Shape Resonances in the Hydrogen Stark Effect in Fields up to 3 MV/cm

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We observe the Stark effect in hydrogen by photoionizing a relativistic hydrogen beam prepared by photodetachment of the 800-MeV H^- beam at the Clinton P. Anderson Meson Physics Facility. Photoexcitation of H^0 is performed in a magnetic field (up to 6.5 kG) that appears in the atomic frame as an electric field up to 3 MV/cm. Resonances observed with an angle Doppler-tuned laser beam match calculated energies. At sufficiently high field, near the Stark-Coulomb potential-barrier peak, we observe shape resonances with an apparent elevation of the base line on the high-energy side.

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This report demonstrates the capabilities of a relativistic atomic beam for observations of the Stark effect in hydrogen. By working at very high electric fields (in the atomic frame) and low quantum numbers, we are able to study individual resonances near the top of the effective Stark-Coulomb potential with no background from other Stark channels. Observed Stark shifts and shapes agree well with calculations. The most striking observation, however, is that over much of the regime studied, resonance shapes depart significantly from the ideal Lorentz form (and from other presently available analytic line-shape expressions) so that a linewidth parameter cannot be rigorously defined or fitted to the data.

Despite their fundamental significance and numerous theoretical studies, ionization linewidths and line shapes for hydrogen atoms in an electric field have rarely been measured.[1] Early observations[2] of hydrogen atoms in ionizing fields as high as 1.1 MV/cm were performed with emission spectroscopy. The lines disappeared at fields for which the ionization rate was comparable to the radiative decay rate, and no ionization broadening could be observed. Recently,[3] ionization rates for several levels, $n=30$ to 40, have been measured in fields of 400 to 800 V/cm, and found to agree with the more precise theoretical methods. We are also aware of current work in two laboratories[4] in which the photoionization of hydrogen atoms in fields up to 10 kV/cm is observed following one- or two-photon excitation of $n=2$. Studies at very high fields complement observations at normal laboratory fields and make it feasible to study low-n states, making possible a search for effects that vary inversely with n.

These observations come at a time of renewed interest in the theory of the Stark effect. Numerical methods,[5,6] such as we use to analyze the present data, are now capable of solving the nonrelativistic hydrogen Stark equations as exactly as computer precision allows. WKB methods have now also been brought to high accuracy,[7] and perturbation theory has been carried to high order.[8] Complex coordinate rotation[9] methods have been used to locate resonance poles in the complex energy plane. The relationship between experimental observations and complex pole parameters is one of the questions raised by the results given here.

Tunable single-photon excitation of hydrogen atoms in large electric fields is made possible by the transformation from a laboratory frame to the rest frame of a relativistic beam[10]; ultraviolet laser light is Doppler shifted to energies sufficient to excite Lyman-series transitions, and laboratory magnetic fields transform into large electric fields in the atom's frame. Our experiments were performed at the Clinton P. Anderson Meson Physics Facility

(LAMPF) with an 800-MeV H^- beam and laser facilities much as described for previous experiments[10] on resonance states of H^-. A schematic diagram of the experimental configuration is shown in Fig. 1. The fundamental of a neodymium-doped yttrium aluminum garnet (YAlG) pulsed laser, with laboratory energy $E_L = 1.17$ eV, is used to photodetach an electron from H^-. The fourth harmonic ($E_L = 4.66$ eV) of the same YAlG laser then excites the resultant hydrogen atom at the center of a pair of Helmholtz coils. By varying the angle α between the fourth-harmonic laser beam and the H^-/H^0 beam, it is possible to scan the energy range of interest, according to the formula

$$E = \gamma E_L(1+\beta\cos\alpha), \qquad (1)$$

where $\beta = v/c$, c is the speed of light in vacuum, and $\gamma = (1-\beta^2)^{-1/2}$.

The Helmholtz coils, 1.1 cm in diameter and constructed of copper strips potted in heat-conducting epoxy,[11] could sustain currents as high as 7 kA in 1.8-μsec pulses so as to produce fields up to 7 kG. For $\beta = 0.842$, corresponding to an 800-MeV H^- beam, a vertical magnetic field of 1 kG transforms into the rest frame of the atom as the sum of a horizontal electric field of 468 kV/cm perpendicular to the beam velocity and a vertical magnetic field of 1.853 kG. By reference to an accurate computer model, the field is estimated to be uniform to 1% over a diameter of 1 cm, which covers the region of overlap between the particle and laser beams.

After intersecting the uv laser beam in the magnetic field, the particle beam traverses a bending magnet that separates H^-, H^0, and H^+ components. The H^- beam is collected in a Faraday cup, and the H^0 and H^+ beams are detected 2–3 m downstream by 1-cm-high scintillators. Atoms excited to $n = 4$ in fields of 3.5 kG (for $n_1 = m_L = 0$) to 5.4 kG (for $n_1 = 3$, $m_L = 0$) or higher are calculated to ionize within 1 cm and thus form protons while traversing the same field that induces the Stark shift. The 3.6-kG bending magnet ionizes some of the remaining atoms. The counting rate in the proton scintillator is the signal for this experiment.

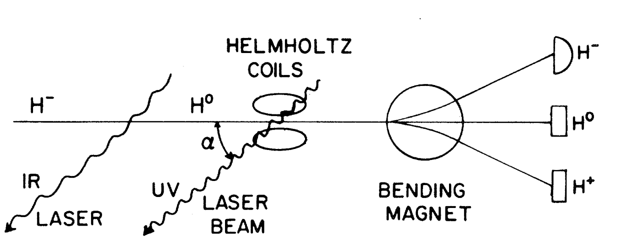

FIG. 1. Schematic diagram of the apparatus. The YAlG fundamental laser beam photodetaches H^- to produce H^0, which is then excited in the center of a Helmholtz coil by the YAlG fourth harmonic at angle α with respect to the beam axis. When α is tuned to match a Stark resonance, the excited atom ionizes in the coil or in the 3.6-kG bending magnet. The product H^+ is deflected up to 11 mrad into a detector 2.7 m downstream.

Before presenting scans over resonance lines, we show the overall structure of hydrogen Stark levels near $n = 4$ in Fig. 2. The solid ($m_L = 0$) and dashed ($|m_L| = 1$) lines are resonance energies obtained from numerical solution of the separated equations in parabolic coordinates, as described previously.[5,12] The n_1 quantum number is the number of nodes in the ξ coordinate wave function. When broadening is appreciable, the shaded area denotes the interval between half-maximum intensity values.

The energy scale for the experimental points in Fig. 2 is established by reference to zero-field tran-

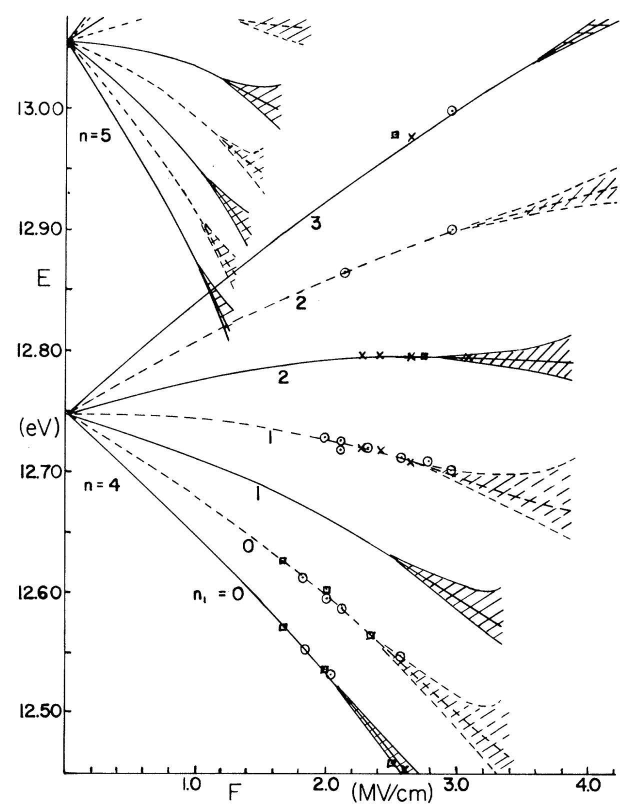

FIG. 2. Hydrogen Stark energy levels for the region studied. Solid lines denote $m_L = 0$, dashed lines $|m_L| = 1$ energies. Crosshatching indicates the interval between half-maximum intensity points. Circles, squares, and crosses denote data sets distinguished by coil geometry and pulse timing.

sitions in H^0. The data sets denoted by circles, squares, and crosses were each fitted to separate coil calibration factors (tesla/ampere) by comparing observed and calculated resonance energies as a function of the voltage across a resistor in series with the coils. The calibration factor differed from one data set to another because of changes in the coil geometry and in pulse timing. Efforts to calibrate the field independently of Stark theory have been complicated by induction and timing effects in the pulse circuit. The extent of experimental corroboration of theoretical Stark shifts in this unprecedented high-field regime is expressed by the $\sim 2\%$ standard deviation of the fitted field calibration factor for each of the three data sets.

Data from individual scans of the most downward-going $n=4$ component $(n,n_1,m_L=4,0,0)$ are shown in Fig. 3. The statistical uncertainties have been obtained by sampling the pulse-to-pulse variation of the signals and are found to vary roughly linearly with signal intensity rather than as the square root of intensity as for Poisson statistics. This unusual behavior is suspected to arise from the nature of the temporal overlap between the laser pulses (8-nsec duration) and H^- beam micropulses (0.25-nsec width, spaced by 5 nsec). The instrumental contribution to the resonance shape is obtained from scans over resonances for which the intrinsic atomic width is essentially negligible. Figure 3, curve *a*, is one example. In observations of the narrow H^- resonance at 10.926 eV, the instrumental shape has been found to be nearly Gaussian with a width of 5–8 meV, determined by the energy spread and spatial divergence of the H^- and laser beams.[10] However, to fit the present data, we found it necessary to use an instrumental function consisting of two Gaussian shapes superimposed. This additional component is associated with a secondary momentum distribution in the primary H^- beam that can probably be eliminated in future experiments. The instrumental line shape masks some of the intrinsic atomic line asymmetry, and accounts for the inflection of the fitted curve in Fig. 3, curve *a*.

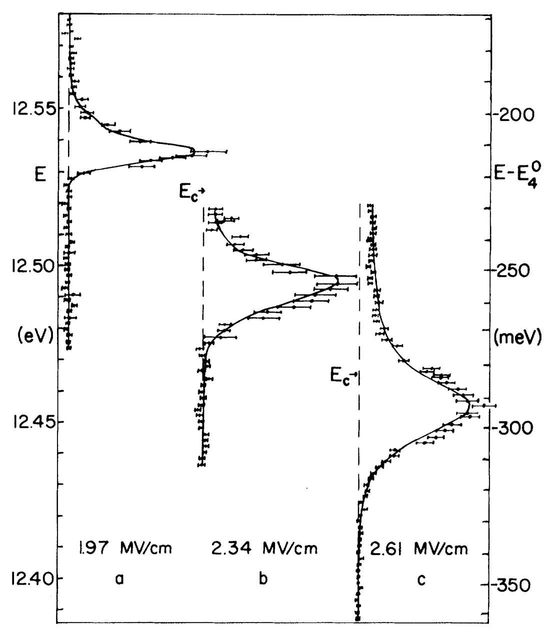

FIG. 3. Three individual scans over the lowest $n=4$ Stark component $(n_1=m_L=0)$ at increasing field values. In curve *a*, the data scan displays the instrumental shape function, which has been fitted by a superposition of two Gaussian shapes. The fitted curves for *b* and *c* were obtained by convoluting the theoretical photoionization cross section with an instrumental function determined from data runs as in curve *a*. E_c denotes the energy for which the η coordinate wave function lies at the top of the effective Stark-Coulomb potential barrier.

As a Stark component is followed to higher fields, as in Fig. 3, curves *b* and *c*, the intrinsic atomic line-shape effects gradually dominate the instrumental shape. For Fig. 3, curves *b* and *c*, the fitted (solid) curve was obtained by convoluting the numerical computed point-by-point photoionization cross section with an instrumental profile deduced from data for narrow resonances. Three parameters were fitted: an amplitude scale factor, an instrumental base line, and a small energy shift to compensate for the small uncertainty in the field calibration factor. The good quality of this fit corroborates the overall theoretical line shape. The numerical $\sigma(E)$ function is entirely consistent with that obtained by semiclassical methods.[7] It will be noted that far beyond statistical uncertainty and beyond distortions from the instrumental line shape, the apparent base line is higher on the high- than on the low-energy side. This is typical of shape resonances near the top of a potential barrier. The apparent elevation of the base line on the high-energy side is due to transitions to continuum levels above the barrier maximum, denoted by E_c in Fig. 3.

The resonance shapes in Fig. 3, curves *b* and *c*, exemplify some half-dozen cases in our data runs for which the atomic linewidth is greater than the experimental width of ~ 6 meV. The departures from Lorentz shape (quite apart from instrumental factors) complicated fittings of the resonance energies and linewidths. Furthermore, as is evident from the data of Fig. 3, curve *c*, and from the theoretical $\sigma(E)$ photoionization cross-section function, neither the general Breit-Wigner form (Lorentz shape plus dispersion term plus background) nor the Fano shape formula[13] strictly applies, although of course any additional parameters will improve the fit to the data. These forms have a dip on one side of the resonance and return to a constant or smoothly varying background on either side. In the sense that the data agree with a theoretical $\sigma(E)$ function, one may say that the physics is understood. However, in order to compare calculated values[5–9] for resonance energies and widths with experimental data, one needs an analytic line-shape expression, or a procedure for weighting the poles in the complex plane to represent phenomena on the real energy axis. To the approximation that hydrogen Stark resonances are described by the Fano shape formula, asymmetry (q) parameters have recently been deduced by semiclassical methods.[14] This is an improvement over Lorentz-shape parametrization, but the present observations indicate that the Fano formula (with energy-independent parameters) reproduces actual data only near the resonance peak.[15]

For resonances further below the barrier maximum, deviations from Lorentz shape are less significant, but not always negligible. When these deviations are significant, there is normally a substantial background from other n, n_1, m_L channels. This is the case, for example, for the undulations near and above the zero-field threshold, first reported for rubidium[16] and sodium[12] photoionization in an electric field, and recently observed also with hydrogen.[4] By studying Stark resonances of low-lying states at extremely high electric fields, we are able to observe isolated resonances with no background from other channels. The present experiments therefore raise the question of the hydrogen Stark line shape in a particularly unambiguous manner.

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