Ionization of Na atoms by 8-GHz electric fields

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The ionization of Na atoms by 8-GHz electric fields from principal quantum number $n = 16$—42 exhibits a threshold for the $|m| = 0$ and 1 states of $E \approx 1/3n^5$, and two thresholds for the $|m| = 2$ states of $E \approx 1/9n^4$ and $E \approx 1/21n^4$ depending upon the n state. The $|m| = 0$ and 1 thresholds show a departure from a $1/n^5$ scaling at high n which we interpret as being due to the fact that the relatively slower atomic frequencies at high n no longer match the 8 GHz microwave frequency. The $E = 1/21n^4$ $|m| = 2$ threshold has not to our knowledge been observed before, and we interpret it as arising from the ionization of the highest energy, or blue, Stark state at the classical limit for ionization.

I. INTRODUCTION

In spite of the fact that electric field ionization has been understood for decades,[1,2] many subtleties have recently been uncovered. An example of this is the fact that the field ionization of many-electron atoms differs substantially from the field ionization of hydrogen.[3] Similarly it is only recently that the dynamics of ionization of atoms exposed to time-varying fields has been appreciated.[4,5] Even for fields with frequency components ~ 1 MHz these dynamic effects are important. Not surprisingly they appear in a dramatically different way in microwave ionization.[6–8] For example the Na $|m| = 0$ and 1 states exhibit a $1/3.7n^5$ threshold field for ionization by a 15-GHz electric field, a sharp departure from the previously observed $1/n^4$ scalings.[6,8] Here m is the azimuthal orbital angular momentum quantum number and n is the principal quantum number. The $1/3.7n^5$ threshold variation is associated with a Landau-Zener transition from the highest energy, bluest, Stark state of the n manifold to the lowest energy, reddest, Stark state of the $n+1$ manifold.[6] These two states have an avoided crossing at a field of $1/3n^5$, leading to the observed $1/3.7n^5$ scaling of the threshold field. An important point to note is that the Na $|m| = 0$ and 1 states have avoided crossings $\omega_0 \sim 1$ cm^{-1} at $n = 20$, roughly equal to the microwave frequency, a requirement for a high Landau-Zener transition probability. In contrast the $|m| = 2$ states have such small avoided crossings that the 15-GHz frequency ensures that the crossings are traversed diabatically resulting in a hydrogenic $1/9n^4$ dependence for the ionization field.

Here we report measurements of the ionization of Na atoms by an 8 GHz microwave field as a first step in bridging the gap between the existing 1-MHz and 15-GHz measurements. Not unexpectedly, many of the results are similar to those obtained with a 15 GHz field. However, new insights have emerged, including a better understanding of the n dependence of the $|m| = 0$ and 1 thresholds and the discovery of a new, nonhydrogenic, $|m| = 2$ threshold.

II. EXPERIMENTAL APPROACH

The approach we have used is essentially the same as that used in our previous experiments at 15 GHz,[8] so our general description here is brief with detailed descriptions only of the changes. Na atoms in a thermal beam pass through a microwave cavity where they are excited by two counter-propagating dye laser beams which excite the transitions $3s \to 3p$ and $3p \to ns,nd$, respectively. About 100 ns after the 5-ns dye laser pulses, a 500-ns pulse of microwave power is put into the cavity. Approximately 300 ns after the microwave pulse, a strong (~ 10 kV/cm) field pulse is applied to the atoms. The leading edge of the pulse drives any ions produced by microwave ionization out of the cavity to an electron multiplier, and the peak of the field pulse ionizes any residual atoms and drives them out of the cavity to the electron multiplier. This results in time-resolved microwave-ionization and field-ionization signals, either one of which can be captured with a gated integrator and recorded with an x-y recorder.

The only substantial differences are in the microwave system. First, we have made a new cavity which is a piece of WR90 waveguide 2.900 cm long, closed at the ends, and containing a 0.75-mm-thick copper septum to allow the application of a field pulse as shown in the inset of Fig. 1. The septum is supported by Teflon supports in the corners of the cavity where there is little electric field. The inside dimensions of the cavity are $2.900 \times 2.286 \times 1.016$ cm^3 and we operate it in the TE_{101} mode which resonates at 8.188 GHz. The cavity was silver plated resulting in a Q of 940. This cavity has a slightly lower Q than the one used in our previous 15-GHz measurements,[8] but its much smaller volume, 6.37×10^{-6} m^3, enables us to more efficiently convert the incident power to electric field in the cavity. The energy density is 6.69 dB higher. Specifically, the incident power P is converted to peak electric field amplitude E according to

$$E = 509[P(\mathrm{W})]^{1/2}\ \mathrm{V/cm}\ . \qquad (1)$$

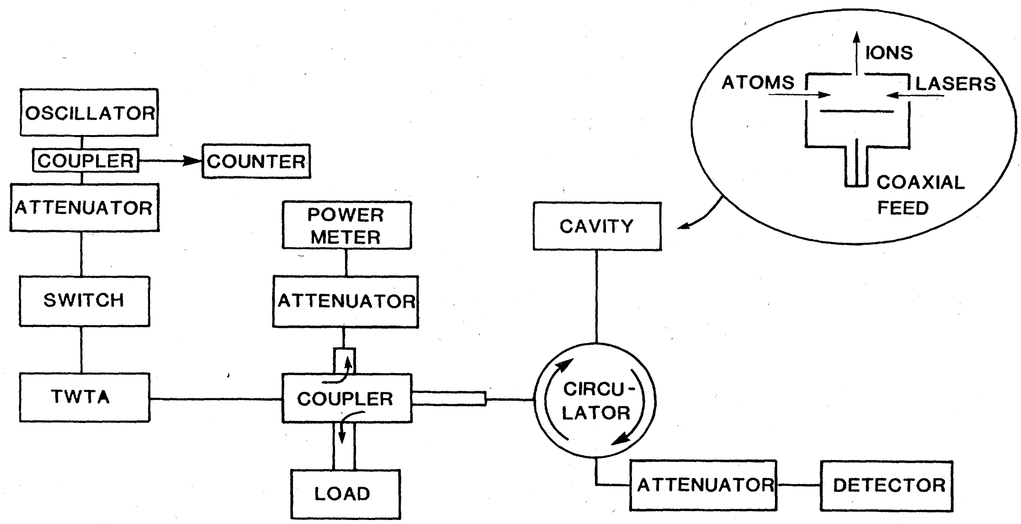

FIG. 1. Block diagram of the microwave system with the cross section of the cavity shown in the inset. Waveguide connections (=), coaxial connections (—).

As shown by the inset of Fig. 1, the coaxial atomic beam and laser beams enter the cavity from opposite sides through 1-mm-diam holes 2 mm above the septum, thus creating a cylindrical sample of excited atoms. Of these, only those in the center of the cavity can be extracted through the 1-mm-diam hole in the top of the cavity ensuring that we are only observing signals from atoms in the antinode of the microwave field.

Second, we have altered our method of bringing the microwave power to the cavity to enable us to measure the incident power more accurately. The new arrangement is shown in Fig. 1, a diagram of the microwave system. The major components are as follows.

The oscillator is an Avantek Model No. AVD7872 yttrium iron garnet (YIG) tuned oscillator. Some of the power is split off with a 6-dB coupler to measure the frequency with a Hewlett-Packard (HP) Model No. 5343 counter. The main output of the oscillator passes through a HP Model No. X352 precision variable attenuator and a HP Model No. 8495A step attenuator which are used to control the microwave power. The switch, a General Microwave Model No. FM862B switch, has a switching time of 10 ns. The traveling wave tube amplifier (TWTA), a Hughes Model No. 1277H02, can deliver 20 W of power. After the TWTA the microwave power passes through a WR90 waveguide to a 20-dB cross-guide coupler which is used for the power measurements as shown in Fig. 1 and then to a Teledyne Model No. C-4563T-10 circulator. The incident microwave power passes through the circulator to the cavity, and the power reflected by the cavity is directed by the circulator to the attenuator and crystal detector.

This arrangement improves our ability to calibrate the microwave electric field strength in the cavity. First we can measure the incident power more accurately. As shown in Fig. 1, using the cross-guide coupler 1% of the microwave power going to the cavity goes to the power meter. Since the duty cycle of the actual experiment is low due to the low repetition rate of the laser (10 Hz), the time-averaged microwave power is too low to be measured accurately. Previously the power calibration was therefore done with continuous operation of the TWTA.[8] Under these circumstances, dissipation in the cavity changes the resonance frequency of the cavity and therefore the amount of the reflected power. It is therefore desirable to do the power calibration in pulsed operation, keeping the power dissipation in the cavity low (duty cycle of 10^{-2}) but with sufficiently large (~ 1 mW) average microwave power at the power meter. For comparison the duty cycle in the actual experiment is 5×10^{-6}. Second we have improved the measurement of the cavity Q. The Q of the cavity is determined by measuring the reflected power as a function of the frequency of the microwaves. Earlier this was done with a diode and a cross-guide coupler. However, from the point of view of suppressing the standing waves it is advantageous to use a circulator for this purpose. In sum we feel that we are able to determine the microwave field in the cavity with an accuracy of 7%.

As a consistency check, for microwave fields <1000 V/cm we have also used our previous cavity,[8] a piece of WR90 waveguide 20.32 cm long operating in the TE_{107} mode at 8.2 GHz. The two power calibrations are independent, and all the results for the thresholds are consistent. This gives some confidence that not only are the relative values for the thresholds correct, but also that the absolute values lie within the uncertainties given.

III. RESULTS AND DISCUSSION

The measurements of the ionization threshold fields are made by monitoring the number of atoms remaining after the microwave pulse. Typical results are shown in Fig. 2 which shows the ionization thresholds of the 16d and 38d

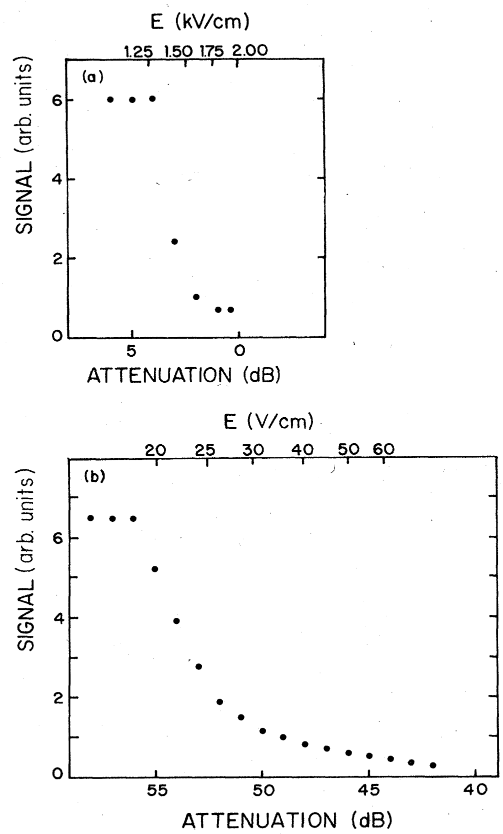

FIG. 2. Ionization thresholds for the (a) $16d$ state and (b) $38d$ state. In both cases the signal represents the number of remaining atoms and the lasers are both polarized parallel to the microwave field.

states. The data of Fig. 2 were obtained with the two lasers linearly polarized parallel to the microwave field to preclude excitation of the $m=2$ states. They therefore represent the $m=0$ and 1 thresholds. By applying a static field of 100 V/cm, we have also been able to study the np states. In Table I we list the observed threshold fields, the fields at which half the atoms are ionized. We note that the term threshold becomes less appropriate as the thresholds become wider as shown by Fig. 2. Nonetheless we have chosen to use this definition to be consistent with our earlier work at different frequencies.[4,8]

As for a 15 GHz field the ionization field is slightly less than $1/3n^5$. Fitting the threshold fields E_s and E_d for the s and d states to a $1/n^5$ dependence yields

$$E_s=1.405(14)\times 10^9 n_e^{-5}\ \text{V/cm}$$
$$=1/3.66(4)n_e^5\ \text{a.u.}\,, \tag{2a}$$

$$E_d=1.510(11)\times 10^9 n_e^5\ \text{V/cm}$$
$$=1/3.40(2)n_e^5\ \text{a.u.} \tag{2b}$$

In Eqs. (2) the fields are given in both atomic units (a.u.) and V/cm. The effective quantum number n_e is given by $n_e=n$ for nd states and $n_e=n-1$ for ns states. Note that in Eqs. (2) the ns states ionize with a slightly lower threshold field. We attribute this to the fact that only the $|m|=0$ states are involved in the ionization of the s states while $|m|=0$ and 1 states are involved in the ionization of the nd states. The intersection of the blue and red $|m|=1$ states of n and $n+1$ occurs at a slightly ($\sim 5\%$) higher field than $1/3n^5$ so it is not surprising that the threshold field is higher for the d states.

Recognizing the approximate $1/3n^5$ dependence of the threshold fields, it is interesting to examine the deviations from $1/3n^5$. This is easily seen if we plot the ratio of the microwave field or power required to that expected for a $1/3n^5$ field dependence. This is shown in Fig. 3 for the nd $|m|=0$ and 1 states. Figure 3 makes it apparent that the field relative to $1/3n^5$ increases as n increases. If we go back to Fig. 2 we see that the threshold for the $16d$ state is about 1 dB wide, which is substantially sharper than the $38d$ state which is about 5 dB wide. If we had chosen to take the field for which 20% ionization occurs as the threshold, the threshold fields would follow a $1/n^5$ scaling much more closely. The high-lying states require that the field very nearly reach the Landau-Zener crossing. This is in reasonable accord with the calculations reported earlier[8] which show that for a constant frequency, as the size of the avoided crossing ω_0 between the highest energy n Stark state and the lowest energy $n+1$ Stark state is decreased below the microwave frequency ω, that the probability of making the Landau-Zener transition decreases. Not surprisingly a careful inspection of the microwave ionization data taken at 15 GHz reveals the same phenomenon.

Unlike the $|m|=0$ and 1 states the $|m|=2$ states exhibit behavior in an 8 GHz field which differs from that in a 15 GHz field. At 15 GHz we found a $1/9n^4$ threshold field for the $|m|=2$ states which is the field at which hydrogen ionizes. In an 8 GHz field though, we observe a second threshold as well. Examples of this are shown in Fig. 4, recordings of the remaining atom signal obtained with the lasers polarized perpendicular to the microwave field for several nd states. For $n\geq 29$ we observe

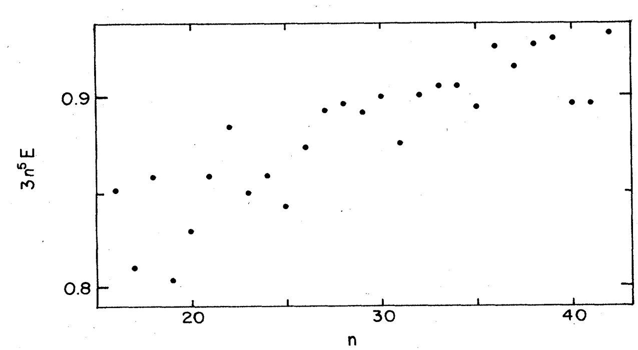

FIG. 3. A plot of the ratio of the threshold fields to $1/3n^5$. The fact that the threshold field increases to $1/3n^5$ as n increases is quite apparent.

TABLE I. Ionization threshold fields (the statistical uncertainties are given in parentheses).

n	s $\mid m \mid =0$ (V/cm) ($\pm 4\%$)	p $\mid m \mid =0,1$ (V/cm) ($\pm 5\%$)	d $\mid m \mid =0,1$ (V/cm) ($\pm 4\%$)	d $\mid m \mid =2blue$ (V/cm) ($\pm 10\%$)	d $\mid m \mid =2red$ (V/cm) ($\pm 4\%$)
15			> 1910		
16			1390		
17	1370		978		
18	967		778		
19	769		557	1720	
20	556	613	445	1240	
21	424	495	361	1300	
22	330	384	294	955	
23	260	316	226	955	
24	210	262	185	761	
25	174		148	718	
26	140		126	539	
27	116		107		
28	103		89	428	
29	81		75	339	852
30	73		63	351	760
31	63		52		659
32			46		576
33			39.7		512
34			34.1		462
35			29.1		408
36			26.2		390
37			22.6		320
38			20.0		292
39			17.7		264
40			15.0		235
41			13.2		
42			12.2		

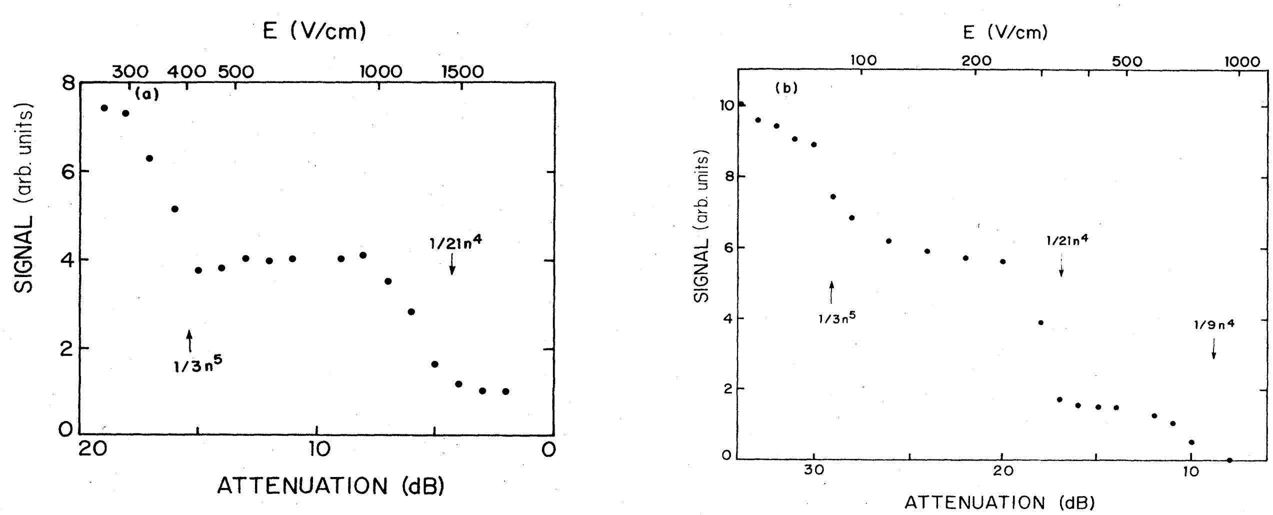

FIG. 4. Ionization thresholds obtained with the lasers polarized perpendicularly to the microwave field direction. In both cases the signal is the remaining atom signal. (a) $21d$ state. The $1/3n^5$ and $1/21n^4$ thresholds are indicated. (b) $29d$ state. The $1/3n^5$, $1/21n^4$, and $1/9n^4$ thresholds are indicated.

the same $1/9n^4$ threshold observed at 15 GHz which is given by

$$E_{\text{red}} = 6.13(4)\times 10^8 n^{-4}\ \text{V/cm} = 1/8.39(5)n^4\ \text{a.u.} \tag{3}$$

For $19 \le n \le 30$ we also observe a second threshold which occurs at a lower field given by

$$E_{\text{blue}} = 2.49(8)\times 10^8 n^{-4}\ \text{V/cm} = 1/20.7(7)n^4\ \text{a.u.} \tag{4}$$

For $n = 29$ and 30 we observe both.

The newly observed $|m| = 2$ thresholds, at $E_{\text{blue}} = 1/21n^4$ correspond to the ionization of the bluest Stark state where it intersects the classical ionization limit. It is straightforward to show that this occurs for $|m| = 0$ states at

$$E_{\text{blue}} = 1/(11+4\sqrt{7})n^4 \tag{5}$$

or

$$E_{\text{blue}} = 1/21.58n^4 . \tag{6}$$

For $|m| = 2$ states a slightly higher, (5–10)%, field is required.

In general, the ionization at the blue threshold is not complete, and the ionization probability may continue to increase as the field is raised until $1/9n^4$ is reached, at which point the ionization is always complete. For the lower n states, $n \sim 20$, the ionization is complete before $1/9n^4$, but for $n \sim 30$ the ionization displays a very apparent threshold at $1/9n^4$. The possibility of ionization from the blue Stark state, while unexpected in hydrogen, has already been shown in Na by Rolfes *et al.*[9] who observed in the diabatic ionization of the bluest $|m| = 2$ states that substantial ionization occurred before the field reached the point where hydrogen would ionize. We also observe maxima in the $|m| = 2$ ionization (minima in the surviving atom signal) for fields as low as $1/3n^5$ but less than $1/21n^4$. These maxima are strongly dependent on the presence and magnitude of a small (0–3 V/cm) static field which suggests that they may be resonance phenomena such as were observed by Bayfield *et al.*[10]

Both the maxima and the $1/21n^4$ threshold phenomena are associated with incomplete ionization of the $|m| = 2$ states, and thus reflect ionization rates $\sim 10^6\ \text{s}^{-1}$ and should therefore exhibit a noticeable dependence on the length of the microwave pulse. Due to geometrical constraints we are only able to vary the microwave pulse width over a range of 0.3–1.0 μs without exposing the atoms to different field amplitudes, nonetheless we are able to see a time dependence of the $|m| = 2$ signals, as expected.

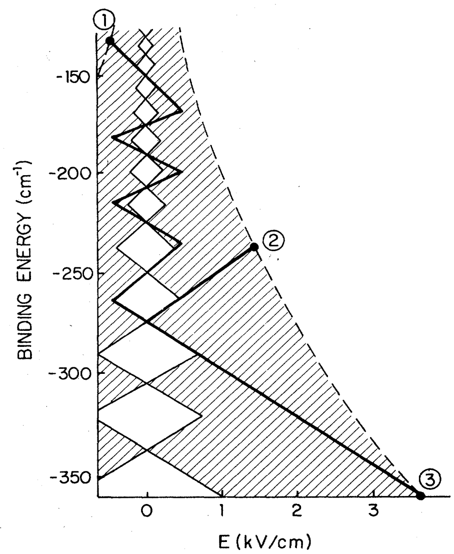

FIG. 5. Methods by which Na atoms ionize in an 8-GHz field. ① the $1/3n^5$ ionization of $|m| = 0$ and 1 states, ② the $1/21n^4$ ionization of the $|m| = 2$ states, ③ the $1/9n^4$ ionization of the $|m| = 2$ states.

The appearance of the blue thresholds, at $1/21n^4$, and ionization at fields as low as $1/3n^5$ is not so surprising when we recall that the ionization of the $|m| = 2$ states should show a $1/3n^5$ dependence when the frequency is in the 500 MHz range. The fact that the $m = 0$ and 1 states are ionized by the 15 GHz field even for $n = 40$, suggests that an 8 GHz field might be somewhat effective in ionizing the $n = 20$ $|m| = 2$ states.

In Fig. 5 we show very schematically the predominant ways in which a Na atom ionizes in an 8-GHz electric field. The $1/3n^5$ ionization of the $|m| = 0$ and 1 states is the same as previously observed with a 15 GHz field. The $1/9n^4$ $|m| = 2$ threshold is also the same, however the $1/21n^4$ $|m| = 2$ threshold was not previously observed and is apparently a new phenomenon which occurs at 8 GHz, and presumably lower frequencies.

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