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PHOTOIONIZATION OF ATOMS

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I. PHOTOIONIZATION OF ATOMS: EXPERIMENT

A. Introduction

There were two main goals in the experimental study of photoionization. One was to provide accurate data on the results of photon-atom collisions. Studying, for example, the absolute probability for ejecting electrons from specific orbitals and determining their angular distributions. Also of interest was the probability for one photon to eject two or more electrons. The other goal was to make measurements of specific interactions that would provide sensitive tests for the various theoretical approximations used in calculating photoionization cross sections. To achieve these two goals care was taken in the selection of the various experiments and in the use of the most appropriate and sophisticated equipment. For example, the techniques of Photoelectron Spectroscopy, Photoionization - Mass Spectrometry, and Synchrotron radiation were used in many of the experiments.

The following measurements and results were achieved under this program.

B. Measurement of the $^2p_{3/2}:^2p_{1/2}$ Branching Ratio in the Rare Gases.

Previous measurements of this ratio had been made by the present investigators in certain spectral regions. These measurements suggested that the ratio may vary rapidly in regions of autoionizing structure. If this were so then the results could provide an excellent test for the need to include configuration interaction into theoretical models.

To investigate this effect further it was necessary to obtain a continuously tunable source of vacuum ultra-violet radiation, i.e., synchrotron radiation. For this purpose an existing photoelectron spectrometer system in this laboratory was modified to be compatible with the storage ring and

horizontally dispersing normal incidence monochromator at the synchrotron radiation facility Tantalus 1 at the Physical Sciences Laboratory of the University of Wisconsin in Stoughton, Wisconsin. This involved the addition of a sealed 1000 Å aluminum window to separate the high pressure photoelectron spectrometer chamber (10^{-4} torr) from the synchrotron (10^{-10} torr), two turbomolecular pumps for clean pumping of the main chamber and window cavity, a sorption rough pumping system and a pair of plain gold-coated mirrors to re-focus the divergent radiation from the monochromator onto the spectrometer target region.

The autoionizing level which was studied was the $5s5p^6p(^1P_1)$ resonance of Xe which occurs at a wavelength of 591.77 Å (20.951 eV). As the photon wavelength was scanned through this resonance the branching ratio was indeed found to depart dramatically from its usual value of 1.55. The experimental data followed closely the theoretical expression due to Starace, which arises from a description of the configuration interaction between the discrete state and the continuum and has two adjustable parameters. (See Bibliography, Journal Articles 2 and 5.)

C. Angular Distribution of Atomic Oxygen and Cesium

There is a lack of experimental photoionization data for open shell atoms. This is a serious drawback for the development of theory. Thus, measurements of the angular distributions of photoelectrons from atomic oxygen were initiated. The angular distribution of photoelectrons from atomic oxygen has been successfully measured for the wavelengths 584Å and 736Å. The technique used involved a rotatable vacuum uv polarizer and a fixed electron energy analyzer. Knowing the degree of polarization and the angle between the electric vector and the direction of the ejected electron, we were able to determine

the angular distribution of the photoelectrons. This technique is extremely accurate because it eliminates any systematic errors caused by unknown electric fields (e.g. due to contact potentials) and stray magnetic fields. In fact, the results, at $584\text{\AA}$, contradicted findings by another group and caused them to reinvestigate their results. It turned out that they had serious problems with contact potentials, but they now agree with our findings. Thus, whereas their original value disagreed with the theoretical predictions, there is now excellent agreement with the theoretical results of Starace et al. at $584\text{\AA}$ (See Bibliography, Journal Article 4). At $736\text{\AA}$ the angular distribution of the photoelectrons is influenced by the proximity of autoionizing resonances in the ionization continuum.

Measurements of the angular distribution of electrons from Cesium were started because of theoretical predictions that the angular distribution of the outer s-subshell electron deviated from the expected cosine squared relation given by the single electron model (that is, a β parameter equal to 2). The more sophisticated theory (See Bibliography, Journal Article 13), considered the spin-orbit interaction and found that this had a large effect on the β parameter near the photoionization threshold (specifically, in the region of the "Cooper Minimum"). Preliminary results in this program have provided the first direct measurements that this is in fact the case. Work is continuing in this area to refine the results.

D. Multiple Photoionization of the Rare Gases

We have made preliminary measurements of the ratio of double to single photoionization of the rare gases. However, we believe there may be systematic errors caused by the response of the detector to ions of different charge. Thus, we have made some major changes in our mass spectrometer and its gas

handling system to allow us to overcome any discriminatory effects. It should be noted that all previous measurements quoted in the literature assume a constant detector response to the variously charged ions. We are planning a program to study the detector response to ions of single and multiple charges. This will allow us to make unambiguous measurements of the multiple photoionization cross sections.

E. Total Photoionization Cross Sections

1. Closed-Shell Atoms. The total photoionization cross sections of the rare gases have been measured with an accuracy of $\pm 3\%$. However, because it is important to know these cross sections with as high a degree of accuracy as possible we embarked on a program to reduce the errors to $\pm 1\%$.

The three primary measurements that must be made accurately are (i) the gas pressure, (ii) the length of the ion chamber electrodes, and (iii) the ion currents i_1 and i_2 to each electrode. We have now calibrated an MKS Baratron pressure gauge against a precision oil manometer to an accuracy of 0.1% in the pressure range of interest. The precision oil manometer was similar to that used by N.B.S. The length of the ion chamber electrodes can easily be measured to an accuracy of $\pm 1\%$. However, the practical length of the double ion chamber electrodes is measured from the entrance slit of the ion chamber to its central position and from the central position to the rear termination grid. These two lengths should be equal. These distances have been determined now to an accuracy of $\pm 0.5\%$. To measure the ion currents we purchased two Keithley 642 electrometers, which approach the state-of-the-art for accurate current measurements in the 10^{-12} Ampere range. With these new electrometers we have been able to obtain an accuracy in the current ratios

to better than $\pm 1\%$ using the technique of reversing the electrometers and taking an average of the resulting current ratios.

We have made preliminary cross section measurements of Ar as a function of pressure. A sensitive test of the operation of the double ion chamber is that the cross section should remain constant for all values of the ratio i_1/i_2 . This test is especially sensitive at low gas pressure when i_1/i_2 falls below 2. We see less than a $\pm 1\%$ change in the cross section for i_1/i_2 varying between 2 and 160. This is an extremely large range. for i_1/i_2 lying between 1.5 and 2 we have about a 5% change. This indicates some end effect problems. To investigate the end effect problems we have also developed a filter valve that allows a simple mounting of a gas tight window made from a thin film of Al about 1500 Å thick. This will allow measurements to be made either through a windowless slit (flow system) or through the gas tight window (static system). The results will indicate the presence of systematic errors caused by a flow of gas escaping through the windowless slit.

2. Open-Shell Atoms. Our choices for open shell atoms to study were atomic oxygen and chlorine. Both of these gases have been studied theoretically by Starace. Because of the problems in obtaining the absolute number densities of these gases we confined the investigation to measurements of relative cross sections.

The relative photoionization cross section of a gas can be best measured by observing the appropriate ion using a mass spectrometer and measuring the ratio: (ions)/(photons incident). Our present measurements have been made using a magnetic sector mass spectrometer and a time-of-flight (T.O.F.) mass spectrometer.

The magnetic instrument was used to measure the cross section for dissociative ionization of molecular oxygen. This is a necessary measurement in order to obtain accurate cross sections of atomic oxygen. We prepared oxygen atoms by flowing O_2 through a microwave discharge. The products that enter the mass spectrometer from this discharge are primarily $O_2 + O$ in their respective ground states, along with some excited O_2 molecules. The relative cross sections of atomic oxygen are obtained by direct ionization of O , that is $h\nu + O \rightarrow O^+ + e$. However, at the shorter wavelengths the photon energy is great enough to cause dissociative ionization of O_2 , namely $h\nu + O_2 \rightarrow O + O^+ + e$. To correct for this false production of O^+ ions it is necessary to know the cross section for dissociative ionization. These measurements have been completed and published. Relative cross sections for atomic oxygen have been made in our laboratory between 200 and 600Å. We are now in the process of extending the data to the photoionization threshold where considerable autoionizing lines exist. To observe these lines we require a continuum light source. Thus, these measurements will be continued at the Brookhaven National Light Source facility on Long Island. We have been allocated time on their beam line during January and February, 1982.

We have established the technique for producing Cl by passing a mixture of $Cl_2 + He$ through a microwave discharge. We are working in this direction to obtain relative cross sections of Cl.

F. Branching Ratios of 2s/2p in Helium

We have produced the helium ion in its $n=2$ excited state by the process of photoionization, namely,

The excited ions in the $\text{He}^+ 2p(^2P)$ state decay rapidly to the $n=1$ level of the ion by emission of radiation of wavelength $304\text{\AA}$. The metastable $\text{He}^+ 2s(^2S)$ state, although much longer lived, can be quenched with subsequent emission of $304\text{\AA}$ radiation. By measuring this fluorescent radiation as a function of the incident photon energy we have been able to obtain the cross sections for populating the $2s$ and $2p$ states of He^+ (see Bibliography, Journal Article 21).

Because of the high helium pressure in our fluorescence cell the metastable state was completely quenched. Thus, our observations were of the total fluorescence from both the $2s$ and $2p$ levels of the ion. However, at lower pressure the fluorescence occurs from only the $2p$ state. Thus, it was possible to extract the cross sections for each state separately.

A surprising and unexpected result was our observation of strong autoionizing structure overlying the continuum fluorescence. This represents an exciting new development. This structure arises from the discrete Rydberg levels ($sp, 3n+$) leading to $\text{He}^+ (n=3)$. However, in total absorption cross section studies these states are extremely weak and thus their profiles are poorly determined. Although these Rydberg levels can autoionize into either the $n=2$ or $n=1$ level of the ion, theoretical studies predict that the most favorable transition is into the $n=2$ continuum. This has never been observed experimentally before the present observations. The magnitude of the perturbing effect of the discrete levels on the continuum cross will clearly affect any comparison with theoretically calculated continuum cross sections.

G. Review Articles

The results obtained during the present program have generated numerous review articles on photoionization as can be seen in the bibliography.

II. PHOTOIONIZATION OF ATOMS: THEORY

A. Introduction

The theory program has emphasized the development of new theoretical descriptions of atomic photoionization processes. The main criterion for our choice of problems has been that the processes studied were not well understood theoretically at the time our study commenced. A major additional influence on our choice of photoionization processes to be studied has been the pioneering experimental work carried out by Samson under this contract. Thus, we have developed a new theoretical description of open-shell atom photoionization processes which should be equivalent in accuracy to the closed-shell atom random phase approximation (see Bibliography, Journal Articles 16 and 22). We have developed a new theoretical description for hydrogen atoms in strong magnetic fields which automatically takes into account much of the so-called " λ -mixing" effects and gives rigorous lower and upper bounds on the lowest energy levels (see Bibliography, Journal Article 12). We have used an adiabatic approximation in hyperspherical coordinates to obtain results for the He photoionization cross section which agree with the accurate measurements of Samson to within 1% at threshold (see Bibliography, Journal Article 19). We have developed a graphical method for evaluating spin-orbit matrix elements within a Hartree-Fock basis and used this method to calculate the effect of final state spin-orbit interactions on photoelectron angular distributions of s-subshells (see Bibliography, Journal Articles 8, 13, 17, and 18 and Review Article 2). We have developed a new theoretical parameterization of the behavior of photoelectron partial cross sections and branching ratios in the neighborhood of a resonance and used the formulas to fit measurements of Samson (see Bibliography, Journal Articles 2 and 5). In collaboration

with Professor Steven T. Manson at Georgia State, we have carried out an extensive study of the general behavior of photoelectron angular distributions for open-shell atoms, particularly for s-subshell ionization (see Bibliography, Journal Articles 3, 14, and 15 and Review Article 7). Details of these major works carried out under this five-year DOE contract follow. A Bibliography of all work carried out during this period is given in Section III.

B. Theory of Photoionization of Open-Shell Atoms.

The theory of atomic photoionization has progressed rapidly in the past ten years in response to newly-available experimental measurements in the vacuum ultraviolet wavelength range. For the most part, however, both experiment and theory concentrated on the study of closed-shell atoms since these are the easiest to obtain in the laboratory and since the spherical symmetry of closed-shell systems simplifies the theoretical effort required. It remains true today that approximately 75% of the elements of the periodic table are unstudied in the atomic state (except for independent particle model calculations).

Theoretical understanding of photoionization cross sections for closed-shell atoms is currently based on the Random Phase Approximation (RPA). In addition to the usual final state interactions that are treated by Hartree-Fock or close-coupling calculations, the RPA also treats the effects due to excitations of virtual pairs of valence electrons in both the initial state and the final state. A major result of such virtual excitations is the reduction of the effective strength of final state interactions. Experience has shown that the particular electron correlations included in the RPA for closed-shell atoms are necessary to obtain good agreement of theoretical calculations with experimental data. In particular, the importance of these electron

correlations has been confirmed for closed shell atoms by other theoretical methods. Theoretical understanding of the influence of electron correlations on the photoionization cross sections for open-shell atoms, on the other hand, is less developed. This is due to the greater theoretical difficulty of dealing with atoms which are not spherically symmetric and which thus have a greater number of final state channels. While RPA theories have been developed to treat open-shell atoms, these have been given in the form of matrix or integral equations which require the use of large numbers of basis functions for their solution.

We have developed recently a random phase approximation for transition matrix elements in a way that is independent of whether one is dealing with a closed- or an open-shell atom (see Bibliography, Journal Articles 16 and 22). We begin by calculating the first order transition matrix for a general (open- or closed-shell) atom using a graphical method. This transition matrix may be used to calculate matrix elements of a general one-body operator having rank λ in orbital space and σ in spin space. In particular, it may be used to calculate matrix elements of the electric dipole operator (having $\lambda = 1$ and $\sigma = 0$), from which one may obtain the photoionization cross section. The graphical evaluation of the first order transition matrix greatly simplifies the treatment of antisymmetrization and of angular momentum algebra and in addition affords an insight into the physical processes involved that is similar to that afforded by the diagrams of ordinary many-body perturbation theory.

In evaluating the first order transition matrix we follow Chang and Fano in assuming that the ground state may contain a single pair of virtually excited orbitals. While our graphical procedure allows us to evaluate the

interactions of the virtually excited orbitals with the residual ion, such interactions are exceedingly complex. These particular interaction diagrams are evaluated approximately. We assume, firstly, that when the virtually excited electrons interact with the residual ion there is no exchange of orbital or spin angular momentum, and, secondly, that the Pauli Principle is ignored. Since we find that these approximations give the ordinary RPA equations in the closed shell case, we define our RPA by these approximations whether we are dealing with either an open- or a closed-shell atom.

As a result of our RPA we find that the first order transition matrix for an atom having N final state channels is determined by a set of N final state radial functions and N' initial state radial functions which satisfy $N + N'$ coupled differential equations. (The relation of N' to N depends on the particular atom studied.) Large numbers of basis functions are thus not needed in a calculation by this method. The $(N + N')$ coupled differential equations reduce to familiar forms in the following limiting cases: (1) When initial state correlations are ignored we obtain the N coupled differential equations of the Close-Coupling Approximation; (2) When the atom has only closed shells, $N = N'$ and we obtain the $2N$ coupled differential equations of the Chang-Fano version of the RPA.

We are currently using our open-shell RPA to evaluate the atomic transition matrices needed to calculate the photoionization cross section of atomic chlorine. Photoelectron angular distributions for atomic chlorine will also be calculated. Our first results for the $2S$ photoionization channels show length and velocity dipole matrix elements to agree within 5% over a range of 30 eV above threshold.

C. H-Atom in a Strong Magnetic Field.

We have developed recently an adiabatic approximation in spherical coordinates for calculating the energies and wavefunctions for the lowest states of atomic hydrogen in a large uniform magnetic field (see Bibliography, Journal Article 12). The key simplification of this adiabatic approach is the representation of the angular part of the electron's wavefunction by a single oblate spheroidal angle function. This angle function depends parametrically on the radial coordinate r in such a way that at large distances it represents implicitly a linear combination of a large number of spherical harmonics. Thus the oblate spheroidal angle function implicitly takes into account much of the interaction between states of differing orbital angular momenta (i.e., ℓ -mixing) that occurs owing to the quadratic Zeeman part of the Hamiltonian. Furthermore, the use of spherical coordinates insures a good description of the electron's wavefunction near the origin, where optical absorption takes place.

We have shown that our adiabatic approach using oblate spheroidal coordinates can provide both rigorous upper and lower bounds on the lowest hydrogenic energy levels of a given symmetry in a uniform magnetic field. We have calculated such bounds for the $1s$ and $2p$ ($m_\ell = 0, \pm 1$) levels of hydrogen for fields up to 10^{11} Gauss. For magnetic fields in the range $0 \leq B \leq 10^9$ Gauss we achieve very tight bounds on the energy levels and excellent agreement with variational and eigenfunction expansion calculations. In addition, we obtain accurate wavefunctions comprising a numerically determined radial wavefunction and an analytically known angle function (the oblate spheroidal angle function).

This oblate spheroidal coordinate basis for a hydrogenic atom in a uniform magnetic field was used to calculate the energy levels and oscillator strengths

for the $2 \leq n \leq 35$ odd parity states of hydrogen in a uniform magnetic field B of order 10^5 Gauss (G. L. Webster, Ph.D. Thesis, U. Nebraska 1981). A basis of adiabatic approximation states was used to diagonalize the magnetic interactions (which introduce non-adiabatic coupling terms). In this adiabatic approximation the angular part of the electron's wavefunction is represented by the oblate spheroidal angle function $g_{m\nu}(c, \theta)$. Here m is the magnetic quantum number, ν is an index which corresponds to the orbital angular momentum ℓ in the limit of zero magnetic field, and c is a parameter dependent on the magnetic field strength B and the radial coordinate r . Also in the adiabatic approximation, the radial part $h_{n\nu}(r)$ of the electron's wavefunction is determined by the oblate spheroidal eigenvalues $U_{m\nu}(c)$, which enter the radial hydrogenic Schrödinger equation as an effective angular momentum having the limiting value $\nu(\nu + 1)$ when $r = 0$ or when $B = 0$. The first five odd parity potentials $U_{m\nu}(c)$ for $m = +1$ were calculated. Using these adiabatic states — i.e., a basis of wavefunctions, $h_{n\nu}(r) g_{m\nu}(c, \theta)$ for odd $\nu = 1$ to 7 — all non-adiabatic coupling matrix elements were evaluated and used to obtain the energy spectrum, wavefunctions, and oscillator strengths for principal quantum numbers $2 \leq n \leq 35$. For magnetic fields B in the range $10^4 \leq B \leq 10^5$ Gauss we found that for levels $n \lesssim 12$ the adiabatic representation is very accurate. Inclusion of non-adiabatic coupling terms does not significantly change either the adiabatic energy eigenvalues or the adiabatic eigenfunctions. Within 3-4 units of n above $n = 12$, however, the non-adiabatic coupling terms become very important and there is thus extensive mixing of the adiabatic states. This rapid onset of the non-adiabatic perturbation is due on the one hand to the rapidly decreasing separation between the adiabatic levels ($\propto 1/n^3$) and on the other to the rapidly increasing radii

of the adiabatic states ($\propto n^2$), both of which tend to increase the coupling matrix elements.

We have recently begun the study of He and of H^- in a strong uniform magnetic field. The theoretical difficulty is the simultaneous treatment of both electron correlation effects and strong magnetic field effects. We have developed an adiabatic approach that combines our oblate spheroidal coordinate method for a hydrogenic atom in a uniform magnetic field with Macek's and Fano and Lin's hyperspherical coordinate method for treating two electron atoms. We have found that the two-electron Schrodinger equation in hyperspherical coordinates is modified only slightly in the presence of a uniform magnetic field: namely, the one electron total angular momentum operators (which normally have eigenvalues $\ell(\ell + 1)$) are replaced by operators dependent on the magnetic field whose eigenvalues are the oblate spheroidal eigenvalues in an adiabatic approximation. We are currently solving our adiabatic equations for the energy levels and wavefunctions of low-lying states of helium and of H^- .

D. He Photoionization in Hyperspherical Coordinates

Our calculation of the He ground state photoionization cross section using the hyperspherical coordinate method has given remarkably accurate results near threshold (see Bibliography, Journal Article 19). We calculated the dipole amplitude for the process

The radial ground state two electron wavefunction was calculated by solving for the lowest energy level in the first 1S_0 adiabatic potential. When the diagonal non-adiabatic coupling terms are included, we obtain a ground state

energy of -2.8952 a.u., which compares well with Pekeris's essentially exact non-relativistic energy of -2.9037 a.u., and is considerably improved over the Hartree-Fock energy of -2.8617 a.u. (Note that Eq. (1) indicates only the dominant configurations in the ground state and in the final state. In the hyperspherical coordinate method, the wavefunctions corresponding to the adiabatic states already include extensive configuration interaction.) The final state two electron wavefunction was taken to be the adiabatic state calculated in the lowest 1P_1 potential at the photon energy of interest. Our photoionization cross section calculated using these initial and final adiabatic wavefunctions is in essentially exact agreement with the measurements of Samson. At 1 a.u. above threshold we are approximately 10% below both experiment and the close-coupling calculations of Jacobs.

We had expected that once coupling to the $n = 2$ and $n = 3$ "+" channels were included in our calculations, agreement with experiment at higher energies would be improved. Extensive unpublished numerical investigations carried out here by D. L. Miller indicate however that many more adiabatic channels must be taken into account near the origin, where the hyperspherical potentials are too repulsive. A possible solution to this theoretical difficulty is outlined in a contract proposal entitled "Hyperspherical Coordinate Theory of Two-Electron Atomic Processes," by J. Macek and A. F. Starace, which has been submitted to D.O.E. in September 1981.

E. Spin-Orbit Effects in Atomic Photoionization.

We have derived a new form for the matrix element of the two-particle mutual spin-orbit interaction in the Breit-Pauli approximation (see Bibliography, Journal Article 8 and Review Article 2). The complexity of standard

tensor-operator expansion techniques is obviated by suitably decomposing the mutual spin-orbit interaction into products of spin and orbital angular momentum operators. Graphical procedures have been developed to facilitate the calculation of these matrix elements between arbitrary atomic configurations in LS-coupling and in jj-coupling. The significance of this work is that it provides a convenient, but realistic, means of treating spin-orbit effects perturbatively. Apart from the obvious application of the new procedure in accurate spectroscopic studies, we developed it primarily for application to the study of spin-orbit interaction effects in atomic photoionization.

We have used the graphical procedures mentioned above to evaluate the effect of final-state spin-orbit interactions on the photoionization of the 6s electron in cesium (see Bibliography, Journal Article 13), i.e., on the process

Our results for the photoionization cross section, photoelectron angular distribution asymmetry parameter, and photoelectron spin polarization are quite competitive with the results of relativistic Dirac-Fock calculations. The predicted sharp variation of the β parameter just above threshold has been measured by Professor Samson in this laboratory. (The variation of β from the non-relativistic value 2 is due to interference between the $J = 3/2$ and $J = 1/2$ final state channels.)

Similar calculations were carried out for photoionization of the 5s-subshell in xenon, i.e., for the process:

(See Bibliography, Journal Article 17.) Non-relativistically, of course, only the 1P channel is allowed and the angular distribution asymmetry parameter is constant with value 2. Dehmer, however, has measured β at 304Å for process (3) and found a value $\beta = 1.4 \pm 0.1$. Dill interpreted this deviation of β from the value two as due to the interference between the allowed 1P channel and the spin-orbit-populated (forbidden) 3P channel. We have calculated the β -parameter for the 5s subshell of xenon including spin-orbit interactions between the two channels in process (3) as well as spin-orbit and electron correlation interactions resulting in inter-channel coupling with the 5p-subshell channels. Our results are in qualitative agreement with experiment in that we find a drop in β to the value 1.8 near the cross section minimum for the 5s-subshell. Our result is, however, substantially higher than the measured value of 1.4 and also substantially higher than the minimum value of zero obtained by Johnson and Cheng using the relativistic random phase approximation, which now sets the standard for closed-shell atom photoionization processes.

The reason for the success of our calculations for cesium and the inadequacy of our calculations for xenon is understood by us as follows. In cesium the spin-orbit interaction serves to split the fine structure components (i.e., $J = 3/2$ and $J = 1/2$) of a non-relativistically allowed transition (cf. (2)). In xenon, however, the spin-orbit interactions serve to populate a non-relativistically forbidden (i.e., 3P) transition (cf. (3)). Forbidden transition intensities are notoriously difficult to calculate accurately and this is our explanation for the poor quantitative accuracy of our calculation. We do, however, obtain the correct qualitative behavior of the xenon 5s β parameter. We also note that the minimum value reached by β in our calculations is a very

sensitive function of the cancellation between real and imaginary dipole amplitudes for both the $1P$ and $3P$ transitions. Despite the poor quantitative agreement with experiment, our calculation nevertheless provides detailed information on the role of spin-orbit interactions and of the importance of a fully relativistic treatment when calculating forbidden transition probabilities.

In a third calculation (see Bibliography, Journal Article 18) we extended our previous ab initio theoretical calculations of the Cs 6s photoionization cross section to include interchannel interactions between the 6s and 5p subshells over the energy region from threshold up to 1 a.u. (27.2 eV) above. We found that above the near threshold minimum the cross section is dominated by $5p \rightarrow 5d$ resonance transitions. No experimental data exist for this energy region.

Our previous ab initio theoretical calculations of the cross section, photoelectron angular distribution, and photoelectron spin polarization resulting from photoionization of the 6s electron in cesium started from a basis of non-relativistic Hartree-Fock wavefunctions and treated final-state spin-orbit interactions in the Breit-Pauli approximation exactly. Only $6s \rightarrow \epsilon p$ transitions were considered over the photoelectron energy range $0 \leq \epsilon \leq 1$ a.u. Our results agreed with experimental measurements just above threshold, but our cross sections beyond 2 eV above threshold failed to rise as rapidly as the experimental measurements.

Our more recent calculations included the following final state channels:

$$\text{Cs}5p^6 6s(^2S_{1/2}) + h\nu \rightarrow \text{Cs}^+5p^6(^1S_0) \epsilon p(^2P_{3/2,1/2}) \quad (4)$$

$$\rightarrow \text{Cs}^+5p^5 6s(^3P) \epsilon d(^2P_{3/2,1/2}) \quad (5)$$

$$\rightarrow \text{Cs}^+5p^5 6s(^1P) \epsilon d(^2P_{3/2,1/2}) \quad (6)$$

The final state $J = 3/2$ and $J = 1/2$ channels, of course, do not interact. For each value of J , however, essentially all final state electrostatic and spin-orbit interactions were included. For photoelectron energies $\epsilon > 0.3$ a.u. our calculated cross section for the $6s \rightarrow \epsilon p$ transition rises rapidly under the influence of the $5p \rightarrow 5d$ resonance transitions, which have large oscillator strengths. We have not given any quantitative predictions in the resonance region since the resonances induce such rapid oscillations in our calculations that we do not have a sufficiently fine energy mesh to describe them. Nevertheless, we expect the shapes of the discrete oscillator strength distributions to be reflected in the $6s \rightarrow \epsilon p$ cross section in the resonance region. Above the threshold of the d-channels, i.e., for photoelectron energies $\epsilon > 0.6$ a.u., our predicted $6s$ cross section decreases smoothly from a value of approximately 2 Mb. Most of this oscillator strength in the $6s \rightarrow \epsilon p$ channel is also borrowed from the $5p \rightarrow \epsilon d$ channels.

F. Photoelectron Branching Ratios in the Vicinity of a Resonance.

Theoretical formulas have been derived to describe the behavior of partial cross sections and branching ratios in the neighborhood of an isolated resonance. We find that the partial cross sections have a Fano-type line shape within a resonance and that the ${}^2P_{3/2}:{}^2P_{1/2}$ photoelectron branching ratio in the rare gases oscillates once below and once above its value outside the resonance (see Bibliography, Journal Article 5). The theoretical formulas derived were fitted to the experimental measurements of Kemeny and Samson for the ${}^2P_{3/2}:{}^2P_{1/2}$ branching ratio for the process

in the neighborhood of the autoionizing resonance $\text{Xe} 5s^2 5p^6 ({}^1P_1)$. The fitted

theoretical curve predicts that the $^2P_{3/2}:^2P_{1/2}$ branching ratio has a maximum value of 8.8 within the resonance, which is almost six times the nearly constant value of 1.55 found outside any resonance (see Bibliography, Journal Article 2).

G. Non-Relativistic Open-Shell Atom Photoelectron Angular Distributions

1. p-Subshells. Photoelectron angular distributions were calculated for the outer p-subshell of the halogen atoms F, Cl, Br, and I, which have the ground state configuration $np^5(^2P_{1/2})$, and for the chalcogen atoms O, S, Se, and Te, which have the ground state configuration $np^4(^3P_{2,1,0})$. The LS-coupling, angular momentum transfer theory of Dill, Starace, and Manson was used. We found that the effects of anisotropic interactions on the photoelectron angular distribution do not keep increasing with increasing atomic number but seem to peak in the second row of the periodic table (see Bibliography, Journal Article 15).

2. s-subshells. It has been shown theoretically that the photoelectron angular distribution of s electrons in an open-shell atom having the configuration ns^2np^q is not described by the asymmetry parameter $\beta = 2$, as predicted by more approximate theories, but has dramatic variations with energy even within LS-coupling. Calculations of β in Hartree-Fock approximation were carried out for the 3s subshell in atomic Cl using the LS-coupling angular momentum transfer theory of Dill, Manson, and Starace. We computed the angular distribution of photoelectrons resulting from the process

The simple theoretical prediction that $\beta = 2$ (corresponding to a $\cos^2\theta$ angular distribution, where θ is measured from the axis of linear polarization of

the incident light) derives from the assumption that the term structure of the ion core (i.e., $1,^3P$) and of the final state (i.e., 2D , 2P , 2S) does not influence the dynamics of reaction (7). Our calculations for β indicate however that this term structure has an important influence on the dynamics of reaction (7). We find that, firstly, the two groups of photoelectrons corresponding to the $1,^3P$ ion core term levels have different angular distributions at any given photon energy, and secondly, that for each group of photoelectrons β varies as a function of photon energy between the values $\beta \approx 0$ (corresponding to an isotropic angular distribution) and $\beta \leq 2$ (corresponding to a $\cos^2\theta$ angular distribution). Similar, though less pronounced, results were found also for the photoelectron angular distribution for the 3s-subshell of atomic aluminum (see Bibliography, Journal Articles 3 and 14).

H. Review Articles

During the five years of DOE support a number of theoretical review articles were written, as listed in the Bibliography. Of particular mention are, firstly, the review of the theory of atomic photoionization to be published in the Handbuch der Physik in 1982, and, secondly, the analysis of s-subshell photoelectron angular distributions to appear in Review of Modern Physics, also in 1982.

III. BIBLIOGRAPHY

A. Review Articles

1. J. A. R. Samson, ULTRAVIOLET RAYS, in The World Book Encyclopedia 1979.
2. K.-N. Huang, GRAPHICAL EVALUATION OF RELATIVISTIC MATRIX ELEMENTS, Rev. Mod. Phys. 51, 215 (1979).
3. A. F. Starace, TRENDS IN THE THEORY OF ATOMIC PHOTOIONIZATION, Applied Optics 19, 4051 (1980).
4. J. A. R. Samson, ANGULAR DISTRIBUTIONS AND CROSS SECTIONS IN THE VACUUM UV REGION in Electron Spectroscopy: Theory, Techniques, and Applications, C. R. Brundle and A. D. Baker, eds. (Academic Press, New York, 1981), Vol. 4, pp. 361-396.
5. J. A. R. Samson, PHOTOIONIZATION-EXPERIMENTAL, Handbuch der Physik, Vol. 31, Edited by W. Mehlhorn (Springer-Verlag, Berlin, 1982).
6. A. F. Starace, THEORY OF ATOMIC PHOTOIONIZATION, Handbuch der Physik, Vol. 31, Edited by W. Mehlhorn (Springer-Verlag, Berlin, 1982).
7. S. T. Manson and A. F. Starace, PHOTOELECTRON ANGULAR DISTRIBUTIONS: ENERGY DEPENDENCE FOR s-SUBSHELLS, Rev. Mod. Phys. (April 1982).

B. Scientific Journal Articles

1. A. F. Starace and L. Armstrong, Jr., PHOTOIONIZATION CROSS SECTIONS FOR ATOMIC CHLORINE USING AN OPEN-SHELL RANDOM PHASE APPROXIMATION, Phys. Rev. A 13, 1850 (1976).
2. P. C. Kemeny, J. A. R. Samson, and A. F. Starace, MEASUREMENT OF THE XENON $\sigma_{3/2}:\sigma_{1/2}$ BRANCHING RATIO WITHIN THE Xe 5s5p6p(1P_1) RESONANCE, J. Phys. B 10, L201 (1977).
3. A. F. Starace, R. H. Rast, and S. T. Manson, PHOTOELECTRON ANGULAR DISTRIBUTIONS OF s-ELECTRONS IN OPEN-SHELL ATOMS, Phys. Rev. Letters 38, 1522 (1977).
4. J. A. R. Samson and W. H. Hancock, ANGULAR DISTRIBUTION OF PHOTOELECTRONS FROM ATOMIC OXYGEN AT 736Å AND 584Å, Phys. Letters 61A, 380 (1977).

5. A. F. Starace, BEHAVIOR OF PARTIAL CROSS SECTIONS AND BRANCHING RATIOS IN THE NEIGHBORHOOD OF A RESONANCE, Phys. Rev. A 16, 231 (1977).
6. K. N. Huang, LAGRANGIAN MULTIPLIERS IN FROZEN CORE HARTREE-FOCK CALCULATIONS, Phys. Letters 64A, 39 (1977).
7. K. N. Huang, LAGRANGIAN MULTIPLIERS IN FROZEN CORE DIRAC-FOCK CALCULATIONS, Phys. Letters 67A, 113 (1978).
8. K. N. Huang and A. F. Starace, GRAPHICAL APPROACH TO THE SPIN-ORBIT INTERACTION, Phys. Rev. A 18, 354 (1978).
9. E. T. Arakawa, M. W. Williams, and J. A. R. Samson, POLARIZATION BY GRATINGS USED AT GRAZING INCIDENCE, Appl. Optics 17, 2502 (1978).
10. G. Wendin and A. F. Starace, PERTURBATION THEORY IN A STRONG INTERACTION REGIME WITH APPLICATION TO 4d-SUBSHELL SPECTRA OF Ba AND La, J. Phys. B 11, 4119 (1978).
11. J. A. R. Samson, VACUUM ULTRAVIOLET PHOTOELECTRON SPECTROSCOPY OF ATOMS AND MOLECULES, Invited paper presented at the Australian Conference on Electron Spectroscopy, Melbourne, Australia, August 1978, J. Elect. Spectroscopy and Rel. Phen. 15, 257 (1979).
12. A. F. Starace and G. L. Webster, HYDROGEN ATOM IN A UNIFORM MAGNETIC FIELD: LOW-LYING ENERGY LEVELS FOR FIELDS BELOW 10^9 GAUSS, Phys. Rev. A 19, 1629 (1979).
13. K.-N. Huang and A. F. Starace, AB INITIO TREATMENT OF FINAL STATE SPIN ORBIT INTERACTIONS: PHOTOIONIZATION OF THE 6s ELECTRON IN CESIUM, Phys. Rev. A 19, 2335 (1979).
14. S. Shahabi, PHOTOELECTRON ANGULAR DISTRIBUTION OF THE 3s-SUBSHELL OF ATOMIC ALUMINUM, Phys. Letters 72A, 212 (1979).
15. S. T. Manson, A. Msezane, A. F. Starace, and S. Shahabi, PHOTOIONIZATION OF CHALCOGEN AND HALOGEN ATOMS: CROSS SECTIONS AND ANGULAR DISTRIBUTIONS, Phys. Rev. A 20, 1005 (1979).
16. A. F. Starace and S. Shahabi, A GRAPHICAL METHOD FOR CALCULATING FIRST ORDER TRANSITION MATRICES FOR OPEN-SHELL ATOMS IN THE RANDOM PHASE APPROXIMATION. Physica Scripta 21, 368 (1980).
17. K.-N. Huang and A. F. Starace, PHOTOIONIZATION OF THE 5s-SUBSHELL OF XENON: A MULTI-CHANNEL K-MATRIX CALCULATION INCLUDING SPIN-ORBIT INTERACTIONS. Phys. Rev. A 21, 697 (1980).
18. K.-N. Huang and A. F. Starace, ADDENDUM TO "AB INITIO TREATMENT OF FINAL-STATE SPIN-ORBIT INTERACTIONS: PHOTOIONIZATION OF THE 6s ELECTRON IN CESIUM." Phys. Rev. A 22, 318 (1980).

19. D. L. Miller and A. F. Starace, PHOTOIONIZATION CROSS SECTION FOR HELIUM IN THE HYPERSPHERICAL COORDINATE METHOD, J. Phys. B 13, L 525 (1980).
20. P. R. Woodruff and J. A. R. Samson, MEASURED CROSS SECTIONS FOR PHOTOIONIZATION OF GROUND-STATE He TO He⁺ (n=2), Phys. Rev. Letters 45, 110 (1980).
21. A. F. Starace and S. Shahabi, A RANDOM APPROXIMATION TO ONE-BODY TRANSITION MATRIX ELEMENTS FOR OPEN-SHELL ATOMS, Phys. Rev. A (in press).

C. Papers Presented at Scientific Meetings

1. A. F. Starace, BEHAVIOUR OF PHOTOELECTRON BRANCHING RATIOS ACROSS A RESONANCE, Abstracts of the Fifth International Conference on Atomic Physics, 26-30 July 1976, Berkeley, California, p. 368 (Contributed paper) (Report No. C00-2892-2).
2. S. T. Manson, A. Msezane, and A. F. Starace, PHOTOELECTRON ANGULAR DISTRIBUTIONS OF OPEN-SHELL ATOMS: TELLURIUM AND IODINE, Abstracts of the Fifth International Conference on Atomic Physics, 26-30 July 1976, Berkeley, California, p. 427. (Contributed paper) (Report No. C00-3892-3).
3. G. Webster and A. F. Starace, FINAL STATE INTERACTION EFFECTS ON THE BRANCHING RATIO OF NEON K-KL_{2,3} SHAKE-OFF TRANSITIONS, Bull. Am. Phys. Soc. 21, 1247 (1976). (Contributed paper) (Report No. C00-3892-4).
4. A. F. Starace, THE RANDOM PHASE APPROXIMATION AND THE THEORY OF ATOMIC PHOTOIONIZATION, Bull. Am. Phys. Soc. 21, 1263 (1976). (Invited paper) (Report No. C00-3892-5).
5. P. C. Kemeny, J. A. R. Samson, and A. F. Starace, MEASUREMENT OF THE XENON $\sigma_{3/2}:\sigma_{1/2}$ BRANCHING RATIO WITHIN THE Xe 5s5p⁶p(¹P₁) RESONANCE, Proceedings of the 1976 Synchrotron Radiation Users Group Meeting, 25-27 October 1976, Physical Sciences Laboratory, University of Wisconsin, Stoughton, Wisconsin. (Report No. C00-3892-6).
6. K. N. Huang and A. F. Starace, A GRAPHICAL APPROACH TO THE SPIN-ORBIT INTERACTION, Abstracts of Papers, Tenth International Conference on the Physics of Electronic and Atomic Collisions, Paris, France, 21-27 July, p. 609. (Report No. C00-2892-8).
7. A. F. Starace, S. T. Manson, and R. H. Rast, ANGULAR DISTRIBUTION OF Cl 3s → ϵ p PHOTOELECTRONS: DIRECT EVIDENCE FOR ANISOTROPIC FINAL STATE INTERACTIONS, Abstracts of Papers, Tenth International Conference on the Physics of Electronic and Atomic Collisions, Paris, France, 21-27 July 1977, p. 1196. (Report No. C00-2892-9).

C. Papers Presented at Scientific Meetings (continued)

8. K. N. Huang and A. F. Starace, PHOTOELECTRON ANGULAR DISTRIBUTION FOR THE 5s-SUBSHELL OF XENON, Bull. Am. Phys. Soc. 22, 1325 (1977). (Report No. C00-2892-10).
9. P. C. Kemeny and J. A. R. Samson, MULTIPLE PHOTOIONIZATION OF THE NOBLE GASES Ne, Ar, Kr, AND Xe IN THE 600-100Å REGION, Bull. Am. Phys. Soc. 22, 1325 (1977). (Report No. C00-2892-11).
10. A. F. Starace and G. L. Webster, ENERGY LEVELS FOR A HYDROGEN-LIKE ATOM IN A HIGH MAGNETIC FIELD, Bull. Am. Phys. Soc. 22, 1335 (1977). (Report No. C00-2892-12).
11. G. H. Rayborn, J. A. R. Samson, and P. N. Pareek, PARTIAL PHOTOIONIZATION CROSS SECTIONS FOR O₂ FROM 595Å TO 116Å, Bull. Am. Phys. Soc. 23, 1097 (1978). (Report No. C00-2892-14).
12. S. Shahabi and A. F. Starace, GRAPHICAL METHOD FOR THE CALCULATION OF ATOMIC TRANSITION MATRICES, Bull. Am. Phys. Soc. 23, 1101 (1978). (Report No. C00-2892-15).
13. G. L. Webster and A. F. Starace, HIGH RYDBERG LEVELS OF A HYDROGENIC ATOM IN A HIGH MAGNETIC FIELD, Bull. Am. Phys. Soc. 23, 1103 (1978). (Report No. C00-2892-16).
14. K. N. Huang and A. F. Starace, PHOTOIONIZATION OF THE 6s ELECTRON IN Cs, Bull. Am. Phys. Soc. 23, 1106 (1978). (Report No. C00-2892-17).
15. J. A. R. Samson, T. Masuoka, and P. Pareek, PHOTOIONIZATION MASS SPECTROSCOPY AND PHOTOELECTRON SPECTROSCOPY OF ATOMS AND MOLECULES, Abstracts of the U.S.-Japan Joint Seminar on Plasma Spectroscopy, 7-11 May 1979, Kyoto, Japan (Report No. C00-2892-19).
16. T. Masuoka and J. A. R. Samson, DISSOCIATIVE PHOTOIONIZATION, Abstracts of the 27th Annual Meeting on Mass Spectroscopy and Allied Topics 4-8 June 1979, Seattle, Washington (Report No. C00-2892-20).
17. S. T. Manson, A. Msezane, A. F. Starace, and S. Shahabi, PHOTOIONIZATION OF CHALCOGEN AND HALOGEN ATOMS: CROSS SECTIONS AND ANGULAR DISTRIBUTIONS, Abstracts of the XIth International Conference on the Physics of Electronic and Atomic Collisions, Kyoto, Japan, 29 August - 4 September 1979, pp. 16-17 (Report No. C00-2892-21).
18. K.-N. Huang and A. F. Starace, AB INITIO TREATMENT OF FINAL STATE SPIN ORBIT INTERACTION: PHOTOIONIZATION OF THE 6s ELECTRON IN CESIUM, Abstracts of the XIth International Conference on the Physics of Electronic and Atomic Collisions, Kyoto, Japan, 29 August - 4 September 1979, pp. 18-19 (Report No. C00-2892-22).

C. Papers Presented at Scientific Meetings (continued)

19. P. R. Woodruff and J. A. R. Samson, THE MEASURED RELATIVE CROSS SECTION FOR $\text{He} + h\nu \rightarrow \text{He}^+(n=2) + e^-$, Abstracts of the Division of Electron and Atomic Physics Meeting, 10-12 December 1979, Houston, Texas (Report No. C00-2892-23).
20. S. T. Manson and A. F. Starace, PHOTOELECTRON ANGULAR DISTRIBUTIONS FOR s^2p^n OPEN-SHELL ATOMS: s-ELECTRON PHOTOIONIZATION, Bull. Am. Phys. Soc. 24, 1175 (1979). (Report No. C00-2892-24).
21. D. L. Miller and A. F. Starace, CROSS SECTIONS FOR PHOTOIONIZATION AND SIMULTANEOUS EXCITATION OF HELIUM USING THE HYPERSPHERICAL COORDINATE METHOD, Bull. Am. Phys. Soc. 24, 1176 (1979). (Report No. C00-2892-25).
22. S. Shahabi and A. F. Starace, AN OPEN-SHELL RANDOM PHASE APPROXIMATION FOR ATOMIC TRANSITION AMPLITUDES, Bull. Am. Phys. Soc. 24, 1203 (1979). (Report No. C00-2892-26).
23. G. L. Webster and A. F. Starace, ENERGY SPECTRUM AND OSCILLATOR STRENGTHS FOR A HYDROGENIC ATOM IN A LARGE MAGNETIC FIELD, Bull. Am. Phys. Soc. 24, 1194 (1979). (Report No. C00-2892-27).
24. D. L. Miller and A. F. Starace, PHOTOIONIZATION CROSS SECTION FOR He IN THE HYPERSPHERICAL COORDINATE METHOD, VI International Conference on Vacuum Ultraviolet Radiation Physics, Charlottesville, Virginia, 2-6 June 1980, Extended Abstract No. II-58. (Report No. C00-2892-28)
25. P. R. Woodruff and J. A. R. Samson, PHOTOIONIZATION OF HELIUM TO $\text{He}^+(n=2)$, VI International Conference on Vacuum Ultraviolet Radiation Physics, Charlottesville, Virginia, 2-6 June 1980. (Report No. C00-2892-29)
26. J. A. R. Samson, FLUORESCENT STUDIES OF DOUBLY EXCITED STATES OF He^+ , Gordon Conference on Atomic Physics, Wolfburo, NH, July 6-10, 1981.

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4. Gary L. Webster (Ph.D. 1981).