(1975).
[6]J. J. O'Brien, E. Liarokapis, and J. S. Greenberg, to be published.
[7]K. Taulbjerg, J. S. Briggs, and J. Vaaben, J. Phys. B 9, 1351 (1976); J. U. Andersen, E. Laegsgaard, M. Lund, and C. D. Moak, Nucl. Instrum. Methods 132, 507 (1976).
[8]R. Anholt, Z. Phys. A 289, 41 (1978), and private communication.
[9]J. S. Greenberg, C. K. Davis, and P. Vincent, Phys. Rev. Lett. 33, 473 (1974); G. Kraft, P. H. Mokler, and H. J. Stein, Phys. Rev. Lett. 33, 476 (1974); W. Wölfli, Ch. Stoller, G. Bonani, M. Stöckli, and M. Suter, Phys. Rev. Lett. 36, 309 (1976).

Diabatic Field Ionization of Highly Excited Sodium Atoms

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Data demonstrating that, contrary to earlier results, laser-excited sodium Rydberg atoms may pass from low-electric field strengths to ionizing electric field strengths along two quite distinct paths is presented. One path involves predominantly adiabatic passage while the other path involves predominantly diabatic passage. Data are presented along with a model that supports this conclusion.

Electric field ionization has become a common technique for the detection and study of highly excited atoms. Proper application of the technique requires an understanding of the possible results of applying an increasing electric field to an atom.

We report the first observation of a completely new feature in the field ionization spectrum of highly excited states of sodium. All previous work on sodium Rydberg states (cf., Gallagher *et al.*[1] in the region $n = 15-20$, and Vaille and Duong[2] in the region $n = 20-54$) indicates that the path taken to ionization by such atoms in an increasing electric field is primarily adiabatic (i.e., states of the same $|m_l|$ quantum number undergo avoided crossings). We report new observations of sodium atoms excited to high-Rydberg d states ($|m_l| = 2$) whose passage, from small electric fields to ionizing electric fields, is primarily diabatic. Data demonstrating both adiabatic and diabatic ionization thresholds are presented along with a consistent model for predicting the field strengths for each.

In the present experiment, excited sodium atoms are produced in zero electric field in a magnetically shielded region. A sodium beam is intersected at right angles by the output of two simultaneously pumped pulsed dye lasers. One laser beam excites the $3^2S_{1/2} - 3^2P_{3/2}$ transition ($\lambda = 5890$ Å) while the other laser beam excites the $3^2P_{3/2} - n^2S_{1/2}$ or $3^2P_{3/2} - n^2D_{3/2,5/2}$ transition ($\lambda \simeq 4100$ Å). The excited atoms are ionized by a pulsed electric field ~3 μsec after excitation. (The laser polarizations are perpendicular to the direction of this field.) The electric field strength, which rises from 0 to 1100 V/cm in ~1 μsec, is generated between two grids parallel to the plane of the sodium and laser beams and centered about their intersection. The electrons liberated at ionization are detected by an electron multiplier whose output goes to a time-to-amplitude converter (TAC). The TAC is started at the beginning of the ionizing voltage ramp and is stopped by the first electron pulse subsequently registered by the detector. The TAC output is fed into a standard multichannel pulse analyzer. For sufficiently low count rates (<0.1 per laser shot) the multichannel analyzer stores data proportional to the probability of a field ionization event per unit time during the 1 μsec ramp. Measurement of the time dependence of the ionizing voltage waveform permits determination of the field strengths at which the ionization events occur. It is necessary to allow for delays associated with electron flight time ($\simeq$6 nsec), transit time in the electron multiplier (~25 nsec), and cables and amplifiers (~30 nsec). The uncertainties in delay measurement and instrument calibrations and in our estimation of field penetration in the interaction region combine to yield a $\pm 5\%$ net uncertainty in the ionization field strength determination.

Figure 1(a) illustrates our field ionization data for sodium d states with $n = 30$, 32, 34, and 36. There are two major ionization thresholds in each profile, one at low electric fields and one at

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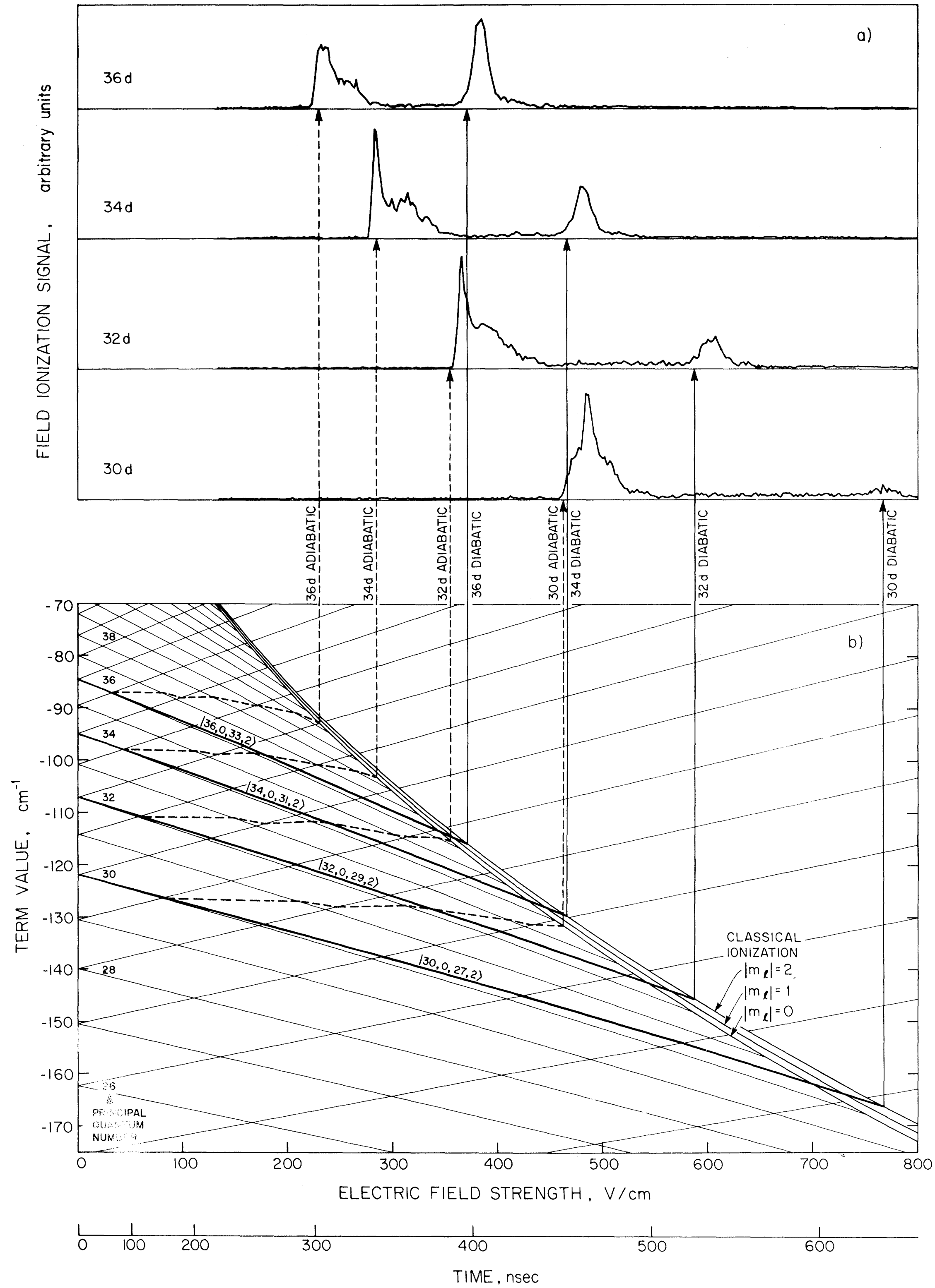

FIG. 1. (a) Field ionization data for d states of $n=30$, 32, 34, and 36. (b) Light lines: extreme members of $|m_l|=0$ Stark manifolds (fourth order perturbation theory); dotted lines: adiabatic paths to ionization for $n=30$, 32, 34, and 36; dark lines: diabatic paths to ionization for lowest members of $|m_l|=2$ manifolds for $n=30$, 32, 34, and 36. Classical ionization lines calculated on the basis of Ref. 5.

high electric fields. This is in marked contrast to all previous work[1,2] ($15 \leq n \leq 54$) in which only a single major threshold was reported for each state.

A similar low-field threshold is also exhibited by s and p states. By slewing through these low-field thresholds at a much lower rate, structure within them is revealed. In general, s, p, and d states have at least 1, 2, and 3 separate thresholds, respectively, within the broad low-field threshold. This observation is consistent with the observations of adiabatic ionization by Gallagher *et al.*[1] and by Vaille and Duong.[2]

The data in Fig. 1(a) may be understood by considering the nature of adiabatic and diabatic passage. Adiabatic passage of an excited atom initially in state A, through a crossing with state B, results whenever the two states can interact and when the electric field slew rate is sufficiently low. The result of such a passage is that the excited atom assumes the character of state B. Figure 2(a) illustrates a completely adiabatic passage through a region of intersecting manifolds. The atom, initially in a state of low $|m_l|$, successively changes its effective Stark state as the field increases. The path continues until it makes a crossing with an already highly-ionizing

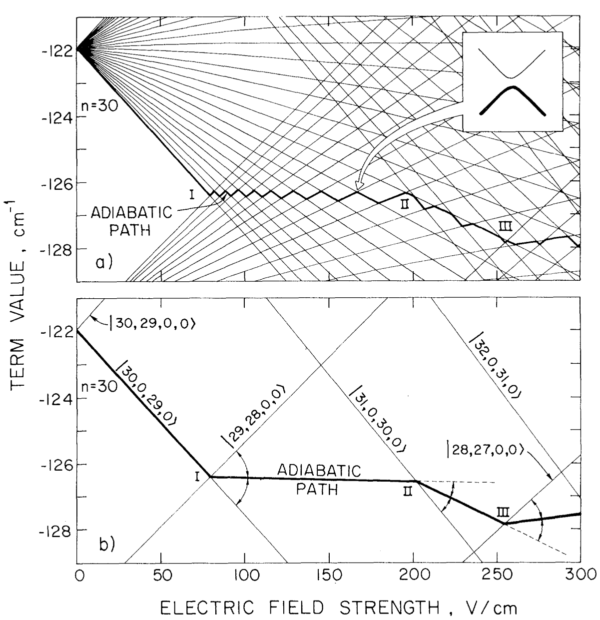

FIG. 2. (a) Schematic representation of the adiabatic path taken by the lowest member of the $|m_l| = 0$ Stark manifold for $n = 30$. Inset shows the nature of adiabatic crossing. (b) Geometric construction, described in text, to approximate adiabatic path.

state of the same $|m_l|$ from the lowest member of a higher principal quantum number Stark manifold. At this crossing, the atom assumes the character of this highly ionizing state and ionizes. Since the thresholds of quantum mechanical ionization for the lowest members of a succession of Stark manifolds, with the same $|m_l|$, coincide with the ionization thresholds predicted by classical theory, states that pass from zero to high electric fields along adiabatic paths would be expected to ionize near the classical ionization threshold.

The adiabatic path for an extreme member of a Stark manifold can be approximated by the construction shown in Fig. 2(b): At every intersection of the excited-state path with the path of an extreme member of another Stark manifold, the excited state will closely follow the line that bisects these paths. When this line intersects the extreme member of another Stark manifold, a similar construction is made and a new bisector formed. This construction is valid in the limit of high n, where the number of states within a single Stark manifold is large and does not change appreciably for adjacent manifolds. Because the $n+1$ manifold intersects the n manifold before the $n-1$ manifold intersects the n manifold, and the $n+2$ before the $n-2$, the adiabatic path is pushed to lower energies. The adiabatic paths shown in Fig. 1(b) are a result of this construction.

The electric field strengths at which the adiabatic paths shown in Fig. 1(b) intersect the classical ionization line are in good agreement with the experimentally determined low-field ionization thresholds shown in Fig. 1(a). Thus, the low-field ionization thresholds of Fig. 1(a) are attributed to states that have passed to ionization along predominantly adiabatic paths.

The high-field ionization threshold of each profile shown in Fig. 1(a) occurs at the field strength appropriate to quantum mechanical ionization[3] for the lowest member of the $|m_l| = 2$ Stark manifold, and is attributed to states with $|m_l| = 2$ passing from a low electric field to an ionizing electric field along predominantly diabatic paths.

Littman *et al.*[4] have shown that intermanifold interactions are strongly $|m_l|$ dependent. The larger the value of $|m_l|$, the smaller the interaction between states of identical $|m_l|$ at level crossings. States of higher principal quantum number also exhibit less interaction at level crossings. Thus, the probability of diabatic passage for a given electric field slew rate should increase as either n or $|m_l|$ increases.

As seen in Fig. 1(a), the diabatic signal does indeed increase as the value of n increases. In addition, both ionization features are evident at slew rates differing by a factor of 2 from that used to obtain the data in Fig. 1.

When both lasers are polarized parallel to the direction of the electric field, then theoretically no $|m_l|=2$ can be produced and, in this case, we observe a dramatic decrease in the signal obtained at the diabatic threshold. In view of this test, and since the probability for diabatic passage in a given field slew rate is larger for $|m_l|=2$ states than for $|m_l|=1$ or $|m_l|=0$ states, we conclude that the diabatic high-field peak is due primarily, if not wholly, to $|m_l|=2$.

The signal at electric fields between the adiabatic threshold and the diabatic threshold is attributed to a combination of adiabatic and diabatic passage through level crossings. As n increases, the ratio of this intermediate signal to the diabatic signal drops rapidly.

These measurements demonstrate, for the first time, the passage of highly excited atoms from low electric fields to ionizing electric fields along predominantly diabatic paths. Clearly, it is important to account for the possibility of diabatic thresholds whenever one observes atomic states of high n using field ionization.

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[1]T. F. Gallagher, M. L. Humphrey, R. M. Hill, and S. A. Edelstein, Phys. Rev. Lett. 37, 1465 (1976); T. F. Gallagher, M. L. Humphrey, W. E. Cooke, R. M. Hill, and S. A. Edelstein, Phys. Rev. A 16, 1098 (1977).

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

[3]M. H. Rice and R. H. Good, Jr., J. Opt. Soc. Am. 52, 239 (1952).

[4]M. G. Littman, M. L. Zimmerman, T. W. Ducas, R. R. Freeman, and D. Kleppner, Phys. Rev. Lett. 36, 788 (1976).

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

Formation of a Spheromak Plasma Configuration

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A compact, toroidal configuration of magnetized plasma is produced by a combination of Z- and θ-pinch discharges. A paramagnetic toroidal field is produced by currents circulating in the plasma on closed flux surfaces.

We report here our initial results on the formation of a plasma confinement configuration with the generic name of spheromak.[1,2] This compact toroidal configuration has both toroidal (B_φ) and poloidal (B_r, B_z) magnetic field components with the toroidal field maintained by circulating plasma currents rather than by an external coil through the toroidal hole, as in a tokamak. Configurations of this type were first studied theoretically in an astrophysical context.[3,4] Related laboratory experiments involving plasma guns,[5,6] electron beams,[7] and pinches[8] have been performed. Our experiment, called paramagnetic spheromak (PS-1), makes use of Z- and θ-pinch techniques to produce a prolate spheroid configuration. The results show, for the first time, that it is possible to establish the desired closed poloidal flux surfaces with a stabilizing paramagnetic toroidal field (i.e., with the peak magnitude of B_φ near the magnetic axis).

Figure 1 illustrates the formation phase. We start with a cylindrical deuterium gas column of radius 11.4 cm and a pressure of 15 mTorr. The column contains an axial bias magnetic field ($-B_z$) produced by I_φ currents[9] in an external, single-turn mirror coil with a mirror ratio of 1.1. The bias field is produced by a 20-kV, 18-μF capacitor bank capable of producing fields with magnitude up to 8 kG. Typically fields of 4 kG are used. The field rises in 3 to 5 μsec (depending on the external inductance) and is clamped. Following this a Z-directed current shell is produced by discharging a second capacitor bank (30 μF, 10–20 kV) between two annular electrodes with a radius of 7.6 cm located at the ends of the coil. The I_z current rises to a peak value of about 150 kA in 4 μsec. The I_z circuit creates an annular shell of plasma and a slight

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