Analysis of long range interactions between two $^1S$ calcium atoms

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Cooling and trapping

- Mg and Ca optical frequency standard
- perspective of achievement of Sr BEC

$^1S$ ground state + no hyperfine structure

- testing ground for cold collision descriptions

Cold collision phenomena predictions

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Accurate interaction potentials especially at long internuclear distances

- Measurements
- Potential energy curve
- Discussion on long range extention
- s-wave scattering length
- Continuation of this study
Calcium frequency standard [1]:

- collisional perturbations on the $^3P_1 - ^1S_0$ clock transition

Photoassociation on $^1P_1 - ^1S_0$ [2]:

- interpretation of the recent observations
- intensity pattern.

s-wave scattering length:

- evaporative cooling
- Bose-Einstein condensate stability.


Experiment

new data by fluorescence progressions

$v^\prime J^\prime \rightarrow B^1\Sigma_u^+$

remove influence of excited state by construction of sets of differences

Production of calcium dimers in heat pipe oven (1300 K)

resonance by tunneling

LIF

$\text{Ar}^++2\omega\text{Nd:YAG Lasers}$

Experimental uncertainty $0.008 \text{ cm}^{-1}$

$\lambda_{\text{Ar}} = 514.1 \text{ nm}$

$P(160) 2-7$, $R(158) 2-8$, $P(162) 2-8$, $R(160) 2-9$, $R(160) 2-8$

$\Delta v \sim 0.07 \text{ cm}$

$\Delta v \sim 0.5 \text{ cm}$
More than 6500 differences between 730 levels

Construction of potential energy curve (PEC):

- IPA using set of points connected by cubic spline function
- Analytical function \( \sum a_i f(R-Re) \)

2 methods

accurate descriptions of observed levels \( \sigma = 0.0065 \text{ cm}^{-1} \)
with both methods

The eigenvalues obtained by both methods agree to within 0.0024 cm\(^{-1}\)
Differences between several potentials obtained by the two different methods

We can’t rely on the region around the last turning point to extend the potential
Using the correct model we might avoid oscillations of the PEC from 9.5 Å to 13.1 Å (19 levels).

We discovered that the measured levels can be described by the dispersion potential
\[ \text{De} - \frac{C_6}{R^6} - \frac{C_8}{R^8} - \frac{C_{10}}{R^{10}} \]

weak exchange contribution [3]

Several possible long range potentials
\[ C_n \text{ coefficients directly fitted on the obs. levels} \]

Not enough data to experimentally define the dispersion coefficients. 19 levels between 9.5 and 13 Å.

We should rely on the theoretical prediction of

\[ 1101.99 \text{ cm}^{-1} < D_e < 1102.17 \text{ cm}^{-1} \]

with agreement with the exp. data, smooth connection, within a range of ±5% around the theoretical value of \( C_6 \).

\[ \text{C}_6, \text{C}_8, \text{C}_{10}, D_e \text{ varied all possible potentials} \]

Dissociation energy of the $X^1\Sigma_g^+$ state

the experimental observations limit the dissociation energy to:

\[ \text{De} = 1102.08 \pm 0.09 \text{ cm}^{-1} \]

or with respect to $v = 0, J = 0$

\[ \text{Do} = 1069.88 \pm 0.09 \text{ cm}^{-1} \]

which significantly differs from the value of the previous study: $1095 \pm 0.5 \text{ cm}^{-1}$
Within this **long range model** (±5% variation of $C_6$) calculations of the scattering length lead to:

\[ 112a_0 < a < 850a_0 \]

Positive range!

With further constraints on the value of $C_6$ (±1%) we obtain:

\[ 160a_0 < a < 320a_0 \]

region forbidden by our data

rely mainly on the experimental uncertainty on $v''=35; J''=20, 22$
Simplified level scheme for $\text{Ca}_2$

Current and future experiments on $\text{Ca}_2$

1. Asymptotic levels of $X^1\Sigma_g^+$
   - better description of the long range behaviour
   - s-wave scattering length

2. Spectroscopy of the $A^1\Sigma_u^+$ and $B^1\Sigma_u^+$
   - fill the gap to the asymptotic levels obtained by PA spectroscopy on B state
   - production of cold $\text{Ca}_2$ by spontaneous emission possible?
   - ground state scattering length via PA ($\mu$K) intensity patern

3. Study of the $^3\Pi + ^1S$ asymptote
   - deperturbation study on $A^1\Sigma_u^+$ and $c^3\Pi_u$ states
   - collisional shift of the Ca clock frequency
   - production of cold $\text{Ca}_2$ by spontaneous emission possible?