Avoided level crossings between *s* states and Stark states in Rydberg Rb atoms

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We have measured the locations and widths of the avoided level crossings between $(n+3)s$ states and n,k Stark states in Rydberg Rb atoms with principal quantum numbers n between 16 and 25. We use two-step laser excitation to excite $(n+3)s$ states in the presence of an electric field and observe a change in the number of atoms driven to higher-lying states by blackbody radiation as the electric field is tuned through the avoided level crossings. We have measured both the positions and widths of the avoided crossings. [S1050-2947(96)05509-6]

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In the heavier alkali-metal atoms, K, Rb, and Cs the $\ell \geq 3$ states all have quantum defects less than 0.05, and of the $\ell < 3$ states the one with a quantum defect the closest to an integer is the s state. Here ℓ is the orbital angular momentum quantum number. Consequently, when an electric field is applied the $\ell \geq 3$ states are converted to a manifold of Stark states, with linear Stark shifts at low fields, and the first $\ell < 3$ state the Stark manifold intersects is the s state, to which it is only weakly coupled [1].

In Rb the Stark states of principal quantum number n intersect the $(n+3)s$ states, as shown by Fig. 1 for $n=21$. The avoided crossings between the 24s state and the 21,k Stark states are quite small, since the s state is only weakly coupled to the Stark manifold. We denote the Stark states n,k, where n and k are the zero field n and ℓ quantum numbers of the state to which the Stark state is adiabatically connected. In an electric field the total azimuthal angular momentum quantum number m_j is a good quantum number, and the energy levels shown in Fig. 1 are $m_j = \frac{1}{2}$ levels. In addition, the azimuthal orbital and spin angular momenta m_ℓ and m_s are almost good quantum numbers since there is little spin-orbit coupling in any of the $\ell \geq 3$ states and none in the s states. For this reason the 24s avoided crossings with the $m_\ell = 0$ states are larger than those with the $|m_\ell| = 1$ states, as shown by the insets of Fig. 1. Finally, we note that states of the same $|m_s|$, $|m_\ell|$, and $|m_j|$ are degenerate in an electric field.

Here we report the measurements of the avoided crossings of the Rb $(n+3)s$ states with the three lowest energy n,k Stark states, $3 \leq k \leq 5$, for $16 \leq n \leq 25$. We have used the method of Stoneman, Janik, and Gallagher [2]. A rather different method was used by Nosbaum *et al.* to measure the analogous avoided crossings in Cs [3]. The essential idea of the experiment is the following. Rb atoms in an atomic beam are excited from the ground state to the $5p_{3/2}$ state and then to the $(n+3)s$ state in a static field by two 5-ns dye laser

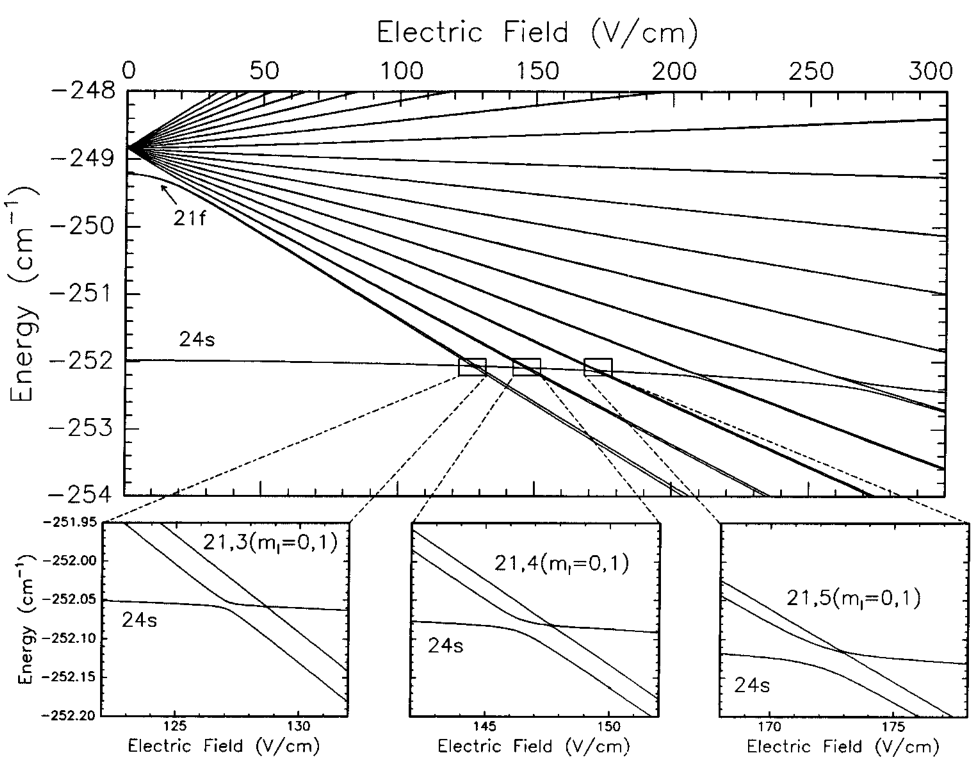

FIG. 1. Energy eigenvalues of Rb in an electric field calculated by numerical diagonalization of the truncated Stark Hamiltonian. Each inset shows an enlargement of an avoided crossing between the 24s state and an $n=21$ Stark state. For each 21,k Stark state there are $|m|=0$ and 1 states that have avoided crossings with the s state.

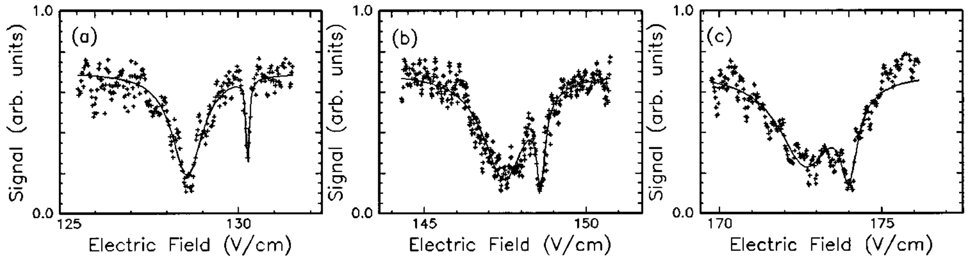

FIG. 2. Experimental traces for the avoided crossings of the 24s state with the first three Stark states of the $n=21$ manifold. The energy levels are shown in Fig. 1. (a) the 24s-21,3 avoided crossings, (b) the 24s-21,4 avoided crossings, (c) the 24s-21,5 avoided crossings. In each case two distinct Lorentzian dips in the signal are observed, corresponding to avoided crossings with both the $|m_\ell|=0$ and 1 Stark states.

pulses. The n,k Stark states cannot be excited since they contain only $\ell \geqslant 3$ angular momentum components. The field is provided by a pair of capacitor plates 1.582(1) cm apart. After a delay of 5 μs, which allows blackbody radiation to drive transitions to other states, we apply a field ionization pulse that has sufficient amplitude to ionize the $(n+3)p$ state, but not the $(n+3)s$ state populated by the laser. The ions produced pass through a 0.5-mm-diam hole in the upper capacitor plate and impinge upon a microchannel plate detector. The signal from the detector is captured with a gated integrator. Over many shots of the laser the static field is slowly swept through the field of an avoided crossing and the signal recorded in a computer. We repeat the scans of the field over the anticrossing until a reasonable signal-to-noise level is obtained. At the avoided crossing the two eigenstates are 50-50 linear combinations of the $(n+3)s$ and n,k sta-

TABLE I. $|m_\ell|=0$ avoided crossings.

	Experiment			Matrix diagonalization	
n,k	Position (V/cm)	Width (FWHM) (V/cm)	$\omega_0/2\pi$ (GHz)	Position (V/cm)	$\omega_0/2\pi$ (GHz)
16,3	515.37(31)	5.46(28)	2.084(23)	526.1	1.874
16,4	636.44(38)	11.40(55)	3.35(16)	646.0	3.88
17,3	374.44(23)	3.00(31)	1.32(14)	382.1	1.30
17,4	456.80(27)	8.39(90)	2.90(31)	460.7	2.38
17,5	579.87(35)	20.70(22)	5.76(60)	587.1	6.55
18,3	277.98(17)	2.28(32)	1.14(16)	283.1	1.04
18,4	333.01(20)	3.96(21)	1.62(9)	336.3	1.74
18,5	412.77(25)	14.07(18)	5.00(61)	415.3	5.19
19,3	209.59(13)	1.90(35)	0.66(21)	213.6	0.90
19,4	248.12(15)	2.28(14)	1.08(7)	250.1	1.45
19,5	301.54(18)	7.31(50)	3.14(22)	303.2	4.47
20,3	161.96(9)	1.49(14)	0.98(9)	163.5	0.68
20,4	187.82(11)	2.44(22)	1.30(12)	189.6	1.24
20,5	224.50(14)	4.61(21)	2.16(10)	225.9	3.02
21,3	126.04(8)	1.02(6)	0.72(4)	126.9	0.55
21,4	144.50(9)	1.89(15)	1.17(9)	145.6	1.02
21,5	169.85(10)	3.89(27)	1.92(13)	171.3	1.97
22,3	99.35(6)	0.61 (6)	0.47(5)	99.80	0.38
22,4	112.56(7)	1.13(1)	0.716(8)	113.4	0.73
22,5	130.96(8)	2.72(27)	1.55(15)	131.8	1.60
23,3	79.28(5)	0.51(4)	0.44(3)	79.32	0.40
23,4	88.70(5)	0.88(13)	0.66(10)	89.46	0.57
23,5	102.35(6)	1.85(18)	1.23(12)	103.3	1.34
24,3	63.88(4)	0.43(4)	0.41(4)	63.72	0.28
24,4	70.89(4)	0.73(21)	0.60(18)	71.37	0.49
24,5	80.77(5)	1.50(11)	1.41(10)	81.41	1.38
25,3	50.95(3)	0.35(5)	0.36(5)	51.69	0.27
25,4	57.14(3)	0.47(13)	0.43(11)	57.45	0.36
25,5	64.61(4)	0.90(8)	0.71(14)	65.11	0.73

TABLE II. $|m_\ell|=1$ avoided crossings.

	Experiment			Matrix diagonalization	
n,k	Position (V/cm)	Width (FWHM) (V/cm)	$\omega_0/2\pi$ (MHz)	Position (V/cm)	$\omega_0/2\pi$ (MHz)
16,3	522.61(31)	0.41(4)	156(14)	533.5	179
16,4	640.76(38)	1.57(18)	462(53)	652.4	197
17,3	379.90(23)	0.20(6)	88(26)	387.6	154
17,4	460.02(28)	0.98(16)	338(55)	465.1	147
18,3	281.62(17)	0.23(8)	115(40)	287.1	100
18,4	335.80(20)	1.44(11)	587(45)	339.3	126
18,5	413.64(25)	2.13(18)	693(1)	417.9	473
19,3	212.39(13)	0.098(6)	59(4)	216.4	76
19,4	250.29(15)	1.76(16)	834(76)	252.4	107
19,5	301.57(18)	0.88 (5)	378(22)	304.3	442
20,3	164.05(10)	0.092(8)	60 (5)	165.6	59
20,4	189.27(11)	0.27 (5)	51(9)	191.1	86
20,5	224.81(13)	0.40(2)	189(9)	226.7	375
21,3	127.64(7)	0.141(8)	99(6)	128.5	56
21,4	145.62(8)	0.30(5)	185(30)	146.8	69
21,5	170.47(10)	0.36(6)	179(30)	172.1	
22,3	100.65(6)	0.24(6)	187(47)	101.0	46
22,4	113.43(7)	0.12(3)	76(19)	114.4	49
22,5	131.44(8)	0.22(9)	124(52)	132.5	236
23,3	80.20(5)	0.063(8)	54(7)	80.32	41
23,4	89.45(5)	0.10(4)	77(27)	90.30	46
23,5	102.71(6)	0.42(6)	279(41)	103.5	200
24,3	64.64(4)	0.05(2)	50(15)	64.41	34
24,4	71.36(4)	0.13(4)	105(36)	71.97	38
24,5	81.23(5)	0.35(8)	333(80)	81.81	200
25,3	51.53(3)	0.05(1)	51(11)	52.19	44
25,4	57.54(4)	0.07(4)	63(32)	57.95	33
25,5	65.00(4)	0.20(9)	157(70)	65.41	122

tes. Since the 1-cm^{-1} bandwidth of the laser is substantially larger than the width of the avoided crossing, the same number of atoms is excited to the pair of states at all fields, but at the anticrossing the blackbody radiation transition rate to the $(n+1)p$ state is reduced by a factor of 2 for both eigenstates. Consequently, a 50% decrease in the detected signal is expected at the anticrossing.

While it is straightforward to separate the field ionization signals of the $(n+3)p$ and $(n+3)s$ states, it is not possible to completely separate those from the $(n+3)p$ and low-lying $(n+1),k$ Stark states, which are populated by blackbody radiation transitions from the n,k states. Consequently, in practice the observed decrease in the signal is not as large as 50%. Nonetheless, the method works quite well.

In Fig. 2 we show as examples signal traces for the avoided crossings of the 24s state with the three lowest Stark states of the $n=21$ manifold, the 21,3; 21,4; and 21,5 states, which are connected to the 21f, 21g, and 21h states in zero field. In the case of the avoided crossings between the s state and the 21,3 state two well-separated features are observed, each approximately Lorentzian. The traces obtained for the crossings with the next Stark state, the 21,4 state, also show two distinct features, which are less well resolved, while features from the 21,5 state avoided crossings are hardly resolved at all. As shown in the insets of Fig. 1, the two features arise from avoided crossings between the s state and the pair of $|m_\ell|=0$ and 1 states. Recall that m_ℓ is not a strictly good quantum number.

We fit all our signals to the sum of two Lorentzians and a linearly changing background to obtain the positions and widths of both $|m_\ell|=0$ and 1 avoided crossings simultaneously. The linear background allows for the change in the signal resulting from the temporal shift of the field ionization signal relative to the gate of the integrator as the applied field is scanned. Our measurements of the avoided crossing fields and widths of the $|m_\ell|=0$ and 1 states are presented in Tables I and II. We also present the values of the frequency separation $\omega_0/2\pi$ at the avoided crossings determined from the experimental field widths and the calculated Stark shifts of the n,k levels. For comparison, we give the positions and values of $\omega_0/2\pi$ calculated by numerical diagonalization of a truncated Hamiltonian matrix for the $|m_j|=\frac{1}{2}$ states [1]. All $|m_j|=\frac{1}{2}$ states for n values within ± 3 of the n under study were included in the matrix. As can be seen in Tables I and II, for $|m_\ell|=0$ and 1 the measured and calculated fields agree generally to within 2%, with the measured values being systematically lower. As shown by Table I, the agreement between theory and experiment for the $|m_\ell|=0$ widths is generally within 20%, and again the experimental results are systematically lower. We are not sure of the origin of the discrepancy, but it is not due to truncation of the Hamiltonian matrix. For the narrower $|m_\ell|=1$ avoided crossings, which are harder to measure, the measured and calculated widths are typically within a factor of 2 of each other.

In conclusion, we have measured the positions and widths of the avoided crossings of the Rb $(n+3)s$ and n,k Stark states for $16\leqslant n\leqslant 25$ and $3\leqslant k\leqslant 5$, and the measured values are in reasonably good agreement with the values calculated by numerical diagonalization of a truncated Hamiltonian matrix.

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