Laser-rf Double-Resonance Hyperfine Structure Measurements of the Metastable $3d4s\,^1D_2$ State of $^{43}$Ca

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The hyperfine structure of the $(3d4s)^1D_2$ metastable state of $^{43}$Ca has been measured using the ABMR-LIRF method (atomic beam magnetic resonance, detected by laser induced resonance fluorescence). The measurements yielded for the magnetic dipole and electric quadrupole constants $A = -17.650(2)$ MHz and $B = -4.642(12)$ MHz, respectively. From the measured $B$ factor the spectroscopic electric quadrupole moment (uncorrected for shielding effects) has been calculated to be $Q^{(43}\text{Ca}) = -0.062(12)$ barn. In addition, isotope shifts in the lines $(3d4s)^1D_2(3d4p)^1P_0$ and $(3d4s)^1D_2(4s5p)^1P_1$ for the stable calcium isotopes have been obtained by high resolution laser spectroscopy.

Introduction

In the recent past a number of experiments using different methods have been performed on many Ca isotopes to obtain detailed information about their nuclear charge distribution [1]. These isotopes have mass numbers between the double magic nuclei $^{40}$Ca and $^{48}$Ca.

Informations about the nuclear properties of Ca can be obtained for instance, by investigations of isotope shifts in the series of Ca isotopes and hyperfine structure (hfs) measurements on the odd isotopes. $^{43}$Ca, which has a very low natural abundance (0.14%), is the only stable Ca-isotope with a non zero nuclear spin. Hfs measurements in the $(4s4p)^3P_2$ metastable state of $^{43}$Ca by Grundevik et al. [2] and in the $(4s4p)^3P_1$ metastable state of $^{43}$Ca by Bergmann et al. [3] yielded slightly different values for the nuclear quadrupole moment of $^{43}$Ca.

In the configuration $(3d4s)$ of Ca with an open $3d$-shell the $^1D_2$ state at 21,850 cm$^{-1}$ above the ground state is also metastable. Therefore, it seemed desirable to measure the hfs of the fairly high lying $^1D_2$ state applying the very precise ABMR-LIRF method [5] (atomic beam magnetic resonance, detected by laser induced resonance fluorescence) to obtain additional information on the quadrupole moment of $^{43}$Ca from hfs measurements in another electronic configuration. On the other hand, hfs investigations on elements with an unfilled $3d$-shell performed in this laboratory [4-6] have shown, that the ABMR-LIRF technique with its very high sensitivity is especially suitable for the investigation of higher lying and consequently only fairly weak populated metastable states of rare isotopes. In addition, many parameters, which can contribute to the evaluation of the electric quadrupole moment of $^{43}$Ca, can be estimated from the studies of the influence of configuration interaction effects on the $3d$-shell hfs done in this laboratory.

Apparatus and Measurements

The general principles of the ABMR-LIRF technique and the apparatus have been described elsewhere (e.g. [4]). The experimental arrangement is schematically shown in Fig. 1. In an atomic beam oven natural Ca was evaporated from a carbon crucible heated by a focussed and orthogonally deflected electron beam of a 15 kV electron gun. The metastable atomic states in the calcium atomic beam
were excited by electron or ion bombardment mainly by means of an auxiliary electric discharge. It was arranged in front of the crucible and provided by a tungsten cathode supplied by a separated voltage supply. The population of the metastable $^1D_2$ state achieved with this arrangement was sufficient to perform the experiment.

The calcium atomic beam running vertically into the apparatus was crossed twice orthogonally by the same laser beam. At the first crossing point one of the hfs levels of the metastable fine structure (fs) state $^1D_2$ is selectively depleted by optical pumping. At the second crossing point this change in the population of the depleted level is detected by the decrease of the laser induced fluorescence light. Between the two laser interaction regions an rf loop, carefully shielded against magnetic fields, is mounted, which repopulates the depleted hfs level from an adjacent hfs-level by magnetic dipole transitions, if the rf is tuned to resonance. This resonance is very easily detected by the increase of the laser induced fluorescence light at the second crossing point of laser and atomic beam.

In the first interaction zone a multiple pass system is installed for improving the efficiency of the optical pumping effect. In the second interaction zone a special imaging system based on an elliptical mirror [6] focussed about 65% of the laser induced fluorescence light on a photomultiplier window. This optical system was very carefully shielded against scattered light from the oven and the laser beam.

The laser system consists of a single mode cw dye laser (Spectra-Physics model 375, modified version) pumped by an argon-ion laser. The dye laser output power and frequency were actively stabilized. To avoid power broadening the laser beam intensity at the upper crossing point was adjusted to about 0.5 mW/mm².

In order to obtain a rough information about the hfs splitting of the spectral line $\lambda=5.042\text{Å}$ ($^1D_2-^1P_1$) the laser wavelength was tuned to this line and varied over the full range of its hfs. The resonance fluorescence light showing the hfs splitting of the fs levels was synchronously registered by the photomultiplier. For these measurements only the upper laser-atomic beam interaction zone was used. The hfs splittings of the metastable ($3d4s$) $^1D_2$ state and the short living ($4s5p$) $^1P_1$ state of Ca are displayed in the left part of Fig. 2. Figure 3 shows a fluorescence spectrum of the 5.042 Å line of $^{43}$Ca corresponding to the hfs components shown in the right side of Fig. 2. From the fluorescence spectroscopic measurement we obtained the signs of the hfs splittings and predictions for the rf transition.