Precise ground-state hyperfine splitting in ^{173}Yb II

A. Münch, M. Berkler, Ch. Gerz, D. Wilsdorf, and G. Werth
Institut für Physik, Johannes Gutenberg-Universität, Staudinger Weg 7, Postfach 3890, D-6500 Mainz, West Germany
(Received 19 November 1986)

A laser-microwave double-resonance experiment on electrodynamically trapped $^{173}Yb^+$ ions has been performed and a value of $\Delta\nu_{hfs}=10\,491\,720\,239.55\pm0.09$ Hz for the ground-state hyperfine separation has been determined. This value is corrected for small Zeeman and second-order Doppler shifts. Combined with a previous similar measurement on $^{171}Yb^+$ and with the known g_I values of both isotopes, we obtain a value of $-0.004\,25(6)$ for the differential hyperfine anomaly $^{171}\Delta^{173}$.

I. INTRODUCTION

Measurements of the ground-state hyperfine separation of alkali-metal-like ions using the ion-storage technique in recent years have resulted in a number of very precise A factors whose uncertainty is often limited only by the available frequency reference.[1,2] This is why ion traps themselves are regarded as potentially very accurate frequency standards and first successful realizations of such devices have been reported.[3–6] Because of its simple level structure due to the nuclear spin $\frac{1}{2}$, $^{171}Yb^+$ is regarded as a possible candidate in this context.[7] The other stable odd Yb isotope of mass 173 has the disadvantage of $I=\frac{5}{2}$ and consequently a more complex spectrum. Having developed the techniques required for the measurement on $^{171}Yb^+$, it seemed worthwhile to extend the experiment to $^{173}Yb^+$ in order to demonstrate the potential of ion traps for accurate determinations of hyperfine anomalies from the comparison of two isotopes.

II. EXPERIMENT

Isotope-separated $^{173}Yb^+$ ions were produced by surface ionization on a hot Pt filament near the inner surface of a rf ion-trap electrode. At light buffer-gas (He, H_2) pressures between 10^{-8} and 10^{-5} mbar, a fraction of the trapped ions, estimated to be of the order of 10^{-3}, was slowed down and confined inside the trap volume for times which in general exceeded several hours. The number of trapped ions was about 10^5 in an active trap volume of 1 cm^3. Light from a pulsed dye laser, tuned to one of the hyperfine components of the $6S_{1/2}$-$6P_{1/2}$ resonance transition at 369.5 nm (Fig. 1) depopulated one hyperfine state which is indicated by the decrease in the observed fluorescence light at the same wavelength. A microwave transition connecting the $F=2$ and $F=3$ state at 10.5 GHz repopulated the depleted state and is monitored by the according increase in fluorescence intensity. Due to the 8-nsec lifetime of the $P_{1/2}$ state the fluorescence quanta appeared during and shortly after the 6-nsec laser pulse and could not be counted independently. Instead the total charge appearing at the anode of a phototube within a gate of variable length (typically 20 nsec) was converted into a count rate and stored in the channels of a multiscaler (MCS) (Fig. 2). After careful shielding of the laser stray light we obtained typically 20 background counts from the laser at 10-W peak power and 10 fluorescence counts during a single counting gate, when the microwave frequency was at resonance. Repetitive sweeping of the microwaves across the resonance and changing the MCS channels accordingly resulted in improved signal-to-noise ratio of a microwave resonance. The microwaves were produced by a backward wave oscillator, phase locked to a quartz synthesizer, which was referenced to a laboratory Rb frequency standard that provided a short-term stability of 1×10^{-11}. Long-term stability and absolute frequency accuracy to 1×10^{-12} was made by comparison to the broadcasted 77.5-kHz signal provided by the Physikalisch-Technische Bundesanstalt. By internal mixing and formation of sum frequencies of two quartz syn-

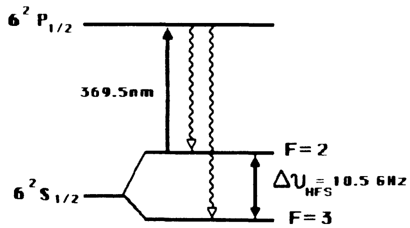

FIG. 1. Energy levels of $^{173}Yb^+$.

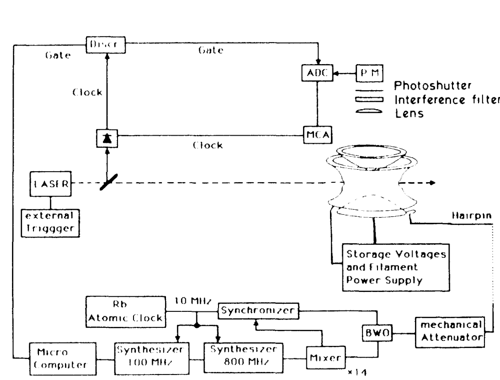

FIG. 2. Experimental setup for the laser-microwave double resonance experiment on $^{173}Yb^+$.

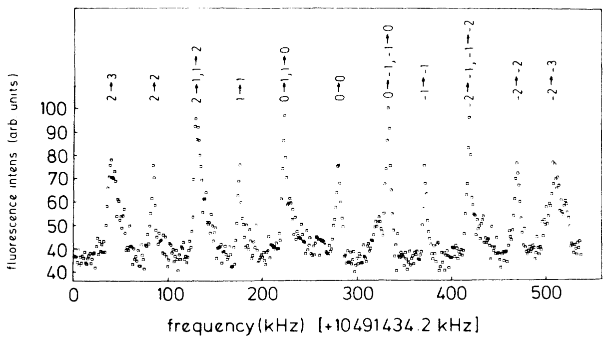

FIG. 3. Ground-state hyperfine Zeeman spectrum of $^{173}Yb^{+}$ at $B=10^{-5}$ T. The numbers (i,j) at each line correspond to the initial (i) and final (j) m_F state of the $F=3$-$F=2$ transition.

thesizers we could vary the microwave frequency in steps of 1 mHz. Step control and data handling was performed by a personal computer.

III. MEASUREMENTS

A residual magnetic field at the trap position splits the $F=2$-$F=3$ hyperfine transition into a total of 15 $\Delta m_F=0,\pm 1$ Zeeman transitions. While the complete Zeeman spectrum has been observed (Fig. 3), we used the $|2,0\rangle$-$|3,0\rangle$ transition for accurate determination of the hyperfine-structure (hfs) splitting due to its insensitivity to magnetic field strength and inhomogeneities and the adjacent $|2,1\rangle$-$|3,0\rangle$ and $|2,0\rangle$-$|3,1\rangle$ transitions for magnetic field determination. The linewidth of the $|3,0\rangle$-$|2,0\rangle$ transition depends on the microwave power, the laser repetition rate, and the operating conditions of the trap. In the adiabatic approximation, when the ion motion is described by a single harmonic oscillation of frequency ω (secular motion) with superimposed amplitude modulation by the rf trapping field (micromotion) and higher harmonics are neglected, the time-averaged three-dimensional potential well depth $\overline{D}$ is given by

$$\overline{D}=\tfrac{1}{8}m\Omega^2(\beta_r^2 r_0^2+\beta_z^2 z_0^2)\ ,$$

where the dimensionless constants β_r and β_z depend on the amplitude and frequency of the trapping voltages and are of typical value 0.1—0.5. Ω is the trapping field oscillation frequency and r_0 the trap radius which, in our case, was $2\pi\times 450$ kHz and 2 cm, respectively. $2z_0$ is the distance between the endcaps given by $r_0/z_0=\sqrt{2}$. The secular motion frequency is given by $\omega_{r,z}=\beta_{r,z}\Omega/2$.

Since the optimum operating point of the rf trap, where the number of stored ions was a maximum, occurs near $\beta_r=0.22$, $\beta_z=0.45$,[8] which leads to an ellipsoidal shape of the potential well, we started our measurements, in particular the magnetic field dependence of the transition, under these conditions and achieved a linewidth of about 20 Hz in the 10.5 GHz transition. Later on, however, we found that for spherically symmetric potential wells the linewidth could be reduced to about 1 Hz. At the same time sidebands occurred which are not understood so far. Since the complete sideband spectrum was symmetric around the center frequency, it does not influence the position of the central resonance, which could be well fitted by a Lorentzian line shape (Fig. 4).

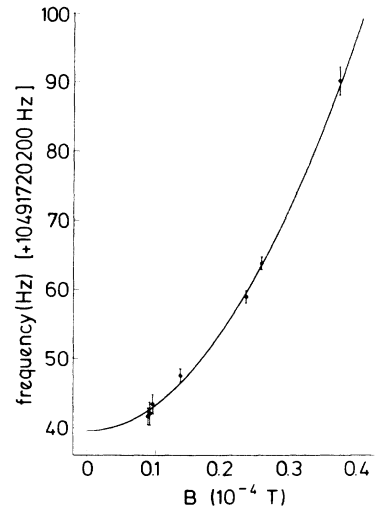

FIG. 5. Magnetic field dependence of the $F=3,m=0$—$F=2,m=0$ hyperfine transition. Fit according to the Breit-Rabi formula to the experimental points.

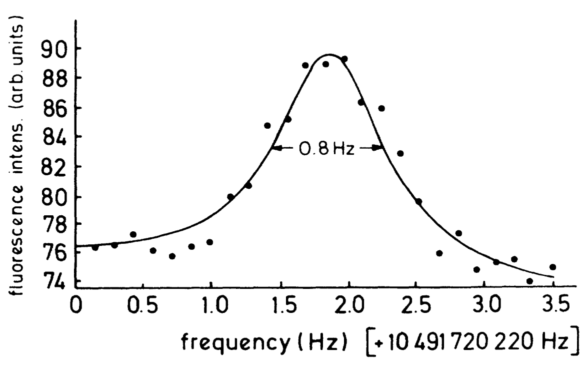

FIG. 4. Magnetic field "independent" $F=3,m=0$—$F=2,m=0$ transition. The solid line corresponds to a Lorentzian line shape and a linear decreasing background.

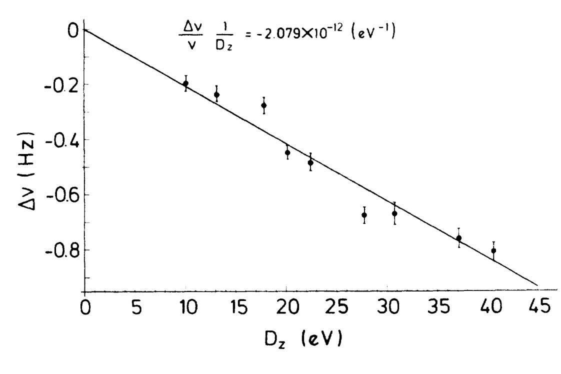

FIG. 6. $|3,0\rangle$-$|2,0\rangle$ resonance frequency vs average trap potential depth for spherical potential shape.

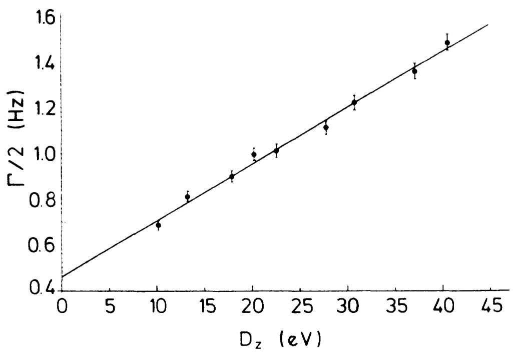

FIG. 7. $|3,0\rangle$-$|2,0\rangle$ linewidth [full width at half maximum (FWHM)] vs trap potential depth.

Zeeman effect. We varied the laboratory magnetic field by using additional coils between 0.09 and 0.4×10^{-4} T. From the $\Delta m_F=\pm1$ transitions of typically 800-Hz width we determined the magnetic field to an accuracy of a few parts in 10^{-4}. Data were taken at seven different field values and the $|2,0\rangle$-$|3,0\rangle$ transition frequency extrapolated to $B=0$ according to the Breit-Rabi formula (Fig. 5),

$$\nu_{00}(B)=\nu_{00}(0)(1+\tfrac{1}{2}x^2)\ ,$$

$$x=B(g_J\mu_B-g_I\mu_k)/3A\ .$$

The remaining error was 0.088 Hz due to the statistical uncertainty of the 20-Hz-wide line.

Potential depth. The average value of the ions kinetic energy is proportional to the trap potential depth.[8,9,10] In the presence of a buffer gas the secular motion is damped by collisions, while the amplitude of the micromotion in extended ion clouds may reach large values, when the ions move outside the trap center in high electric trapping fields.[11] The microwave spectrum does not show a first-order Doppler effect;[12,13] however, the resonance frequency may be shifted by the corresponding second-order effect. This shift, composed of both the secular motion and the micromotion, has been measured and linearly extrapolated to zero potential depth (Fig. 6). From the slope one can determine the ions' average kinetic energy $\overline{E}_k$. For He background pressure of 10^{-7} mbar we obtain $\overline{E}_k=0.112(3)$ eV per eV potential depth. This coincides with previous results from the spatial distribution of an ion cloud.[10] A value for $\overline{E}_k$ can be obtained also from the width of the resonance line when we assume a broadening by the second-order Doppler effect. When we regard in spite of the asymmetric Maxwell-Boltzman distribution of energy the line shape in first order as symmetric and plot the Lorentzian width at different trap potentials, we find a linear dependence. Assuming that the extrapolated width at $\overline{D}=0$ is for ions of velocity zero and the additional broadening at a given potential depth is due to the ions' kinetic energy, we obtain a value of $\overline{E}_k=0.126$ eV per eV potential depth in fair agreement with the determination from the frequency shift (Fig. 7).

A possible Stark shift of the hyperfine transition due to the electric trapping field, which would be included in the potential-well dependence, is estimated too small to contribute within the experimental errors.[14] The same holds for an ac Stark shift from the laser because of its low power and the duty factor of 10^{-7}.

IV. RESULTS

The final result for the ^{173}Yb$^+$ hyperfine splitting after extrapolation to zero magnetic field and zero potential depth is

$$\Delta\nu_{\rm hfs}=10\,491\,720\,239.550\pm0.093\ \text{Hz}\ .$$

The quoted 1σ error is the square root of the quadratically added uncertainties from the B-field extrapolation (88 mHz), from the potential-depth extrapolation (28 mHz), and the absolute uncertainty of our frequency reference system (10 mHz). The tenfold improvement in precision over our previous ^{171}Yb$^+$ experiment is mainly due to an improved version of our frequency calibration system and a better compensation of the outer magnetic field.

If we combine our result with a previous determination of the hfs splitting in ^{171}Yb$^+$ (Ref. 7) and the known g_I values of 0.987 34(2) and $-0.271\,956(12)$ for ^{171}Yb and ^{173}Yb, respectively,[15] we obtain a value for the differential hyperfine anomaly of two isotopes 1 and 2 which reflects the change in magnetization over the nuclear volume. It is defined as

$$^{1}\Delta^{2}=A(1)g_I(2)/A(2)g_I(1)-1\ .$$

A is the hyperfine splitting constant. Our result for Yb$^+$ is $^{171}\Delta^{173}=-0.004\,25(6)$. From level-crossing experiments[16] and optical hyperfine splittings[17] of the $^3P_1$ state of neutral Yb atoms, one deduces a value of the hyperfine anomaly of $-0.003\,44(20)$ and $-0.003\,82(19)$ respectively. A computation using Nilsson nuclear wave functions depends strongly on the assumed nuclear deformation, but for an asymmetry $\beta=0.3$ it gives for the neutral atom a value of -0.0031, which is a mixture of contributions from s and p electrons. To our knowledge no computation exists for the Yb$^+$ ion, but the result could be expected somewhat larger since only s electrons contribute to the anomaly.

ACKNOWLEDGMENTS

We are indebted to Professor Guthörlein (Hamburg) for a supply of isotope pure ^{173}Yb. The experiment was supported by the Deutsche Forschungsgemeinschaft.

[1] D. J. Wineland *et al.*, in *Atomic Physics*, edited by R. S. van Dyck, Jr. and N. E. Fortson (World Scientific, Singapore, 1985), Vol. 9.

[2] G. Werth, in *Atomic Physics*, edited by R. S. van Dyck, Jr. and N. E. Fortson (World Scientific, Singapore, 1985), Vol. 9.

[3] M. Jardino *et al.*, Appl. Phys. **24**, 107 (1981).

[4] J. J. Bollinger *et al.*, Phys. Rev. Lett. **54**, 1000 (1984).

[5] H. Knab, K. D. Niebling, and G. Werth, IEEE Trans. Instrum.

Meas. **34**, 238 (1985).
[6]L. Cutler, R. Giffard, and M. McGuire, in *Proceedings of the 37th Annual Frequency Control Symposium, Philadelphia, 1983* (Systematics General Corp., Washington, D. C., 1983), p. 32.
[7]R. Blatt, H. Schnatz, and G. Werth, Z. Phys. A **312**, 143 (1983).
[8]R. Iffländer and G. Werth, Metrologia **13**, 167 (1977).
[9]R. D. Knight and M. H. Prior, J. Appl. Phys. **50**, 3044 (1979).
[10]H. Schaaf, U. Schmeling, and G. Werth, Appl. Phys. **25**, 249 (1981).
[11]F. Vedel *et al.*, Phys. Rev. A **27**, 2321 (1983).
[12]H. A. Schuessler, Appl. Phys. Lett. **18**, 117 (1970).
[13]F. G. Major and J. L. Duchene, J. Phys. (Paris) **36**, 953 (1975).
[14]W. M. Itano, L. L. Lewis, and D. J. Wineland, Phys. Rev. A **25**, 1237 (1981).
[15]*Table of Isotopes,* edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978), 7th ed.
[16]B. Budick and J. Snir, Phys. Lett. **24B**, 276 (1967).
[17]D. L. Clark *et al.*, Phys. Rev. A **20**, 239 (1978).