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High-Resolution Isotope Shift Measurement of the Mg I $^1S_0 - {}^3P_1$ Intercombination Transition

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Abstract. We measured the isotope shift of the Mg I intercombination line $3s3p\,^3P_1$–$3s^2\,^1S_0$ ($\lambda = 457$ nm) for the three stable isotopes ^{24}Mg, ^{25}Mg and ^{26}Mg. The measurement was performed by optical Ramsey spectroscopy (respectively saturation spectroscopy for ^{25}Mg) on a magnesium atomic beam. The rf precision of the measurement was achieved by using optical sideband techniques for the stabilization and tuning of a dye laser relative to an ultrastable cavity.

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Neutral magnesium is an interesting candidate for a future frequency standard in the submilimeter and optical wavelength region using the fine structure transition $3s3p\,^3P_0$–$3s3p\,^3P_1$ ($\lambda = 498\,\mu$m) [1] or the intercombination transition $3s3p\,^3P_1$–$3s^2\,^1S_0$ ($\lambda = 457$ nm) [2] (see Fig. 1). Efficient laser cooling and control of the atomic motion via the fast $^1S_0$–$^1P_1$ transition in the singulett system [3] or the $^3P_2$–$^3D_3$ transition in the triplett system [4] can reduce possible systematic frequency shifts. For the even isotopes ^{24}Mg and ^{26}Mg with nuclear spin $I = 0$ both cooling transitions constitute closed two level systems, whereas ^{25}Mg ($I = 5/2$) shows hyperfine splitting in the excited states. The isotope shift measurements presented here provide a connection between singulett and triplett isotope shift measurements of magnesium [5].

Experimental Apparatus

For ultrahigh-resolution spectroscopy on Mg we use a four-zone optical Ramsey setup [6, 7]. An effusive beam of neutral Mg atoms is produced by an oven operating at 700 K. The atoms cross two parallel pairs of counterpropagating laser beams. Exact parallelism of these laser beams is provided by two so called "cat's eyes".

The successive interaction with the four laser beams leads to an interference pattern in the excitation probability [8] (see Fig. 2). These Ramsey fringes are superposed on the Lamb dip due to incoherent saturated absorption. The excited atoms are detected by monitoring their fluorescence 20 cm downstream the excitation region by a photomultiplier. A magnetic field of a few Gauss inside the interaction region separates the transition frequencies for the $\Delta m \neq 0$ transitions in the case of ^{24}Mg and ^{26}Mg.

For the laser excitation of the 457 nm transition a stilbene 3 dye laser is used. The laser is stabilized to a non-tunable reference cavity (finesse 800) utilizing the light reflected from the cavity. An electrooptic modulator inside the laser cavity acts as fast servo element [9]. The residual frequency fluctuations of $1\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$, inferred from the electronic error signal, correspond to a laser linewidth of several Hz relative to the reference cavity. The cavity consists of two dielectric mirrors epoxied to a Zerodur spacer (length 500 mm, diameter 100 mm) which is suspended by two steel wires in a vacuum vessel pumped by an ion-getter pump. The temperature of the cavity is stabilized to better than 1 mK.

The frequency of the laser can be tuned by introducing a variable frequency offset with respect to the reference

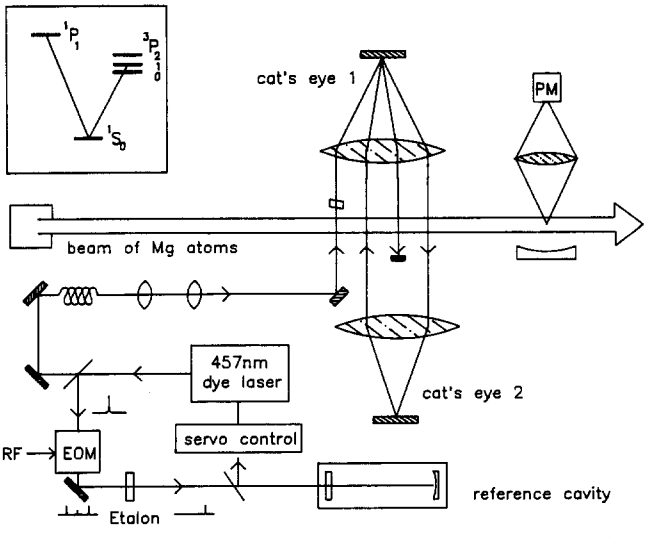

Fig. 1. Experimental setup and relevant part of the atomic level scheme

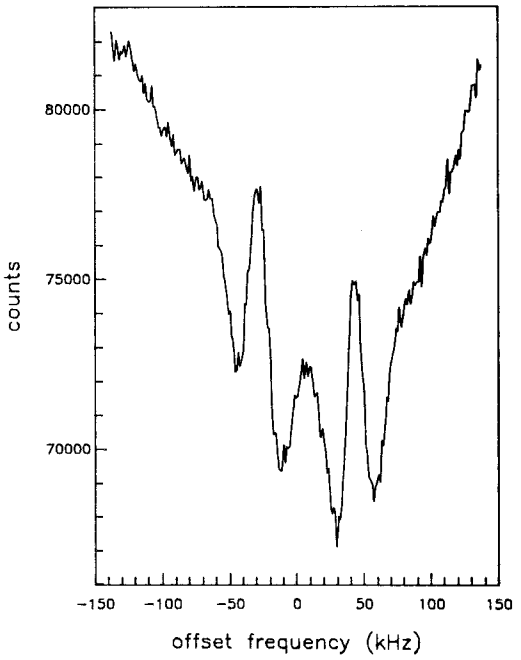

Fig. 2. Scan of the central part of the ^{24}Mg intercombination line, showing the Lamb dip with superimposed Ramsey fringes

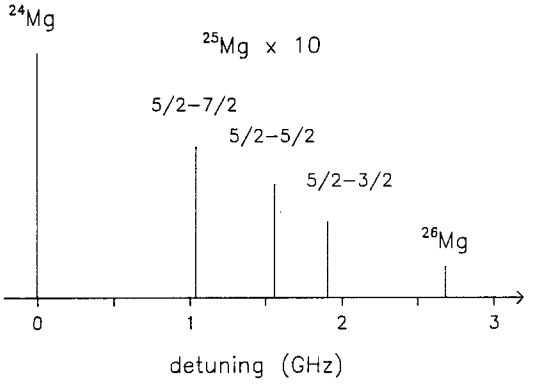

Fig. 3. Overview of the Mg intercombination transition with hyperfine and isotope structure. The amplitudes correspond to the observed intensities (^{25}Mg components multiplied by 10)

cavity. This is achieved by modulating the phase of one part of the laser beam in a specially designed, broadband $LiTaO_3$ travelling-wave electrooptic modulator. This phase modulation creates optical sidebands on the laser spectrum with a separation equal to the modulation frequency. With a solid etalon one sideband is selected for the stabilization of the laser frequency on the reference cavity. As this sideband is locked to a fixed eigenfrequency of the cavity, tuning the rf frequency results in a well defined shift of the laser frequency [10].

The absolute frequency drift of the reference cavity due to the aging of the spacer material has been measured to be in the order of 10 Hz/s. The drift during the measurement was checked with respect to the transition frequency of the ^{24}Mg line component. Due to the nondegenerate mode structure of the cavity, the locking point is independent of the mismatch between the cavity and the laser beam. Therefore no systematic error is introduced by a pointing instability of the laser beam.

All relevant transitions have been recorded with the modulated laser sideband locked to the same longitudinal mode of the reference cavity. The modulation frequencies necessary to measure the spectra ranged from 0.7 to 3.7 GHz and were supplied by a frequency-multiplied synthesizer.

Results

For the even isotopes ^{24}Mg (natural abundance 79%, nuclear spin $I = 0$) and ^{26}Mg (natural abundance 10%, nuclear spin $I = 0$) we have recorded Ramsey-fringe patterns (Fig. 2) on the $\Delta m = 0$ transition, which is undisturbed to first order by magnetic fields. For the odd isotope ^{25}Mg (natural abundance 11%, nuclear spin $I = 5/2$) all Zeeman components are sensitive to magnetic fields, and thus no Ramsey fringes could be detected due to residual magnetic-field inhomogeneities in the present apparatus. The observed intensities are in agreement with the natural abundance of the isotopes (Fig. 3).

The measured frequency differences between the center of both recoil components of the Ramsey pattern of the even isotope respectively the line center of the Lamb dip for the hyperfine components of ^{25}Mg are given in Table 1. The well known hyperfine splittings of the $^3P_1$ state of ^{25}Mg [11] have been used to check the precision of our measurement.

Table 1. Difference between the transition frequencies ν of the components of the Mg intercombination line in comparison with previous measurements. For ^{25}Mg, F and F' denote the total spin of the excited and ground state, respectively and ν_C denotes the line center of the hyperfine components. The normal mass shift has been calculated with the help of the energy-level data of Mg [15]

Pair of transitions	Measured shift	Normal mass shift	Specific mass shift	Previous results
^{25}Mg $\nu(F' = 3/2\text{–}F = 5/2)\text{–}\nu(F' = 5/2\text{–}F = 5/2)$	350.06 ± 0.1 MHz			349.987 ± 0.01 MHz [11]
^{25}Mg $\nu(F' = 7/2\text{–}F = 5/2)\text{–}\nu(F' = 5/2\text{–}F = 5/2)$	516.15 ± 0.1 MHz			516.140 ± 0.01 MHz [11]
$\nu(^{24}\text{Mg})\text{–}\nu_C(^{25}\text{Mg})$	1405.18 ± 0.1 MHz	595.12 MHz	810.06 ± 0.1 MHz	1109 MHz [12]
$\nu(^{24}\text{Mg})\text{–}\nu(^{26}\text{Mg})$	2683.18 ± 0.02 MHz	1144.43 MHz	1538.75 ± 0.02 MHz	2482 ± 20 MHz [13]

Compared to previous measurements [12, 13] the accuracy of the isotope shift could be improved by several orders of magnitude.

Neglecting the volume shift the line and level shifts are inversely proportional to sum of nuclear and electron mass [14]. This renders for the ratio of the shifts

$$[\nu(^{26}\mathrm{Mg}) - \nu(^{25}\mathrm{Mg})]/[\nu(^{25}\mathrm{Mg}) - \nu(^{24}\mathrm{Mg})] = 1.91937\,,$$

where ν denotes the transition frequency. From our experimental data we deduce a ratio of 1.90949(13), indicating a small contribution of the volume effect to the isotope shift of the order of one percent.

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