HYPERFINE STRUCTURE CONSTANTS OF THE CaII STATES $4s\ ^2S_{1/2}$ AND $4p\ ^2P_{1/2,3/2}$ AND THE NUCLEAR QUADRUPOLE MOMENT OF ^{43}Ca

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ABSTRACT

The hyperfine structure splittings of the $4s\ ^2S_{1/2} \rightarrow 4p\ ^2P_{1/2,3/2}$ transitions in $^{43}\text{CaII}$ have been measured by fast ion beam collinear laser spectroscopy. The resonant laser interaction was observed using non-optical detection based on optical ground state depopulation pumping, state selective neutralization and charge state separated particle counting. The extracted magnetic dipole hyperfine structure constants for ^{43}Ca $A(^2S_{1/2}) = -805(2)\text{MHz}$, $A(^2P_{1/2}) = -145.5(1.0)\text{MHz}$ and $A(^2P_{3/2}) = -91.9(0.2)\text{MHz}$ are in excellent agreement with relativistic many body perturbation theory predictions available for this alkali-like ion. The combined results are used to evaluate the semi-empirical analysis method. From the electrical quadrupole hyperfine structure constant $B(^2P_{3/2}) = -6.7(1.4)\text{MHz}$ and the calculated B/Q value for this one valence electron configuration, the nuclear quadrupole moment $Q(^{43}\text{Ca}) = -0.043(9)\text{b}$ is derived. This result supports a previous evaluation based on the hyperfine structure of the two valence electron 3P configurations of CaI.

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Hyperfine structure constants of the CaII states $4s\ ^2S_{1/2}$ and $4p\ ^2P_{1/2,3/2}$ and the nuclear quadrupole moment of ^{43}Ca

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1. Introduction

Hyperfine structures (hfs) of the one valence electron alkali-metal atoms and the isoelectronic alkaline-earth ions have been extensively investigated during the last decade using relativistic many-body perturbation theory (RMBPT)[1-4]. The calculated magnetic dipole hfs constants for the low lying $ns\ ^2S_{1/2}$, $np\ ^2P_{1/2,3/2}$ and $(n-1)d\ ^2D_{3/2,5/2}$ states generally are in good agreement with the experimental values for these one-electron configurations. From the systematics one could establish trends over the whole series for both the absolute values and the relative importance of the first-order, core-polarization and correlation contributions to the magnetic hyperfine field. The comparison of these different contributions for the neutral atoms to those for the isoelectronic ions also reflects the physical expectation of an ionic core being less deformable than the one of the isoelectronic neutral atom. Furthermore, nuclear quadrupole moments extracted from a combination of experimental and RMBPT electric quadrupole data have reduced the uncertainties of nuclear moments previously deduced using semi-empirical formulae [5].

So far, the experimental knowledge of the CaII hfs was hampered by the experimental limitations of the spectroscopic methods applicable to calcium. However the hyperfine interaction in calcium is particularly important for several reasons. The description of relaxation processes in NMR studies of calcium containing biological systems requires the knowledge of the nuclear quadrupole moment $Q(^{43}\text{Ca})$ [6] which can only be deduced from the measurement of an electric quadrupole hfs constant combined with a reliable theoretical electronic factor. From a nuclear physics point of view, isotope shifts and hfs constants of the series of calcium isotopes are a first-class testing ground for advanced shell model calculations [7]; again, a reliable theoretical electric quadrupole electronic factor is required to deduce spectroscopic quadrupole moments from the measured hfs splittings.

In contrast to the CaII system, the CaI system has been extensively studied for the series of isotopes $20 \leq N \leq 28$ [8-11]. In order to extract $Q(^{43}\text{Ca})$ from those data, RMBPT calculations were performed for the two valence electron configurations [12-13]. However, the strong correlation between the two valence electrons severely complicates the calculations and, as pointed out in ref. 3, calls for extreme care in the theoretical treatment. This is illustrated by the fact that the theoretical electronic quadrupole factors had to be "scaled" by the ratio of experimental versus theoretical electronic magnetic dipole factors in order to obtain consistent values for $Q(^{43}\text{Ca})$ from the $4s\ 4p\ ^3P$ and the $4s\ 3d\ ^1D$ terms.

In this paper we report on the measurement of the magnetic dipole hfs constants $A(^2S_{1/2})$, $A(^2P_{1/2})$, $A(^2P_{3/2})$ and the electric quadrupole hfs constant $B(^2P_{3/2})$ of the 4s and 4p states in CaII for the $I=7/2$ isotope ^{43}Ca . This allows a stringent test of the RMBPT calculations, a reliable determination of $Q(^{43}\text{Ca})$ and indirectly also a test of the RMBPT calculations for the electronic quadrupole factor in CaI. The experimental results, combined with the RMBPT data, allowed an evaluation of the standard semi-empirical method for hfs analysis.

The experimental knowledge of the CaII hfs was until recently restricted to $A(^2S_{1/2})$ obtained using Doppler-broadened gas discharge and Fabry-Perot interferometry techniques [14]. After completion of our work, an extension of the interferometric work was reported [15]. From their low resolution spectra, the authors also derived an $A(^2P_{1/2})$ value, plus an $A(^2P_{3/2})$ value based on the assumption that $B(^2P_{3/2})$ equals zero. A comparison between these and our results is included in this paper.

For our CaII measurements a laser spectroscopic method with both high resolution and very high sensitivity was developed. Therefore, these measurements serve also as a feasibility test for experiments on isotope shifts and nuclear moments of short-lived calcium nuclei. This aspect is briefly discussed.

2. Experimental procedure

Fast ion beam collinear laser spectroscopy has been applied previously for the hfs investigation of a number of stable and radioactive isotopes [5,16-18]. It provides the necessary resolution and intrinsic sensitivity for the case of calcium as well. The CaII optical excitation/detection wavelengths ($\lambda < 400$ nm), however, are far from being optimal for narrow-band cw lasers and moreover, the only stable odd isotope ^{43}Ca has a very low natural abundance of 0.14 %. Therefore, and also in view of hfs measurements on short-lived calcium isotopes, we have used a measuring scheme which is especially adapted to the study of calcium isotopes.

A schematic diagram of the experimental setup is shown in Fig. 1. Isotopically pure Ca^+ beams are produced at ISOLDE (CERN) by a surface ionization source, 33 kV extraction and subsequent mass separation. The selected ion beam is superimposed on the beam of a frequency stabilized cw dye laser fixed at one of the Doppler-shifted CaII transition wavelengths under study ($^2S_{1/2} \rightarrow ^2P_{1/2,3/2}$, $\lambda = 397.0$ nm and $\lambda = 393.5$ nm). The basic procedure has been described in ref. 19. Therefore the following description gives only a brief outline of the method and its adaptation to calcium. The measuring scheme

basically consists of three steps. First, the ion beam interacts collinearly with the cw dye laser light, while Doppler-tuning is used to scan over the $^2S_{1/2} \rightarrow ^2P_J$ transitions. At resonance the ions in the ground state are partially transferred to the metastable 2D_J states by depopulation pumping (see the inset of Fig. 1). Second, the passage through a sodium vapour target induces state selective neutralization of the ion beam. Third, the remaining ions are electrostatically separated from the neutral atoms and the latter are counted as a function of the scanning voltage applied to the optical pumping zone.

The state selectivity of the charge exchange is due to the difference in the ground and metastable state cross sections. These cross sections strongly depend upon the energy defects involved in the charge exchange process and on the kinetic energy of the projectiles [19]. It has been shown that for impact energies above 30 keV, the ratio of cross sections for Ca^+ on Na, $\sigma(^2D)/\sigma(^2S)$ is nearly unity, whereas this ratio reaches a maximum of about three at 3 keV [20]. Therefore, the electrostatic decelerator in front of the charge exchange cell, consisting of fifty electrodes and designed for minimal defocussing transmission losses (see Fig. 1), was used at 30 kV for the calcium measurements.

3. Experimental results

3.1. Hyperfine structure constants

Examples of the optical $4s\ ^2S_{1/2} \rightarrow 4p\ ^2P_{1/2,3/2}$ resonance signals for ^{43}Ca are presented in fig. 2 ; scanning voltages were converted to transition frequency differences. Least squares fitting of all registered spectra resulted in the set of hfs constants given in the first row of table 1.

The $A(^2S_{1/2})$ and $A(^2P_{1/2})$ values derived from the interferometric experiments [15] (see table 1) deviate somewhat from our results. This may be due to the fact that the hfs splittings had to be extracted from non isotopically pure spectra with linewidths of about 1 GHz. The $A(^2P_{3/2})$ value derived from those spectra, under the assumption that $B(^2P_{3/2})$ equals zero, turns out to be a good estimate, as our results prove that the electric quadrupole hfs constant indeed is very small.

Before turning to the discussion of the ^{43}Ca hfs results, we discuss briefly the sensitivity of the method.

3.2. Sensitivity considerations

The application of a laser spectroscopic method to isotope shift and hfs measurements of short-lived radioactive isotopes produced in minor quantities only strongly depends upon the overall sensitivity of the technique. Among the measuring schemes used for calcium in the past, the collimated atomic beam – crossed laser experiments by Andl et al. have proven to be the most sensitive [11]. In those experiments, the resonance signal of 1 pg of ^{49}Ca , corresponding to a primary atomic beam intensity $> 3 \cdot 10^7$ atoms/s for $T_{\text{meas}} < T_{1/2} = 8.7$ min, could not be detected. Our ^{43}Ca experiments were performed with a primary ion beam intensity of 10^6 ions/s. Still, this gave a neutralized particle count rate of $4 \cdot 10^4$ c/s with a peak to background (P/B) ratio of the order of 10 %. Spectra registered with higher laser intensity showed much larger P/B ratios, however at the expense of some loss in resolution due to power broadening. The resonance signals of even isotopes, for which both ground state splitting as well as hyperfine pumping are absent, showed P/B ratios larger than 200 %. Therefore the resonance signal of the very low abundant (0.003 %) ^{46}Ca isotope could readily be detected (primary beam intensity $2 \cdot 10^4$ ions/s).

These data illustrate the feasibility of using this technique to extend calcium isotope shift and hfs constant measurements beyond the series of calcium isotopes studied so far.

4. Discussion

4.1. Comparison with RMBPT results

An extensive RMBPT evaluation of the CaII hfs constants has been performed by Mårtensson–Pendrill and Salomonson [3]. In these calculations, not only core–polarization, but also correlation effects are treated explicitly and relativistic effects are included. These CaII calculations, combined with derived trends in the different contributions over the series of alkali–metal atoms and alkaline–earth ions, previously served as a basis to calculate hfs constants in the heavier ions ; good agreement with experimental values was found [4,5]. Recently we extended the SrII data [21]. Here we compare the $^{87}\text{SrII}$ data with the theoretical predictions (see lower part of Table 2). The magnetic dipole hfs constants again turn out to be in excellent agreement with the theoretical values. The success of the CaII–based procedure can therefore already be considered as an *indirect* proof of the validity of the extensive CaII treatment.

The RMBPT values for CaII are given in the second row of Table 2. The comparison of experimental and calculated *magnetic dipole* hfs constants shows excellent agreement for all three states. This gives a *direct* proof of the reliability of the RMBPT treatment for these ionic one valence electron states. The experimental ^{43}Ca electric quadrupole hfs factor $B(^2P_{3/2})$, combined with the RMBPT value for B/Q , therefore results in a reliable determination of the nuclear quadrupole moment $Q(^{43}\text{Ca}) = -0.043(9)\text{b}$.

4.2. Comparison with semi-empirical analysis

Before comparing this Q value to those derived from CaI hfs constants, it is worthwhile to examine the results of a semi-empirical analysis of our hfs data. Previous semi-empirical analyses of hfs data of one valence electron systems in some cases turned out to give quite good results, whereas in others large differences with the results of ab initio calculations and/or discrepancies between the results from different states were found [5,17]. The reason for this can be clarified by considering the approximations made to derive semi-empirical results and comparing them with the detailed RMBPT data. This can best be done using the effective operator formalism (EOF) [23,3].

In this formalism, the effective magnetic dipole and electric quadrupole hyperfine operators are expressed using radial integral parameters connected to the magnetic orbital ($\langle r^{-3} \rangle_l$), the spin-dipole ($\langle r^{-3} \rangle_{sd}$), the contact ($\langle r^{-3} \rangle_c$) and the electric quadrupole orbital ($\langle r^{-3} \rangle_q$) contributions to the hyperfine fields (in the following the small purely relativistic quadrupole parameters are omitted).

For one valence electron systems with $l > 0$, the hfs constants are given by

$$\begin{aligned} A(L_{l-1/2}) &= \frac{\mu_0 \mu_B g_I \mu_N}{4\pi h} \frac{2}{2l+1} \left[2(l+1) \langle r^{-3} \rangle_l + \frac{2(l+1)}{2l-1} \langle r^{-3} \rangle_{sd} - \langle r^{-3} \rangle_c \right] \\ A(L_{l+1/2}) &= \frac{\mu_0 \mu_B g_I \mu_N}{4\pi h} \frac{2}{2l+1} \left[2l \langle r^{-3} \rangle_l - \frac{2l}{2l+3} \langle r^{-3} \rangle_{sd} + \langle r^{-3} \rangle_c \right] \\ B(L_{l-1/2}) &= \frac{1}{4\pi\epsilon_0} \frac{e^2 Q}{h} \frac{2(l-1)}{2l+1} \langle r^{-3} \rangle_q \\ B(L_{l+1/2}) &= \frac{1}{4\pi\epsilon_0} \frac{e^2 Q}{h} \frac{2l}{2l+3} \langle r^{-3} \rangle_q \end{aligned} \quad (1)$$

and for s states

$$A(S_{1/2}) = \frac{\mu_0 \mu_B g_I \mu_N}{2\pi h} \langle r^{-3} \rangle_c$$

Semi-empirical analysis of hfs constants are based on the non-relativistic central field limit ignoring all polarization and correlation contributions, such that

$$\text{for } l > 0 \quad \langle r^{-3} \rangle_l = \langle r^{-3} \rangle_{sd} = \langle r^{-3} \rangle_q \rightarrow \langle r^{-3} \rangle_{nl} \quad \text{and} \quad \langle r^{-3} \rangle_c = 0 \quad (2)$$

whereas

$$\text{for } l=0 \quad \langle r^{-3} \rangle_c \rightarrow \frac{2}{3} 4\pi |\Psi_{ns}(0)|^2 \quad (3)$$

The resulting expressions for the hfs constants are often refined by multiplying the $\langle r^{-3} \rangle_{nl}$ with appropriate relativistic correction factors [24] and for the A-factors by applying the Breit–Rosenthal–Schawlow and Bohr–Weisskopf nuclear volume corrections. For the $Z=20$ CaII systems, these corrections are very small.

The $A(S_{1/2})$ hfs constant is directly related to the electronic field shift factor for the $S_{1/2} \rightarrow P_J$ transition. If $|\Psi_{np}(0)|^2$ is taken to be zero :

$$F(S_{1/2} \rightarrow P_J) = \frac{\pi a_0^3}{Z} f(Z) |\Psi_{ns}(0)|^2 \quad (4)$$

with $f(Z)$ the finite nuclear size factor [25]. The $f(Z)$ includes relativistic corrections, which for calcium again are small. Isotope shift measurements combined with muonic x-ray data resulted in an experimental electronic field shift factor of 285(30) MHz/fm² [26].

In a semi-empirical analysis for one valence electron hfs constants, hydrogen-like wave functions are adopted. For s states this gives

$$|\Psi_{ns}(0)|^2 = \frac{Z_a^2 Z}{\pi a_0^3 n_*^3} \left(1 - \frac{\delta\Delta}{\delta n}\right) \quad (5)$$

with Z_a the effective atomic core charge (i.e. one for atoms and two for singly charged ions). The quantum defect Δ and the effective quantum number n_* are obtained from the term energy values, resulting in the well known Goudsmit–Fermi–Segré (GFS) estimate for $A_{ns}(^2S_{1/2})$.

For states with $l > 0$

$$\langle r^{-3} \rangle_{nl}^{FSS} = \frac{1}{n_*^3 (l+1)(l+1/2)l} \frac{Z_a^2 Z_i}{a_0^3} \quad (6)$$

for which the effective charge Z_i , felt by the valence electron at small distances to the nucleus, is obtained from an approximate expression for the fine structure splitting (FSS) [27] :

$$\Delta_{FSS} = \alpha^2 \frac{Z_a^2 Z_i^2}{n_*^3 l(l+1)} R_y \quad (7)$$

To extract a semi-empirical value for the nuclear quadrupole moment from the measured B-factors, either $\langle r^{-3} \rangle^{FSS}$ or $\langle r^{-3} \rangle^{HFS}$ derived from the measured A-factors can be used. The latter choice has the advantage that the contact contribution to $A(P_J)$, taken to be zero by the approximations mentioned above, can be accounted for by summing

$A(P_{1/2})$ and $A(P_{3/2})$ as can be seen from eqs. (1). However, the approximation $\langle r^{-3} \rangle_l = \langle r^{-3} \rangle_{sd} = \langle r^{-3} \rangle_q = \langle r^{-3} \rangle_{nl}$ is still required.

Some classes of many-body effects are often taken into account explicitly by calculated correction factors : the effect on the electronic field shift factor by the screening of the core electrons by the s valence electron [28], and the effect of orbital core-polarization on the electric quadrupole interaction i.e. Sternheimer shielding or antishielding [29].

The results of a semi-empirical hfs evaluation for the 4s and 4p CaII states are the following : $F^{GFS}(S \rightarrow P) = 316 \text{ MHz/fm}^2$ (352 MHz/fm² screening correction included), $A^{GFS}(^2S_{1/2}) = -827 \text{ MHz}$, $A^{FSS}(^2P_{1/2}) = -141 \text{ MHz}$, $A^{FSS}(^2P_{3/2}) = -28.2 \text{ MHz}$, $Q^{FSS} = -0.048 \text{ b}$ and $Q^{HFS} = -0.045 \text{ b}$ (corrected $\approx -0.036 \text{ b}$ and $\approx -0.034 \text{ b}$ respectively, using an estimated antishielding factor of $\approx 25 \%$). The agreement with the experimental and RMBPT results (see table 1) is remarkably good (corrected values are discussed below).

The question to be answered is why the semi-empirical analysis does give the right results in this case, whereas it fails for some other systems such as for example the one valence electron D_J states in BaII [5]. Part of the answer can be found by comparing the assumptions (2) with the results of the detailed RMBPT CaII calculations [3]. These show that for the 4p state $\langle r^{-3} \rangle_l : \langle r^{-3} \rangle_{sd} : \langle r^{-3} \rangle_q : \langle r^{-3} \rangle_c = 0.972 : 1 : 1.062 : 0.12$, which makes (2) a good assumption in this case. It should be noted however that the small contact contribution to the hyperfine field is due to polarization and correlation contributions of opposite sign and comparable amplitude. Furthermore, the many-body contributions to $\langle r^{-3} \rangle_l$, $\langle r^{-3} \rangle_{sd}$ and $\langle r^{-3} \rangle_q$ are roughly the same. So, the validity of assumptions (2) for the CaII p states is not at all trivial.

For the CaII 3d state, the RMBPT results show a completely different situation. For the contact parameter, the negative polarization contribution is four times bigger than the positive correlation contribution, the polarization effects on $\langle r^{-3} \rangle_l$ and $\langle r^{-3} \rangle_{sd}$ also differ by a factor of two, whereas the polarization plus correlation effect on $\langle r^{-3} \rangle_q$ nearly vanishes, resulting in $\langle r^{-3} \rangle_l : \langle r^{-3} \rangle_{sd} : \langle r^{-3} \rangle_q : \langle r^{-3} \rangle_c = 1.19 : 1 : 1.32 : -3.0$. This explains why e.g. the semi-empirical determination of the nuclear quadrupole moment of ¹³⁷Ba from the 6p and 5d BaII hfs data showed internal discrepancies of about 30 %, whereas a RMBPT analysis, based on the extended CaII calculations and derived trends over the one valence electron series [4], gave consistent results for all states [5].

In order to obtain satisfactory semi-empirical estimates, not only assumption (2) has to be fulfilled, but eqs. (5) and (6) should also give the right absolute values for

$|\Psi_{ns}(0)|^2$ and $\langle r^{-3} \rangle_{nl}$. The $A^{\text{GFS}}(^2S_{1/2})$ and $F_{\text{uncorr}}^{\text{GFS}}(S \rightarrow P)$ values are in good agreement with the experimental results, although the RMBPT calculation shows that about 30 % of the electron density at the nucleus stems from polarization plus correlation effects, not taken into account in the semi-empirical analysis. As already observed before in other systems (see e.g.[16]), this agreement once more points into the direction of an unintended inclusion of these many-body effects in the GFS formula. The agreement of the semi-empirical values, based on the FSS formula, with experiment is also good. As many-body effects here too have been shown to increase the lowest-order values of the radial integrals by about 50 %, this indicates an unintended correct scaling of the wave functions in the procedure for $\langle r^{-3} \rangle_{nl}^{\text{FSS}}$ too. The idea that many-body effects are already implicitly incorporated in the GFS formula, and at least for calcium also in the FSS formula, is supported by the fact that explicit corrections of the semi-empirical F and Q calcium values (see above) do clearly not improve the agreement with the results from experiment and RMBPT.

It has been shown by many-body perturbation theory [4] that the fractions of the polarization and correlation contributions to the hyperfine fields, relative to the first-order results, remain roughly constant for the ns and np states of the single valence electron series CaII to RaII and RbI to FrI. This fact, combined with the CaII evaluation given above, elucidates the reason for a more than reasonable success of the semi-empirical analysis procedure for ns and np one valence electron systems.

4.3. Comparison with Q values from CaI data

Finally our $Q(^{43}\text{Ca})$ result is compared to previous evaluations of this quadrupole moment based on experimental ^{43}CaI results (see table 2). The value of Q from the metastable 3P_2 state was obtained by a laser-ABMR B-factor measurement combined with first-order Hartree-Fock (HF) calculations and an estimate of polarization and correlation effects [8]. The latter were taken from a multiconfigurational HF evaluation of the analogous 3s3p configuration in Mg. From the laser - atomic beam $B(^3P_1)$ value, an independent value of Q was derived using semi-empirical formulae including relativistic corrections and the Sternheimer antishielding correction [9]. A combined interpretation of experimental A- and B-factors from laser-ABMR experiments on the metastable 1D_2 state led to a third value of Q after a number of approximations and estimates concerning configuration mixing, sl dependence of radial parameters and relativistic effects [10]. Finally Olsson and Salomonson [12] and Salomonson [13]

reevaluated the measured CaI B-factors using RMBPT theory. The strong correlation between the valence electrons was treated self consistently, starting from orbitals in the Ca^{2+} HF potential and including contributions from other angular symmetries in the wave function for the valence electrons and an estimate of relativistic effects. The calculated result for the ^3P term was believed to be more reliable than the one for the ^1D term, since the former is less deformed. Using the calculated value for the ^1P quadrupole radial integral parameter, Salomonson also extracted a quadrupole moment from the reported experimental value of $B(^1\text{P}_1)$ [11]. The result differs considerably from the values based on $^3\text{P}_J$, and the discrepancy was ascribed to a serious underestimation of the experimental error. A comparison of our value for CaII with those for CaI supports the validity of the RMBPT CaI evaluation for the weakly perturbed two valence electron $^3\text{P}_J$ states.

5. Summary and conclusion

Experimental hfs constants for the $^2\text{S}_{1/2}$ and $^2\text{P}_{1/2,3/2}$ states in CaII have been obtained by fast beam collinear laser spectroscopy. The theoretical RMBPT treatment of the magnetic dipole interaction in this one valence electron alkaline-earth ion is in excellent agreement with the experimental results. This allowed the extraction of a new value for the nuclear quadrupole moment of ^{43}Ca . The ultra high sensitivity of the applied laser spectroscopic method opens perspectives for measurements of isotope shifts and nuclear moments of the short-lived neutron rich calcium nuclei.

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Table 1. Comparison of experimental and RMBPT hfs coupling constants

	$A(^2S_{1/2})$ (MHz)	$A(^2P_{1/2})$ (MHz)	$A(^2P_{3/2})$ (MHz)	$B(^2P_{3/2})$ (MHz)	Q (b)
$^{43}\text{CaII}$					
Expt.	-805(2) -797.5(2.4) ^a	-145.5(1.0) -158.0(3.3) ^a	-31.9(2) -29.7(1.6) ^a	-6.7(1.4)	-0.043(9)
RMBPT ^b	-819	-148	-30.9	155 Q/b	
$^{87}\text{SrII}$					
Expt.	-1001(2) ^c -1000.5(1.0) ^d	-178.6(5) ^c	-36.0(4) ^d	88.5(5.4) ^d	0.336(2)
RMBPT ^e	-1000	-175	-36	263 Q/b	

^a From Ref. 15, in which $B(^2P_{3/2})=0$ was assumed ; ^b From Ref. 3 ; ^c From Ref. 22 ;^d From Ref. 21 ;^e From Ref. 4, correlation contribution included**Table 2.** Nuclear quadrupole moment values (in barn) of ^{43}Ca deduced from hfs coupling constants

		CaI		CaII
$4s4p\ ^3P_2$	$4s4p\ ^3P_1$	$4s3d\ ^1D_2$	$4s4p\ ^1P_1$	$4p\ ^2P_{3/2}$
-0.065(20) ^a	-0.040(8) ^b	-0.062(12) ^c		
	-0.049(5) ^d	-0.057 ^e	-0.15 ^f	-0.043(9)

^a From Ref. 8 ; ^b From Ref. 9 ; ^c From Ref. 10 ; ^d From Ref. 13 ;^e From Ref. 13, no error quoted^f From Ref. 13 (using data from Ref. 11), no error quoted

Figure captions.

Fig. 1. Schematic diagram of the experimental setup.

Inset: partial CaII level diagram.

Fig. 2. Optical $^{43}\text{CaII } 2S_{1/2} \rightarrow 2P_{1/2}$ (a) and $2S_{1/2} \rightarrow 2P_{3/2}$ (b) resonance signals, detected by state selective particle detection.

Fig. 1.

Fig. 2.