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Precise measurement of the Stark shift of the rubidium and potassium $D1$ lines

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The dc Stark shift of the $D1$ lines of rubidium and potassium are observed using a pair of cavity-stabilized diode lasers locked to resonance signals. The heterodyne signal from the two lasers and the optical measurements of the electrode spacing yield high-precision results. The observed scalar shifts are found to be 61.153(8) kHz $(\mathrm{kV/cm})^{-2}$ for rubidium and 39.400(5) kHz $(\mathrm{kV/cm})^{-2}$ for potassium. These results represent more than three orders of magnitude improvement in our knowledge of these Stark shifts.

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An alternative method for the measurement of optical Stark shifts was recently developed in atomic lithium [1]. In order to test the validity of multiconfigurational Hartree-Fock (MCHF) and many-body perturbation theory (MBPT) calculations used in the prediction of atomic parity violation, the method was subsequently applied to cesium [2]. In cesium the precision of the measurement was about 130 ppm, the most precise Stark shift measurement that we are aware of. These initial measurements have stimulated a flurry of theoretical activity that attempts to refine the atomic calculations to a comparable precision [3–5]. In order to establish similar benchmarks in other atomic systems, we have applied this refined method of measurement to rubidium and potassium. We have achieved results more than three orders of magnitude more precise than any previous measurements. These results provide valuable tests of atomic structure calculations, placing constraints on the large r behavior of the atomic wave functions and testing various techniques for summing the relevant infinite series.

The method used for these measurements has been described in detail in Refs. [1,2]. One laser is locked to an atomic resonance line either in an atomic beam or in a saturated absorption cell. The frequency of this laser is fixed and serves only as a heterodyne reference. The second laser beam has its frequency shifted 60 MHz by an acousto-optic modulator (AOM). The shifted beam intersects an atomic beam at the center of a pair of precision electrodes. This second laser's frequency is then locked so that the shifted frequency beam remains centered on the atomic resonance. The direct (unshifted) outputs of the two lasers interfere on an avalanche photodiode. The resulting beat frequency (initially about 60 MHz) is monitored on a frequency counter. A well calibrated voltage is then applied to the electrodes, shifting the resonance frequency and the frequency of the second laser. The resulting change in the beat frequency, combined with the well-known electric field, yields a calibrated measurement of the Stark shift.

The atomic-beam apparatus, the electrode structure, and its calibration are nearly identical to that previously described. For the rubidium experiment we use a saturated absorption cell with a length of 3 in., maintained at a temperature of about 55 °C to lock the reference laser. In potassium, we lock the reference laser to a second atomic beam, created by adding a pair of new apertures to our collimating plates in the atomic-beam apparatus. This second atomic beam was approximately 4 mm below the main beam and was monitored in the "field free" viewing region (see Ref. [1]). This separation of the source into two beams eliminated the possibility that optical pumping of the atomic beam in the first region (field free) might result in a shift in the second (field) region. The operating temperature for the atomic-beam oven was typically 175 °C for rubidium and 200 °C for potassium.

The cavity stabilized diode lasers are similar to those described in Ref. [2]. Sharp model LT022MC laser diodes are used for generating the 795 nm light for the

TABLE I. Rubidium Stark shift as a function of run. N is the number of data files contained within the run. The quoted uncertainties are only statistical. Spacing uncertainties of 40 ppm must be included in order to compare the different runs.

Run	N	Shift [kHz $(\mathrm{kV/cm})^{-2}$]	$\chi^2/(N-1)$
1	18	61.1450(21)	1.77
2	11	61.1529(23)	1.95
3	24	61.1567(12)	1.45
4	8	61.1456(52)	2.56
5	9	61.1531(43)	0.73
6	31	61.1510(16)	1.41
All	101	61.1527(8)	1.76

TABLE II. Potassium Stark shift as a function of run. As in Table I the uncertainties are purely statistical and a 40 ppm uncertainty associated with the electrode spacing must be included to compare different runs.

Run	N	Shift [kHz $(\mathrm{kV/cm})^{-2}$]	$\chi^2/(N-1)$
1	26	39.3989(12)	0.85
2	30	39.4031(17)	1.26
3	33	39.4003(13)	0.85
All	89	39.4003(8)	1.01

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TABLE III. Stark Shift of the various isotopes and hyperfine transitions of rubidium. Vertical (V) polarization is parallel to E while horizontal (H) is perpendicular. F and F' are the total angular momentum quantum numbers for the ground and excited states, respectively. Only statistical uncertainties have been included.

	Transition	Shift [kHz $(\text{kV/cm})^{-2}$]		
Isotope	(F-F')	V	H	Av.
87	1-1	61.1283(126)		61.1283(126)
87	1-2	61.1676(198)		61.1676(198)
87	2-1	61.1553(13)	61.1453(28)	61.1534(12)
87	2-2	61.1577(30)		61.1577(30)
85	2-3	61.1531(21)	61.1504(66)	61.1528(20)
85	3-2	61.1504(16)	61.1501(45)	61.1503(15)

rubidium $D1$ line and Panasonic model LN9705 diodes are used to generate the 770 nm radiation for the potassium $D1$ line. The laser diodes are all antireflection coated by applying a quarter wave of silicon monoxide to the output facet. The grating-feedback geometry and locking and detection circuitry are all identical to that which was previously described.

The data acquisition followed the same procedure as that used in the earlier cesium experiment. The results as a function of run are shown in Tables I and II. The uncertainties displayed in the tables are only statistical. In order to compare the run-to-run variations it is necessary to fold in the 40 ppm uncertainty associated with the spacing measurement for each run. With the inclusion of this uncertainty the data from the different runs agree rather well, though the agreement is clearly better for potassium than for rubidium. In addition, the calculated χ^2 per degree of freedom for the rubidium data is significantly greater than one. We believe the poorer quality of the rubidium data to be associated with laser instability. The rubidium diodes were more difficult to maintain single mode than the potassium diodes, probably because it was necessary to pull their center frequency further with the grating feedback. The observed χ^2 per degree of freedom would suggest that the inclusion of the noise associated with the laser mode instability would increase the stated uncertainties for rubidium by about 40%.

Tables III and IV show the results obtained for different isotopes, hyperfine transitions, and polarizations. At the present levels of sensitivity one does not expect the tensor polarizability to be sufficiently large to produce any significant differences in the observed shifts. This expectation is well confirmed for the potassium. Several of the ^{87}Rb numbers deviate from the mean by more than two standard deviations and the vertical polarization data on the $F=2$ to $F'=1$ transition deviates by more than three standard deviations. However, given that the different transitions and polarizations were often studied on different days (with slightly different spacings) and that the quoted uncertainties neglect the noise associated with the laser instability, we do not view these deviations as evidence for a tensor polarizability.

Tables V and VI show the results of dividing the data according to various criteria. No significant dependence on intensity, laser bandwidth, voltage applied, or isotope is observed. However, the shift clearly depends on the sign of the voltage difference applied between the electrodes. This difference is consistent with the 0.24 V contact potential discovered in the earlier work with cesium. When averaged over the different field polarities, its contribution to the observed shift is effectively eliminated.

Averaging over all the data yields the best values for the shifts of 61.1527(8) and 39.4003(8) kHz $(\text{kV/cm})^{-2}$, respective, for rubidium and potassium. We associate an additional systematic uncertainty of 0.002 kHz $(\text{kV/cm})^{-2}$ with the rubidium to take into account the noise introduced by the laser instability. Spacing uncertainties (40 ppm) and voltage uncertainties (50 ppm) are combined in quadrature to yield a field uncertainty of 64 ppm. The fractional systematic uncertainty in the Stark shift is twice this. Combining this dominant field uncertainty in quadrature with the other uncertainties yields the final results of 61.153(8) kHz/$(\text{kV/cm})^{-2}$ for rubidium and 30.400(5) kHz/$(\text{kV/cm})^{-2}$ for potassium.

To compare our results with theory it is useful to express them as the difference in the scalar polarizabilities of the ground state and the lowest $P_{1/2}$ level in each atom.

For Rb

TABLE IV. Stark shift of the various hyperfine transitions of potassium 39. The parameters are as described in Table III.

Transition	Shift [kHz $(\text{kV/cm})^{-1}$]		
(F-F')	V	H	Av.
1-1	39.4000(47)		39.4000(47)
1-2	39.3973(28)	39.3991(42)	39.3978(23)
2-1	39.4009(10)	39.3980(23)	39.4004(9)
2-2	39.4018(25)	39.4048(66)	39.4021(23)

TABLE V. The rubidium data sample divided according to various criteria. Electric field polarities of + and − refer to the sign of the voltage difference between the "top" and "bottom" electrodes. The "beat width" is the frequency spread in the lasers' beat frequency observed on a spectrum analyzer. Only statistical uncertainties are included.

Data selection criteria		Shift [kHz $(\text{kV/cm})^{-2}$]
Intensity	Full	61.1530(9)
	27%	61.1509(20)
Voltage	5 kV	61.1538(9)
	4 kV	61.1472(24)
	3 kV	61.1509(28)
	2 kV	61.1380(87)
	1 kV	61.1304(293)
E-field Polarity	+	61.1473(10)
	−	61.1578(11)
Beat width	25–30 MHz	61.1505(16)
	40 MHz	61.1560(14)
	50–60 MHz	61.1569(35)
Isotope	85	61.1512(12)
	87	61.1539(11)
All data		61.1527(8)

$$a_0(5P_{1/2})-a_0(5S_{1/2})=72.932(10)\times10^{-24}\ \text{cm}^3$$
$$=492.20(7)a_0^3\ .$$

For K

$$a_0(4P_{1/2})-a_0(4S_{1/2})=46.989(6)\times10^{-24}\ \text{cm}^3$$
$$=317.11(4)a_0^3\ .$$

The scalar polarizability differences observed for rubidium and potassium are in good agreement, respectively, with the previously measured values [6,7] of $72(16)\times10^{-24}$ cm^3 and $50(12)\times10^{-24}$ cm^3. Our new results are more than 1000 times more precise than these earlier values.

TABLE VI. The potassium data sample divided according to the same criteria as were used in Table V.

Data selection criteria		Shift [kHz $(\text{kV/cm})^{-2}$]
Intensity	Full	39.3999(10)
	25%	30.4010(13)
Voltage	5 kV	39.4003(9)
	4 kV	39.3979(24)
	3 kV	39.4084(62)
	2 kV	39.4017(90)
E-field Polarity	+	39.3986(11)
	−	39.4023(11)
Beat width	25 MHz	39.3999(19)
	30–35 MHz	39.4003(13)
	40–45 MHz	39.3996(12)
	50–60 MHz	39.4091(36)
All data		39.4003(8)

The ground-state polarizabilities of rubidium and potassium were previously measured to be $47.3(9)\times10^{-24}$ and $43.4(9)\times10^{-24}$ cm^3, respectively [8]. Our present results may be combined with these earlier measurements to yield values for the excited state polarizabilities of $a_0(5P_{1/2})=120.2(9)\times10^{-24}$ cm^3 for rubidium and $a_0(4P_{1/2})=90.4(9)\times10^{-24}$ cm^3 for potassium.

These precise measurements of atomic polarizabilities should provide stringent tests for new atomic calculations in these atoms. With this paper we have completed the measurement of all the stable alkali-metal-atom *D*1 line Stark shifts, with the exception of sodium. Application of this method to sodium will have to await the arrival of laser diodes capable of producing the requisite 589 nm radiation.

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