

Research Article

Isotope Shifts in High Lying Levels of Dy I and Er I by High-Resolution UV Laser Spectroscopy

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High-resolution atomic-beam ultraviolet (UV) laser spectroscopy in Dy I and Er I has been performed. Isotope shifts have been measured for two transitions in Dy I and one transition in Er I. Specific mass shifts and field shifts have been derived for the studied transitions, and large differences between the two $4f^{10}6s^2-4f^{10}6s6p$ transitions in Dy I have been found. From the derived specific mass shifts and field shifts, configuration mixing at the upper levels of transitions has been discussed.

1. Introduction

High-resolution laser spectroscopy continues to play an important role in obtaining atomic spectroscopic data such as isotope shift (IS). The IS contains fundamental atomic properties such as electronic configuration and wave function. Recently, theoretical calculations of IS have been reported by different groups using various methods for light elements of Li, Na, and Mg [1–3]. Dysprosium and erbium, two typical rare-earth elements, have the $4f$, $5d$, $6s$, $6p$ open shells, which yield complicated atomic structures. Such a kind of complex heavy atoms provides a challenge to theoretical atomic calculations of many-electron atoms [4]. Moreover, Dy and Er are prime candidates for the study of ultracold dipolar physics [5, 6]. On the other hand, measurements of IS yield the mass dependence of nuclear charge radii, a key information for the study of unstable nuclei [7, 8]. Study of IS is, therefore, of much interest not only from the point of view of atomic physics but also from the point of view of nuclear physics.

Many studies of IS have been reported for Dy I and Er I in the visible and near-infrared regions by laser spectroscopy [5, 9–16]. For the ultraviolet (UV) region, corresponding to high lying levels at energy about 25000 cm^{-1} , only several measurements have been reported. ISs in high lying levels of Dy I have been measured by using a Fabry-Perot spectrometer [17] and those of Er I by Doppler-reduced saturation

absorption spectroscopy [18]. Strong configuration mixing is considered in such high lying levels and may yield different ISs.

In our previous papers [19–21], we reported high-resolution atomic-beam UV laser spectroscopy in Gd I and Er I around 395 nm by frequency doubling of a diode laser beam. The present work is to extend previous measurements to the wavelength region of about 402 nm in Dy I and Er I. In this paper, ISs are measured for two UV transitions in Dy I and one transition in Er I. From ISs, field shifts and specific mass shifts are obtained, and results are discussed.

2. Experiment

The present experiment was performed using an atomic beam and a UV laser beam. The experimental setup is essentially identical to that used in our previous experiments [19–21]. An atomic vapor was ejected from a 1-mm-diameter hole of a molybdenum oven heated to about 1400°C by an electron-bombardment heating method. An atomic beam was formed by a 2-mm-diameter aperture at a distance of 30 cm from the oven.

A laser beam with a wavelength of about 804 nm and a power of about 20 mW was produced using a commercial tunable diode laser with an external cavity system (Newport 2010M). A UV beam with a wavelength of about 402 nm and a power of about $10\mu\text{W}$ was obtained by frequency

TABLE 1: Wavelengths of the studied transitions and properties of the lower and upper levels in Dy I and Er I.

Element	Wavelength (nm)	Lower level			Upper level		
		Configuration	Level	Energy (cm ⁻¹)	Configuration	Level	Energy (cm ⁻¹)
Dy	401.382	$4f^{10}6s^2$	5I_8	0.0	$4f^{10}6s6p$	(6,2) ₇	24906.86
	404.597	$4f^{10}6s^2$	5I_8	0.0	$4f^{10}6s6p$	(8,1) ₇	24708.96
Er	400.796	$4f^{12}6s^2$	3H_6	0.0	$4f^{12}6s6p$	(6,1) ₇	24943.272

TABLE 2: Measured isotope shifts in Dy I and Er I.

Element	Wavelength (nm)	Isotope shift (MHz)			
		164–162	162–160	160–158	158–156
Dy		164–162	162–160	160–158	158–156
	401.382	–959.0(16)	–1036.5(18)	–1023.1(28)	–1520.4(36)
	404.597	–375.7(14)	–398.3(15)	–397.9(23)	–530.2(29)
Er		170–168	168–166	166–164	164–162
	400.796	–866.5(15)	–855.2(17)	–859.3(16)	–1028.7(28)

doubling using a cw frequency doubler (Spectra-Physics, Wavetrain).

The laser beam crossed the atomic beam perpendicularly in order to reduce the Doppler broadening. A spherical mirror was used to collect laser-induced fluorescence from the atomic beam which was detected with a cooled photon-counting photomultiplier (Hamamatsu R2257P). An interference filter with a 40 nm width at 400 nm was used in front of the photomultiplier, and, therefore, the background from the intense oven light was greatly suppressed. The spectrum of transmitted light through a confocal Fabry-Perot interferometer (FPI) with a free spectral range of 300 MHz was measured simultaneously with the fluorescence spectrum for relative frequency calibration.

3. Results

Two transitions in Dy I and one transition in Er I were studied in this experiment. Wavelengths of the transitions, electronic configurations, and energies of the lower and upper levels [22–24] are presented in Table 1. For Dy, two transitions are from the ground state $4f^{10}6s^2\ ^5I_8$ to the levels of the $4f^{10}6s6p$ configuration. For Er, the transition is from the ground state $4f^{12}6s^2\ ^3H_6$ to the (6,1)₇ level of the $4f^{12}6s6p$ configuration. All transitions belong to s^2 - sp transitions.

Figure 1 shows the observed fluorescence spectrum for the 400.796 nm transition in Er I. Peaks of the four even-mass isotopes ^{170}Er , ^{168}Er , ^{166}Er , ^{164}Er could be easily identified from their peak intensities together with their isotopic abundances. The peak of the lowest abundance (0.14%) isotope ^{162}Er was also clearly observed. Other peaks are hyperfine structure peaks of the odd-mass isotope ^{167}Er , with the nuclear spin of 7/2, has rich hyperfine structure peaks which are mainly overlapped with strong peaks of even-mass isotopes. The full width at half maximum (FWHM) of peaks is approximately 70 MHz and is mainly from the natural width of the upper level of the transition and the residual Doppler effect of the interaction between the atomic beam and laser beam; the linewidth of the laser is less than 1 MHz.

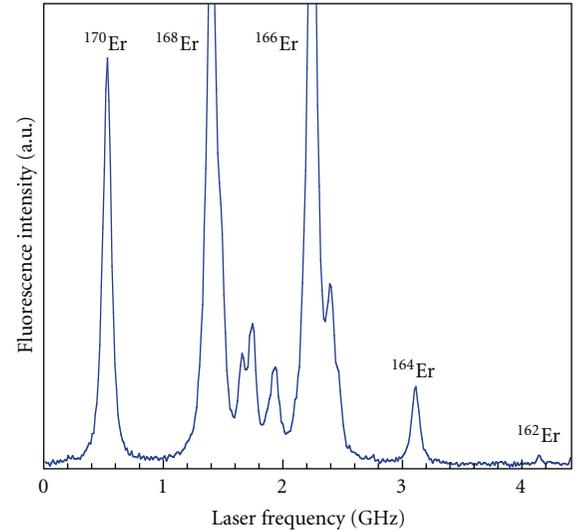


FIGURE 1: Observed fluorescence spectrum of the $4f^{12}6s^2\ ^3H_6 - 4f^{12}6s6p(6, 1)_7$ transition at 400.796 nm in Er I. Peaks of the even-mass isotopes are labeled with their atomic symbol. Other peaks are hyperfine structure peaks of the odd-mass isotope ^{167}Er .

Measured spectra were fitted with a Lorentz function and calibrated with the FPI spectra. For each transition, measurement was repeated about 20 times. Thus, ISs were obtained for the studied transitions and are listed in Table 2. The uncertainties of measured ISs are 2–4 MHz and contain the error of peak-center determination, the error of the free spectral range of the FPI (0.046 MHz), and the error of linearity correction for frequency scanning.

For Dy, the IS is –959 MHz for the isotope pair of 164–162 for the 401.382 nm transition while the IS is –376 MHz, more than twice smaller, for the 404.597 nm transition. For the Er 400.796 nm transition, the IS is –867 MHz for the isotope pair of 170–168.

TABLE 3: Determined SMS factors M_{iSMS} and electronic factors F_i in Dy I and Er I.

Element	Wavelength (nm)	M_{iSMS} (10^5 MHz)	F_i (GHz/fm ²)
Dy	401.382	-1.5(30)	-8.21(45)
	404.597	-20.4(16)	-2.12(13)
Er	400.796	-13.4(62)	-7.86(53)

TABLE 4: Derived specific mass shifts and field shifts in Dy I and Er I.

Element	Wavelength (nm)	Specific mass shift (MHz)				Field shift (MHz)			
		164-162	162-160	160-158	158-156	164-162	162-160	160-158	158-156
Dy		164-162	162-160	160-158	158-156	164-162	162-160	160-158	158-156
	401.382	-11(22)	-11(23)	-12(24)	-12(24)	-979(22)	-1057(23)	-1044(24)	-1542(24)
	404.597	-153(12)	-157(12)	-161(13)	-165(13)	-253(12)	-272(13)	-269(13)	-398(13)
Er		170-168	168-166	166-164	164-162	170-168	168-166	166-164	164-162
	400.796	-94(44)	-96(45)	-98(46)	-101(47)	-801(44)	-788(45)	-791(46)	-959(47)

4. Analysis and Discussion

The isotope shift $\delta\nu_i$ between the isotopes with the mass numbers A and A' , for a transition i , contains the mass shift and field shift (FS). The mass shift includes the normal mass shift (NMS) and specific mass shift (SMS) [25, 26]. The NMS $\delta\nu_{iNMS}$, due to the change in the reduced mass of electron and nucleus, can be calculated easily using the transition frequency. The SMS $\delta\nu_{iSMS}$ is caused by the influence of correlations in the motion of electrons on the recoil energy of the nucleus and is expressed as

$$\delta\nu_{iSMS} = M_{iSMS} \frac{A' - A}{AA'}, \quad (1)$$

where M_{iSMS} is the factor of the SMS. The FS $\delta\nu_{iFS}$ originates from the change in the nuclear charge distribution and is written as

$$\delta\nu_{iFS} = F_i \lambda, \quad (2)$$

where F_i is the electronic factor related to the change of the electron charge density at the nucleus and λ is called the nuclear parameter associated with the change in mean-square nuclear charge radii $\delta\langle r^2 \rangle$ [26].

When the modified IS $\delta\nu_i^{\text{mod}}$ and modified nuclear parameter λ^{mod} are defined as

$$\delta\nu_i^{\text{mod}} = (\delta\nu_i - \delta\nu_{iNMS}) \frac{AA'}{A' - A} \cdot \frac{2}{A_1 \cdot A_2}, \quad (3)$$

$$\lambda^{\text{mod}} = \lambda \frac{AA'}{A' - A} \cdot \frac{2}{A_1 \cdot A_2},$$

a following linear relation is obtained:

$$\delta\nu_i^{\text{mod}} = F_i \lambda^{\text{mod}} + M_{iSMS} \frac{2}{A_1 \cdot A_2}, \quad (4)$$

where $A_1 = 164$, $A_2 = 162$ for Dy and $A_1 = 170$, $A_2 = 168$ for Er. The relation of (4) is called King plot [27]. Using the knowing nuclear parameter λ , the SMS factor M_{iSMS} , and electronic factor F_i , that is, the SMS and FS, can be obtained from the measured IS by the King plot.

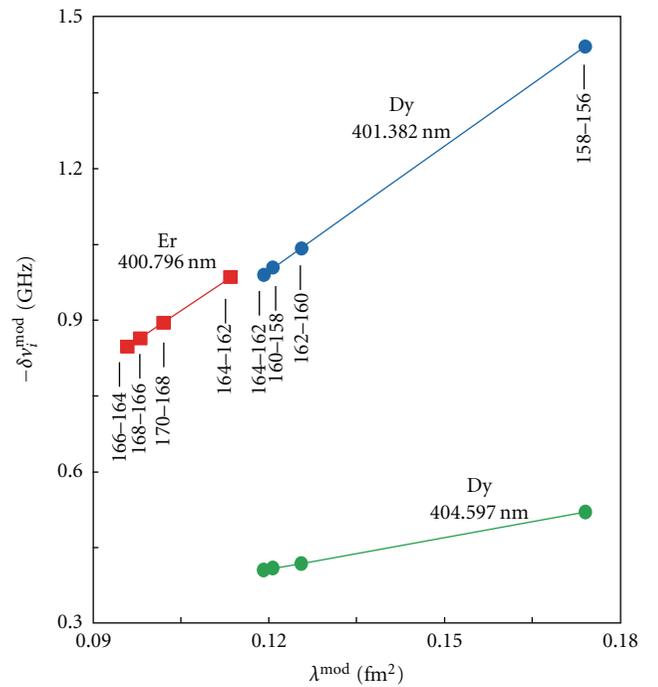


FIGURE 2: King plots for the three transitions in Dy I and Er I. Errors of both $\delta\nu_i^{\text{mod}}$, the y axis, and λ^{mod} , the x axis, are within symbols. Lines are the results of a least-squares fit.

Figure 2 shows King plots for the studied three transitions in Dy I and Er I. In the King plot we used values of the nuclear parameter λ derived from optical IS measurements with the experimental uncertainty [13, 14]. Good linear relations are seen for all King plots. From the King plot, the electronic factor F_i and SMS factor M_{iSMS} were obtained and are listed in Table 3 for all transitions studied. Uncertainty of 5% was included in the error of the electronic factor F_i as in [14]. Using the SMS factor M_{iSMS} , SMS was obtained and FS was further deduced from the measured IS. The derived SMSs and FSs are listed in Table 4 for the different isotope pairs.

It can be seen from Table 4 that, for the Dy 401.382 nm transition, the SMSs are negligibly small within experimental uncertainties and the FSs, that is, the ISs, are comparable to those observed in the visible region [14]. This shows that the Dy 401.382 nm transition is a pure s^2 - sp transition. For the Dy 404.597 nm transition, however, the SMS is -153 MHz and the FS is -253 MHz for the isotope pair of 164–162, largely deviating from those of the 401.382 nm transition. This is considered to be due to strong configuration mixing at the upper level of the 404.597 nm transition. For the Er 400.796 nm transition, the SMS is -94 MHz and the FS is -801 MHz for the isotope pair of 170–168, significantly deviating from those observed in the visible region [13]. This shows that significant configuration mixing exists at the upper level of the 400.796 nm transition in Er I.

For the odd-parity levels of Dy I and Er I, configurations of $4f^N 6s6p$, $4f^{N-1} 5d6s^2$, and $4f^{N-1} 5d^2 6s$ are involved and mixing between these three configurations is possible. For the transitions of $4f^{10} 6s^2 - 4f^9 5d6s^2$ in Dy I and $4f^{12} 6s^2 - 4f^{11} 5d6s^2$, $4f^{12} 6s^2 - 4f^{11} 5d^2 6s$ in Er I, the SMS factor M_{iSMS} and electronic factor F_i have been reported and have a sane order of magnitude for Dy and Er [10, 21]. Using the derived SMS factor M_{iSMS} and electronic factor F_i in Table 3 and those reported for the transitions of $4f^{10} 6s^2 - 4f^9 5d6s^2$ in Dy I and $4f^{12} 6s^2 - 4f^{11} 5d6s^2$, $4f^{12} 6s^2 - 4f^{11} 5d^2 6s$ in Er I, percentage of configuration mixing at the upper levels of the studied transitions can be estimated. For the upper level $4f^{10} 6s6p (8,1)_7$ of the 404.597 nm transition in Dy I, considering a mixing from the $4f^9 5d6s^2$ configuration, we obtained 25(5)% mixing using the SMS factor M_{iSMS} and 27(4)% mixing using the electronic factor F_i . However, by supposing a mixing from the $4f^9 5d^2 6s$ configuration, mixing of 94(16)% was estimated and was unreasonably too large. Therefore, we concluded that there is 26(3)% mixing from the $4f^9 5d6s^2$ configuration at the upper level $4f^{10} 6s6p (8,1)_7$ of the 404.597 nm transition in Dy I. In a similar way, 10(3)% mixing from the $4f^{11} 5d6s^2$ configuration at the upper level $4f^{12} 6s6p (6,1)_7$ of the 400.796 nm transition in Er I was estimated using the electronic factor F_i .

5. Summary

High-resolution laser spectroscopy in the UV region of Dy I and Er I has been performed using frequency doubling of the diode-laser beam together with the collimated atomic beam. ISs have been measured for two UV transitions in Dy I and one transition in Er I. SMSs and FSs as well as SMS factors M_{iSMS} and electronic factors F_i have been derived from the measured ISs using the known nuclear parameter. From the derived SMSs and FSs, it has been found that the 401.382 nm transition in Dy I can be considered as a pure s^2 - sp transition, and, for the upper level $4f^{10} 6s6p (8,1)_7$ of the 404.597 nm transition, strong mixing of 26(3)% from the $4f^9 5d6s^2$ configuration was estimated. For the upper level $4f^{12} 6s6p (6,1)_7$ of the 400.796 nm transition in Er I, significant mixing from the $4f^{11} 5d6s^2$ configuration was found and estimated to be 10(3)%.

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