Matter and Radiation at Extremes | RESEARCH ARTICLE | scitation.org/journal/mre

Precise wavelength measurements of potassium He- and Li-like satellites emitted from the laser plasma of a mineral target

Cite as: Matter Radiat. Extremes 6, 014402 (2021); doi: 10.1063/5.0019496
Submitted: 23 June 2020 • Accepted: 28 October 2020 •
Published Online: 7 December 2020

S. N. Ryazantsev,[1,2,a] I. Yu. Skobelev,[1,2] E. D. Filippov,[2,3] A. S. Martynenko,[2] M. D. Mishchenko,[1,2] M. Krůs,[4] O. Renner,[4,5,6] and S. A. Pikuz[1,2]

AFFILIATIONS

[1]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe Shosse 31, 115409 Moscow, Russia
[2]Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, 125412 Moscow, Russia
[3]Federal Research Center Institute of Applied Physics of the Russian Academy of Sciences, 46 Ulyanov Str., 603950 Nizhny Novgorod, Russia
[4]Laser Plasma Department, Institute of Plasma Physics of the CAS, Za Slovankou 1782/3, Libeň, 182 00 Prague, Czech Republic
[5]Department of Radiation and Chemical Physics, Institute of Physics of the CAS, Na Slovance 1999/2, 182 21 Prague, Czech Republic
[6]ELI-Beamlines, Institute of Physics of the CAS, Za Radnicí 835, 252 41 Dolní Břežany, Czech Republic

Note: This paper is part of the Special Issue on Atomic and Molecular Physics for Controlled Fusion and Astrophysics.
[a]**Author to whom correspondence should be addressed:** sergryaz@mail.ru

ABSTRACT

Atomic models of high-Z multicharged ions are extremely complex and require experimental validation. One way to do so is to crosscheck the predicted wavelengths of resonance transitions in He- and Li-like ions against precise spectroscopic measurements that use the spectral lines of H-like ions for spectra calibration; these reference data can be modeled with outstanding precision. However, for elements with Z of at least 15, it is quite difficult to create a hot dense plasma with a large concentration of H-like charge states. To mitigate this issue, the suggestion here is to use as laser targets particular minerals comprising elements with moderate (between 15 and 30) and low (less than 15) Z, with emission from the latter delivering perfect reference lines over a whole range of He- and Li-like moderate-Z emission under examination. This approach is implemented to measure the wavelengths of resonance transitions ($1snp \rightarrow 1s^2$ for $n = 2, 3$) in He-like K ions and their dielectronic satellites by irradiating plates of orthoclase ($KAlSi_3O_8$) with 0.5-kJ subnanosecond laser pulses. X-ray spectra of the laser-generated plasma contain the investigated lines of highly charged K ions together with precisely known reference lines of H-like Al and Si atoms. The K-shell spectral line wavelengths are measured with a precision of around 0.3 mÅ.

I. INTRODUCTION

X-ray spectroscopy is used widely for laser plasma diagnostics[1–3] and is suitable for investigating inertial thermonuclear plasmas. However, for this diagnostic tool to be applicable, one must know the spectroscopic parameters of various multicharged ions, among which the most important are the wavelengths of radiative transitions. Once measured, these values can be used not only to investigate inertial confinement fusion (ICF) but also across a range of fundamental (atomic physics, quantum electrodynamics, laboratory astrophysics) and applied (e.g., x-ray lithography, medical and biological radiography) fields.

For a given ion, a full set of spectroscopic properties can be obtained only by theoretical calculations. However, only an atomic system with one electron has an exact relativistic equation; the spectroscopic characteristics of ions with two or more electrons are obtained using approximate means such as variational methods or perturbation theory, and in neither case are accuracy estimates available *a priori* to help choose the most suitable calculation method. The only way to estimate the accuracy of the atomic calculations is to compare (i) the energy-level structure obtained using a particular method for a particular ion with (ii) the wavelengths of spectral lines emitted by this ion, a procedure that requires precise spectroscopic measurements.

The past 100 years have seen investigations aimed at observing, identifying, and measuring the wavelengths of spectral lines emitted by highly charged ions. This activity began with pioneering work on vacuum sparks[4] and then developed over the 1970s, 1980s, and 1990s with ICF-oriented investigations of hot plasmas in experiments involving, for example, tokamaks,[5] beam-foil setups[6] in heavy-ion accelerators, and electron-beam ions traps,[7] which allowed measurements to be made on a huge variety of highly charged ions including ultra-heavy ones such as H-like uranium.[8]

Since the 1970s, many spectroscopic measurements have also been made using laser facilities that are capable of generating high-intensity laser pulses. Even the moderate (by modern standards) facilities with intensities of no more than 10^{14} W/cm^2 yielded much experimental data on ions with low ionization potential, which exist in plasmas with sub-kiloelectronvolt temperature (e.g., see SPECTR-W3[9,10]). However, significantly more powerful kilojoule laser facilities[11–19] are required to investigate heavy ions, and spectroscopists have gained access to such facilities only recently. Large-scale facilities usually necessitate careful experimental planning because the allocated time (and sometimes even the number of laser pulses) is limited. Therefore, all numerical estimations and calculations should ideally be done in advance so that their results can be compared there and then with the experimental ones and the experimental conditions changed promptly if needed.

To obtain highly accurate wavelength measurements, obviously one must know the dispersion curve of any spectrometer being used, and this can be obtained by observing spectral lines with well-known wavelengths, known as reference lines. However, for a plasma of multicharged ions, the available data on x-ray reference lines are quite limited. Despite there being much experimental data on ions in low-charge states, the accuracy of the measured spectral-line wavelengths is either unavailable or so low that one cannot, for example, choose the suitable atomic-characteristic calculations for the investigated ion.

The best candidates as reference lines are the spectral lines of H-like ions. Calculated analytically considering quantum electrodynamics effects (e.g., see Ref. 20), the wavelengths of these lines are known with a precision better than that achievable experimentally. On one hand, the close ionization potentials of H-like and He-like ions of the same element means that the fraction of H-like ions in the plasma is sufficiently high in only a very narrow temperature range. On the other hand, the significant difference (approximately fourfold) in the He- and Li-like ionization potentials means that the concentration of He-like multicharged ions is high in a wide temperature range. A temperature that is sufficiently high for ionizing an Li-like ion (a process preceding the creation of the He-like state) is too low to ionize a He-like ion. Consequently, the spectral lines of He-like ions are the ideal reference data if their wavelengths have been measured sufficiently accurately based on, for example, the reference line positions of H-like ions.

Herein, we show how to determine with high accuracy the radiative spectrum of He-like K XVIII ions, including dielectronic satellites due to transitions in the Li-like K XVIII ions, by using spectral lines of Al XIII and Si XIV H-like ions as reference lines. Of course, this approach could be implemented for many other He-like ions, and the precisely measured positions of He-like-ion lines could be used as references for investigating ions with more-complicated energy-level structures with ground states corresponding to partially filled L and M shells.

II. OPTIMAL CONDITIONS FOR EXCITATION AND REGISTRATION OF REFERENCE AND MEASURED SPECTRAL LINES

The proposed experiment is aimed at measuring the x-ray spectral-line wavelengths emitted by various K ions. For such measurements, one must create the investigated multicharged ions in excited states and then register their emission via a calibrated spectrometer. The feasibility of generating the required multicharged ions is determined by the parameters of the lasers used, in particular their energy and intensity, and the required high-precision measurements can be made by using a focusing spectrometer with spatial resolution (FSSR)[21–23] with unique properties.

As mentioned above, precise wavelength measurements require the spectrometer dispersion curve to be known exactly. Generally speaking, it can be obtained analytically by using geometrical optics, but such calculations involve a cumbersome procedure to obtain various parameters associated with the relative positions of the spectral source (the plasma), dispersive crystal, and detector. Even if the dispersion curve is derived exactly for the ideal experimental geometry, unavoidable uncertainties associated with the spectrometer alignment introduce substantial errors. Based on much research experience, the absolute accuracy of the wavelength measurements cannot better several tens of milliångstroms unless additional spectral references (distinct lines with well-known wavelengths) are used.

The error can be reduced significantly (down to several milliångstroms) by combining the calculated dispersion curve with a reference line, thereby avoiding one of the main sources of measurement error, namely determining inaccurately the absolute spectral-line positions on the detector. A further improvement in measurement accuracy (reaching several tenths of a milliångstrom) results from using at least three reference lines, this being because, for the chosen spectrometer observation range, the dispersion curve can be fitted very precisely (with error less than 0.1 mÅ) with a parabolic function whose coefficients are determined easily from three reference lines. In that case, the accuracy of the wavelength measurement is independent of FSSR parameters such as the dispersive-crystal interplanar spacing and geometry (degree of sphericity) and is affected only by the signal-to-noise ratio of the detected signal and the natural width of the crystal rocking curve,[23] which results in additional line broadening. For example, such an approach has been used for high-precision measurements of the spectral-line wavelengths of Kr multicharged ions.[24]

Herein, we propose using transitions in the H-like ions Al XIII and Si XIV as reference lines. Being known accurately, they should allow us to obtain the radiation spectra of the He-like K XVIII ion, including dielectronic satellites that arise because of transitions in the Li-like K XVII ion (hereinafter referred to as Li-like satellites), with accuracy no worse than 0.6 mÅ. For that purpose, targets with a complex chemical composition were irradiated by laser pulses. The plasma kinetic calculations presented herein show that all essential lines, both investigated and reference ones, should be excited effectively in the plasma at the same electron temperature, thereby making the proposed experiment feasible. Note also that there is no blending of the measured lines and those emitted by the reference material.

A highly abundant feldspar, namely $KAlSi_3O_8$ (microcline or orthoclase[25]), can be used as the laser target. The radiation spectrum of the plasma, which comprises the aforementioned elements, is

shown in Fig. 1. The calculations were performed using the PrismSPECT radiative-collision code[26] using the steady-state approximation for the electron temperature T_e = 1000 eV and the electron density $N_e = 10^{21}$ cm^{-3}, i.e., the critical electron density for the laser wavelength of 1 μm. The temperature was chosen to provide comparable intensities of the measured and reference spectral lines.

The dispersive elements (spherically bent crystals) of the x-ray spectrometer that is used may reflect radiation effectively in different diffraction orders, so Fig. 1 shows how the spectral-line intensities depend on $n\lambda$ (λ - *wavelength*) for n = 1–5. The spectrometer was aligned to observe wavelengths between λ_1 and λ_2 in first-order reflection, and also spectra emitted between $\lambda_1 \times n$ and $\lambda_2 \times n$. This is very important because it extends significantly the range of applicability of the reference lines. If the measured and reference lines are registered in different orders of reflection, then one must consider the difference between refraction indices for significantly different wavelengths. This is usually done by including an effective interplanar distance $(2d)_n$ that depends on the reflection order (e.g., see Ref. 27). Figure 1 shows that the lines of K and the reference ions can be registered simultaneously in different spectral ranges (as mentioned already). Two cases are considered below: the first anticipates an application involving an α-quartz crystal, and the second a mica crystal.

A. Spectrometer with α-quartz crystal

Consider a spherically bent α-quartz crystal with Miller indices (100) ($2d$ = 8.512 Å), radius of curvature R = 150 mm, located 626 mm from the plasma source, and aligned according to the one-dimensional[28] scheme with a central wavelength of 6.55 Å. In that case, the wavelength range of 5.8 Å–7.17 Å [see Fig. 2(a)] would be observed, and the corresponding length of the spectrum on a detector would be 29 mm. The precision of measuring the spectral-line positions is limited by detector pixel size. Widely used image plates (such as TR by Fujifilm) can be scanned with a spatial resolution of up to 25 μm, giving the accuracy of wavelength measurements as 1 mÅ. The accuracy improves to 0.5 mÅ when using a CCD camera with a pixel size of 13.5 μm, and to 0.26 mÅ for a fine-grain x-ray film. For K spectral lines, the accuracy would be two times better given that in the proposed scheme they undergo second-order reflection. Figure 2(a) shows that high-precision data can be obtained for the $1s2p \rightarrow 1s^2$ and $1s3p \rightarrow 1s^2$ resonance lines of K XVIII ions and their dielectronic satellites.

B. Spectrometer with mica crystal

Consider a spherically bent mica crystal ($2d$ = 19.9149 Å) with radius of curvature R = 150 mm, located 440 mm from the plasma source, and aligned according to the two-dimensional[28] scheme with a central wavelength of 13.5 Å. In that case, the wavelength range of 11.65 Å–15.11 Å [see Fig. 2(b)] would be observed.

The corresponding size of the spectrum on a detector is 57 mm, and the accuracy of measuring the spectral-line positions is again limited by the detector pixel size. With an image plate, the wavelength measurement accuracy is 1.5 mÅ for first-order reflection, improving to 0.8 mÅ with a CCD camera with a pixel size of 13.5 μm, and to 0.36 mÅ with a fine-grain x-ray film. The accuracy for K spectral lines would be four times better (and approximately that with the quartz crystal) given that in the proposed scheme they undergo fourth-order reflection. Figure 2(b) shows that high-precision data can be obtained for the $1s2p \rightarrow 1s^2$ and $1s3p \rightarrow 1s^2$ resonance lines of K XVIII ions and their dielectronic satellites.

III. PREFERABLE LASER PARAMETERS

As mentioned above, the measured and reference spectra have close intensity values under steady-state conditions with temperature T_e = 1000 eV, thereby facilitating high-precision measurements. Results of time-dependent plasma kinetics calculations using PrismSPECT show that the plasma ionization becomes steady after approximately 200 ps, which means that the

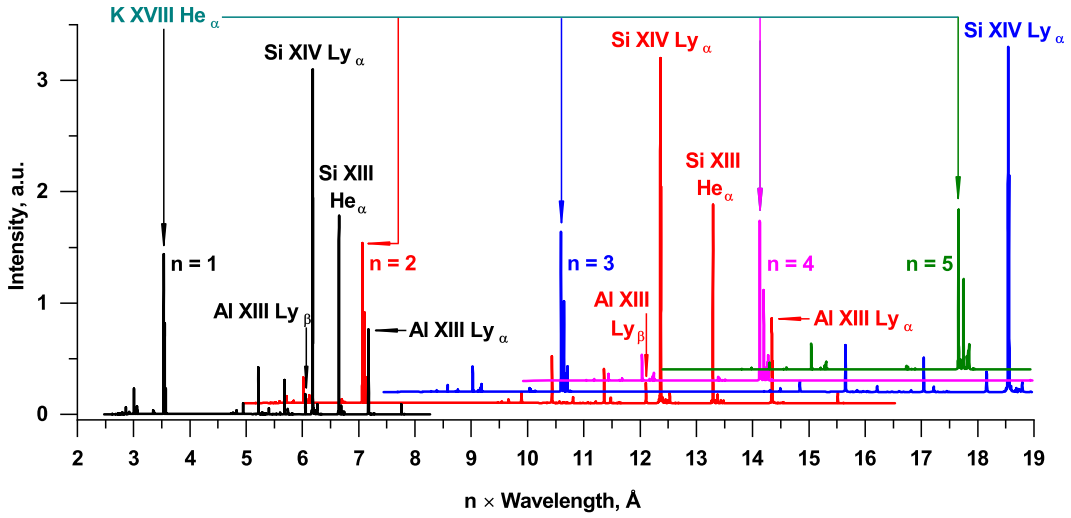

FIG. 1. Radiation spectrum of $KAlSi_3O_8$ plasma in x-ray wavelength range calculated using steady-state approximation for electron temperature T_e = 1000 eV and electron density $N_e = 10^{21}$ cm^{-3}. Intensity vs $n\lambda$ is shown for reflection order n = 1–5 of diffraction crystals (each order is associated with its own color).

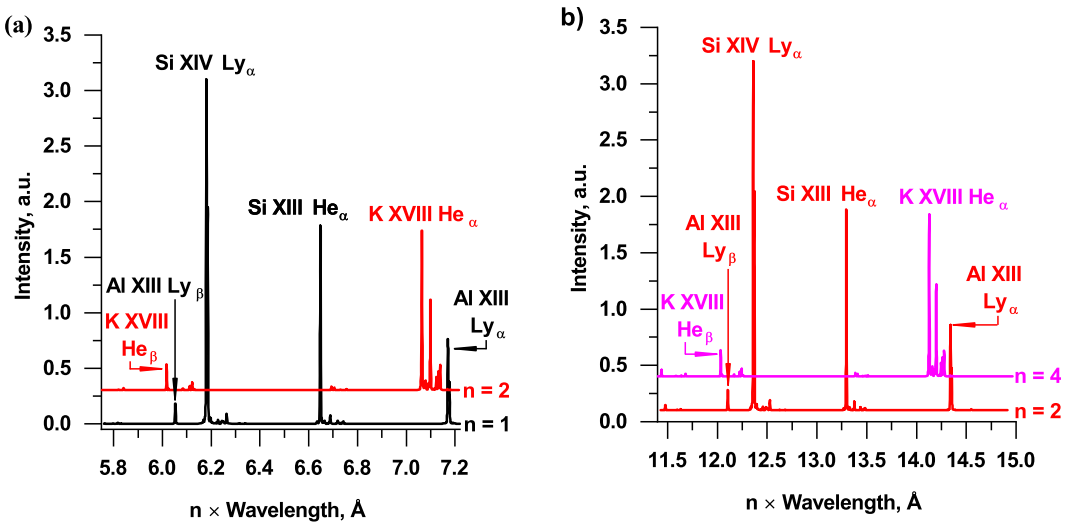

FIG. 2. Spectrum of radiation emitted by $KAlSi_3O_8$ plasma in wavelength range of (a) 5.8–7.2 Å and (b) 11.6–15.1 Å calculated for conditions from Fig. 1. Intensity vs $n\lambda$ is shown for reflection order n = (a) 1 and 2 and (b) 2 and 4. Each order is associated with its own color.

optimal way to create the plasma is to use subnanosecond laser pulses with an on-target intensity of approximately 10^{16} W/cm^2. Filters that block radiation in the ultraviolet and visible parts of the electromagnetic spectrum are usually used during the experiments. These filters are also not fully transparent for soft x rays, and their opacity is higher for the softer reference spectra. Therefore, a slightly lower plasma temperature (600–800 eV) may be required to adjust the intensities of the registered lines, thereby facilitating more-moderate laser intensities of between 10^{15} W/cm^2 and 10^{16} W/cm^2. Note that for a 100-μm laser focal spot, the laser pulse energy should be approximately 200 J.

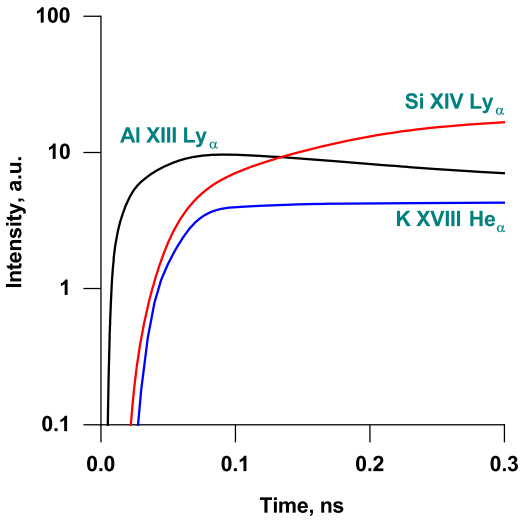

FIG. 3. Temporal dependencies of intensities of spectral lines emitted by Al, Si, and K ions. The curves were obtained using a time-dependent kinetic model for a plasma with electron temperature T_e = 1000 eV and $N_e = 10^{21}$ cm^{-3}. In the initial state, all ions are singly ionized.

Regarding the possibility of using lasers with shorter pulse duration for plasma generation, note that the plasma ionization would then not become steady. However, if the temporal intensity dependencies of the investigated and reference lines are quite similar, then even a non-steady-state plasma could be used for x-ray spectral measurements.

Figure 3 shows the results of calculations performed with a time-dependent kinetic model for a plasma with electron temperature T_e = 1000 eV, electron density $N_e = 10^{21}$ cm^{-3}, and containing only singly ionized ions at time $t = 0$. As shown, steady ionization is reached after 0.2 ns, but before then the intensities of all relevant lines have comparable values after only 30 ps–40 ps. This means that not only subnanosecond but also picosecond lasers can be used for the described experiment.

IV. EXPERIMENTAL IMPLEMENTATION

The feasibility of the discussed experiment was demonstrated at the PALS laser facility.[29] In the experiment, a laser pulse with a duration of 480 ps and a full energy of 600 J was focused on the surface of a flat and approximately 1-mm-thick orthoclase plate to a spot with a diameter of 100 μm. The indicated laser parameters correspond to intensity $I = 1.5 \times 10^{16}$ W/cm^2. The spectra were obtained using an α-quartz crystal (100) spherically bent to a radius of 150 mm. The FSSR was installed close to the target normal to ensure symmetry of the observed line broadening due to the macroscopic Doppler shift induced by accelerated ions. Fuji IX80 x-ray film[30] covered by a 1.5-μm-thick Al foil to avoid exposure from visible light was used as an x-ray detector. The recorded spectra were digitized using an Epson V700 scanner with a resolution of 4800 dpi (pixel size 5.29 μm). The recorded spectrum is shown in Fig. 4.

The set of observed lines agrees exactly with Fig. 2(a) and contains three H-like ion spectral lines, namely Ly$_\alpha$ (λ = 7.170 908 Å),

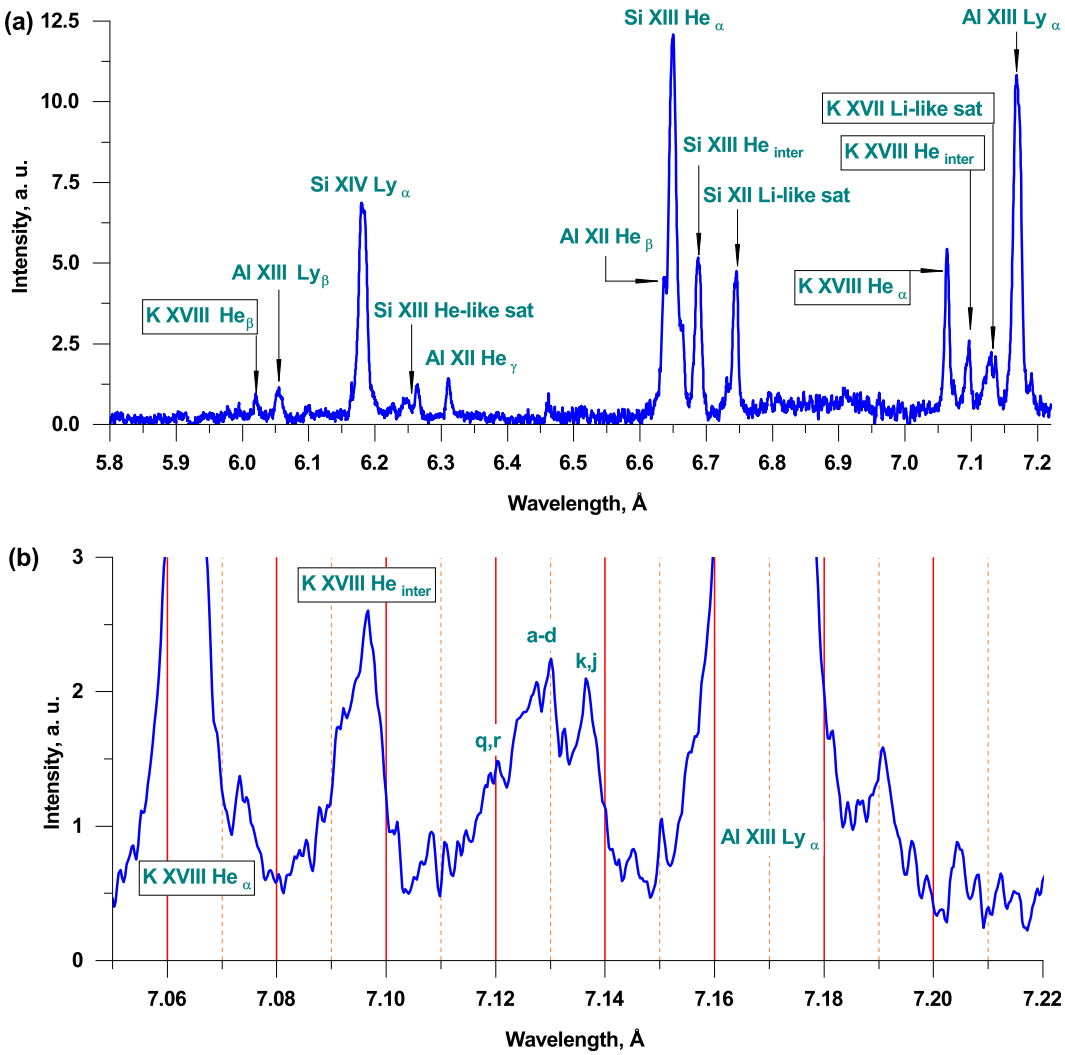

FIG. 4. (a) Spectrum of x-ray radiation emitted during irradiation of orthoclase crystal by (600-J, 480-ps) laser pulse. Indicated are the most intense spectral lines corresponding to the radiative transitions in multicharged ions of Si, Al, and K (K spectral lines are observed in the second order of reflection). (b) Enlarged region with three groups of KHe_α line satellites corresponding to transitions in Li-like ion K XVII. The upper and lower configurations for each group of satellites are listed in Table I.

Ly_β (λ = 6.052 53 Å) of Al XIII, and Ly_α (λ = 6.180 428 Å) of Si XIV, thereby allowing us to obtain the exact dispersion curve and measure the positions of the He-like K-ion spectral resonance lines. The wavelengths indicated in parentheses are theoretical values calculated for isolated ions. In a plasma, their observed positions can be shifted by the Doppler effect, asymmetrical Stark broadening, shape distortion by plasma, or laser satellites. For the last of these, higher laser intensity is required. Stark broadening is symmetrical for the given experimental values of electron density and does not cause any shifts. The Doppler-effect influence can be significant, but the shifts should be the same for all observed lines because the investigated and reference ions move similarly. Therefore, none of these effects can affect the measurement results.

The Li-like satellites comprising three overlapping peaks correspond to different groups of transitions in Li-like K ions, which are labeled according to the notation introduced in Ref. 31. All the measured spectral-line positions are listed in Table I. The values were obtained under the assumption that the observed peaks have

TABLE I. Measured wavelengths of transitions in He- and Li-like K ions. Li-like satellites are labeled in accordance with notation introduced in Ref. 31.

Line name [transition(s)]	λ (mÅ)	$\Delta\lambda$ (mÅ)
K He_β $(1s3p\,^1P_1 \rightarrow 1s^2\,^1S_0)$	3010.26	0.6
K He_α $(1s2p\,^1P_1 \rightarrow 1s^2\,^1S_0)$	3532.55	0.6
K He_{inter} $(1s2p\,^3P_{2,1} \rightarrow 1s^2\,^1S_0)$	3549.35	0.6
q, r $(1s2p[^1P]2s^2P \rightarrow 1s^22s^2S)$	3560.87	0.6
a–d $(1s2p^2\,^2P \rightarrow 1s^22p^2P)$	3565.06	0.6
k, j $(1s2p^2\,^2D \rightarrow 1s^22p^2P)$	3569.1	0.6

Gaussian shape. The measurement accuracy is considered as being twice the pixel width at the center of a particular peak. The Li-like satellites comprise three overlapping peaks corresponding to different groups of transitions in Li-like K ions, thus the measured wavelengths correspond to the group centers.

V. CONCLUSION

The wide abundance of different mineral targets of various chemical compositions opens broad possibilities for extensive application of the approach described herein. Our view is that the first targets to be investigated should be those that facilitate high-precision data for multicharged He- and Ne-like ions with fully filled inner shells. Such ions exist in a wide temperature range and have a rather simple spectral structure. The measured wavelengths of those spectral lines could then be used as references in studies of the spectral emission from other ions that have more-complicated emission features.

ACKNOWLEDGMENTS

The reported study was funded by RFBR, project number 19-32-60050, and the Ministry of Education, Youth, and Sports of the Czech Republic [Project No. LM2018114 (PALS Infrastructure)], and it was conducted within the framework of the State Assignment of the Ministry of Science and Higher Education to JIHT RAS. The authors thank M. Červeňák for preparing the targets, and they thank the staff of the PALS laser facility for providing the opportunity to perform the described experiment.

REFERENCES

[1]C. Kaur, S. Chaurasia, A. A. Pisal *et al.*, "X-ray and ion emission studies from subnanosecond laser-irradiated SiO_2 aerogel foam targets," Laser Part. Beams **35**, 505–512 (2017).
[2]A. Y. Faenov, T. A. Pikuz, G. A. Vergunova *et al.*, "Ultra-bright keV X-ray source generated by relativistic femtosecond laser pulse interaction with thin foils and its possible application for HEDS investigations," Laser Part. Beams **35**, 450–457 (2017).
[3]C. Deutsch, H. B. Nersisyan, and A. Bendib, "Diagnosing dense and magnetized plasmas irradiated by a petawatt laser," Laser Part. Beams **34**, 61–71 (2016).
[4]H. Flemberg and Z. Ark, Ark. Mat. Astr. Fys **28A**(18), 1 (1942).
[5]P. Beiersdorfer, M. Bitter, S. von Goeler *et al.*, "Experimental study of the x-ray transitions in the heliumlike isoelectronic sequence," Phys. Rev. A **40**, 150–157 (1989).
[6]E. Träbert, "Beam–foil spectroscopy—Quo vadis?," Phys. Scr. **78**, 038103 (2008).
[7]P. Beiersdorfer, "A 'brief' history of spectroscopy on EBIT," Can. J. Phys. **86**, 1–10 (2008).
[8]C. Brandau, C. Kozhuharov, A. Müller *et al.*, "First dielectronic recombination measurements with H-like uranium," Radiat. Phys. Chem. **75**, 1763–1766 (2006).
[9]I. Y. Skobelev, P. A. Loboda, S. V. Gagarin *et al.*, "The Spectr-W^3 database on the spectroscopic properties of atoms and ions," Opt. Spectrosc. **120**, 507–514 (2016).
[10]I. Y. Skobelev, P. A. Loboda, A. Y. Faenov *et al.*, "Spectr-W^3 online database on atomic properties of multicharged ions," J. Phys.: Conf. Ser. **653**, 012022 (2015).
[11]W. Zheng, X. Wei, Q. Zhu *et al.*, "Laser performance upgrade for precise ICF experiment in SG-III laser facility," Matter Radiat. Extremes **2**, 243–255 (2017).
[12]S. Weber, S. Bechet, S. Borneis *et al.*, "P3: An installation for high-energy density plasma physics and ultra-high intensity laser–matter interaction at ELI-beamlines," Matter Radiat. Extremes **2**, 149–176 (2017).
[13]J. P. Zou, C. L. Blanc, P. Audebert *et al.*, "Recent progress on LULI high power laser facilities," J. Phys.: Conf. Ser. **112**, 8–12 (2008).
[14]B. C. Stuart, J. D. Bonlie, J. A. Britten *et al.*, "The titan laser at LLNL," in *Optics InfoBase Conference Paper* (IEEE, 2006), pp. 4–5.
[15]H. Shiraga, S. Fujioka, M. Nakai *et al.*, "Fast ignition integrated experiments with Gekko and LFEX lasers," Plasma Phys. Control. Fusion. **53**, 124029 (2011).
[16]V. Bagnoud, B. Aurand, A. Blazevic *et al.*, "Commissioning and early experiments of the PHELIX facility," Appl. Phys. B **100**, 137–150 (2010).
[17]I. Musgrave, M. Galimberti, A. Boyle *et al.*, "Review of laser diagnostics at the Vulcan laser facility," High Power Laser Sci. Eng. **3**, 1–10 (2015).
[18]V. V. Lozhkarev, G. I. Freidman, V. N. Ginzburg *et al.*, "Compact 0.56 Petawatt laser system based on optical parametric chirped pulse amplification in KD*P crystals," Laser Phys. Lett. **4**, 421–427 (2007).
[19]T. Gong, L. Hao, Z. Li *et al.*, "Recent research progress of laser plasma interactions in Shenguang laser facilities," Matter Radiat. Extremes **4**, 055202 (2019).
[20]V. A. Boyko, V. G. Pal'chikov, I. Y. Skobelev *et al.*, *Spectroscopic Constants of Atoms and Ions: Spectra of Atoms with One or Two Electrons* (Begell House, 1994).
[21]M. A. Alkhimova, I. Y. Skobelev, A. Y. Faenov *et al.*, "Accounting for the instrument function of crystal spectrometers operating in many reflection orders in the diagnostics of laser plasma from its continuum spectrum," Quantum Electron. **48**, 749–754 (2018).
[22]A. Y. Faenov, S. A. Pikuz, A. I. Erko *et al.*, "High-performance x-ray spectroscopic devices for plasma microsources investigations," Phys. Scr. **50**, 333–338 (1994).
[23]M. S. del Rio, L. Alianelli, A. Y. Faenov *et al.*, "X-ray reflectivity of curved alpha-quartz crystals," Phys. Scr. **69**, 297–302 (2004).
[24]V. M. Dyakin, I. Y. Skobelev, A. Y. Faenov *et al.*, "Precision measurements of the wavelengths of spectral lines of multiply charged krypton and argon ions formed in a gas target heated by laser radiation," Kvantovaya Elektron. **24**, 713–714 (1997).
[25]D. S. Coombs, "Ferriferous orthoclase from Madagascar," Mineral. Mag. J. Mineral. Soc. **30**, 409–427 (1954).
[26]J. J. Macfarlane, I. E. Golovkin, P. R. Woodruff *et al.*, "Simulation of the ionization dynamics of aluminum irradiated by intense short-pulse lasers," in *Inertial Fusion Science and Applications 2003 (IFSA 2003) State Art 2003*, edited by B. A. Hammel, D. D. Meyerhofer, J. Meyer-ter-Vehn, and H. Azechi (American Nuclear Society, La Grange Park, IL, 2004), p. 457.
[27]O. Renner and F. B. Rosmej, "Challenges of x-ray spectroscopy in investigations of matter under extreme conditions," Matter Radiat. Extremes **4**, 024201 (2019).
[28]B. K. F. Young, A. L. Osterheld, D. F. Price *et al.*, "High-resolution x-ray spectrometer based on spherically bent crystals for investigations of femtosecond laser plasmas," Rev. Sci. Instrum. **69**, 4049–4053 (1998).
[29]K. Jungwirth, A. Cejnarova, L. Juha *et al.*, "The Prague Asterix Laser System," Phys. Plasmas **8**, 2495–2501 (2001).
[30]Fujifilm, Fujifilm industrial x-ray film, https://www.fujifilm.com/products/ndt/ix-film/#IX80.
[31]A. H. Gabriel, "Dielectronic satellite spectra for highly-charged helium-like ion lines," Mon. Not. R. Astron. Soc. **160**, 99–119 (1972).