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Astrophysics in laboratory: Opacity measurements

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Abstract

Recent measurements of the absorption coefficients of *L* transitions in iron and nickel hot plasmas are reported following a brief review of the published experiments on opacities and absorption coefficients which have been performed until now in laser-heated cavities and *Z*-pinches. Emphasis is put on the impact of these measurements in astrophysics.

Keywords: Absorption coefficients; Hot plasma; Opacity; Stellar atmospheres

1. INTRODUCTION

Behavior of stars is dominated by the transfer of radiative energy, from their hot center to the outer layers. This energy transfer is maximum in the XUV range mainly from 50 to 1000 eV. Indeed this spectral range is around the maximum of the Planck function for the temperatures reached inside the stars. Stars are mainly composed of hydrogen and helium, which do not radiate as they are completely ionized in most of the volume of the star. Heavier elements like iron represent only a small fraction of the total mass (3×10^{-5} abundance of hydrogen), but they are mostly responsible of radiative transfer as their ionic species emit a rich XUV spectrum, absorbed and re-emitted on a short-range scale. For example, the $\Delta n = 0$ transitions (3–3 and 4–4) of iron are in the range 50–120 eV, and the *L*-band is around 700 eV. Opacity calculations are needed to model the radiative transfer that rules other measurable parameters such as oscillation or pulsation periods of stars. These calculations have to be benchmarked versus experimental data which can be obtained in laboratory plasmas. High energy lasers and large *Z*-pinches are the main tools that can produce plasmas in the conditions achieved inside stars, that is, plasmas at temperatures of 10–1000 eV and high densities (1 to 1/1000 solid density). Radiative transfer depends mainly on the Rosseland opacity χ_R, which is a mean of absorption coefficients defined by

$$\chi_R^{-1} = (\pi/4\sigma_R T^3) \int_0^\infty \chi_\nu^{-1} (\partial B_\upsilon / \partial T)\, d\nu,$$

where χ_ν is the absorption coefficient at frequency ν, T is the radiative temperature, and B_υ is the Planck function (Mihalas, 1978).

The Rosseland opacity is very sensitive to the wings of lines and to the gaps between lines. Opacities can be obtained with codes that calculate absorption coefficients of local thermodynamic equilibrium (LTE) plasmas on a wide spectral range. These codes have been regularly compared in workshops (Rickert, 1995; Serduke *et al.*, 2000, Rose, 2001). For very rich spectra, a detailed description is difficult due to the very high number of lines involved, and statistical descriptions based on the unresolved transition array (UTA) proposed by Bauche and Bauche-Arnoult (1994) are more efficient. Among these codes, one can mention the STA and SCO codes based on the UTA formalism, and developed by Bar-Shalom *et al.* (1989, 1994), and Blenski *et al.* (1997), respectively. The OPAL code (Rogers & Iglesias, 1992), which calculates the spectra with detailed lines for low- and medium-*Z* elements, and with the UTA formalism for high-*Z* elements has also been used very efficiently to analyze laboratory experiments, and also in astrophysical situations. Measurements of absorption coefficients in different spectral ranges test these codes. They are real benchmarks when the plasma parameters are determined independently from the absorption measurement, and when the plasma is in LTE.

We review here the experimental data obtained until now, and the difficulties encountered in measuring absorp-

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Address correspondence and reprint requests to: C. Chenais-Popovics, Laboratoire pour l'Utilisation des Lasers Intenses, UMR No. 7605 CNRS, CEA École Polytechnique, Université Paris VI, École Polytechnique, 91128 Palaiseau cedex, France. E-mail: claude.chenais-popovics@polytechnique.fr tion coefficients in a well-diagnosed plasma. Examples will be given of astrophysical applications for which laboratory experiments have been important. Recent progress in calculations that have been tested versus absorption coefficients measurements of nickel samples will then be reported.

2. REVIEW OF PREVIOUS WORK

Measurement of absorption coefficients in plasmas is based on the technique of point projection spectroscopy, first introduced by Lewis and McGlinchey (1985). This technique is based on a small plasma produced by tightly focusing a laser on a massive or a fiber target to create a point-like X-ray source. It has been used to probe expanding plasmas (see, e.g., Balmer *et al.*, 1989; Chenais-Popovics *et al.*, 1989; Bruneau *et al.*, 1991*a*; O'Neill *et al.*, 1991), and was first used to probe a radiatively heated aluminum plasma (Davidson *et al.*, 1988). Different measurements have been performed in the range of temperatures from 10 to 80 eV, and densities mainly in the range of 0.1 to 300 mg/cm^3.

Very low-Z elements (C, N, B, Be) were studied in an open cavity by Hammel *et al.* (1991) and Seely *et al.* (1994) and in a closed cavity by Eidmann *et al.* (1994), Merdji *et al.* (1997*a*), and Gilleron *et al.* (2001). The backlighter (BL) was a gold target. The measured absorption lines were the Rydberg series in the 20 to 70 Å spectral window. The plasma temperature was 5 to 30 eV and the mass density 4 to 100 mg/cm^3. For low-Z elements, the density can be determined from the Stark broadening of lines, which has been done, except for the very preliminary experiments.

The Kα lines of light elements, which are in the kiloelectron-volt range, have been studied extensively, in open and closed geometry. Mg was studied by Koch *et al.* (1995) with a uranium BL, for a temperature of 23–31 eV and a density of 9–44 mg/cm^3. Aluminum is easy to produce in thin foils and was studied using samarium as a BL (Davidson *et al.*, 1988; Perry *et al.*, 1991, 1994; Smith *et al.*, 1994; Iglesias *et al.*, 1995; Merdji *et al.*, 1997*b*; Chenais-Popovics *et al.*, 2000*a*). The temperature range covered was 15–58 eV, with densities from 3–300 mg/cm^3. The main codes used for the analysis of the Kα lines are based on *ab initio* atomic calculations (Klapisch *et al.*, 1977; Cowan, 1981; Abdallah & Clark, 1991; Bar-Shalom *et al*., 2001). Chlorine Kα lines have also been investigated with foils by Edwards (1991*a*, 1991*b*) and with foams which permit lowering the plasma density by Renaudin *et al.* (1997). Additionally, the L-band of aluminum has been studied in the XUV range, using a gold BL, by Winhart *et al.* (1995, 1996), in the regime $T_e = 20$ eV, $\rho = 10$ mg/cm^3. For these low-Z Kα lines, the opacity calculations can be performed with a detailed description of the lines. This provides a very good agreement of experiments with calculations. The Kα lines of aluminum have the advantage of providing absorption structures well separated ion by ion, due to electron screening differences. As Al is easy to deposit, it has driven the idea to use Al Kα absorption to get a measurement of the temperature independent of the measurement of absorption of higher-Z elements. This has been done for the L-band transitions in Ge by Perry *et al.* (1995) and Back *et al.* (1997), in Nb by Springer *et al.* (1991) and Perry *et al.* (1996), and in Ni by Chenais-Popovics *et al.* (2001*c*).

Medium-Z elements (Fe, Ni, Ge, Nb), which are ruling radiative transfer in stars, have been largely studied in the L-band (2–3 and 2–4 transitions) and also for $\Delta n = 0$ transitions, specifically the 3–3 and 4–4 transitions. Germanium L-band transitions, whose energy is around 1.5 keV, were measured by Bruneau *et al.* (1991*b*), Foster *et al.* (1991), Gary *et al.* (1995), Perry *et al.* (1995), and Back *et al.* (1997). Temperatures were 10 to 76 eV, with densities from 3 to 50 mg/cm^3. Fe has been studied mainly for the M-band, in the XUV range (50 to 120 eV), with a gold BL by Da Silva *et al.* (1992), Springer *et al.* (1992, 1994, 1997), and Winhart *et al.* (1995, 1996), in a spectral range of high interest for astrophysics. Most of these experiments used closed laser-heated hohlraums with temperatures of 25 and 59 eV and densities of 8 and 10 mg/cm^3, respectively. One experiment was performed at very low density (0.1 mg/cm^3) with a Z-pinch by Springer *et al.* (1997), and measured the 3–3 transitions, for a temperature of 20 eV. Important improvements of the OPAL opacity code (Rogers & Iglesias, 1992) have been obtained by the analysis of these X-UV experiments.

Using a silver BL, measurements of the L-band, in the 700-eV spectral range, were obtained for a temperature of 20 eV, and a density around 3 mg/cm^3 by Chenais-Popovics *et al.* (2000*b*). The L-band of nickel has been measured in the 900-eV spectral region, at a 20-eV temperature by Chenais-Popovics *et al.* (2000*a*, 2001*a*, 2001*b*). Calculations performed with the UTA formalism have been tested and improved by comparison with these experiments (see Sect. 5). Niobium has been studied at a temperature of 48 eV and a density of 26 mg/cm^3 in multilayered Al/Nb targets by Springer *et al.* (1991), and Perry *et al.* (1996). The element to be studied was mixed with aluminum, which provided a thermometer from its ionization state, as mentioned above.

Additionally, a few data were published concerning the M-band absorption of higher-Z elements. Ho ($Z = 67$) was studied by Winhart *et al.* (1995), Sm ($Z = 62$) by Merdji *et al.* (1998), and Au ($Z = 79$) by Eidmann *et al.* (1998) at a temperature around 20 eV and rather low densities (4 to 10 mg/cm^3). Samarium was analyzed with the SCO code based on UTAs which gave absolute values of transmission that were too low. Tm ($Z = 69$) was measured at a higher temperature (45 eV) and a density of 90 mg/cm^3 by Smith (1998). The mixture Au/Gd was also studied by Orzechowski *et al.* (1996) with the aim of obtaining an absorption spectrum in which lines overlap and fill the gaps to increase the Rosseland opacity. These measurements are very relevant to indirect drive inertial confinement fusion (ICF), to understand the behavior of the plasma produced on the wall of the cavity, and these high-Z elements could also be present in stars.

The experiments performed in the 1990s have permitted progress concerning the detailed opacity calculations, in particular the OPAL code, specifically in the XUV domain of the $\Delta n = 0$ transitions. Experiments done more recently were testing the efficiency of the codes based on the UTA formalism which was suspected to reproduce poorly the absolute value of transmission of a sample, as shown, for example, for the Sm absorption case (Merdji *et al.*, 1998).

3. DISCUSSION ON THE TECHNICAL DIFFICULTIES

Ideally, the parameters (density and electron temperature) of the probe have to be perfectly known in these benchmark experiments. The plasma has to be in LTE and the parameters have to be stable in space and time. The experiments performed with large experimental facilities such as the NOVA laser and the Saturn Z-pinch are very close to these conditions and the requirements to reach these conditions have been well described by Perry *et al.* (1994, 1996). Figure 1 shows the experimental mounting used in the NOVA experiments. The sample is heated inside a hohlraum leading to LTE conditions. The use of two samples of different thicknesses check that the absorption lines are not saturated (see Sect. 5). The use of two simultaneous backlighters and the high temperature reached in the hohlraum gave the opportunity to measure the density of the sample during the absorption coefficient measurement. In the experiments performed with smaller installations, the density is rarely measured and is taken from hydrodynamic simulations. This is justified because the ionization changes only slowly with density, and this parameter is difficult to measure. Indeed, the X-ray shadowgraphy technique used at high temperature is inefficient, as the expansion of the sample is too small ($<10\ \mu$m) for low temperatures. Also, except for elements of very low atomic numbers ($Z < 10$), Stark broadening of the lines is negligible for the low density obtained and cannot provide the density from the absorption line width.

Most of the recent experiments use the technique of mixing the probed element with aluminum in order to measure the temperature from the aluminum absorption as mentioned previously. Ideally, Al and the sample absorption have to be measured during the same laser shot, which supposes that two wavelength ranges are simultaneously measured. Also, obtaining homogeneity of the sample is a difficult challenge to meet. Nickel is a better candidate than iron to make thin foils of uniform thickness due to oxidation. Using a laser beam shorter than the heating laser beam is also important to prevent the time variations of the parameters. Even if this was not possible with all the installations, all the

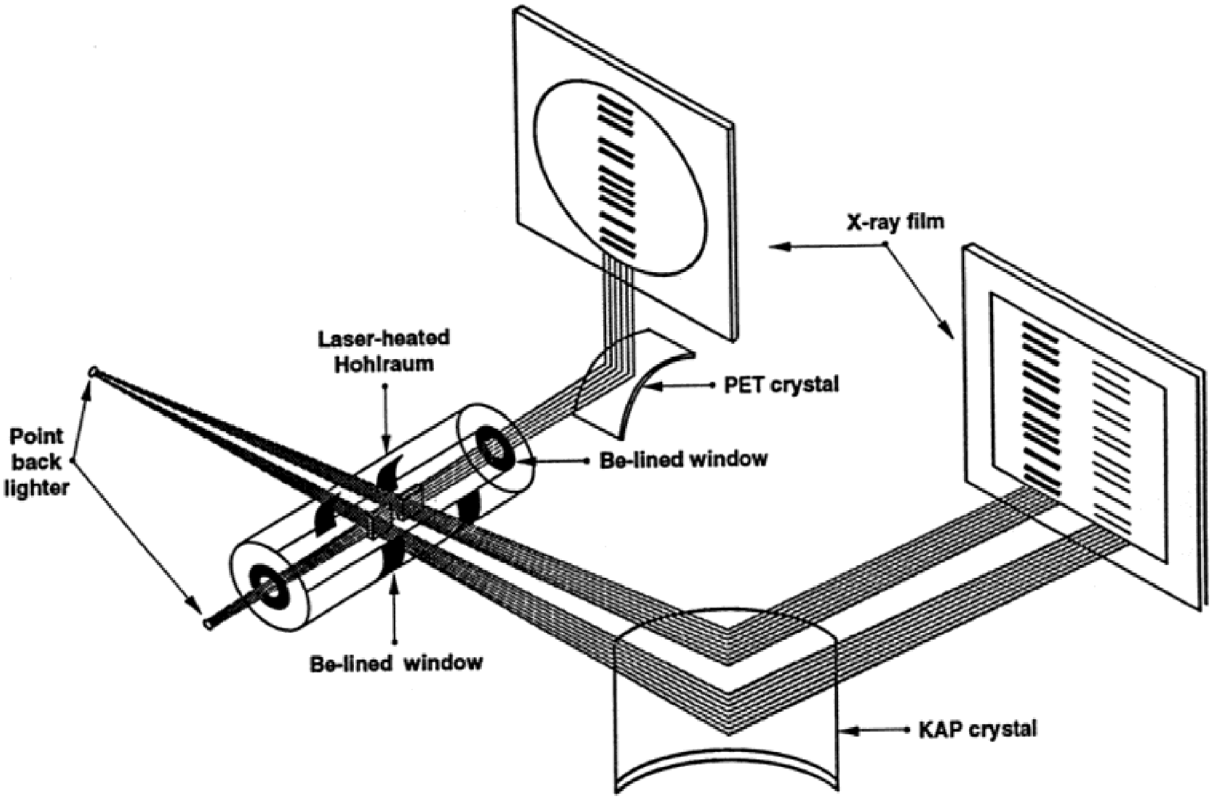

Fig. 1. A schematic diagram of the NOVA experiment showing the two point projection spectrometers used to simultaneously measure the density, temperature, and X-ray transmission of the Al/Ge samples (reproduced with permission of Elsevier).

measurements have allowed to test development of opacity codes. The opening of new facilities, such as the LULI 2000 and the LIL, prototype of the LMJ megajoule laser, in which a high energy short laser pulse will be synchronized with kilojoule or multi-kilojoule nanosecond laser beams will revive the possibility of benchmark experiments reaching the best quality requirements as described by Perry *et al.* (1996).

4. ASTROPHYSICAL APPLICATIONS

As iron is a dominant element for radiative transfer in the interior of stars, measurements of its absorption coefficients have been directly used to explain different phenomena sensitive to radiative transfer, such as the oscillations of the convection layer of the sun, observed by helioseismology (Turck-Chièze *et al.*, 1993; Brun *et al.*, 1998), the pulsation of Cepheid variable stars (Rogers & Iglesias, 1994; Gautschy & Saio, 1995), and the absorption of external layers of stars in the X-ray range (Sako *et al.*, 2001). The measurement of the $\Delta n = 0$ transitions by Da Silva *et al.* (1992) has been decisive to model the Cepheid pulsation and helioseismology, because it led to real improvements of opacity codes. Indeed, the opacity codes did not include the $\Delta n = 0$ transitions, as they were based on hydrogenic average atom models, which included only the principal quantum number n. Refining the atomic physics by introducing the orbital quantum number l permitted us to describe properly the opacity in the XUV range where Δn transitions play an important role. This is the spectral region in which radiative transfer is mostly efficient. The opacity code OPAL (Rogers & Iglesias, 1992) has been used to calculate radiative transfer in the astrophysical situations of Cepheids and of the sun. It has to be noted that the iron absorption measurements performed on Saturn by Springer *et al.* (1997) were obtained for plasma parameters very close to the conditions in which stellar pulsation instabilities were observed.

Recently, the measurement of the iron L-transitions absorption in the 800-eV spectral range performed in a laser experiment by Chenais-Popovics *et al.* (2000*b*) permitted the identification of an absorption structure of the IRAS 13349 + 2438 infrared quasar recorded with the NEWTON XMM observatory X-ray spectrograph by Sako *et al.* (2001). Figure 2 shows the comparison of the astrophysics and laboratory measurements. In Figure 2a is shown the 2–3 transitions of iron measured with the Asterix laser facility, compared to the calculation performed with the code SCO (Blenski *et al.*, 1997). Figure 2b shows the measurement of the absorption spectrum of the IRAS 13349 + 2438 quasar. The broad absorption due to 2–3 transitions of iron looks like the laboratory absorption structure. This indicates that the iron ionic composition and the plasma conditions of the absorbing region are very similar in the astrophysical and laboratory situations. A recent measurement of the same spectral region performed by Paerels *et al.* (2001) with the Chandra X-ray observatory in the binary star X0614 + 091 showed a much narrower L-band iron absorption, indicating a lower temperature in the absorbing region of the star.

5. NICKEL ABSORPTION : COMPARISON WITH DETAILED UTA CALCULATIONS

L-band or M-band absorption spectra of intermediate- to high-Z elements involve a very large number of transitions. Three to 10 ionic species contribute to the absorption and the number of lines becomes unmanageable if they are represented individually. Calculations based on the UTA formalism (Bauche *et al.*, 1988; Bauche & Bauche-Arnoult,

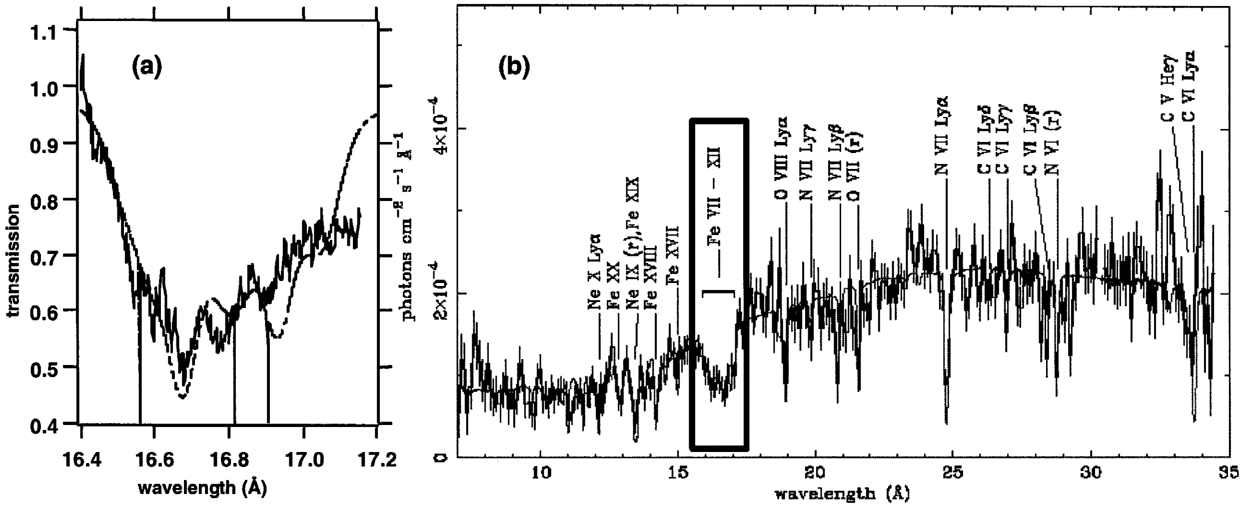

Fig. 2. Absorption of the L–N transitions of iron. a: Measurement in a laser–plasma experiment using the Asterix laser. The black line is a simulation obtained with the SCO code. b: Measurement of the quasar IRAS 13349 + 2438 measured with the X-ray spectrograph of the Newton-XMM observatory. The smoot's line is a least-squares fit of the experimental data. (Fig. 2b was reproduced with permission of *Astrophysics and Astronomy Journal*).

1994), on the superconfiguration concept (Bar-Shalom *et al.*, 1989), and on the spin-orbit-split arrays (SOSA; Bauche-Arnoult *et al.*, 1985; Bauche *et al.*, 1991*a*) permit us to reproduce the measured spectra with very good accuracy in a reasonable computing time. These calculations are still under development and need to be compared to benchmark experiments.

Recent measurement of the *L*–*M* and *L*–*N* nickel transitions in the 700-eV spectral range have permitted new developments. A method, based on the calculation of absorption of individual ions (Bauche-Arnoult *et al.*, 1985; Bauche *et al.*, 1991*a*), has permitted us to infer the composition of the plasma without relying on the LTE assumption. Calculations are performed for each individual ion (in this case Ni VI to Ni XII) and a least-squares fit of the experimental spectrum gives the percentage of the individual ions (Chenais-Popovics, 2001*b*). Moreover, the problem of the saturation of the absorption lines has been revisited, interpreting the same *L*-band nickel spectrum using a resolved transition array (RTA) method (Bauche *et al.*, 1991*b*; Duffy *et al.*, 1991; Bauche & Bauche-Arnoult, 1996). Different measured spectra of intermediate- or high-*Z* elements were reproduced by codes based on the UTA formalism, and the absolute value of the measured transmission could not be reproduced using the experimental areal density. This value had to be lowered, sometimes by a factor around 2. For the accuracy of the measurement of the areal density, the uniformity of the foils was questioned and checked. The other possibility was that the UTA formalism, which groups lines and does not represent them individually with an accurate width, could underestimate the absorption. This is due to the fact that the saturation of the individual lines, studied by Davidson *et al.* (1989) and Chenais-Popovics *et al.* (1990), cannot be correctly described with UTA models.

The RTA formalism, based on the UTA concept, introduces the huge number of individual lines participating in the absorption by simulating them statistically. The main remaining problem is to calculate reasonable individual line widths. In the nickel absorption case, line widths have been evaluated for the dominating ion Ni VIII. Doppler broadening was dominating, and gave a Gaussian broadening of $\lambda/\Delta\lambda = 25{,}000$. The comparison of the experimental spec-

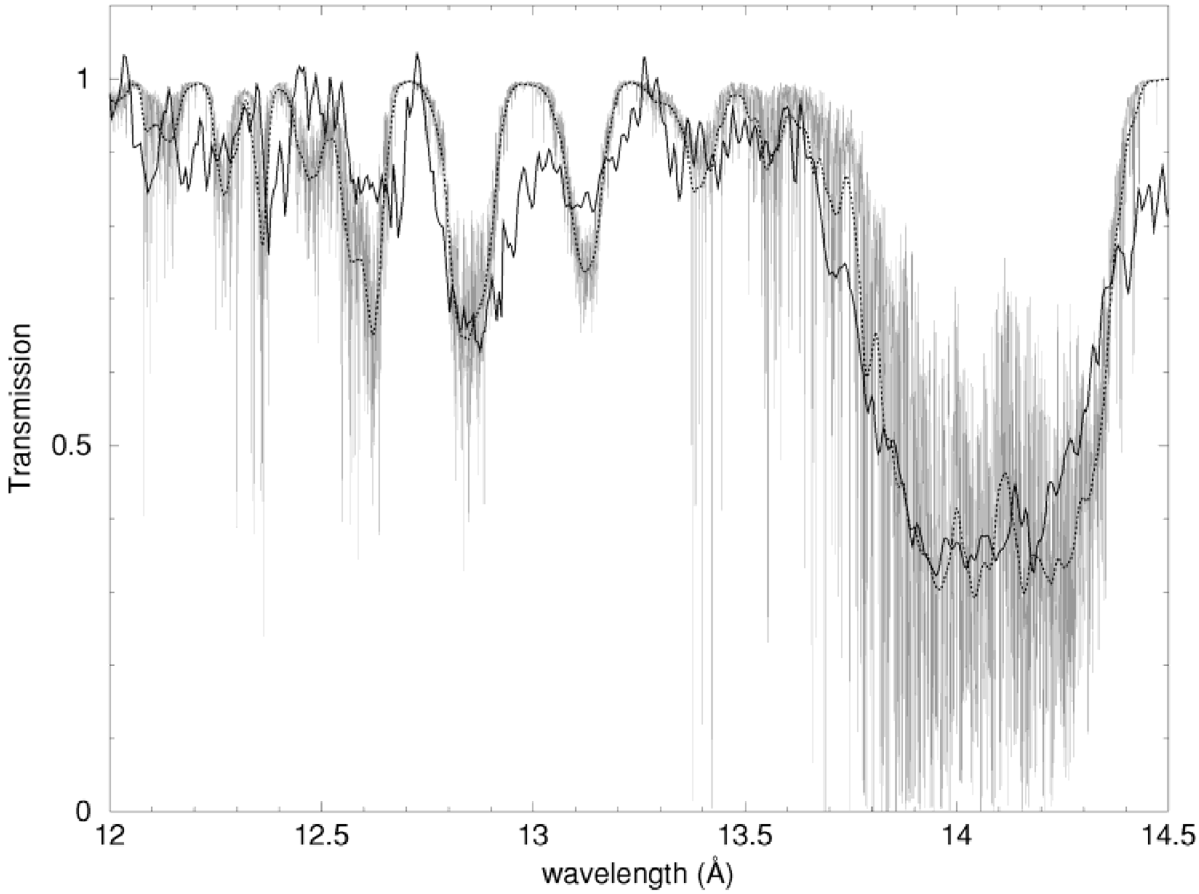

Fig. 3. Comparison of a nickel experimental spectrum, obtained for a 40-μg/cm^2 sample, with RTA calculations. Full gray thin line: individual line (RTA) calculation done for an areal density of 40 μg/cm^2, with the ionic distribution given by the detailed SOSA calculation; dotted line: RTA profile convolved with the instrumental profile ($\lambda/\Delta\lambda = 700$). (reproduced with permission from *Physical Review E*).

trum with the calculation performed with the RTA formalism is shown in Figure 3. The calculated spectrum convolved with the instrumental broadening $\lambda/\Delta\lambda = 700$ reproduces very well the experimental spectrum. The saturation effect was evidenced, not only for individual lines where transmission goes to zero, but also for partially saturated lines. The saturation problem evidenced here raises more questions: The difficult problem of determination of the width of the lines involved remains and concerns a very large number of lines. Moreover, the Rosseland opacity which is very sensitive to the line width will be also modified when saturation effects occur.

6. CONCLUSIONS AND PERSPECTIVES

Absorption coefficients have been measured in different conditions and induced important improvements in the opacity codes. The density range covered by published experiments is limited due to the heating conditions of the sample foil. Astrophysical situations cover densities very much higher and lower than what has been measured until now. The temperature range should also be extended. The possibility of using a picosecond or subpicosecond laser pulse synchronized with a nanosecond pulse in future laser facilities like LULI 2000 will increase the temperature and density domain, as the high time resolution will allow us to probe the sample foil during the whole plasma duration. It will also improve the quality of the measurements, as the X-ray probe will be much shorter than the time scale of the hydrodynamics of the heated sample. Small scale experiments which can be performed on available lasers can be interestingly performed, to have more tests of the codes based on the UTA formalism, and in particular the RTA model. The opening of the megajoule lasers NIF and LMJ in a few years and the LIL will give the opportunity of measuring absorption coefficients in conditions of interest for astrophysics and for ICF. One of the domains which should be more explored is the measurement of $\Delta n = 0$ transitions in the X-UV range. Measurements in this domain are very important as they concern directly the domain of interest for radiative transfer. However, these experiments are more difficult to perform: first, self-emission of the plasma can perturb the measurement because this spectral region is close to the maximum of the heating Planck function; additionally, there are more technical difficulties in this spectral range, such as the use of submicron filters.

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