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Spectral Catalogue of Kr Optical Lines for the Development of Diagnostics for Fusion Plasmas

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Abstract

We made an inventory of krypton spectra over the wavelength range 3700 - 6000 Å for the development of fusion plasma diagnostics. The measurements were performed using a Steinheil prism spectrometer on the LLNL low energy electron beam ion trap (EBIT II). With the electron energy from 150 eV to 17000 eV, we recorded low ionization stages together with a number of magnetic dipole transitions from higher charge states. In total, we observed over 80 lines, of which about 70% of the lines have not been listed in the literature. This measurement established a baseline for future extension using spectrometers with very high resolution. As an example, we present the Kr spectra from 3770 Å to 3900 Å measured with a transmission grating spectrometer that has a resolving power of about 15000. Among the 41 lines observed, only 6 lines have been listed in the databases.

Introduction

Optical transitions offer excellent opportunities for plasma diagnostics given the state-of-the-art in optical instruments that may include light fiber optics, laser tagging, and solid-state optical elements. For example, the "laser tagging" technique uses a laser to excite a resonance transition and detect the induced fluorescence radiation. It has been used to measure ion density, transport and turbulence in various plasmas [1- 6]. In tokamak and stellarator fusion plasmas, optical spectroscopy is of particular interest following the development of radiative cooling scenario [7]. Due to the range of temperatures and densities in the edge and divertor region, optical lines from impurities are abundant, and optical diagnostics of the edge plasma parameters, such as impurity density fluctuations, radiation and transport are fundamentally important to understand the confinement of the fusion plasmas.

Noble gas impurities such as neon, argon and krypton, which are often used as radiation media in the edge and divertor plasma to establish a radiative cooling cushion [7], can also provide candidate transitions for the diagnostics. Atomic modeling using the HULLAC code has shown many potential transitions from these elements that may be used to diagnose plasma using the laser-induced fluorescence technique [5, 8]. Unfortunately, the atomic data for optical transitions of those elements are largely unknown. As will be shown in this paper, most lines have never been identified.

Our optical measurements used the low-energy electron beam ion trap (EBIT II) at Lawrence Livermore National Laboratory. EBIT provides an ideal source for spectral measurement of lines relevant to fusion plasma [9, 10]. Compared to glow discharges, which have been used to obtain most of the existing optical spectral data for Ne, Ar and Kr [11-13], the EBIT source provides the appropriate charge states found in fusion plasmas at densities comparable to that in laboratory fusion plasmas. Moreover, EBIT has a well-confined ion source that allows steady state measurement of ion spectra even at low electron energies (150 eV or higher).

Previous measurements of the visible spectrum of highly charged ions in LLNL EBIT have been reported in [14, 15]. Our measurements of neon and argon using prism spectrometer have been reported in [16]. In this paper, we present the results of Kr measurements with both prism and transmission grating spectrometer.

Experiment setup

The setup of the spectrometers is illustrated in figure 1. The Steinheil prism spectrometer has one prism configuration that uses two lenses. The collection and the focus lens have 13 cm and 7.6 cm diameters, respectively. The system magnification is 0.64. The resolving power of the prism spectrometer is moderate: $\lambda/\Delta\lambda$ is from 1000 at 5500 Å to 4000 at 3800 Å. The transmission grating spectrometer (TGS) has a high transmission efficiency (approx. 94% at 351 nm), large quartz grating with 15.2 cm diameter and 0.64 cm thickness [17]. Both the collection lens and focus lens is 13 cm in diameter and 40 cm in focal length. The resolving power of the TGS system is about 15500 at 3875 Å as measured with a standard platinum lamp and a 30 μm slit on a tabletop set up.

The line-of-sight of the spectrometer looks directly into the trap region. In the trap region, the mono-energetic electron beam has a diameter of about 60 μm, and it was used as entrance slit of the spectrometer. Spectra from both spectrometers were recorded using a cryogenically cooled CCD camera. The camera has 1024×1024 pixels with each pixel 24 $\mu m \times 24$ μm in size. During the data acquisition, CCD pixels in the non-dispersion direction were binned to 256 to enhance the signal-to-noise ratio and to reduce the signal read out time. Exposure time for each spectrum was 20 min, which produced reasonably intense spectra without severe accumulation of background signal. The background signals are mostly spikes resulting from energetic particles (presumably cosmic rays) striking the CCD. Fortunately, after data acquisition, these background signals can be taken out using software, since they tend to be in a single pixel and very intense. Figure 2 shows a typical raw spectral image taken on the CCD camera.

The noble gases were injected into the trap using a differentially pumped gas injector. There are several sources of the background lights in the drift tube. The ion gauge, electron gun and emission from the residual ions. To reduce the background signals, the ion gauge in the upper chamber of the drift tube was switched off. Slightly lower voltage (5.5 volts) and current (0.45 mA) were applied to the electron gun filament, compared to the normal operation condition where the filament has 6 volts and 0.5 mA.

The wavelength calibration of the prism spectrometer used several sources, including high-pressure scandium and mercury lamps on a desktop setting, and nitrogen injection on the EBIT II. To ensure reproducibility, the same spectrometer setup position was kept during the measurements. However, there were up to 2 pixels shifts (about 50 μm) in the spectrograph position over the period of a few days, probably caused by the mechanical vibration of the surrounding area. In order to eliminate this shift, lines with well-known measured wavelength from singly or doubly ionized ions [18] were used to do the *in situ* wavelength cross-calibration.

For the TGS system, we used lines from singly and doubly ionized Ne, Ar and Kr for the *in situ* calibration following the gas injections. A small spectral shift was also observed during the measurement due to changes in the surrounding conditions such as temperature [19]. These effects have been taken into account in the data analysis.

Data

Kr spectra were taken using the prism spectrometer at different assigned electron beam energies. Each beam energy was chosen so that we can scan though each ionization stage of Kr: we started from the lowest possible beam energy, 150 eV and stepped up to 17000 eV. Because Kr gas flows continually into the trap, lines of neutral Kr and many low charge-states (Kr I to Kr V) are seen in the spectra.

Kr spectra at different electron beam energies are shown in Figure 3. Once the electron energy exceeds the ionization potential of the ions, we expect to see the lines from that ionization state. Altogether, 11 optical lines of ionization states from Kr X to Kr XXIII have been observed. A prominent feature of the Kr spectra is the line at 3842±2.8 Å. It first appears at the electron energy 950 eV that associates with Kr XXIII. This line is the well-known magnetic dipole transition of Si-like Kr ($3s^2 3p^2\ {}^3P_1$ - ${}^3P_2$), which has been observed in tokamak fusion plasma at 3840.9 ± 0.3 Å [20] as well as EBIT devices at 3840 Å [21, 22] although theory predicts this line to be at 3832 Å [23]. Another strong line at 4029 ± 2.9 Å was observed at the electron energy of 750 eV and it is identified to be of Kr XIX. This agrees with the wavelength of 4627 Å measured in a previous measurement made in LLNL EBIT [14], where its preliminary identification was given as $3p^5 3d^1\ {}^3P_2 - {}^3P_1$. The atomic structures for the rest of the high charge-state lines have not yet been identified. Table 1 is the summary of lines including the identified charge states, the wavelength and the electron beam energy.

Additional spectral information is given in Figure 4 for the 1150 eV electron beam energy, which includes most of the low charge-state lines. The wavelength of the lines is listed together with their references from the standard database [18, 24]. Most of the published list of the low charge-state Kr spectral lines comes from the intensive and thorough investigations in 1930s by Humphreys et al [13, 25] using vapour lamps (Geissler tubes). As is shown, a large percent of the lines are not yet listed in published standard lists such as in [18, 24].

With the high resolution TGS, many more Kr lines are observed. An example spectrum is shown in Figure 5, taken at electron beam energy of 3100 eV. Note that the wavelength coverage of the TGS spectrum, in Figure 5, is less than one fifteenth of that in Figure 4 taken with the prism spectrometer. The magnetic dipole transition of Si-like Kr XXIII is measured to be at 3840.9 ± 0.2 Å. In total, only 6 lines of the 41 observed have been listed in the standard database [24].

Conclusion

We presented krypton optical spectral measurements using both prism and transmission spectrometers in LLNL EBIT II. Our broadband spectral survey reveal a large number of spectral lines that are not yet listed in standard databases, and even more new lines have been recorded with a high resolution transmission grating spectrometer. These optical lines are potential candidates for fusion diagnostics using techniques such as laser tagging in edge and divertor region, especially following gas injection in radiative cooling experiments.

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Reference

[1] J. Amorim, G. Baravian and J. Jolly, J. Phys. D: Appl. Phys. **33**, R51 (2000)

[2] X.-P. Huang, J. J. Bollinger, T. B. Mitchell, W. M. Itano and D. H. E. Dubin, Phys. Plasmas **5**, 1656 (1998)

[3] F. Anderegg, X.-P. Huang, E. Sarid and C. F. Driscoll, Rev. Sci. Instrum. 68, 2367 (1997)

[4] F. Orsitto, M. Borra, F. Coppotelli, G. Gatti and E. Neri, Rev. Sci. Instrum. **70**, 921 (1999)

[5] C. H. Skinner, S. J. Zweben, F. M. Levinton, J. M. McChesney, Rev. Sci. Instrum. **70**, 917 (1999)

[6] S. Barshkin and J.O. Stone, "Atomic Energy Levels and Grotrian Diagrams" (North-Holland, Amsterdam, 1975)

[7] D. Post, G. Janeschitz, A. Kukushkin, H. Pacher, M. Sugihara, J. Mandrekas, and W. Stacey, Phys. Plasmas **4**, 2631 (1997)

[8] J. M. McChesney, K.I. Lippman, W. Goldstein, and K.B. Fournier, Rev. Sci. Instrum. **66**, 600 (1995)

[9] M. A. Levine, R. E. Marrs, J. R. Hederson, D. A. Kannp, and M. B. Schneider, Physica Scripta **T22**, 157 (1988)

[10] P. Beiersdorfer, G.V. Brown, H. Chen, M.F. Gu, S.M. Kahn, J.K. Lepson, D.W. Savin,S.B. Utter, "Laboratory Data for X-Ray Astronomy", at the Workshop on "Atomic Data Needs for X-ray Astronomy", NASA's Goddard Space Flight Center, December 16-17,1999 Conference proceedings, http://heasarc.gsfc.nasa.gov/docs/heasarc/atomic/

[11] C. Norlen, Physica Scripta, **8,** 249 (1973)

[12] W. Persson, Physica Scripta, **3,** 133 (1971)

[13] C. J. Humphreys, Phys. Rev **47**, 712 (1935)

[14] J. R. Crespo Lopez-Urrutia, P. Beiersdorfer, K. Widmann and V. Decaux, Physica Scripta, T**80**, 448 (1999)

[15] S. B. Utter, P. Beiersdorfer, J. R. Crespo Lopez-Urrutia, and E. Träbert, Rev. Sci. Instrum. **70**, 288 (1999)

[16] H. Chen, P. Beiersdorfer, and S. Utter, to be submitted to Physica Scripta

[17] H. T. Nguyen, B. W. Shore, S. J. Bryan, J. A. Britten, R. D. Boyd, and M. D. Perry. Optical Letters. **22,** 142 (1997)

[18] "CRC handbook of chemistry and physics: a ready-reference book of chemical and phyical data" editor-in-chief, David R. Lide. 73rd ed. Publisher Boca Raton, FL: CRC Press (1992)

[19] S. B. Utter, P. Beiersdorfer, and G. V. Brown, Phys. Rev. A **61**, 030503-1 (2000)

[20] J. R. Roberts, T. L. Pittman, J. Sugar, V. Kaufman, and W. L. Rowan, Phys Rev. A **35,** 2591 (1987)

[21] F. G. Serpa, E. W. Bell, E. S. Meyer, J. D. Gillaspy and J. R. Roberts, Physical Review A **55,** 1832 (1997)

[22] E. Träbert, S. B. Utter and P. Beiersdorfer, Physics Letters A, 1999 (in press)

[23] V. Kaufman and J. Sugar, J.Phys. Chem. Ref. Data, vol **15,** No. 1 (1986)

[24] "NIST Atomic Spectra Database", Web based Version 2.0, http://physics.nist.gov) (2000)

[25] T. L de Bruin and C. J. Humphreys and Wm. F. Meggers, Bur. Standards, J. Research **11,** 409 (1933)

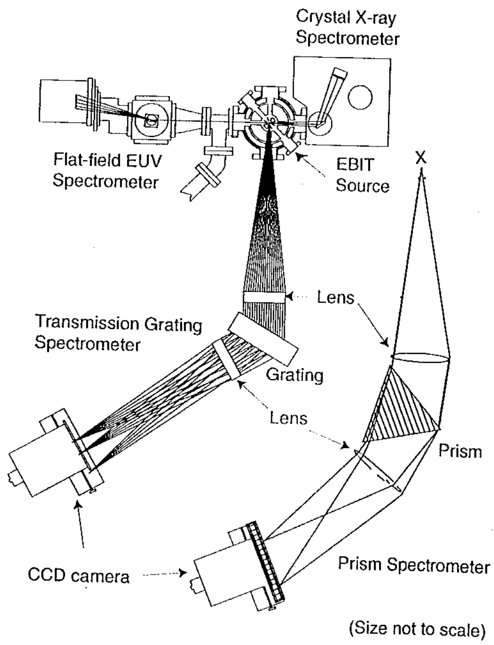

Figure 1. Schematic view of the experimental set up. The positions are shown relative to EBIT including the transmission grating spectrometer and Prism spectrometer (interchangeable), as well as the EUV and x-ray spectrometer on EBIT.

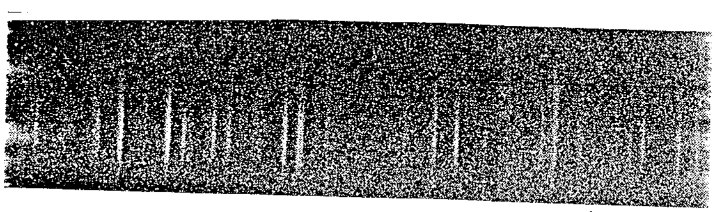

Figure 2. A raw TGS Kr spectral image taken by the CCD camera (1024 $\times$ 256 pixels). The white dots in the background are from energetic particles (cosmic rays).

Table 1. Lines of highly charged Kr from prism spectrometer.

Ion	I_p (eV)	E_{beam} (eV)	λ (Å)
Kr XXIII	935.4	950	3842.4 ± 2.8
Kr XIX	639.6	750	4029.1 ± 2.9
Kr XV	441.6	470	4365.1 ± 3
Kr X	233.3	250	4371 ± 5.2
Kr XV	441.6	470	5060 ± 16
Kr XIII	353.2	390	5151 ± 11.5
Kr XV	441.6	470	5159 ± 11.9
Kr XII	311.5	330	5204.3 ± 9.8
Kr X	233.3	250	5328 ± 18.3
Kr XVII	538.4	550	5454 ± 20
Kr XIX	639.6	750	5795 ± 11.8

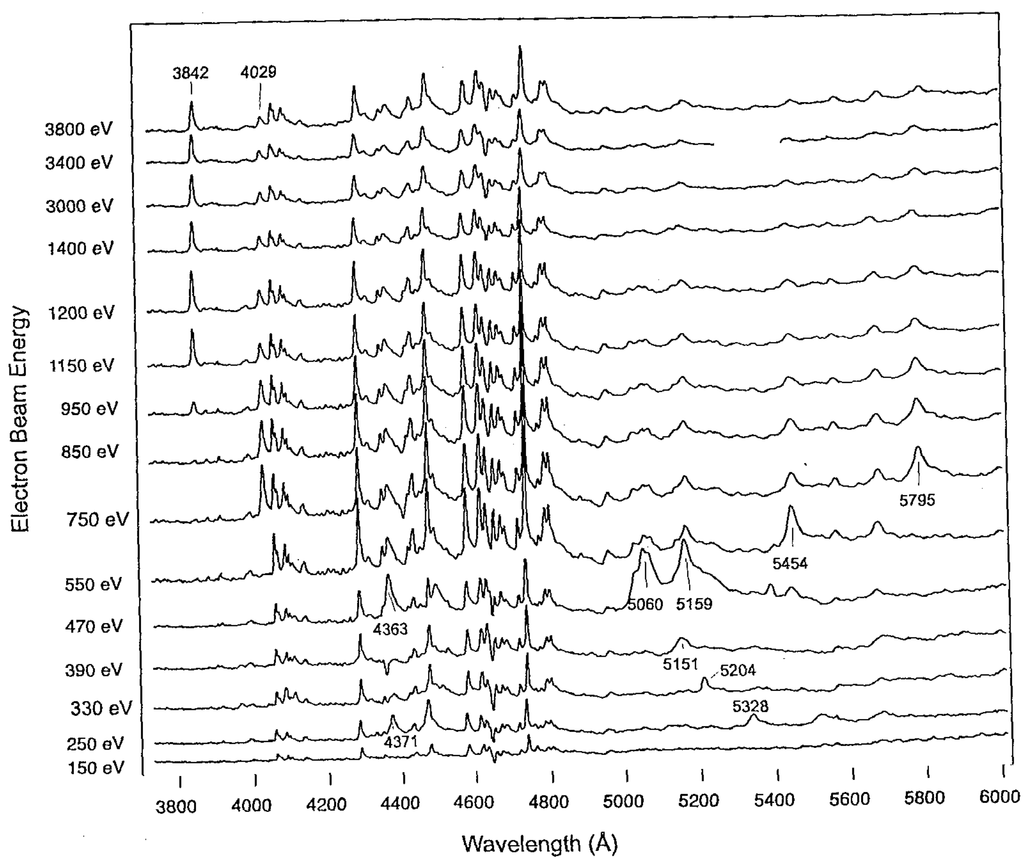

Figure 3. Kr spectrum at various electron beam energies using the prism spectrometer. The wavelength (in Å) of the lines from highly charged Kr is indicated.

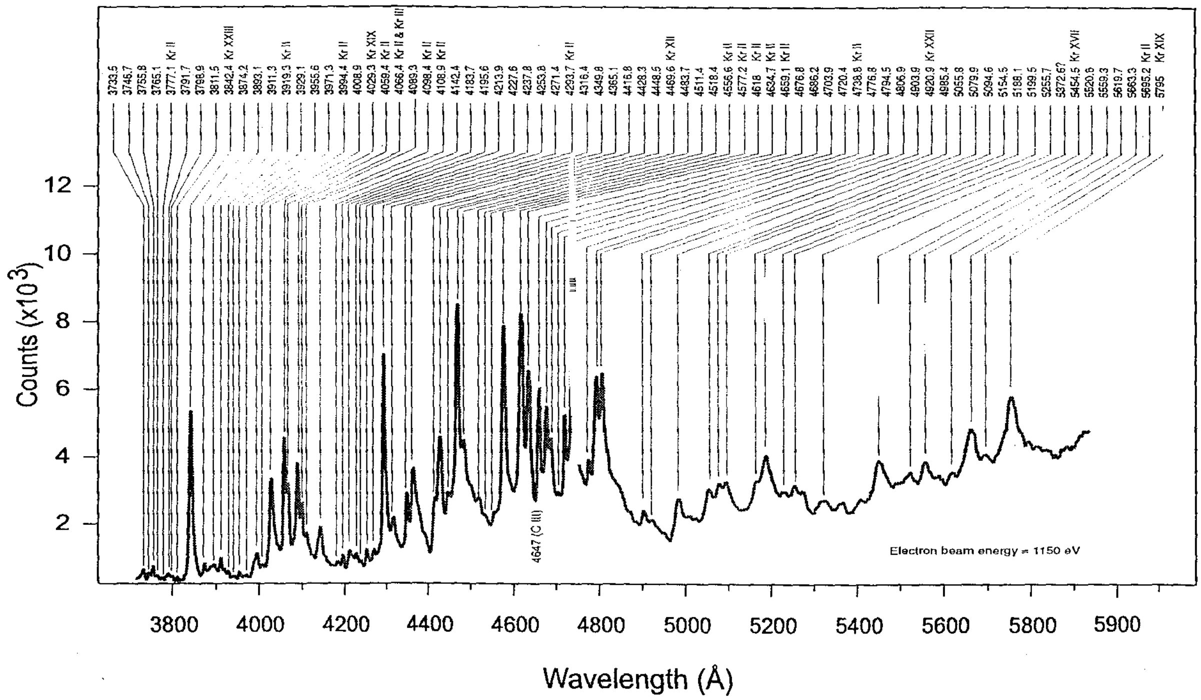

Figure 4. Kr spectrum from the prism spectrometer at electron beam energy of 1150 eV. The wavelength is in Å, and the references are from [18] and [24].

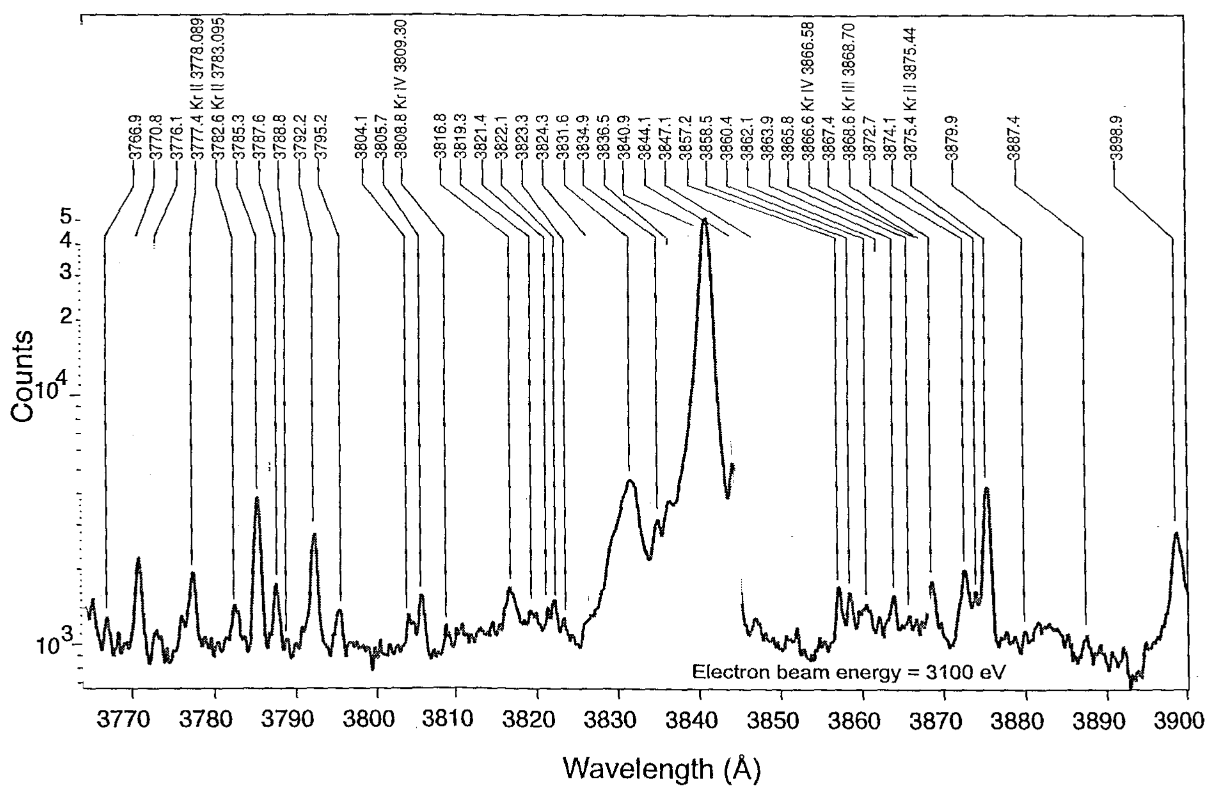

Figure 5. Kr spectrum from TGS at electron beam energy of 3100 eV. The wavelength is in Å, and the references are from [18] and [24].