Final-State Symmetry for the $n = 2$ States in Photoionized Helium Determined by Theory and Experiment

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Experiment and theory have been used to determine the final-state symmetry for the $n = 2$ state in photoionized helium. The angular asymmetry parameter β has been measured as a function of photon energy by means of angle-resolved photoelectron spectroscopy. From these measured β values, which are a weighted average of β_{2s} and β_{2p}, together with the theoretical values of β_{2p} and β_{2s}, the ratio, R, of the partial $2p$ photoionization cross section to the partial $2s$ photoionization cross section has been obtained.

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The Coulomb field provides a unique opportunity to study different theoretical many-body formalisms because the Coulomb force governing the correlated motion of the atomic electron cloud is precisely known. Helium is the simplest system that exhibits correlation effects in the photoionization process. Because of its general importance as a test case, the photoionization cross section has been studied in great detail[1] over a broad photon energy range. Many calculations have been performed with techniques of greater and greater sophistication.[2]

We present measurements of the photoionization from the ground state of helium, using synchrotron radiation, leading to the determination of the ratio, R, of the $2p$ to $2s$ partial photoionization cross sections. We have used the technique of photoelectron spectroscopy to measure the angular distribution of the final continuum-state electron as a function of photon energy in the process $h\nu + \mathrm{He}(1s) \rightarrow \mathrm{He}^{+}(2s, 2p) + e$, from which the angular asymmetry parameter, β, has been determined for the first time.

The technique of photoelectron spectroscopy (PES) has been used to study the fraction of residual ions in the $n = 2$ state[3,4] and more recently the $n = 3$ state.[5] From these measurements, it was possible to make a sensitive test of theories[6-9] which describe photoionization plus excitation. From the PES measurements, the total cross section for the ionization and excitation to the $n = 2$ state of the helium ion has been obtained.[10] More recently, Woodruff and Samson[11] have obtained a relative measurement of the $n = 2$ cross section by a fluorescence technique. When normalized to the measurements by Wuilleumier *et al.*,[10] the two sets of cross sections are in good agreement.

The most recent calculations of the[8,9] total cross section for ionization and excitation to the $n = 2$ state of helium are in relatively good agreement although the correlations included vary considerably. A more sensitive test of the various calculations would be to measure the symmetry of the final state by determining the ratio, R, of the cross section for leaving the ion in the $2p$ state to the cross section for leaving the ion in the $2s$ state as a function of photon energy. If initial-state correlations of s^2 configurations dominate, R will be a quantity $\ll 1$ and a slowly varying function of photon energy. If final-state correlations are important, R will be larger and a function of photon energy. Depending on the type of correlation, the magnitude of R will be quite different. For example, in the close-coupling calculations of Jacobs and Burke,[8] who used a $1s$, $2s$, and $2p$ close-coupling continuum wave function and a 56-term Hylleraas bound-state wave function, the ion is left predominantly in the $2p$ state near threshold. In the many-body calculation of Chang,[9] the ion is left predominantly in the $2s$ state near threshold. A measurement of R would provide evidence to discriminate between these calculations. Photoelectron spectroscopy or the fluorescence technique can be used to determine R.[12] In the present work, we used angle-resolved photoelectron spectroscopy (ARPES) to measure the asymmetry parameter β for the experimentally indistinguishable $n=2$ final ionic states and obtained R from these measurements.

The differential photoionization cross section for partially or elliptically polarized radiation, $d\sigma_i/d\Omega$, for the ith channel is[13,14]

$$d\sigma_i/d\Omega=(\sigma_i/4\pi)\{1-\tfrac{1}{2}\beta_i[P_2(\cos\theta_z)-\tfrac{3}{2}p(\cos^2\theta_y-\cos^2\theta_x)]\}, \quad (1)$$

where β_i is the angular asymmetry parameter for the ith channel, p is the magnitude of the polarization, P_2 is the Legendre polynomial of second order, and θ_x, θ_y, and θ_z are the angles the photoelectron makes with the x, y, and z axes, respectively. The photons propagate in the z direction. Since the energies of the $He^+(2s)$ and $He^+(2p)$ states are almost degenerate, the photoelectrons, associated with either the $2s$ or $2p$ ion final state, have almost the same kinetic energy. (The energy difference between the two states is less than 1 meV.) The form of the total differential cross section for the $n=2$ state is the same, but σ_i is replaced by $\sigma_{n=2}$, the sum of the $2s$ and $2p$ partial cross sections, and β_i is replaced by β, a weighted asymmetry parameter, and is the quantity determined in this experiment. The form for β is

$$\beta=(\sigma_{2s}\beta_{2s}+\sigma_{2p}\beta_{2p})/\sigma_{n=2}. \quad (2)$$

It has been shown[8,15] for electrons leaving the ion in the $2s$ state that β must be equal to 2. Thus, from calculated values of β_{2p} and measured values of β, one can determine the ratio $R=\sigma_{2p}/\sigma_{2s}$ and make a sensitive test of the amount of correlation and coupling between the electrons. The ratio of the partial cross sections of the $n=2$ state is

$$R=\sigma_{2p}/\sigma_{2s}=(2-\beta)/(\beta-\beta_{2p}). \quad (3)$$

Data to determine the weighted asymmetry parameter β were obtained with use of a new high-throughput monochromator[16] [output flux at ~100 eV is ~10^{12} photons/s$\cdot$eV$\cdot$(100 mA)] attached to the ACO storage ring at the Laboratoire pour l' Utilisation du Rayonnement Electromagnétique (LURE) in Orsay. The same, carefully characterized cylindrical mirror photoelectron spectrometer that was used earlier[10] to determine $\sigma_{n=2}$ was modified by aperturing the inner cylinder to restrict the azimuthal acceptance. Only those electrons were detected that were emitted into an angular sector ±2° in the θ_z direction centered about 54°44′, the magic angle, and ±7° in the azimuthal direction perpendicular to the axis of symmetry of the spectrometer (see Fig. 1). Photoelectron counts were measured

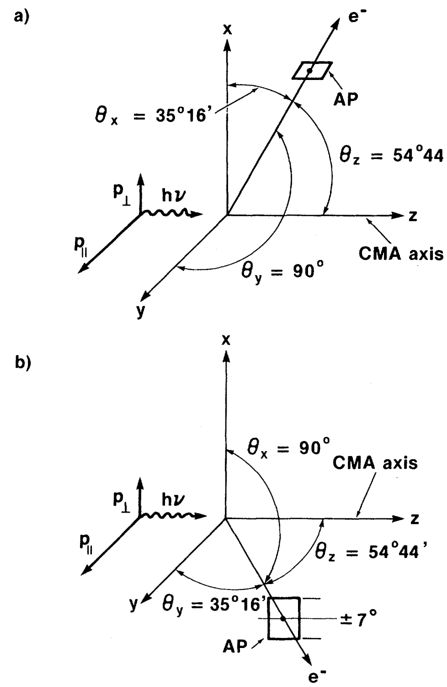

FIG. 1. Experimental geometry. Photons propagating along the z axis interact with helium to eject photoelectrons. $P_{\parallel}$ and $P_{\perp}$ are the polarization directions parallel and perpendicular to the electron orbital plane. (a) Electrons passing through the aperture AP oriented as shown with respect to the coordinate system are detected in the cylindrical mirror analyzer (CMA) whose axis is coincident with the photon direction. (b) The aperture AP is rotated 90° and lies perpendicular to the synchrotron orbital plane. The angle $\theta_z = 54°44'$ is the magic angle.

as a function of wavelength for the sector positioned as shown in Fig. 1, either with $\theta_y = 90°$ or with $\theta_x = 90°$. Under these conditions Eq. (1) reduces to $d\sigma/d\Omega = \sigma_{n=2}[1 \pm \frac{1}{2}\beta p]/4\pi$. The plus (minus) sign is used for $\theta_x = 90°$ ($\theta_y = 90°$). From the counting rate at the two angles, the value of the asymmetry parameter can be obtained if the polarization p is known. The magnitude of p was determined from the knowledge that $\beta = 2$ for the $n = 1$ channel. The spectra containing the $n = 1$ and $n = 2$ photoelectron peaks were recorded as a function of photon energy and angle, and the values of p and β were extracted from these data.

The value of the experimentally determined asymmetry parameter, β, for photoelectrons leaving the ion in the $n = 2$ state is shown as a function of photon energy in Fig. 2. The value of β varies from about 0.6 at 75 eV to 1.6 at 130 eV. The solid curve in Fig. 2 is β_{2p} obtained from the calculations of Jacobs and Burke[8] and the dotted curve is our calculated value of β_{2p} obtained from many-body wave functions according to the formalism outlined in Ref. 9. If one uses the calculated cross sections from Ref. 9 and β_{2p} to compute the weighted asymmetry parameter, one obtains the dash-dotted curve which is in good agreement with the experimental values. Notice that β_{2p} obtained from Ref. 8 differs little from the present calculations.

The values of R obtained from the present angular distribution measurements and present calculated value of β_{2p} are shown in Fig. 3. Earlier measurements,[4] shown as triangles, utilizing discrete x-ray sources, are consistent with the present data.

Photoionization calculations[6] with initial-state correlations between s^2 configurations predict $R = 0$. If the photoionization calculations[7] with initial-state correlation include p^2 configurations as well, R is very small, but is a slowly varying function of the photon energy. The present results (Fig. 3) indicate that R is slowly varying of order 1 over a broad energy range of ~60 eV. These results suggest that final-state correlation has a dominating influence on R as is shown by calculations that include final-state and ground-state correlation. The close-coupling calculations by Jacobs and Burke[8] (Fig. 3) suggest the cross section near threshold is dominated by the photoionization process that leaves the ion predominantly in the $2p$ state. By contrast, the solid line, obtained from the many-body calculation described in Ref. 9, suggests that the cross section is dominated by the photoionization process that leaves the ion in the $2s$ state at threshold. At $h\nu > 100$ eV, both theories are in good agreement. As the photon energy increases further, the $2s$ final ionic state becomes more probable. This tendency is expected because, as the photon energy becomes larger, the sudden approximation becomes more appropriate and R becomes a measure of the overlap between the hydrogenic $2s$ final state and the correlated

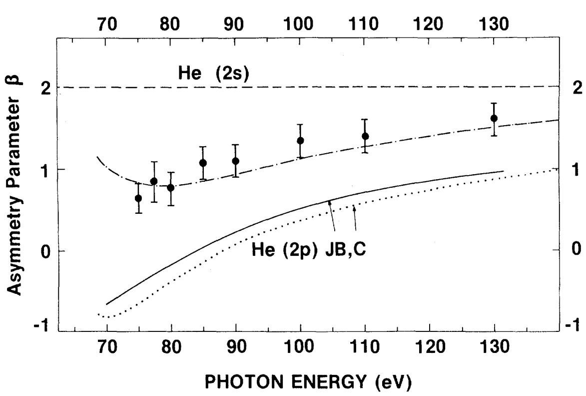

FIG. 2. The asymmetry parameter β vs photon energy. Present measurements, circles. Calculation of β_{2p} from Ref. 8, solid curve. Present calculation of β_{2p}, dotted curve. Asymmetry parameter $\beta_{2s} = 2$, dashed line. Calculated value of β with $\beta_{2s} = 2$, the present calculation of β_{2p}, and the calculated cross section from Ref. 9 for σ_{2s} and σ_{2p}, dot-dashed curve.

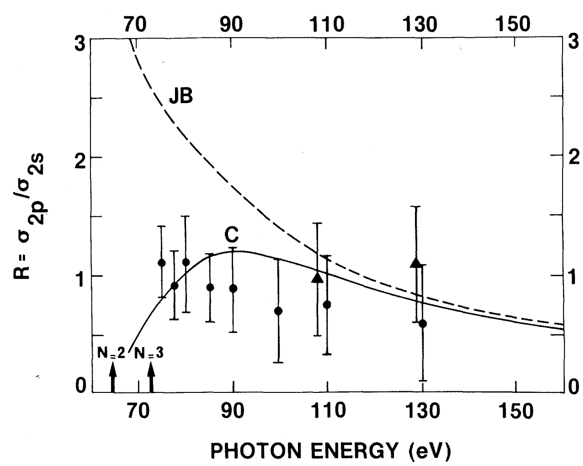

FIG. 3. The value of $R = \sigma_{2p}/\sigma_{2s} = (2-\beta)/(\beta - \beta_{2p})$ vs photon energy (circles). Measurements from Ref. 4 are shown as triangles. Theoretical values of R are obtained from Ref. 8 (dashed curve) and from Ref. 9 (solid curve). The ionization plus excitation thresholds for the $n = 2$ and $n = 3$ final states of the helium ion are shown as the vertical arrows.

initial state.

Near threshold, where the difference between the calculations is greatest, the present results are in closer accord with the many-body calculations[9] than the close-coupling calculations.[8] Channels with $n \geq 3$ have not been included in either the many-body calculations or the close-coupling calculations. It is near threshold where these other channels would have the largest effect. We have also found that, if the values of β_{2p} of Ref. 8 are used, together with our measured β, the value of R is 10%–20% larger and is in still closer accord with the many-body calculations.[9]

In this paper, we have described measurements of the ratio of the partial cross sections for photoionizing helium and exciting the ion to the $2p$ or $2s$ state obtained by the technique of ARPES. These measurements probe some of the subtleties of the Coulomb interaction in a simple three-body system and suggest that close to the $n=2$ threshold the many-body calculations[9] are in closer agreement with these measurements than the close-coupling calculations.[8]

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