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Hyperfine structure of singly ionized lanthanum and praseodymium

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Hyperfine structure spectra of singly ionized lanthanum and praseodymium have been measured by collinear fast-ion-beam laser spectroscopy. All the spectral lines were resolved and the magnetic dipole and electric quadruple coupling constants of the metastable levels and excited levels were determined. Our results are in agreement with the published data within the experimental uncertainty. For praseodymium ions, the accuracy of the magnetic dipole coupling constants are improved by one order of magnitude compared with other published data, and the electric quadruple coupling constants are reported for the first time.

Keywords: hyperfine structure, fast-ion-beam laser spectroscopy, magnetic dipole and electric quadruple coupling constants

PACC: 3290

1. Introduction

Hyperfine structure (HFS) in atomic ions is caused by the electromagnetic interaction between the nucleus and orbital electrons. Information of the nuclear structure and the electronic properties of ions can be obtained through studying HFS. Several techniques have been developed to study HFS by using laser and ion beams. Andrä[1] introduced the laser-induced quantum-beat method. Wing *et al*[2] first demonstrated the velocity-bunching effect. Then, the method was used by Meier *et al*[3] and Holt *et al.*[4] Dufay and Gaillard[5] initiated the in-flight lamb-dip technique for the measurement of HFS. Bellah-Mansour *et al*[6] measured the HFS of Sc II by using a radio-frequency laser double-resonance method. Kuwamoto *et al*[7] have studied HFS in Pr I by Doppler-free atomic-beam laser spectroscopy. Ginibre[8] measured the fine structure and HFS of Pr II by using grating photographic spectrograms and Fourier transform interferograms.

Andrä[9] first introduced the laser excitation of fast ion beams. Bengtson *et al*[10] used collinear fast-ion-beam laser spectroscopy for HFS measurements in Cs II. The collinear geometry technique provides a powerful method of high precision spectroscopy. Because of the kinematic compression when ions are accelerated, sub-Doppler resolution can be obtained with a collinear geometry. Using an isotope separator permits selective measurements of different isotopes. These two properties make the collinear fast-ion-beam laser spectroscopy method very powerful and accurate. In this paper, the magnetic dipole coupling constant (A) and electric quadruple coupling constant (B) of $^{139}La^{+}$ and $^{141}Pr^{+}$ are obtained.

2. Experimental results

In first-order perturbation theory, the hyperfine energy splitting ΔE is expressed as the sum of the magnetic dipole term $\Delta E_{\rm MD}$ and the electric quadruple term $\Delta E_{\rm EQ}$ as follows

$$\begin{aligned}\Delta E =&\Delta E_{\rm MD} + \Delta E_{\rm EQ}\\ =&\frac{1}{2}KA + \frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}B. \quad (1)\end{aligned}$$

Here

$$K = F(F+1) - I(I+1) - J(J+1),$$

A and B are the magnetic dipole and electric quadruple coupling constants, respectively, I is the nuclear spin and J is total quantum number of electrons. The conserved quantum number is the total angular momentum $F = I + J$.

The energy shift $\Delta E_{\rm MD}$ is caused by the interaction between the internal magnetic field produced at

the nucleus by orbital electrons and the nuclear magnetic dipole moment. In the same way, $\Delta E_{\rm EQ}$ corresponds to the interaction between the electric field gradient and the nuclear quadruple moment. The relative intensities of all hyperfine splitting transitions satisfy the iterative rule. The intensity is proportional to the statistical weight of the lower level (IJF) and upper level $(IJ'F')$ and to the 6-j symbol[11] as follows

$$gf_{\rm HFS}(IJF \to IJ'F') \propto (2F+1)(2F'+1) \times \left\{ \begin{array}{ccc} J & I & F \\ F' & 1 & J' \end{array} \right\}. \quad (2)$$

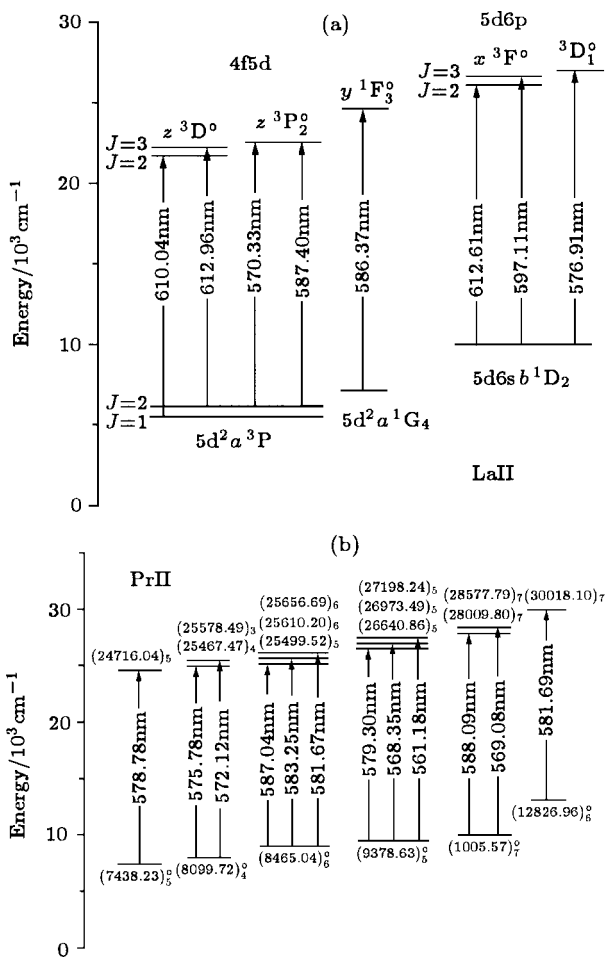


Fig.1. A partial energy level diagram of La II (a) and Pr II (b). The laser-excited transitions from the metastable levels are indicated by upward arrows.

For lanthanum and praseodymium, each has only one stable odd isotope. Partial fine energy levels of $^{139}La^+$ and $^{141}Pr^+$ investigated in this work are shown in Fig.1. The experimental set-up is shown in Fig.2. A 30 kV electronic isotope separator (Danfysik 1080-30) was used to produce singly charged $^{139}La^+$ or $^{141}Pr^+$ ion beams. An isotopically pure ion beam was selected. The ion beam passed through a vacuum tube and entered the chamber. The beam current was typically about 2μA when chlorides were used as a precursor in the ion source. A single-mode Coherent 899-29 ring dye laser was used to provide light with a bandwidth less than 1 MHz.[12] The laser beam was steered through a Browster window into the chamber and then through a set of apertures that define the ion beam path. In this way, it was possible to obtain a good counter-propagating overlap between the laser and the ion beams in the detection region. A glass filter and a monochromator were used to suppress stray laser light. By scanning the laser over a frequency region, the entire fluorescence spectrum was obtained. The hyperfine splitting resonant spectrum was recorded by using the fluorescence to the ground state or lower metastable states. The fluorescence light was focused by a set of lenses and detected by a photomultiplier (EMI 9789B).

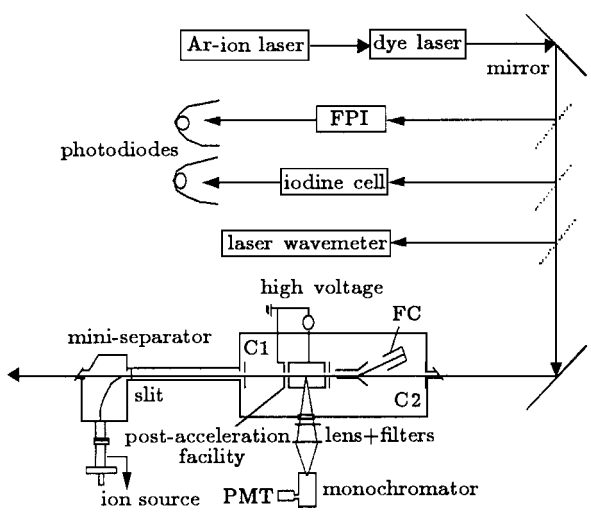


Fig.2. The experimental set-up: PD, photodiode; HV, high-voltage power supply; PMT, photomultiplier tube; FC, Faraday cup; C1 and C2, collimators; FPI, Fabry–Perot interferometer.

The typical hyperfine resolved spectra in 5d6s $b^1D_2 \to x^3F^\circ$ (J'=2,3) transitions of $^{139}La^+$ are shown in Figs.3(a) and 3(b), respectively. Assigned transitions between hyperfine splitting levels were determined by combining a least-squares fit to Eq.(1) with Eq.(2) of the relative intensity. For La, the nuclear spin I is 7/2. In Fig.3(a), the quantum numbers of the lower and upper levels are 11/2, 9/2, 7/2, 5/2, 3/2 and 9/2, 7/2, 5/2, respectively. Three hyperfine transitions for $\Delta F = F' - F = 0, \pm 1$, respectively, were resolved. In Fig.3(b), the quantum numbers of the lower and upper levels are 11/2, 9/2, 7/2, 5/2,

3/2 and 13/2, 11/2, 9/2, 7/2, 5/2, 3/2, 1/2, respectively. Five hyperfine transitions for $\Delta F = 0, \pm 1$, respectively, were observed, but the relative intensity for hyperfine transitions of 9/2→7/2 and 11/2→9/2 is close to the background noise. Four hyperfine coupling constants of the upper and lower levels were determined by combining a least-squares fit to Eq.(1) and Eq.(2) of the relative intensity of the other thirteen hyperfine transitions. Then the hyperfine transitions of 9/2→7/2 and 11/2→9/2 could be determined.

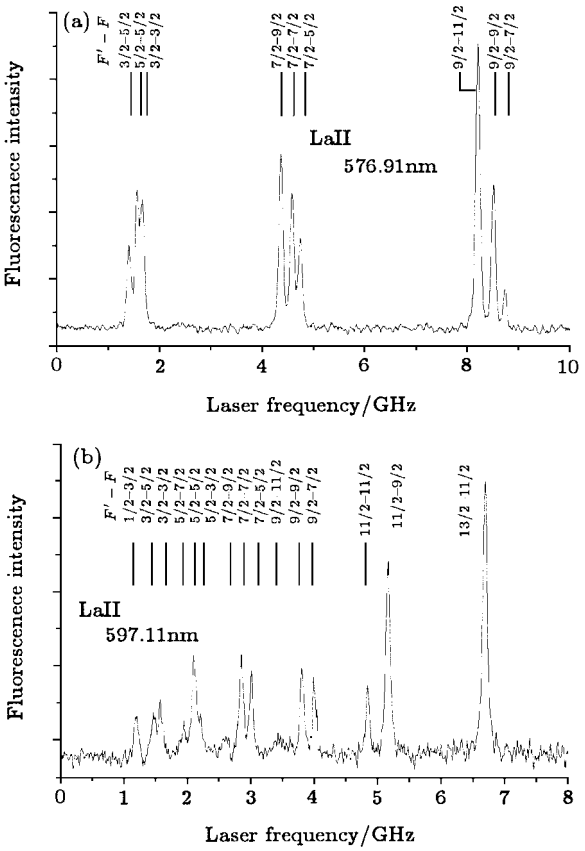


Fig.3. HFS spectra of $5d6s^2 {}^1D_2 \rightarrow x^3F^\circ$ (J'=2,3) transitions for $^{139}La^+$. F and F' are the quantum numbers of the lower and upper levels, respectively.

The typical hyperfine resolved spectra in $(7438.23)^\circ_5 \rightarrow (24716.04)_4$ and $(8099.72)^\circ_4 \rightarrow (25578.49)_3$ transitions of $^{141}Pr^+$ are shown in Figs.4(a) and 4(b), respectively. The nuclear spin I for Pr is 5/2. In Fig.4(a), the quantum numbers of the lower and upper levels are the same, that is, 15/2, 13/2, 11/2, 9/2, 7/2, 5/2. Five hyperfine transitions for $\Delta F = \pm 1$, respectively, and six for $\Delta F = 0$ are resolved. In Fig.4(b), the quantum numbers of the lower and upper levels are 13/2, 11/2, 9/2, 7/2, 5/2, 3/2 and 11/2, 9/2, 7/2, 5/2, 3/2, 1/2, respectively. Six hyperfine transitions for $\Delta F = -1$, five for $\Delta F = 0$, and four for $\Delta F = +1$, are resolved.

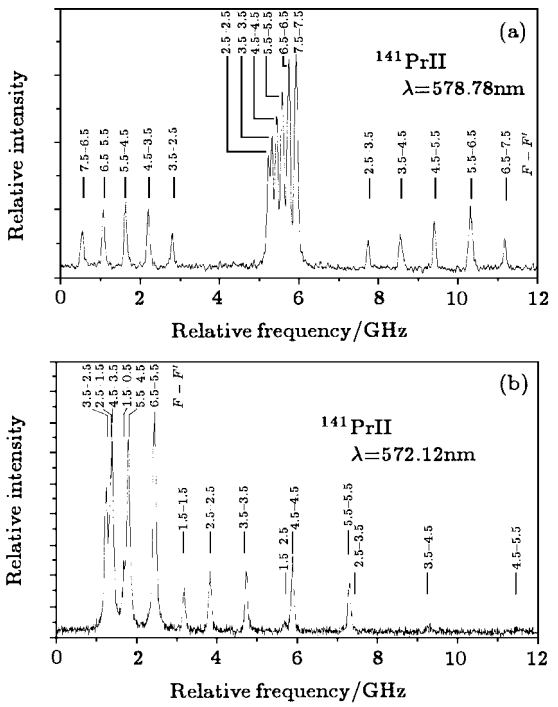


Fig.4. HFS spectra in $(7438.23)^\circ_5 \rightarrow (24716.04)_4$ and $(8099.72)^\circ_4 \rightarrow (25578.49)_3$ transitions for $^{141}Pr^+$. F and F' are the quantum numbers of the lower and upper levels, respectively.

3. Analysis and discussion

The measured hyperfine coupling constants A and B of the metastable levels and excited levels of $^{139}La^+$ and $^{141}Pr^+$ are listed in Tables 1 and 2. The analysis of the measured results is subject to possible systematic errors caused by experimental uncertainties, such as laser frequency calibration, uncertainties in determining the centres of the peaks in the HFS spectrum, and the ion velocity distribution. The line broadening is partly due to the limited quality of the ion beam. Some additional energy dispersion may arise from plasma ion source instabilities. Such energy fluctuations lead to a spread of the velocity distribution. The experimental uncertainties are listed together with Tables 1 and 2. For comparison, the results published by Höhle *et al*[13] are listed in Table 1 and data published by Ginibre[8] are listed in Table 2. The measured hyperfine coupling constants A and B of $^{139}La^+$ are in agreement with the results of Höhle *et al.* Ginibre[8] has measured the magnetic dipole coupling constants A of $^{141}Pr^+$ by assuming that the electric quadruple coupling constant B is zero. The measured magnetic dipole coupling constants A of $^{141}Pr^+$ are in agreement with Ginibre's data within experimental uncertainty, and the accuracy of our results is

improved by one order of magnitude compared with Ginibre's data. The electric quadruple coupling constants B of $^{141}Pr^{+}$ are small compared with the magnetic dipole coupling constants A, but not zero.

Table 1. Measured hyperfine coupling constants A and B of $^{139}La^{+}$, and values A_H and B_H quoted from Ref.[13].

Wavelength/nm	Level	Our results		Results of Höhle *et al*[13]	
		A/MHz	B/MHz	A_H/MHz	B_H/MHz
610.04	$z\ ^3D_2^\circ$	127.8±2.4	2.6±7.5		
	$a\ ^3P_1$	−223.1±1.5	17.0±5.6		
570.33		34.9±1.2	14.2±4.5		
	$a\ ^3P_1$	−227.2±1.6	35.1±5.2		
587.40	$z\ ^3P_2^\circ$	35.0±0.6	9.2±3.6		
	$a\ ^3P_2$	−159.0±1.5	−32.6±4.5		
612.96	$z\ ^3D_3^\circ$	100.9±1.2	−31.2±6.9		
	$a\ ^3P_2$	−161.6±1.8	−42.6±4.2		
576.91	$^3D_1^\circ$	886.9±1.5	−18.9±4.8		
	$b\ ^1D_2$	47.8±0.6	43.1±4.5		
597.11	$x\ ^3F_3^\circ$	258.9±1.5	114.3±7.6		
	$b\ ^1D_2$	49.5±1.2	41.0±4.6		
612.61	$x\ ^3F_2^\circ$	251.0±1.8	44.5±6.6	250.53	51.9
	$b\ ^1D_2$	48.1±2.4	34.3±6.9		
586.37	$y\ ^1F_3^\circ$	162.0±2.1	22.3±4.2	164.28	20.4
	$a\ ^1G_4$	148.1±1.2	156.3±2.4	150.06	151.8
mean	$a\ ^3P_1$	−225.2±1.1	26.0±3.8	−224.61	20.4
	$z\ ^3P_2^\circ$	35.0±0.7	11.7±2.9	34.47	11.1
	$a\ ^3P_2$	−160.4±1.2	−37.6±3.1	−158.22	−45.0
	$b\ ^1D_2$	48.5±0.9	39.5±3.1	48.15	39.9

Table 2. Measured hyperfine coupling constants A and B of $^{141}Pr^{+}$, and A_G quoted from Ref.[8].

Wavelength/nm	Energy level/cm^{-1}	A/MHz	B/MHz	A_G/MHz
578.78	7438.23	709.3±1.2	19.5±6.0	714±6
	24716.04	735.0±1.1	15.9±3.5	732±22
581.67	8465.04	572.9±1.2	−4.1±7.0	
	25656.69	656.4±1.0	−10.0±2.1	657±46
587.04	8465.04	574.1±1.3	−8.0±6.0	
	25499.52	632.1±1.3	−14.5±4.1	639±55
583.25	8465.04	574.8±1.0	−3.1±5.0	
	25610.20	543.2±0.7	−7.2±3.1	546±46
572.12	8099.72	768.4±1.2	37.9±6.8	
	25578.49	1031.6±2.2	12.2±6.6	891±17

575.78	8099.72	773.1±1.3	31.5±6.3	
	25467.47	736.2±1.5	16.2±6.6	732±67
561.18	9378.63	612.7±1.5	9.3±9.7	
	27198.24	583.3±1.1	–4.6±4.3	600±55
568.35	9378.63	613.7±1.5	8.1±9.0	
	26973.49	601.7±1.2	–1.6±3.7	612±22
579.30	9378.63	615.1±1.3	10.0±9.1	
	26640.86	619.1±1.0	5.4±4.0	588±54
588.09	11005.57	546.3±1.3	10.3±9.9	
	28009.80	558.2±1.0	5.4±4.0	576±40
569.08	11005.57	547.0±1.5	9.1±9.8	
	28577.79	530.8±1.1	–4.9±5.4	537±16
581.69	12826.94	487.3±1.0	–17.4±5.6	489±46
	30018.10	525.9±1.1	4.0±3.7	495±40
mean	8465.04	573.9±0.7	–5.1±3.5	576±5
	8099.72	770.8±0.9	34.7±4.6	768±13
	9378.63	613.8±0.8	9.1±5.4	612±11
	11005.57	546.7±1.0	9.7±7.0	558±40

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