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Field ionization of the $n = 8—15$ states of sodium

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We report the electric field ionization of the $n = 8—15$ levels of Na using field pulses of rise time $\sim 1\ \mu s$. The passage from low to high field is adiabatic, and the fields required for $|m_l| = 0$, 1, and 2 states are $3.12(9)\times 10^8 n_s^{-4}$ V/cm, $3.37(11)\times 10^8 n_s^{-4}$ V/cm, and $3.68(21)\times 10^8 n_s^{-4}$ V/cm. Here n_s is the effective quantum number in the ionizing field. These values are in agreement with those determined previously for higher-lying states.

Because of its simplicity, efficiency, and relatively high selectivity, electric field ionization using pulses of $\approx 1\ \mu s$ rise time has become a very useful tool for the study of atomic Rydberg states.[1] As a rule it has only been applied to states within a few hundred wave numbers of the ionization limit. For lower-lying states, $n < 15$, other approaches such as fluorescence or photoionization are more commonly used.

Whether or not field ionization is useful for the study of lower-lying states depends upon two factors: the technical difficulties inherent in producing the requisite high fields, and whether or not the passage from low to high field occurs in as simple a fashion as for states of higher principal quantum numbers. For example, does the electron spin remain coupled to the orbit for lower-n states? To address these questions we have undertaken measurements of the field ionization of the Na $n = 8—15$ states which we report here.

The experimental setup is described in detail elsewhere,[2] so only a sketch of it will be presented here. The vacuum chamber is held at a pressure of 10^{-6} torr. The atomic source produces an effusive beam with a density of $10^8—10^{10}$ atoms/cm^3 in the interaction region. The beams from two tunable dye lasers, pumped by a Nd-YAG (yttrium aluminum garnet) laser, intersect the atomic beam between two field plates. The first laser is tuned to one of the resonance lines of sodium, $3s_{1/2}$-$3p_{1/2}$ or $3s_{1/2}$-$3p_{3/2}$; the second is used to drive the transition from the $3p_j$ state to a Rydberg level, ns, nd, or np (with the assistance of a dc field which is approximately 1% of the field necessary for ionization). Approximately 400 ns after the Rydberg level is populated, a high-voltage pulse is applied to the lower plate that defines the interaction region. Ions produced by field ionization are extracted through a hole in the upper plate and detected with an electron multiplier. The signal is then captured with a gated integrator, and the resultant averaged signal is recorded on an X-Y plotter.

To produce the 100-kV/cm fields, necessary for the lowest-n states studied here, the field plates and high-voltage pulsing circuit used in Ref. 2 had to be changed. The upper plate is a 5×8-cm^2 aluminum plate, 6 mm thick, with a 6-mm-diam. hole drilled in its center. A 0.025-mm-thick etched tungsten mesh with 0.20 square holes spaced 0.025 mm between centers (60% transparency) is glued over the bottom of the hole in the plate with a ring of epoxy 1.5 cm in diameter. The mesh was held flat against the plate with a 1.2-cm-diam. clamp while the glue dried. The excess epoxy was then removed with a razor blade and all epoxy lightly coated with silver paint. The lower plate is a piece of aluminum 3×5 cm^2 with a raised center area 1.25×1.25 cm^2 whose sides were rounded to avoid-high voltage breakdown. It is suspended from the upper plate by Bakelite standoffs 8 mm long, and the two plates are held together with nylon screws. The final separation of the plates is 0.2564(25) cm. To further restrict the possible volume from which we could collect ions, we inserted a bushing of 1.51-mm inner diameter in the 6-mm-diam. hole in the top plate. In principle this arrangement should produce a field homogeneity better than 1% over a 1-mm cube centered between the plates. In fact the homogeneity is approximately 0.3% as shown by Fig. 1.

The pulsing circuit consists of a commercial trigger transformer; maximum output +20 kV, rise time 0.5 μs; that is connected to the lower plate. With this arrangement the field strength necessary for $n \geq 10$ can be attained. To ionize states of $n < 10$ we use a second pulsing

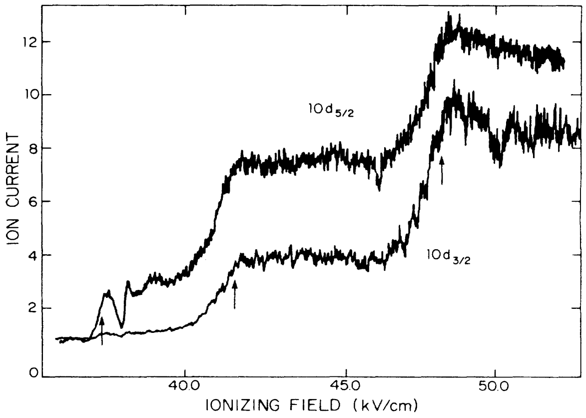

FIG. 1. Na $10d$ field ionization signals vs ionizing field amplitude $10d_{3/2}$ state (lower trace) showing the $|m_l| = 1$ and 2 thresholds. $10d_{5/2}$ (upper trace) observed with lasers polarized perpendicular to a small static field to allow the population of the $|m_l| = \frac{5}{2}$ states. The $|m_l| = 0$, 1, and 2 thresholds, as indicated by the arrows, are evident. Note the decrease in $|m_l| = 0$ signal at field of 38 kV/cm.

circuit to produce the negative complement of the first pulse, and this negative pulse is applied to the upper plate. With the triggering synchronized to within 25 ns, the field strength was essentially doubled, so that $n \geq 8$ could then be ionized. The pulse voltages were measured using the combination of a Tektronix P6015 high-voltage probe and a Tektronix 2213 60-MHz oscilloscope. The dominant uncertainty in the measurement is the $\pm 3\%$ accuracy of the probe, as stated by the manufacturer and verified independently.

The thresholds for ionization of the different states were taken by slowly scanning the voltage supplied to the pulsing circuit connected to the plates. Figure 1 shows typical scans for the $10d_{3/2}$ and $10d_{5/2}$ states which show two and three thresholds, respectively. The $nd_{5/2}$ states have three thresholds, the $nd_{3/2}$ and $np_{3/2}$ states have two thresholds, and the $np_{1/2}$ and $ns_{1/2}$ states have only one. This is consistent with completely adiabatic passage from the low-field to high-field states. The threshold fields are thus assigned in precisely the manner described in Ref. 2 to the high-field $|m_l|$ states and are listed in Table I. Here m_l is the azimuthal orbital angular momentum quantum number.

Figure 1 shows another interesting feature. At a field of 38 kV/cm, just above the $|m_l|=0$ threshold, the $|m_l|=0$ field ionization signal disappears. This is a clear manifestation that the classical threshold field for ionization, $E_c = 1/16n_s^4$, is only a necessary condition. Also required is an interaction with a rapidly ionizing state of higher principle quantum number leading to ionization. If there is a fairly weak and localized interaction with a rapidly decaying state, as observed by Littman *et al.*,[3] it is possible to have the nonmonotonic behavior exhibited in Fig. 1. We observed similar behavior for the Na $12d$ $|m_l|=0$ threshold. Recently this phenomenon has been studied carefully both experimentally and theoretically in He by van de Water *et al.*[4]

The data of Table I are plotted in Fig. 2 with the data of Ref. 2 to show the continuity. The line corresponds to the classical ionization limit of an $|m_l|=0$ state, $1/16n_s^4$, which can be simply derived from a classical description of an atom in an electric field. Here, as in Ref. 2, n_s is the effective quantum number of the atom when the Stark shift of the adiabatic passage to the ionizing field is taken into account. Explicitly it is defined by the energy W_s of the atom at the point that it ionizes relative to the zero field limit by $W_s = -1/2n_s^2$. For the Na s, p, and d states the appropriate values of n_s for $|m_l|=0$ are adequately given by

$$\begin{aligned} s&:\ n_s = n - \tfrac{3}{2}\ , \\ p&:\ n_s = n - \tfrac{1}{2} - 1/n\ , \\ d&:\ n_s = n - \tfrac{1}{2} + 1/n\ . \end{aligned} \tag{1}$$

The origin of the $\frac{3}{2}$ for the s state and the $\frac{1}{2}$ for the p and d states is shown graphically and explained in Ref. 2. The small $1/n$ terms, which were used in plotting Fig. 13 of Ref. 2 but which were not explained in the text of that paper, arise in the following way. For each n mainfold there are n $|m_l|=0$ states which we assume to be evenly spaced in the strong-field region. Thus two adjacent $|m_l|=0$ states of principal quantum number n differ in n_s by $1/n$.

TABLE I. Threshold fields (uncertainties are $\pm 3\%$).

State	$\|m_l\|=0$ (kV/cm)	$\|m_l\|=1$ (kV/cm)	$\|m_l\|=2$ (kV/cm)
9*s*	95.49		
10*s*	58.08		
11*s*	38.24		
12*s*	25.38		
13*s*	17.49		
14*s*	12.90		
15*s*	9.71		
10*p*	39.46	42.68	
11*p*	26.37	27.62	
12*p*	18.21	19.61	
13*p*	12.97	13.32	
14*p*	10.38	10.93	
15*p*	7.59	7.97	
8*d*	90.34	104.55	
9*d*	55.11	63.03	69.32
10*d*	36.88	40.52	47.04
11*d*	24.51	27.09	29.17
12*d*	17.00	18.29	20.79
13*d*	12.52	12.86	13.51
14*d*	9.52	9.90	10.38

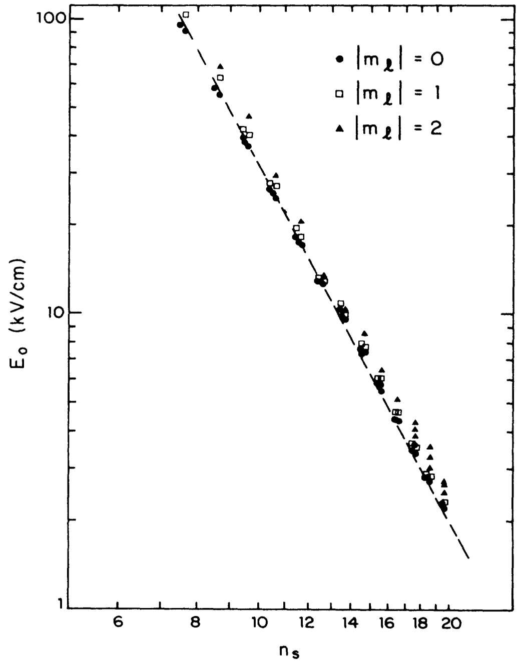

FIG. 2. Plot of observed ionizing fields for Na from $n = 8$–20 plotted vs n_s, the effective quantum number in the strong field. The line indicates the classical ionization threshold.

A $1/16n_s^4$ threshold field dependence implies that the fractional difference in the ionizing field, $\Delta E/E$, between two states which pass adiabatically to two adjacent strong-field $|m_l|=0$ states is obtained by differentiating and noting that $\Delta n_s \approx 1/n_s$. Thus

$$\Delta E/E = 4/n_s^2 \ . \tag{2}$$

For high-n states the difference in ionizing fields is quite small, but the lower-n data of Table I allow a test of Eq. (2). Upon the application of the field pulse, the s and d states pass to adjacent strong-field states (recall that the energy ordering in low field is preserved in the passage to high field), and thus the difference in their ionizing fields should be given by Eq. (2). In Fig. 3 we plot $\Delta E/E_{s\text{-}d}$, the fractional difference in the $(n+1)s$ and nd $|m_l|=0$ threshold fields, as well as the prediction of Eq. (2) versus $4/n_s^2$. In our opinion the agreement is quite good showing the utility of this model.

Fitting the data points of Table I to an n_s^{-4} dependence gives the following threshold behavior:

$$\begin{aligned} |m_l|=0&: \ E=3.12(9)\times 10^8 n_s^{-4} \ \text{V/cm} \ , \\ |m_l|=1&: \ E=3.37(11)\times 10^8 n_s^{-4} \ \text{V/cm} \ , \\ |m_l|=2&: \ E=3.68(21)\times 10^8 n_s^{-4} \ \text{V/cm} \ . \end{aligned} \tag{3}$$

The uncertainties given in Eq. (3) are the standard deviations of the fits. These measurements are in agreement with the previous measurements[2,5] to within the stated uncertainties of both measurements.[2,5] The origin of the $|m_l|$ dependence of Eq. (3) has been described previously.[2,6]

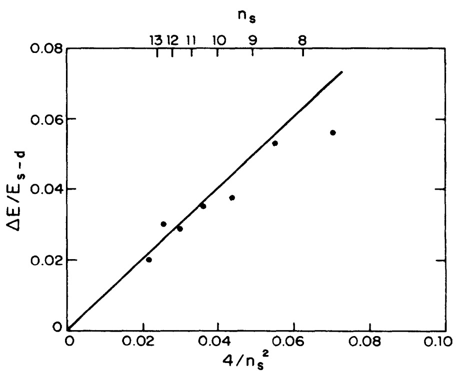

FIG. 3. Plot of $\Delta E/E_{s\text{-}d}$ the fractional difference in the threshold fields of the $(n+1)s$ and nd states plotted vs $4/n_s^2$. The solid straight line is the prediction of Eq. (2).

This work shows that the lower-lying Na states are ionized by a pulsed field in the same fashion as are the higher-lying $n=15$—20 states, i.e., the electron spin becomes uncoupled as the field rises and the passage to the high-ionizing field is adiabatic with respect to $|m_l|$. Furthermore it shows that selective field ionization of these low-lying states is straightforward and thus should be useful in a variety of experiments.

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[1] J. A. C. Gallas, G. Leuchs, H. Walther, and H. Figger, in *Advances in Atomic and Molecular Physics,* edited by D. Bates and B. Bederson (Academic, New York, 1985), Vol. 20.

[2] T. F. Gallagher, L. M. Humphrey, W. E. Cooke, R. M. Hill, and S. A. Edelstein, Phys. Rev. A **16**, 1098 (1977).

[3] M. G. Littman, M. L. Zimmermann, and D. Kleppner, Phys. Rev. Lett. 37, 486 (1976).

[4] W. van de Water, D. R. Mariani, and P. M. Koch, Phys. Rev. A **30**, 2399 (1984).

[5] J. L. Vialle and H. T. Duong, J. Phys. B **12**, 1407 (1979).

[6] W. E. Cooke and T. F. Gallagher, Phys. Rev. A **17**, 1226 (1978).