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Strong, Quasiperiodic Dependence of Autoionization Shape Parameters on Projectile Energy in H^+ + He Collisions

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Strong, Quasiperiodic Dependence of Autoionization Shape Parameters on Projectile Energy in H^+ + He Collisions*

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Profiles of the $2s^2$ (^1S) autoionizing state in He have been observed in the ejected-electron spectrum of H^+ + He for small angles of ejection and for H^+ energies of 6 to 150 keV. The shape parameter q shows an increasing dependence on projectile energy as the angle of ejection is decreased, with strong, quasiperiodic oscillations appearing at 10°.

Autoionization profiles in atomic systems are described by the following formula[1]:

$$\sigma(\epsilon)=\sigma_A(q+\epsilon)^2/(1+\epsilon^2)+\sigma_B, \qquad (1)$$

where σ_A and σ_B are the resonant and nonresonant parts of the cross section, respectively, and

$$\epsilon=(E-E_r)/\tfrac{1}{2}\Gamma$$

is the energy of excitation or emission relative to the corresponding resonance energy E_r in units of the natural half-width $\frac{1}{2}\Gamma$. The shape parameter q is given by certain matrix elements of the interaction and thus depends on the means of excitation.

Profiles of the form (1) have been observed in photoabsorption[2] and electron impact[3-5] spectra, and in ejected-electron spectra produced by electrons[6-9] and ions.[10-13] Until recently, the profiles observed with excitation by ions have been predominantly Lorentzian, corresponding to large q in Eq. (1). The observations of Bordenave-Montesquieu and Benoit-Cattin[12] and Stolterfoht,[13] however, indicate that asymmetric profiles can be expected at the higher ion energies and smaller ejection angles.

We report here on a study of the ejected-electron spectra resulting from H^+ + He collisions at H^+ energies of 6 to 150 keV and ejection angles of 10°, 20°, and 30° with respect to the proton beam. The apparatus has been described previously.[14,15]

At angles of 20° and 30° our results agree qualitatively with those reported in Refs. 12 and 13, in which the smallest angles used were 17° and 18°, respectively. At a given angle the autoionization profiles show increasing asymmetry with increasing proton energy, the effect becoming more pronounced with decreasing angle. At an angle of 10°, however, the profiles observed in the present study show a very strong dependence on proton energy and appear to oscillate in a quasiperiodic fashion as the proton energy is varied.

Examples of the 10° spectra in the region of the $2s^2$ (^1S) state are shown in Fig. 1. This state occurs at an excitation energy of 57.8 eV, or at an ejected-electron energy of 33.2 eV. The energy calibration used here is such that when the profile is Lorentzian, the $2s^2$ (^1S) peak is at 33.2 eV and the $2s2p$ (^1P) peak is at 35.5 eV. Addition of the ionization potential then yields the spectroscopic energy of the latter state.[2]

The profile of the ^1S state appears as a fairly sharp, symmetric peak at the lowest proton energies in Fig. 1. As the energy is increased, a dip forms on the low-energy side of the peak and broadens until it dominates the profile at 22 keV. At 24 keV a sharp peak emerges within the dip,

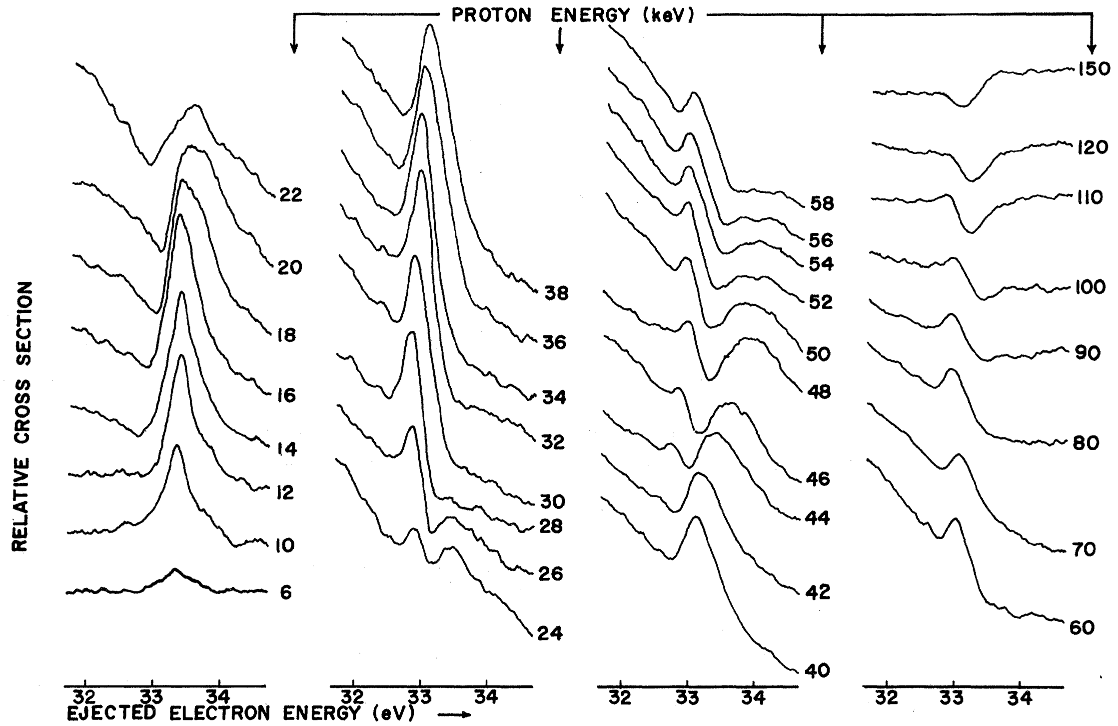

FIG. 1. Ejected-electron spectra from $H^+ + He$ collisions in the region of the $2s^2(^1S)$ state for an ejection angle of 10°. The heights of the spectra in the first two columns have been multiplied by 2 relative to those in the last two columns. The zeros have been shifted for display.

and the profile then goes through a sequence of asymmetric shapes until in the 30-keV range it is again symmetric. As the energy is increased further, the peak broadens; and at 44 keV, another sharp peak emerges. The asymmetric sequence followed by the broadening then repeats in the 50–60-keV range. In the 70-keV range a dip forms on the high-energy side of the peak and shifts to lower energies as the proton energy is increased. The profile is a pure dip at 120 keV. The rapidity of the variations seen here can be appreciated by noting that a change in the proton energy of less than 5% can in some instances produce a dramatic change in the profile.

Aside from changes in magnitude and the sloping background, the behavior described above can be attributed to a dependence of the shape parameter q on proton energy. We have made preliminary estimates of the q values by measuring the separation in electron energy of the maxima and minima of the profiles. In the absence of instrumental broadening this separation would be given by $\frac{1}{2}\Gamma(1+q^2)/q$, since the maximum of (1) occurs at $\epsilon = 1/q$ and the minimum at $\epsilon = -q$. Note that the minimum separation here occurs where $q = \pm 1$, and has the value $\pm\Gamma$. Thus, the minimum observed separation can be taken as a measure of the effective width, including the instrumental resolution. An effective q value can then be obtained from

$$\Delta E = \tfrac{1}{2}\Delta E_{\min}(1+q^2)/q,$$

where ΔE is the observed separation of the maximum and minimum for any given profile, and $\Delta E_{\min}$ is the minimum observed separation. While this analysis ignores the details of the resolution function, it should yield relative q values as a function of proton energy, since in the experiment the resolution did not change with energy. As a check on this method, Eq. (1) was folded with a triangular resolution function, and the results were compared with the observed spectra. The triangular function has been shown to be a reasonable approximation to the resolution function of the parallel-plate electrostatic analyzer used in this work. In the folding, calculated widths of 0.30 and 0.14 eV[16] were used for the resolution and natural widths, respectively. The dependence of σ_A and σ_B on proton energy was ignored, since these quantities appeared only as scaling factors in the folded function. Plots of the effective q values obtained by these

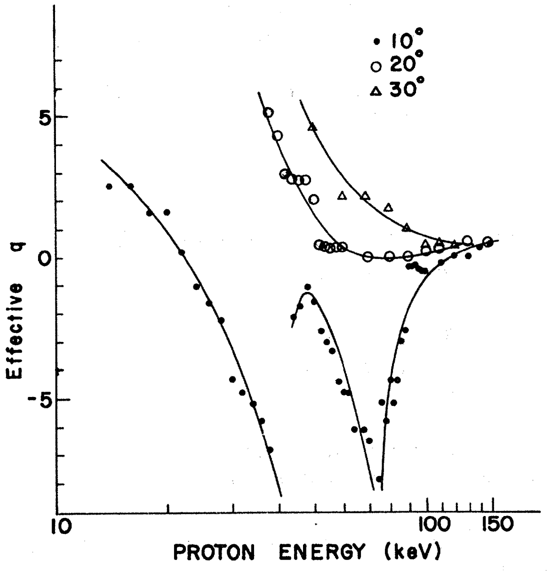

FIG. 2. Effective q values versus proton energy for three ejection angles. The relative uncertainty in q due to measurement uncertainties alone is about ±1.

procedures versus proton energy are shown in Fig. 2.

The most remarkable features of the curves in Fig. 2 are the rapid variations in q with proton energy, and the quasiperiodic nature of the 10° curve. Note that what appeared to be a discontinuity at 24 keV in Fig. 1 is a smooth transition through $q = 0$ in Fig. 2. The points at 42 and 74 keV, as well as all other points lying off the graph, are ones for which the q values are too large to measure with the present experimental sensitivity.

The precise origin of the behavior shown in Fig. 2 is unknown. Certain implications are clear, however, and are worth mentioning at this point. Since q includes an amplitude for exciting continuum states near the resonance,[1] we suspect that the "forward peak" in the continuum is in some way responsible for the observed behavior of q at the low angles.[17] This peak, which has been observed by Crooks and Rudd,[18] and is accounted for in theories by Macek[19] and Salin,[20] occurs in the forward direction and at an electron energy where the velocity is equal to that of the incident proton. The mechanism responsible for the peak has been interpreted as charge transfer to continuum states of the projectile.[19] In our case the forward peak lies in the vicinity of the $2s^2$ (^1S) state when the proton energy is about 56 keV, and contributes to the continuum for a range of proton energies that becomes broader as the angle of ejection is increased (see, for example, the data of Rudd, Sautter, and Bailey[21]). The q values shown in Fig. 2 are rapidly decreasing for all three angles at proton energies in the 50-keV range, and the two points where q becomes very large and negative in the 10° curve are displaced by approximately equal energies to either side of this range.

We also point out that the curves in Fig. 2 contain information on the phases of the ejected-electron wave functions. These phases influence the resonance profiles via interference between the amplitude for exciting the continuum and the amplitude for exciting the discrete state. In the case of elastic electron scattering, the phase shift is given by $\cot^{-1}q$. Although no such simple relation exists in the present case, a functional dependence is expected. In this sense then, the observed behavior of q at small angles reflects the modification of the phase shifts brought about by the close proximity of the outgoing electron to the scattered proton; i.e., through the final-state interaction implied by "charge transfer to continuum states of the proton."

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