this ratio should be 0.6000, and our experimental value is 0.5996. *Consequently, we conclude that the theory of Jette, Lee, and Das*[3] *is accurate within the limits of our measurements.*

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Observation of Electric-Field-Induced Resonances above the Ionization Limit in a One-Electron Atom

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Measurements of the relative photoionization cross sections of Rb in the presence of various strengths of external electric fields are reported. Systematic, field-dependent, resonance structure is observed not only for energies above the classical field-ionization limit, but above the zero-field ionization limit as well. A striking dependence of the cross section upon light polarization is also observed.

We report the results of an investigation of the wavelength dependence of the single-photon photoionization cross section of ground-state Rb in the presence of externally applied electric fields. For each field value, a systematic resonance structure versus wavelength was observed, not only for energies above the classical field-ionization threshold (which has been previously reported), but *above the zero-field ionization limit as well.* The observation of electric-field-dependent resonances in the photoionization cross section above the zero-field limit in a one-electron-like atom is surprising and to our knowledge has not been previously reported. In this Letter we present some relevant results of our experiment, discuss the physical mechanism responsible, develop a model whose predictions are in good agreement with our data, and attempt to place the results in proper perspective relative to recent measurements of field ionization and Stark effects in alkali atoms.

For detailed study of the cross section, we employed a collison-free, low-density ($\lesssim 10^9/cm^3$) atomic beam. The Rb atomic beam was irradiated by a pulsed (10 pps) laser beam (wavelength between 3005 and 2960 Å and focused power density of 100 kW/cm^2) between electric field plates which produced a uniform (to within 2%) electric field variable up to approximately 7 kV/cm. The ions produced in the photoionization process were accelerated by the electric field through a grid structure in one of the plates into an electron multiplier (RCA No. C31019B). Our detection scheme recorded all ions linearly without saturation, and was sensitive to ionization rates greater than approximately 5×10^4 sec^{-1}.

The uv light was produced by second-harmonic generation in an angle-tuned potassium dihydrogen phosphate crystal whose angular orientation was automatically locked by a servo mechanism to the phase-matching angle appropriate for the fundamental wavelength.[1] The fundamental was derived from a Hänsch-type dye laser pumped with a Q-switched Nd-doped yttrium aluminum garnet pulsed laser. The uv light had a spectral width of approximately 0.5 cm^{-1}. On a pulse-to pulse basis, the uv light intensity was sampled and divided into the sampled signal intensity from the electron multiplier. This technique automatically compensated for variations in uv output with wavelength (reduced to that resulting from variation of the fundamental power by the servo mechanism).

Considerable effort was expended to insure that the recorded wavelength dependence of the cross section was independent of laser intensity, atomic beam density, electron multiplier gain, or position of excitation between the plates. The ion current was observed to be linear in the uv laser power, and independent of tightness of focus in the interaction region. The uv light was focused in the interaction region to reduce any line broadening due to residual electric field inhomogeneities.

Measurements of the wavelength dependence of the photoionization cross section were recorded at electric field values between 0 and approximately 6500 V/cm. A typical result is shown in Fig. 1, where the electric field is 4335 V/cm; the wavelength dependence of the cross section was recorded for light polarizations perpendicular as well as parallel to the external field. The zero-field ionization limit is marked, along with the classical field-ionization threshold energy, E_c ($|E_c| = 2\sqrt{F_0}$ a.u., where F_0 is the electric field). The essential experimental result is that for light polarizations parallel to the electric field, the cross section shows a regular variation, yielding resonance structure that extends *beyond* the zero-field ionization limit. For polarizations perpendicular to the electric field, the variations in the cross section damp out at lower energies and show no resonance structure near or beyond the ionization limit. With increasing values of the field, the resonances become more widely spaced and more pronounced (see Fig. 4 for results of measurements of resonance spacing at other fields). For example, at 1016 V/cm, near the field-ionization limit the depth of modulation is ~9%, with resonance width of ~4 cm^{-1}

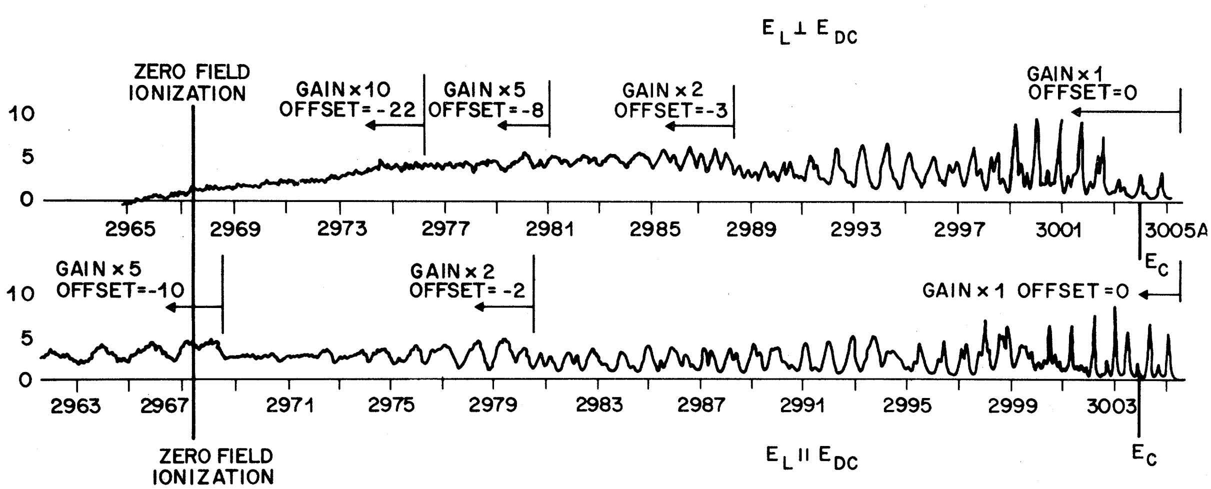

FIG. 1. Relative photoionization cross section as a function of laser frequency in Rb in the presence of 4335 V/cm. Note the relative gain and offset settings. For light polarizations parallel to the electric field, field-dependent resonance structure extends *beyond* the zero-field limit. No structure is observed for the case of light polarized perpendicular to the field.

separated by nearly 7 cm^{-1}; at 6416 V/cm, the corresponding resonances have a depth of up to 25%, width of 16 cm^{-1}, and a separation of 28 cm^{-1}. At zero field the resonance structure disappears altogether, and a Rydberg series of $5s \to np$ resonances terminating on the zero-field ionization limit is observed. In all cases, the resonance structure near and above the limit was observed only for light polarizations parallel to the electric field.

The rather sharp resonances in the cross section near and above the classical field-ionization threshold shown in Fig. 1 (and observed for other field values as well) are not unexpected and have been previously observed.[2] From an experimental standpoint, the concept of a classical threshold has proved useful and is an adequate description of the ionization behavior of low-angular-momentum states in alkali atoms.[3,4] However, recent measurements[5,6] suggest that for hydrogen, the stability of any state in an electric field is given by its tunneling rate in that field.[7] Thus, the photoionization cross section at any energy will reflect the presence of Stark states ionizing at varying rates. Since the higher-angular-momentum states of an alkali atom are essentially hydrogenic,[8] the presence of resonance structure in the photoionization cross section in the vicinity of the "classical field-ionization limit" is not unexpected.

The argument for the presence of broad, widely spaced, field-dependent resonances above the zero-field ionization limit is, at first approach, less transparent. Unlike the case of intense magnetic fields, where quasi Landau levels are observed above the zero-field ionization limit,[9] the free electron cannot undergo periodic motion in the external electric field alone. However, in the following discussion we argue that there do indeed exist electron orbits in the total field of the nucleus and external electric field that are stable, or nearly stable, even for total electron energies which are considerably greater than zero (i.e., above the zero-field ionization limit).

The potential energy diagram for a point nucleus at the origin ($\rho = 0$, $z = 0$) in an electric field along the z axis is shown in Fig. 2. Consider the classical motion of an electron starting at rest at some ($-z$, $\rho = 0$) value with $E > -|E_c|$. Under these circumstances the electron "slides" down the potential, through $z = \rho = 0$ and up over the potential hill on the positive z side and ionizes. However, as originally suggested in Ref. 6, if the electron starts with $\rho \neq 0$, or $V_\rho \neq 0$, its motion along the z axis is coupled by the nucleus to the ρ motion; instead of moving off to positive z values, the electron bends in a highly eccentric orbit passing close to the nucleus, "misses" the low potential hill on the positive z axis, and moves off in the negative z direction where it again reverses direction under the influence of the electric field. This is the case even for energies above the zero-field ionization limit. When the electron is close to the nucleus the effect of the electric field is small so that for $E > 0$ the electron is essentially in an unbound hyperbolic orbit described by the usual equations of motion. When the electron turns around and moves in the negative z direction, the electric field prevents it from escaping to $z = -\infty$ (ionization). The classical motion can thus be thought of roughly as a "hyperbola with end points," with the end points determined by the energy of the electron and the slope of the linear hill which the electric field presents to the electron. We have numerically calculated classical orbits which show that for motion tightly constrained along (but not degenerate with) the negative z axis, the electron executes nearly closed, highly eccentric orbits even for total energies several hundred reciprocal centimeters above zero. Note that this classical motion corresponds to wave functions which are elongated along the $-z$ axis, and necessarily are composed primarily of $m = 0$ components (and thus can be excited only with light polarizations parallel to the electric field).

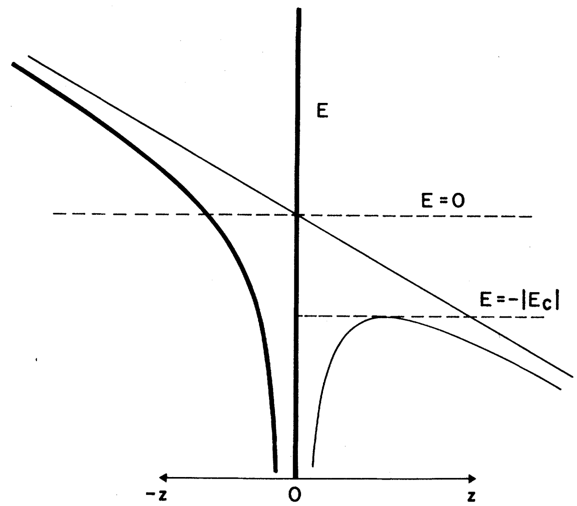

FIG. 2. Potential diagram showing a cut along the z axis ($\rho = 0$) for an applied field. The classical field-ionization energy is indicated. The dark lines mark the model potential boundaries.

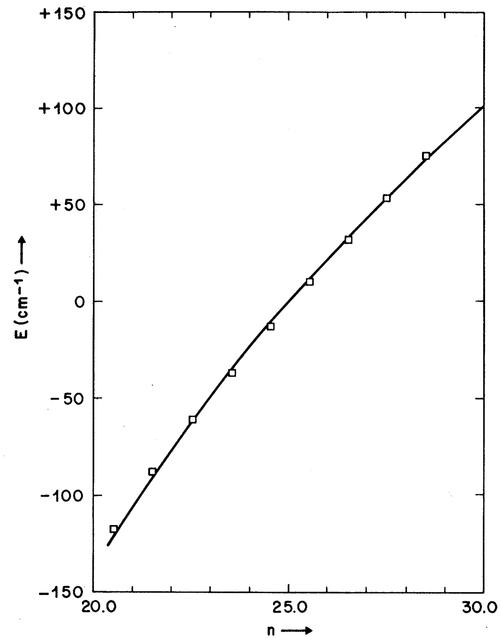

FIG. 3. The WKB prediction (solid line) of resonance position in energy, where $E=0$ is the zero-field ionization limit. The data are plotted using the more readily identifiable sharp minima in the resonance structure.

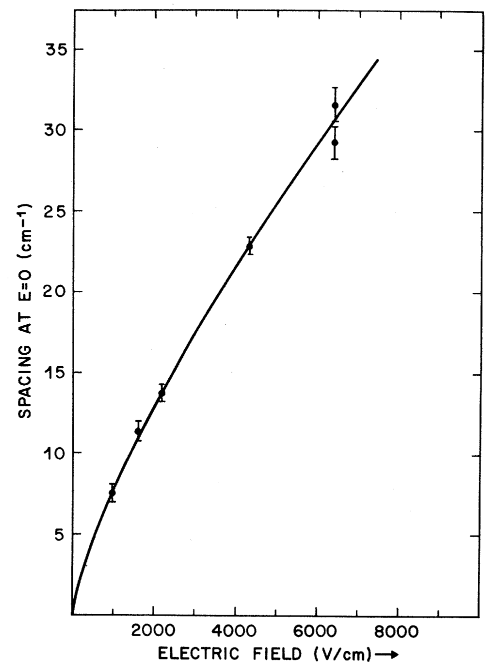

FIG. 4. The WKB prediction (solid line) of the spacing of the resonances at $E=0$ as a function of applied field. The data with their estimated errors are also shown.

We have made a WKB calculation to compare with our experiment by taking advantage of the insight gained in the classical calculations. We have employed an effective potential outlined in heavy markings in Fig. 2: $V_{\rm eff} = +e^2/z + eFz$ for $z < 0$. We have replaced the potential at $z=0$ by a "hard wall," thus producing a one-dimensional modified triangular potential.[10] Applying Bohr-Sommerfeld quantization to this potential yields the prediction of the spacing of the resonances near the ionization limit ($E=0$) for 4335 V/cm for increasing resonance number; this prediction is shown as the solid line in Fig. 3. The squares are the data, where we have plotted the sharp minima, arbitrarily assigning the resonance nearest the ionization limit to the predicted n value of the model for $E=0$. Note that the model potential correctly predicts the variation in the resonance position with energy.

The model potential also makes specific predictions about the spacing at $E=0$ as a function of applied field. This prediction is the solid line in Fig. 4. The data, with probable error limits, are also plotted. As there are no adjustable parameters in this calculation or fit, the comparison between model prediction and experiment must be deemed excellent.

In conclusion, we have observed electric-field-induced resonances in the continuum of a one-electron-like atom. We have shown that there exist quantized energy levels in the presence of electric fields large enough to otherwise ionize the atom and have constructed a model potential based on physical arguments that predicts the location and spacing of the resonances. The possibility of field-induced resonances in continuum states may have implications for high-resolution Stark-effect work in autoionizing continua of two-electron atoms.[11]

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Pulsed–X-Ray Shadowgraphy of Dense, Cool, Laser-Imploded Plasma

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Laser implosion of 87-bar neon-filled glass microballoon targets produces a dense, cool plasma whose development in time and space is recorded by pulsed–x-ray shadowgraphy with soft x rays from a separate laser-produced plasma. Compressed densities of 4 g cm^{-3} are estimated from the data by comparison with numerical simulations of the implosion.

A new approach to space- and time-resolved diagnosis of dense plasmas produced by laser-driven implosions has been developed. Pulsed–x-ray shadowgraphy, with a separate laser-produced plasma as the x-ray source, has given images of plasmas of high density but low temperature which cannot be diagnosed by the more usual methods based on the emission of x rays and fusion-reaction particles.

In this initial investigation a target design was chosen to create plasmas of density >1 g cm^{-3} and temperature <100 eV, and to implode in 500 ps when driven by a 4-J, 100-ps, Nd-glass laser pulse. The targets were glass microballoons filled with neon at 87 bar, typically of 66 μm diam and of 1.3 μm glass shell thickness. They were irradiated by two beams with $f/1$ lens focusing. A laser pulse of 5 J in 100 ps, and variable delay with respect to the beams irradiating the microballoon, was directed through one of the lenses and focused on a brass (Cu + Zn) target as

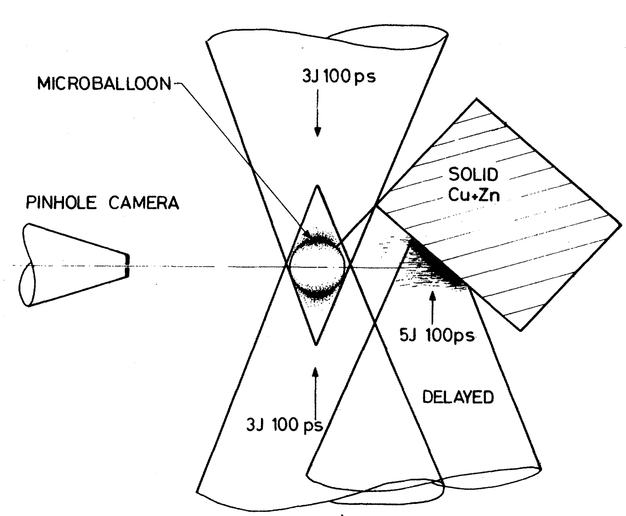

FIG. 1. Experimental configuration for pulsed–x-ray shadowgraphy. The 66-μm-diam microballoon, its support fiber, and the plasma on the brass target are drawn in correct relative scale. The schematic pinhole was 2.5 cm from the microballoon.