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The influence of plasma nonequilibrium ionization state on spectra and mean opacities of the multicharged ion plasmas

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Abstract

The results of theoretical investigation of importance of radiative processes at forming of atomic spectra of multicharged ions plasma are presented in this work. An approximation of nonequilibrium ionization state of plasma (or on other terminology, plasma in collisional-radiative equilibrium - CRE) more precisely correlates with conditions of real experiments in comparison with often-used LTE approximation. For example, in plasma of laser targets on various stages of interaction process, plasma can be found both in equilibrium state (LTE or coronal equilibrium) and in intermediate CRE state when is essential to consider whole collection of elementary processes. The calculations of the plasma optical coefficients were carried out by means collisional-radiative model DESNA [1] and the programs on base of this model. This model produces satisfactory results in a wide range of changing of electron temperatures T_e=1 eV÷10 keV and ion concentrations $N_i=10^{14}÷10^{24}$ cm^{-3} including both area of equilibrium ionization state of plasma and area of nonequilibrium conditions.

It is shown, that under certain conditions an equilibrium approximations is turned out to be inapplicable and for calculation tasks and interpretation of experimental data it is necessary to consider whole collection both collisional and radiative processes. In particular, the influence of photorecombination and spontaneous radiative transitions on results of calculations of spectral emissivity was investigated for task of modeling of experimental spectra obtained at interaction of powerful ultrashort laser on targets of various compositions. Moreover, the comparison of results was carried out for series of model situations when Rosseland mean and Planck mean opacities were calculated in two cases: 1) LTE approximation and 2) the common case when equilibrium is absent. Also the questions connected with influence upon spectra of photoionization and photoexcitation processes are discussed in this presentation. The role of such processes becomes essential at presence of strong radiation field.

Definitions

Local thermodynamic equilibrium (LTE) approximation: collisional processes such as the ionization by electron impact, the three-body recombination, the collisional excitation and deactivation define the ionization state densities (given by Saha equation) and the population of excited levels (given by Boltzmann equation like a $n_k=n_0 \exp[-E_k/kT]$). Radiative and dielectronic recombination and spontaneous radiative transitions do not influence upon the ionization balance and populations.

Coronal equilibrium approximation: realized mainly at low densities. Tree body recombination and collisional deactivation do not influence upon the ionization balance and populations.

Nonequilibrium ionization state (or collisional-radiative equilibrium, CRE): whole collection of main elementary processes must be considered (excepting photoionization and photoexcitation).

Fully nonequilibrium plasma state: more close to real plasma situation. All processes must be considered, including self-consisted consideration of opposite influence of plasma intrinsic radiation on the populations of excited levels and spectra, self-absorption effects, non- Maxwellian distribution of electrons over velocities, and other effects.

The influence of plasma nonequilibrium ionization state on spectra

At present the necessity in the modeling and interpretation of real experimental emission and absorption spectra of multicharged ions is high enough. Such investigation allows both to explain the experimental data obtained and to make verification of theoretical model. Usually, this work incorporates the joint calculations by means the hydrodynamic, spectral codes, and some other techniques. Model must includes maximally possible number of the important effects and phenomena to well reproduce experimental spectra and to avoid the large errors. In the modern experiments a variation range of plasma conditions is broad enough. For example, in plasma of laser targets on various stages of interaction process, plasma can be found both in equilibrium state (LTE or coronal equilibrium) and in intermediate CRE state when is essential to consider whole collection of elementary processes. The main aim of this part of poster is to show importance of the depopulating (transitions from states with larger energy to states with lower energy) radiative processes such a photorecombination and the spontaneous radiative transitions at the calculations of spectra of multicharged ion plasmas.

For the plasma diagnostics when it is necessary on experimental spectrum to define the density and/or temperature of the plasma, or on the contrary, when it is necessary to predict the result of the expensive experiment by using self-consistent modeling with the help of hydrodynamic and spectral models, the accounting of nonequilibrium nature of the plasma intrinsic radiation is a key circumstance of the successful investigations. Comparison of the experimental and calculated on DESNA model spectrum shows that to achieve an good agreement with experimental data at the reasonable (no contradictory to results of complicated hydrodynamic modeling) plasma temperatures and densities, it is necessary obviously to take into account whole collection both collisional and radiative processes. Results are presented on figures 1, 2, and 3.

Considered experimental spectra

- ✓ Soft x-ray region
- ✓ H-like and He-like ions
- ✓ Spectra is simple enough and there are low number of lines
- ✓ Nonequilibrium conditions in plasma
- ✓ In calculations with satisfactorily accuracy we can use a steady-state approximation
- ✓ Self-absorption effect there is for some lines.

Experiment I. The interaction of ultra-short laser pulses with aluminum and copper targets [2]. The experiments were carried out on a laser facility "Neodim" at TSNIIMASH (town of Korolev). The intensity of the main pulse is equal to 10^{17} W/cm^2, intensity of a prepulse is $3\cdot10^{13}$ W/cm^2. A delay between of the prepulse and main pulse was 13 ns. The main pulse would interact not with a solid matter, but with quite a rarefied and extended plasma. The time-integrated line spectra of the multicharged ions were recorded in experiment. Numerical modeling of hydrodynamic processes was carried out by means of codes RAPID-SP [3] and RADIAN [4].

Experiment II. Irradiation by subpicosecond laser pulses of solid carbon disk target (University of Michigan). The experiments were conducted with a 10 Hz, 100 fs Ti:sapphire laser. The temperature and density of a plasma were defined by the analysis of experimental spectrums. Results are presented in work [5].

Experiment III. The experiments were carried out using the VULCAN laser at CLF of Rutherford Appleton Laboratory. The target consisted of an aluminum microdot, 200μmx200μm square and 1 μm thick, coated onto a 6 μm plastic foil [7]. This target and laser arrangement ensured a 1-D Al plasma expansion. The hydrodynamic properties of the plasma were measured by monitoring the Thomson scattering and calculated by means a 1-D planar geometry hydrodynamic simulation using the code MEDUSA [6].

Consolidated experimental conditions

No	Laser wave-length, μm	Pulse duration, ns	Pulse energy, J	Power density on the target, W/cm^2	Target material	Spectral range, Å	Reference
I	1.055	10^{-3}	1.0	10^{17}	Al, Cu	5.5-8.0	[2]
II	0.780	10^{-4}	$5\cdot10^{-2}$	10^{17}	C	25-36	[5]
III	1.054	1.0	900	$3.5\cdot10^{14}$	Al	5.5-6.8	[7]

Self-absorption effect can be estimated by formula for spectral brightness of flat layer with thickness Δ [8]:

$$S_\nu = S_{\nu p}\left[1 - 2\mathrm{E}_3(k_\nu \Delta)\right]$$

where $S_{\nu p}$ is the black body spectral brightness; E_3, the exponential integral of third order; k_ν, the spectral opacity.

The influence of plasma nonequilibrium ionization state on the mean opacities

The main results of comparison of the Rosseland mean and Planck mean opacities calculated by means of DESNA model with results of other codes in LTE approximation for wide range of the temperatures and densities were presented in [10]. Here we show only some results for LTE approximation. The main attention is devoted to present the results for nonequilibrium (CRE) plasma and to show importance of the radiative processes. Results are presented on figures 4-7.

The influence of photoionization and photoexcitation on the ionization composition and populations of excited levels

At the presence of a strong external or intrinsic radiation field the processes of photoionization and photoexcitation can influence on the ionization state densities and population of excited levels. In is necessary to include in the system of kinetic equations the rates of these processes.

The radiative rates ($\alpha_{\mu\nu}^{abs}$ for absorption in spectral lines and α_{ν}^{phi} for photoionization and in 1/sec per one ion) are expressed in terms of the corresponding cross-sections taking into account the radiation field with given intensity I_{ω} [11]:

$$\alpha_{\mu\nu}^{abs} = \int \frac{\sigma_{\mu\nu}^{bb}\Phi_{\mu\nu}(\omega)}{\hbar\omega}\left(\int I_{\omega}d\Omega\right)d\omega$$

$$\alpha_{\mu}^{phi} = \int \frac{\sigma_{\mu}^{bf}(\omega)}{\hbar\omega}\left(\int I_{\omega}d\Omega\right)d\omega$$

Here $\sigma_{\mu\nu}^{bb}(\omega)$, $\sigma_{\mu}^{bf}(\omega)$ are the cross-sections of absorption in spectral lines and photoionization respectively; $\Phi_{\mu\nu}(\omega)$ is the line profile; $\mu = nlj$, $\nu = n'l'j'$ are the sets of quantum numbers which define the electron states, with *n* is the principal quantum number, *l* is the quantum number of orbital momentum and *j* is the quantum number of total electron momentum; $\hbar\omega$ is the photon energy, $d\Omega$ is a solid angle element.

The investigations of role of such processes are the subject of our future research.

Results

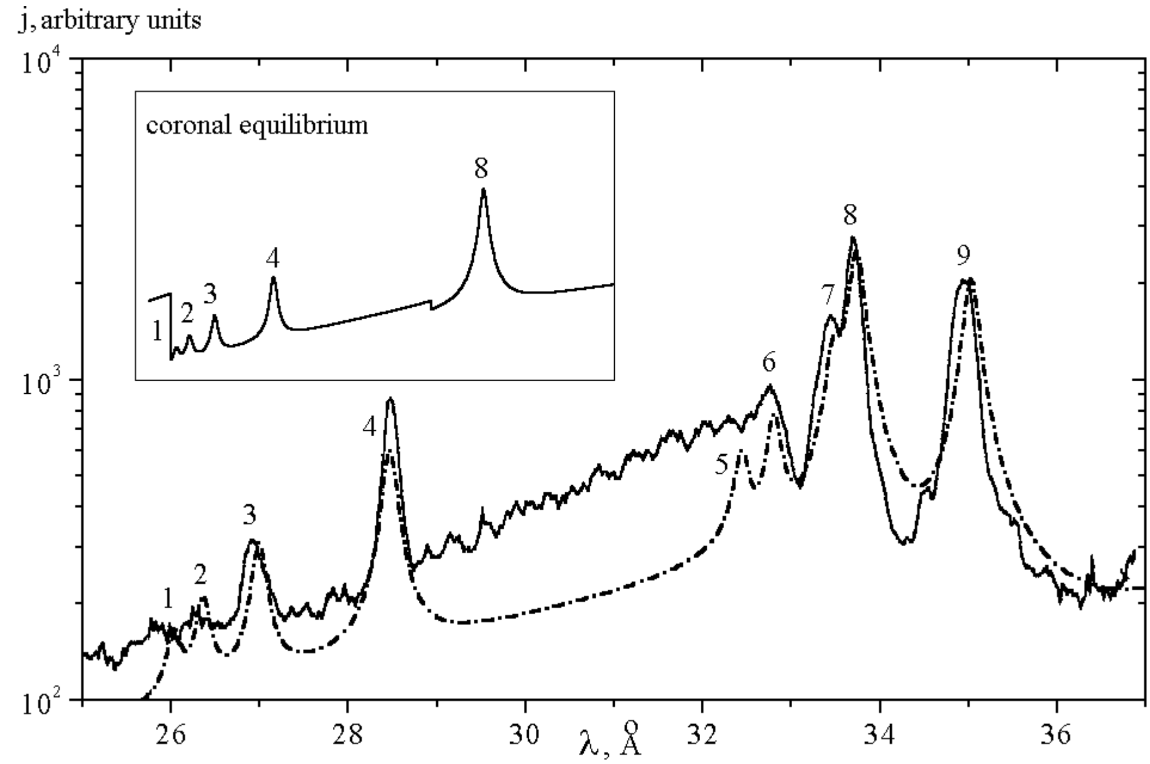
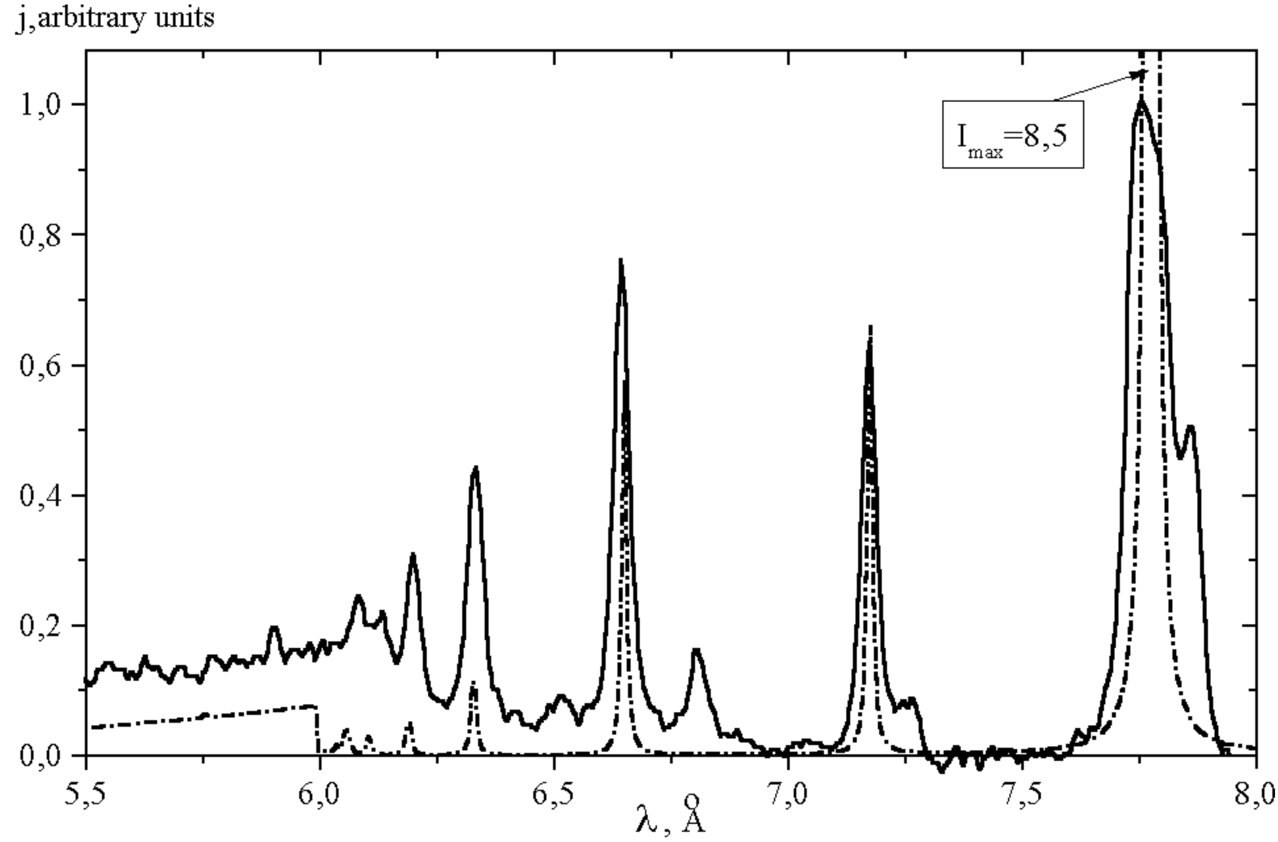


Fig.1 Experimental (solid line) and calculated (dash dot line) spectra of the carbon plasma. On the insertion presented result of the calculation in a coronal approximation for the same T_e and N_e, but in other scale on ordinate axis. (Experiment II)



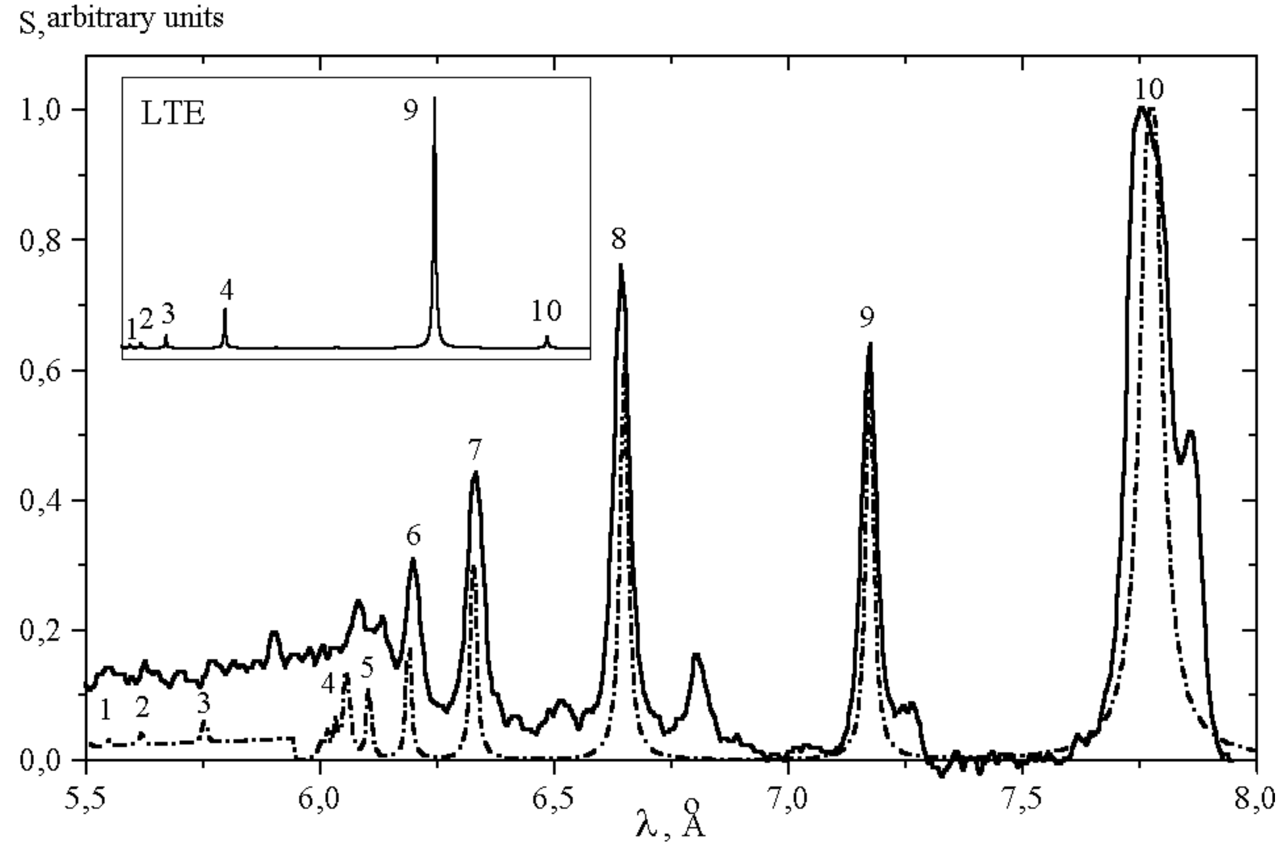
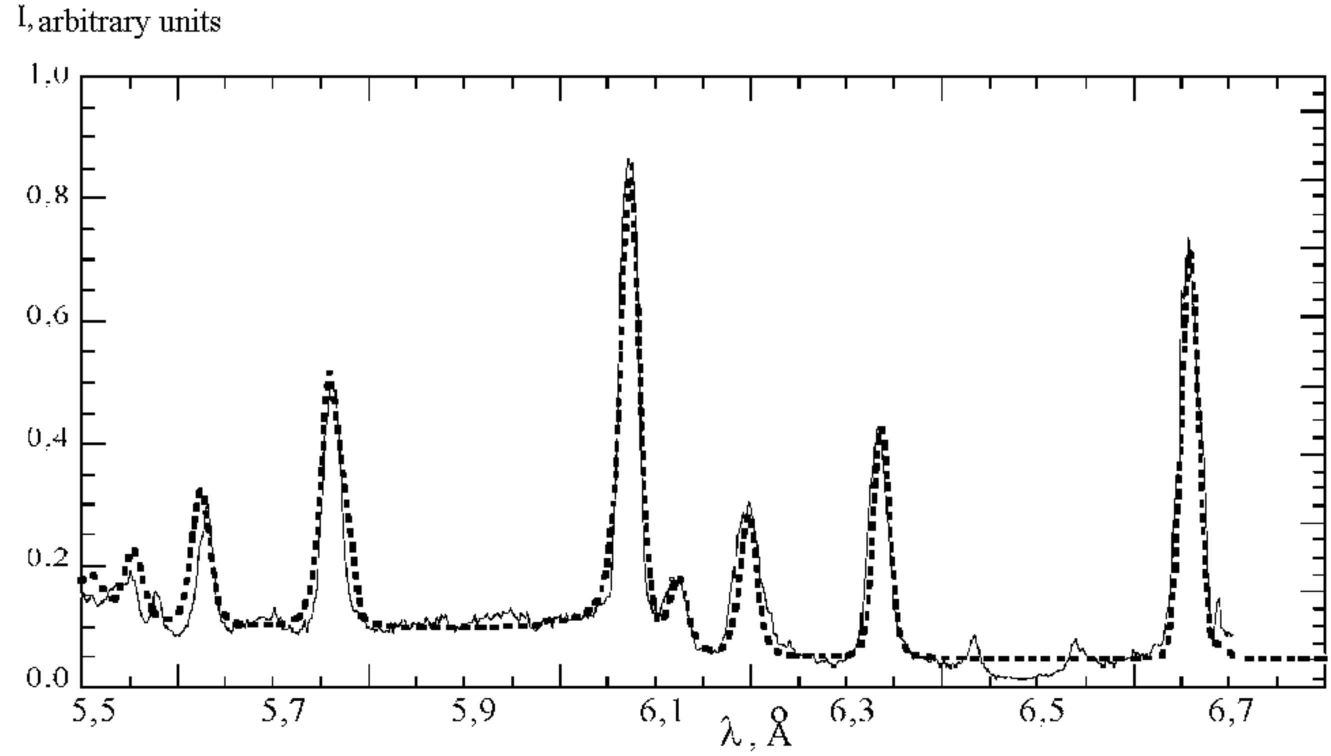


Fig.2 Comparison of experimental (solid line) and calculated on DESNA model (dash-dot line) spectrums of the aluminum plasma. On upper figure – calculated emissivity of optical transparent plasma, on lower figure - results of calculation of spectral brightness of a flat plasma layer. On the insertion - a result of calculations in LTE approximation. (Experiment I)



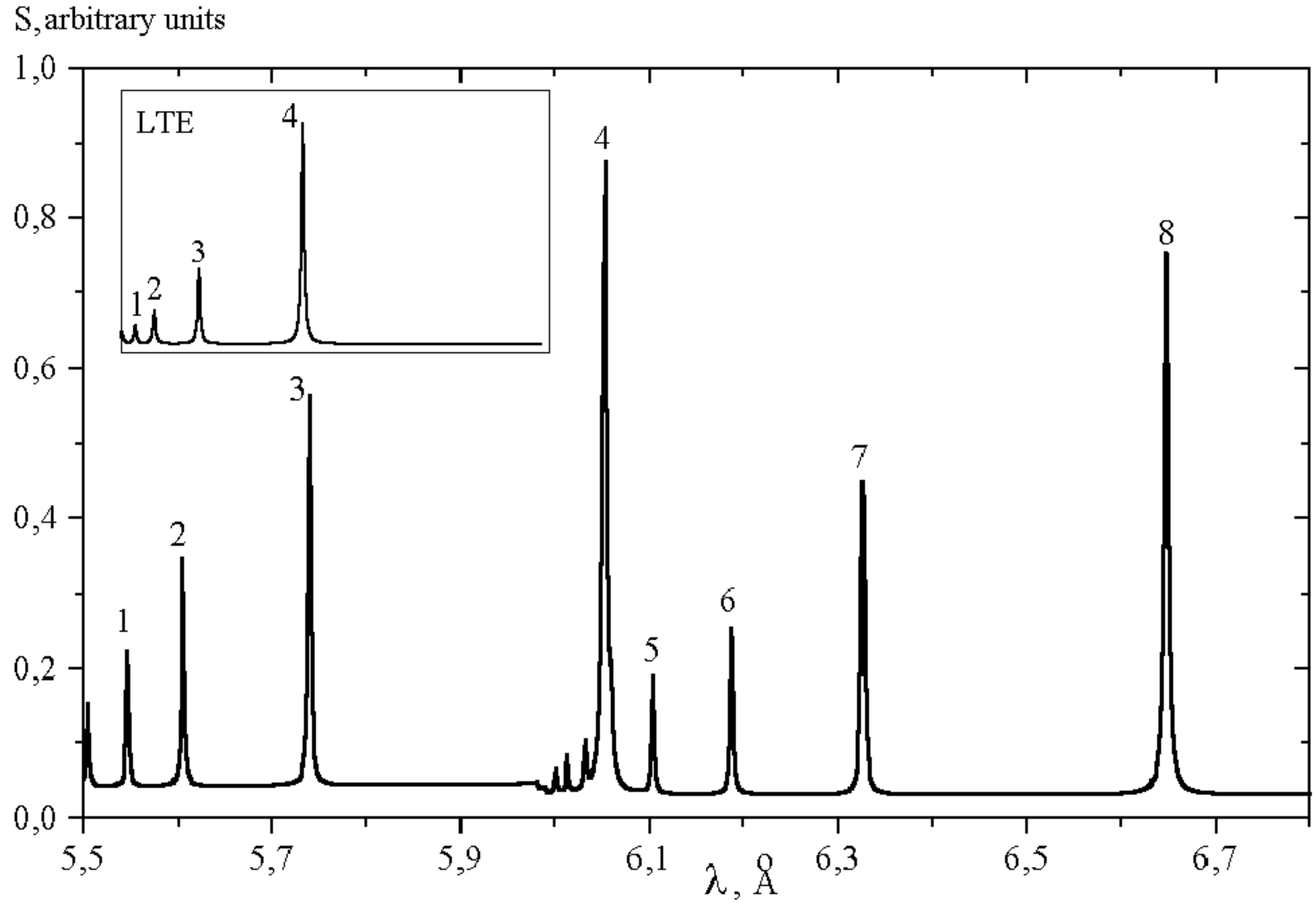


Fig.3 Calculated and experimental spectrums for the aluminum plasma. On upper graph - data from work [7]. Dotted line is marked a result of calculations. On lower graph - a result of calculations of authors on DESNA model (on the insertion shown result of calculations for LTE approximation under the same initial conditions). (Experiment III)

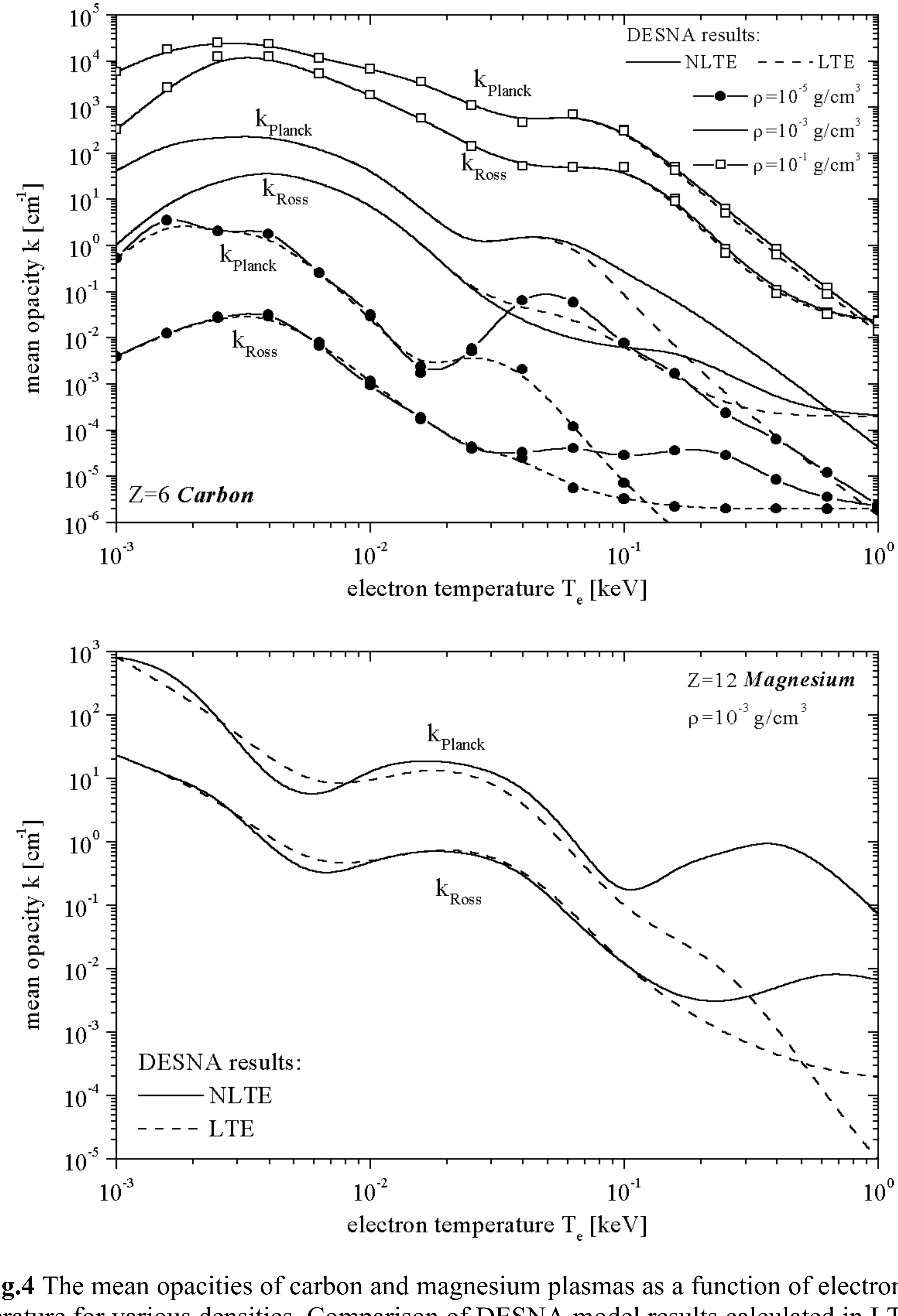
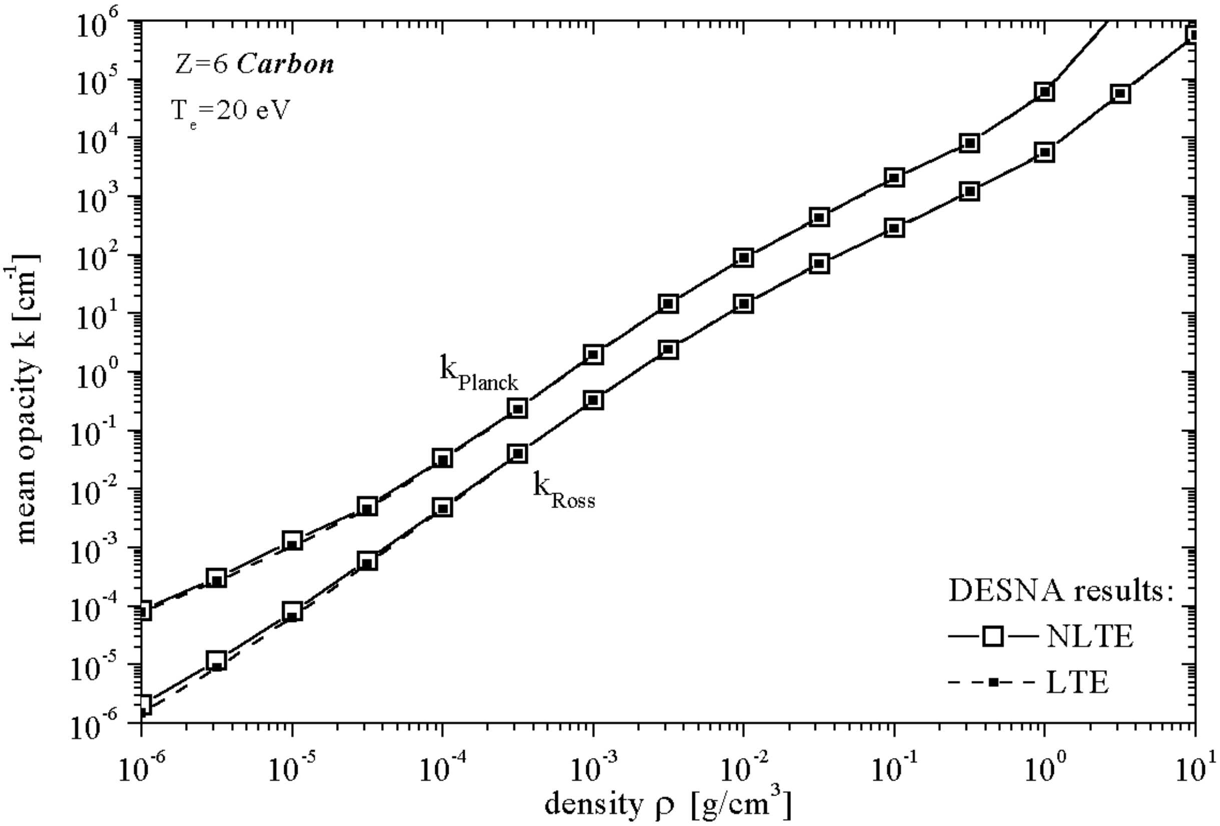


Fig.4 The mean opacities of carbon and magnesium plasmas as a function of electron temperature for various densities. Comparison of DESNA model results calculated in LTE approximation with the nonequilibrium results.



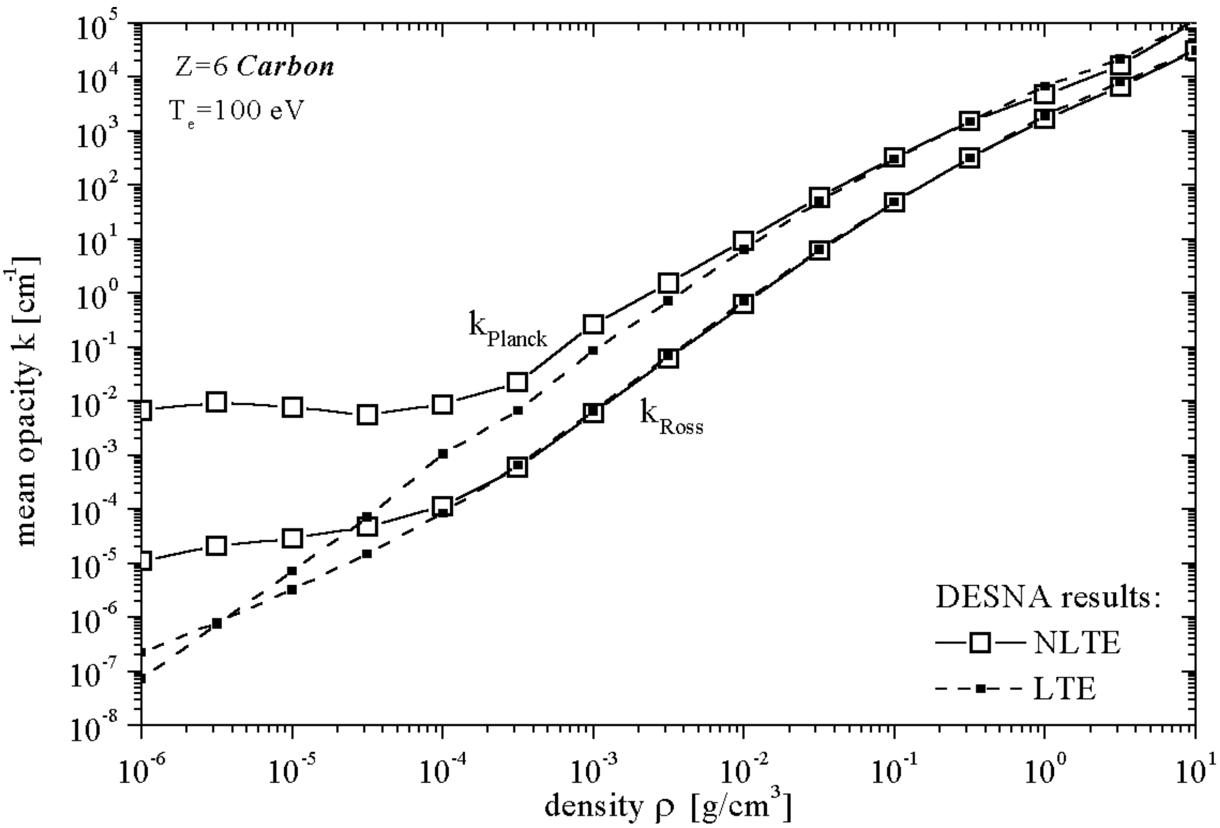


Fig.5 The mean opacities of carbon plasmas as a function of density for electron temperatures 20 and 100 eV. Comparison of the nonequilibrium data with LTE results.

Aluminum Al (Z=13)

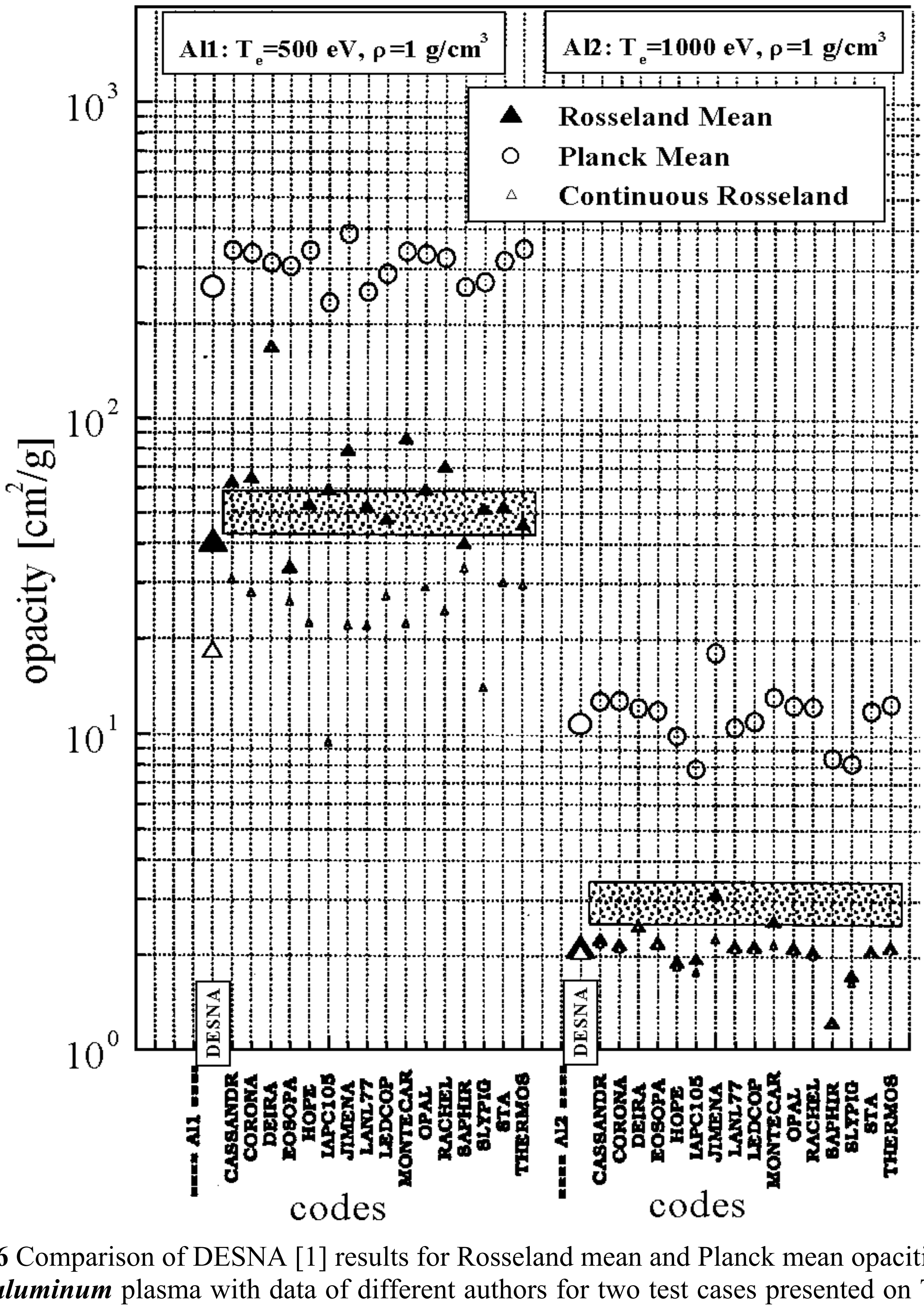


Fig.6 Comparison of DESNA [1] results for Rosseland mean and Planck mean opacities of the ***aluminum*** plasma with data of different authors for two test cases presented on Third International Opacity Workshop & Code Comparison Study (Garching, March 7-11, 1994)

SiO_2 – "glass"

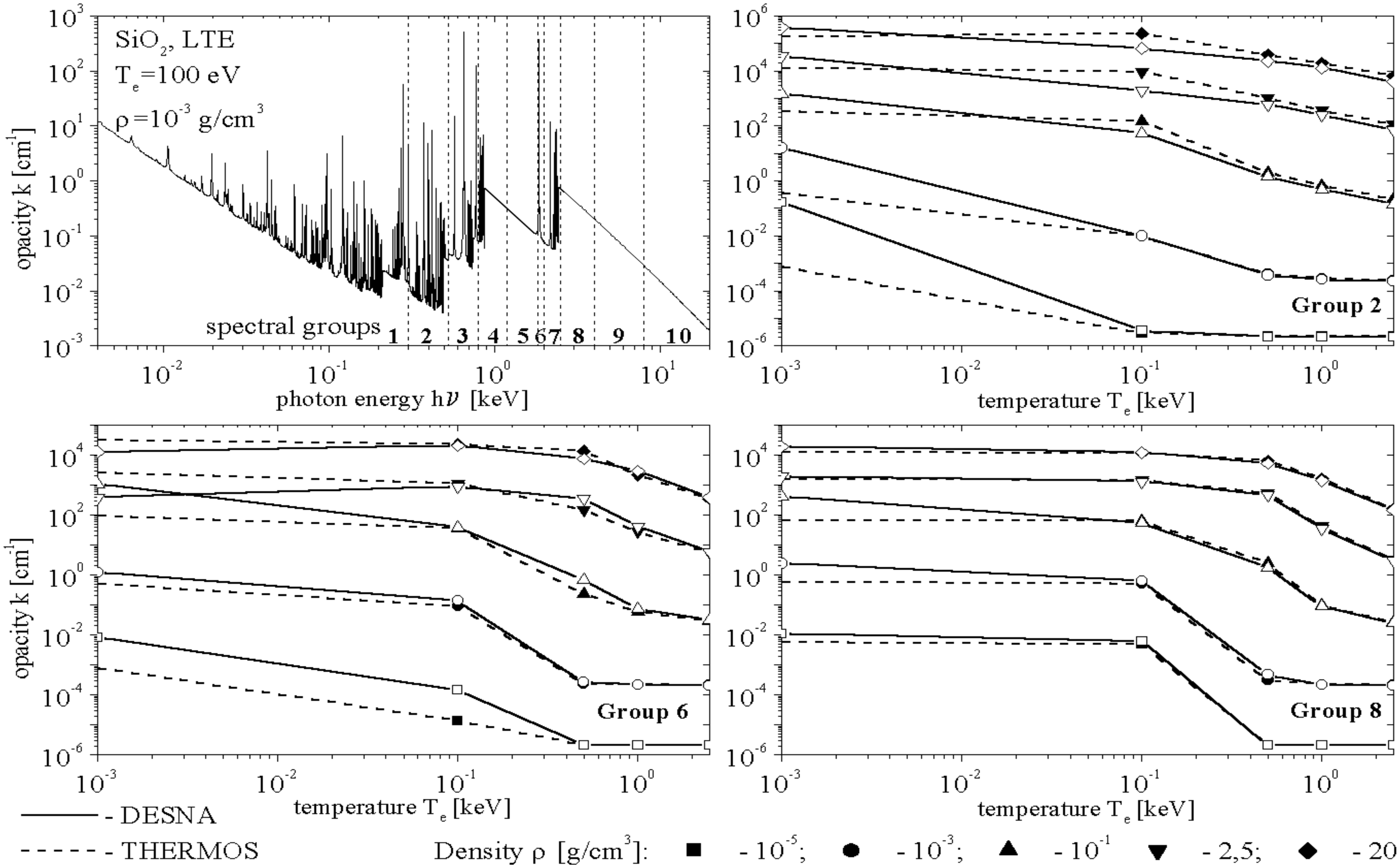


Fig.7 The example of partition on spectral group and Rosseland meangroup absorption coefficients of the ***SiO_2*** plasma versus temperature for several densities. Comparison of DESNA [1] and THERMOS [9] results for group number 2, 6 and 8. (THERMOS uses Hartree-Fock-Slater model of self-consistent field).

Conclusions

- It is shown what under certain conditions an equilibrium approximations are turned out to be inapplicable and for calculation tasks and interpretation of experimental data it is necessary to consider whole collection both collisional and radiative processes. Particularly, in the equilibrium (LTE or coronal) approximations the relative intensities of spectral lines for calculated spectra can not coincide with the experimental data at temperatures and densities which were extracted from the results of complicated and exact enough hydrodynamic calculations.
- The calculations of the mean opacities of the plasma have shown that at the high temperatures (or at the low densities) results obtained for LTE can differ from the results for CRE up to several orders of the value. This circumstance is necessary to take into account in any tasks connected with radiative transfer.
- Of course, for some special experiments or in narrow area of temperature and density equilibrium approximations can produce the perfect results. However, follows to be very careful using equations for LTE of coronal equilibrium in practice.
- It is undoubtedly that at present radiative processes (photorecombination and spontaneous radiative transitions) must be accounted at any calculations of the spectra, ionization state densities, and populations of the excited levels by means spectral models like a DESNA model.
- There is wide range of situations when even CRE approximation can produce insufficiently exact results and it is necessary to consider the more complicated nonequilibrium conditions with accounting for influence on spectra and other plasma properties of photoionization and photoexcitation, and with self-consisted consideration of opposite influence of plasma intrinsic radiation on the populations of excited levels and spectra. The investigations of role of such processes are the subject of our future research.

Acknowledgments

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