Ionization of Rydberg atoms by a precessing electric field of constant amplitude

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We have studied in detail the continuous evolution from static field ionization to ionization by a circularly polarized microwave field by combining a z-polarized static field with a circularly polarized microwave field in the x-y plane. We have measured the ionization threshold for Na states of $27 \leqslant n \leqslant 50$ in the precessing total field $\overline{F}_t$, as a function of its angle θ from the z axis. For low n, $F_t \cong 1/16n^4$, independent of θ. For $n \geqslant 45$, F_t decreases from $1/16n^4$ to $0.8/16n^4$ as θ is increased from 0° to 25°, and it remains at this value until $\theta = 90°$. We also observe ionization at quite low values of F_t, which we attribute to resonantly enhanced ionization, with the resonances driven by a stray static field in the x-y plane.

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I. INTRODUCTION

Although ionization of alkali-metal Rydberg atoms by a linearly polarized microwave field occurs at the field amplitude $F \cong 1/3n^5$ [1], ionization by a circularly polarized microwave (CPMW) field occurs at the very different field amplitude of approximately $F = 1/6n^4$, the classical static field for ionization [2]. The similarity between ionization by a circularly polarized field and ionization by a static field has been attributed to the fact that, in a frame rotating at the microwave frequency, the circularly polarized microwave field is static and cannot drive transitions. There is, however, no transformation that can make the linearly polarized microwave field appear static, resulting in the much lower threshold fields for ionization by linearly polarized microwave fields. While linearly and circularly polarized microwave fields have very different effects on alkali-metal atoms, they have almost identical effects on H atoms [3], the difference being due to the finite size of the ionic core of an alkali-metal atom.

By combining a static field in the z direction, $\overline{F}_{dc}$, with the circularly polarized field in the x-y plane, $\overline{F}_{CPMW}$, we have produced a precessing field $\overline{F}_t = \overline{F}_{dc} + \overline{F}_{CPMW}$, of constant amplitude. This field is static in the frame rotating with the microwave field, and by changing the angle θ that the resultant field $\overline{F}_t$ makes with the z axis, we can change the field continuously from static to circularly polarized. We have measured the ionization threshold in the resulting total field F_t for $n = 27$, 30, 33, 37, 38, 41, 45, and 50. Since $F_t \sim 1/16n^4$ for $\theta = 0°$ and 90°, it is not a complete surprise that ionization occurs at or near the field $F_t = 1/16n^4$ for $0° < \theta < 90°$. We also see, at much lower total field, a small ionization feature that we attribute to a resonance driven by a small residual static field in the x-y plane, which appears as a time varying field in the rotating frame.

II. EXPERIMENT

The experimental apparatus is very similar to that described elsewhere [4]. The circularly polarized microwave field is produced by generating two orthogonal, linearly polarized fields having equal amplitudes and a 90° phase shift. Specifically, we use the two degenerate TE111 modes at a frequency of 8.00 GHz in a cylindrical cavity, and excite them through irises in the cylindrical end caps from orthogonally polarized waveguides. The cavity has an inside diameter of 6.400 cm and an inside length of 1.976 cm. The Q parameters are 3576 and 3514 for the two different polarizations, and the decay time constant of the cavity is measured to be 70 ns.

A Litton 624 gated traveling-wave tube amplifier is used to amplify the output of a Hewlett-Packard (HP) 83 620A synthesized sweep oscillator to generate microsecond pulses at powers of up to 100 W. The microwave power of the amplified pulses is adjusted by directly changing the output level of the HP 83 620A sweep oscillator using its internal attenuator. After amplification, the microwave pulse is split in half between the two paths that feed the x and y polarized cavity modes. An HP X885A phase shifter is used in one path to produce a 90° phase shift between the two polarizations. A Waveline 622 precision rotary vane attenuator and an HP 8495 step attenuator in the other path allow one to make fine power adjustments in order to match the field strengths of the two polarizations. We produce circular polarization by using the field-ellipticity dependence of the CPMW field ionization signal [2,6]. The phase mismatch from 90° is less than 0.3°, and the field-strength mismatch between the two polarizations is less than 3%. We are able to generate 1.1 kV/cm of CPMW field with this cylindrical cavity and the associated microwave equipment. There is a 5.8% systematic uncertainty and a 1.5% random uncertainty in the microwave field-strength measurement, leading to a combined uncertainty of 6% in the CPMW field.

As shown in Fig. 1, the symmetry axis of the cavity is vertical, and the bottom half of the cavity is insulated from the top half of the cavity and the feed waveguide. This design allows us to apply a dc voltage of up to 11 kV to the bottom half of the cavity. We have used the SIMION program to determine the dc field strength from the known geometry of the cavity and the applied voltage. The dc field is 1.2% lower than the field between two infinite parallel plates separated by the cavity length, and the uncertainty in the dc field is less than 1%.

During the experiment, Na atoms in a thermal beam are optically excited to Rydberg states by two pulsed dye laser

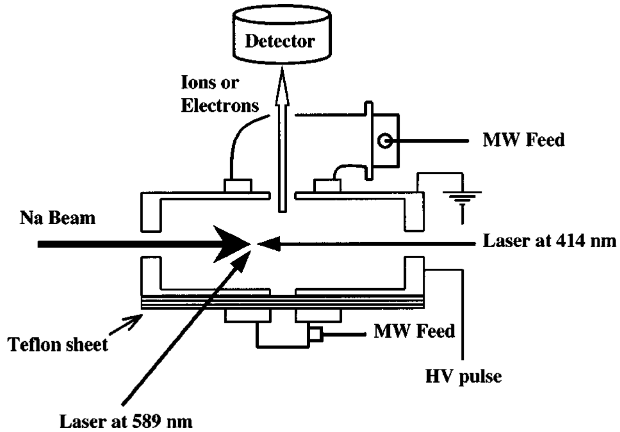

FIG. 1. The interaction region of the apparatus. The microwave cavity consists of two circular end caps. Two laser beams and the Na beam pass through the gap between the end caps. Microwave power is fed into the cavity through two rectangular waveguides, one on the top and one on the bottom, oriented perpendicular to each other. A 1.5-mm hole is drilled in the top waveguide to allow ions and electrons to pass. A high-voltage pulse is applied to the bottom end cap, which is insulated from the waveguide by an 0.8-mm-thick Teflon sheet.

beams. One beam is tuned to $3s$-$3p$ transition at 589 nm and propagates at a right angle to the atomic beam, crossing it 1.6 mm upstream from the cavity center. The other one is tuned to the wavelength of the zero-field $3p$-nd transition at ~414 nm and is counterpropagating to the atomic beam. A 4.1-μs CPMW pulse is fed into the cavity 3.0 μs before the laser excitation takes place. Thus the Na atoms are optically excited in a well-established CPMW field. After the optical excitation takes place, the Na atoms are exposed to the full CPMW field strength for 500 ns before the microwave power is linearly reduced by 63% in the last 600 ns of the pulse and then turned off in 10 ns. This scheme minimizes the possibility of ionization by the slightly elliptically polarized microwave field produced during the decay period due to the slight difference in the Q's of the two polarizations. While the states excited in the field are well defined, they are not the zero-field states. In previous measurements, exciting the atoms in the zero field and applying a pulsed, nominally circularly polarized field gave results similar to those obtained by exciting the atoms in the presence of the microwave field [2].

We apply a negative dc voltage to the bottom plate and collect the electrons produced by ionization with a microchannel plate (MCP) detector located above the cavity. We have chosen to detect electrons because it is difficult to detect ions produced by ionization in very small dc fields. Due to their thermal motion they miss the small detection aperture in front of the MCP detector. We have experimentally verified that there is no observable difference between electron and ion detection when the applied dc field is high.

III. RESULTS AND DISCUSSION

Typically, we measure the ionization signal as the microwave field amplitude is scanned with the static field fixed,

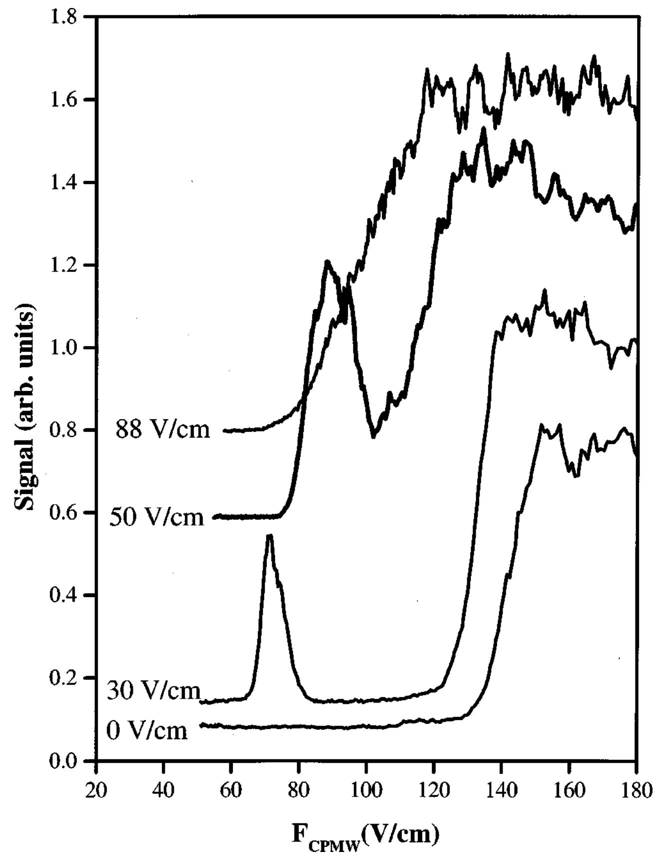

FIG. 2. Ionization signal from $n=38$ obtained by scanning the amplitude of the microwave field for several values of the static field, which are the field values specified in the figure to the left of the traces. It is quite evident that adding the static field reduces the threshold field for ionization. A resonance feature is very evident for static fields of 30 and 50 V/cm.

and one set of threshold scans of $n=38$ is shown in Fig. 2 for several static fields. The ionization trace shows the expected threshold at 141 V/cm when there is no static electric field present. As expected, with a dc electric field in the z direction, the threshold moves to a lower microwave field. Unexpectedly, in the presence of the static field there is a peak in the ionization at very low field strength, as shown by Fig. 2. This unexpected ionization feature has been observed for Rydberg states from $n=34$–50, and we attribute it to a resonance driven by a stray static field.

A. Threshold behavior

We have defined $\overline{F_t}$, the total field in the rotating frame, as the vector sum of the static and microwave fields. Its amplitude is given by

$$F_t=\sqrt{F_{\rm dc}^2+F_{\rm CPMW}^2}, \tag{1}$$

where $F_{\rm dc}$ and $F_{\rm CPMW}$ are the static field amplitude in the z direction and the circularly polarized field amplitude, respectively. From data such as those shown in Fig. 2 we have determined the values of F_t at which 50% ionization occurs, and in Fig. 3 we have plotted the scaled field, $16n^4F_t$ for

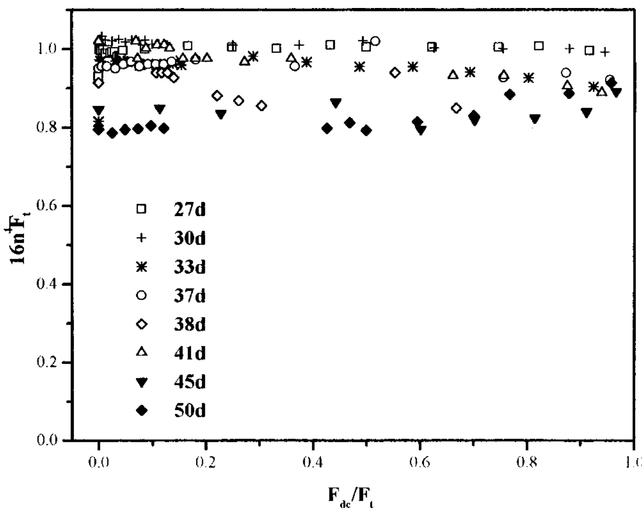

FIG. 3. Scaled 50% ionization field, $16n^4F_t$ vs the ratio of the static field to the total field, F_{dc}/F_t, for $27 \leqslant n \leqslant 50$. To a first approximation, the ionization field is independent of the composition of the field.

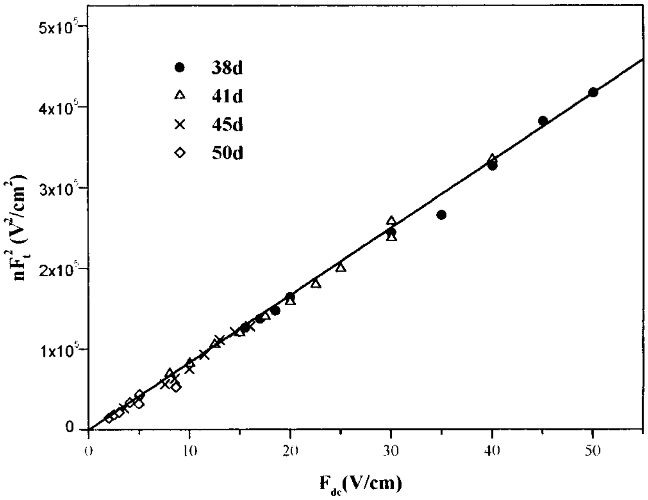

FIG. 4. The scaled-squared total field at which the resonance is found, nF_t^2 vs the static field, F_{dc} for $37 \leqslant n \leqslant 50$. The data are fit very well by the straight line, $nF_t^2=(4/3)\omega F_{dc}$, which is Eq. (4).

50% ionization versus the ratio F_{dc}/F_t, which is cos(θ). As shown, in all cases the values are near 1. Although we did not measure it here, in a static field the value is 1 for all *n*. In a pure CPMW field the value is 1 at low *n* ($n=27$) but falls to 80% of that value by $n=50$. The deviation of the scaled field from 1 at high *n* is consistent with earlier measurements [2,5,6] and the suggestion by Nauenberg [7] that the ionization field should be suppressed in a rotating frame due to the Coriolis force. The data of Fig. 3 fall into three patterns. For $n=27$ and 30 the scaled ionization field is flat at 1. For $33 \leqslant n \leqslant 41$, the scaled field decreases slowly from 1 to 0.9 as F_{dc}/F_t is increased from 0 to 0.9 and then increases sharply back to 1 as F_{dc}/F_t goes to 1. For $n=45$ and 50, the scaled ionization field is constant at 0.8 as F_{dc}/F_t is increased from 0 to 0.9, then it sharply increases to 1 as F_{dc}/F_t approaches 1. The $n=45$ and 50 cases are surprising in that even when 90% of the field is from the static field, the ionization field has the low value characteristic of a pure rotating field.

B. Resonance-enhanced ionization

As shown by Fig. 2, with a static field we observed unexpected ionization at fields well below the threshold field, and it seems to have the signature of resonance behavior. In Fig. 2, the low field feature appears as a peak, and as the dc field is increased, both its height and width increase, and the peak position shifts monotonically toward a higher CPMW field. Eventually, the ionization fraction of the peak approaches 100%, and the peak starts to overlap the ionization threshold. From low values of F_{dc}/F_t we know how the resonance moves, and in making the plot of Fig. 3 we have excluded field values for which the resonance overlapped the threshold. For example, there are no $n=50$ points for $0.15 < F_{dc}/F_t < 0.40$, and there are analogous gaps for other values of *n*. Since there is a field dependence in the ionization efficiency and an apparent resonance requirement, leading to the shifting position, we conclude that the peak is due to a series of resonant transitions through higher states, allowing ionization at a lower value of F_t. The resonantly enhanced ionization can be observed when a small dc field is present for the Rydberg states with *n* ranging from 34 to 50. Resonant transitions cannot occur if only the static field in the *z* direction and the circularly polarized field in the *x*-*y* plane are present, for the resulting field is then static in the rotating frame. Consequently, we believe that there is a static field in the *x*-*y* plane that comes from stray charges accumulated on the surfaces or imperfections in the cavity construction, preventing the applied static field from being perfectly perpendicular to the CPMW field. Unfortunately, with the design constraints of the apparatus we are not able to distinguish between these two. Based on experiments with elliptically polarized microwave fields, we estimate that any *x*-*y* static field that is 5% of the total field could produce the resonance. Such a field would not significantly alter the total field magnitude, but it is a little hard to believe that either of the above sources could lead to this large-area *x*-*y* static field.

The peak position of the resonance-enhanced ionization has been measured in terms of the dc electric field and the CPMW field for $n=38$, 41, 45, and 50, with the results plotted in Fig. 4. Empirically, we have found a good fit to the data using the following relation:

$$nF_t^2=n(F_{\mathrm{CPMW}}^2+F_{\mathrm{dc}}^2)=\frac{4}{3}\,\omega F_{\mathrm{dc}}. \tag{2}$$

Although the origin of the resonance is not obvious from the above equation, in the limit of small fields we can show that it corresponds to the one photon resonance between states differing in *m* by 1. Here *m* is the azimuthal angular momentum quantum number.

Consider the atom in the presence of only the rotating microwave field. In the frame rotating at the microwave frequency, the splitting between energy levels differing in *m* by 1 is [8]

$$\Delta E_{\mathrm{CPMW}} = \sqrt{\omega^2 + \left(\frac{3nF_{\mathrm{CPMW}}}{2}\right)^2}. \tag{3}$$

When the CPMW field is sufficiently weak, the splitting of Eq. (3) is given by

$$\Delta E_{\mathrm{CPMW}} \cong \omega + \frac{1}{2\omega}\left(\frac{3nF_{\mathrm{CPMW}}}{2}\right)^2. \tag{4}$$

According to Eq. (4), in a pure CPMW field it is impossible to have a one-photon resonance, except at zero field. However, we have to consider the effect of a weak static electric field applied along the z axis. This dc field lifts the degeneracy of states of the same m in the CPMW field. In the laboratory frame, the splitting between energy levels differing in m by 1 is

$$\Delta E_{\mathrm{dc}} = \frac{3}{2} nF_{\mathrm{dc}}, \tag{5}$$

and the splitting is the same, modulo ω, in the rotating frame. If the shift of Eq. (5) offsets the field-dependent part of the separation of Eq. (4), then adjacent states differing in m by 1 are in one-photon resonance at nonzero fields. Explicitly, the criterion is

$$\frac{F_{\mathrm{CPMW}}^2}{F_{\mathrm{dc}}} = \frac{4\omega}{3n}. \tag{6}$$

Since we have assumed that $F_t \approx F_{\mathrm{CPMW}}$, Eq. (6) is equivalent to Eq. (2), showing that Eq. (2) does in fact correspond to the condition for a one-photon resonance.

If we define the values of F_t at which the resonance reaches an amplitude of 5% ionization as $F_{5\%}$ we can estimate how far the sequence of transitions goes above the initially excited state before ionization occurs. These field values are fit by

$$F_{5\%} = 0.95/n^5, \tag{7}$$

which suggests that the state n_F from which ionization occurs is related to the initial n by $n_F \cong (n^{5/4})/2$. For $n=40$, $n_F=50$, so the sequence of transitions evidently passes through many states.

IV. CONCLUSION

We have demonstrated the continuity between static field ionization and ionization by a circularly polarized microwave field by superimposing a static field along the symmetry axis of the microwave field. It is well known that for high n, or high frequency, ionization occurs in a circularly polarized field of amplitude less than $1/16n^4$. What is surprising is that the same reduced field requirement is observed even if 90% of the field is static. In other words, a small rotating component has a disproportionate effect. We have also observed what we believe to be resonantly enhanced ionization at lower fields. It is presumably due to a series of resonant transitions to a higher-lying, more easily ionized state, driven by a stray static field in the plane of the microwave field.

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