Hyperfine-structure measurements in Xe II

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The hyperfine structures and constants of the $5d\ ^4D_{7/2}$, $6p\ ^4P_{5/2}$, $6p\ ^2D_{5/2}$, and $6p\ ^4D_{7/2}$ levels have been experimentally determined with the use of a fast ion-beam-laser technique.

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INTRODUCTION

In the 1970s it was realized that laser excitation of fast ion beams provided a powerful method of high precision spectroscopy [1,2]. Three specific properties of a fast ion beam are useful. First, the high velocity of the ions can be utilized in measurements of atomic lifetimes [3,4]. Typical velocities of the order of 1 mm/ns relate well to typical lifetimes in the ns region so that time-of-flight methods can be used for lifetime determinations. Since the excitation process is selective, cascade problems are avoided and very accurate results can be obtained. Second, because of the kinematic compression [5], which occurs when ions are accelerated, very high spectral (sub-Doppler) resolution can be obtained with a collinear geometry. Third, the use of an isotope separator permits selective studies of the different isotopes. These three properties make the method of fast ion-beam-laser spectroscopy (FIBLAS) very powerful and accurate. The method is, however, restricted to transitions that can be accessed by available lasers.

The singly ionized xenon ion has been studied by different variations of FIBLAS. This ion has a number of metastable states about 15 eV above the ground state [6,7]. From these metastables, a number of other excited states can be excited by use of cw lasers in the visible wavelength region. The metastables are usually strongly populated in ordinary ion sources, and strong laser-induced fluorescence signals can be obtained. The xenon ion has consequently served as a test case for experiments involving both lifetime measurements and high precision spectroscopy (such as hyperfine-structure determinations) based on the FIBLAS concept.

We have recently published the results of an investigation of Xe II [8] using a version of the FIBLAS method previously developed by us [9]. In this work the lifetimes of five different levels were determined. We also found the reason for a previously puzzling discrepancy between different measurements of the lifetime of the $6p\ ^4D_{5/2}$ state. This problem turned out to be due to problems with previous assignments of certain transitions.

In the present paper we report on a continuation of our study of the singly charged xenon ion. As mentioned, several papers have been previously published on hyperfine-structure measurements on the transition $5d\ ^4D_{7/2}$–$6p\ ^4P_{5/2}$ using different versions of FIBLAS. In particular, a very accurate measurement of the lower level of the transition was reported by Rosner, Gaily, and Holt [10] using a rf-laser double-resonance method. Except for these two states, however, to the best of our knowledge, no hyperfine structure has been reported for any other level in Xe II. In this work we present a determination of hyperfine structure in two different levels, namely, $6p\ ^2D_{5/2}$ and $6p\ ^4D_{7/2}$.

EXPERIMENT

The experiment was performed at the Manne Siegbahn Laboratory. At the CRYRING facility there is an isotope separator, INIS, that was built as an ion injector for the ion source CRYSIS (an EBIS source for production of highly charged ions). INIS can, however, also be used for laser experiments at a separate beam line, as described previously [8,11] (cf. Fig. 1). The ions are produced in a low-voltage, hot cathode ion source. Relatively low gas pressure was used in the ion source to favor a high fraction of metastables in the ion beam. The ion source is raised to a potential of nominally 25 kV to accelerate the ions. The accelerated ion beam is deflected in a 90° magnet, in order to separate the different xenon isotopes. The mass resolution is sufficient to clearly separate all xenon isotopes. Electrostatic quadrupole lenses are used to focus the ion beam, and deflection plates are used to steer the beam into the center of the interaction chamber. The beam path is defined by two 4-mm apertures on each side of the interaction chamber (1.4 m apart). For the hyperfine-structure measurements presented here, the isotopes ^{129}Xe and ^{131}Xe were used. The ion current for these isotopes was typically 0.5–1 μA in the interaction region. More details of the experimental setup have been given earlier [8,9,11].

Laser light was provided by a ring dye laser, a Coherent 699-29 with Autoscan. The dye laser was pumped by a Coherent argon-ion laser (CR 18). In the present experiment the dyes Rhodamine 110 and Rhodamine 6G were used to produce laser light at the wavelengths needed to excite the states mentioned above. Laser light was introduced collinearly into the vacuum system in order to utilize the kinematic compression effect to obtain high spectral resolution. Linewidths of 150–200 MHz were obtained, reflecting the velocity spread in the ion beam. The Autoscan function of the dye laser includes an internal wavemeter specified for an accuracy of 200 MHz on an absolute scale and with a reproducibility of 60 MHz. The laser is controlled by a personal computer (PC) with a special Autoscan program developed by Coherent Inc. The linearity of the scanning is, however, not sufficient to be used directly for evaluation of the recorded spectra. To control the frequency scale, part of the laser was directed into a commercial Fabry-Pérot interferometer (free spectral range, nominally 300 MHz). The free spectral range (FSR) of the
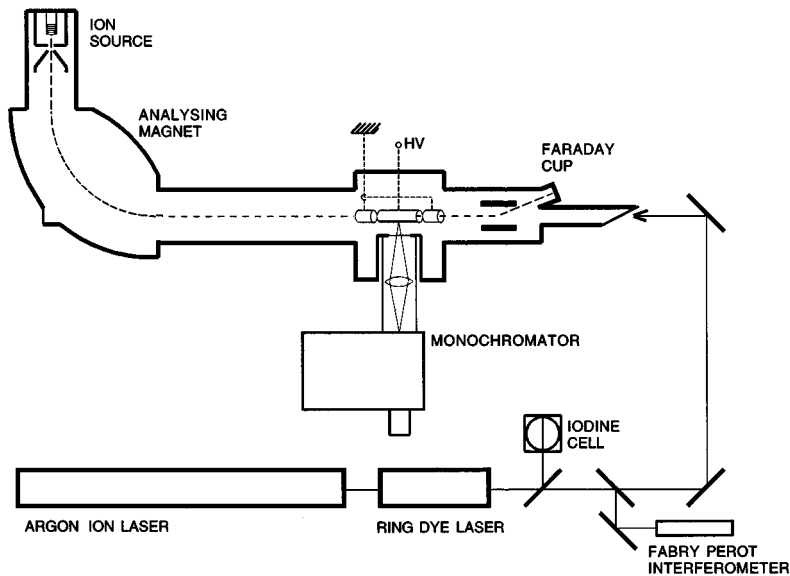
FIG. 1. Schematic figure of the experimental setup. Details of the equipment are given in the text.

interferometer was calibrated using an iodine spectrum measured over a range of more than 400 fringes. This procedure yielded a FSR of 298.32 ± 0.12 MHz. Part of the laser light was also directed into an iodine cell for a simultaneous recording of an iodine spectrum in order to have an extra check on the absolute frequency scale.

Laser-induced fluorescence was observed by a broadband monochromator (Heath EUE-700) equipped with a cooled EMI 9789 QA photomultiplier and a dark current of about 1 count per second. To avoid depletion of the metastable states by optical pumping before the ions entered the observation region, the ion beam velocity was changed locally. This was achieved by use of a cylindrical electrode, maintained at a high voltage, through which the ion beam had to pass. Thus a local change in the Doppler shift was obtained. This Doppler tuning device (DTD) can also be utilized for lifetime measurements, as described earlier [8,9]. In the present experiment the DTD voltage was kept fixed at typically -1000 V while the laser frequency was scanned. This extra acceleration voltage moved the resonance frequency about 40 linewidths.

DATA ANALYSIS

For each run, four data sets were stored in the PC, which was used to control the laser. The data sets were the curve from the internal wavemeter (the so-called VET signal), the iodine spectrum, the Fabry-Pérot fringes, and finally the hyperfine spectrum obtained from the laser-induced fluorescence signal. The first two data sets were only used to check that the run had been performed correctly. The Fabry-Pérot fringes were used to establish the frequency scale of the laser scan.

The positions of the fringes were determined by fitting Gaussian functions of equal height and equal width to the recorded peaks. To utilize the fact that the fringes are equidistant in the frequency domain, the peak positions as a function of the fringe number were fitted to a polynomial, usually of the fifth degree. This frequency calibration function was used to determine the frequencies corresponding to the peak positions found for the hyperfine peaks. These spectral lines

were also fitted by Gaussian line shapes. In most cases the shape of the fit function reflected the experimental shape better if the Gaussians were given exponential wings. This peak shape can be understood from the experimental geometry.

The fitting procedure gave statistical errors composed of both the uncertainty in the peak position determination and the uncertainty originating from the frequency calibration function. It was found, however, that the spread between different runs was larger than the statistical errors implied. These occasional errors could, for instance, be caused by changes in the total acceleration voltage. The error estimates given in this paper correspond to one standard deviation of the spread between different runs. Thus, the given errors include both known and unknown occasional errors as well as statistical errors.

The ^{131}Xe spectra contained several hyperfine components. The splittings gave information on the magnetic dipole constant A and the electric quadrupole constant B [12] of the upper and lower levels. These overdetermined equation systems were solved according to the least-squares criteria.

RESULTS

Three different transitions were studied: $5d\ ^4D_{7/2}-6p\ ^4P_{5/2}$ (6051 Å), $5d\ ^4D_{7/2}-6p\ ^4D_{7/2}$ (5472 Å), and $5d\ ^4D_{7/2}-6p\ ^2D_{5/2}$ (5531 Å). All these transitions have a common lower state ($5d\ ^4D_{7/2}$). Xenon has a rich spectrum of isotopes of which mass numbers 129, 131, 132, 134, and 136 have a natural abundance of about 10% or more. The odd number isotopes 129 and 131 have nuclear spin $I=\frac{1}{2}$ and $\frac{3}{2}$, respectively, and show hyperfine structure.

For mass 129, each level splits up into a hyperfine doublet for which the hyperfine constant A can be extracted ($\Delta E = A\ \mathbf{I} \cdot \mathbf{J}$). For mass 131, the levels split up into four hyperfine levels, which makes it possible to extract both the magnetic dipole constant A and the electric quadrupole constant B [12]. In the present experiment these constants have been determined for the four previously mentioned states for both isotopes.

The hyperfine structure of the common lower state has

TABLE I. Hyperfine constants obtained for $^{129}Xe^+$ and $^{131}Xe^+$ in the four levels studied in this work. These values are compared with available data in the literature. The uncertainty given in this work corresponds to one standard deviation.

Level	Constant	This work (MHz)	Holt et al. [13] (MHz)	Alvarez et al. [14] (MHz)	Borghs et al. [15] (MHz)	Bingham et al. [16] (MHz)	Rosner et al. [10] (MHz)
$5d\ ^4D_{7/2}$	A_{129}	-502 ± 4	-515.7 ± 8.9			-502.1 ± 2.0	$-503.075\ 80\pm0.000\ 35$
	A_{131}	150 ± 2	149.4 ± 3.2			149.3 ± 0.7	$149.155\ 60\pm0.000\ 16$
	B_{131}	70 ± 13	76.1 ± 27.5			70.1 ± 5.1	$71.110\ 1\ \pm0.001\ 1$
$6p\ ^4P_{5/2}$	A_{129}	-1633 ± 11	-1667.5 ± 18.7	-1641 ± 9	-1634.9 ± 0.9	-1637.7 ± 2.0	
	A_{131}	487 ± 4	487.5 ± 5.2	487.3 ± 0.5	485.3 ± 0.3	484.3 ± 1.1	
	B_{131}	-129 ± 16	-107.2 ± 52.3	-126 ± 6	-116.5 ± 2.0	-116.6 ± 4.7	
$6p\ ^2D_{5/2}$	A_{129}	-1387 ± 9					
	A_{131}	409 ± 2					
	B_{131}	-117 ± 10					
$6p\ ^4D_{7/2}$	A_{129}	-1164 ± 5					
	A_{131}	346 ± 2					
	B_{131}	-230 ± 11					

been accurately determined by Rosner et al. [10] using an rf-laser double-resonance technique. Using this technique, they were able to determine the constants with an accuracy of, at best, about 10^{-6}. This method is, however, only applicable to the long-lived metastable states. For the other states,

which are short-lived (7–10 ns [8]), the ordinary laser-induced fluorescence technique is suitable and capable of achieving an accuracy of about 10^{-2}–10^{-3}.

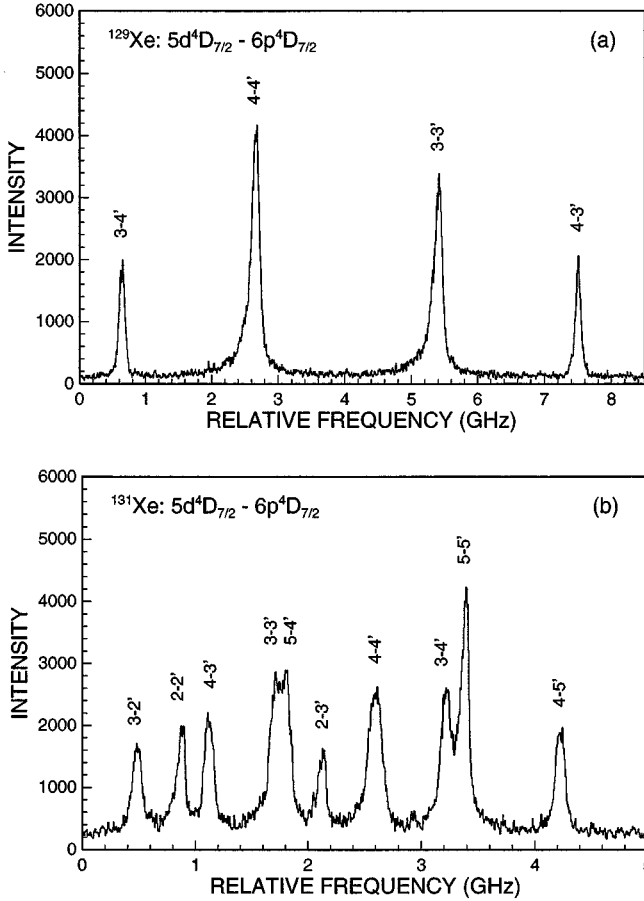The transition $5d\ ^4D_{7/2}$–$6p\ ^4P_{5/2}$ at 6051 Å has three components in $^{129}Xe^+$ and nine components in $^{131}Xe^+$ (of

FIG. 2. Examples of spectra recorded for the $5d\ ^4D_{7/2}$–$6p\ ^4D_{7/2}$ transition at 5472 Å in $^{129}Xe^+$ and $^{131}Xe^+$. Fluorescence was observed at 4844 Å. Intensity of fluorescence in arbitrary units.

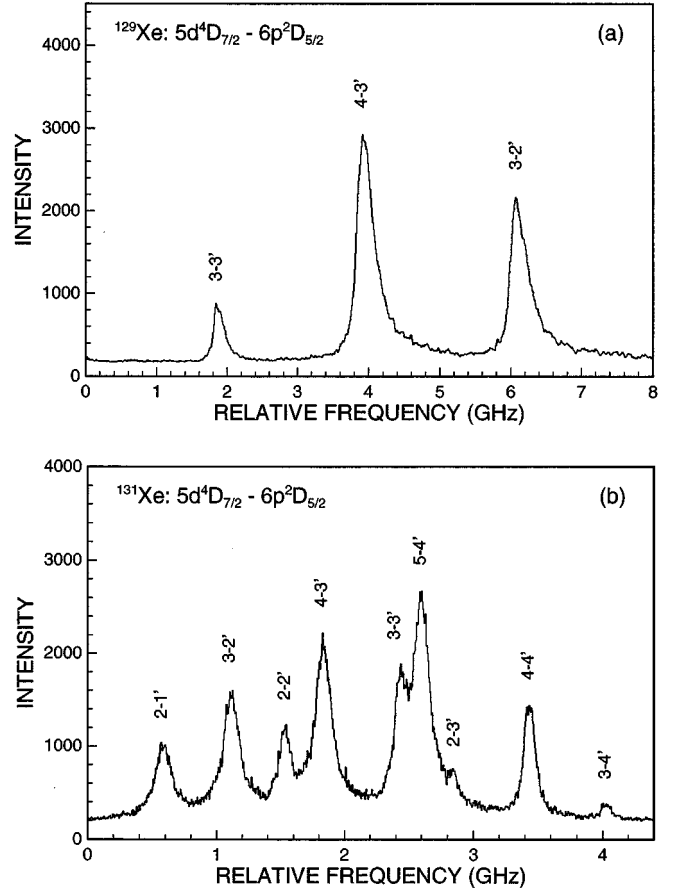FIG. 3. Examples of spectra obtained for the $5d\ ^4D_{7/2}$–$6p\ ^2D_{5/2}$ transition at 5531 Å in $^{129}Xe^+$ and $^{131}Xe^+$. Fluorescence light was observed at 5419 Å. Intensity of fluorescence in arbitrary units.

which two are very weak). This transition has been recorded several times earlier [13–16]. For the lower state $5d\ ^4D_{7/2}$, the reported results were consistent with the high precision measurement [10], which is also the case for our measurement. For the upper level $6p\ ^4P_{5/2}$, there is good agreement between the previous measurements and the present ones. We regard this measurement as a valuable checkpoint in relation to the new measurement. For these and the other states $6p\ ^4D_{7/2}$ and $6p\ ^4D_{5/2}$ the results have been collected in Table I. Recorded spectra are shown in Figs. 2 and 3. No other measurements of the hyperfine structure of these states have, to the best of our knowledge, been performed.

CONCLUSION

The hyperfine structure of four levels in Xe II have been determined by a fast ion beam-laser technique. For the two levels with hyperfine structure previously reported, the new values show good agreement. For the two other levels neither theoretical nor other experimental values are available for comparison.

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