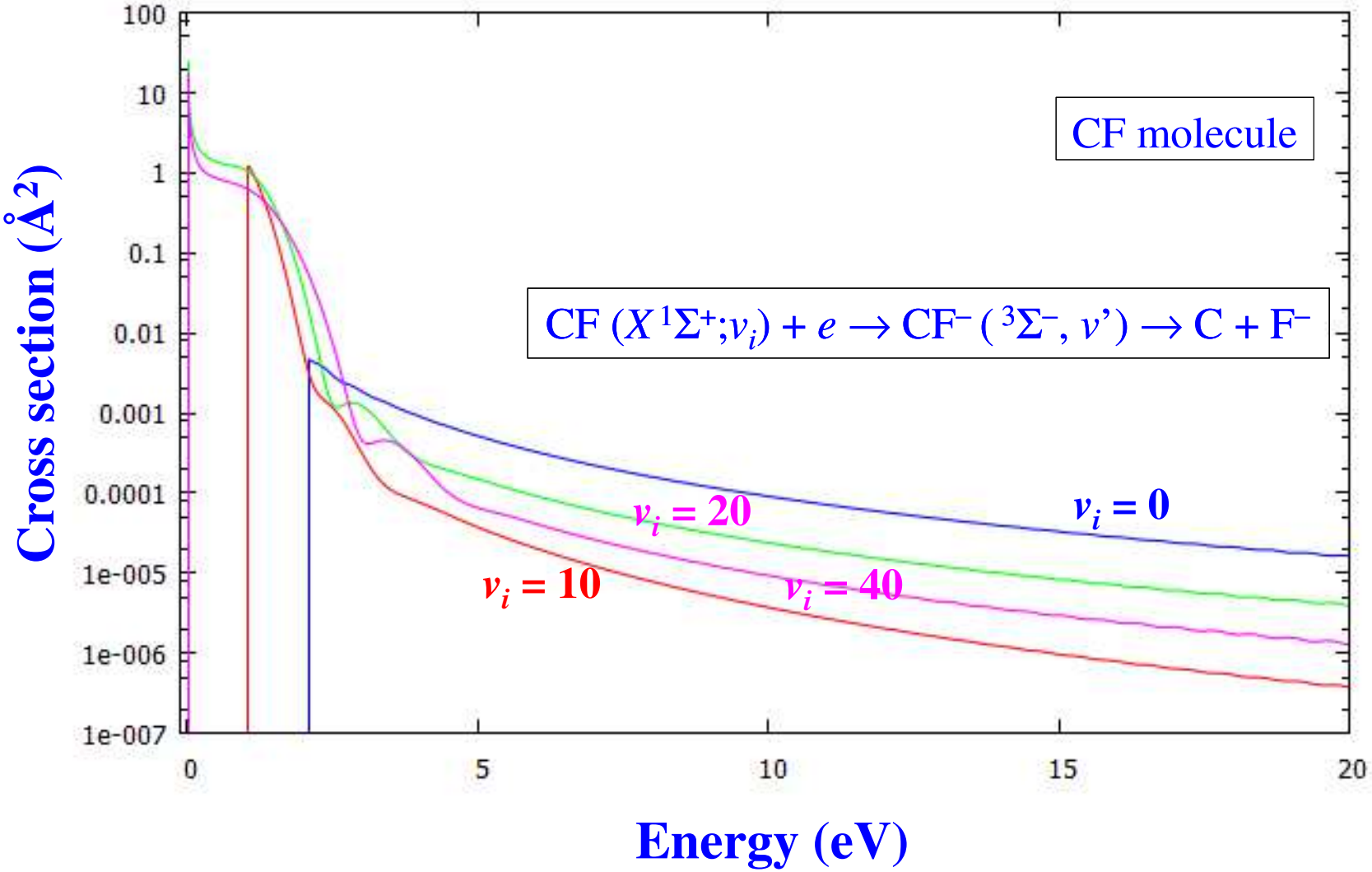


Rozum, Mason & Tennyson,
J. Phys. B (2013)

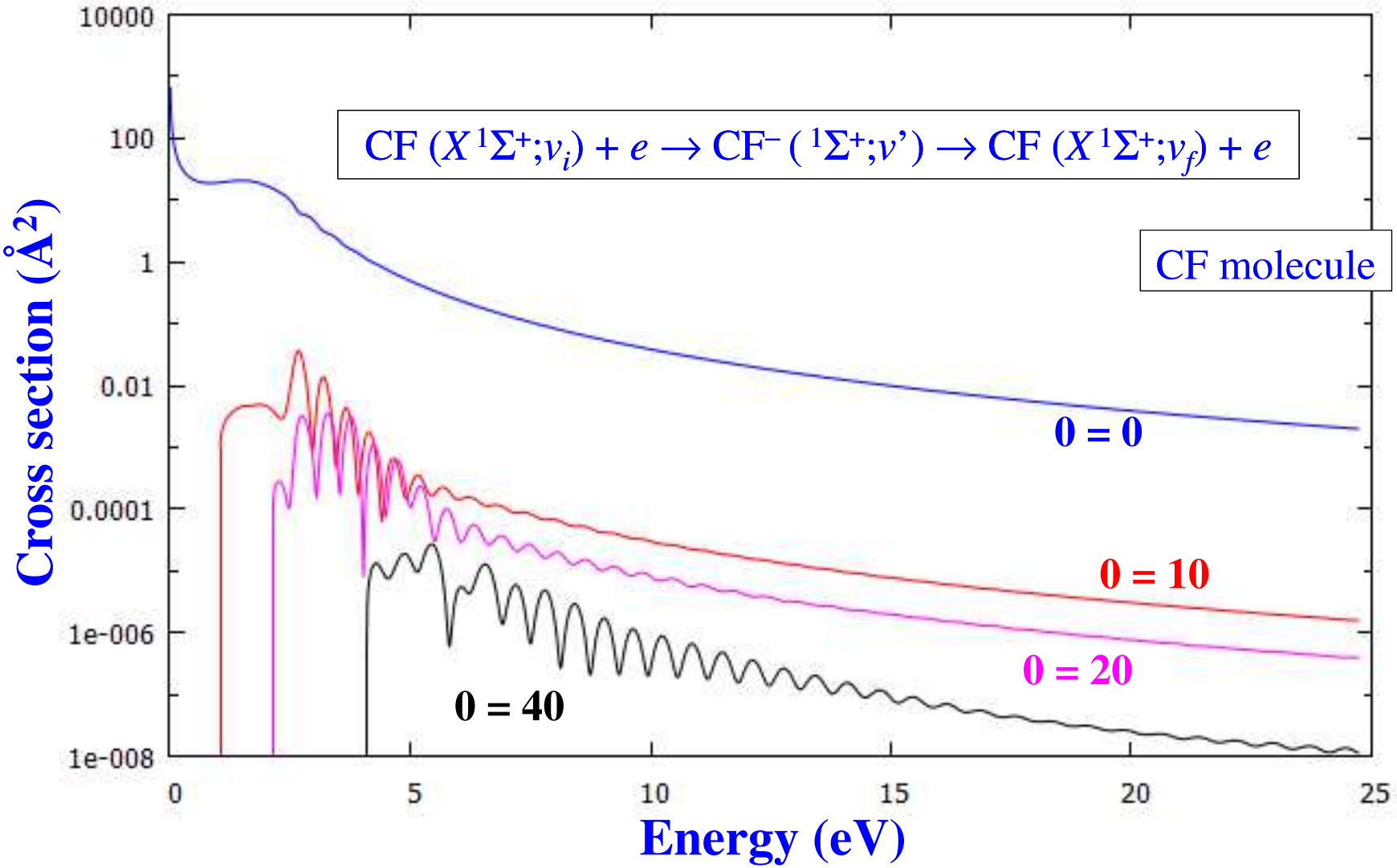


Rozum, Mason & Tennyson,
J. Phys. B (2013)

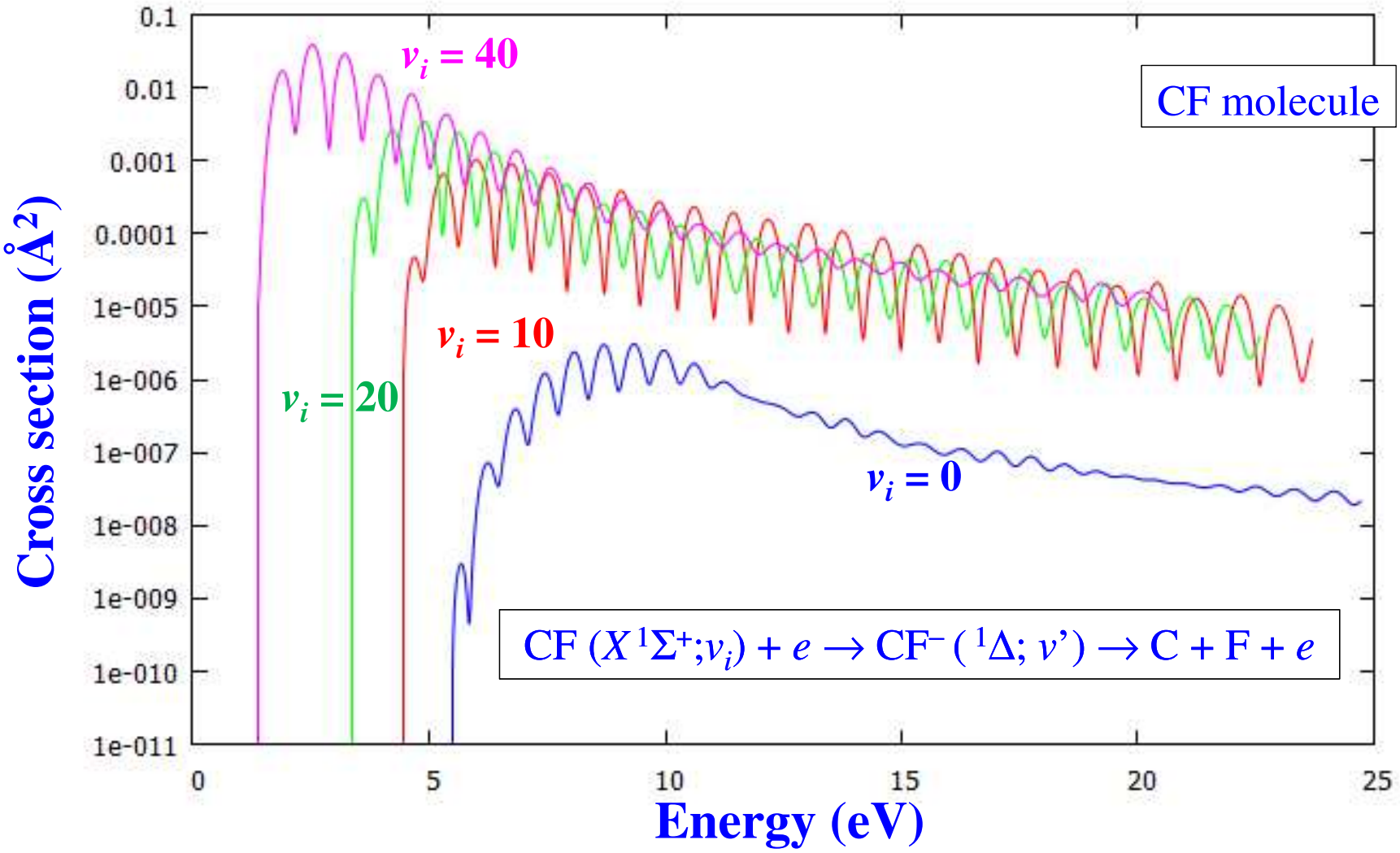
Dissociative attachment



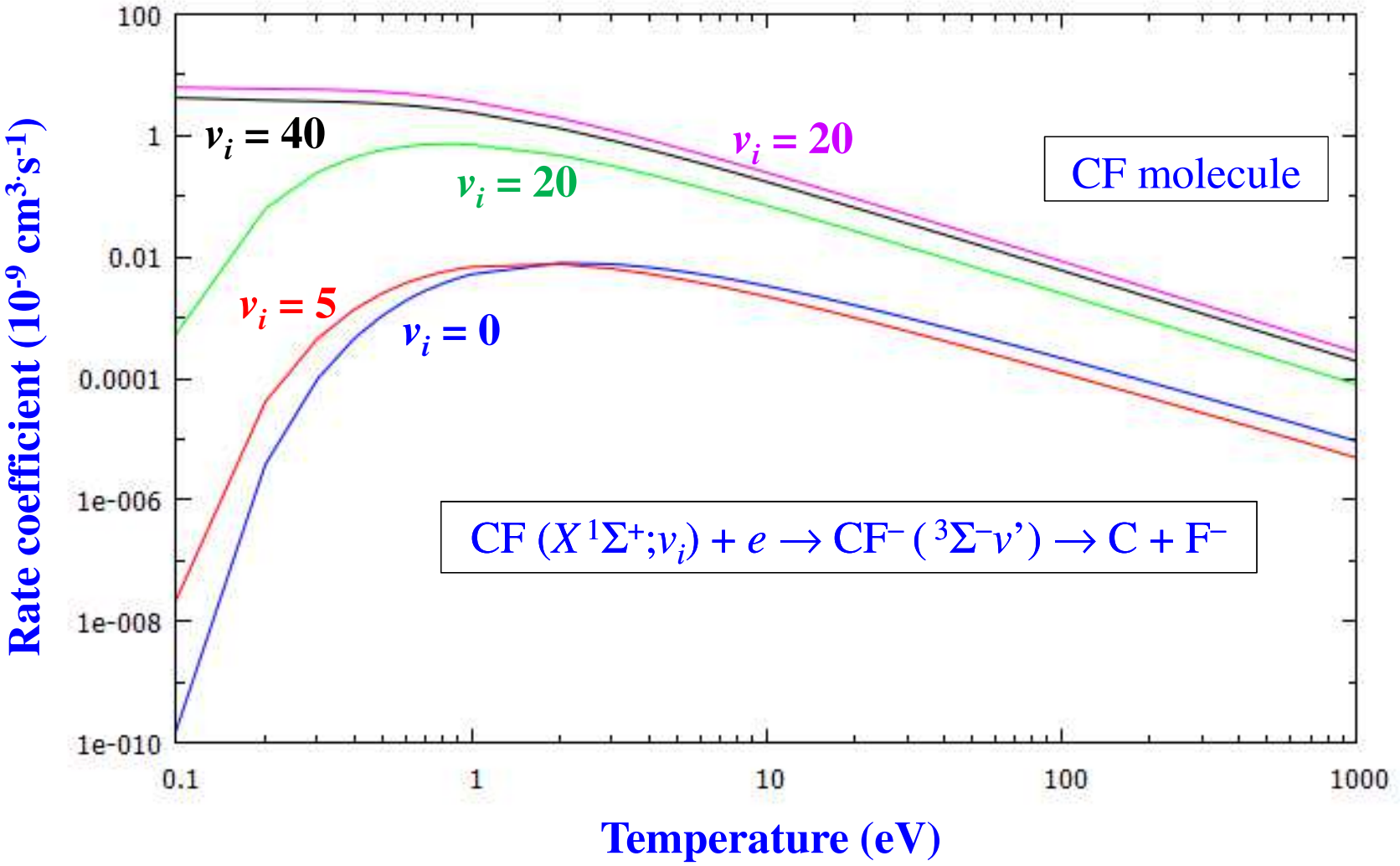
Resonant vibrational excitation



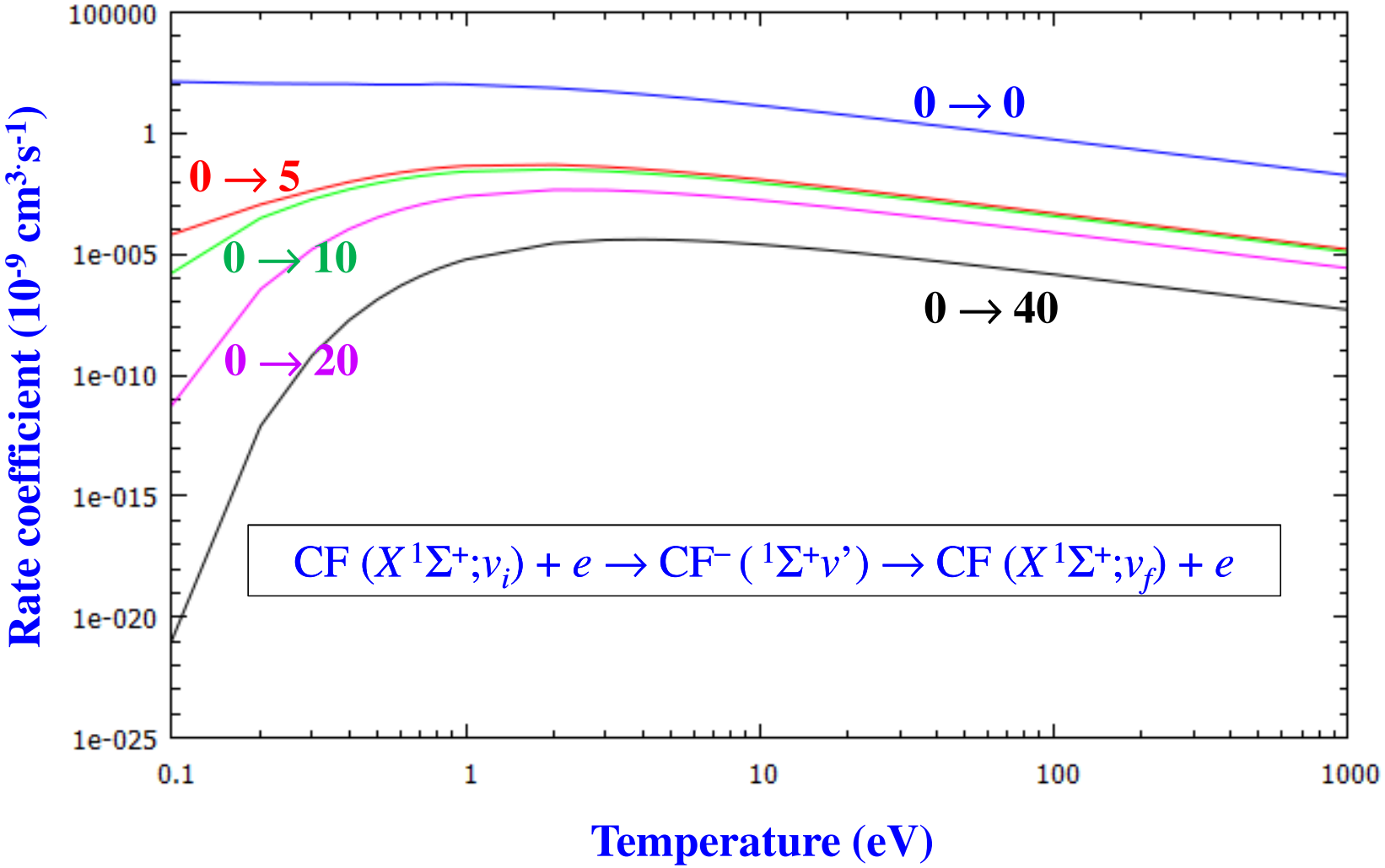
Dissociative excitation



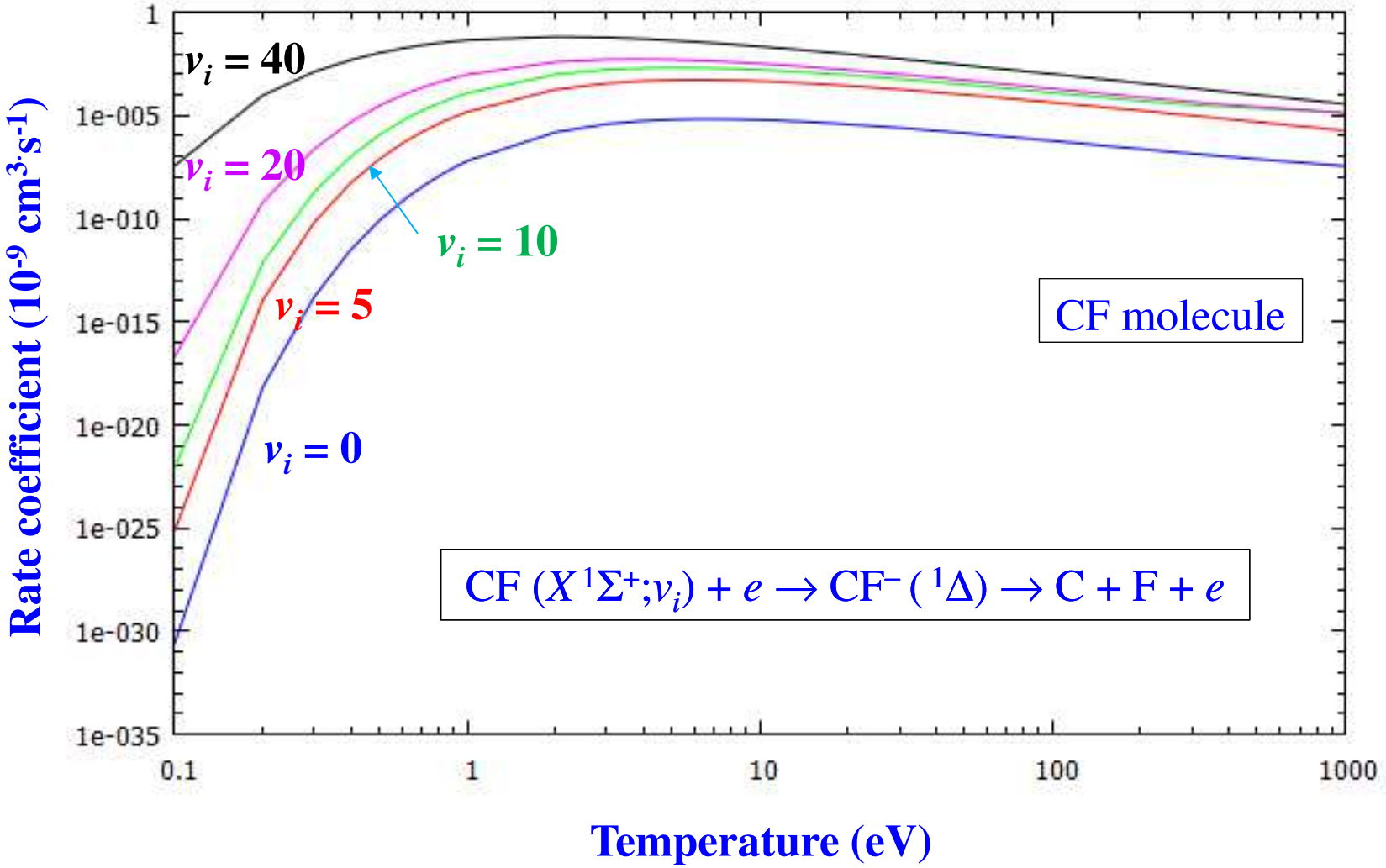
Dissociative attachment



Resonant vibrational excitation



Dissociative excitation



$$\mathbf{CH + e^- \rightarrow CH^* + e^-}$$

$X\,^2\Pi(v_i) \rightarrow A\,^2\Delta(v_i)$, $B\,^2\Sigma^-(v_f)$ and $C\,^2\Sigma^+(v_f)$

(R. Celiberto, R.K. Janev and D. Reiter, 2009)

$$\mathbf{BeH^+ + e^- \rightarrow BeH^{+\,*} + e^-}$$

$X\,^1\Sigma^+(v_i) \rightarrow A\,^1\Sigma^+(v_f)$, $B\,^1\Pi(v_f)$

(R. Celiberto, R.K. Janev and D. Reiter, 2012)

$$\mathbf{BeH + e^- \rightarrow BeH^* + e^-}$$

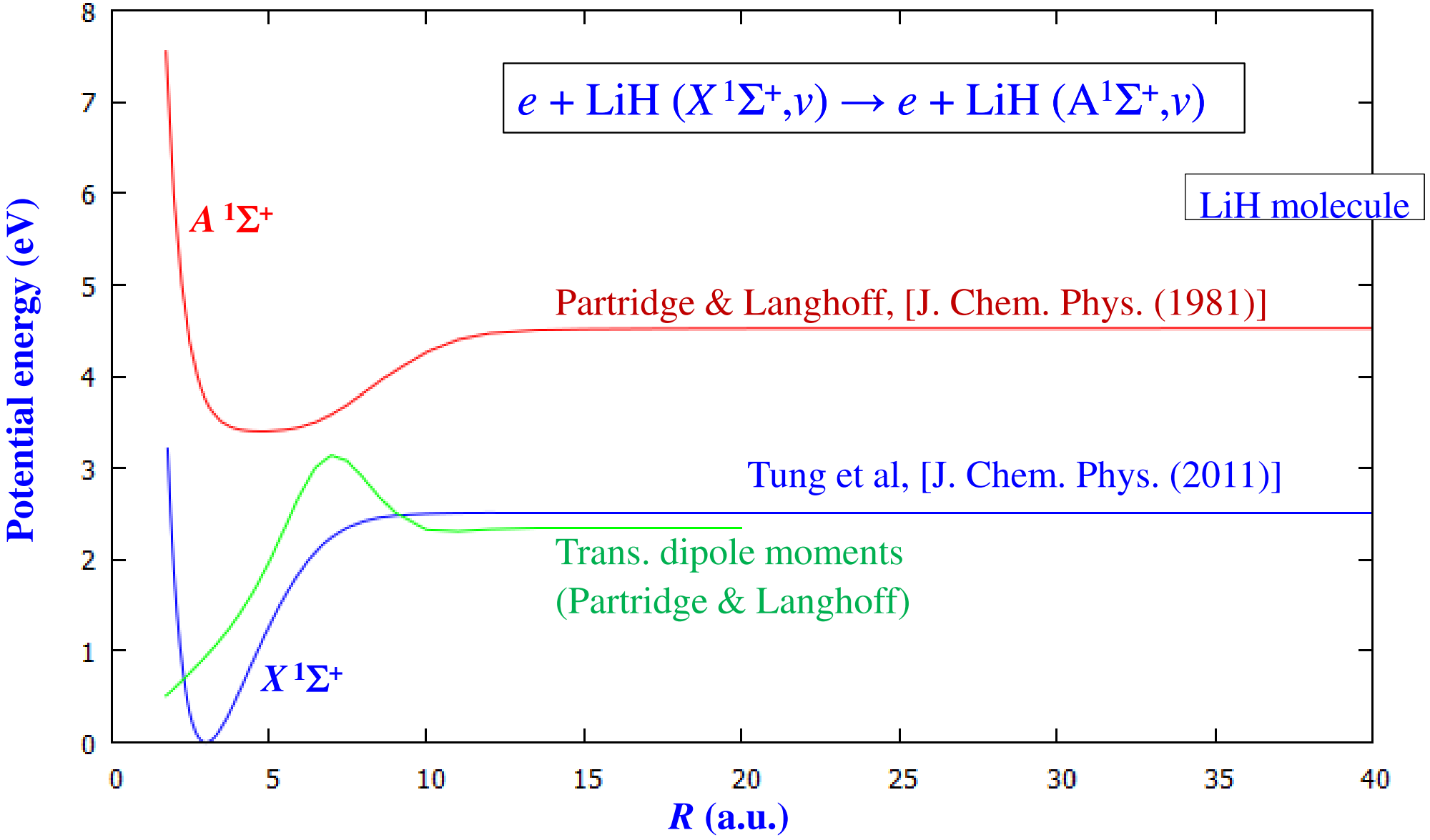
$X\,^2\Sigma^+(v_i) \rightarrow A\,^2\Pi(v_f)$

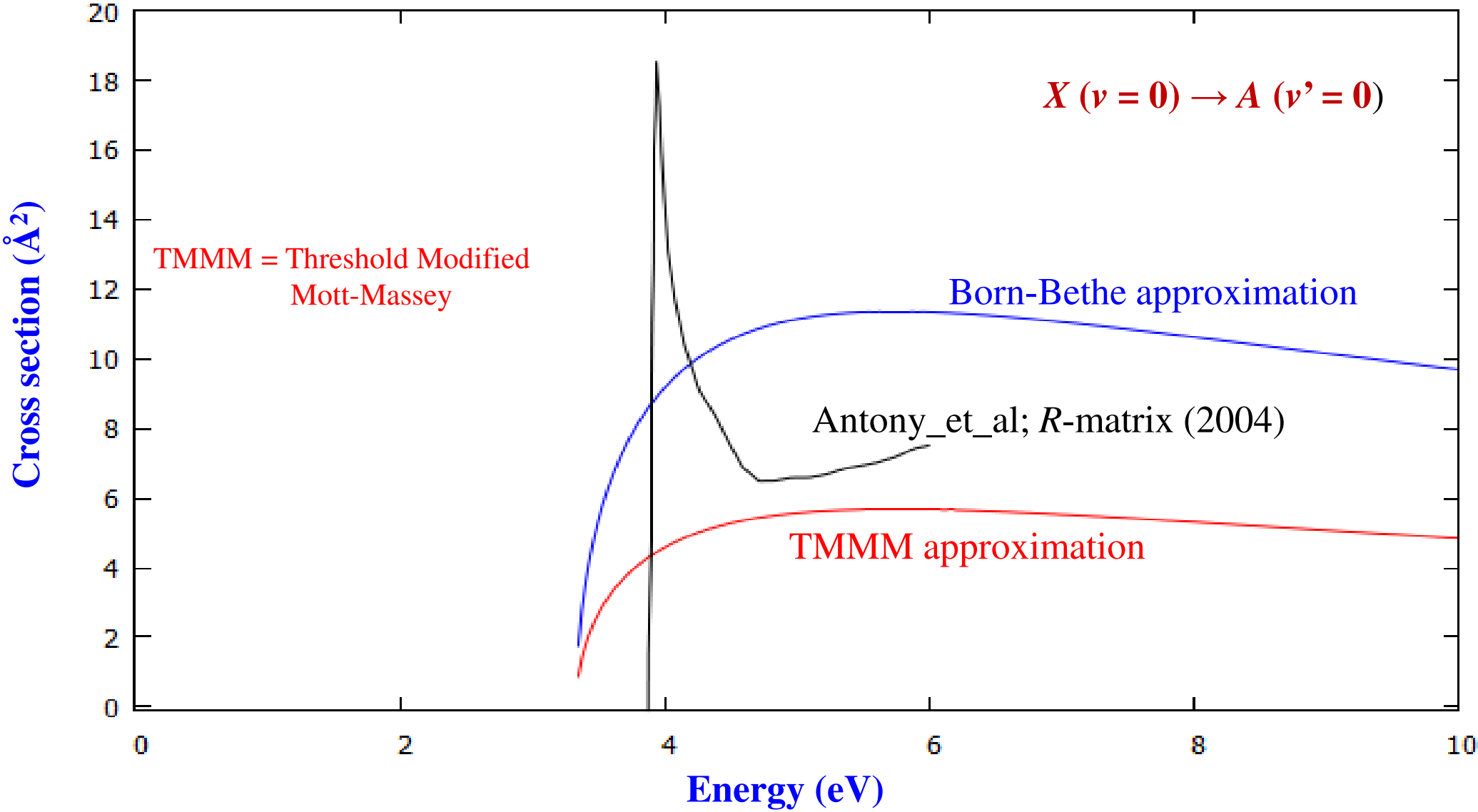
(R. Celiberto, K.L. Baluja and R.K. Janev, 2013)

$$\mathbf{He_2^+ + e^- \rightarrow He_2^{+\,*} \rightarrow He + He^+ + e^-}$$

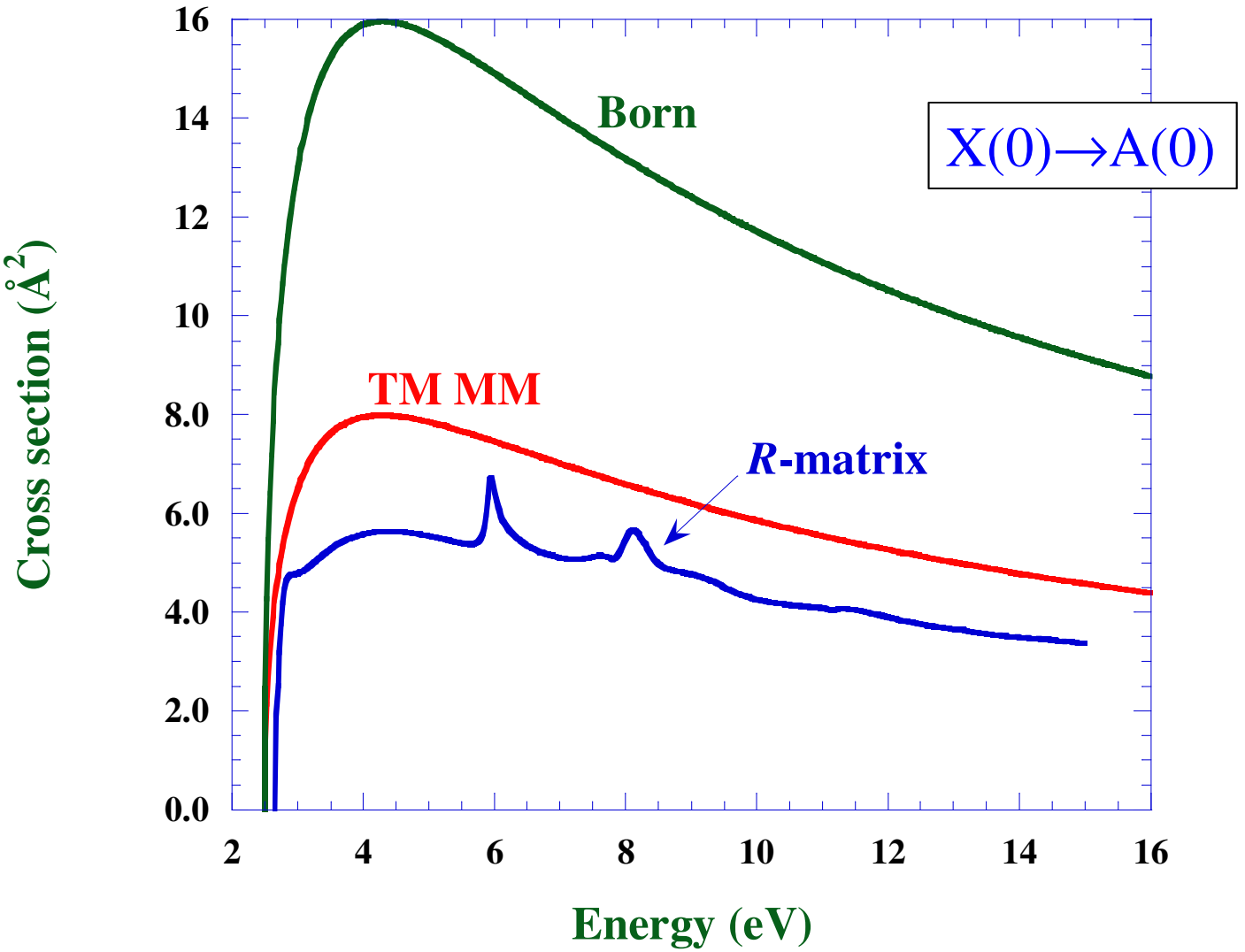
$X\,^2\Sigma^+(v_i) \rightarrow A\,^2\Sigma^+(\textit{repulsive})$

(R. Celiberto, K.L. Baluja, R.K. Janev and V. Laporta, 2015)

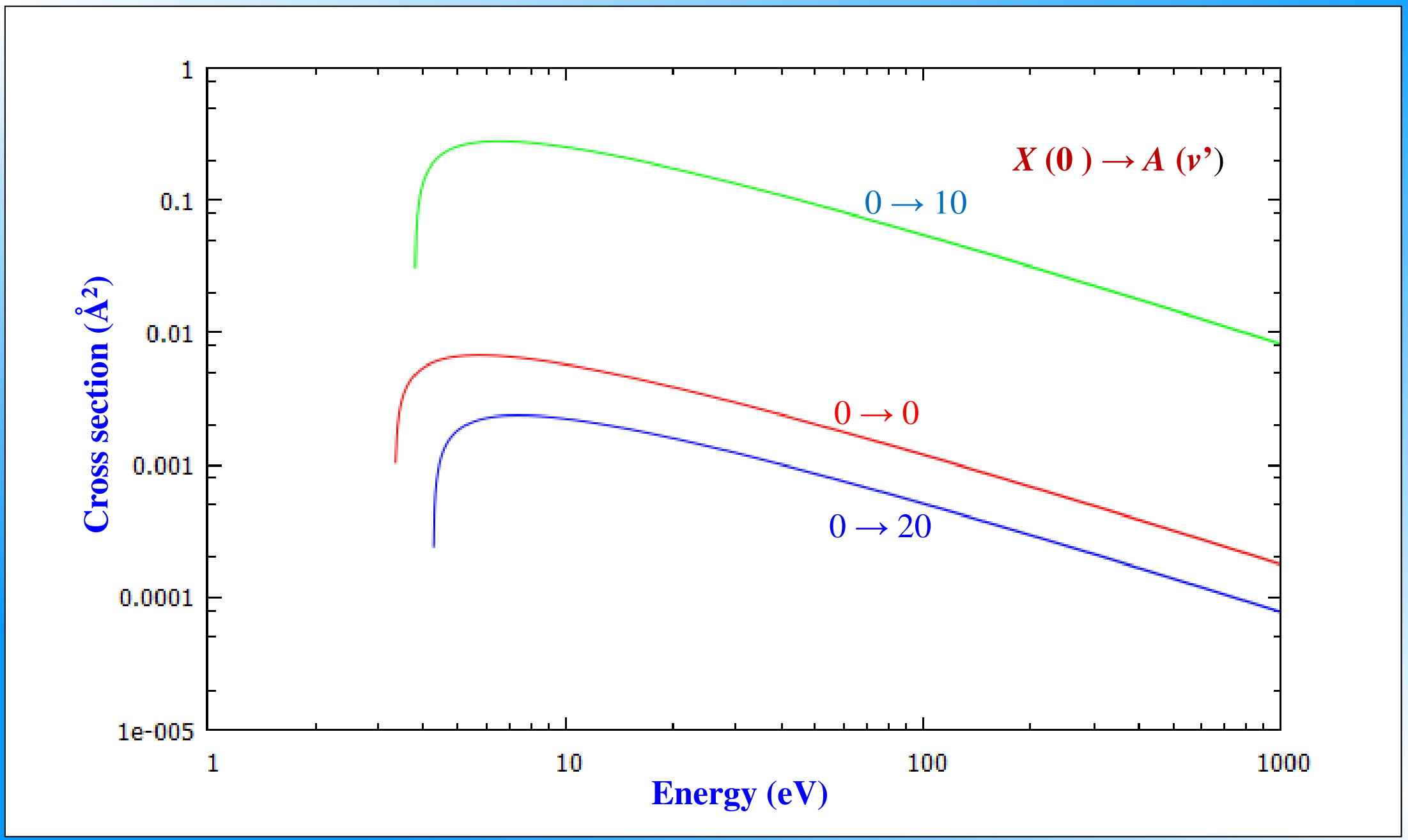

$e + \mathrm{LiH}\,(X\,^1\Sigma^+,v) \rightarrow e + \mathrm{LiH}\,(\mathrm{A}^1\Sigma^+,v)$
LiH molecule
$A\ ^1\Sigma^+$
Partridge & Langhoff, [J. Chem. Phys. (1981)]
Tung et al, [J. Chem. Phys. (2011)]
Trans. dipole moments
(Partridge & Langhoff)
$X\ ^1\Sigma^+$
Potential energy (eV)
R (a.u.)
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30
35
40

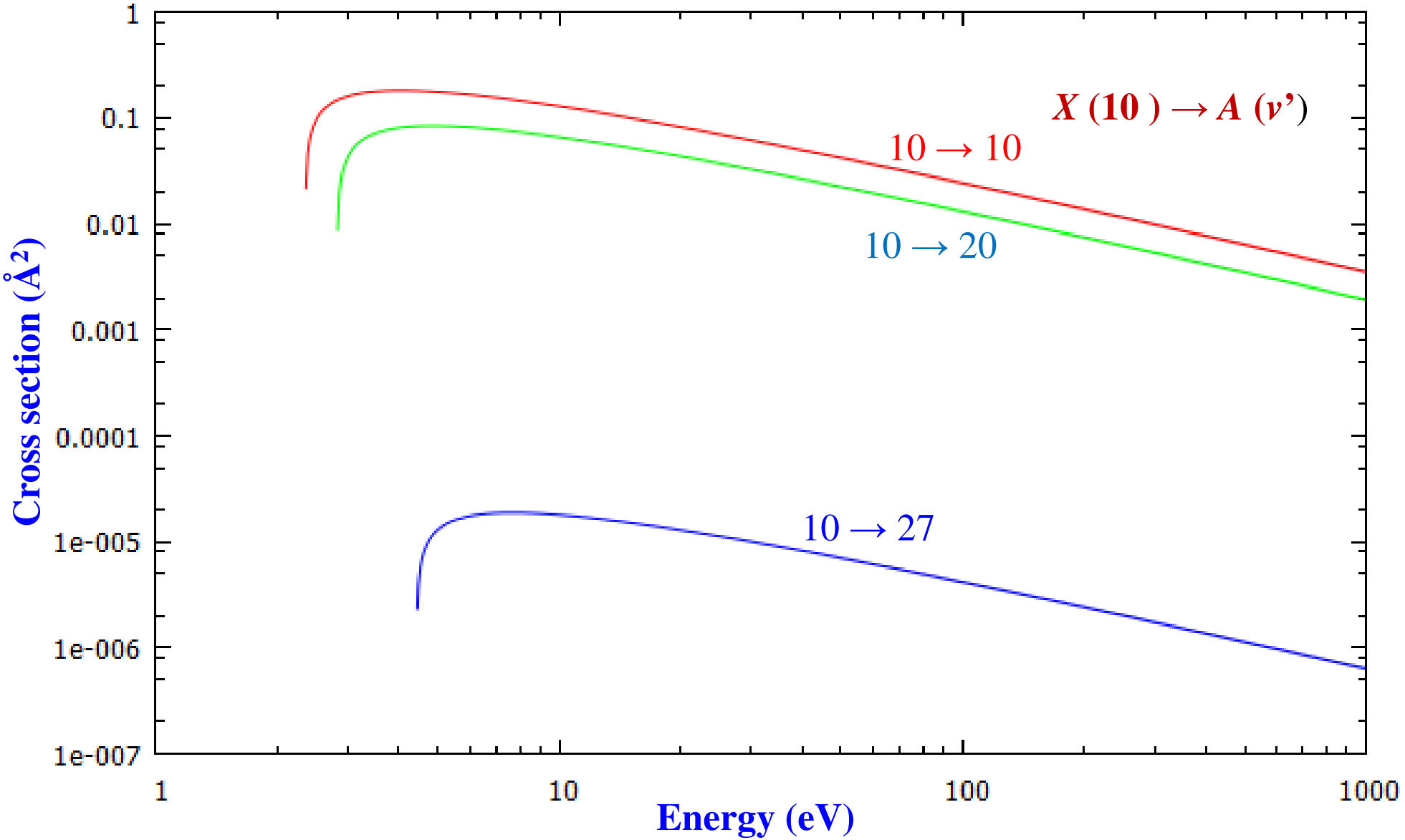

$X\ (v = 0) \rightarrow A\ (v' = 0)$
TMMM = Threshold Modified Mott-Massey
Born-Bethe approximation
Antony_et_al; R-matrix (2004)
TMMM approximation
Cross section (Å²)
Energy (eV)
0
2
4
6
8
10
12
14
16
18
20

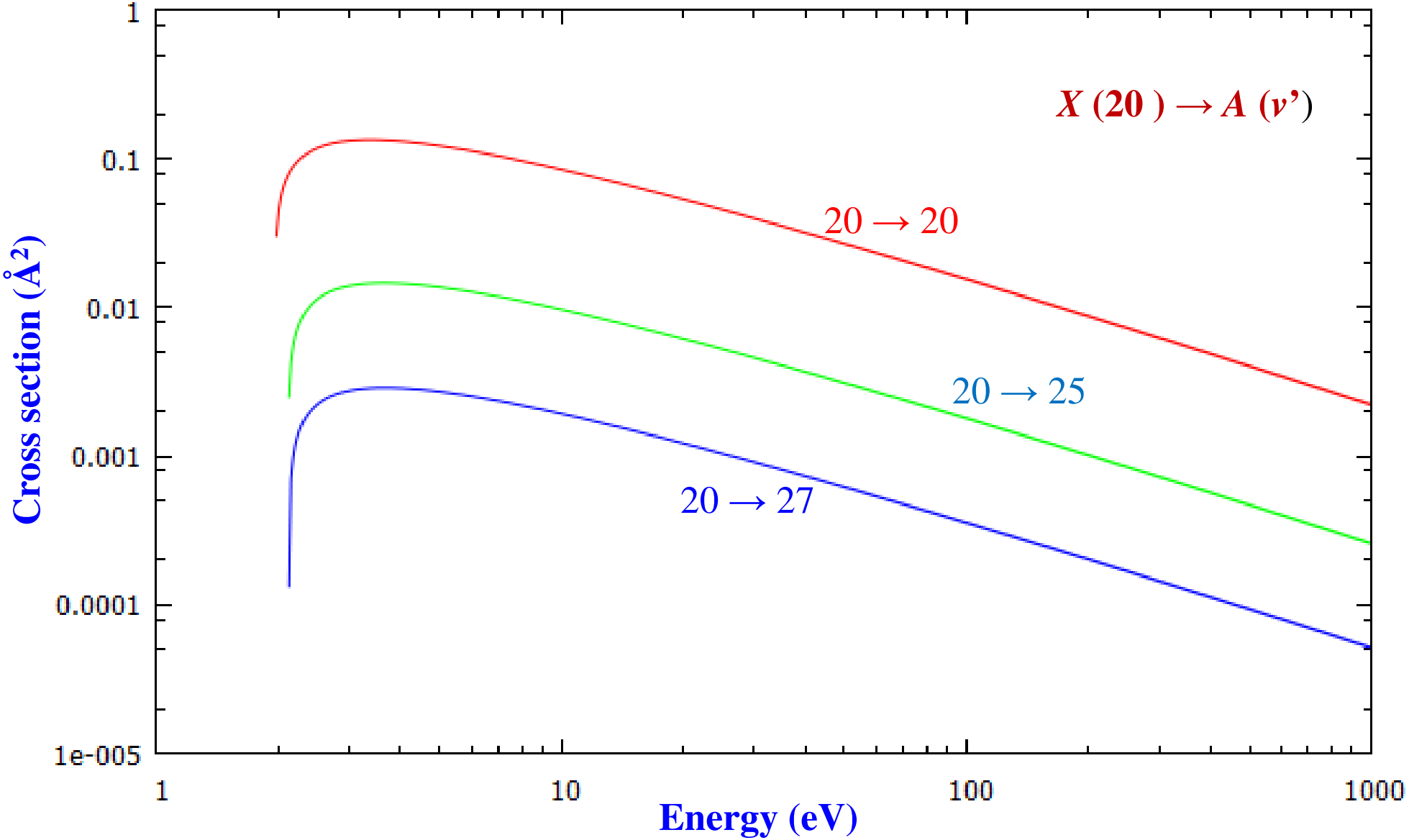
BeH



R Celiberto,
K L Baluja
& R K Janev
Plasma Source
Science &
Technology, 2013


X (0) → A (v')
0 → 10
0 → 0
0 → 20
Cross section (Å²)
Energy (eV)
1
0.1
0.01
0.001
0.0001
1e-005
1
10
100
1000


X (10) → A (v')
10 → 10
10 → 20
10 → 27
Cross section (Å²)
Energy (eV)
1
0.1
0.01
0.001
0.0001
1e-005
1e-006
1e-007
1
10
100
1000


X (20) → A (v')
20 → 20
20 → 25
20 → 27
Cross section (Å²)
Energy (eV)
1
0.1
0.01
0.001
0.0001
1e-005
1
10
100
1000