# Measurement of the $(3s3p)^1P$–$(3s3d)^1D$ isotope shift in Mg I

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We present measurements of the isotope shift for the $(3s3p)^1P$–$(3s3d)^1D$ transitions at 881 nm in Mg I. The three stable magnesium isotopes yielded a shift $^{24}$Mg–$^{25}$Mg of (1342 ± 20) MHz and $^{25}$Mg–$^{26}$Mg of (1175 ± 23) MHz. Measured shifts are consistent with recent relativistic many-body calculations of the mass effect.

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## I. INTRODUCTION

The interest in alkaline-earth-metal systems has increased significantly in recent years. One of the main interests in these systems is their applications to high-resolution spectroscopy and atomic-frequency standards, as they offer very narrow electronic transitions [1]. In connection with novel cooling schemes for magnesium atoms and applications for optical clocks, we have measured isotope shifts for central transitions. In this Brief Report we present measurements of the isotope shift of the $(3s3p)^1P$–$(3s3d)^1D$ transitions. For all magnesium isotopes it is a challenge to cool the sample into the micro-Kelvin regime where the atoms can, for example, be loaded efficiently into an optical lattice. Several cooling strategies have been pursued [2–6]. One method involves two photon excitations to the $(3s3d)^1D_2$ state, but has only been explored for the bosonic isotope. Other techniques explore the metastable $^3P_2$ state aiming at cooling on the $^3P_2$–$^3D_3$ transition, currently under investigation for the bosonic isotope. Similarly, new *ab initio* models are developed for calculations of the isotope shift in two-electron systems [7]. In this connection we find data on the magnesium very valuable as a benchmark system.

## II. EXPERIMENTAL SETUP

In Fig. 1, we show the relevant energy levels and transitions in our experiment. The 285-nm transition is used for cooling and trapping the atoms while the 881-nm transition is used for spectroscopy of the $(3s3d)^1D$ state.

We trap and cool magnesium in a standard magneto-optical trap (MOT) using three retro-reflected beams with an average intensity of 13 mW/cm$^2$. When we scan the 285-nm laser over a 2.4-GHz range, three individual magnesium MOTs appear, one for each stable isotope: $^{24}$Mg, $^{25}$Mg, and $^{26}$Mg. The number of trapped atoms is about $N \sim 10^7$, with a temperature $T \approx 5$ mK and a rms diameter of $d = 2$ mm. For IR spectroscopy we use a 881-nm linearly polarized laser at 2.5 mW. The 881-nm beam is collinear with one of the 285-nm MOT beams (see Fig. 2). The 881-nm power is modulated at 60 kHz by an acousto-optic modulator (AOM), which enables phase-sensitive detection of the IR fluorescence by a lock-in amplifier. The photomultiplier used for IR-detection is equipped with an interference filter centered at 881 nm. A fraction of the beam is split off and sent to a reference cavity for frequency diagnostics and calibration. By ramping the 881-nm diode laser frequency slowly in a cycle of 50 s, we are able to change the trapping 285-nm laser detuning to capture all three isotopes during a single 881-nm scan. Figure 3 shows a typical scan, with a strong signal belonging to the $^{24}$Mg isotope and a smaller signal for the $^{25}$Mg and $^{26}$Mg isotope due to their lower natural abundances.

To calibrate the frequency axis we use the free spectral range (FSR) of an ultralow expansion (ULE) cavity placed in a temperature-stabilized vacuum chamber. In Fig. 3 we show the zeroth- and the first-order FSR shifted by an AOM at 82.5 MHz. Precision measurements of the FSR were carried out by using the third-order diffraction from an AOM operating at 407.7 MHz. By matching the zeroth- and third-order diffraction from the AOM to the FSR signal, we obtain a FSR = (1223.0 ± 0.9) MHz.

## III. RESULTS

In Table I we show our measured isotope shift by 36 independent measurements of the difference in central frequency for the three isotope fluorescence signals, as illustrated in Fig. 3.

Generally, the isotope shift of a transition is the sum of two effects: the mass effect and the field shift. The mass effect accounts for the finite mass of the nucleus and the field shift accounts for the finite size of the nuclear charge distribution.

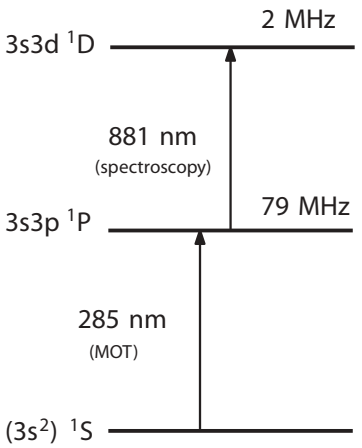


FIG. 1. Energy levels relevant for the $^1S \rightarrow {}^1P \rightarrow {}^1D$ spectroscopy. The linewidth of the $^1P$ level is 79 MHz; for the $^1D$ level it is 2 MHz.

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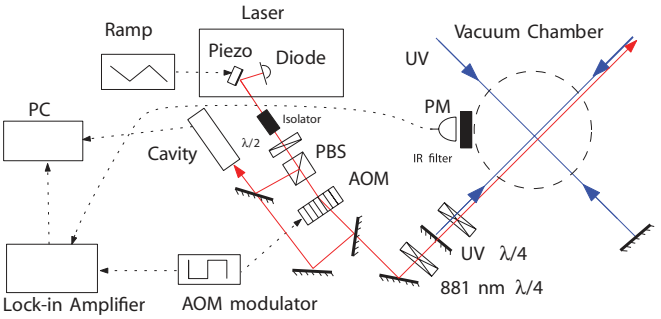


FIG. 2. (Color online) Schematic experimental setup. A frequency generator ramps the 881-nm laser piezo cryatal at 20 mHz. The laser passes through an AOM, which is turned on and off by a square pulse at 60 kHz. The first-order signal from the AOM is led into the reference cavity and the MOT. The spectroscopic signal is selected through an interference filter at 881 nm and detected in a photomultiplier. Both the lock-in and the cavity signal is recorded.

Typically, field effects can be neglected compared to the mass effect.

The ratio between $^{24}$Mg–$^{25}$Mg shift and $^{25}$Mg–$^{26}$Mg shift given by the mass effect can be calculated as [7,8]:

$$\frac{\Delta(^{24}\mathrm{Mg}\text{–}^{25}\mathrm{Mg})}{\Delta(^{25}\mathrm{Mg}\text{–}^{26}\mathrm{Mg})} = \frac{(25-24)25\times 26}{(26-25)24\times 25} = 1.08.$$

The relative isotope shift based on the experimental values in Table I gives a ratio of

$$\frac{\Delta\nu(^{24}\mathrm{Mg}\text{–}^{25}\mathrm{Mg})}{\Delta\nu(^{25}\mathrm{Mg}\text{–}^{26}\mathrm{Mg})} = 1.14 \pm 0.03.$$

The measured relative isotope shift is two standard deviations from the normal mass shift. The isotope shift has recently been evaluated using relativistic many-body calculations by Berengut *et al.* [7]. Their calculations ignore the field shift, but report it to be of the order of 20–30 MHz, the same

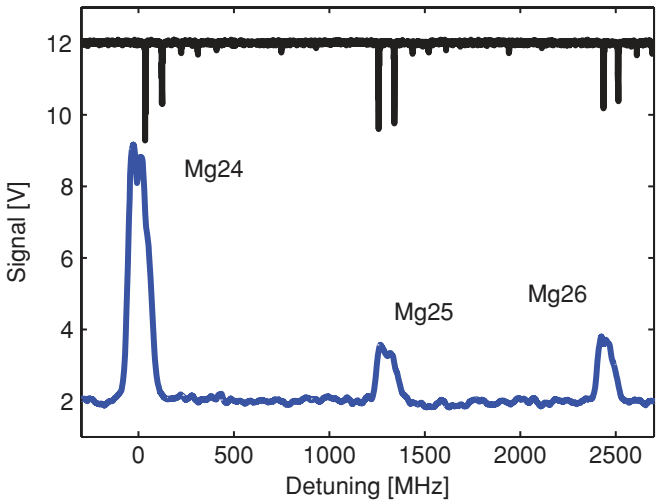


FIG. 3. (Color online) Spectroscopic signal from the three Mg I isotopes—$^{24}$Mg,$^{25}$Mg,$^{26}$Mg—at 881 nm. The top curve is cavity resonance lines, with the double peaks being the zeroth- and first-order diffraction from an AOM operating at 82.5 MHz, repeated for each FSR.

TABLE I. Mean isotope shift, $\Delta\nu$, and statistical uncertainties, $\sigma_{\mathrm{stat}}$, based on 36 data series and the systematic uncertainties $\sigma_{\mathrm{sys}}$.

| | $\Delta\nu$ (MHz) | $\sigma_{\mathrm{stat}}$ (MHz) | $\sigma_{\mathrm{sys}}$ (MHz) |
|---|---|---|---|
| $^{24}$Mg–$^{25}$Mg | 1342 | 15 | 13 |
| $^{25}$Mg–$^{26}$Mg | 1175 | 15 | 18 |

size as their computational uncertainties. Comparing with our measurements gives

$$\Delta\nu^{24,25}_{\mathrm{measurement}} - \Delta\nu^{24,25}_{\mathrm{theory}} = 11 \pm 41\ \mathrm{MHz},$$
$$\Delta\nu^{25,26}_{\mathrm{measurement}} - \Delta\nu^{25,26}_{\mathrm{theory}} = -53 \pm 42\ \mathrm{MHz}.$$

The uncertainty in the measurements, as well as in the theoretical values, is used in the preceding comparison. Taking into account the uncertainty in the calculated isotope shift, the theoretical results are in very good agreement with our data.

We summarize the sources of uncertainty in Table II.

The piezo crystal used for scanning the 881-nm laser was measured to have a 2.5% nonlinearity over a range of one cavity FSR (1223 MHz). This was corrected by matching the FSR signal and the spectroscopic signal, as shown in Fig. 3. Since the FSR is well determined, the nonlinearity only affects the small difference between a spectral peak and the nearest calibration signal. This difference was approximately 30 MHz and the maximum resulting error is below 0.8 MHz. The total effect on the isotope shift is less than 0.1%.

In each run we manually tune and optimize the 285-nm detuning to get the largest signal for each isotope. The absolute detuning of the 285-nm laser is referenced to the R(115)20-1 iodine hyperfine transitions [2,9] and is measured to (62 ± 6) MHz for $^{24}$Mg, (59 ± 11) MHz for $^{25}$Mg, and (63 ± 14) MHz for $^{26}$Mg. The UV detuning affects the measured isotope shift due to the two-photon resonance condition. The isotope shift is corrected for this and the uncertainty is reported in Table II.

The AC Stark shift due to difference in the power of the MOT beams for the different isotopes has been measured to give a relative isotope shift of less than 0.01%.

In Fig. 4 we show the isotope shift for three different values of the current in the MOT coils. We observe no significant systematic effect. The maximum shift, based on the uncertainty, is calculated to ±0.4 MHz per ampere for the $^{24}$Mg–$^{25}$Mg transition and ±0.3 MHz per ampere for the $^{25}$Mg–$^{26}$Mg transition. With a stable power supply the effect on the relative isotope shift is less than 0.01%.

TABLE II. Systematic uncertainties relative effect on the isotope measurements.

| Source | $\sigma_{24-25}$ (%) | $\sigma_{25-26}$ (%) |
|---|---|---|
| Piezo nonlinearity | <0.1 | <0.1 |
| FSR | <0.1 | <0.1 |
| ac Stark shift | <0.01 | <0.01 |
| UV detuning | 0.9 | 1.5 |
| *B* field | <0.01 | <0.01 |
| Total | 0.9 | 1.5 |

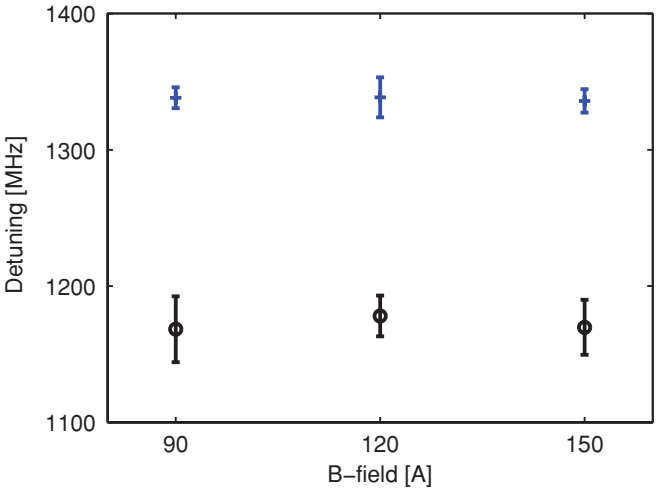


FIG. 4. (Color online) Isotope shift for different values of current in the Helmholtz coils. The circles closer to the bottom of the figure belong to the $^{24}$Mg–$^{25}$Mg transition; the crosses closer to the top belong to the $^{25}$Mg–$^{26}$Mg transition. The error bars give a possible sensitivity to varying $B$ field at $\pm 0.4$ MHz per ampere for the $^{24}$Mg–$^{25}$Mg transition and $\pm 0.3$ MHz per ampere for the $^{25}$Mg–$^{26}$Mg transition.

Our atom trap may be located in a nonzero $B$ field. The atoms are displaced due to the force by the UV beams from all six directions. If one laser beam is weaker, the atoms move out of the zero magnetic field region until the Zeeman shift balances the difference in intensity. This effect was observed for $^{24}$Mg isotope, where Fig. 5 shows a splitting of the Zeeman levels in the $^1P_1$–$^1D_2$ transition. The five peaks we attribute to the effective two-level system $^1S_0$–$^1D_2$ in the weak pump limit, where the $^1P_1$ state can be omitted [10].

The width of the peaks are determined from four effects: the natural linewidth of the $^1D_2$ level, the finite Doppler temperature of the MOT, the gradient of the $B$ field across the MOT, and power broadening of the 881-nm transition. The power broadening is the dominant factor for the three center peaks, but the gradient of the $B$ field dominates for the two outer peaks.

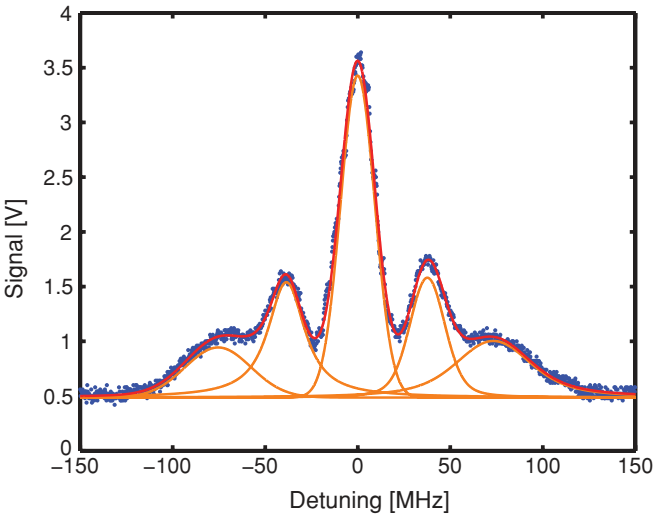


FIG. 5. (Color online) $^1P_1 \rightarrow {}^1D_2$ fluorescence spectrum for $^{24}$Mg in constant magnetic field, with fit to five Voigt distributions plotted separately and together.

## IV. CONCLUSION

We have measured the $(3s3p)^1P$–$(3s3d)^1D$ isotope shift in Mg I with a relative uncertainty better than 2%. The findings are compared to theoretical calculations and is consistent with the mass effect. Studies of the $^{24}$Mg isotope shows Zeeman splitting in five levels.

## ACKNOWLEDGMENTS

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