The $^1S+^1S$ asymptote of Sr_2 studied by Fourier-transform spectroscopy

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(Dated: October 29, 2018)

An experimental study of the long range behavior of the ground state $X^1\Sigma_g^+$ of Sr_2 is performed by high resolution spectroscopy of asymptotic vibrational levels and the use of available photoassociation data. Ground state levels as high as $v'' = 60$ (outer turning point at 23 Å and 0.1 cm^{-1} below the asymptote) could be observed by Fourier-transform spectroscopy of fluorescence progressions induced by single frequency laser excitation of the $v' = 4$, $J' = 9$ rovibrational level of the state $2^1\Sigma_u^+$. A precise value of the scattering length for the isotopologue $^{88}Sr_2$ is derived and transferred to all other isotopic combinations by mass scaling with the given potential. The derived potential together with already published information about the state $2^1\Sigma_u^+$ directs to promising optical paths for producing cold molecules in the electronic ground state from an ultracold ensemble of Sr atoms.

PACS numbers: 34.20.Cf, 31.50.Bc, 33.20.Kf, 33.20.Vq

I. INTRODUCTION

Our spectroscopic work on this molecule is motivated by the current high interest in ultracold ensembles of Strontium atoms [1–4], which could be a candidate for an optical frequency standard [5–7], and also by interest in ultracold Sr_2 molecules [8, 9]. Though for all these experiments reliable knowledge of collision properties for Sr atoms like scattering lengths would be of advantage, there was no sufficiently precise ground state potential available from *ab initio* calculations or experimental work, from which these quantities could be derived by directly solving the radial Schrödinger equation.

In [10] we reported on the optical spectrum of the system $2^1\Sigma_u^+$ — $X^1\Sigma_g^+$ with more than 10300 transitions which involve the term energies of nearly 60% of the existing rovibrational levels of the ground state for the main isotopologue $^{88}Sr_2$ and additionally many levels for the isotopologues $^{86}Sr^{88}Sr$ and $^{87}Sr^{88}Sr$. We reached vibrational levels up to $v'' = 49$ and rotational levels up to $J'' = 224$. Using this data set we had to correct the rotational assignment given by [11] by four units and were able to construct a potential energy curve (PEC) which is reliable in the range from 4 to 11 Å, covering an energy region from the bottom up to 9 cm^{-1} below the dissociation asymptote. With the help of theoretically calculated long range coefficients C_6 and C_8 [12, 13] and at that time available node positions of the scattering wave function at large internuclear separation for a kinetic energy of a few microkelvins [14] and 2 mK [1] from photoassociation, we estimated a complete set of scattering lengths for all combinations of naturally abundant Sr isotopes. Using our derived potentials to calculate Franck-Condon factors we proposed spectroscopic schemes to measure the highest existing vibrational levels of the ground state. Meanwhile new work on photoassociation [15] was performed and the binding energy of the last vibrational level $v'' = 62$ for $^{88}Sr_2$ was determined and for ^{84}Sr two groups reached Bose-Einstein condensation [16, 17].

In this work we report on successful experiments in the proposed direction and derive ground state levels close to the asymptote with which we extend the precisely known potential region significantly into the long range regime. With these data the experimental knowledge about the long range coefficients C_6, C_8 and C_{10} and the precision in the scattering lengths will be improved.

The paper is organized as follows: Section II describes the experimental methods, Sec. III shows the obtained data set and discusses the measurement uncertainties, Sec. IV presents the resulting ground state potential and scattering lengths. Sec. V gives conclusions and a short outlook.

II. EXPERIMENT

The apparatus is the same as in [10], the experimental procedure is an extension of the earlier one. Strontium is filled into a stainless steel heatpipe, which is heated to a temperature of about 1220 K under 20 mbar of argon as a buffer gas. To keep the optical path free from condensing strontium crystals growing at both ends of the heatpipe, the oven has to be moved every two hours to bring this Sr back to the heated zone. This means, that the heated cell is not working perfectly as a heatpipe where the condensed substance flows back to the heated region.

The molecules are excited to the $v' = 4$ level of the state $2^1\Sigma_u^+$ by light from a Coherent CR 699 ring dye laser operated with Rhodamine 6G at frequencies close to 17635 cm^{-1} (depending on the rotational quantum number J). The power of the dye laser was about 70 mW in front of the heatpipe. The fluorescence light emitted antiparallel to the beam direction of the laser is imaged into a Bruker IFS 120 HR Fourier-transform spectrometer.

To measure the highest vibrational levels of the ground state, the vibrational band of the excited state with $v' = 4$ and the rotational levels with $J' = 25$, $J' = 21$, $J' = 17$, $J' = 13$, and $J' = 9$ were selected. Low J are very important for observing asymptotic levels because high J are not existing for these v. For measuring the progres-