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Research Article

Zeeman Effect of Sm Atoms by High-Resolution Diode-Laser Spectroscopy

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High-resolution atomic-beam diode-laser spectroscopy in Sm I has been performed. Zeeman spectra have been measured for the three optical transitions at different external magnetic fields and well resolved at the magnetic fields of stronger than 6.0 mT. Using the known precise Landé g-factors of the ground multiplet, the Landé g-factors of the upper $4f^6 6s6p\ {}^9F_1$ and ${}^9D_3$ levels have been determined, and their precision has been improved compared with the reference values.

1. Introduction

Studies of the interaction of atoms with an external magnetic field, the Zeeman effect, have a long history and have been of repeated interests to spectroscopists [1–5]. The atomic Landé g-factor, a measure of the atomic magnetic moment, can be deduced from the Zeeman spectroscopy and provides a sensitive test of atomic calculation [6–8]. The Zeeman effect is also related to the research of the atomic parity nonconservation [9]. Moreover, precise information of magnetic fields for interstellar clouds, which is important for understanding the role played by magnetic fields in star formation, can be obtained from the Zeeman observation [10–12]. Study of the Zeeman effect is, therefore, of much interest not only from the point of view of atomic physics but also from the point of view of other fields such as astrophysics.

Samarium, a typical rare earth element, is suitable for measurements of the Zeeman effect because it has rich optical transitions and many stable isotopes. The Landé-g factors of the ${}^7F$ ground multiplet were precisely determined using an atomic-beam magnetic resonance [13, 14]. Some high-lying levels were measured by means of atomic-beam laser spectroscopy [15–17]. Martin et al. [18] tabulated Landé-g factors for almost all known excited levels of Sm, and errors were not given.

In this paper, we report high-resolution atomic-beam diode-laser spectroscopy in Sm I around 680 nm. Zeeman spectra at different external magnetic fields are measured and analyzed for three transitions. Using the known precise values of the Landé g-factor of the ground multiplet, the Landé g-factors of the upper levels are obtained, and results are discussed.

2. Experiment

The present experiment was performed using a diode-laser beam and an atomic beam. The experimental setup is shown in Figure 1 and is essentially identical to that used in our previous works [19, 20]. Evaporation of Sm atoms was made using a resistance heating of a molybdenum oven. The oven temperature was controlled at about 900°C in order to produce a sufficient vapor pressure for Sm. An atomic beam was formed by a 2 mm diameter aperture at a distance of 30 cm from the oven.

A laser beam was produced using a commercial tunable diode laser with an external cavity system (EOSI ECU2010-01A). The wavelength of the laser, from 665 nm to 690 nm, was measured with a high-precision wavemeter. The output power was about 8 mW and the linewidth of the laser beam was smaller than 100 kHz.

In order to reduce the Doppler broadening, the laser beam crossed the atomic beam perpendicularly. At the interaction region, the intensity of the atomic beam with a diameter of about 2 mm was estimated to be about 2×10^{12}

Table 1: Wavelengths of the studied transitions and properties of the lower and upper levels in Sm I.

Wavelength (nm)	Lower level Configuration	Lower level Level	Lower level Energy (cm^{-1})	Upper level Configuration	Upper level Level	Upper level Energy (cm^{-1})
672.59	$4f^66s^2$	$^7F_0$	0.0	$4f^66s6p$	$^9F_1$	14863.85
680.30	$4f^66s^2$	$^7F_2$	811.92	$4f^66s6p$	$^9D_3$	15507.35
686.09	$4f^66s^2$	$^7F_1$	292.58	$4f^66s6p$	$^9F_1$	14863.85

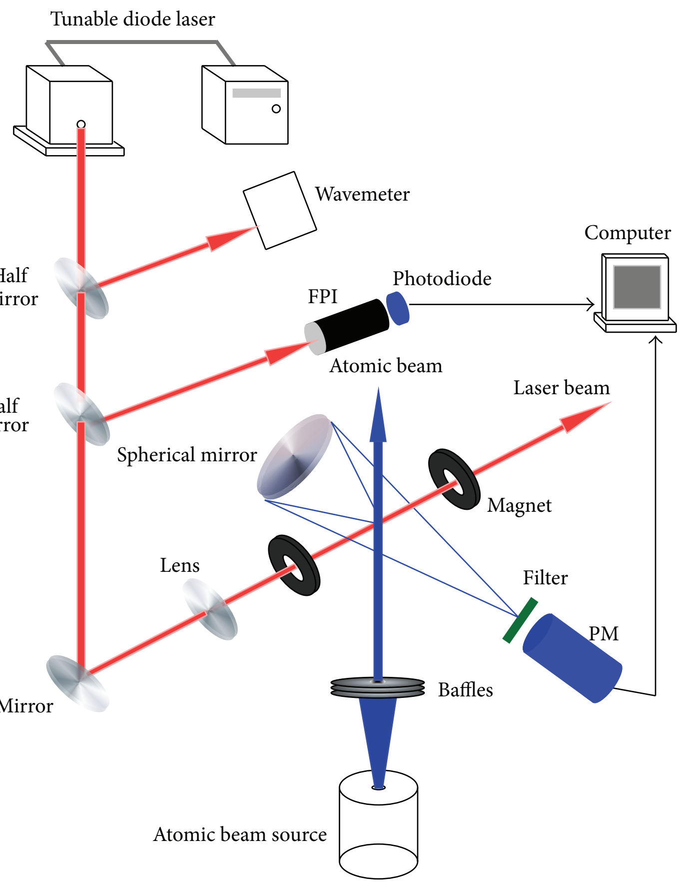

Figure 1: Experimental setup. FPI denotes Fabry-Perot interferometer and PM photomultiplier.

atoms/s from the oven temperature using the equation given by Ramsey [21], and the intensity of the laser beam with a diameter of about 3 mm was estimated to be about 3×10^{15} photons/s. Fluorescence from the atomic beam, induced by the laser beam, was collected with a spherical mirror and detected with a cooled photon-counting photomultiplier (Hamamatsu R2257P). Relative frequency calibration was made by measuring the spectrum of transmitted light through a confocal Fabry-Perot interferometer (FPI) with a free spectral range of 300 MHz.

The magnetic field at the interaction region between the laser beam and the atomic beam was produced using a pair of permanent magnets. The magnets had a ring shape with an inner diameter of 13–32 mm, an outer diameter of 40–60 mm, and a thickness of 4.9–8.2 mm, and the magnetic field could be changed using different magnets. The magnets were set along the laser beam and, therefore, the magnetic field was almost parallel to the laser beam, that is, perpendicular to the atomic beam.

3. Results and Analysis

Three transitions in Sm I were studied in this experiment. Wavelengths of the transitions, electronic configurations, and energies of the lower and upper levels [18, 22] are presented in Table 1. All transitions are from the levels of the ground term $4f^66s^2$ ^7F to the levels of the $4f^66s6p$ configuration, that is, the s^2-sp transitions. For the 672.59 nm and 686.09 nm transitions, the upper levels are of a same level of $4f^66s6p$ $^9F_1$.

Figure 2 shows a typically observed fluorescence spectrum for the 680.30 nm transition in Sm I. Stable Sm has five even-mass isotopes, ^{144}Sm, ^{148}Sm, ^{150}Sm, ^{152}Sm, and ^{154}Sm, and two odd-mass isotopes, ^{147}Sm, and ^{149}Sm. ^{147}Sm and ^{149}Sm, both, with the nuclear spin of $I = 7/2$, have

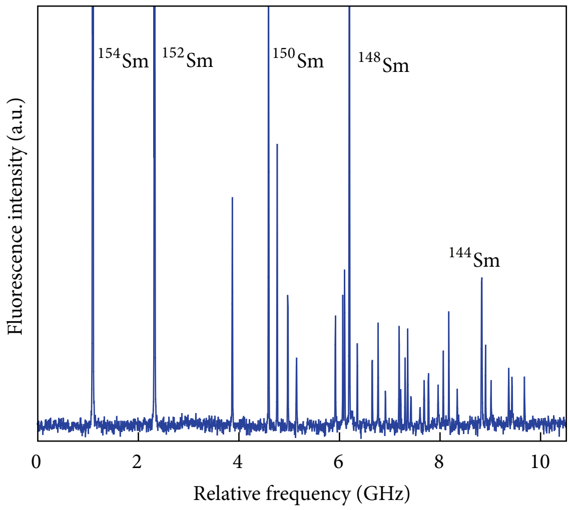

Figure 2: Observed fluorescence spectrum of the $4f^6 6s^2\ ^7F_2$–$4f^6 6s6p\ ^9D_3$ transition at 680.30 nm in Sm I. Peaks of the even-mass isotopes are labeled with their atomic symbol. Other peaks are hyperfine structure peaks of the two odd-mass isotopes ^{147}Sm and ^{149}Sm.

complicated hyperfine structures. No hyperfine structures exist for the even-mass isotopes because they have no nuclear spin: the even-mass isotopes are suitable for studying the Zeeman effect. It can be seen from Figure 2 that there are no other peaks around the peaks of ^{152}Sm and ^{154}Sm. Therefore, spectra of ^{152}Sm and ^{154}Sm were used for measurement of the Zeeman effect in this experiment.

Zeeman spectra were observed at three different magnetic fields. The observed Zeeman spectra of ^{152}Sm and ^{154}Sm are shown in Figure 3 for the 680.30 nm transition. Since the Zeeman spectra were observed with the permanent magnets, and the fluorescence spectra were observed without the permanent magnets, starting of the frequency scanning was different for these two spectra as shown in Figures 2 and 3. Splittings of the spectra become larger as magnetic fields become stronger. At the magnetic field of 4.1 mT, the spectra overlap considerably while the spectra become well resolved at the magnetic fields of stronger than 6.0 mT. The spectra of ^{154}Sm show a same pattern as those of ^{152}Sm. The full width at half maximum (FWHM) of the peaks is about 14 MHz. This width is considered to be due to the natural width of the upper level of the transition and the residual Doppler broadening of the atomic beam since the linewidth of the laser is smaller than 100 kHz.

Peak centers of the measured spectra were determined from a least-squares fit with a Lorentz function and calibrated with the FPI spectra. For each transition, measurements were performed more than 10 times. Thus, relative differences between different peaks were determined with the uncertainty of about 0.5 MHz, which includes 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 atoms in an external magnetic field B, the atomic level with an electronic angular momentum J splits into $(2J + 1)$

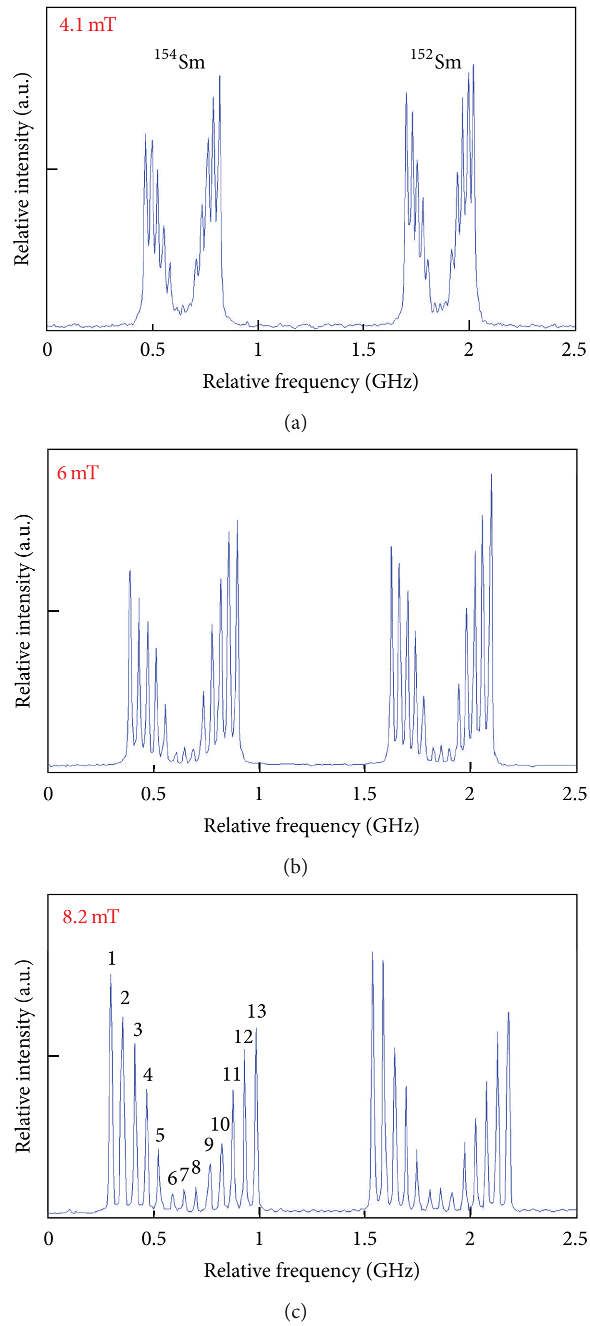

Figure 3: Observed Zeeman spectra of ^{152}Sm and ^{154}Sm at the 680.30 nm transition for three magnetic fields. The numbers labeled on peaks correspond to the numbers on Zeeman transitions in Figure 4.

magnetic sublevels with a magnetic quantum number m_J. The Zeeman energy ΔE from the interaction between the external weak magnetic field and the atomic magnetic moment is expressed as follows [23]:

$$\Delta E = m_J g_J \mu_B B, \tag{1}$$

where g_J is the atomic Landé g-factor and μ_B is the Bohr magneton.

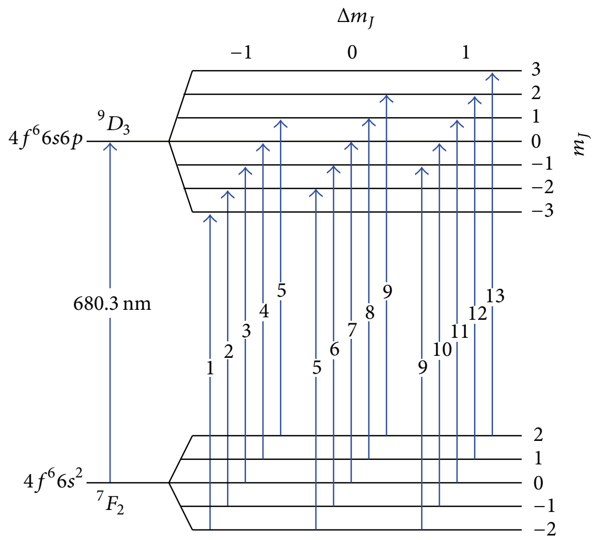

FIGURE 4: Zeeman splittings and transitions for the 680.30 nm transition. m_J is the magnetic quantum number and Zeeman transitions are divided into the three series of $\Delta m_J = -1, 0, +1$. The numbers on the Zeeman transitions correspond to the numbers labeled on peaks in Figure 3.

TABLE 2: Determined atomic Landé g-factors, g_J, for the $4f^6 6s6p\ ^9F_1$ and $^9D_3$ levels in Sm I together with the reference values.

Magnetic Field (mT)	g_J			
	$^9F_1$		$^9D_3$	
	^{154}Sm	^{152}Sm	^{154}Sm	^{152}Sm
6.0	3.097 (3)	3.094 (3)	1.946 (3)	1.946 (3)
8.2	3.094 (3)	3.087 (3)	1.955 (3)	1.956 (3)
Average	3.093 (2)		1.951 (3)	
Reference [18]	3.10		1.965	

For the 680.30 nm transition, the lower $4f^6 6s^2\ ^7F_2$ level with $J = 2$ splits into the 5 sublevels, and the upper $4f^6 6s6p\ ^9D_3$ level with $J = 3$ splits into the 7 sublevels. The Zeeman splittings of the 680.30 nm transition are shown in Figure 4 together with the possible transitions according to the selection rule of $\Delta m_J = m_J$ (the upper $^9D_3$ level) $-m_J$ (the lower $^7F_2$ level) $= 0, \pm 1$.

The observed Zeeman spectra were identified with the Zeeman transitions as shown in Figure 4. For the 680.30 nm transition, the observed spectra shown in Figure 3 can be divided into three series of $\Delta m_J = -1, 0, +1$. The peak intensities of the $\Delta m_J = -1$ series are comparable with those of the $\Delta m_J = +1$ series. Peaks of the $\Delta m_J = 0$ series are also observed with lower intensities, and two of them are overlapped with those of the $\Delta m_J = \pm 1$ series.

From the observed Zeeman spectra, Zeeman splitting energies of both the lower and the upper levels can be obtained and are related to the external magnetic field and the g_J values of the lower and upper levels as shown in (1). Using the known precise g_J values of the $^7F_1$ and $^7F_2$ levels, the external magnetic fields B were calibrated from the measured Zeeman splitting energies of the lower levels. Since the g_J values of the lower levels were precisely measured, the uncertainty of the external magnetic field was determined by the uncertainty of the measured Zeeman splitting energies (about 0.5 MHz) to be about 0.1–0.2%. Further, the g_J values of the upper levels were determined and are presented in Table 2. The g_J values were derived from the spectra at the magnetic fields of 6.0 mT and 8.2 mT; data at the magnetic field of 4.1 mT were not used because the spectra are overlapped considerably. The uncertainty of the g_J values of the upper levels was determined by the uncertainties of the measured Zeeman splitting energies and the calibrated magnetic field and is about 0.1–0.2% as shown in Table 2.

It can be seen from Table 2 that the g_J values at the magnetic field of 6.0 mT agree with the values at the magnetic field of 8.2 mT at the margin of experimental uncertainties. The g_J values of ^{154}Sm are in good agreement with those of ^{152}Sm and this shows that the Landé g-factor is independent of the isotope. Thus, the averaged g_J values were obtained for the $4f^6 6s6p\ ^9F_1$ and $^9D_3$ levels. The g_J values tabulated by Martin et al. [18] are also listed in Table 2 for comparison. The reference g_J values are very close to the present values. Because errors are not given for the reference g_J values, it is difficult to make detailed comparison between the present values and the reference values. For the $4f^6 6s6p\ ^9F_1$ level, the precision of the present g_J value is, however, improved at least one order of magnitude compared with the reference value.

4. Summary

High-resolution laser spectroscopy in Sm I has been performed using the diode-laser beam together with the collimated atomic beam. Fluorescence spectra have been observed for the three optical transitions, and the spectra of ^{152}Sm and ^{154}Sm have been used for measurements of the Zeeman effect. The Zeeman spectra have been measured at the three external magnetic fields and well resolved at the magnetic fields of stronger than 6.0 mT. The observed spectra have been identified with the Zeeman transitions and the magnetic fields have been calibrated with the known precise g_J values of the ground multiplet. The g_J values of the upper $4f^6 6s6p\ ^9F_1$ and $^9D_3$ levels have been determined and show no isotopic dependence. The precision of the present g_J values is improved compared with the reference values. The precise g_J values of various atomic levels are useful for astrophysics.

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