The near-infrared spectra and distribution of excited states of electrodeless discharge rubidium vapour lamps*

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The population ratio between the excited states of rubidium in the electrodeless discharge rubidium vapour lamp is calculated according to the near-infrared spectra in the region of 780–1550 nm. By using a 1529 nm laser, we measure the density of natural rubidium atoms at the $5P_{3/2}$ level. The populations of different excited states are then clarified.

Keywords: electrodeless discharge rubidium vapour lamp, near-infrared spectra, population

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1. Introduction

The electrodeless discharge alkali vapour lamp has been used for optical pumping since the 1950s.[1] Nowadays, it plays an important role in many fields, such as the Rb atom frequency standard[2] and atomic magnetometers.[3] Atoms in the lamp are excited by radio frequency (rf) power, so all of the excited states should have different populations when the lamp is lit. For the application to the locking frequency of the transition between high excited states, compared with double resonance spectroscopy and the frequency stabilization method,[4,5] the lamp could cause the intermediate state to be easily populated. Besides, among the rich spectral signals emitted by the lamp, the signals from the transitions between the first excited states and the ground state are much stronger than the others. So the lamp could perhaps replace the pumping laser in the double resonance optical pumping experiment[6] to simplify the 1.5-μm wavelength standard for optical communication applications.

A basic knowledge about the lamp is meaningful for the exploration of further applications. The spectra of the Rb vapour lamp in the 400–1000 nm region have been reported.[7,8] In this paper, we calculate the population ratio between excited states of rubidium in the lamp according to the near-infrared spectra in the 780–1550 nm region.[9] By using a 1529 nm laser, we measure the density of natural rubidium atoms at the $5P_{3/2}$ level. The populations of different excited states are clarified.

2. Spectra experiment and results

We used two different Rb vapour lamps. By comparing their spectra, the accuracy of the experiment can be confirmed. Conveniently, the two lamps are called lamps 1 and 2. The bulb in lamp 1 is a cylindrical glass cell with a length of 1 cm and a diameter of 0.8 cm. It contains natural Rb atoms and Ar gas at 2.7×10^2 Pa, and is supplied with radio frequency power of 135 MHz through a copper wire winded around the bulb. Lamp 1 can reach a maximum temperature of 120 °C and can output light from one (end) side of the bulb. Lamp 2 is similar to lamp 1 but with several differences. The bulb in lamp 2 is bigger than that in lamp 1, it has a length of 3 cm and a diameter of 3 cm. Containing natural Rb atoms and Xe gas at 2.7×10^2 Pa, the bulb is supplied with 178 MHz rf power and can be heated from

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room temperature to 200 °C. Lamp 2 is designed to output light from both (ends) sides of the bulb, so a laser could pass through the lamp.

Experimentally, lamp 2 can operate in three spectral modes. Two of them are the so-called red mode and the ring mode,[8] and the remaining one, which will be called the weak mode, has not been reported before. When turning the rf power from high to low, the ring, the red and the weak modes appear in sequence. Operating in the weak mode, the lamp lights very weakly and the bulb appears to be almost extinguished. The first excited states of Rb could gather most atoms when lamp 2 is working at the turning point between the red and the weak modes, which will be discussed later. The spectral mode turning point is more attractive for our research because the lamp can absorb the 1529 nm (corresponding to the transition of $5P_{3/2} \rightarrow 4D_{3/2,5/2}$) laser most strongly and generates an absorption signal with a high signal-to-noise ratio.

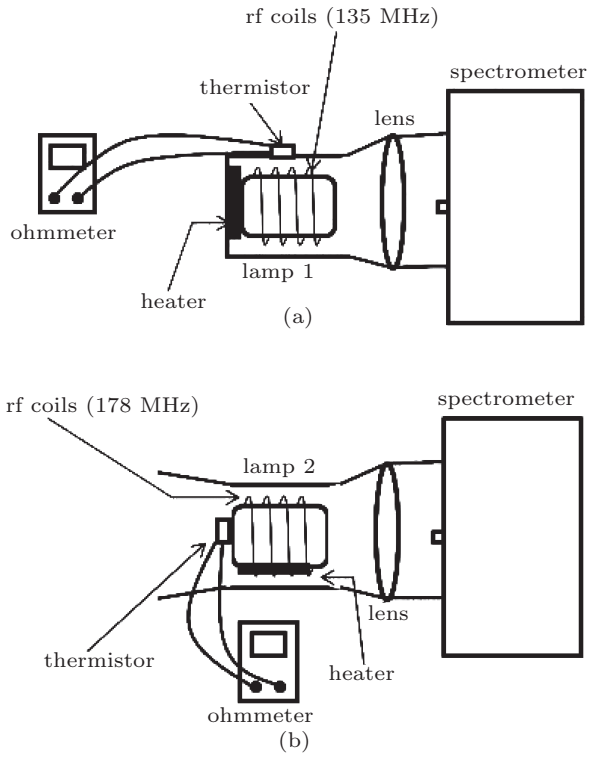


Fig. 1. The experimental schemes of (a) lamp 1 and (b) lamp 2 for spectrum research.

The two near-infrared region spectra (750–1550 nm) of the two lamps are measured by a spectrometer (HP 70952B) when they operate in the red mode near the spectral turning point. Figure 1 shows block diagrams of our experimental arrangement, and Table 1 lists all the spectra measured. The signal intensities normalized to the 780 nm signals of lamps 1 and 2, respectively, are plotted in Fig. 2.

Table 1. Spectral signal intensities.

Wavelength/nm	Signal intensity/pW	
	lamp 1	lamp 2
780	185.50	227
795	116	173
1324	2.16	5.50
1344	4	–
1366	3.10	4.90
1475	9.20	11.50
1529	15.60	13.07

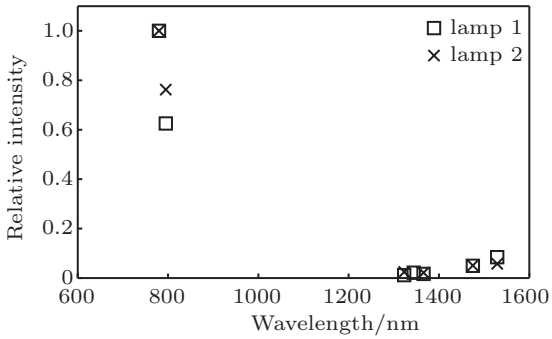


Fig. 2. The relative intensities of the Rb spectral signals.

Although the two lamps have different operational conditions, such as rf frequency, rf power and temperature, their spectra are very similar. The signals of transitions $5S_{1/2} \rightarrow 5P_{3/2}$ and $5S_{1/2} \rightarrow 5P_{1/2}$ are much stronger than those of the transitions between the higher excited states. The results show that there are many more atoms in the first excited states than those in the higher ones.

3. Population ratio between excited states

The transition energy related to the spectral signal shown in Table 1 can be illustrated in Fig. 3. The energy states are numbered, which can facilitate the discussion below.

The power (P) of the transition signal between two energy states can be expressed as

$$P_\lambda = n_j A_{ji} h\nu, \tag{1}$$

where λ is the wavelength, n_j is the atom density in the level numbered j, A_{ij} is the spontaneous transition probability, ν is the transition frequency and h is

the Planck constant. The transitions studied can be expressed clearly as

$$P_{780} = n_3 A_{31} h\nu_{780}, \quad (2)$$

$$P_{795} = n_2 A_{21} h\nu_{795}, \quad (3)$$

$$P_{1324} = n_4 A_{42} h\nu_{1324}, \quad (4)$$

$$P_{1344} = n_7 A_{75} h\nu_{1344,1} + n_7 A_{76} h\nu_{1344,2}, \quad (5)$$

$$P_{1367} = n_4 A_{43} h\nu_{1367}, \quad (6)$$

$$P_{1475} = n_5 A_{52} h\nu_{1475}, \quad (7)$$

$$P_{1529} = n_5 A_{53} h\nu_{1529,1} + n_6 A_{63} h\nu_{1529,2}, \quad (8)$$

where $\lambda_{1344,1}$, $\lambda_{1344,2}$, $\lambda_{1529,1}$, and $\lambda_{1529,2}$ are the transition wavelengths between $4D_{3/2}$ and $4F_{5/2}$, between $4D_{5/2}$ and $4F_{7/2}$, between $5P_{3/2}$ and $4D_{3/2}$, and between $5P_{3/2}$ and $4D_{5/2}$, respectively.

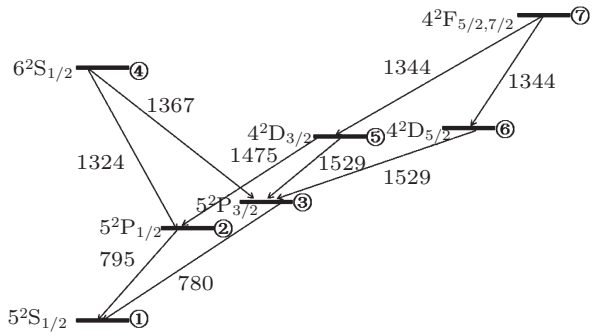


Fig. 3. An energy diagram of the transitions.

The spontaneous transition probabilities and the wavelengths involved in the calculation are listed in Table 2. The calculation results of n_j/n_i are shown in Fig. 4 and Table 3.

Table 2. Spontaneous transition probabilities and wavelengths.

$A_{ji}/10^6$ s^{-1}	λ/nm[10]
A_{31}=38.1[10]	λ_{780}=780.0268
A_{21}=36.1[10]	λ_{795}=794.7603
A_{42}=6.62[11]	λ_{1324}=1323.517
$A_{75,76}$=17.48[12]	$\lambda_{1344,1}$=1344.357
	$\lambda_{1344,2}$=1344.281
A_{43}=12.9[11]	λ_{1367}=1366.501
A_{52}=10.7[11]	λ_{1475}=1475.241
A_{53}=1.98[11]	$\lambda_{1529,1}$=1528.843
A_{63}=11.9[11]	$\lambda_{1529,2}$=1528.948

Figure 4 shows that the distributions of the atoms in the excited states of the two lamps are similar. There are more atoms in $5P_{3/2}$ than in $5P_{1/2}$, however, transition between them is forbidden by the electric dipole selection rules. There are no other population inversions between the transition levels in the case of rf discharge pumping.

Table 3. The calculation results of n_j/n_i.

n_j/n_i	Lamp 1	Lamp 2
n_2/n_3	0.67	0.82
n_4/n_3	0.10	0.18
n_5/n_3	0.33	0.34
n_6/n_3	0.47	0.31
n_4/n_2	0.15	0.21
n_5/n_2	0.49	0.41

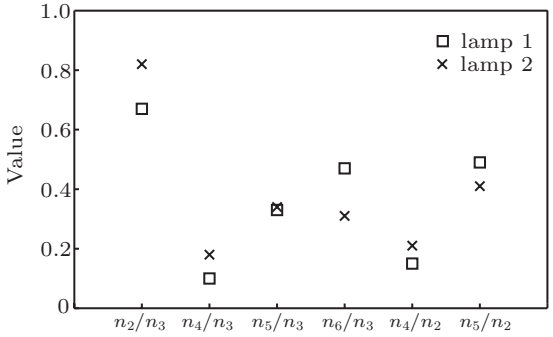


Fig. 4. The values of n_j/n_i in the two lamps.

4. The measuring population at the $5P_{3/2}$ level

The population at the $5P_{3/2}$ level cannot be obtained simply by the calculation stated before, but can be measured using a 1529 nm laser. From Fig. 3, we can see that the 1529 nm laser can transmit through lamp 2 without obvious absorption when the lamp is powered off, because there is almost no population in the first excited state. Once the lamp is on, the laser should be absorbed much more strongly. Through comparing the transmitted signals in the two cases, we can measure the density of the active atoms in $5P_{3/2}$. Figure 5 shows a block diagram of the experimental arrangement.

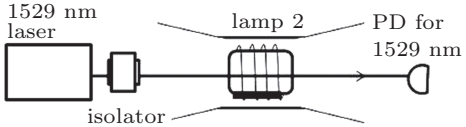


Fig. 5. The experimental setup for obtaining the transmission signal of the 1529 nm laser. PD stands for photodiode.

Several absorption signals of the 1529 nm laser are generated when we scan the frequency. With the

help of the spectrograph, one of the absorption spectra with a wavelength of 1529.37 nm (in vacuum) is measured, which corresponds to the transition of $5P_{3/2}$ $(F = 3) \rightarrow 4D_{5/2}$.

Lamp 2 has different absorptances for the 1529 nm laser in different spectral modes. Once the rf power is very low and the spectral mode is at the turning point between the red and the weak modes, the 1529 nm laser is absorbed most strongly. The highest absorptance indicates that the first excited states can gather most atoms under this spectral mode condition.

Having been strongly absorbed, the power of the transmitted light is 2.72 mW. Then the lamp is turned off, and the new value of the transmitted signal power is 4.6 mW. The temperature of lamp 2 is 152 °C. Here, the detector we used is PDA10CF from Thorlabs Inc., and the output voltage value is converted to the light power at 1529 nm by the use of a thermoelectric power meter.

According to Lambert–Beer's law[13]

$$\frac{P_{\rm o}}{P_{\rm i}} = {\rm e}^{-n'l\sigma}, \tag{9}$$

where $P_{\rm o}$ is the power of the transmitted signal of the 1529 nm laser, $P_{\rm i}$ is the power of the incident laser and is expected to be equal to 4.6 mW, n' is the population in $5P_{3/2}$ $(F = 3)$ of the ^{87}Rb atoms, and l is the length of the bulb. σ is the absorption cross section and can be expressed as

$$\sigma_{ij} = \frac{A_{ij}\lambda^2 g_{\rm D}}{8\pi}\frac{g_i}{g_j}, \tag{10}$$

with

$$g_{\rm D} = \frac{2\sqrt{\ln 2/\pi}}{\Delta\nu_{\rm D}}, \tag{11}$$

where

$$\Delta\nu_{\rm D} = 7.163 \times 10^{-7}\nu_0\sqrt{\frac{T}{M}}, \tag{12}$$

T is the temperature, M is the relative atomic mass of ^{87}Rb, and g_i is the weight factor of level i. We have $\sigma = 4.99 \times 10^{-12}$ cm^2, and $l = 3$ cm, so $n' = 3.51 \times 10^{10}$ cm^{-3}.

As the collision effect is much more serious when the lamp is on, the populations in the hyperfine states of $5P_{3/2}$ of the ^{87}Rb atoms are expected to be balanced. Due to the hyperfine energy splitting being small, it is possible to estimate the population in the $5P_{3/2}$ level as

$$n_3 = \frac{n'}{g_{F3}} \times (g_{F3} + g_{F2} + g_{F1} + g_{F0}) = \frac{16}{7}n' = 8.02 \times 10^{10}\ {\rm cm}^{-3}. \tag{13}$$

The density of natural Rb atoms (N) in the vapour can be obtained by[13]

$$\log(N) = 34.8675 - \frac{4529.6}{T} - 3.991 \times \lg T + 0.00059 \times T, \tag{14}$$

so $N = 9.34 \times 10^{13}$ cm^{-3}. The abundance of ^{87}Rb in the natural Rb is 27.8%. So about 0.3% of the ^{87}Rb atoms are pumped to the $5P_{3/2}$ level under the rf discharge condition.

5. Conclusion

We investigated the spectra of two Rb vapour lamps and calculated the population ratio between the excited states of natural Rb atoms. By using the 1529 nm laser, the populations of the first excited states were obtained.

The result shows that there is no inversion between the transition levels in the case of rf discharge pumping, except that between $5P_{3/2}$ and $5P_{1/2}$. Apart from the so-called ring mode and red mode, lamp 2 can also operate in a third distinct spectral mode, the weak mode. When lamp 2 operates in the red mode near the turning point with a temperature of 152 °C, the density of the ^{87}Rb atoms in the $5P_{3/2}$ level reaches a value of 8.02×10^{10} cm^{-3}, which is 0.3% of the total density of the ^{87}Rb atoms in the vapour. When the two lamps both operate near the turning point, they have similar spectra and similar values of n_j/n_i. Since we know n_j/n_i and the density in $5P_{3/2}$, we can find the densities in all the excited states mentioned above.

We are more interested in the turning point because the first excited states could collect the most atoms. In this case, the lamp can absorb the 1529 nm laser most strongly and generate an absorb signal with a line width of several hundred MHz and a high signal-to-noise ratio, which could allow the lamp to be used in a simple frequency locking system for optical communication. Besides, the strength of the first resonance emission of the Rb atom (795 and 780 nm) can reach a maximum value due to the populations in the first excited states being highest, so that the lamp could achieve the biggest efficiency to pump other Rb atoms from the ground state to the first excited states. Knowledge of the Rb lamp is meaningful for the exploration of further applications of the Rb lamp in the wavelength standard.

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