Review of the phenomenon of dips in spectral lines emitted from plasmas and their applications

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Abstract. The review covers theoretical and experimental studies of two kinds of dips (local depressions) in spectral line profiles emitted by plasmas: Langmuir-wave-caused dips (L-dips) and charge-exchange-caused dips (X-dips). Positions of L-dips (relative to the unperturbed wavelength of a spectral line) scale with the electron density $N_e$ roughly as $N_e^{1/2}$, while positions of X-dips are almost independent of $N_e$. L-dips and X-dips phenomena are interesting and important both fundamentally and practically. The fundamental interest is due to a rich physics behind each of these phenomena. As for important practical applications, they are as follows. Observation of L-dips constitutes a very accurate method to measure the electron density in plasmas – the method that does not require the knowledge of the electron temperature. L-dips also allow measuring the amplitude of the electric field of Langmuir waves – the only one spectroscopic method available for this purpose. In the most recent laser plasma experiments, L-dips were found to be a spectroscopic signature of the two-plasmon decay instability. This instability causes hot-electron generation and is a critical part in laser-driven inertial confinement fusion program. As for observations of X-dips, they serve to determine rates of charge exchange between multicharged ions. This is an important reference data virtually inaccessible by other experimental methods. The rates of charge exchange are essential for magnetic fusion in tokamaks, for population inversion in the soft x-ray and VUV ranges, for ion storage devices, as well as for astrophysics (e.g., for the solar plasma and for determining the physical state of planetary nebulae).

1. Langmuir-Wave-Caused Dips

1.1. Theory of L-dips

Langmuir-wave-caused dips (L-dips) in profiles of spectral lines in plasmas were discovered experimentally and explained theoretically for dense plasmas, where one of the electric fields $F$ experienced by hydrogenic radiators is quasi-static. This field can be the ion micro-field and (or) a low frequency electrostatic turbulence.

There is a rich physics behind each of these phenomena. L-dips result from a resonance between the Stark splitting $\omega_F = 3nhF/(2Zem_e)$ of hydrogenic energy levels, caused by a quasistatic field $F$ in a plasma, and the frequency $\omega_L$ of the Langmuir waves, which practically coincides with the plasma electron frequency $\omega_p(N_e) = (4\pi^2N_e/m_e)^{1/2} \approx 5.641 \times 10^4 \left[N_e/(\text{cm}^3)\right]^{1/2}$. $\omega_F = s\omega_L(N_e), s = 1, 2, \ldots$. 

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Even for the most common case of \( s=1 \), it is actually a multi-frequency resonance phenomenon despite the electric field of the Langmuir wave is considered to be single-frequency (monochromatic): \( E_0 \cos \omega pt \). Its multi-quantum nature has been revealed in paper [1]: it is a resonance between many quasienergy harmonics of the combined system “radiator + oscillatory field” caused simultaneously by all harmonics of the total electric field \( E(t) = F + E_0 \cos \omega pt \), where vectors \( F \) and \( E_0 \) are not collinear.

The history of dips covers a long period from 1977 to 2013, during which they have been studied experimentally at different plasma sources, such as gas-liner pinch, laser-produced plasmas, Z-pinch plasmas. These experiments, performed by various groups, required specific configurations and improved high-resolution X-ray spectrometers. The theory of L-dips from [2-5] provided a diagnostic tool for measuring the electric field amplitude \( E_0 \) of the Langmuir waves and an independent method for measuring the electron density \( N_e \). The resonance \( \omega_F = s\omega_p(N_e) \) translates into specific locations of L-dips in spectral line profiles depending on \( N_e \) and provides a simple, but accurate \( N_e \)-diagnostic.

Each L-dip represents a structure consisting of the dip itself (the primary minimum of intensity) and two surrounding bumps. The bumps are due to a partial transfer of the intensity from the wavelength of the dip to adjacent wavelengths. The total structure can lead to a secondary dip (or a small shoulder).

The half-width of the L-dip, controlled by the amplitude \( E_0 \) of the electric field of the Langmuir wave, is given by

\[
\delta \lambda_{1/2} \approx \frac{3}{2} \lambda_0^2 n_e^2 E_0/(8\pi m_e e c Z_r),
\]

where \( \lambda_0 \) is the unperturbed wavelength of the spectral line. Thus, by measuring the experimental half-width of L-dips, one can determine the amplitude \( E_0 \) of the Langmuir wave.

1.2. Experimental Observations of L-dips

1.2.1. Gas-Liner Pinch Experiments in Germany. The first observations of L-dips were made in a gas-liner pinch [6]. It is characterized by a density \((1-3) \times 10^{18} \text{ cm}^{-3}\) and a relatively low temperature \(10-13 \text{ eV}\).

The electron densities were obtained by an independent diagnostic: coherent Thomson scattering. The first-order dips (due to the one-quantum resonance \( \omega_F = \omega_p \)) and the second-order dips (due to the two-quantum resonance \( \omega_F = 2\omega_p \)) were observed in the profile of the Ly \( \alpha \) line of hydrogen in a helium plasma and their positions were in agreement with the theory. The detailed bump-dip-bump structure in the profile of each Stark component was revealed for the first time (figure 1).

![Figure 1. Bump-dip-bump structure in the H I Ly \( \alpha \) line observed at a gas-liner pinch [6].](image)

The gas-liner pinch experiments allowed two important diagnostics: the electron density \( N_e \) from the location of the dips and the Langmuir wave amplitude from the half-width of the L-dips. It turned out that measuring \( N_e \) from the L-dips yielded the same high accuracy as the much more complicated diagnostic using the coherent Thomson scattering.
1.2.2. Laser Produced Plasma Experiments in France. The experiment was performed at the nanosecond Nd: glass laser facility at LULI. A single laser beam with the intensity $2 \times 10^{14} \text{W/cm}^2$ was focused onto a structured target: an Al strip sandwiched between magnesium substrate [7, 8]. The Al plasma was well confined and the transverse emission was optimized. The plasma parameters $N_e=5 \times 10^{22} \text{cm}^{-3}$ and $T_e=300 \text{eV}$ were estimated by hydrodynamic simulations. They confirm a resonant coupling between the ion micro-field F and the Langmuir field E. A Vertical-geometry Johann Spectrometer VJS with high spectral (4200) and spatial resolutions was specially designed for revealing fine structures in the red wing of Al XIII Ly $\gamma$ line.

Theoretically expected L-dip positions were confirmed by the experiment (figure 2). The simultaneous production of a pair of symmetric spectra with this spectroscopic diagnostic provided a reference point for the computational reconstruction of raw data, thus increasing the confidence in the identification of the dips.

![Figure 2](image_url)

**Figure 2.** L-dips in the experimental profiles of Al XIII Ly $\gamma$ line from a plasma produced by the LULI laser [7, 8]. Only the red dips are visible, the blue dips are merged with the noise. The different spectra correspond to the emission from different distances from the target (i.e., different densities).

This experiment in a laser produced plasma confirmed the dependence of the dips positions on the density, thus allowing a density diagnostic. The density values were similar to the ones obtained from line broadening simulations (IDEFIX code at LULI and PIM PAM POUM code at PIIM-Marseille).

1.2.3. The latest experimental application of the theory of L-dips in Z-pinch plasma in China at Chongqing University. At the Yang accelerator Z-pinch aluminum plasmas, characterized by a density $N_e=5 \times 10^{23} \text{cm}^{-3}$, the electron temperature $T_e=500 \text{eV}$ and the ion temperature $T_i=10 \text{keV}$, were obtained by imploding aluminum wire-array [9]. The experimental Stark broadened profiles of Al XIII Ly $\alpha$ and Al XIII Ly $\gamma$ lines were recorded with a high spectral resolution (2500) of a uniform dispersion mica crystal spectrograph. These lines, emitted from different regions, exhibited...
bump-dip-bump structures. They corresponded to slightly different densities and to different radial temperature gradients. The relationship between the positions from the line center of red Langmuir dips and electron density was studied. The electron densities deduced from the red dips were compared to those derived from measurements of the Plasma Polarization Shift (PPS) of the entire spectral line. There was a 5% difference in the electron densities obtained the two methods, which was due to the uncertainty of determining the average $T_e$ required for the PPS method (but not required by the method based on the L-dips).

2. Charge-Exchange-Caused Dips

2.1 Theory of X-dips

The charge-exchange-caused-dips (X-dips) in profiles of spectral lines are due to the Charge Exchange (CE) in a plasma containing ions of at least two different nuclear charges $Z$ and $Z' \neq Z$. The history of X-dips covers a long period from 1995 to 2012. Until recently the theoretical studies focused at the X-dips are caused by CE at quasi-crossings of the energy terms $E(R)$ of the quasi-molecule $Z$-$e$-$Z'$ made up of a H-like radiating ion Z and a perturbing fully stripped ion $Z'$ [10–12].

Two independent complementary mechanisms explain the formation of X-dips in spectral line profiles [12]: one through the behavior of the transition energies $\Delta E(R)$ and another through the dynamical broadening $\gamma(R) = \gamma_{CE}(R) + \gamma_{nonCE}(R)$. The bump-to-dip ratio of intensities is a function of the ratio of the two parts of the dynamical broadening $r = \gamma_{CE}(R_c)/\gamma_{nonCE}(R_c)$. This function was calculated analytically in [12]. As $r$ increases, the bumps move away from the center of the X-dip and their intensities decrease. The bump-to-dip ratio measurement $r_{exp}$ allows deducing the rate of CE [12] as follows $<v \sigma_{CE}(v)> = \gamma_{nonCE}(R_c) r_{exp}/N_i$, where $N_i$ is the ion density. The quantity $\gamma_{nonCE}(R_c)$, representing the frequency of inelastic collisions with electrons and ions leading to virtual transitions from the upper state of the radiator to other states, can be calculated for given plasma parameters $N_e$, $N_i$, $T_e$, and $T_i$ by using one of few contemporary theories (presented, e.g., in book [13]). The experimental determination of the rates of CE for multicharged ions from using X-dips is an important reference data virtually inaccessible by other experimental methods.

2.2 Experimental Observations of X-dips

2.2.1. The first observation at the gas-liner pinch, Germany. The X-dip was observed in the blue side of the H $\alpha$ line emitted by hydrogen atoms ($Z=1$) perturbed by fully stripped helium ($Z'=2$) – for a relatively small range of electron densities around $10^{18}$ cm$^{-3}$ [10]. For lower densities the quasi-crossing distance $R_c$ was much lower than the mean inter-ionic distance $R_i$, and for higher densities the dynamical broadening $\gamma_{nonCE}(R_c)$ was smoothing the dip structure, both reasons being unfavorable for experimental observations. In these experiments the electron density $N_e$ was measured by Thomson scattering and it was verified that the positions of the X-dips did not depend on $N_e$.

2.2.2. Laser Produced Plasma Experiments in France. The X-dips were observed in laser-produced plasmas characterized by $N_e=10^{22} - 3\times10^{22}$ cm$^{-3}$ [12,14]. The setup was implemented at LULI using the same nanosecond laser at $10^{14}$W/cm$^2$ and the same high-resolution Vertical-geometry Johann Spectrometer (R=8000) as in the experiments devoted to the observation of L-dips [7,8]. The targets used for the observation of X-dips were aluminum carbide Al$_4$C$_3$ strips inserted in carbon substrate. The emission from the heterogeneous plasma made up of Al and C ions exhibited spectroscopic signatures of CE. X-dips were observed for the first time in the experimental profile of the Ly $\gamma$ line of Al XIII ($Z=13$) perturbed by fully stripped carbon CVI ($Z'=6$), as shown in figure 3.

From the experimental bump-to-dip ratio, the rate of charge exchange between a hydrogenic aluminum ion in the state $n=4$ and a fully stripped carbon was found to be [12]:

$$<v \sigma_{CE}(v)> = (5.2 \pm 1.1) \times 10^6 \text{ cm}^3/\text{s}. $$
2.2.3. Laser-produced plasma experiments in Prague. The X-dips were studied in Plasma Wall Interaction (PWI) experiments performed at PALS [15]. A plasma jet of aluminum ions, produced by the nanosecond iodine laser (intensity $3 \times 10^{14} \text{ Wcm}^{-2}$), incident on a foil, interacted with a massive carbon target. The high spectral and spatial resolution Vertical-geometry Johann Spectrometer was adjusted for the observation of X-dips in the experimental profile of the $\text{Ly} \gamma$ line of Al XIII ($Z=13$). The X-dips were clearly visible in the red wing as the signatures of CE phenomena accompanying the PWI. The electron densities simulated by codes PALE [16] and MULTIF [17] could reach $5 \times 10^{22} \text{ cm}^{-3}$ which is higher than those achieved at LULI. A weak dependence of the positions of the dips on $N_e$ was detected and explained by simulations [12]. Also the L-dip was visible in the far-red wing, thus providing a spectroscopic diagnostic of the electron density.

![Figure 3](image)

Figure 3. Observation of the X-dip structures $X_1$, $X_2$, $X_3$ in the red wing of the Al XIII Ly $\gamma$ line perturbed by fully-stripped carbon in laser-produced plasma experiments at LULI. The L-dips are also visible but less pronounced than the X-dips.

More details on all theoretical and experimental studies noted above can be found in the review [18].
3. The latest experiment: two-plasmon decay instability’s signature in spectral lines and spectroscopic measurements of CE rate in a femtosecond laser-driven cluster-based plasma

This is the first study of both L-dips and X-dips in spectral lines from femtosecond laser-driven cluster-based plasma [19]. The experiments were performed at Kansai Photon Science Institute, Japan Atomic Energy Agency. Two Ti:sapphire laser facilities were used: wavelength approximately 800 nm, pulse duration 40 fs. The clusters were created when a gas of a high initial pressure was expanded into vacuum through a specially designed supersonic nozzle, which consisted of three coaxial conical surfaces. CO₂-clusters with a diameter of about 0.5 mm for pure CO₂ (gas pressure 20 bar) and 0.22 mm for the mixed gas of 90% He + 10% CO₂ (gas pressure 60 bar) were produced in both experiments. The spectral resolution of a focusing spectrometer was ~ 4000.

From the theoretical point of view, we found a unique opportunity. For the line Ly ϵ of O VIII perturbed by He+², the three possible X-dips should occur practically at the same location in the profile – merging into one “X-superdip” located at (30 ± 3.5) mA in the red wing. The experimental results far exceeded the expectations: we observed not only the X-superdip, but also L-dips (figure 4). The latter allowed an accurate experimental determination of the electron density (as well as of the amplitude of the electric field of the Langmuir wave) leading to the conclusion that we observed the spectroscopic signature of the two-plasmon decay instability (TPD).

![Figure 4](image)

**Figure 4.** Typical spectra of the O VIII Ly δ and Ly ϵ lines obtained in femtosecond laser-driven cluster-based experiments. Enlarged spectra of the O VIII Ly ϵ line in the inset show the positions of the L- and X- dips in more detail.

The value of the plasma electron frequency ωₚ deduced from the separation of the experimental L-dips is ωₚ = 1.26×10¹⁵ s⁻¹, while the laser frequency is ω激光 = 2.4×10¹⁵ s⁻¹. It is seen that ω激光 = 2ωₚ (within the accuracy of 5%). This means that we observed in the spectral line profile a signature of the TPD instability, occurring at the quarter-critical density: the decay of one quantum of the laser radiation into two Langmuir quanta (plasmons).

The TPD instability is a significant concern in the inertial confinement fusion (ICF). Hot electrons generated by TPD can preheat the target shell and degrade the implosion. Understanding and
controlling TPD hot-electron generation is critical for ICF. Besides, TPD can be used for the temperature diagnostic in the coronal region of the ICF plasmas.

The ability to detect TPD via L-dips opens up a new avenue for diagnosing TPD. The most important is that this is the only non-perturbing method to measure the amplitude of the Langmuir waves resulting from TPD and thus to test theories of TPD.

In shot #1 the interaction of laser radiation of the very high laser intensity $3 \times 10^{18}$ W/cm$^2$ with CO$_2$-He mixture caused Langmuir waves strong enough to produce pronounced L-dips. In distinction, in shot #2 the laser intensity was by an order of magnitude smaller ($4 \times 10^{17}$ W/cm$^2$). Therefore, Langmuir waves (if any) were significantly weaker and did not manifest as identifiable L-dips in the profile. The electron density deduced from the separation of the two L-dips is $N_e = 5.0 \times 10^{20}$ cm$^{-3}$. It is consistent with $N_e$ deduced from the shift of the center of gravity of the two L-dips. From the halfwidth of the L-dips in shot #1 we found the amplitude of the electric field of the Langmuir wave was $E_0 = 40$ MV/cm.

The theory predicts also a possible X-superdip at (30±3.5) mA in the red wing of the O VIII Ly-epsilon line. This X-dip is clearly visible in shot #2: it is marked by the solid vertical line in the inset in the figure below. The central minimum of the experimental x-dip is at 27 mA (in a good agreement with the theory) and is surrounded by two bumps, as predicted by the theory. In the profile from shot #1, the possible X-dip at 27 mA was practically “swallowed” by the near bump of the L-dip. More accurately, in the profile from shot #1, the bump between the central minimum of the L-dip at 37 mA and the central minimum of the X-dip at 27 mA is a superposition of the near bump of the L-dip and of the far bump of the X-dip. This is why this bump is so intense.

As for shots #3 and #4 without the admixture of He, there is no X-dip at 27 mA. This is expected for the plasma without He and thus further confirms the identification of the X-dip in CO$_2$–He mixture. Whether or not there were Langmuir waves in the plasma from shots #3 and #4 is hard to determine reliably because the modulations of the profile at the possible locations of the L-dips are the level of the noise. We note that the shot #1, where the L-dips were reliably identified, had the laser intensity by 50% greater than shots #3 and #4.

From the experimental bump-to-dip-contrast $a_{exp}$ of the X-dip in profile #2, we obtained the rate of charge exchange between the ion O$^+$ in the state of $N=6$ and the ion He$^{2+}$ in the state of $n'=2$: 

$$\langle v \sigma_{CE}(v) \rangle = (1.5 \pm 0.3) \times 10^6 \text{ cm}^3/\text{s}. $$

This is a new fundamental data virtually inaccessible by other experimental methods.

4. The latest theoretical development on x-dips
Up to now the X-dips were considered to be possible only in spectral lines of H-like ions (perturbed by fully stripped ions). However, recently we showed that the X-dips are also possible in spectral lines of He-like ions from laser-produced plasmas [20]. We presented a table containing 15 prospective He-like spectral lines and 10 corresponding solid targets for observing x-dips in laser-produced plasmas. For completeness we presented also a similar table for H-like lines: 16 prospective H-like spectral lines and 11 corresponding solid targets. This should very significantly extend the range of fundamental data on charge exchange between multicharged ions that can be obtained only via the X-dip phenomenon.

Acknowledgements
A.F. was partly supported by the RFBR research projects14-22-02089 and 14-02-91171-GFEN_a.

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