Precision Fast Ion Beam Laser Spectroscopy of Ar^+

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Abstract. Absolute measurements of spectral lines of Ar^+ ions using collinear and anticollinear geometries were performed. To provide a precise reference for the laser wavelength, iodine saturation spectroscopy was applied. The precision of this reference is effected by observing the beat node between the spectroscopy laser and the corresponding mode of a femtosecond laser frequency comb. Laser-induced fluorescence allowed to perform precision frequency measurements of an Ar+ transition in collinear and anticollinear geometries simultaneously; then an exact relativistic formula for the absolute transition frequency $\nu_0 = \sqrt{\nu_c \nu_a}$ was used. In this geometry the influence of ion source instabilities due to pressure and anode voltage fluctuations was minimized. The result is ν_0=485,573,619.7(3) MHz, which corresponds to $\Delta\nu/\nu=6*10^{-10}$. This represents an improvement of two orders of magnitude over the previous NIST published value.

Keywords: Precision Laser Spectroscopy, Collinear Fast Beam Spectroscopy, Ar^+ Ion Beam, Frequency Comb.
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INTRODUCTION

Since the pioneering work of Kaufmann[1] collinear fast ion beam laser spectroscopy has been developed into a powerful method of obtaining precision spectroscopic data. The advantage of the collinear fast beam technique is that it is free from the Doppler broadening. The significant reduction of the Doppler width in the collinear fast beam method is achieved by narrowing the velocity spread of accelerated ions by velocity bunching. In the present work, Doppler-free spectral line measurements combined with a wavelength calibration system based on the "femtosecond frequency comb" make it possible to achieve ultra high precision.

There has been an ongoing interest for absolute wavelength measurements with high precision in astrophysics [2]. Also modern atomic theory can predict atomic level energies with great accuracy allowing deducing the absolute value of the nuclear volume effect. In particular, ultra precise measurements of certain atomic levels with

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fast beam collinear laser spectroscopy were used to perform accurate isotope shift [3] and high voltage [4] measurements and also detect possible variations of the fundamental constants [5,6].

EXPERIMENTAL

A collinear fast beam laser apparatus was set up at RIKEN, Japan combining collinear and anticollinear geometries for laser excitation. This apparatus was employed for precision laser spectroscopy measurements with the metastable transition $^2G_{7/2}$-$^2F_{5/2}$ ($\lambda_0 \approx 617$ nm) of Ar^+.

The ion beam of $^{40}Ar^+$ was produced with a plasma hollow-cathode ion source (Danfysk 911 A) and then accelerated up to the energy of 20 keV. The ion beam was manipulated by ion optics (ion extractor, Einzel lens, bending capacitors, a quadrupole quartet and triplet) and also mass separated by a 90-degree dipole magnet. After mass separation the ion beam was merged with the laser radiations in both collinear and anticollinear directions.

The fluorescence detection region was held at a fixed potential (-150 V) to observe the fluorescence occurrence only in front of the fluorescence detection system. The resonant frequency was very sensitive to the beam energy (1 eV change in the beam energy corresponded to 13.5 MHz detuning in the frequency domain of the resonance). The acceleration voltage was stabilized to < 0.1 V by employing an accurate voltage divider and a computer-controlled feedback loop. However, even with a constant acceleration voltage there is a noticeable velocity drift due to small variations in the Ar gas pressure and anode voltage fluctuations in the ion source. To reduce the influence of the velocity drift of the ion source beam, we measured the transition frequency simultaneously in collinear and anticollinear geometries with two independent dye lasers. The frequencies of these two laser beams were simultaneously determined with a frequency comb.

A mode-locked femtosecond laser with a micro structured fiber provides a frequency comb with about 10^6 spectral modes in the visible to IR spectral range with exact intervals equal to the repetition rate of the laser (f_{rep}=250 MHz). The two dye laser beams were merged and interfered with the frequency comb radiation. The resulting beat signals were detected by avalanche photo detectors. A schematic representation of the experimental setup is shown in Fig. 1. Due to a slight, but sufficient difference (≈1.5 nm) of the wavelengths of the two lasers, two beat signals can be detected independently using a grating. The dye laser frequency is determined as

$$\nu_{dye} = nf_{rep} \pm f_{beat} \pm f_{offset}, \quad (1)$$

where n is an integer indicating n-th peak of the comb and f_{offset} is the offset of the first comb peak from the origin. The sign ± and n are determined from the saturation spectroscopic measurements of I_2 molecules, which are performed in parallel. The

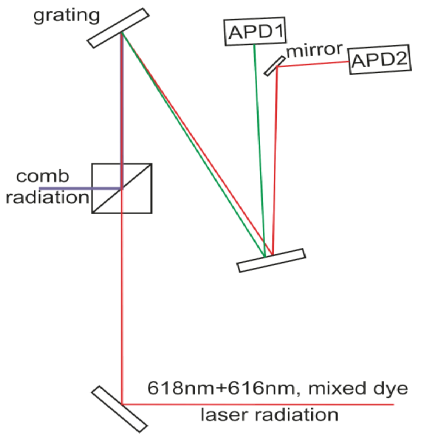

FIGURE 1. Simultaneous measurements of two beat frequencies by two different detectors.

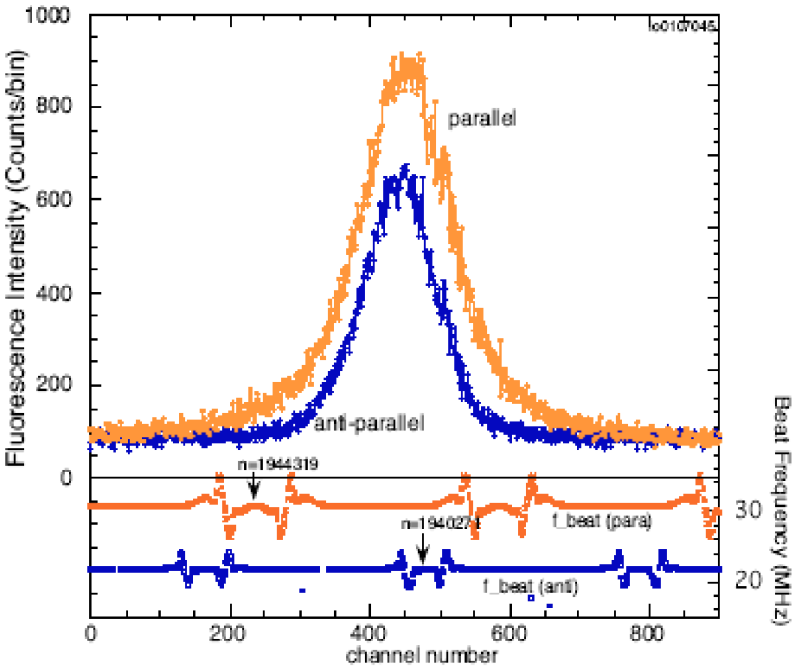

FIGURE 2. Laser induced fluorescence spectra of an $^{40}Ar^{+}$ ion beam with collinear and anticollinear laser radiation. The absolute laser frequencies are obtained from the beat frequencies with the frequency comb.

offset frequency f_{offset} is locked to 40 MHz with a standard technique for the carrier-envelope phase stabilization of a frequency comb [7].

RESULTS AND DISCUSSION

Figure 2 shows the experimental result. The formula to obtain the absolute transition frequency ν_0 is relativistically exact and given by:

$$\nu_0 = \sqrt{\nu_c \nu_a} \ . \tag{2}$$

Here ν_c and ν_a are the Doppler shifted laser frequency in collinear and in anticollinear geometries, respectively. Several measurements at different kinetic energies of the beam and different ion source conditions showed good agreement in ν_0 and are compiled in Fig.3. Each individual line shape was fitted by a Voigt function. The kinetic energies of the beam are presented in Table 1.

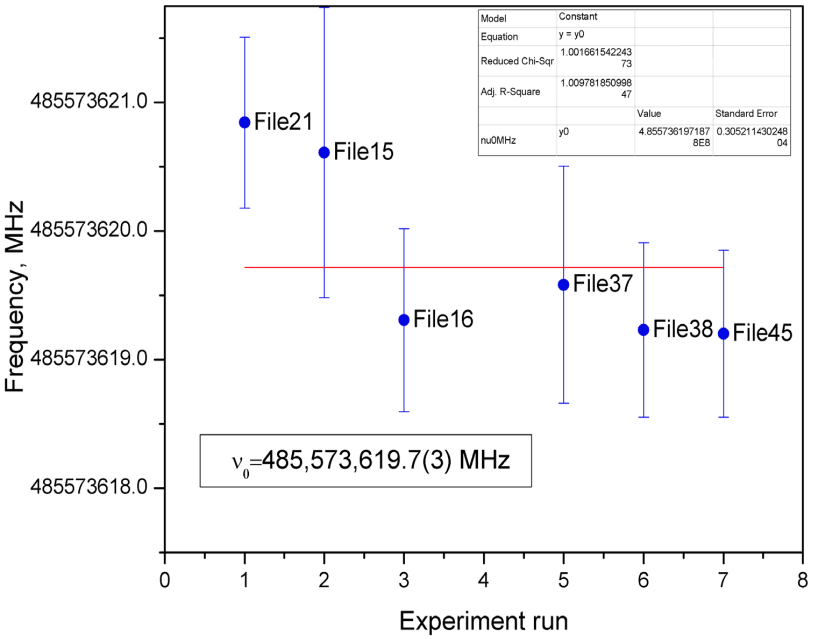

FIGURE 3. Absolute transition frequency ν_0 for different kinetic energies of the beam and different ion source conditions.

TABLE 1. Different acceleration voltages. The acceleration voltage is the sum of high voltage applied to the ion source and the post acceleration voltage.

File number	Acceleration voltage, V	Uncertainty, V
File 21	20,198.077	0.028
File 15	20,198.879	0.047
File 16	20,198.345	0.030
File 37	20,216.377	0.038
File 38	20,216.010	0.028
File 45	20,215.839	0.027

We preliminary determined the transition frequency as

$$\nu_0 = 485{,}573{,}619.7(3)\,\text{MHz}. \qquad (3)$$

These measurements have a higher accuracy of two orders of magnitude than the previous data [5].

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