Ion Dynamics and Effects of Microfield Rotation

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Outline of the talk

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- Lyman-α is the simplest transition; but paradoxically, agreement between different models is worse for this line.

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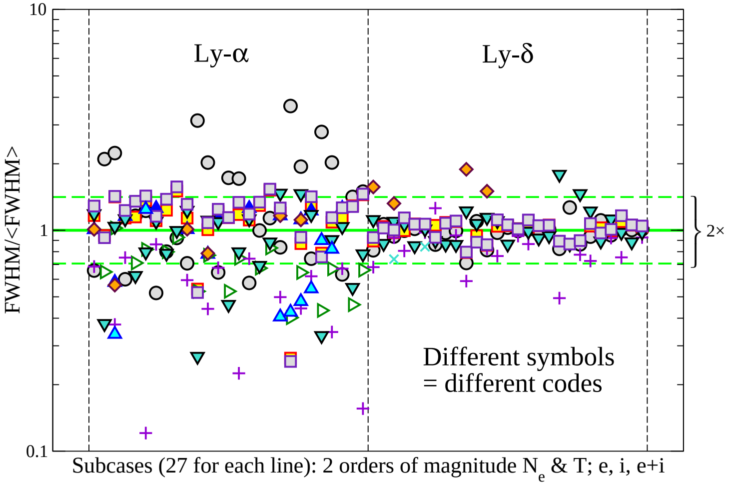

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SLSP 1&2 analysis: Ion dynamics (again)! [Ferri et al., 2014]

A short historical background

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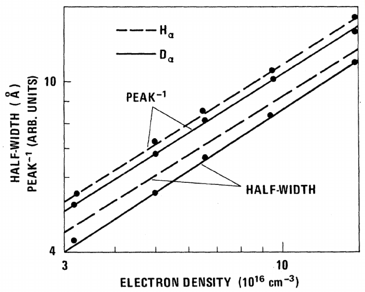

The physical reason for the observed reduced-mass dependence has not yet been established. In fact, recent theoretical treatments of ion dynamics predict very small or negligible effects. It is therefore of interest to perform further studies on the Balmer lines. It would be especially interesting to check whether the observed effects scale as the relative radiator-perturber velocities, as suggested by the approximate $1/\sqrt{\mu}$ dependence. In this case one would really expect a $(T/\mu)^{1/2}$ dependence, which we could not check since we worked with all plasmas in the same very narrow temperature range. A measurement of the temperature dependence at constant N_e and μ would thus be very desirable in this regard. Attempts by us in this direction have not been successful as yet because we have been unable to obtain sufficient temperature variation with the arc source.

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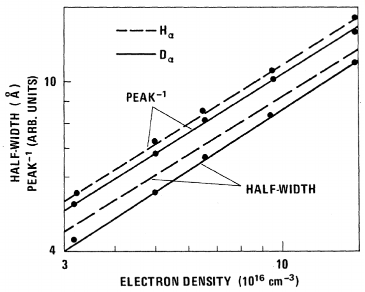

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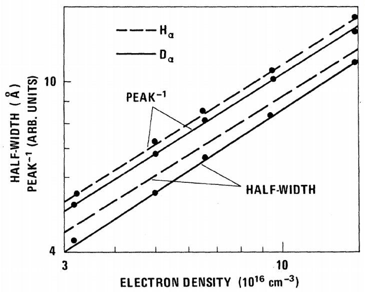

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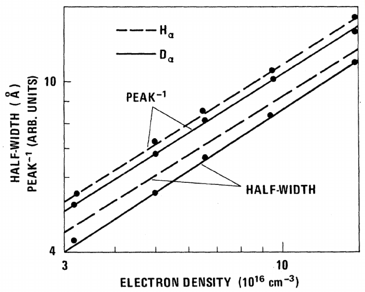

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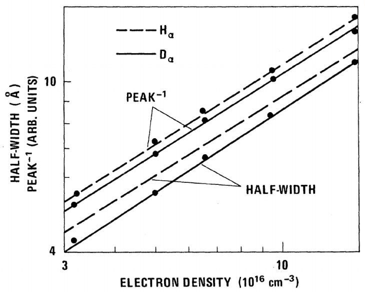

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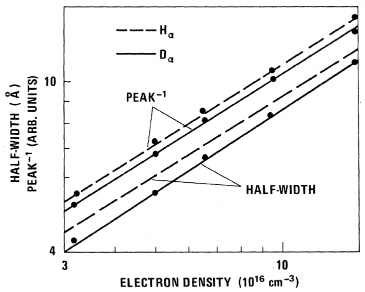

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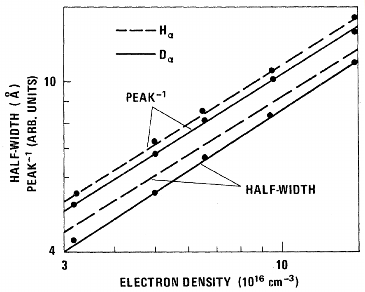

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Finally, do we today really understand what ion dynamics is?

Models and simulations

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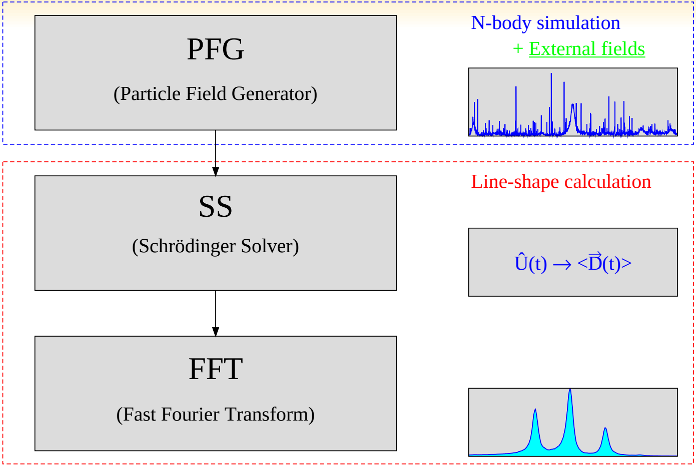
Computer simulations :: Scheme



Several implementations since [Stamm and Voslamber, 1979].

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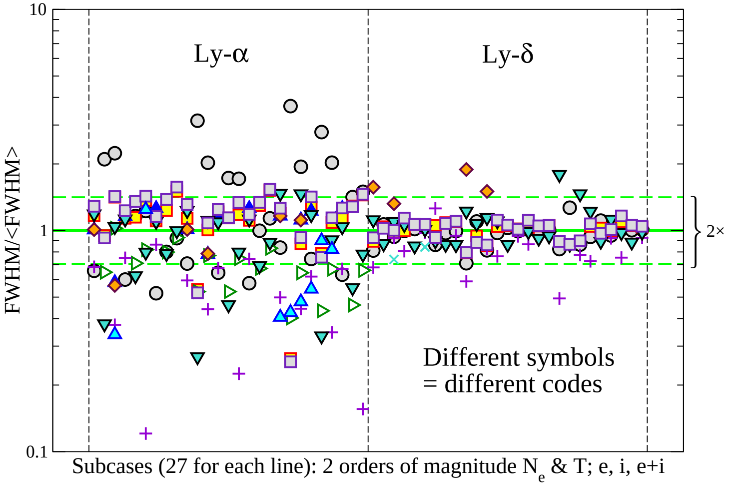

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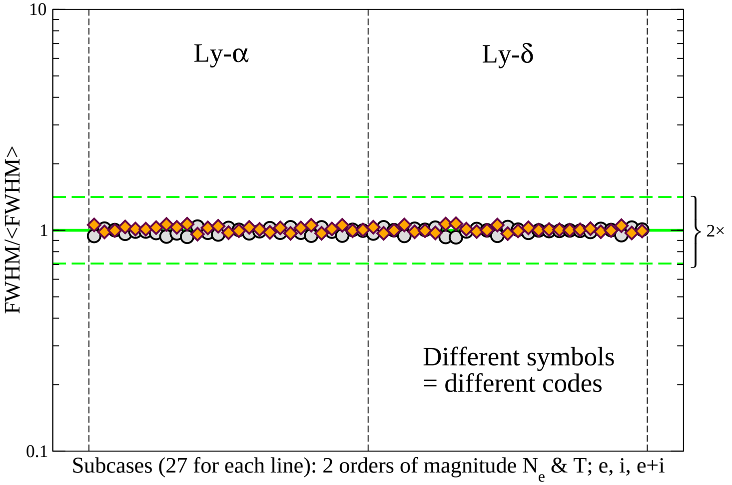

Computer simulation (CS) results are nearly identical.

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Here, we claim to have found it [Stambulchik and Demura, 2015].

Outline of the talk

Dimensionality analysis

Consider a one-component plasma; temperature T, density N_p of particles with charge Z_p and reduced mass M_p^*. H-like radiator.

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If $w_{\rm st}, w_{\rm dyn} \ll E_{ij}^0 \Rightarrow E_{ij}^0$ can be ignored. Thus, only $w_{\rm st}$ and $w_{\rm dyn}$.

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From the dimensionality considerations, the line width w (say, FWHM) can be written as

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What if $w_{\rm st} \ll w_{\rm dyn}$ or $w_{\rm st} \equiv 0$ (the central component of Lyman-α)? Then only the term with $p_k = 0$ remains; $\Rightarrow w = C_0 w_{\rm dyn}$.

Dimensionality analysis (cont.)

Again:

$$w = C_0 w_{\rm dyn} \sim (T/M_p^*)^{1/2} N_p^{1/3}$$

This expression “knows” nothing about the radiator! One is tempted to put $C_0 = 0$.

Yet this is the only term with $\sim (T/M_p^*)^{1/2} \sim 1/\sqrt{\mu}$!

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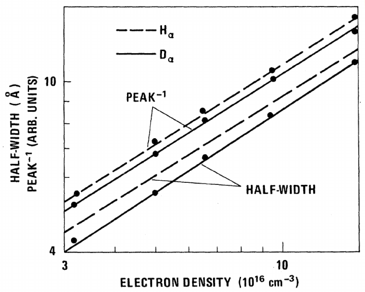

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We call this broadening regime “rotational”.

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“Rotational” vs “vibrational” broadening

Let us define “rotational” and “vibrational” microfield pseudocomponents as

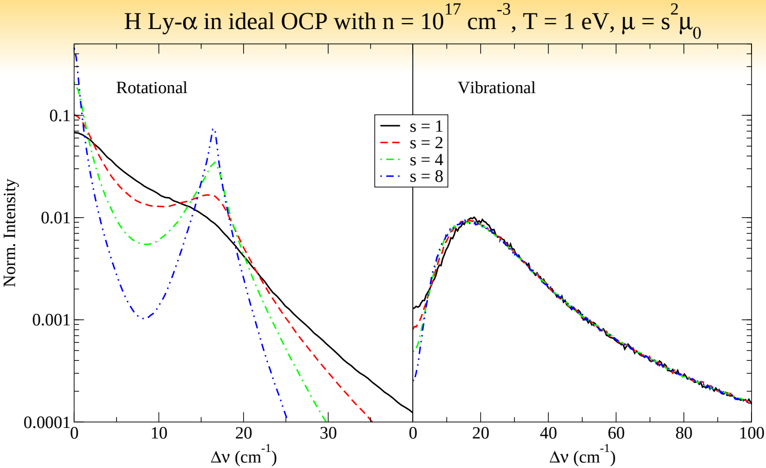
$$\vec{F}_{\mathrm{rot}}(t) = F_0 \frac{\vec{F}(t)}{F(t)}$$

and

$$\vec{F}_{\mathrm{vib}}(t) = \vec{n}_z F(t),$$

respectively.

"Rotational" vs "vibrational" broadening :: μ sensitivity



"Rotational" field: affects both the central and lateral components.
"Vibrational" field: slightly influences the lateral components; the central one remains a δ-function [Demura and Stambulchik, 2014].
He II: [Calisti et al., 2014].

Outline of the talk

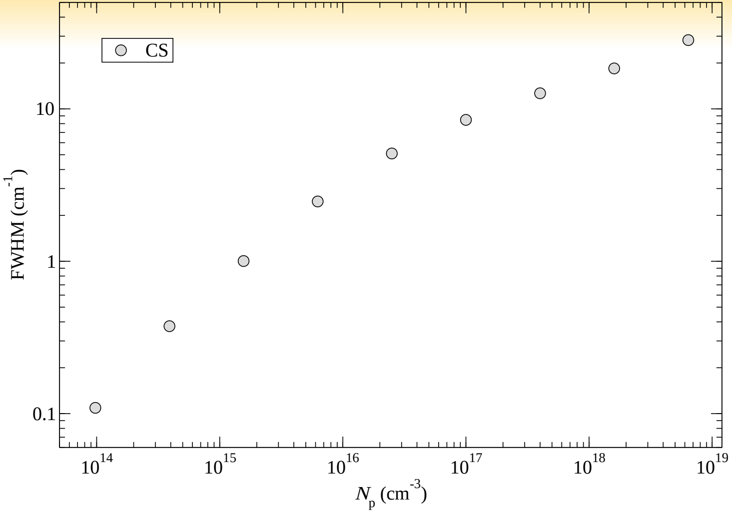
Simulation setup

Consider H Lyman-α broadened by an ideal (no interactions) OCP.

Assume the non-quenching approximation (no *LS* coupling, no mixing of states with $\Delta n \neq 0$), and only dipole interactions.

Our "reference" plasma conditions are $T^0 = 1\,\mathrm{eV}$, $N_p^0 = 10^{17}\,\mathrm{cm}^{-3}$, $Z_p^0 = 1$, and $M_p^* = m_p/2$ (m_p is the proton mass). 8,000 particles were included in the simulations.

Lyman-α in an ideal OCP :: Varying N_p



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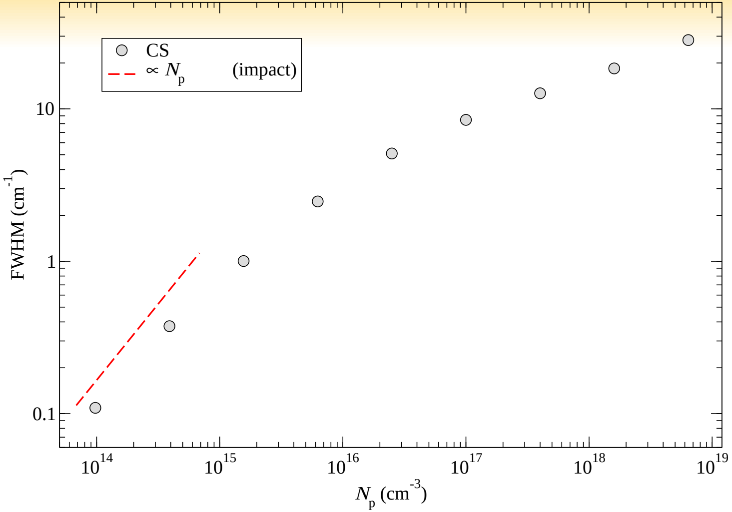

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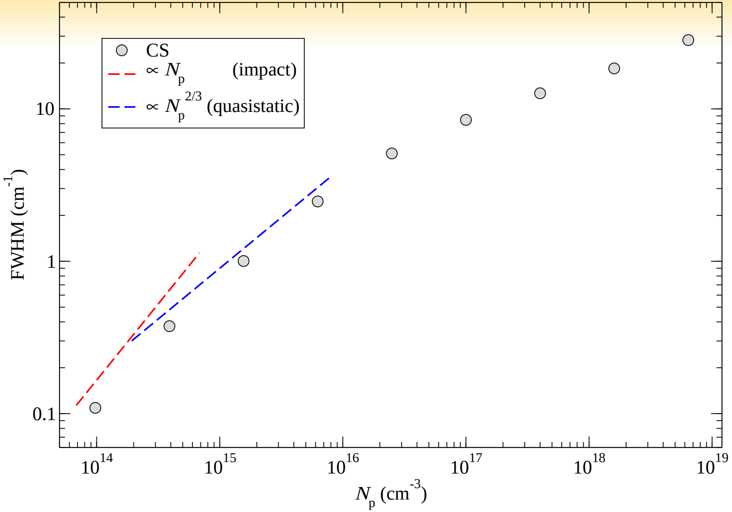

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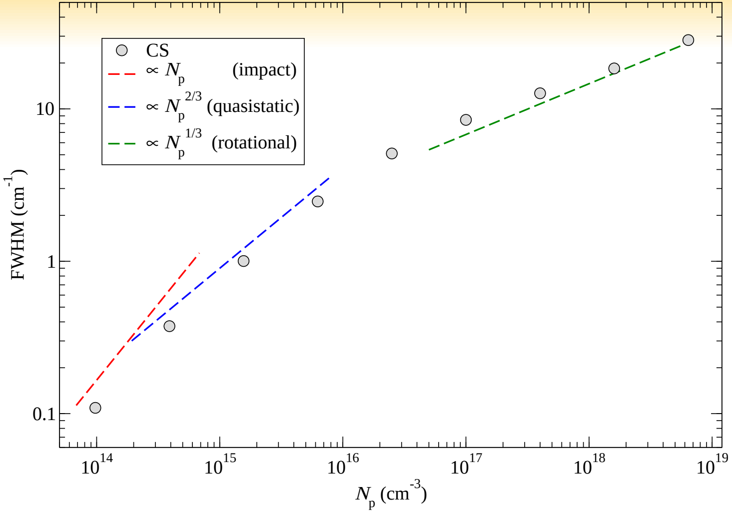

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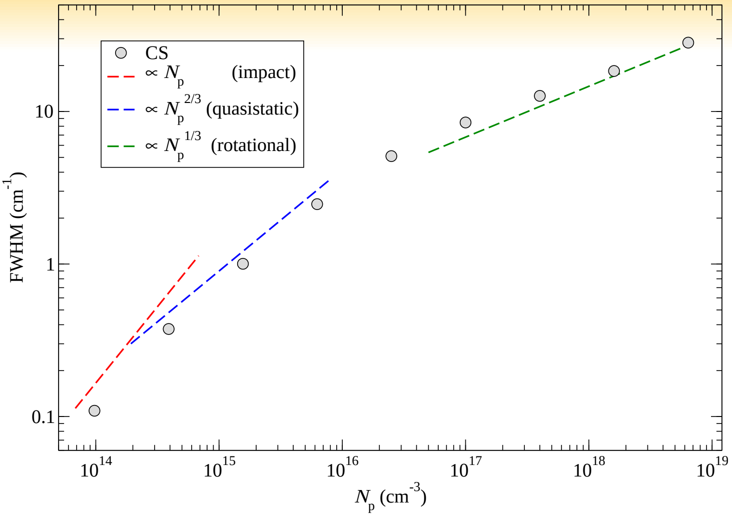
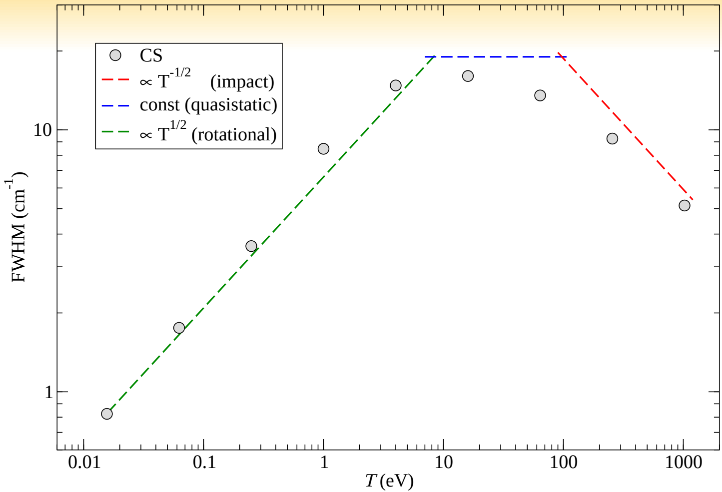


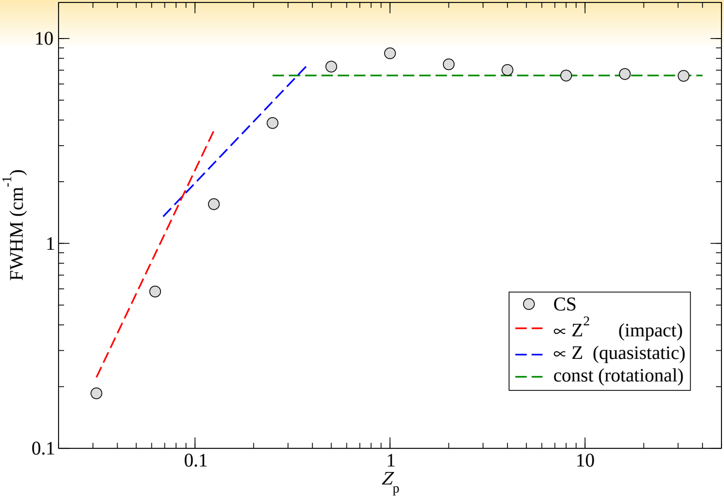
By varying N_p, broadening changes from the impact to rotational regime. Quasistatic-like dependence is just an intermediate case!

Lyman-α in an ideal OCP :: Varying T



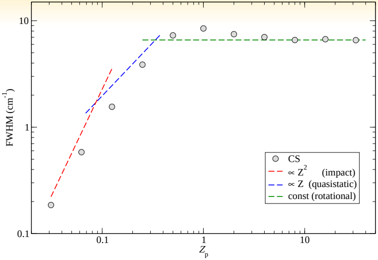
Again, broadening changes from the impact to rotational regime, with the quasistatic-like dependence as an intermediate case.

Lyman-α in an ideal OCP :: Varying Z_p



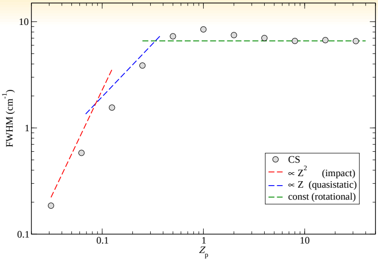
Again, broadening changes from the impact to rotational regime, with the quasistatic-like dependence as an intermediate case.

Lyman-α in an ideal OCP :: Varying Z_p



Increasing field (via Z_p) does not increase line broadening after some point!

Lyman-α in an ideal OCP :: Varying Z_p



Increasing field (via Z_p) does not increase line broadening after some point!

[Demura et al., 1977]:

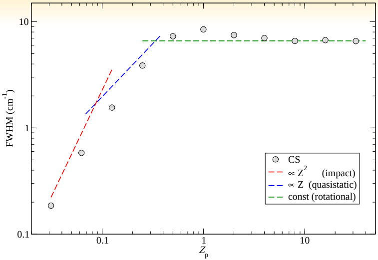
According to (16) and (18), in the case of lines of the type n_α (Ly-α, H_α, P_α, and so on), for which the principal fraction of the intensity goes to the unshifted component, the change in the intensity at the center is always negative, i.e., an effective increase of the "linewidth" takes place. Conversely, in the case of lines without a central component (Ly−β, H_β, H_δ and so on) the intensity at the center increases.

In the case of the Ly−α line, the thermal correction $I^{(1)}(\Delta\omega)$ near the center, calculated according to (16) and (18), is determined by the expression

$$I^{(1)}_{Ly-\alpha}(\Delta\omega)=\frac{10\lambda}{\pi}\frac{(T_i/\mu)N^{1/3}}{w^2}\frac{1}{CF_0}\left[\frac{CF_0}{w}F_{1-\alpha}(x)+F_{2-\alpha}(x)\right], \quad (20)$$

where w is the impact electron width of the central component (001) → (000)[15,16]; $C\equiv ea_0/\hbar$, $x\equiv\Delta\omega/w$.

Lyman-α in an ideal OCP :: Varying Z_p



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In the case of the Ly$-\alpha$ line, the thermal correction $I^{(1)}(\Delta\omega)$ near the center, calculated according to (16) and (18), is determined by the expression

$$I^{(1)}_{Ly-\alpha}(\Delta\omega) = \frac{10\lambda}{\pi}\frac{(T_i/\mu)N^{1/3}}{w^2}\frac{1}{CF_0}\left[\frac{CF_0}{w}F_{1-\alpha}(x)+F_{2-\alpha}(x)\right], \quad (20)$$

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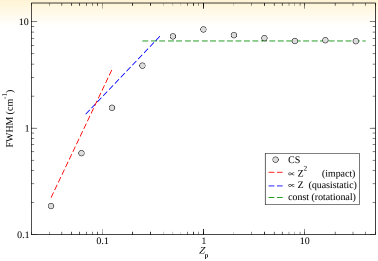
Lyman-α in an ideal OCP :: Varying Z_p



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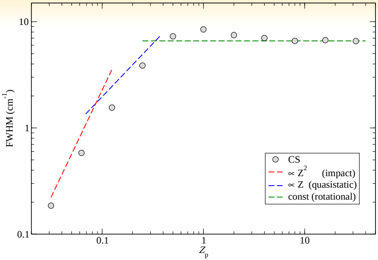
In the case of the Ly-α line, the thermal correction $I^{(1)}(\Delta\omega)$ near the center, calculated according to (16) and (18), is determined by the expression

central lateral

$$I^{(1)}_{\mathrm{Ly}\text{-}\alpha}(\Delta\omega)=\frac{10\lambda}{\pi}\frac{(T_i/\mu)N^{2/3}}{w^2}\frac{1}{CF_0}\left[\frac{CF_0}{w}F_{1-\alpha}(x)+F_{2-\alpha}(x)\right], \quad (20)$$

where w is the impact electron width of the central component $(001)\to(000)$[15,16]; $C\equiv ea_0/\hbar$, $x\equiv\Delta\omega/w$.

Lyman-α in an ideal OCP :: Varying Z_p



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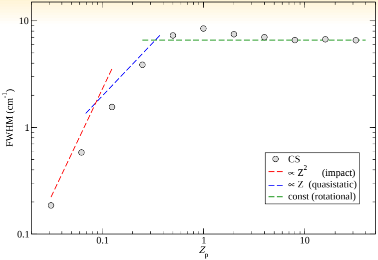
Lyman-α in an ideal OCP :: Varying Z_p



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In the case of the Ly$-\alpha$ line, the thermal correction $I^{(1)}(\Delta\omega)$ near the center, calculated according to (16) and (18), is determined by the expression

central lateral

$$I^{(1)}_{Ly-\alpha}(\Delta\omega)=\frac{10\lambda}{\pi}\frac{(T_i/\mu)N^{2/3}}{w^2}\frac{1}{CF_0}\left[\frac{CF_0}{w}F_{1-\alpha}(x)+F_{2-\alpha}(x)\right], \qquad (20)$$

where w is the impact electron width of the central component (001) → (000)[15,16]; $C\equiv ea_0/\hbar$, $x\equiv\Delta\omega/w$.

The broadening of the central component is affected neither by the field magnitude (F_0) nor by the atomic properties (C)!

A unified (impact + rotational) model

Let's write an empiric expression covering impact and rotational regimes asymptotically:

$$w^{-1} = w_{\mathrm{imp}}^{-1} + w_{\mathrm{rot}}^{-1},$$

where w_{imp} and w_{rot} are the Stark broadenings in the impact and rotational limits.

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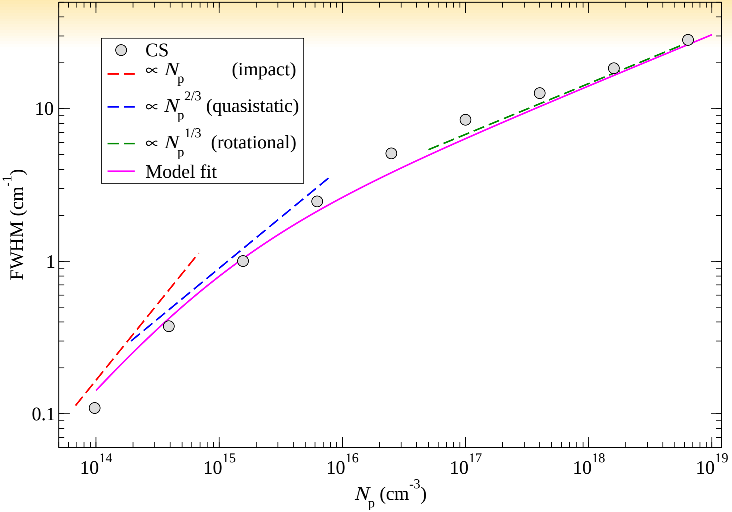
Thus,

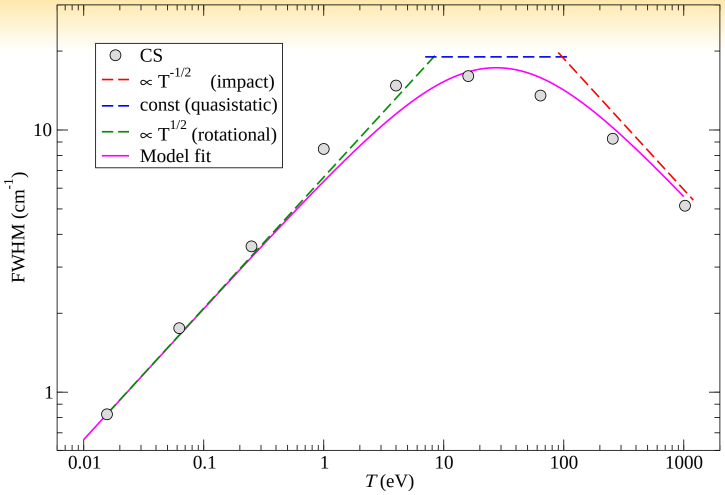
$$w^{-1} = \alpha \left(\frac{Z}{Z_p}\right)^2 \left(\frac{T}{M_p^*}\right)^{1/2} N_p^{-1} + \beta^{-1} \left(\frac{M_p^*}{T}\right)^{1/2} N_p^{-1/3},$$

where α and β are some universal constants.

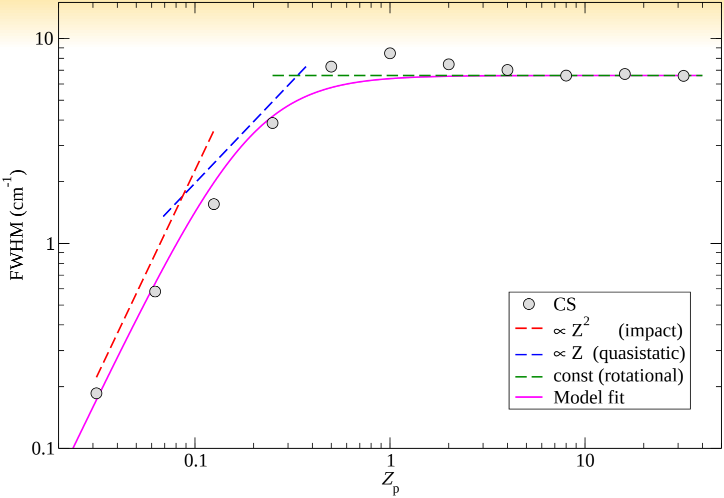
Lyman-α in an ideal OCP :: Varying N_p



Lyman-α in an ideal OCP :: Varying T



Lyman-α in an ideal OCP :: Varying Z_p



Outline of the talk

Two-component plasmas

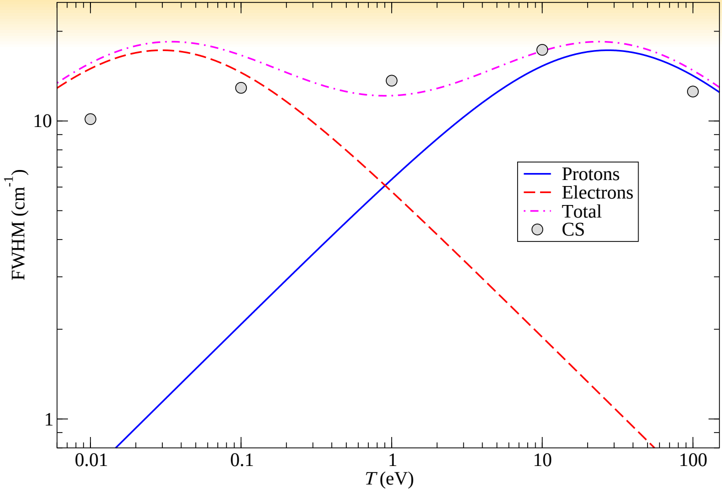
We have only considered a one-component proton plasma.

However, the model is also applicable to other types of ions as well as to electrons.

Assuming additive contributions of ions and electrons:

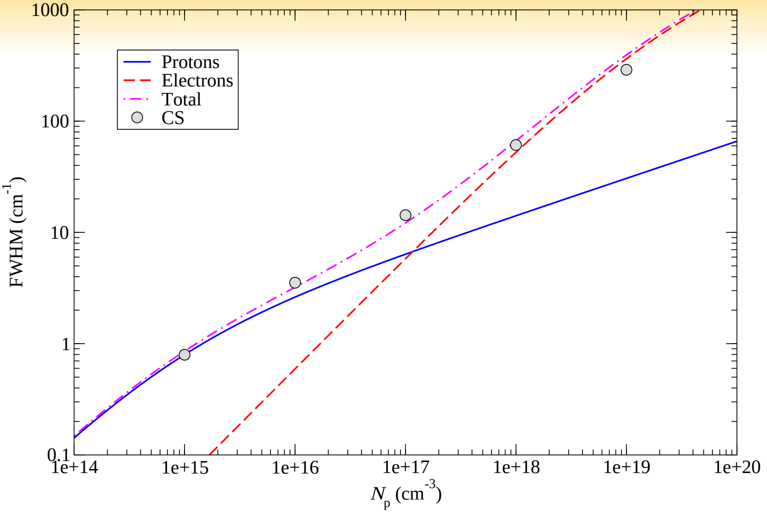
$$w_{\mathrm{tot}} = w_i + w_e.$$

Lyman-α in an ideal TCP :: Varying T



Over four orders of magnitude of T, FWHM changes only by $\sim 50\%$! (Coincidentally, quasistatic-like dependence.)

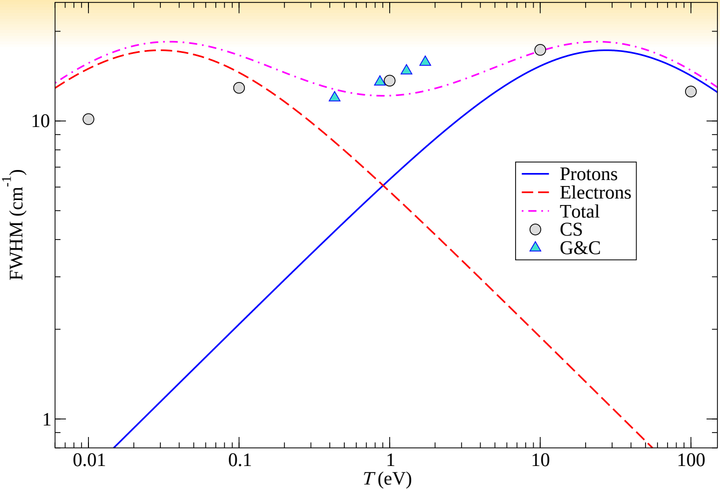
Lyman-α in an ideal TCP :: Varying N_p



Over six orders of magnitude of N, FWHM scales close to $\sim N_p^{2/3}$. (Coincidentally, quasistatic-like dependence.)

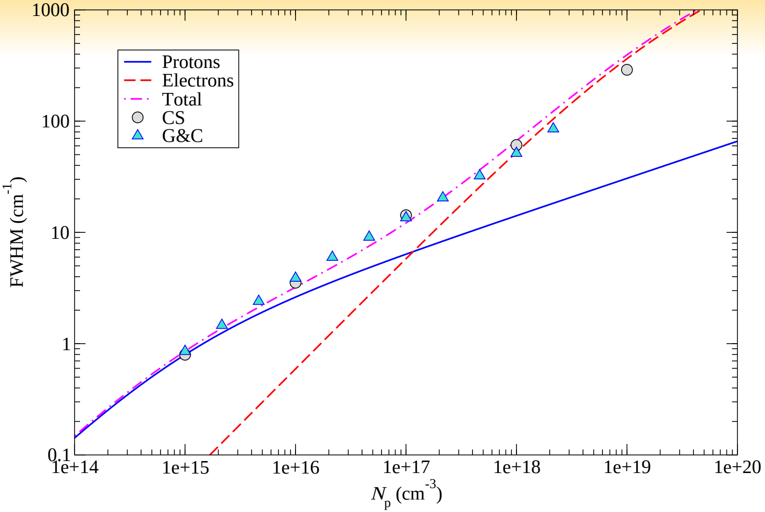
Outline of the talk

Ideal vs. non-ideal TCP :: Varying *T*



Only minor corrections due to Debye screening (“G&C” = tables for real plasmas, [Gigosos and Cardeñoso, 1996]).

Ideal vs. non-ideal TCP :: Varying N_p



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Outline of the talk

Conclusions

- Spectral lines with a central, unshifted Stark component are broadened by plasma in a unique manner:
  - The quasistatic broadening regime is never realized for the lineshape core.
  - Instead, the broadening changes from the impact regime to another, also dynamical in nature, “rotational” one.
  - In the latter, the line width only depends on the typical frequency of the plasma microfields [i.e., $\propto N_p^{1/3}(T/M_p^*)^{1/2}$] and is independent of the microfield magnitudes and the atomic properties of the transition.

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- A simple analytic expression for the linewidth is suggested, applicable to broadening of Lyman-α in H or H-like ions due to electrons and ions alike—separately or together, in a broad range of parameters.

Thank you!

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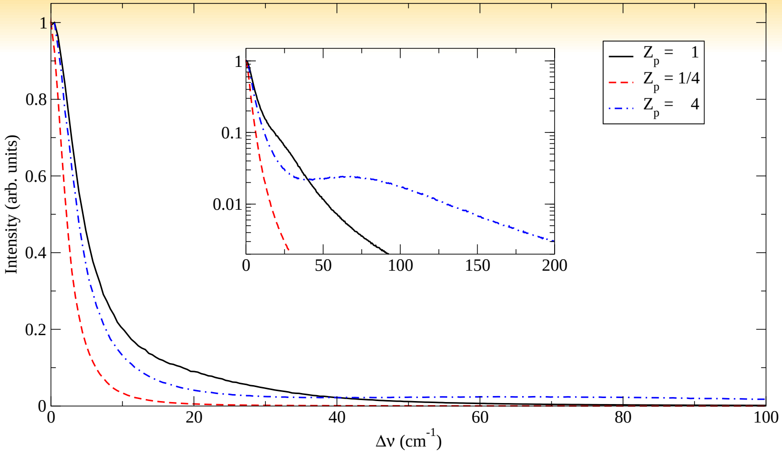
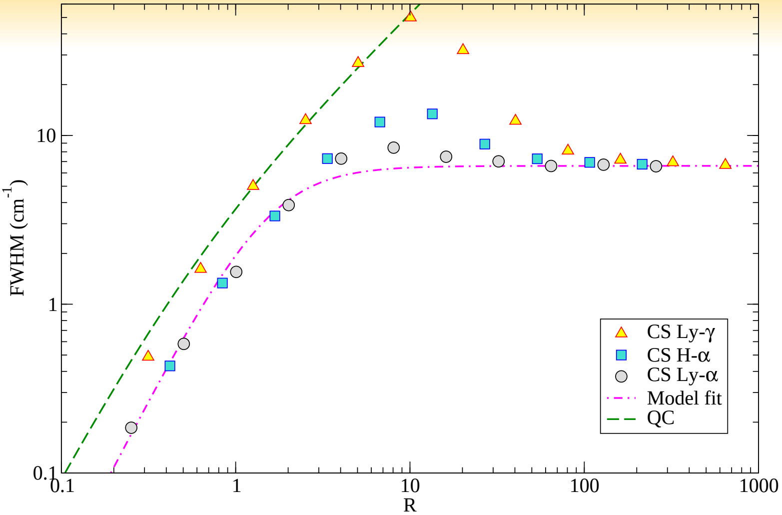
Extra material

Lyman-α in an ideal OCP :: Varying Z_p



As the lateral components are progressively shifted and broadened, the FWHM becomes mainly determined by the width of the central component.

Other lines with central component :: Varying Z_p



$$R = w_{\mathrm{qs}}/w_{\mathrm{dyn}} \approx 7\frac{|Z_p|(n^2 - n'^2)M_p^{*\,1/2}N_p^{1/3}}{ZT^{1/2}}$$