Precision energies and hyperfine structures of the $5s5p\, ^3P^0_{0,1,2}$ and $5s\, 6s\, ^3S_1$ levels in In II

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Abstract. Absolute frequencies of hyperfine components of the 230.6 nm ($5s^2\, ^1S_0-5s\, 5p\, ^3P^0_1$), 193.6 nm ($5s\, 5p\, ^3P^0_0-5s\, 6s\, ^3S_1$), 197.7 nm ($5s\, 5p\, ^3P^0_1-5s\, 6s\, ^3S_1$) and 207.9 nm ($5s\, 5p\, ^3P^0_2-5s\, 6s\, ^3S_1$) transitions in In II emitted from a hollow-cathode source have been measured using a high-resolution, scanning échelle monochromator. The measured frequencies of these four transitions have been used to determine the energies and hyperfine interaction constants of the $5s\, 5p\, ^3P^0$, $5s\, 6s\, ^3S_1$ and $5s\, 6s\, ^3S_1$ levels in In II. The hyperfine interaction constants for the dominant isotope $^{115}\text{In}$ are found to be:

- $5s\, 5p\, ^3P^0_1\, A=0.2322(2)\, \text{cm}^{-1}$, $B=-0.0159(9)\, \text{cm}^{-1}$
- $5s\, 5p\, ^3P^0_2\, A=0.1699(4)\, \text{cm}^{-1}$, $B=0.021 (6)\, \text{cm}^{-1}$
- $5s\, 6s\, ^3S_1\, A=0.4022(4)\, \text{cm}^{-1}$, $B=0.002 (2)\, \text{cm}^{-1}$

The absolute frequency of the very narrow, strongly forbidden In II 236.5 nm ($5s^2\, ^1S_0-5s\, 5p\, ^3P^0_2$) transition, which has been proposed as a candidate for a new optical frequency standard, is found to be $42275.986(7)\, \text{cm}^{-1}$.

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1. Introduction

There is currently much interest in the spectroscopy of the strongly forbidden 236.5 nm ($5s^2\, ^1S_0-5s\, 5p\, ^3P^0_2$) transition in In II [1]. Because of its extremely small natural linewidth ($\Gamma_{\text{nat}}/2\, \pi \approx 1.1\, \text{Hz}$ [1]) and insensitivity to magnetic and electric fields, this transition when probed in a single laser-cooled In$^+$ ion stored in a Paul radiofrequency trap has been proposed as a candidate for a new optical frequency standard [2, 1]. However, in order to detect such a weak transition ($f \approx 6 \times 10^{-9}$) in a single, trapped In$^+$ ion, it is important first to know the absolute frequency of the transition to moderately high accuracy, preferably to within 1 GHz. The only reported determination of the frequency of the In II $5s^2\, ^1S_0-5s\, 5p\, ^3P^0_2$ transition to date are the 1938 data of Paschen and Campbell [3], for which two frequency values are given that differ by 0.69 cm$^{-1}$, or 21 GHz. Differences of this order are also found between Paschen and Campbell’s results for the strong 230.6 nm ($5s^2\, ^1S_0-5s\, 5p\, ^3P^0_1$) transition and recent results obtained by laser-induced fluorescence from trapped In$^+$ ions [1].

Attempts to detect the very weak 236.5 nm ($5s^2\, ^1S_0-5s\, 5p\, ^3P^0_2$) transition either by laser-induced fluorescence or optogalvanic detection in an In/Ne sputtering cell [4] or by optical-optical double resonance in laser-cooled In$^+$ ions stored in a radiofrequency trap [5] have to date proven to be unsuccessful. Furthermore, we have as yet been unable to find any evidence of the 236.5 nm transition in monochromator scans of the emission from a commercial indium hollow-cathode lamp.
alternative approach is to determine the frequency of the \(5s^2 \, ^1S_0 \rightarrow 5s \, 5p \, ^3P_0\) transition indirectly from the frequencies of a sequence of three strong transitions that link the \(5s^2 \, ^1S_0\) ground level to the \(5s \, 5p \, ^3P_0\) excited level via two other levels, such as the sequence \(5s^2 \, ^1S_0 \rightarrow 5s \, 5p \, ^3P_1 \rightarrow 5s \, 6s \, ^3S_1 \rightarrow 5s \, 5p \, ^3P_0\) shown by the bold lines in Fig. 1. Unfortunately, the only data available for transitions from the \(5s \, 5p \, ^3P_0\) and \(^3P_1\) levels to higher levels in In II are the 1931 data of Lang and Sawyer [6] and these yield a number of frequency values for the 236.5 nm \((5s^2 \, ^1S_0 \rightarrow 5s \, 5p \, ^3P_0)\) transition that are in very poor agreement from one sequence of transitions to another (standard deviation \(\approx 3\, \text{cm}^{-1}\) for 5 sequences).

In this paper we report determinations of the absolute frequencies of hyperfine components of the 230.6 nm \((5s^2 \, ^1S_0 \rightarrow 5s \, 5p \, ^3P_1)\), 193.6 nm \((5s \, 5p \, ^3P_0 \rightarrow 5s \, 6s \, ^3S_1)\), 197.7 nm \((5s \, 5p \, ^3P_1 \rightarrow 5s \, 6s \, ^3S_1)\) and 207.9 nm \((5s \, 5p \, ^3P_0 \rightarrow 5s \, 6s \, ^3S_1)\) transitions in In II. The measurements were made on In II lines emitted from a neon-filled indium hollow-cathode lamp using a high resolution (bandwidth \(\approx 0.0003\, \text{nm}\)), scanning échelle monochromator whose wavelength scale was calibrated by simultaneously scanning iron reference lines [7, 8] from a hollow-cathode lamp using a high resolution \((\text{bandwidth} \approx 0.0003\, \text{nm})\), scanning échelle monochromator whose wavelength scale was calibrated by simultaneously scanning iron reference lines [7, 8] from a hollow-cathode lamp. From the measured frequencies of the hyperfine components of these four transitions, precision energies and hyperfine interaction constants are determined for the \(5s \, 5p \, ^3P_0\), \(^3P_1\), \(^3P_2\) and \(5s \, 6s \, ^3S_1\) levels in In II and the absolute frequency of the strongly forbidden 236.5 nm \((5s^2 \, ^1S_0 \rightarrow 5s \, 5p \, ^3P_0)\) transition is deduced, with an estimated uncertainty of 0.007 cm\(^{-1}\) (200 MHz).

2. Experimental

2.1. Indium II

Figure 1 shows a partial energy level diagram for Indium II, illustrating the transitions investigated in this work. Level lifetimes are taken from [1]. The extremely weak 236.5 nm \((5s^2 \, ^1S_0 \rightarrow 5s \, 5p \, ^3P_0)\) transition occurs on account of mixing between the \(5s \, 5p \, ^3P_0\), \(F=9/2\) and \(5s \, 5p \, ^3P_1\), \(F=9/2\) hyperfine states, which are separated by 1074 cm\(^{-1}\).

Natural indium consists of two odd isotopes, \(^{113}\text{In}\) (4.3\%) and \(^{115}\text{In}\) (95.7\%), both of which have a nuclear spin of 9/2 and almost identical nuclear magnetic moments \([\mu (^{113}\text{In})=+5.523 \mu_N; \mu (^{115}\text{In})=+5.534 \mu_N]\) and electric quadrupole moments \([Q (^{113}\text{In})=+0.82\, \text{b}; Q (^{115}\text{In})=+0.83\, \text{b}]\). The hyperfine splittings of the atomic levels are thus almost the same for both isotopes. However, because of the relative abundances of the two isotopes, the energies and hyperfine splittings reported in this paper are essentially those of the dominant isotope, \(^{115}\text{In}\).

2.2. Light sources

The indium wavelength measurements were performed on lines emitted from a sealed indium hollow-cathode lamp (Varian-Techtron) which was filled to about 9 Torr of neon and operated with a (square-wave) modulated current of 15 mA. A similar hollow-cathode lamp, operating at 20 mA, was used to provide reference lines of iron [7, 8] for accurate wavelength calibration of the monochromator scans.

2.3. Monochromator

The In II lines were scanned using a 2.5 m scanning monochromator fitted with a 316 lines/mm échelle grating having a blaze angle of 63° and mounted in a Czerny-Turner configuration. The monochromator was not evacuated, but could be purged with dry nitrogen. A detailed description is given in [9]. Diffraction orders for the different lines were normally chosen to be close to the blaze angle. The instrumental width of the monochromator was typically 0.0003 nm (FWHM) for the range of In II wavelengths (193–236 nm) and diffraction orders (24–29) used.

2.4. Calibration and linearisation of wavelength scans

Lines from the indium hollow-cathode lamp and the iron reference lamp were scanned simultaneously by combining the light from the two lamps on to a 50:50 beam splitter and focussing the combined beam on to the entrance slit of the monochromator. The UV light at the exit slit was detected using a single Hamamatsu R166 solar-blind photomultiplier and the signals from the two lamps were separated by employing different modulation frequencies (near 285 Hz) in the lamps and using lock-in detection in two separate amplifiers referenced to the modulation frequencies. The data from the two amplifiers were recorded in two analogue-to-digital channels of a desk-top computer, which also controlled the wavelength scan of the monochromator. The widths of the observed In II profiles were typically 0.15 cm\(^{-1}\), including instrumental broadening.

A third channel of the computer was used to simultaneously record fringes from a He-Ne laser interferometer, in which the two arms were reflected from different points on the surface of the rotating grating of the monochromator. Recording of the interferometer fringes permitted continuous monitoring of the smoothness of the monochromator scans and allowed corrections to be made for any irregularities in the uniformity and linearity of the wavelength drive. The separation of the interferometer fringes was about 0.24 cm\(^{-1}\).

The iron reference lines selected for wavelength calibration of the In II lines are listed in Table 1, along with the vacuum wavenumber values reported recently by Nave et al. [7] and O’Brian et al. [8]. The wavenumber values from these two independent sets of measurements have been calibrated against Ar II lines (accuracy 0.0003 cm\(^{-1}\)) measured interferometrically by Norlén [10]. The third column of wavenumbers in Table 1 represents the difference between the mean energies of the upper and lower Fe I levels determined by O’Brian et al. from a number of different transitions and these were the actual Fe I wavenumber values used in our calibration. The uncertainty in the wavenumbers of the Fe I reference lines is