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Hyperfine structure of the NaCs $b^3\Pi_2$ state near the dissociation limit $3S_{1/2} + 6P_{3/2}$ observed with ultracold atomic photoassociation

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We report new observations of the hyperfine structure in three ro-vibrational levels of the $b^3\Pi_2$ state of NaCs near the dissociation limit $3S_{1/2} + 6P_{3/2}$. The experiment was done via photoassociation of ultracold atoms in a dual-species dark-spot magneto-optical trap, and the spectra were measured as atomic trap losses. The simulation of the hyperfine structure showed that the greater part of the observed structure belongs to almost isolated levels of the $b^3\Pi_2$ state, but there are other parts of mixed character where the contribution from the ${}^{1}\Sigma$ symmetry dominates.

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I. Introduction

Ultracold polar diatomic molecules have recently offered exciting new possibilities for research in the field of quantum statecontrolled chemistry,^{1,2} tests of fundamental physics,^{3,4} and formation of exotic quantum matter.⁵⁻⁷ Especially, the anisotropic dipole-dipole interaction between molecules can be freely engineered by exploiting their intrinsic large permanent electric dipole moments,^{1,8,9} which are usually inaccessible in ultracold atomic species, thus making ground state ultracold molecules ideal candidates in the applications of quantum simulation of many-body systems,¹⁰⁻¹² quantum information processing,^{13,14} and precision measurements.^{15,16} Although in recent years great strides have been made towards direct laser cooling of molecules,^{17,18} ultracold polar molecules, such as bosonic ⁸⁷Rb¹³³Cs and ²³Na⁸⁷Rb molecules¹⁹⁻²¹ and fermionic ⁴⁰K⁸⁷Rb and ²³Na⁴⁰K molecules,^{10,22,23} in the rovibrational ground state with high phase space density, have been conventionally produced by optically transferring weakly bound

Feshbach molecules via Stimulated Raman Adiabatic Passage (STIRAP).24,25

In the Lambda scheme of STIRAP, the initial weakly bound polar Feshbach molecules are transferred to the final absolute ground molecular states via two coherently overlapping laser pulses by virtue of an intermediate electronically excited state that possesses favorable dipole transition probabilities with both the initial and final states.²⁵ Many studies on the ground electronic states of heteronuclear polar molecules have been accomplished, but efforts are still required to obtain precise knowledge of the excited electronic molecular structures, especially the hyperfine structures (HFS).²⁶⁻²⁸ Ultracold dimer molecules have rich and complicated spin structures due to the presence of two nuclei with nonzero spins interacting with one another and with the molecular rotation.^{8,29,30} The interactions often lead to fertile molecular HFSs. In ultracold studies, the HFS plays an important role. The hyperfine energy splittings are often of the same magnitude as the thermal energy.²⁰ In addition, the molecules have to be in the same hyperfine level to reach Fermi degeneracy or Bose-Einstein condensation (BEC).^{1,31} Particularly, precise understanding and control over the complex intermediate HFS quantum states is crucial to ensure optimum population transfer efficiency during the absorption-emission cycles in the Lambda scheme into triplet or singlet ground states for ultracold molecule creation.²⁹ Finally, HFS states in rotational ground state molecules have been expected as potential qubits for quantum information processing.32,33

Compared with the HFSs in weakly bound levels in Feshbach molecules, the HFSs in an electronically excited state are often intrinsically complicated as it contains a ground-state ²S atom and

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Paper

an excited-state ²P atom, *i.e.*, an extra nonzero angular momentum has to be considered. High resolution Photoassociation Spectroscopy (PAS), whose tiny kinetic energy spread and precise control over the ultracold molecular states result in an accuracy of kHz level,^{34–38} is often advantageous in the detection of molecular HFS structures over the traditional thermo-luminescence spectroscopy or laser induced fluorescence (LIF) spectroscopy techniques with a precision of the order of a wavenumber (cm⁻¹).^{26,39–41} PAS has enabled researchers to obtain rich information about molecular structures, to determine the long-range behaviour of the molecular potential energy curves (PECs), and to precisely measure fundamental physical constants, including their hypothetical time variation,^{42–45} and the s-wave scattering lengths.^{46,47}

As a simple and versatile method to reach weakly bound ultracold molecules far below 1 mK, photoassociation (PA) has been widely applied in the production of heteronuclear molecules that are composed of different precooled alkali species (*e.g.* LiNa, LiRb, LiCs, KRb, NaK, NaCs, and RbCs)^{36,37,48-52} or alkaline-earth metals (*e.g.* LiYb, RbYb, CsYb, and RbSr).⁵³⁻⁵⁷ All these molecules demonstrate a van der Waals potential proportional to $1/R^6$ (where *R* is the inter-nuclear distance) in their excited molecular states at large inter-nuclear separations. Among these molecules, the ²³Na¹³³Cs molecule possesses the second largest permanent electric dipole moment (EDM, 4.6 Debye),⁵¹ and its ground state is chemically stable and immune to reactive collisions.⁵⁸ In view of these virtues, NaCs molecules are advantageous in the exploration of long-range dipole–dipole interactions.¹

Ultracold NaCs molecules were produced for the first time about two decades ago.⁵⁹ Since then, PAS for different electronic states (e.g. $1^{1}\Sigma^{+}$, $c^{3}\Sigma^{+}$, $B^{1}\Pi$, and $X^{1}\Sigma^{+}$ states) in the NaCs molecule has been achieved using a highly sensitive ionization detection technique.^{28,51,59,60} However, some important information including the PA transition intensities would vanish in the detection process due to the use of the ionization laser. More importantly, the method is limited to detecting some ro-vibrational states rather than specific HFS components of these states. Comparatively, high-resolution trap-loss spectroscopy (TLS), which is performed by monitoring the fluorescence of trapped ultracold atoms, provides a unique, nondestructive and simply equipped detection approach to explore the PAS of molecular long-range states including their HFSs and to acquire their binding energy and transition strength information. Very recently, a single NaCs molecule has been created in an optical tweezer by addressing the chemical reactions between single sodium and single caesium atoms in a photoassociation process.61

In our previous work, TLS of NaCs molecules has been reported. The NaCs molecular ro-vibrational levels and their HFSs components in the $(c^{3}\Sigma^{+}, A^{1}\Sigma^{+} \sim b^{3}\Pi)$ electronic states have been observed^{28,62} with high sensitivity, based on which laser-induced frequency shifts (LIFSs) of NaCs molecular hyperfine levels have been reported with high precision.⁶³ However, to the best of our knowledge, the HFSs in the levels of the $b^{3}\Pi_{2}$ (Hund's case (a) designation) state have never been observed before. The complicated angular momentum vector coupling models could be one of the explanations for why hyperfine splittings should be quite small for most electronic states of NaCs.⁴⁰ It should be noted that NaCs molecules in the absolute ro-vibrational ground state have not been created yet. And the strong spin–orbit mixing in the NaCs excited $A^1\Sigma^+ \sim b^3\Pi$ state complex often gives rise to large wavefunction perturbations, thus resulting in radiative stabilization directly into the vibrational ground states.³⁹ Therefore, it is well-worth investigating the HFSs of the $b^3\Pi_2$ state of the NaCs molecule utilizing the PAS technique.

In this paper, we demonstrate high-resolution TLS of the HFSs of ultracold polar NaCs molecules below the Na $(3S_{1/2})$ + Cs $(6P_{3/2})$ asymptote (corresponding to the caesium atomic D₂ line at 852 nm). The experiment was carried out in a dual-species Na–Cs magneto-optical trap (MOT). By using a modulation spectroscopy technique, PAS spectra are acquired with high sensitivity and high resolution. HFS components in 3 ro-vibrational levels were observed and analyzed. Although the computational model is simple, it reproduces the overall characteristics of the HFSs in the experimental spectra.

The paper is organized as follows. In Section II, we briefly overview the experimental setup and schemes. In Section III, we demonstrate the experimental results of the PAS of the HFSs in specific ro-vibrational levels of NaCs molecules. The theoretical model simulations for the observed HFSs are presented in Section IV. Finally, the conclusions are presented in Section V.

II. Experimental setup

The details of the experimental setup, similar to that used in ref. 28, 62 and 64, are demonstrated schematically in Fig. 1. A mixture of ultracold sodium and caesium atomic samples was loaded in a standard rectangular quartz vacuum chamber with a background pressure of $\sim 1 \times 10^{-8}$ Pa. Na-Cs dual-species dark-spot magneto-optical traps (dark-SPOTs) were overlapped at the centre of the chamber to provide cold atomic samples with high density and a low light assisted collision rate. The trapping and repumping laser beams for the Na atoms were provided by a high-power, frequency-tunable diode laser (\sim 1 W, line-width 0.5 MHz), while those for the Cs atoms were provided by two external-cavity diode lasers (80 mW, line-width 0.8 MHz). The frequencies of the diode lasers were all stabilized to specific atomic hyperfine transition resonances using saturation absorption spectroscopy (SAS) and detuned by adjusting the frequencies of the corresponding acousto-optic modulators (AOMs). A gradient magnetic field with ~ 15 G cm⁻¹ was generated by a pair of anti-Helmholtz coils. As a result, the ²³Na (¹³³Cs) dark-SPOT typically confines $N_{\rm Na} \sim 1 \times 10^7$ atoms $(N_{\rm Cs} \sim 6 \times 10^7)$ with a density of $n_{\rm Na} \sim 2.0 \times 10^9 {\rm ~cm^{-3}}$ $(n_{\rm Cs} \sim 1.5 \times 10^9 {\rm cm}^{-3})$, where the Na (Cs) atoms were mainly populated in the lower hyperfine level F = 1 (F = 3) of the $3S_{1/2}$ $(6S_{1/2})$ state. The temperature of the ultracold Na (Cs) atomic sample was measured to be $\sim 200 \,\mu\text{K} (\sim 120 \,\mu\text{K})$ using the timeof-flight (TOF) method.



Fig. 1 Energy level diagram for a typical molecule formation and detection process. Atoms are photoassociated into a bound molecular state by a PA photon (PA in the figure). The excited state molecule is allowed to decay to the free atoms *via* spontaneous emission. The Na and Cs ultracold atom samples are trapped in a dual-species MOT.

The PA laser beam was given by a widely tunable continuouswave (cw) Ti:sapphire laser system (MBR110) with a typical linewidth less than 100 kHz and an output power up to 3.5 W, which was pumped by a 532 nm diode laser (Verdi-18, a maximum power of ~18 W). The PA laser beam was set with linear polarization and collimated to a $1/e^2$ diameter of 0.7 mm with a maximum available average intensity of ~800 W cm⁻². The absolute frequency of the PA laser was measured using a wavelength meter (High Finesse-Angstrom, WS/U, accuracy ~30 MHz). The wavelength meter was calibrated against the Cs atomic hyperfine resonant transition, $6S_{1/2}$ (F = 4) $\rightarrow 6P_{3/2}$ (F = 5), corresponding⁶⁵ to 11732.182 cm⁻¹.

In the experiment, a pair of colliding ultracold sodium (Na) and caesium (Cs) atoms resonantly absorbs a photon from the PA laser and forms a NaCs molecule in an excited state, which quickly decays into free atoms or the ground state molecule and escapes from the trap. This process leads to losses of both trapped Na and Cs atoms. Consequently, the photoassociation of ultracold NaCs molecules can be detected by measuring the number of trapped atoms in the MOT *via* fluorescence as a function of the PA laser frequency. In this way, as a simple technique to detect PA transitions, a typical PA spectrum is acquired, *i.e.* trap-loss spectroscopy (TLS). However, direct fluorescence detection is usually hindered due to the weak signal and environmental stray light. So we use a photo-multiplier (PMT) to detect the Na atomic fluorescence from the dark SPOT and an avalanche

photodiode (APD) to detect that for the Cs atoms. Bandpass filters (589 nm for Na and 852 nm for Cs) covered the PMT and APD, respectively, to shield the stray light from detection.

Meanwhile, we applied a technique of phase-sensitive detection (PSD)⁶⁴ to enhance the detection sensitivity of TLS. The ultracold atoms, as well as their fluorescence, are modulated through altering the trapping laser frequency with a conventional function generator. Fig. 2(a) demonstrates the modulation scheme of Na atoms in the MOT. A sine wave modulation signal is added to the trapping laser controller to modulate the laser current, thus the instantaneous frequency of the laser is given as $f(t) = f_0 + \Delta \sin(\omega t)$, where f_0 is the centre frequency, which was red detuned by 10 MHz from the Na atomic transition of $3S_{1/2}$ (F = 2) \rightarrow $3P_{3/2}$ (F = 3), and the modulation amplitude is set as 2.3 V. Here, $\Delta \sin(\omega t)$ is the timedependent frequency of the modulation signal, and Δ is the modulation depth of the frequency. For the caesium atoms the modulation scheme was the same. Finally, lock-in amplifiers (Stanford Research SR830) were used to demodulate the fluorescence from the Na and Cs MOTs. It should be noted that the modulation signals (3.58 kHz for the Na atoms and 3.3 kHz for the Cs atoms) served as reference signals both in the demodulation process and in the frequency stabilization of the trapping lasers.

The noise power spectra of sodium atomic fluorescence are shown in Fig. 2(b) as a function of modulation frequency.



Fig. 2 (a) Principle modulation diagram for the ultracold Na atom. (b) Noise power spectra of cold atomic fluorescence *versus* the modulation frequency. (c) Typical loading sequence of the Na + Cs dual MOT. Trapping of Na (red curve) and Cs (blue curve) is controlled by switching the corresponding repumping beam off or on.

The atomic fluorescence can be clearly found at four different orders of demodulation frequencies. The noise at low frequency (black curve) was mainly caused by 1/f noise. The signal at the first harmonic of the modulation frequency ω (3.58 kHz) of the trapping laser is much larger than that of the higher order 2ω , 3ω , and 4ω harmonic frequencies. So we choose $\omega/2\pi$ = 3.58 kHz as the modulation frequency. The inset reveals the sine modulation signal (yellow curve) and the corresponding well-modulated fluorescence signal (green curve) of the Na MOT. Thus far, we have obtained high-resolution fluorescence signals from the dual-species Na-Cs MOT. A typical event for the time evolution of the fluorescence from Na and Cs atoms with or without each other is shown in Fig. 2(c). The modulated fluorescence is not strictly sinusoidal like the modulation signal. This is mainly caused by a relatively longer atomic loading time (3 s) and an additional integration time (300 ms) for the lock-in amplifier.

At t = 5 s the Cs MOT was first loaded and at t = 13.5 s the Na MOT was loaded along with it for 8.5 s. Then the Cs repump beams were blocked, which led to an increment of the Na atoms in the MOT. At t = 43 s, the Cs beams were unblocked and the Cs MOT loaded again with the Na MOT. The Na atoms are gradually lost in the presence of the Cs MOT, reaching a new steady state. This means that the Na–Cs MOTs were well overlapped and their collisions were beneficial to form NaCs molecules. It should be noted that the large excess of Cs atoms leads to a relatively small increase in loss compared with that for Na atoms. So in the PA process, where a PA resonance resulted in the formation of the NaCs molecules and the losses of both Na and Cs atoms, the fluorescence of the Na atoms as a



Fig. 3 Experimental trap loss spectrum of ultracold photoassociation into the NaCs $b^3\Pi_2$ state; the circle indicates the position of the level v = 92, J = 2 reported in ref. 66; the square bracket indicates the spectral fragments with the hyperfine structure of this level (compare Fig. 4 and 5); the dashed vertical lines indicate the peaks listed in Table 1. The origin of the energy scale is the atomic limit Na($3S_{1/2}$) + Cs($6P_{3/2}$).

function of the PA laser frequency was monitored and recorded as the TLS of the ultracold polar NaCs molecules.

III. Experimental results

We found three PA resonances, which could be assigned to the ro-vibrational levels of the $b^3\Pi_2$ state. The preliminary assignment was based on the closeness of the resonance positions to the term values reported in ref. 66. The corresponding trap loss spectra, measured by us, are shown in Fig. 3–5 (solid lines) along with the positions of the term values from ref. 66 (circles),



Fig. 4 Experimental trap loss spectrum of ultracold photoassociation into the NaCs $b^3\Pi_2$ state; the circle indicates the position of the level v = 94, J = 2 reported in ref. 66; the square bracket indicates the spectral fragments with the hyperfine structure of this level (compare Fig. 3 and 5); the dashed vertical lines indicate the peaks listed in Table 1. The origin of the energy scale is the atomic limit Na(3S_{1/2}) + Cs(6P_{3/2}).



Fig. 5 Experimental trap loss spectrum of ultracold photoassociation into the NaCs $b^3\Pi_2$ state; the circle indicates the position of the level v = 98, J = 2 reported in ref. 66; the square bracket indicates the spectral fragments with the hyperfine structure of this level (compare Fig. 3 and 4); and the dashed vertical lines indicate the peaks listed in Table 1. The origin of the energy scale is the atomic limit Na(3S_{1/2}) + Cs(6P_{3/2}).

closest to our PA resonances. The tabulated local peak positions of all three HFS spectra are presented in Table 1. All three spectra exhibit clear hyperfine structures of similar patterns. The overhanging square brackets indicate the spectral fragments, which were eventually assigned to the $b^3\Pi_2$ state (Section IV); the similarity between the structures in these fragments can be seen.

IV. Model simulation

We simulated the observed hyperfine structure with the same model that was used in our previous work.^{28,62} All the necessary equations and computational details can be found in ref. 28. Briefly, it considers four molecular vibrational levels of symmetries ${}^{1}\Sigma$, ${}^{3}\Sigma$, ${}^{1}\Pi$, and ${}^{3}\Pi$, corresponding to the symmetries of electronic states at the atomic limit $S_{1/2} + P_{3/2}$ of alkali metal dimers, which are coupled by fine and hyperfine interactions (namely, effective electron spin–electron orbit, electron

Table 1 The positions E (cm⁻¹) of the HFS peaks in the observed PA spectra (v = 98, J = 2; v = 92, J = 2; and v = 94, J = 2 levels of the NaCs b³ Π_2 state) and the corresponding binding energies $E - E_b$ relative to the center of weight of the upper state atomic hyperfine structure, where $E_b = 11732.4796$ cm⁻¹ is the energy gap (ref. 65) between the initial Cs (6S_{1/2}) (F = 3) state and the upper Cs (6P_{3/2}) center of gravity

E(v = 98)	$E - E_{\rm b}$	E(v = 94)	$E - E_{\rm b}$	E(v = 92)	$E - E_{\rm b}$
11712.1497	-20.3299	11680.1249	-52.3547	11655.8344	-76.6452
11712.1521	-20.3275	11680.1296	-52.3500	11655.8406	-76.6390
11712.1541	-20.3255	11680.1435	-52.3361	11655.8416	-76.6380
11712.1568	-20.3228	11680.1513	-52.3283	11655.8451	-76.6345
11712.1602	-20.3194	11680.1555	-52.3241	11655.8494	-76.6302
11712.1633	-20.3163	11680.1617	-52.3179	11655.8517	-76.6279
11712.1764	-20.3032	11680.1671	-52.3125	11655.8534	-76.6262
11712.1823	-20.2973			11655.8555	-76.6241
11712.1836	-20.2960				
11712.1869	-20.2927				
11712.1911	-20.2885				
11712.1939	-20.2857				
11712.1952	-20.2844				
11712.1972	-20.2824				
11712.1995	-20.2801				
11712.2022	-20.2774				

spin–nuclear spin, nuclear spin–electron orbit, and electric quadrupole). The relative PA intensities are estimated as probabilities of optical dipole transitions to these levels from the scattering *s*-wave states at the lower atomic limit, and the line profiles are approximated by Lorentzians. The relative positions of the levels, Lorentzian widths, and, optionally, the values of the interaction parameters (including rotational constants) are varied in order to get a reasonable reproduction of the experimental data.

We started our modeling by considering an almost isolated level of ${}^{3}\Pi$ symmetry (the other three levels were separated from it by a gap of ~100 GHz) and tracking its components at the upper fine-structure limit, all the interaction parameters



Fig. 6 Simulation of the photoassociation spectrum of the level v = 98, J = 2 (Fig. 5) using a model of an isolated NaCs $b^3 \Pi_2$ level with asymptotic parameters (upper curve), compared with the experimental trap loss spectrum (lower curve). The origin of the energy scale is shifted to the centre of the spectrum.

Table 2 The fitted values of the rotational constants B_v for the contributing states (GHz, estimated standard deviations in parentheses). The zero-th order rotational constant B_v of the v = 98, J = 2 state was estimated from the term values by Zabawa⁶⁶ as 0.379 GHz

Contributing state	³ П	$^{1}\Sigma$	$^{1}\Pi$	$^{3}\Sigma$
B_{ν}	0.3792(0.0005)	0.3790(0.0005)	0.3790(0.0005)	0.3790(0.0005)

being equal to their asymptotic atomic values,²⁸ and the rotational constant estimated from the ro-vibrational term values of ref. 66 as $B_{\nu} = 0.379$ GHz. At once, this resulted in a very reasonable reproduction of the structure indicated by the overhanging square brackets in Fig. 3–5; this simulation is compared to the experimental spectrum from Fig. 5 in Fig. 6. The quantum numbers of the dominating character in this simulation are $\Omega = 2$ and J = 2, confirming the assignments, which were initially based on the comparison with the results of ref. 66. The hyperfine structure originates almost totally from the interactions between components of the ³ Π symmetry. This computation also shows that our model²⁸ is able to provide very reasonable simulations, despite the fact that many physically significant mechanisms are neglected.

However, the physical nature of the structure in the left parts of the experimental spectra, which were not reproduced in this simulation, remained unclear. Our initial idea was that it should mainly originate from a level of ${}^{1}\Sigma$ character, because it can only interact with the ${}^{3}\Pi$ level *via* hyperfine mechanisms while their (otherwise the strongest) spin–orbit interaction is zero, and hence it is unable to influence the structure of the ${}^{3}\Pi$ level excessively.

In order to check this hypothesis, we shifted the ${}^{1}\Sigma$ level to the neighbourhood of the ${}^{3}\Pi$ level. As expected, its influence on the structure in the right part of the simulated spectrum was minimal, but it only produced one intense peak in the spectral range under consideration. To get a splitting, we also varied the positions of the two other levels. In the final simulation, we also varied the interaction parameters and the rotational constants, keeping them close to their default/asymptotic values.²⁸ Their deviations from those asymptotic values were no more than the estimated characteristic inaccuracies of ~0.0005 GHz (see Tables 2 and 3). The fitting was performed with the use of our package Optimizer described elsewhere.^{67,68}

The best result we were able to achieve is shown in Fig. 7. The simulated individual line positions E_{sim} along with their

Table 3 Effective electron spin–nuclear spin interaction parameters (electronic matrix elements b_k in the notation of our work in ref. 28) (GHz, estimated standard deviations in parentheses) of the NaCs $b^3\Pi_2$ v = 98, J = 2 state. All other fine and hyperfine parameters (electron spin–orbit, nuclear spin–orbit, and electric quadrupole) were not varied and kept their asymptotic values²⁸

Interacting states (nucleus)	Asymptotic [ref. 28]	Fitted
${}^{3}\Sigma \sim {}^{3}\Sigma$ (Na)	1.084895	1.0849(0.0005)
$^{3}\Sigma \sim ^{3}\Sigma (Cs)$	-0.23438	-0.2344(0.0005)
${}^{3}\Pi \sim {}^{3}\Pi (Na)$	1.084895	1.0848(0.0005)
${}^{3}\Pi \sim {}^{3}\Pi (Cs)$	-0.23438	-0.2328(0.0005)
${}^{1}\Sigma \sim {}^{3}\Sigma (Na)$	0.76741	0.7671(0.0005)
${}^{1}\Sigma \sim {}^{3}\Sigma (Cs)$	-0.16573	-0.1659(0.0005)
${}^{1}\Pi \sim {}^{3}\Pi (Na)$	0.76714	0.7671(0.0005)
${}^{1}\Pi \sim {}^{3}\Pi (Cs)$	-0.16573	-0.1657(0.0005)



Fig. 7 Result of fitting of the entire spectrum shown in Fig. 5 (upper curve), compared with the experiment (lower curve). The origin of the energy scale is shifted to the centre of the spectrum.

relative intensities I_{sim} and strict molecular quantum numbers F_{mol} are listed in Table 4. Although not all the peaks were reproduced, those which were reproduced looked similar to the experimental ones. Perhaps better reproduction of the experimental data requires a more elaborate model, which implies a

Table 4 The positions E_{sim} (cm⁻¹) of the simulated HFS lines in the PA spectrum (v = 98, J = 2 level of the $b^3 \Pi_2$ state) relative the center of weight of the upper state atomic hyperfine structure, their relative intensities I_{sim} , and the strict molecular quantum numbers F_{mol}

E _{sim}	I _{sim}	$F_{ m mol}$
-20.32150	0.33	3
-20.32061	0.02	4
-20.31986	0.71	2
-20.31960	0.83	3
-20.31927	0.07	5
-20.31917	0.56	4
-20.31642	0.68	1
-20.31639	1.03	2
-20.31635	1.24	3
-20.31631	1.21	4
-20.31629	0.84	5
-20.30308	2.46	3
-20.29751	1.71	4
-20.29565	1.24	2
-20.29288	1.20	3
-20.28908	0.44	4
-20.28889	0.68	5
-20.28586	0.46	1
-20.28451	0.66	2
-20.28256	0.67	3
-20.28020	0.43	4
-20.27807	0.17	5

Paper

much more resource-consuming computation of full multichannel quantum dynamics in the fields of the potential energy curves of all the coupled electronic states. The simulated left peaks possess mixed electronic symmetry with domination of the ¹ Σ character but with a noticeable presence of the other 3 symmetries; the dominating quantum numbers are $\Omega = 0, J = 1$.

V. Conclusions

We performed experiments with the technique of photoassociation (PA) of ultracold Na and Cs atoms confined in a dual-species dark-spot magnetic trap. We recorded the resolved atomic trap-loss spectra of three registered PA resonances, assigned to the NaCs $b^3\Pi_2$ state near the dissociation limit Na($3S_{1/2}$) + Cs($6P_{3/2}$). All three spectra exhibit a rich hyperfine structure. The simulation was done with the use of the model of four coupled vibrational levels which was developed and employed in our earlier work on hyperfine structures in NaCs. The simulation showed that a considerable part of the structure indeed belongs to the state $b^3\Pi_2$, J = 2. The other part of the registered peaks possesses mixed electronic character with domination of ${}^{1}\Sigma$, $\Omega = 0$, J = 1.

Author contributions

X. W., W. L. and Y. L. peformed the experiments. J. W. and J. M. supervised the experimental work. V. S. and S. O. contributed theoretical analysis. All authors contributed to the analysis and discussion of the results and the preparation of the manuscript.

Conflicts of interest

There are no conflicts to declare.

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