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Spectroscopic comparison method for determining the electron temperature of high-temperature plasmas of heavy elements

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Abstract. **For further development of the comparison method, the X-ray spectra of laser plasmas of light (Si, S, Cl, K, Ca, Ti) and heavy (Mo, W) elements are studied. Plasma is produced by focusing nanosecond laser radiation (λ = 0.53 μm, E_L = 5 J, τ = 2 ns) onto massive solid targets. The spectra are recorded using two focusing crystal spectrometers in the wavelength range λ = 2–11 Å. A detailed analysis of H- and He-like ion spectra is performed to determine the dependence of the electron temperature (T_e = 500–800 eV) on the energy of laser pulses (E_L = 0.5–5 J). Recommendations are given for measuring T_e from the spectra of light elements with maximum accuracy. The comparison method is employed to estimate the electron temperature of the plasmas of heavy elements (Mo, W), whose X-ray spectra are complex in structure.**

Keywords: *diagnostics of high-temperature plasma, X-ray spectroscopy, multiply charged ions, laser-produced plasma, X-ray spectrometers.*

1. Introduction

X-ray spectroscopy techniques are widely used for diagnostics of laboratory and astrophysical plasmas. To date, the most detailed techniques have been developed for spectroscopic diagnostics based on the spectra of hydrogen- and helium-like (H- and He-like) multiply charged ions. The spectra of such ions for elements with atomic numbers A_n = 6–30 have been well studied and are widely used to measure the electron plasma temperature T_e in the range from ~100 eV to several keV (see, for instance, Refs [1–6]). In recent years, great interest has been shown in the studies of heavy-element plasmas, mainly related to the controlled fusion programme and the development of new high-intensity X-ray radiation sources. The X-ray plasma spectra of heavy elements (elements with a high atomic number A_n or a high atomic weight A_w) usually are much more complex in structure, which is different from the structure of H- and He-like ion spectra. Moreover, the superimposition of a huge number of lines in these spectra gives rise to a quasi-continuum, which significantly complicates the spectroscopic diagnostics of such a plasma. Nevertheless, the structure of the spectra and their intensity distribution are highly sensitive to T_e. This circumstance is used in the new comparison technique to estimate the temperature T_e of the plasma of heavy elements [7–11]. The technique is based on a comparison of the spectra under study with the spectra of the well-diagnosed laser-produced plasma of light elements with the structure of H- and He-like ions. This method has been validly employed to diagnose iron plasma [8], the laser-produced plasmas of tungsten [7] and molybdenum [9–11]. A detailed description of the method and the conditions for its applicability are given in Ref. [7].

To efficiently use the comparison method requires data on the spectra of H- and He-like ions in the wide temperature range in which the spectra of heavy elements are studied. Such data, as well as the determination of the dependence of T_e on the energy of laser pulses for light elements, significantly expand the possibilities of the comparison technique.

This work is a continuation of Ref. [12], in which complex diagnostics of high-temperature magnesium laser-produced plasma was carried out: from the spectra of H- and He-like ions, the electron temperature of the plasma was determined in the range 200–550 eV in relation to the energy E_L of laser pulses in a wide energy range (10 mJ–1 J). To measure higher temperatures T_e, it is necessary to proceed to recording the spectra of elements with higher atomic numbers A_n and, therefore, with higher ionisation potentials. The objectives of this work are to determine the electron temperature T_e of the laser-produced plasma from the spectra of H- and He-like ions of the elements from Si to Ti (A_n = 14–22) and to determine the dependence of T_e on the energy E_L of laser pulses. Using the comparison technique, these data made it possible to estimate the electron temperature of the high-temperature laser-produced plasmas of heavy elements (Mo, W), whose X-ray spectra are complex in structure.

2. Description of the comparison technique

In the comparison technique [7], the spectra of heavy elements under investigation are compared with the spectra of a well-diagnosed laser-produced plasma. In this case, the laser-produced plasma diagnostics is carried out using the spectra of light elements with the structure of H- and He-like ion spectra. The spectra of heavy elements are studied at the same at-target laser intensities (or at the same energies of laser pulse) as for light elements. In this case, advantage is taken of an important property of laser-produced plasma: at moderate intensities q of nanosecond laser radiation at the target, the electron temperature of the hot plasma core depends mainly on the value of q and depends only slightly on the atomic weight A_w of the target [13–15]. The structure of the heavy-element spectra and their intensity distribution are highly sensitive to the temperature T_e. The measurement of T_e from the

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spectra of light elements permits ascribing a certain temperature to each spectrum of heavy elements. This approach has significant advantages: it does not require knowledge of the plasma charge state distribution, identification of the spectral lines and their parent transitions, and investigation of the processes that affect the spectra of heavy elements. To estimate T_e, it is sufficient only to have a characteristic structure in the spectra. Subsequently, comparing the structure of the 'T_e-calibrated' spectra with the structures of the spectra of the radiation source under study makes it possible to estimate the temperature of this source.

The conditions for the applicability of the comparison technique are discussed in detail in Ref. [7]. These conditions, which determine the limitations for the use of the technique, are the coronal equilibrium and the equilibrium ionisation in plasma and its quasi-stationarity. In the same work, it was shown that the technique is applicable when the plasma is produced by nanosecond laser radiation with an intensity

$$10^{12} \leqslant q \leqslant 10^{14}\ \mathrm{W\ cm^{-2}}. \quad (1)$$

This range is determined by two factors. First, by the limitation on the value of q in the measurement of the electron temperature from the spectra of H- and He-like ions: $q > 10^{12}$ W cm^{-2}. Second, the equilibrium ionisation and a weak dependence of T_e on A_w take place for a nanosecond laser plasma for $q < 10^{14}$ W cm^{-2}. Condition (1) corresponds to the electron temperature range

$$100 \leqslant T_e \leqslant 1000\ \mathrm{eV}. \quad (2)$$

Conditions (1) and (2) define the limits of applicability of the comparison technique.

The main condition for the applicability of the method is the presence of coronal equilibrium in the plasma. In the coronal model, the charge state distribution does not depend on the electron density N_e. In this approximation, the structure of the spectrum and the charge state distribution of a stationary plasma are described by only one parameter – the electron temperature, which can be used to compare the spectra of different plasma radiation sources. The coronal distribution is also used to determine the electron temperature T_e from the ratio of the intensities of dielectronic satellites to the intensity of the reference resonance line in the spectra of H- and He-like ions.

The condition for the applicability of coronal equilibrium can be written in the form [16]

$$N_e \ll N_e^* = 10^{16} Z^7, \quad (3)$$

where Z is the ion charge; hereafter, the density N_e is taken in cm^{-3}. For a high-temperature plasma with $Z \geqslant 10$, this condition is as follows:

$$N_e \ll 10^{23}\ \mathrm{cm^{-3}}. \quad (4)$$

Similar estimates, expressed in terms of the electron temperature T_e (in eV) [17], are of the form

$$N_e \ll N_e^* = 10^{16} T_e^{7/2}. \quad (5)$$

For $T_e \geqslant 100$ eV, we obtain the condition for the density N_e, which coincides with condition (4):

$$N_e \ll 10^{23}\ \mathrm{cm^{-3}}. \quad (6)$$

Therefore, in a hot ($T_e > 100$ eV) nanosecond laser-produced plasma with an electron density $N_e \approx 10^{20} - 10^{21}$ cm^{-3}, high Z ions always prevail, and the coronal distribution almost always takes place.

3. Experiment

The experimental setup is shown in Fig. 1. The radiation of the second harmonic of an Nd-glass laser (Phoenix facility) was used for plasma production. The laser radiation (λ = 0.53 μm, E_L = 5 J, τ = 2 ns) was focused on massive solid targets by a lens with a focal length of 300 mm. The focal spot diameter was ~20–30 μm, the at-target laser intensity q varied in the range ~$5 \times 10^{13} - 2 \times 10^{14}$ W cm^{-2} when the laser pulse energy varied from 0.5 to 5 J. The following materials were used as laser targets: Si, KCl, Ca, Ti, Mo, and W.

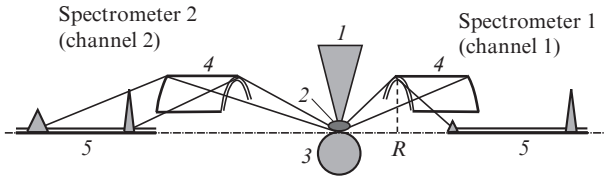

Figure 1. Experimental setup for recording the X-ray spectra of laser-produced plasma using two focusing crystal spectrometers (two recording channels):
(*1*) laser radiation; (*2*) laser-produced plasma; (*3*) target; (*4*) cylindrical mica crystals with a bending radius R = 20 mm; (*5*) radiation detectors (photographic film).

The X-ray spectra of H- and He-like ions were studied using two focusing crystal spectrometers [18, 19] made according to the von Hamos scheme [20]. Important properties of this scheme are high luminosity in a broad spectral range and high spectral resolution for quasi-point (such as laser-produced plasma) radiation sources. An additional advantage is linear focusing, when the spectrum is formed on the spectrometer axis. This makes it possible to use flat-field detectors for recording spectra, such as photographic films and CCD detectors.

The spectrometers used identical cylindrical mica crystals (double interplanar distance $2d$ = 19.84 Å for the first order of reflection) with a bending radius R = 20 mm. The spectra were recorded on a Kodak RAR 2492 X-ray photographic film. The optical film density was converted into intensity using the data borrowed from Ref. [21]. The spectrometers provided for the use of a CCD detector (a Toshiba TCD 1304AP CCD line array). This detector was used to align the axis of the spectrometers with respect to the radiation source.

The method of photographic recording of spectra was chosen for a significant broadening of the spectral range under investigation. This was done in two ways. First, due to the large (70 mm) length of the photographic film on which the spectra were recorded in each spectrometer. Second, the spectrometers were installed at different distances from the radiation source (Fig. 1). In spectrometer 1 (channel 1), for the first order of reflection of a mica crystal, the spectra are

recorded in the range $\Delta\lambda$ = 5.5–11 Å, and in spectrometer 2 (channel 2) in the range $\Delta\lambda$ = 4.5–7.5 Å. Their common spectral range $\Delta\lambda$ = 5.5–7.5 Å was used for 'stitching' the spectra and calibrating the relative sensitivity in the two channels. The total spectral range of the two channels is $\Delta\lambda$ = 4.5–11 Å for the first order of reflection of the mica crystal and 1.5–11 Å with allowance for higher orders of reflection (n = I–IV). As a result, the spectra were recorded both in different orders of reflection of the mica crystal and in two independent channels. This contributed to an increase in the accuracy of measuring the relative intensities of the lines used for plasma diagnostics.

Due to the high efficiency of the spectrometers, each spectrum under investigation was recorded in one laser pulse. In our case, the spectral resolving power of the spectrometers $\lambda/\delta\lambda$ was determined by the size of the source and amounted to 600–1500. This value was determined from the width of the spectral lines. The high spectral resolution made it possible to observe the complete structure of the X-ray spectra of H- and He-like ions: resonance lines and their accompanying satellites. Plasma diagnostics was carried out from the relative intensities of these spectral lines. The electron temperature of He-like ions was measured from the ratio of the intensities of the dielectronic satellites j, k or their sum to the intensity of the resonance line of He-like ions w (hereinafter, the designations are taken from Ref. [1–4]). For a H-like ion, the temperature T_e was determined from the ratio of the intensities of the dielectronic satellite J and the resonance line Ly_α of the H-like ion. In both cases, the data of theoretical calculations of Ref. [4] were used to determine T_e. Table 1 shows the chemical elements of laser targets, the corresponding ions, and their dielectronic satellites, which were used for plasma diagnostics. By way of example, Fig. 2 shows the spectrum in the vicinity of the resonance line of the He-like ion Cl XVI, and Fig. 3 shows the spectrum in the vicinity of the resonance line of the He-like ion Ti XXI recorded in the fourth order of reflection of the mica crystal.

Table 1. Chemical elements of the laser targets, their corresponding ions, the mica crystal reflection orders, the dielectronic satellites (DSs) used for plasma diagnostics, and the temperatures T_e measured from the H- and He-like ion spectra of different elements for different energies E_L of laser pulses.

Element	Ions	n	DS's	E_L/J	T_e/eV
Si	Si XV, Si XIV	I	J	0.5	500 ± 70
S	S XV, S XIV	I	j + k	1.3	560 ± 40
Cl	Cl XVI, Cl XV	II	j	2.3	620 ±20
K	K VIII, K VII	II, III	j, j + k	2.3	690 ± 40
K Cl	K VIII, K VII Cl XVI, Cl XV	II	j, j + k	3.2	700 ± 60
Ca	Ca XIX, Ca XVIII	II, III	j, j + k	4.2	750 ± 30
Ti	Ti XXI, Ti XX	III, IV	j, j + k	4.0	760 ± 50

Figures 4 and 5 depict the spectra of heavy elements. The spectrum of the laser-produced molybdenum plasma was recorded in the first order of reflection of the mica crystal in the range $\Delta\lambda$ = 4.5–5.5 Å. The spectrum of tungsten laser plasma was recorded in two channels and in two orders of reflection (n = I, II) in the range $\Delta\lambda$ = 4.0–11 Å. The channels' common range $\Delta\lambda$ = 5.5–7.5 Å was used to calibrate the relative intensity of the channels, and the range $\Delta\lambda$ = 8.0–10.0 Å

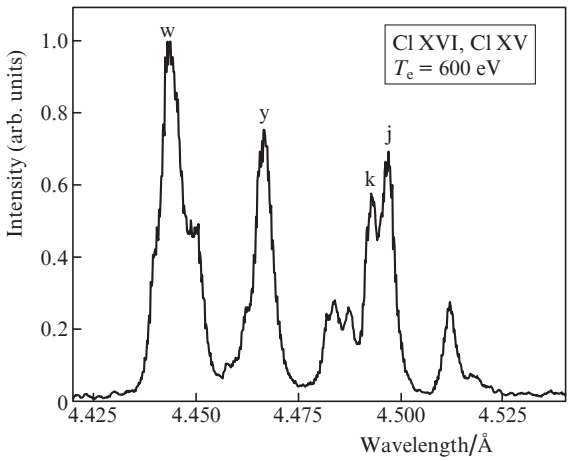

Figure 2. Spectrum in the neighbourhood of the resonance line of the He-like ion Cl XVI obtained for an energy E_L = 2.3 J of the laser pulse.

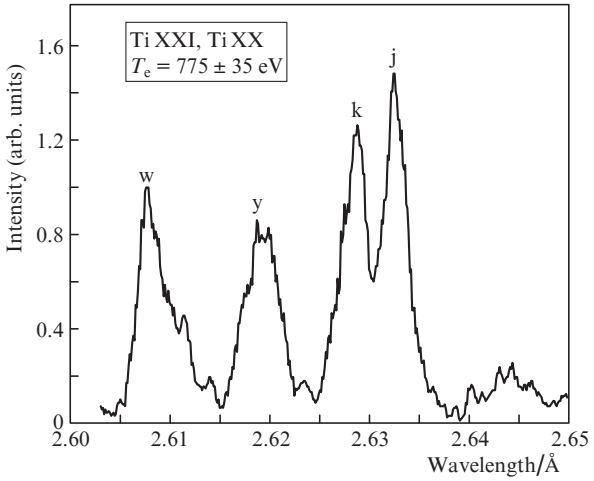

Figure 3. Spectrum in the neighbourhood of the resonance line of the He-like ion Ti XXI recorded in the fourth order of reflection of the mica crystal for an energy E_L = 4.0 J of the laser pulse.

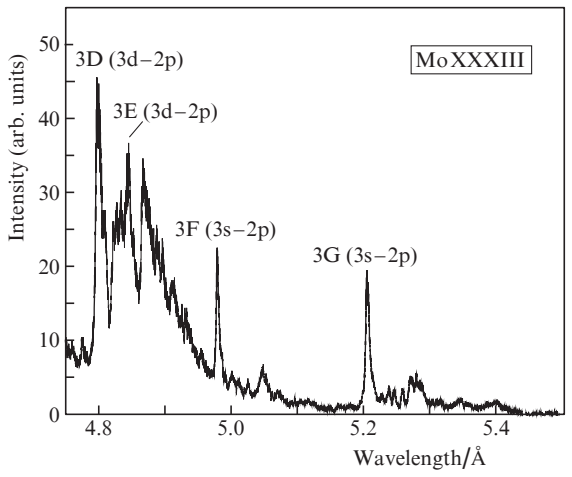

Figure 4. Spectrum of laser-produced molybdenum plasma recorded for an energy E_L = 3.0 J of the laser pulse. Indicated are the lines arising from transitions in the Ne-like ion Mo XXXIII.

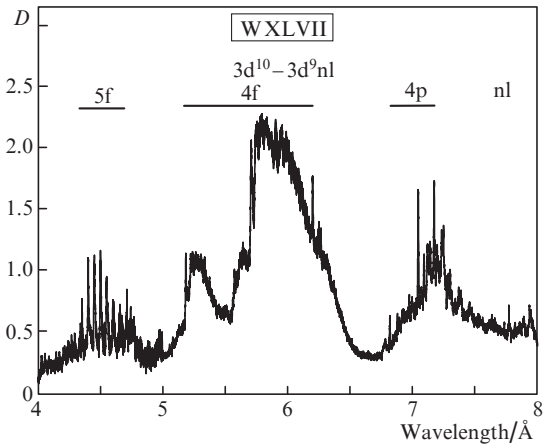

Figure 5. Spectrum of laser-produced tungsten plasma recorded for an energy $E_L = 3.5$ J of the laser pulse. Indicated are the spectral domains of transitions in the Ni-like ion W XLVII; D is the optical photographic-film density.

for the second order of reflection was transferred to the first-order reflection range $\Delta\lambda = 4.0-5.0$ Å. The resultant spectrum in the range $\Delta\lambda = 4-8$ Å is plotted in Fig. 5.

4. Results and discussion

The data of T_e measurements from the spectra of H- and He-like ions of different elements for different energies E_L of laser pulses are collected in Table 1. Figure 6 shows the dependence of T_e on the laser-pulse energy plotted on a logarithmic scale. The uncertainty in T_e measurements given in Table 1 corresponds to the scatter of the experimental data obtained in different orders of reflection of the mica crystal and/or in different recording channels. The experimental data are nicely described by the approximation formula

$$\lg(T_e/1\text{ eV}) = 2.746 + 0.2\lg(E_L/1\text{ J}), \quad (7)$$

i.e. the T_e dependence on E_L is of the form of a power law:

$$T_e \propto E_L^{\alpha} \quad (8)$$

with an exponent $\alpha = 0.20 \pm 0.02$. This dependence is in good agreement with the dependence measured in Ref. [12]

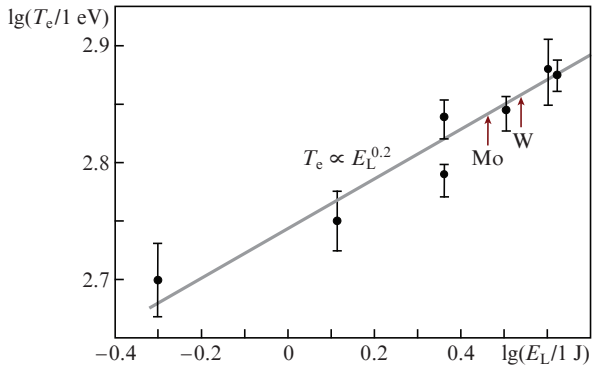

Figure 6. Log–log experimental dependence of the electron temperature T_e (eV) on the energy E_L (J) of a laser pulse.

from the spectra of H- and He-like magnesium ions with an exponent $\alpha = 0.21 \pm 0.025$. Combining the results of this work and of Ref. [12], we come to the conclusion that dependence (8) is observed in a wide range of laser pulse energies: $E_L = 10$ mJ – 5 J. Note that this dependence differs from the canonical dependence $T_e \propto q^{\alpha} \propto E_L^{\alpha}$ with the exponent $\alpha = 4/9 = 0.44$ [15]. Finding out the reason for the deviation of the exponent α from the canonical value 4/9 is beyond the scope of our paper, since it does not affect the applicability of the comparison technique. We only point out that one of the reasons may be an increase in the effective size of the laser-produced plasma due to its expansion during the action of the laser pulse for tight focusing of laser radiation on the target.

In the comparison technique, the spectra of heavy elements are studied at the same fluxes (or at the same energies) of laser radiation on the target as for light elements. In this case, to estimate T_e for heavy elements, in principle, does not require knowledge of the dependence of T_e on E_L. However, determining this dependence for light elements allows for a more reliable estimate of T_e for the plasma of heavy elements. The X-ray spectra of laser-produced molybdenum and tungsten plasmas are depicted in Figs 4 and 5, respectively. Table 2 presents the results of studying the spectra of heavy elements. The energies E_L of laser pulses, at which the plasma of these elements was obtained, are indicated on the $T_e \propto E_L^{0.2}$ dependence (Fig. 6) by arrows, and the corresponding T_e values are given in the last column of Table 2.

Table 2. Chemical elements of laser targets, corresponding ions, orders of reflection of a mica crystal, and temperatures T_e measured for different laser-pulse energies E_L.

Element	Ion	n	E_L/J	T_e/eV
Mo	Mo^{32+}	I	3.0	700 ± 60
W	W^{46+}	I, II	3.5	720 ± 60

The X-ray spectra of the laser-produced plasmas of heavy elements (Figs 4 and 5) had a complex structure. 3D, 3E, 3F, and 3G transitions in Ne-like ions were observed in the spectra of molybdenum plasma [5]. Observed in the spectral regions $\Delta\lambda = 4.8-5.1$ Å and 5.2–5.4 Å was a quasi-continuum, or UTAs (unresolved transition arrays). A comprehensive theoretical analysis of the spectra of molybdenum ions in the vicinity of 3–2 transitions in Ne-like ions was carried out in Ref. [10]. The charge-state distribution and the contribution of various processes (excitation, dielectronic recombination) to the spectrum intensity were investigated, and the dependence of these processes on T_e for $Mo^{29+}-Mo^{34+}$ ions was determined. The temperature T_e in Ref. [10] was determined from the data for He-like ions K VIII and Cl XVI and amounted to 685 ± 55 eV, and $T_e = 650$ eV was obtained as a result of theoretical analysis. In the present work, T_e is somewhat higher (700 ± 60 eV), but it agrees well, within the measurement error, with the data of Ref. [10]. An estimate by the comparison technique for a tungsten laser-produced plasma gave $T_e = 720 \pm 60$ eV. Transitions in the Ni-like ion and UTAs were observed in the spectra of tungsten ions in the spectral range $\Delta\lambda = 5.0-7.5$ Å (Fig. 5). Similar transitions took place in the Ni-like ion Ta XLVI [5].

To measure the electron temperature T_e, we used a method based on measuring the relative intensities of dielectronic satellites and resonance lines of H- and He-like ions [1–4]. The measurement accuracy directly affects the accuracy of estimating the heavy-element plasma temperature T_e. Some of

the characteristics of this method are discussed below and recommendations for measuring T_e with the highest accuracy are given. The method of measuring the relative intensities of dielectronic satellites has a number of advantages [4]. First of all, satellite lines corresponding to one reference line occupy a narrow spectral interval $\Delta\lambda/\lambda \approx 0.01$. This obviates the necessity of calibrating the spectral equipment. At the same time, the temperature dependences of the intensities of the reference line and dielectronic satellites are different, which is used to measure T_e. From the relative intensities of dielectronic satellites of the ions of different multiplicity, one can study the ionisation equilibrium, determine the presence of stationarity, or study the dynamics of plasma development. One of the advantages of the method is also the fact that the same states of the ions are responsible for the dielectronic satellite lines and for the resonance lines. This makes it possible to minimise the influence of inhomogeneities and the charge-state distribution of the plasma on the measurement results.

The indicated advantages of the method for measuring T_e by the relative intensities of dielectronic satellites make it indispensable for diagnostic purposes. However, when use is made of this method to achieve maximum measurement accuracy, a number of recommendations should be observed. This is especially true for the choice of elements that make up the materials of laser targets. The method is applicable for a plasma with a relatively low electron density ($N_e \ll 10^{23}$ cm^{-3}), for which the condition of coronal equilibrium is valid. Such an equilibrium, as a rule, is realised for a nanosecond laser-produced plasma, and multiply charged ions with an ionisation potential $I \approx (8-10)T_e$ are excited in the plasma [14]. This explained the choice of a magnesium target in Ref. [12], since at relatively low temperatures (T_e = 200–550 eV), H- and He-like ions are most abundant in the plasma. With an increase in the electron temperature, when $T_e \gg I/(8-10)$, the diagnostics of magnesium plasma from the spectra of H- and He-like ions becomes difficult because of the nonstationarity of the processes. The charge-state distribution of the plasma is mainly represented by fully ionised ions, and the spectra of H- and He-like ions give information not about the hottest phase of the plasma, but only about transient processes. To measure high temperatures ($T_e \approx$ 400–1000 eV) using the method employed, it is necessary to move to recording the spectra of elements with higher atomic numbers A_n and, therefore, with higher ionisation potentials: $I \approx 3-8$ keV. This motivated the choice of materials for laser targets in this work.

The choice of laser target elements is also due to another factor associated with the temperature dependence of the relative intensity of dielectronic satellites. The results of numerical calculations of the relative intensities of dielectronic satellites can be represented as [4]

$$i = i_d(T_m)\varphi(T_e)/\varphi(T_m), \quad (9)$$

where T_m is the temperature at which the resonance lines have maximum luminence; $i_d(T_m)$ is the relative intensity of the dielectronic satellites for $T_e = T_m$; and $\varphi(T_e)/\varphi(T_m)$ is a function of the temperature dependence of satellite intensities. For H- and He-like ions, the $i_d(T_m)$ values for each satellite line, the temperature T_m for each ion and element are tabulated and given in Ref. [4]. The temperature dependence for each ion is contained in the function $\varphi(T_e)/\varphi(T_m)$ and is calculated as a function of the T_e/T_m parameter for the ions of each element. An example of the function $\varphi(T_e)/\varphi(T_m)$ for the He-like ion Ti XXI is shown in Fig. 7.

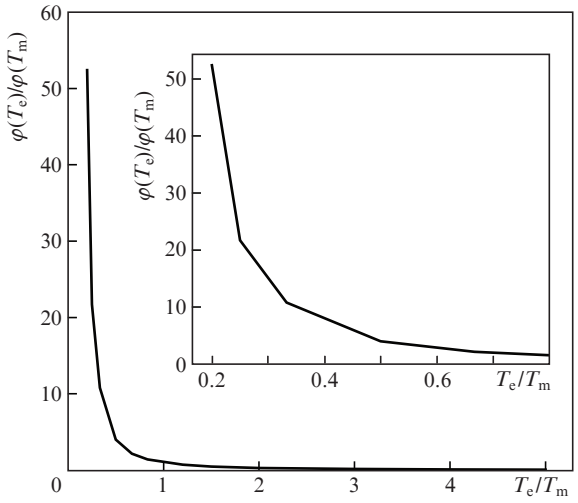

Figure 7. Temperature dependence of the function $\varphi(T_e)/\varphi(T_m)$ for the He-like ion Ti XXI, as well as a fragment of this dependence plotted on a magnified scale on the abscissa.

The values of the function $\varphi(T_e)/\varphi(T_m)$ for He-like ions with A_n = 16–22 are close, and at $T_e/T_m \geqslant 1$ they are actually equal. For $T_e/T_m \leqslant 0.5$, the function $\varphi(T_e)/\varphi(T_m)$ exhibits a sharp dependence on the temperature, and for $T_e/T_m \geqslant 1$ it hardly depends on it. Obviously, the $T_e/T_m \leqslant 0.5$ ratio should be chosen to improve the temperature measurement accuracy. This also determines the optimal choice of target elements for measuring T_e from the spectra of H- and He-like ions.

5. Conclusions

In this work, a new spectroscopic method of experimental evaluation of the electron temperature for the high-temperature plasma of heavy elements was further developed. The method is based on a comparison of the spectra under study with the spectra of a well-diagnosed laser-produced plasma of light elements with the structure of H- and He-like ions. The processing technique is minutely described and a detailed analysis of the spectra of light elements is carried out to determine the dependence of the electron temperature (T_e = 500–800 eV) on the laser pulse energy (E_L = 0.5–5 J). Recommendations are given for measuring T_e from the spectra of light elements with maximum accuracy. The comparison method was used to estimate the electron temperature of the plasma of heavy elements (Mo, W), whose X-ray spectra have a complex structure. For a laser-produced plasma of molybdenum, the temperature is T_e = 700 ± 60 eV, for a laser-produced plasma of tungsten, T_e = 760 ± 60 eV. These results can be used to estimate the electron temperature of the plasmas of heavy elements for other sources, for example, the plasma of high-power Z pinches.

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