ISTITUTO PER LA SCIENZA E TECNOLOGIA DEI PLASMI
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Rotational and vibrational temperatures of Hydrogen nonequilibrium plasmas from Fulcher band emission spectra

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Motivation

T_{rot} and T_{vib} required for plasma modelling

- Rotational temperature is a proxy for gas temperature
- Large sensitivity to vibrational excitation:

Resonant electron attachment:	$e + H_2(X,v) \rightarrow H^- + H$
Dissociative excitation:	$e + H_2(X,v) \rightarrow e + H(1) + H(n)$
Dissociative recombination:	$e + H_2^+(v) \rightarrow H(1) + H(n)$
Charge exchange:	$H_2(X,v) + H^+ \rightarrow H + H_2^+(w)$

Molecular Hydrogen Fulcher band

Spectral model

The Fulcher band is the band originating from the $d^3\Pi_u \rightarrow a^3\Sigma_g^+$ transitions.
A vibro-rotational corona model has been developed.

- Electron impact excitation of the d state from the ground state;
- Spontaneous radiative decay from the d state towards a;
- Predissociation of the d state.

$$e + H_2(X, v, J) \xrightarrow{k^{ei}_{vJ,wK}} e + H_2(d, w, K)$$

$$H_2(d, v, J) \xrightarrow{k^{se}_{vJ,wK}} H_2(a, w, K) + h\nu$$

$$H_2(d, v, J) \xrightarrow{k^{pd}_{vJ}} 2H$$

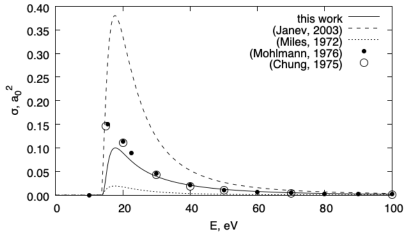
Selection rules

- Λ-doubling is not resolved for d levels;
- In excitation, ΔJ is odd for d^+ and even for d^-;
- In emission, d^+ produces P and R lines whereas d^- produces Q lines;
- d^+ levels above the $H(1s)+H(2l)$ dissociation limit are completely predissociated;
- d^- levels above the $H(1s)+H(2l)$ dissociation limit have finite predissociation lifetimes and are completely predissociated for $v > 9$.

EXCITATION CROSS SECTIONS: $X^1\Sigma_g^+(v,J) \to d^3\Pi_u^\pm(w,K)$

$$\sigma_{X,v,J;d,w,K}(E) = S_r(J,K)\cdot\begin{cases}0 & E < E^d_{wK} - E^X_{vJ}\\ F_{Xd}(E)G_{Xd}Q_{vJ;wK} & v=0,1 \quad J \leqslant 20\\ \sigma_{X,v;d,w}(E) & \text{otherwise}\end{cases}$$

$$S_r(J,K) = (2K+1)\sum_{r=1}^{4}\beta_r\begin{pmatrix}J & r & K\\ 0 & 1 & -1\end{pmatrix}^2$$

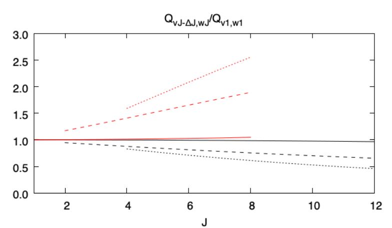


L.H. Scarlett *et al.*, Complete collision data set for electrons scattering on molecular hydrogen and its isotopologues: I. Fully vibrationally-resolved electronic excitation of $H_2(X^1\Sigma_g^+)$, Atomic Data and Nuclear Data Tables **137** (2021) 101361. doi:10.1016/j.adt.2020.101361.

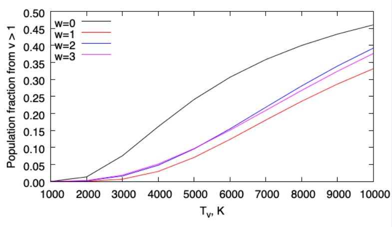
X. Liu, *et al.*, Spectra, Emission Yields, Cross Sections, and Kinetic Energy Distributions of Hydrogen Atoms from $H_2X^1\Sigma_g^+ - d^3\Pi_u$ Excitation by Electron Impact, The Astrophysical Journal **818** (2) (2016) 120. doi:10.3847/0004-637X/818/2/120.

Properties of the excitation function

Multipolar transitions



Vibrational excitation



Emission: $d^3\Pi_u^{\pm}(v,J) \rightarrow a^3\Sigma_g^+(w,K) + h\nu$

$\Delta J = 0, \pm 1$, $\Delta v = 0$

P line: $d^3\Pi_u^+(v,J) \rightarrow a^3\Sigma_g^+(w,J+1) + h\nu$

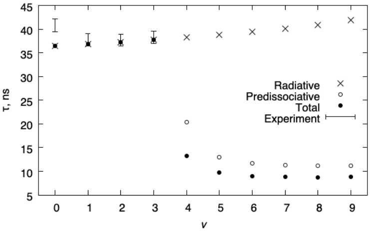
Q line: $d^3\Pi_u^-(v,J) \rightarrow a^3\Sigma_g^+(w,J) + h\nu$

R line: $d^3\Pi_u^+(v,J+1) \rightarrow a^3\Sigma_g^+(w,J) + h\nu$

X. Liu, *et al.*, Spectra, Emission Yields, Cross Sections, and Kinetic Energy Distributions of Hydrogen Atoms from $H_2X^1\Sigma_g^+ - d^3\Pi_u$ Excitation by Electron Impact, The Astrophysical Journal **818** (2) (2016) 120. doi:10.3847/0004-637X/818/2/120.

Predissociation: $d^3\Pi_u^{\pm}(v,J) \rightarrow 2H$

$$d^3\Pi_u^{-}(v) \rightarrow 2H$$



$$d^3\Pi_u^{+}(v,J) \rightarrow 2H$$

		Calculated		Kiyoshima & Sato (1993)	
v	J	$d\ ^3\Pi_u^-$	$d\ ^3\Pi_u^+$	$d\ ^3\Pi_u^-$	$d\ ^3\Pi_u^+$
0	1	36.4	36.4	40.8 ± 1.4	38.6 ± 2.0
	2	36.4	36.4	41.8 ± 3.0[c]	36.0 ± 2.1
	3	36.4	36.4	⋯	34.0 ± 2.5
	4	36.5	36.4	⋯	⋯
1	1	36.8	36.8	37.7 ± 1.3	34.6 ± 1.9
	2	36.8	36.8	40.7 ± 1.9[c]	27.7 ± 1.5
	3	36.8	36.8	⋯	16.9 ± 2.0
	4	36.8	36.8	⋯	⋯
2	1	37.3	37.3	37.7 ± 1.2	38.2 ± 1.2
	2	37.3	37.3	39.0 ± 2.9[c]	31.7 ± 1.4
	3	37.3	37.3	⋯	36.4 ± 1.7
	4	37.3	37.3	⋯	35.1 ± 1.6
3	1	37.7	37.7	38.3 ± 1.3	36.6 ± 1.8
	2	37.7	37.7	40.2 ± 3.4[c]	39.5 ± 1.5
	3	37.7	37.7	⋯	⋯

Electron impact excitation ($e = 18 - 50\ eV$) of cold gas and delayed coincidence detection.

T. Kiyoshima *et al.*, Perturbation effects on lifetimes of d $^3\Pi_u$ states in H_2 and D_2, Physical Review A **48** (6) (1993) 4771.

T. Kiyoshima *et al.*, Competition between predissociative and radiative decays in the e $^3\Sigma_u^+$ and d $^3\Pi_u$ states of H_2 and D_2, Physical Review A **60** (6) (1999) 4494.

Rotational and vibrational temperatures

Level energy

$$E_{vJ} = E_{v0} + (E_{vJ} - E_{v0})$$

Level populations

$$x_{vJ} = \frac{1}{q} e^{-\frac{E_{v0}}{kT_v}} (2J+1)(2-(-1)^J) \left[e^{-\frac{E_{vJ}-E_{v0}}{kT_{r1}}} + \beta_v e^{-\frac{E_{vJ}-E_{v0}}{kT_{r2}}} \right]$$

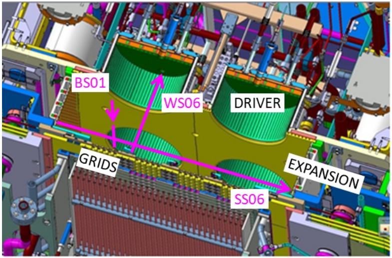
$(2-(-1)^J)$: Nuclear spin degeneracy

$$-\log \beta_v \approx \frac{E_{vJ^*} - E_{v0}}{kT_{r1}}$$

Experimental data

Experimental setup

- 320 mm focal length, 1760 gr/mm grating, 13.5 μm pixel CCD
- 35 nm range with 0.6 Å resolution

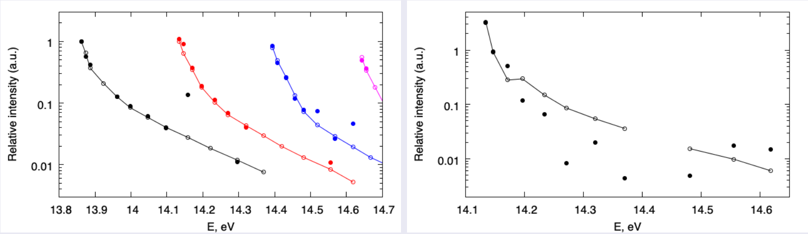


Acquired data

- Power scan: 20-55 kW/driver
- Pressure scan: 0.2-0.6 Pa
- Driver & expansion regions

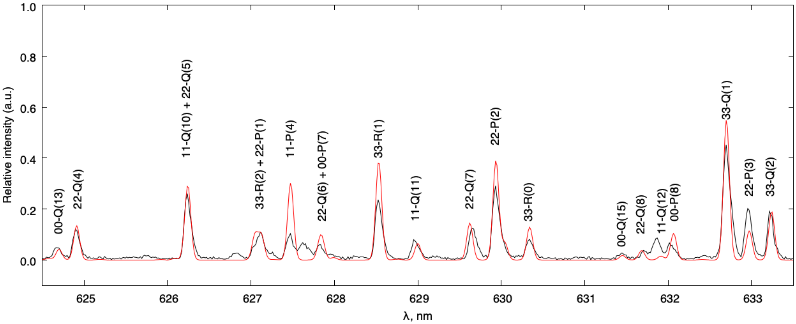
Results: Q & R lines

RF=100 kW; p=0.3 Pa, WS06



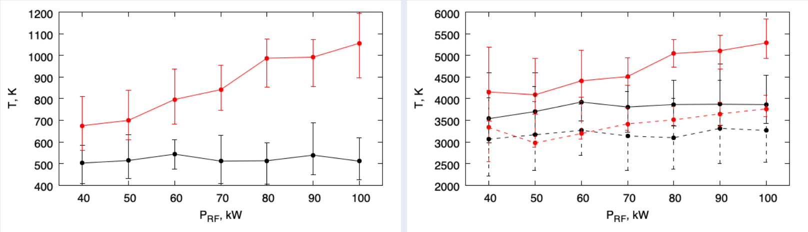
Results: spectra

- Gaussian broadening: $T = T_{r1}$
- Gaussian Instrument Function: HWHM=0.42 Å



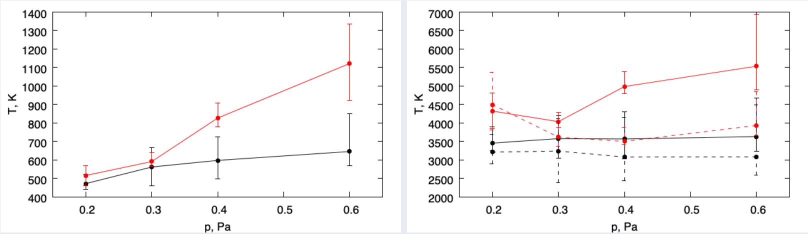
RESULTS: POWER SCAN

4 RF GENERATORS, P=0.3 PA



Results: Pressure scan

1 RF generator, RF=100 kW



Conclusions

Features

- (v,J) corona model
- Excitation cross section: multipolar & high v transitions

Results

- Q lines & 2T distributions
- SPIDER characterization: power & pressure scans
- SPIDER characterization: driver & expansion regions

Takeaways

- Threshold behaviour of excitation cross sections
- Rotational dependence for excitation from higher vibrational levels
- Predissociation probabilities of higher rotational levels