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Research Note

Spectroscopic studies of neutral erbium in a hollow cathode lamp: Electronic temperature and two-step optogalvanic spectroscopy

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ABSTRACT

This work reports the results obtained through spectroscopic studies developed on an erbium-neon hollow cathode lamp. First, emission spectra were obtained in order to estimate the electronic temperature of neutral erbium, which is an important plasma parameter for the calculation of atomic population in different energy levels. It was identified seven pairs of lines that can be used to estimate the electronic temperature of this metal by the two-line Boltzmann method. After these experiments, using the laser multistep excitation technique, three transitions for the first step excitation from the erbium ground state and eight transitions corresponding to the second step were observed. Four of these eight second steps correspond to erbium lines that were not reported in the literature before: 599.44 nm (17,157.31 → 33,844 cm^{-1}), 603.65 nm (17,073.80 → 33,635 cm^{-1}), 597.48 nm (17,029.06 → 33,761 cm^{-1}) and 597.56 nm (17,029.06 → 33,759 cm^{-1}).

1. Introduction

Rare earth elements have been creating a large interest due to their applications in several areas of science and technology. The elements known as rare earth include the lanthanide series, yttrium and scandium and, although the name suggests, they are not as rare as other metals and have several applications in areas such as biology, medicine, electronics, aeronautics and nuclear energy [1]. The erbium (Er), subject of this work, has Z = 68 atomic number, 49,262 cm^{-1} (6.1077 eV) ionization energy and its electronic configuration is [Xe] $4f^{12}6s^2$ [2]. This element has applications in nuclear industry [3,4], in lasers and doped fiber amplifier [5–7], besides studies about the possibility of building optical atomic clocks using neutral erbium [1,8].

On the other hand, there are advantages using sample enriched with some isotopes instead of the natural material. For instance, studies showed that helium-cadmium lasers using some isotopes as a replacement for natural cadmium provided a 30% gain in laser power, with size reduction and increase in coherent radiation [9]. Another example is ^{167}Er, which has being used in commercial nuclear reactor as the active component since the other erbium isotopes dilute and degrade the reactor performance [3].

In order to accomplish the laser isotope separation, it is necessary the atom spectroscopic parameters knowledge, such as the energy levels and absorption frequencies, to perform the correct laser tuning [8,10,11]. This work intends to show some spectroscopic studies and their results including the electronic temperature and two-step photoionization spectroscopy. The electronic temperature in this work was estimated with the Boltzmann plot and the two-line methods, using emission lines. This procedure allows estimating the population distribution of the atom energy levels. Consequently, it is possible to verify if in the conditions of the experiment the ground state presents the largest population, which is interesting to the laser isotope separation [10]. In the two-line method, it was found seven pairs that can be used to estimate the electronic temperature and the population distribution without using several lines. The two-step photoionization spectroscopy was studied by means of the optogalvanic spectroscopy [12,13].

2. Experimental

In this work, both emission and optogalvanic spectroscopy were performed with a commercial hollow cathode lamp (HCL) provided by S&J Juniper &CO, with erbium as the cathode and neon as the buffer gas. For the emission spectroscopy, it was used a TRIAX 550 spectrometer configured to cover the spectrum from 200 nm to 1700 nm. For the optogalvanic spectroscopy it was used two Molectron Corporation model DL II Series dye lasers, pumped by two synchronized copper vapor lasers. This laser system delivers 35 mW average power at 5 kHz repetition rate with 35 ns pulse width and 700 MHz linewidth (~0.001 nm at 595 nm). The wavelength scan is performed by varying the pressure in the chamber that contains the elements of the oscillator tuning. This chamber was filled with SF_6 gas. A scan using this gas allows a rate of 0.00052 nm/Torr. Moreover, the setup also includes a pair of

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mirrors to direct the laser beam from the pump laser to the dye laser, a lens to focus the beam in the hollow cathode lamp, a stabilized voltage source Tectrol (TC 400-0015 model), a lock-in amplifier, two computers, one connected to the laser controllers and another connected to the amplifier and an oscilloscope. Exciton Rhodamine 590 and Kiton Red dyes were employed to cover the desired wavelength region.

Fig. 1 illustrates the experimental apparatus used in the laboratory for one-step and two-step optogalvanic spectroscopy (OGS). For two-step OGS, the first laser (DL1) was tuned and fixed at a wavelength corresponding to a first step transition previously observed [14], and then the second laser (DL2) was scanned in the desired range. When a radiation of the DL2 laser was resonant with a transition, a signal was detected corresponding to a second step transition. In order to ensure that this transition indeed was a second step one, the DL1 laser that was exciting the electrons from the first level was blocked and the DL2 scan was repeated. The spectra with and without the DL1 laser excitation were compared and if the observed second photon resonant signal was not detected, this meant that the transition consisted in a second step.

3. Results and discussions

The results are presented and discussed in two sections: the first one presents the results obtained through the emission spectroscopy used to estimate the electronic temperature of the neutral erbium and then the occupation probability of lower levels for the erbium atom. The second section includes the two-step optogalvanic spectroscopy. All the wavelengths in the figures are given in air. The experimental system is calibrated for vacuum wavelength and the values in air were obtained using the Ciddor equation [15]. Two databases with spectroscopic parameters for neutral erbium have been assembled during this work, which includes lines and energy levels. It was scheduled 697 lines (34 involving the ground state) and 691 energy levels (245 even and 188 odd attributed). The line database presents the wavelength (nm) in vacuum and air, the relative intensity based on NIST [16], the Einstein coefficient of spontaneous emission, A_{ul} (s^{-1}), the A_{ul} deviation, δA_{ul} (s^{-1}), the energy levels of the lower and upper levels and their respective total angular momentum, J. The energy level database presents the total angular momentum of the energy level, the value of the energy in cm^{-1}, the parity of the level, the lifetime (ns) and its experimental error [16–18]. The databases were employed to spectra simulation using the ASAS software [19].

3.1. Emission spectroscopy and electronic excitation temperature

Emission spectra have been obtained from the erbium HCL to identify lines of this atom and neon (the buffer gas). The results obtained through the emission spectroscopy were useful to study previously the region to be analyzed with the optogalvanic spectroscopy and essentially to calculate the electronic excitation temperature, which allows estimating the occupation probability of lower levels. In order to gather a large number of lines by means of this technique, it has been analyzed the region from 290 to 900 nm through emission spectroscopy running the HCL at 7.5 mA. It was obtained 69 erbium emission lines, whose relative intensities were calibrated through a quartz tungsten halogen lamp provided by Newport. From the atomic emission spectroscopy theory, in a local thermal equilibrium, the electronic temperature is given by a Boltzmann function, which relates the plasma temperature to the relative intensity of the spectral lines. The Boltzmann plot is a multiline method in emission spectroscopy that allows estimating the electronic excitation temperature assuming a Boltzmann distribution of the electronic levels populations: the logarithmic term versus the energy of the upper level, E_u, yields a straight line whose slope is equal to $-1/k_BT$ [20–22]:

$$\ln\left(\frac{I_{ul}\lambda_{ul}}{g_u A_{ul}}\right) = C - \frac{E_u}{k_B T} \quad (1)$$

where g_u is the statistical weight of the upper level, A_{ul} is the transition probability, E_u is the energy of the upper level, λ_{ul} is the line wavelength, I_{ul} is the experimental line intensity, k_B is the Boltzmann constant, T is the electronic excitation temperature of the plasma and C is a constant [21]. From the 69 lines observed in this work, twenty of them were employed in the Boltzmann plot. For this purpose, it was considered those with the biggest relative intensity but without saturation in the spectra and minor error on transition probability (A_{ul}). Table 1 presents all these lines and the respective values of the parameters in Eq. (1) [16–18].

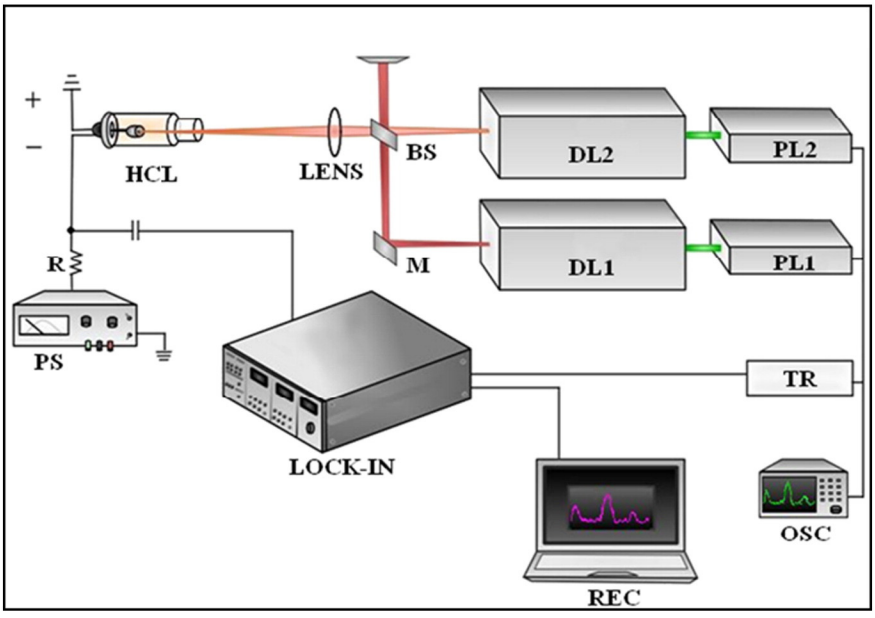

Fig. 1. Two-step optogalvanic spectroscopy setup. HCL: erbium hollow cathode lamp; BS: beam splitter; M: mirror; DL1 and DL2: dye lasers 1 and 2; PL1 and PL2: pump lasers 1 and 2; R: resistor; PS: power supply; REC: recorder; TR: trigger; OSC: oscilloscope.