

Hyperfine structure and isotope shifts in 461.9 nm forbidden line of Pb I

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Studies of the hyperfine structure and the isotope shifts in the 461.9 nm ($^1S_0 \rightarrow ^3P_1$) magnetic-dipole line of Pb I are presented. As a light source the electrodeless discharge tube was used. The high resolution spectral apparatus consisted of a silver coated Fabry–Perot etalon and a grating spectrograph combined with a CCD camera used as a detector. In the analysis of the spectra a computer simulation technique was used. The experiments with the isotope ^{207}Pb yielded the hyperfine structure splitting constant A for the 3P_1 level of the $6s^26p^2$ ground configuration. In the experiment with natural lead the isotope shifts between four stable isotopes (204, 206, 207, 208) were measured.

Keywords: hyperfine structure, isotope shift, forbidden lines, lead.

1. Introduction

The $6s^26p^2$ ground configuration of lead consist of five levels: 3P_0 , 3P_1 , 3P_2 , 1D_2 and 1S_0 . The second-order radiation occurs due to transitions between levels of the same parity, therefore weak magnetic-dipole ($M1$), electric-quadrupole ($E2$) and a mixed type ($M1 + E2$) transitions between levels of the $6s^26p^2$ configuration are permitted.

If the components of the atomic structure are well resolved their relative intensities and individual positions can be easily determined. Problems arise when the structures are partly or completely unresolved. For such a case the computer simulation technique becomes very useful. Recently such a computer technique have been used in the analysis of hyperfine structure (hfs) spectrum of Pb I [1, 2] and isotope shift (IS) study of Pb II [3] and it has proved to be efficient and reliable.

In the present experiment this technique is used to analyse the spectra of the magnetic-dipole 461.9 nm line of Pb I. The experiment with the isotope ^{207}Pb yielded the hfs constant A for the 3P_1 level. In the experiment with natural lead we have measured the isotope shifts between four stable isotopes.

2. Experiment

The experimental arrangement was similar to that used by us earlier in the hyperfine structure analysis of lines of Pb I [1, 2], Pb II [3] and Bi II [4]. In brief, the light source was a quartz discharge tube connected to a vacuum system. To obtain a clear spectrum a very careful outgassing of the tube is necessary. Helium was used as a buffer gas. The discharge was excited by a rf oscillator (100 MHz) connected to the discharge tube by external electrodes. The high resolution spectral apparatus consisted of a silver-coated Fabry–Perot etalon and Carl Zeiss Jena PGS-2 grating spectrograph (1200 grooves/mm, resolution 0.8 nm/mm in the first order) combined with a CCD detector (Hamamatsu model C7041 with head device model S7031-1006).

3. Computer program

The first step in the computer analysis involves finding the positions and relative intensities of all the individual components. This procedure accepts the required atomic data of the investigated line: the I and J quantum numbers of the two energy levels involved. The next procedure sorts all the components according to the wave number. In order to calculate the sum of intensities at each point of the final pattern using estimated values for the line profile coefficients the following intensity distribution function is employed [5–7]:

$$I(\nu) = I_{\text{BN}}(\nu) + C \sum_i^N \frac{I_0^i}{1 + \alpha_1^2 [\text{RL} + (\nu - \nu_i)]^2 + \alpha_2^4 [\text{RL} + (\nu - \nu_i)]^4} \quad (1)$$

where $I_{\text{BN}}(\nu)$ describes the background noise, C is the scaling factor, α_1 , α_2 are the line shape parameters, N is the number of isotopes and hfs components, I_0^i is the maximum intensity of the i -th component (proportional to the transition probability and percentage admixture of each isotope), RL is an adjustable parameter in the wave number scale and ν_i is a position of the component. In the next step the least-squares-fitting procedure is used. The simulated structure is compared with the experimental curve recorded in the digital form. Then the experimental profile is linearized and after linearization is normalized. The simulated contour is fitted into the experimental one by suitable variation of free parameters (*i.e.*, C , α_1 , α_2 , RL).

4. Results

4.1. Hyperfine structure study

The hfs splitting of the 461.9 nm line of the Pb I was observed by the use of metallic isotope 207. Figure 1 presents one of the recorded hyperfine patterns of the observed line. In the studies we used 14 and 16 mm Fabry–Perot spacers. The time of exposition

was about 15 minutes. For all the spectra we analysed the first three visible interference orders.

The observed line contours were analysed by the use of the least-squares-fitting procedure described in section 3. In Fig. 1 black dots represent experimental results while the solid line is the best fit described by formula (1). The dashed and dotted lines represent contributions to the total intensity from each of the hfs component. The computer simulations yielded the A hyperfine constant for the 3P_1 level of the $6s^26p^2$ ground configuration of lead, presented in Tab. 1.

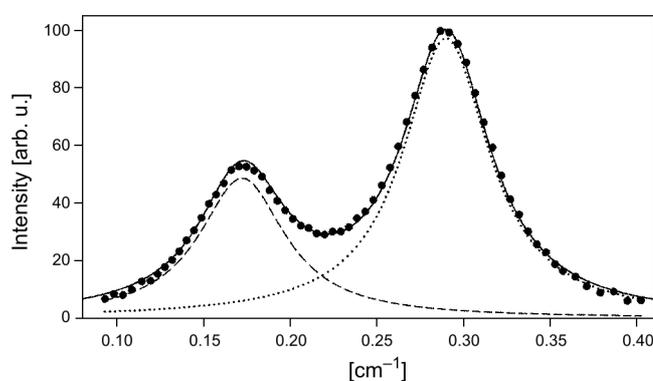


Fig. 1. Experimental hfs trace and calculated best-fit curve for 461.9 nm multipole line of $^{207}\text{Pb I}$. Black dots represent experimental results and the solid line is the best fit.

Table 1. Hfs A constants for the 3P_1 level of the $6s^26p^2$ configuration of Pb I (in mK).

Level	$A^{\text{Present work}}$	$A^{\text{Other authors}}$
3P_1	-80.4 (1.4)	-79.4 (0.7), ref. [8] -87.0 (2.0), ref. [9] -79.70 (0.02), ref. [10] -79.7 (1.5), ref. [11]

This value represents the average of several measurements performed under different experimental conditions. The number in brackets is the standard deviation. In Tab. 1 other experimental results, obtained by the use of various experimental techniques, are given for comparison. Our result is in good overall agreement with earlier studies performed for strong $E1$ lines.

Result from Tab. 1 was used in further studies of isotope shifts measured for natural composition of lead isotopes.

4.2. Isotope shift study

The observation of isotopic structure of multipole lines is very difficult because of relatively small shifts and relative large admixtures of even (206, 208) isotopes.

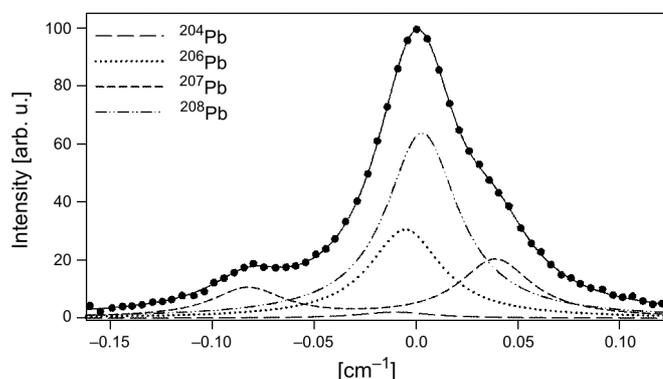


Fig. 2. Experimental IS trace and calculated best-fit curve for 461.9 nm multipole line of natural lead. Black dots represent experimental results and the solid line is the best fit.

Figure 2 presents one of the recorded IS traces and the computer calculated curve. In this figure black dots represent experimental results and the solid line is the best fit described by formula (1). In studies of this line the 12 and 14 mm Fabry–Perot spacers were used and the recording time was within the range of 60–120 minutes.

In the fitting procedure, the hyperfine splitting constant from Tab. 1 and theoretical relative intensity ratios of hfs components were used as fixed parameters. For all the spectra we analysed the first three visible interference orders. In Fig. 2 the dashed and dotted lines represent contributions from each isotope to the total intensity.

The computer simulations yielded the isotope shifts with respect to the center-of-gravity (cg) of the isotope 208 presented in Tab. 2. Each value represents the average of several measurements performed under different experimental conditions. The numbers in brackets are standard deviations. In Tab. 2 also experimental results from [11], obtained by the use of absorption spectroscopy, are given for comparison.

Table 2. Measured isotope shifts relative to ^{208}Pb (in mK).

Line [nm]	$\delta\nu^{208-207\text{cg}}$	$\delta\nu^{208-206}$	$\delta\nu^{208-204}$
461.9	4.2 (1.4)	6.6 (1.5)	12.1 (3.2)
1279.0, ref. [11]	4.6 (0.6)	7.4 (0.5)	

Table 3. Percentage abundance of lead isotopes of masses 204, 206, 207, 208.

	204	206	207	208
Ref. [12]	1.50	23.60	22.60	52.30
Ref. [13]	1.04	27.03	17.65	54.28
Present work	1.4 (0.7)	25.7 (2.5)	16.0 (2.0)	56.9 (2.8)

Table 3 presents the isotopic composition of the lead sample used in the experiment. Admixtures measured by us were derived from maxima of peaks of the line profile function (1).

References

- [1] WAŚOWICZ T.J., DROZDOWSKI R., KWELA J., *Hyperfine structure study of several lines of $^{207}\text{Pb I}$* , *Physica Scripta* **71**(3), 2005, pp. 274–6.
- [2] WAŚOWICZ T.J., DROZDOWSKI R., KWELA J., *Hyperfine structure study of several lines of $^{207}\text{Pb I}$ – Part II*, *Physica Scripta* **72**(2–3), 2005, pp. 200–2.
- [3] WAŚOWICZ T.J., DROZDOWSKI R., KWELA J., *Hyperfine structure and isotope shift study in singly ionized lead*, *The European Physical Journal D* **36**(3), 2005, pp. 249–55.
- [4] GRABOWSKI D., DROZDOWSKI R., KWELA J., J. HELDT, *Hyperfine structure and Zeeman effect studies in the $6p7p$ – $6p7s$ transitions in Bi II*, *Zeitschrift für Physik D: Atoms, Molecules and Clusters* **38**(4), 1996, pp. 289–93.
- [5] HÜHNERMANN H., PhD Thesis, Philipps Universität, Marburg/Lahn 1967.
- [6] HÜHNERMANN H., *J. Phys. (Paris)* **28**, Suppl. C2, 1967, p. 260.
- [7] MÜLLER G., PhD Thesis, Technischen Universität, Berlin 1974.
- [8] MROZOWSKI S., *Hyperfine structure and intensities of the forbidden lines of Pb I*, *Physical Review* **58**(12), 1940, pp. 1086–93.
- [9] SIMONS J.W., PALMER B.A., HOF D.E., OLDENBORG R.C., *Characterization of several ultraviolet-visible emission lines from a lead hollow-cathode lamp*, *Journal of the Optical Society of America B* **6**(6), 1989, pp. 1097–1102.
- [10] BOUAZZA S., GOUGH D.S., HANNAFORD P., LOWE R.M., WILSON M., *Isotope shifts and hyperfine structure in near-ultraviolet transitions of PbI by Doppler-free saturation spectroscopy*, *Physical Review A* **63**(1), 2001, p. 012516.
- [11] REEVES J.M., FORTSON E.N., *Isotope shifts at 1.28 μm in Pb*, *Physical Review A* **44**(3), 1991, pp. R1439–41.
- [12] WEAST R.C., SELBY S.M., [Eds.] *Handbook of Chemistry and Physics*, 46th ed., Chemical Rubber Company, Cleveland, Ohio 1965.
- [13] COLLINS C.B., FARQUHAR R.M., RUSSELL R.D., *Variations in the relative abundances of the isotopes of common lead*, *Physical Review* **88**(6), 1952, pp. 1275–6.

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