A novel method to measure the isotope shifts and hyperfine splittings of all ytterbium isotopes for a 399-nm transition*

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We report the experimental results on measuring the isotope shifts and hyperfine splittings of all ytterbium isotopes for a 399-nm transition by using a quite simple and novel method. It benefits from the advantages of the modulation transfer spectroscopy in an ytterbium hollow cathode lamp and the Doppler-free spectroscopy in a collimated ytterbium atomic beam. The key technique in this experiment is simultaneously measuring the frequency separations of the two spectra twice, and the separation difference between two measurements is solely determined by the well-defined frequency of an acousto-optics modulator. Compared with the most of previously reported experimental results, ours are more accurate and completed, which will provide the useful information for developing a more accurate theoretical model to describe the interaction inside an ytterbium atom.

Keywords: isotope shift, hyperfine splitting, modulation transfer spectroscopy, ytterbium

PACC: 3280, 3290, 4260H, 4265

1. Introduction

Recently, the atomic rare-earth-metal ytterbium (Yb) has become one of the very important atomic species because it is one of the candidates for the next generation optical frequency standards.[1] In addition, it is also a good candidate for studying atomic parity violation[2] and searching for a permanent electronic-dipole moment in atoms.[3] Therefore, the isotope shifts and hyperfine splittings[4−7] of all isotopes for a typical line should be well-determined experimentally for potential applications. There are seven isotopes of the Yb atom, including two odd and five even isotopes. Seven isotopes all have the isotope shifts, and moreover two odd isotopes have the hyperfine splittings. For each transition line, the corresponding resonance frequency of each isotope is located at the different position in spectrum, so that we can measure it using various spectroscopy techniques. For instance, level-crossing and anti-crossing spectroscopy,[8−10] Fabry–Perot cavity,[11] saturated-absorption spectroscopy,[12] photon-burst spectroscopy,[13] optical double-resonance spectroscopy,[14] and a ring-cavity resonator, etc.[15]

Since the 399-nm $6s^2\ {}^1S_0$ to $6s6p\ {}^1P_1$ transition is often utilized in various experiments of Yb atoms,[14,16,17] the isotope shifts and hyperfine splittings of this line are very important for applications. We have measured all shifts for this line by a novel technique. Unfortunately, most of the measurements reported previously for this line showed some discrepancies between each other and did not disclose all shifts in an experiment.[8−14] Our measurements reported in this paper have resolved these discrepancies and obtained all shifts for this 399-nm line. Compared with most of the previous reported experimental results, our results are more accurate and completed. It benefits from the advantages of the modulation transfer spectroscopy (MTS)[18] in an Yb hollow cathode lamp (HCL) and the Doppler-free spectroscopy in a collimated Yb atomic beam. The key technique in this experiment is simultaneously measuring the frequency separations of the two spectra twice, and the separation difference between two measurements is solely determined by the well-defined frequency of an acousto-optics modulator (AOM). Our method is quite simple, and it is able to cancel out several sources of systematic error automatically.

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2. Experimental method and setup

In the experiment, we scan the laser frequency to obtain the MTS in an Yb HCL at 399 nm and the Doppler-free spectroscopy in an Yb atomic beam apparatus. The two spectra are shifted in frequency domain by a set of AOMs. In the measurements, we only change the frequency of one AOM by an amount of Δf. Using this Δf, we can calibrate both of the spectra. For instance, we first find the centre frequencies of the MTS signal and Doppler-free spectrum of ^{174}Yb isotope at t_1 and t_2 (arb. units); then we only change the frequency of the AOM which is used to tune the frequency of the laser that is sent into the beam apparatus by an amount of Δf, so that the Doppler-free spectrum will be shifted relative to the MTS signal, and two centre frequencies become t_1' and t_2' (arb. units); finally we can obtain the scaling factor $\Delta f/((t_2'-t_1')-(t_2-t_1))$. Since we simultaneously measure both the spectra, any frequency drifts will be automatically cancelled out, and the resolution will be determined by the line-widths of the two spectra. Furthermore, in order to reduce the influence from the nonlinearity of the frequency scanning, we group two peaks in each measurement. By using this method, we can map out all shifts of all isotopes for the 399-nm transition.

A schematic diagram of the experimental setup is shown in Fig. 1. The 399-nm laser system from Toptica Photonics has a line-width about 1 MHz. The output laser beam is split into two beams by the first polarizing beam splitter (PBS1): one beam is sent to the MTS setup, and the other is sent into the Yb-beam apparatus. After passing through the PBS2, the laser beam used for the MTS is split into two beams again: one is for pumping, which is modulated by a home-made electro-optic modulator (EOM) with the modulation frequency of 14 MHz and modulation index of 0.4, and the other is for probing. Finally, two beams overlap inside of an HCL. With the nonlinear four-wave mixing process, modulation transfer occurs where the un-modulated probe beam acquires new sidebands. The beating signal between the probe and its newly

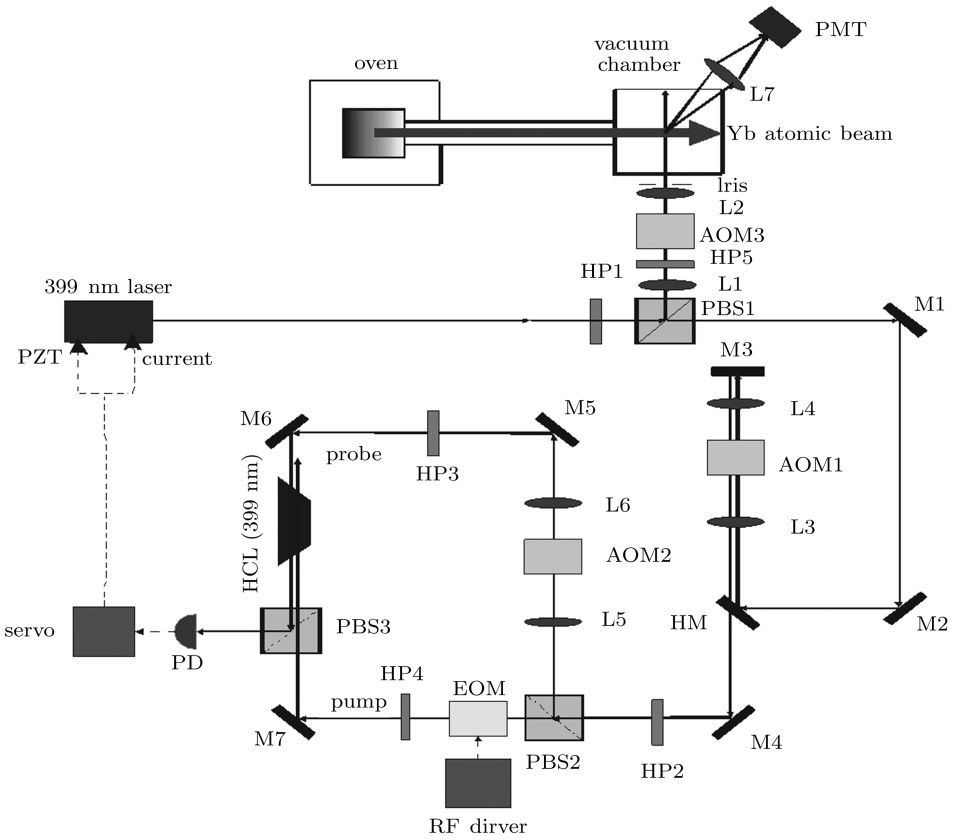


Fig. 1. Experimental setup. HP, half-wave plate; PBS, polarizing beam splitter; L, lens; M, mirror; EOM, electro-optic modulator; AOM, acoustic-optic modulator; HCL, hollow cathode lamp; PD, photodiode. The solid lines indicate the light beam and the dashed lines indicate the electric circuit.

generated sidebands is sent to a servo-locking system, and the MTS signal is obtained. On the other hand, the laser beam sent to the Yb-beam apparatus first goes through an acoustic-optic modulator (AOM3) with a frequency of f_0, and then the first-order diffractive light is sent into the chamber, orthogonally interacting with the collimated Yb-beam which is effused from a high temperature oven containing the Yb metal. A photomultiplier tube (PMT) is located at the position perpendicular to both the laser beam and the atomic beam, detecting the fluorescence signal of the Yb atomic beam. Finally, the Doppler-free spectroscopy of the Yb atomic beam can be obtained.

3. Experimental results and discussion

In our experiment, by scanning the frequency of the 399-nm laser, the MTS signals of all isotopes for the 399-nm transition were observed under the following conditions: the HCL current was 4.0 mA, the pump and probe powers were 2.0 mW and 0.6 mW respectively. On the other hand, the Yb oven was heated to 623 K, and the Yb atomic beam was collimated by a 3-mm diaphragm. The laser entering the chamber was linearly polarized with the power of about 0.1 mW. The Doppler-free spectroscopy of the Yb atomic beam was also measured. The MTS and Doppler-free spectroscopy were simultaneously recorded through the data acquisition system as shown in Figs. 2–5. In the measurements, we took two steps. In the first step, the frequency of the laser sent into the beam chamber was not shifted by AOM3 as shown in figures on the left-hand side labeled as (a); in the second step, the laser frequency was shifted by 320 MHz, sending the first-order light beam of AOM3 into the beam chamber as shown in figures on the right-hand side labeled as (b). Two spectra were fitted to find their centre frequencies for each transition respectively. The MTS signals can be fitted by the expressions in Ref. [19], and the signals of Doppler-free spectroscopy can be fitted by the Lorentzian profiles. To further reduce the influence from the nonlinearity of the frequency scanning, we narrowed the frequency-scanning range to show mainly two isotopes in each measurement.

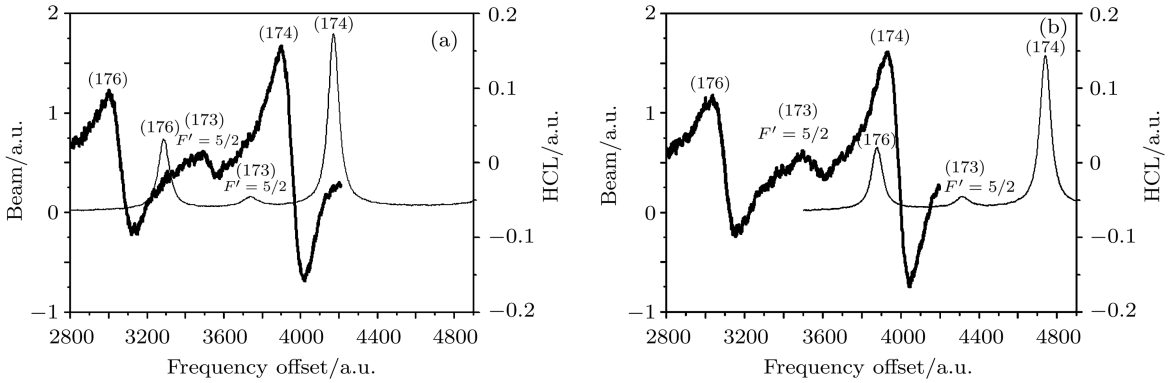


Fig. 2. Measurement of the shift between ^{176}Yb and ^{174}Yb.

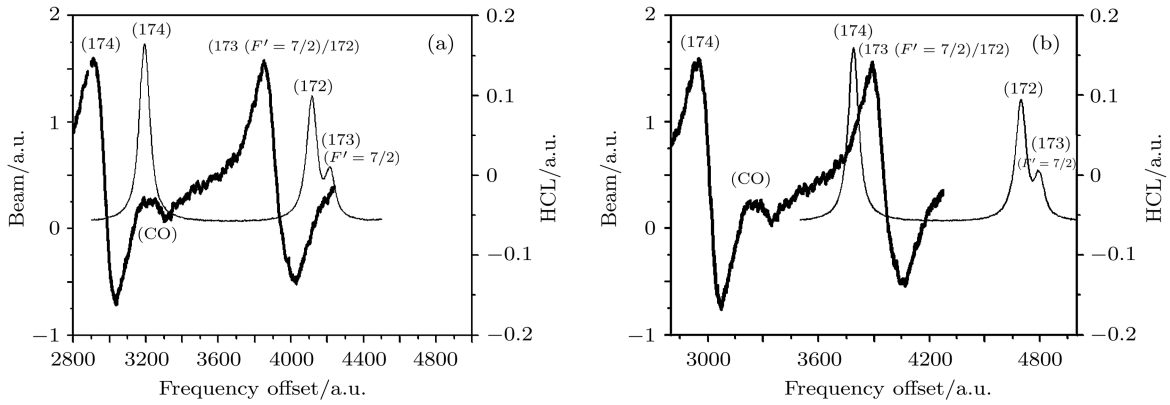


Fig. 3. Measurement of the shift between ^{172}Yb and ^{174}Yb.

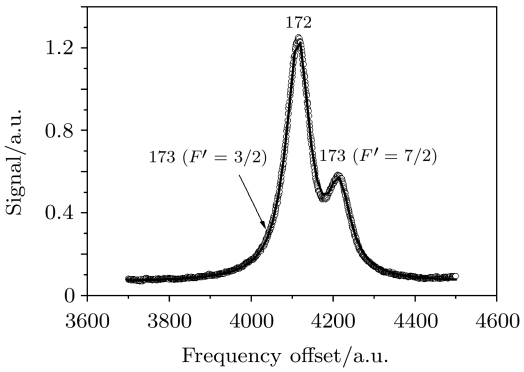


Fig. 4. Three-peak fitting results. The empty circles denote the experimental results, and the solid line denotes the fitting curve.

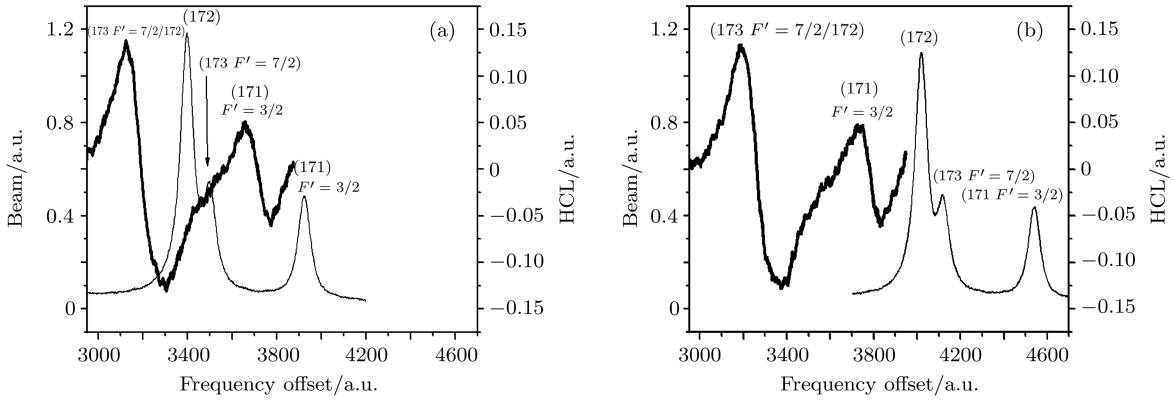


Fig. 5. Measurement of the shift between ^{171}Yb and ^{172}Yb.

In Fig. 2, we have the scaling factor by measuring the peak positions of isotope ^{176}Yb in two cases. Then we obtain the frequency shifts of isotopes ^{176}Yb and ^{173}Yb ($F' = 5/2$) relative to ^{174}Yb respectively.

In Fig. 3, we have the scaling factor by measuring the peak positions of isotope ^{174}Yb in two cases. The frequency shifts of isotopes ^{173}Yb ($F' = 3/2$), ^{172}Yb and ^{173}Yb ($F' = 7/2$) relative to ^{174}Yb are obtained by a three-peak Lorentzian fit as shown in Fig. 4.

We find that the 399-nm transition lines of ^{173}Yb ($F' = 3/2$) and ^{173}Yb ($F' = 7/2$) are located at 20.5 MHz below and 57 MHz above that of ^{172}Yb respectively with the linewidth about 38 MHz.

In Fig. 5, we have the scaling factor by measuring the peak positions of isotope ^{171}Yb ($F' = 3/2$) in two cases. The frequency shift between isotopes ^{171}Yb ($F' = 3/2$) and ^{172}Yb can be found.

In order to observe the rarest isotope ^{168}Yb more clearly, we heat the oven up to 673 K and the peak of isotope ^{168}Yb is obviously seen in Doppler-free spectroscopy in Fig. 6. The scaling factor is obtained by monitoring the isotope ^{171}Yb ($F' = 3/2$). The frequency shift between ^{168}Yb and ^{171}Yb ($F' = 3/2$) has been measured. In addition, using a two-peak Lorentzian fit, we obtain the frequency separations of ^{171}Yb ($F' = 1/2$) and ^{170}Yb relative to ^{171}Yb ($F' = 3/2$) respectively.

Finally, we measure the isotope shifts and hyperfine splittings of all Yb isotopes for the 399-nm transition as shown in Fig. 7. The detailed results are shown in Table 1.

According to Table 1, we find that most of our data are in good agreement with those reported in Ref. [15]. But some discrepancies can still be found. This means that further investigation is needed to resolve these discrepancies. Compared with other techniques discussed in earlier publications,[8−15] our method is quite simple, and is able to cancel out several systematic errors automatically.

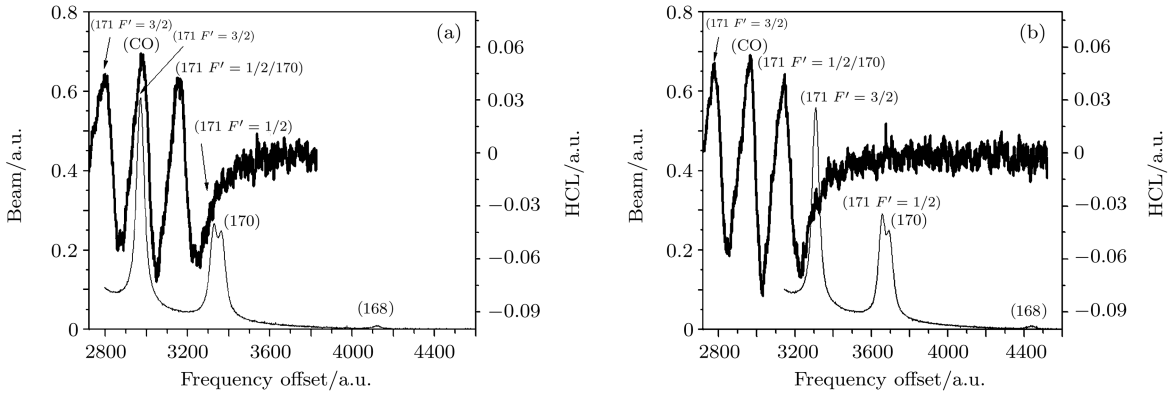


Fig. 6. Measurement of the shift between ^{168}Yb and ^{171}Yb.

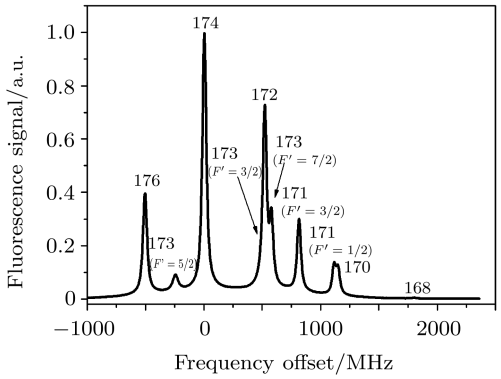


Fig. 7. Measurement of the isotope shifts and hyperfine splittings of all Yb isotopes for the 399-nm transition.

Table 1. Comparison of our results with those of other measurements on the hyperfine splittings and isotope shifts for the 399-nm line of ytterbium, relative to the isotope ^{174}Yb.

isotope	shift from ^{174}Yb/MHz					
	this work	Ref. [15]	Ref. [14]	Ref. [13]	Ref. [11]	Ref. [20]
^{176}Yb	–508.8 (0.5)	– 509.310	–507.2(2.5)		–509.4(4.0)	–469.20(27)
^{173}Yb ($F'=5/2$)	–253.4(0.6)	– 253.418			–291(10)	
^{174}Yb	0	0	0		0	
^{173}Yb ($F'=3/2$)	514.3(0.8)	515.975(200)				
^{172}Yb	529.5(0.6)	533.309(53)	527.8(2.8)		–530(4.0)	530.2(78)
^{173}Yb ($F'=7/2$)	588.2(0.6)	587.986(56)	578.1(5.8)			
^{171}Yb ($F'=3/2$)	833.7 (0.9)	832.436(50)	832.5(5.6)	834.4±4.0		
^{171}Yb ($F'=1/2$)	1153.1(1.1)	1153.696(61)	1151.4(5.6)	1136.2±5.8		
^{170}Yb	1189.4 (1.0)	1192.393(66)	1175.7(8.1)	1172.5±5.7	–1195.0(10.8)	1158.9(114)
^{168}Yb	1887.8(1.7)	1887.400(50)		1870.2±5.2		

For further evaluating the accuracies and uncertainties of our measurements, we have carefully analysed the statistical and systematic errors in our experiments as below.

A. Statistical errors

The primary source of the statistical errors was the frequency instability of the 399-nm laser. In our experiment, the laser linewidth was about 1 MHz, and the long-term drifting of the laser frequency was about 300 MHz/12 h. Therefore, the statistical error was mainly produced by the fluctuation of the laser frequency during the measurements. In addition, the broad linewidth of the $^1S_0$ to $^1P_1$ transition became another source of the statistical errors. In our ex-

periment, the measured linewidth of the fluorescence signal to be employed to determine all isotope shifts was about 38 MHz with the signal-to-noise ratio being about 50. Therefore, the uncertainty for determining each peak position during the fitting was unavoidable.

B. Systematic errors

(i) The first error source came from the differential Doppler-shift due to the fact that the different isotopes left the oven with slightly different velocities. Taking ^{174}Yb and ^{176}Yb for example, the differential shift was about 5 kHz for a misalignment angle of 1 mrad in our experiment.

(ii) The second error source was related to the Zeeman shift induced by the stray magnetic field. In our case, the size of the stray magnetic field was about 0.5×10^{-4} T. With the linearly-polarized light, the first-order Zeeman shifts of even isotopes were zero; while for the odd isotopes, the first-order Zeeman shifts were unavoidable, and the biggest shift calculated was about $\pm$1.8 MHz. Fortunately, the shifts were much smaller than the measured 38-MHz linewidth, and all shifted Zeeman-sublevels were symmetrically distributed on the two sides of the previous unperturbed level, so that the spectra corresponding to all the sublevels were overlapped closely and appeared as a one-peak profile, and the peak position still corresponds to the unperturbed transition frequency. Therefore, in our experiment the first-order Zeeman shifts did not affect the isotope shifts. In addition, the second-order Zeeman shifts of the Yb atoms were less than 1 Hz, however they were cancelled out in the isotope-shift measurements due to their having the same sign.

(iii) The third error source was due to collisions of the Yb atoms in the vacuum chamber. In our experiment, the density of ^{174}Yb was about 4.4×10^6 atom/cc with the flux of 10^{10}/s, so that the estimated collision-shift was less than 1 Hz. Due to the less natural abundance of the other isotopes, the corresponding collisional shifts of other isotopes were also less than 1 Hz. In addition, other errors were all negligible.

Furthermore, based on the data in Table 1 we have calculated the hyperfine-coupling constants in the 6s6p ^{1}P$_1$ states of the odd isotopes ^{171}Yb and ^{173}Yb separately. For ^{171}Yb, the measured hyperfine interval $\{F' = 3/2\text{–}F' = 1/2\}$ was used to calculate the magnetic-dipole coupling constant A_{171}, and we obtained the value $A_{171} = -212.9(0.9)$ MHz. This value was compared to the values reported previously in Table 2.

For ^{173}Yb, the measured hyperfine intervals $\{F' = 7/2\text{–}F'=5/2\}$ and $\{F' = 7/2\text{–}F' = 3/2\}$ were used to calculate the magnetic-dipole coupling constant A_{173} and the electric-quadrupole coupling constant B_{173}. We obtained values of $A_{173} = 57.9(0.2)$ MHz and $B_{173} = 608.4(0.8)$ MHz. These values were compared to earlier results in Table 3. We find that the values for A and B are in good agreement with the values reported recently by Refs. [15] and [21].

Table 2. Magnetic dipole hyperfine interaction constant A_{171} for the 6s6p ^{1}P$_1$ level of ^{171}Yb.

A_{171}/MHz	reference
–212.9(0.9)	this work
–214.173(53)	[15]
–211.9(3.1)	[14]
–201.2(2.8)	[13]
–213.0(10)	[12]
–211.0(1.0)	[10]
–213.4(3.0)	[11]
–216.3(4.4)	[8]

Table 3. Comparison of measurements of hyperfine constants in the 6s6p ^{1}P$_1$ level of ^{173}Yb.

hyperfine constant/MHz		
A_{173}	B_{173}	reference
57.9 (0.2)	608.4(0.8)	this work
57.693(0.006)	609.028(0.050)	[21]
57.682(0.029)	609.065(0.098)	[15]
57.910(0.120)	610.470(0.840)	[22]
58.10(0.3)	588.0(2)	[10]
58.45(0.8)	589.6(13)	[9]
59.75(0.5)	604.0(7)	[8]
	605.0(20)	[11]

4. Conclusions

We have measured the isotope shifts and hyperfine splittings of all Yb isotopes for the 399-nm transition by using quite a simple method. We have also determined the frequency shifts of the ^{173}Yb ($F' = 3/2$) by a three-peak Lorentzian fitting and the least isotope ^{168}Yb. In the comparison of the measured results including ours, we found the most of discrepancies were resolved. Unfortunately, still there are some discrepancies among them. Therefore, further study is necessary. We are going to measure all shifts by beating two 399-nm lasers that will be locked at the 399-nm transition lines of different isotopes respectively.

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