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Photoionization of gallium at $3d-4p$ and $4s-np$ ($n=5,6$) resonances

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The simplest atoms having nonspherical symmetry are those with a single p electron in a valence shell. Of these, the group III B elements are excellent examples. As such, they form test cases for photoionization from open-shell systems. Through photoelectron-spectroscopy techniques, we have examined both partial cross sections and angular-distribution parameters for autoionization corresponding to promotion of a $3d$ electron to the $4p$ shell of gallium. The resulting dp^2 configuration gives rise to a complicated multiplet structure across which the angular-distribution parameter varies considerably. We have also looked at the simpler structure resulting from promotion of one s electron to an np level, $n=5,6$. For these cases, the multiplet structure is simpler, but the influence of the resonance on the cross section and the angular distribution is pronounced. For the $4s4p$ (3P) $5p$ resonance we find a value of $\beta=-1$ at the cross-section minimum. No calculations have been performed for this system, so we attempt a qualitative interpretation of our results based on an angular-momentum-transfer analysis.

I. INTRODUCTION

The theoretical success in handling symmetric, closed-shell systems in photoionization has been exemplary.¹ However, these accomplishments have not been matched for those atoms whose ground state contains one or more unpaired electrons with orbital angular momentum not equal to zero in an outer shell. The resultant couplings of the electrons with the core and with the departing electron lead to the presence of many channels which contribute to the ionization. The process of sorting them out is not at all simple and has been attempted in only a few cases.

Of those open-shell atoms which are accessible to measurement, the halogens have been examined most extensively.²⁻⁵ These atoms contain a single vacancy in the valence shell, and the resultant number of coupled channels is numerous. Interchannel couplings are so large that they contribute heavily to the resultant cross section.³ However, the difficulties of the calculation and discrepancy with experiment in the case of chlorine,⁶ which is especially interesting because of its proximity to argon in the Periodic Table, point out the problems associated with calculations involving open-shell systems.

The nature of the vacancy in chlorine may have a major influence on the resultant interchannel couplings. For this reason, a simpler route to take in examining the effects of the simplest nonspherical system, a lone p electron, should be the investigation of the group III B elements. Each of these has a configuration of the form $(n-1)d^{10}ns^2np$ with a single unpaired p electron in the valence shell. While the total number of states produced by the couplings is the same as for the hole in the halogens, the fact that the lone electron interacts with so few electrons within its own shell should make the theoretical

treatment simpler.

Experimentally, study of this series has been hampered by the fact that, with the exception of Tl, the metals making up this group require high temperature for vapor formation. Before the development of high-temperature metal-vapor effusive ovens as sources for photoelectron spectrometry, a detailed analysis of photoionization of these species in the gas phase was not feasible.

There are four elements making up the group III B series, Al, Ga, In, and Tl. All of these have been studied in photoabsorption,⁷⁻¹⁰ with particular attention having been devoted to the resonances associated with the excitation of a d electron or an s electron. Recently we reported^{11,12} a series of measurements on the photoionization of electrons from the d shells of gallium and indium at the autoionizing resonance $(n-1)d^{10}ns^2np - (n-1)d^9ns^2np^2$, $n=4$ for Ga and $n=5$ for In. In our studies we measured the variation of the partial cross section across the resonance for the production of a given term of the excited-state multiplet. We did this using the technique of constant-ionic-state (CIS) electron spectrometry. For a detailed analysis of the behavior of the partial cross section through the resonance and the resultant coupling with the final state of the ion, this technique is most useful. In addition to separating out the multiplet structure, this method has the advantage that coupling of the "bound" level into each of the final ionic states is differentiated. Through this scheme we can also obtain β values for the various terms of the multiplet. These dynamic parameters are much more sensitive to the individual couplings within the atom and provide additional information beyond that available from absorption spectra.

An energy-level diagram for gallium is shown in Fig. 1. The $3d-4p$ resonance decays by coupling into three ionic states $3d^{10}4s^2^1S_0$, $3d^{10}4s4p^1P$, and $3d^{10}4s4p^3P$. At the

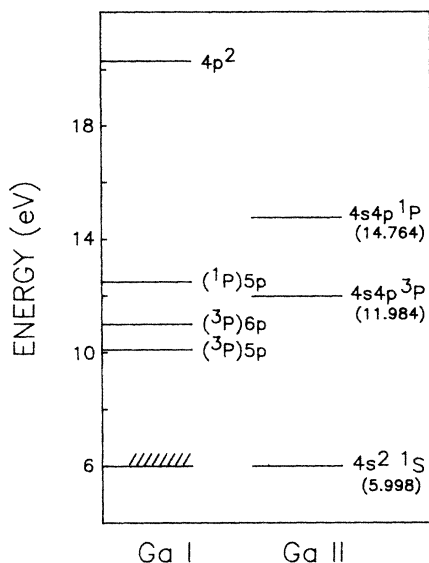


FIG. 1. Energy-level diagram for Ga I and Ga II. The solid lines for Ga I indicate the principal excitations we observe in this work. The lines for Ga II correspond to the three final ionic states.

time of our first measurements we discovered that certain general conclusions could be drawn with regard to the mixing between the autoionizing state and the continuum. In particular, the coupling between the $4p^2$ manifold and the continuum was strongest when the final ionic state had the same symmetry as the core state produced by the p^2 coupling. While looking at the partial cross sections, we also carried out a preliminary investigation of the variation of the angular-distribution parameter associated with the 1S_0 final ionic state through the resonance. As might be expected, this variation is considerable. However, no attempt was made to explain this variation in that early work or to extend the measurements to the other ionic states.

In moving from the $3d$ shell of gallium to the $n = 4$ shell, the system simplifies considerably. Autoionizing resonances correspond to the promotion of one $4s$ electron to an np level, $n \geq 4$. Assignments have been made for the $4s4p^2$ and the $4s4p5p$ configurations.^{8,9} As a target for exploration of photoionization of open-shell atoms, these states should be more amenable to theoretical analysis. Because the ionization does not involve an excitation of the inner core, it would be necessary to treat only the three outer electrons in the coupling scheme. If this can be done without including virtual core excitations, calculations should become more tractable.

In the work which follows we report measurements on the gallium atom in two regions of the spectrum. Firstly, we made angular distribution measurements of photoelectrons corresponding to the formation of each of the three possible final states of the ion for the $3d-4p$ excitation. Together with our earlier work,^{11,12} this will round out our analysis of that spectral regime. Secondly, in a first experimental look at the region corresponding to the $4s-np$ ($n \geq 5$) autoionizing resonances we report partial cross-section and angular-distribution measurements for three of these resonances. In all cases we find broad evi-

dence for the influence of channel couplings on the results. In the absence of any theoretical calculations on this system, we are unable to make quantitative identifications of all the contributions. However, we will attempt to make a qualitative interpretation of our results, which we hope will stimulate calculations on this open-shell system.

II. EXPERIMENTAL

The apparatus which we use for all measurements has been described in detail elsewhere.¹³ It will suffice to give a limited description of those parameters appropriate to the gallium experiment. Ionizing radiation from the University of Wisconsin storage ring Aladdin is dispersed in a Seya monochromator at a resolution of 1.7 \AA . This radiation falls onto a source of gallium vapor which has been generated in a high-temperature effusive furnace heated to 1100 K. Electrons from the gallium are energy analyzed in a spherical sector plate electron analyzer having a resolution of 1% and finally monitored with a channeltron detector. The initial state of gallium is either the $^2P_{1/2}$ or $^2P_{3/2}$ state. Of these the $^2P_{3/2}$ state lies above the $^2P_{1/2}$ state in energy by 0.102 eV. Thus both states will be populated at 1100 K, the $^2P_{3/2}$ state by 68%. With our monochromator bandpass of 1.7 \AA , 14 meV at 10 eV and 55 meV at 20 eV, it is possible for us to discriminate between the $^2P_{1/2}$ and $^2P_{3/2}$ levels in the CIS scan. The discrimination is more complete in the 10–12-eV region than at 20.33 eV. Nevertheless, separation is sufficient to warrant our interpreting the results solely on the basis of a $^2P_{1/2}$ ground state.

CIS spectra are recorded by scanning simultaneously the photon energy and the accelerating voltage of the source cell so as to always observe electrons corresponding to the same final ionic state. The spectra are normalized with the aid of photoelectron spectra taken at constant photon energy (PES). Partial-cross-section measurements are made with two analyzers placed at 180° with respect to each other, both being oriented at the magic angle to remove influence of the angular distribution on the cross section. Using both analyzers allows for correction for any possible asymmetry in the source volume. The β measurements are taken simultaneously with two analyzers at right angles to each other. The parameter which is actually determined is the ratio $R = I(0^\circ)/I(90^\circ)$, where $I(\theta)$ is the intensity measured in the analyzer at angle θ . This ratio is converted to the value of β using the measured value of the polarization P of the ionizing radiation and the relative response function γ of the two analyzers.¹³ We determine P and γ by calibration with the known values of β for the rare gases¹⁴ at 21.22 eV.

III. THE 3d-4p RESONANCE

In Fig. 2 are shown the partial widths of the three exit channels in the decay of the $3d-4p$ resonance. The numbers correspond to the line positions as they have been assigned by Connerade;⁷ they are listed in Table I. We note once again that the system tends to decay in such a way

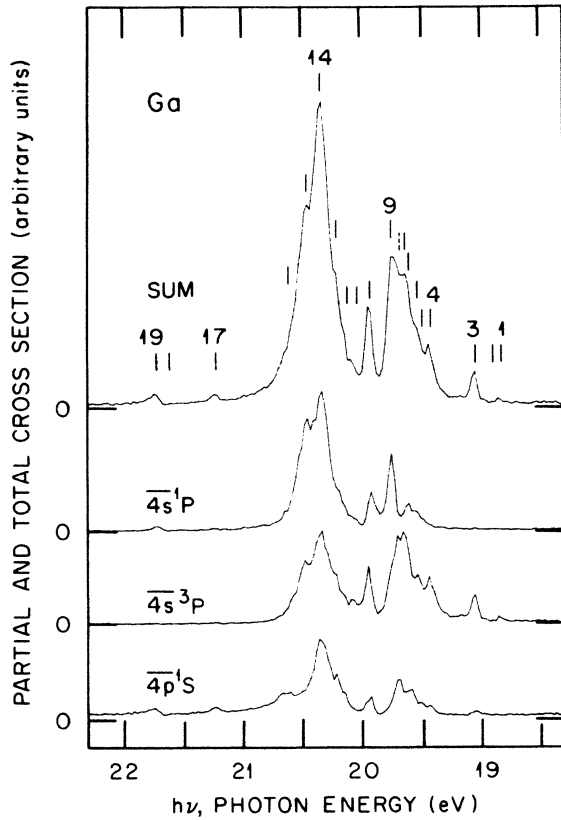


FIG. 2. Partial cross sections for Ga I photoionization at the $3d-4p$ resonance. Taken from Ref. 11.

TABLE I. Line positions in 20.33-eV resonance. Assignments are from Ref. 7.

Number	$h\nu$ (eV)	Assignment: $^2P_{1/2}$ ionization	Assignment: $^2P_{3/2}$ ionization
1	18.81		$(^3P) ^2D_{3/2}$
2	18.88	$(^3P) ^2D_{3/2}$	
3	19.03		$(^3P) ^2D_{5/2}$
4	19.40		$(^3P) ^2P_{1/2}$
5	19.485		$(^3P) ^2P_{3/2}$
6	19.51	$(^3P) ^2P_{1/2}$	
7	19.58	$(^3P) ^2P_{3/2}$	
8	19.61		$(^1D) ^2S_{1/2}$
9	19.74	$(^1D) ^2S_{1/2}$	
10	19.92		$(^1D) ^2P_{3/2}$
11	20.04	$(^1D) ^2P_{3/2}$	
12	20.10		$(^1D) ^2D_{5/2}$
13	20.21		$(^1D) ^2P_{1/2}$
14	20.33	$(^1D) ^2P_{1/2}$	
15	20.46		$(^1D) ^2D_{3/2}$
16	20.62	$(^1D) ^2D_{3/2}$	
17	21.20		$(^1S) ^2D_{5/2}$
18	21.59		$(^1S) ^2D_{3/2}$
19	21.70	$(^1S) ^2D_{3/2}$	

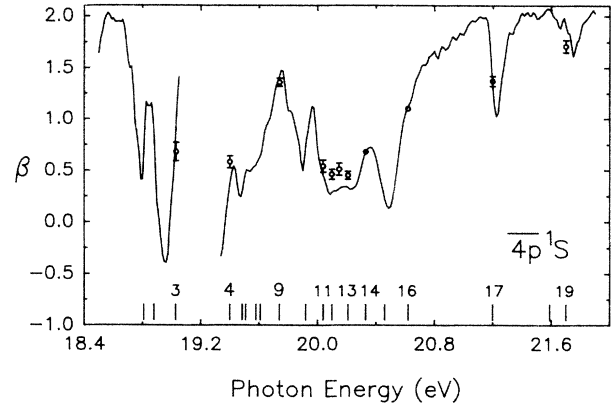


FIG. 3. Angular-distribution parameter β for $3d-4p$ resonance decay into 1S_0 . The solid line is the CIS data; PES results are indicated by circles. Line positions given at the bottom of the graph are taken from Table I. The CIS distribution is normalized at 20.33 eV to $\beta=0.68$.

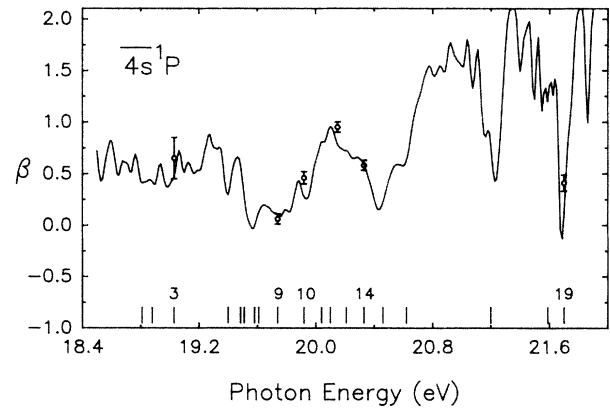


FIG. 4. Angular-distribution parameter β for $3d-4p$ resonance decay into 1P . The solid line is the CIS data; PES results are indicated by circles. Line positions given at the bottom of the graph are taken from Table I. The CIS distribution is normalized at 20.33 eV to $\beta=0.58$.

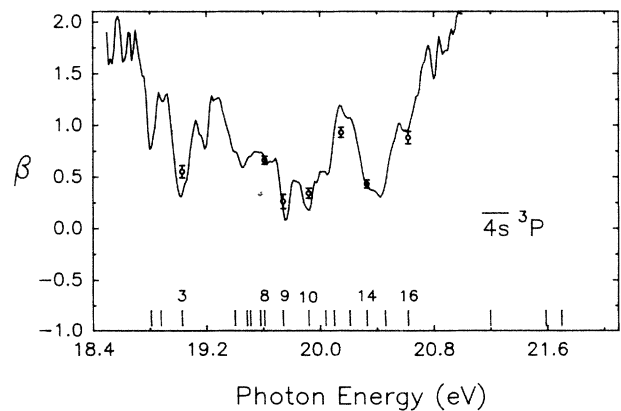


FIG. 5. Angular-distribution parameter β for $3d-4p$ resonance decay into 3P . The solid line is the CIS data; PES results are indicated by circles. Line positions given at the bottom of the graph are taken from Table I. The CIS distribution is normalized at 20.33 eV to $\beta=0.43$.

that the symmetry of the final state remains the same as that of the p^2 configuration.

In Figs. 3–5 are depicted the β values obtained by the CIS technique in a scan through the resonance. These have been normalized by traditional PES measurements at various photon energies, as indicated by the circles in the figures. The linear polarization of the synchrotron radiation using the Seya monochromator is 0.96 at the wavelengths of interest. In general, the agreement between two or more independent measurements is quite good.

As can be expected, we see a strong variation in β as we pass through the resonance. In the absence of detailed calculations it is impossible to make any precise statement about the dynamics which lead to the variation in β . We must be content with making some general observations about the behavior at various points on the curve.

As a suitable reference point for our discussion we choose the angular-momentum-transfer theory formulated by Fano and Dill.¹⁵ Dill¹⁶ has shown this to be a valuable tool for analysis of autoionizing resonance. The contribution of the resonance can be explored in terms of its effect on the various possible angular momentum transfers. Manson and Starace¹⁷ have applied this scheme to the angular distribution of electrons from s subshells, and their results can be applied to part of our analysis.

Ionization from the $4s^2 4p^2 P_{1/2}$ state of neutral gallium produces the $4s^2 1S_0$ state of Ga II with an electron in either an s wave or a d wave. Ionization to the $4s 4p^3 P$ and $1P$ state of Ga II produces primarily an electron in a p wave, although f waves can occur due to interchannel correlation or ground-state configuration mixing.¹⁷ In our analysis we will neglect possible contributions from $l=3$. The Fano profile of an autoionizing transition remains symmetric if the transition is dominated by the resonance route or, as Mies¹⁸ has noted, if a number of overlapping transitions are present within the line profile. The general character of the spectra produced in these group III B elements and the reason for their interest to us is due to the fact that many overlapping transitions are present. Thus it is next to impossible to ascertain on the basis of Fano profiles how much of the ionization proceeds via the resonant and how much via the direct process. However, as there is very little contribution from the direct ionization in the $3d-4p$ transition, we will interpret the angular-momentum-transfer contributions as having come solely from the resonant portion.

An angular-momentum-transfer analysis of the ionization of Ga I to produce each of the final states is given in Table II. For each final ionic state are given the values of the angular momentum transfer j_i associated with that state. These are separated into parity-favored and parity-unfavored contributions. Also listed are the expressions for β . In these expressions the term $S_l(j_i)$ is the photoionization amplitude¹⁶ for angular momentum transfer j_i , resulting in the final value of the electron-orbital angular momentum l . For parity unfavored j_i , $\beta = -1$.

From Figs. 3–5 we see that the influence on the value

TABLE II. Angular-momentum-transfer analysis of β . $S_l(j_i)$ is the reduced dipole matrix element corresponding to the production of a partial wave of angular momentum l with an angular momentum transfer j_i . $\sigma(j_i)$ is the cross section for production of that value of j_i .

Final ion state	Parity favored j_i	Parity unfavored j_i	β
$1S_0$	1	0 ^a	$\frac{\sigma(1)\beta_f(1) - \sigma(0)}{\sigma(1) + \sigma(0)}$
$3P_0$	0	1	$\frac{2\sigma(0) - \sigma(1)}{\sigma(0) + \sigma(1)}$
$3P_1$	0, 2	1	$\frac{2\sigma(0) + 0.2\sigma(2) - \sigma(1)}{\sigma(0) + \sigma(1) + \sigma(2)}$
$3P_2$	2	1	$\frac{0.2\sigma(2) - \sigma(1)}{\sigma(1) + \sigma(2)}$
$1P_1$	0, 2	1	$\frac{2\sigma(0) + 0.2\sigma(2) - \sigma(1)}{\sigma(0) + \sigma(1) + \sigma(2)}$

$$\beta_f(1) = \frac{|S_2(1)|^2 - \sqrt{2}[S_2(1)S_0^*(1) + S_2^*(1)S_0(1)]}{|S_2(1)|^2 + |S_0(1)|^2}$$

^aIn strict LS coupling this transfer would be forbidden.

of β is greater when the final ionic state is a P state, as opposed to an S state. (Compare the expressions for β in Table II.) This is consistent with the $3d^9 4s^2 4p^2$ configuration decaying via a route $4p^2-3d, \epsilon l$ with minimal interference from the two s electrons. Production of the P state must involve loss of one of the s electrons, implying enhanced interaction with the core and thus greater probability for transfer of angular momentum to and from the core. A look at the average values of β for the $3P$ and $1P$ final states from Figs. 4 and 5 indicates that the variation for both is similar throughout the resonance. This is to be expected from the formulas given in Table II and indicates that the spin has little effect on the final value of β .

Direct ionization of the p electron of Ga I should result in the Cooper-Zare¹⁹ result for β , a smoothly varying function of energy. Without knowing the values for the matrix elements in the Cooper-Zare formula it is impossible to ascertain where the curve would lie, although it is likely that the d wave will dominate at this energy. This would give rise to a value of β close to 1.00. Because of the spherical symmetry of the s^2 core we expect no anisotropic interactions between the outgoing electron and this core. Thus the variation in β reflects the interference between the d and s partial waves, even at the resonances, with no parity-unfavored contributions. This is consistent with the recognition¹⁷ that, in strict LS coupling, only one angular momentum transfer is allowed; the parity-favored transition is the only one available. If we follow the assignments of Connerade and Baig,⁹ the P states generally produce a lower value of β and the S and D states a larger value of β . The negative values observed

below 19 eV are very uncertain due to low intensity and poor statistics.

Interpretation of the production of the P states is simpler. In this case the direct process, photoionization from an s subshell, should produce a value of $\beta=2.0$. As we do not resolve the triplet components in the 3P final state, we can use the same expression for β for both singlet and triplet P . The Cooper-Zare model corresponds to a transfer $j_t=0$. That β differs from 2.0 throughout the profile further indicates that, at least to our resolution, no portion of the spectrum is free of the resonance. While the β values for both the 3P and 1P final states are, on the whole, roughly the same, the fact that both curves drop below $+0.2$ indicates considerable contribution from parity-unfavored transfer, as well as a considerable diminution of the $j_t=0$ contribution.

IV. THE $4s$ - np RESONANCES

For the lower-energy region we have examined three of the possible $4s$ - np resonances in detail, both for the partial cross section and for the angular distribution parameter β . Our results are presented in Figs. 6–11. In all cases we have recorded the CIS spectra by monitoring the 1S_0 ground state of the ion, the only channel available up to 12 eV. The intensity scales of the σ curves are normalized to the peak value for the $({}^3P)5p$ resonance ($h\nu=10.084$ eV). The proportions, along with that for the $3d$ - $4p$ resonance, are listed in Table III. We note that the 1P core resonance can decay into the 3P state as well. Preliminary data indicate that the cross section is comparable to that of decay into the 1S state. However, the low energy of the electrons involved in this transition (~ 0.7 eV) makes a more reliable analysis difficult.

The first fact which strikes one upon examining these spectra is the pronounced asymmetry of the lines. This is most visible in the $n=5$ transitions for both core configurations, but is clearly evident in the $({}^3P)6p$ resonance as well. The deep minimum indicates a relative isolation of the principal transition with strong coupling

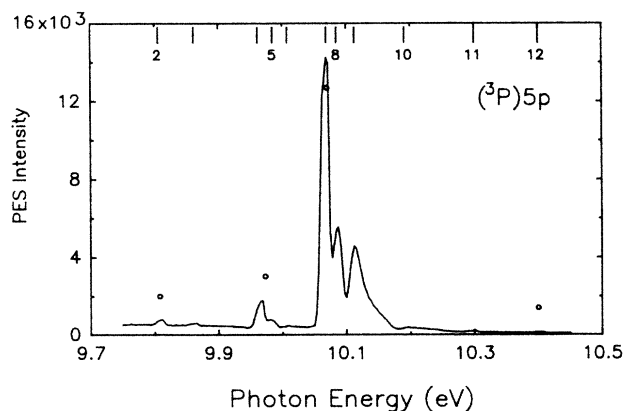


FIG. 6. Cross section for photoionization across the $4s4p({}^3P)5p$ resonance. The solid line is the CIS data scan of the Ga $4p$ photoline; PES results are indicated by circles. Line positions at the top of the graph are taken from Table IV. The CIS distribution is normalized to the PES value at 10.074 eV.

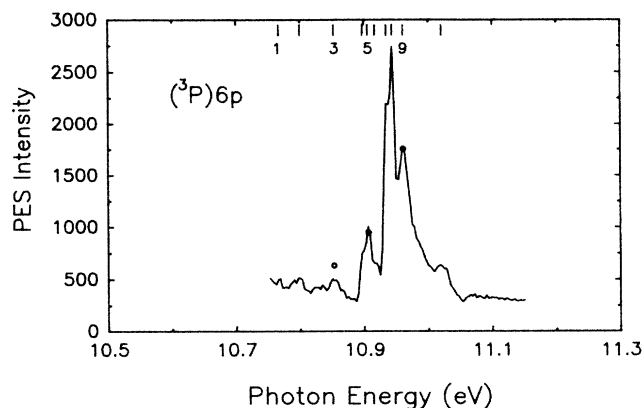


FIG. 7. Cross section for photoionization across the $4s4p({}^3P)6p$ resonance. The solid line is the CIS data scan of the Ga $4p$ photoline; PES results are indicated by circles. Line positions at the top of the graph are taken from Table V. The CIS distribution is normalized to the PES value at 10.996 eV. The vertical scale is adjusted to give a ratio of the $6p$ maximum to the $5p$ maximum of 14%.

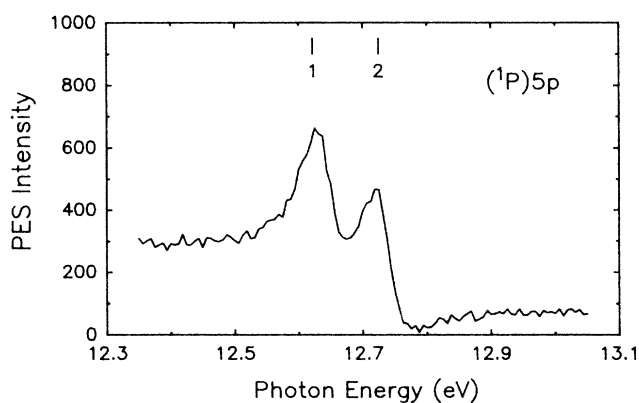


FIG. 8. Partial cross section for photoionization across the $4s4p({}^1P)5p$ resonance as observed in the $4p {}^1S_0$ channel. Lines 1 and 2 are at 12.622 and 12.725 eV, respectively.

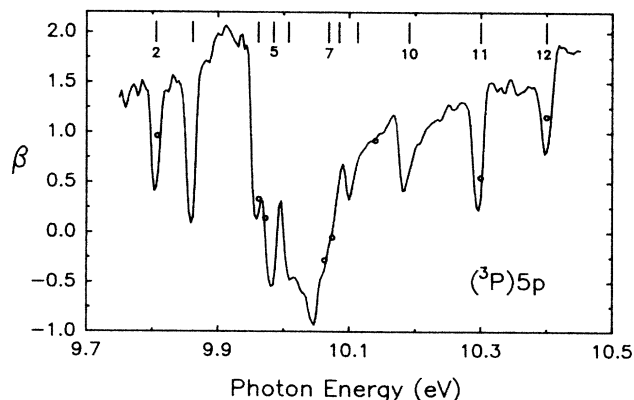


FIG. 9. Angular-distribution parameter β for the $4s4p({}^3P)5p$ resonance. The solid line is the CIS data for the Ga $4p$ photoelectron; PES results are indicated by circles. Line positions are taken from Table IV. The CIS distribution is normalized to $\beta=-0.05$ at 10.074 eV.

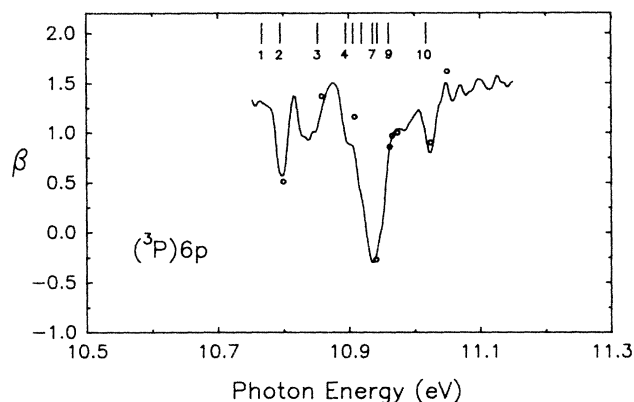


FIG. 10. Angular-distribution parameter β for the $4s4p(^3P)6p$ resonance. The solid line is the CIS data for the Ga $4p$ photoelectron; PES results are indicated by circles. Line positions are taken from Table V. The CIS distribution is normalized to $\beta=0.97$ at 10.966 eV.

to the direct process. The general shape of the resonance structure is similar for both. This includes one dominant peak, with most of the remaining oscillator strength concentrated in nearby-lying resonances at higher photon energy. The q values for the triplet core resonances are positive, while the q value for the $(^1P)5p$ resonance (Fig. 8) is negative. An overlay of the β curve with the σ curve for both $n=5$ resonances shows that the minimum values of β lie at the minima of the cross section. In the case of the $(^3P)5p$ resonance, β is very nearly equal to -1 at this point. This is in agreement with a qualitative interpretation that β should be predominantly determined by the weaker parity-unfavored contributions to the cross section at the minimum. Direct transitions to produce the $4s^2\ ^1S_0$ final state must be parity favored.

The $n=5$ resonance has been analyzed in detail by Connerade and Baig,⁹ and assignments have been made to the various coupling terms. These assignments are listed in Table IV, corresponding to the numbers at the

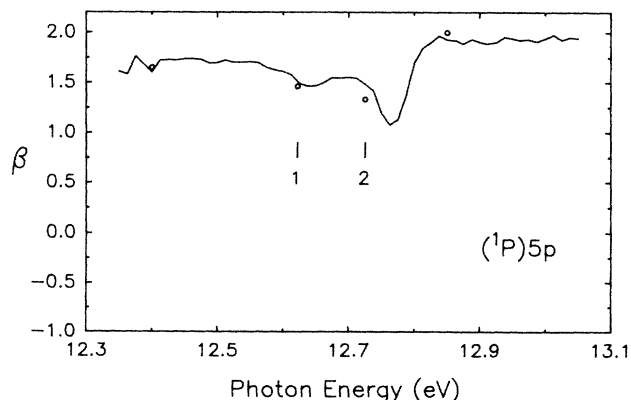


FIG. 11. Angular-distribution parameter β for the $4s4p(^1P)5p$ resonance. The solid line is the CIS data for the Ga $4p$ photoelectron; PES results are indicated by circles. Lines 1 and 2 are at 12.622 and 12.725 eV, respectively. The CIS distribution is normalized to $\beta=1.46$ at 12.622 eV.

TABLE III. Relative peak values of the resonances. Energies are based on calibration with the first three autoionizing resonances in Xe $5p_{1/2}$. Values are taken from Moore's tables. The uncertainty of the calibration is 0.008 eV. Energies in parentheses are from Refs. 7 and 9.

Energy (eV)	Resonance	Relative intensity ^a
10.084 (10.075)	$4s4p(^3P)5p$	100.0
10.966 (10.966)	$4s4p(^3P)6p$	14.5
12.631 (12.622)	$4s4p(^1P)5p$	5.5
13.634 (13.625)	$4s4p(^1P)6p$	2.9
20.339 (20.33)	$3d^9 4s^2 4p^2$	5.7

^aPeak value.

TABLE IV. Energy levels and quantum defects of the terms of the $4s4p(^3P)5p$ multiplet. (See Figs. 6 and 9.) Quantum defects are based on an average value of 11.984 for the 3P ionization limit.

Peak No.	Energy (eV)		δ	Designation ^b
	Ours ^a	Ref. 9		
1		9.741	2.55	$^4D_{1/2}$
2	9.809	9.791	2.52	$^4D_{3/2}$
3	9.864	9.864	2.48	$(^4P_{3/2})^c$
4	9.966	9.973	2.41	$^4P_{3/2}$
5	9.982	9.992	2.40	$(^4S_{3/2})^d$
6	10.010	10.010	2.39	$(^2D_{3/2})^c$
7	10.069	10.074	2.33	$(^2P_{1/2})^d$
8	10.085	10.095	2.33	$^2P_{3/2}$
9	10.113	10.115	2.32	$^2D_{3/2}$
10	10.195	10.19	2.26	$(^2D_{5/2})^c$
11	10.301	10.288	2.17	$(^2S_{1/2})^c$
12	10.403	10.404	2.07	$^2S_{1/2}$

^aAccuracy = ± 0.008 eV.

^bFrom Ref. 9.

^cThermally populated terms inferred from spacing.

^dWe have interchanged the $^2P_{1/2}$ and $^4S_{3/2}$ terms to correspond more closely to the observed intensities. See text for further discussion.

TABLE V. Energy levels and quantum defects of the $4s4p(^3P)6p$ multiplet. (See Figs. 7 and 10.) Energies are our experimental values.

Peak No.	Energy ^a (eV)	δ	Tentative designation
1	10.767	2.66	$^4D_{1/2}$
2	10.800	2.61	$^4D_{3/2}$
3	10.853	2.53	
4	10.898	2.46	$^4P_{3/2}$
5	10.906	2.45	$^4S_{3/2}$
6	10.917	2.43	
7	10.935	2.40	$^2P_{1/2}$
8	10.944	2.38	$^2P_{3/2}$
9	10.961	2.35	$^2D_{3/2}$
10	11.021	2.24	$^2D_{5/2}$

^aAccuracy = ± 0.008 eV.

top of Fig. 6. In their discussions of the location of the terms the authors are ambiguous in the designation of the coupling in the principal peak. According to their Table I this maximum has the designation $^4S_{3/2}$. The $^2P_{1/2}$ term has a small intensity. This is inconsistent with results of earlier measurements on the $4p^2$ resonance and with the dominance of doublet states expected from even partial LS coupling in gallium. In addition, Connerade and Baig⁹ also point out a discrepancy, and the ordering in their Fig. 2 corresponds to what we give here. When this exchange is made, we notice a grouping of the multiplets into a weak set of quartet states and an intense set of doublet states.

As yet no comparable analysis has been made of the $(^3P)6p$ resonance. Energy levels for the various terms of the multiplet are listed in Table V. They correspond to the peak numbering given in Fig. 7. A calculation of the quantum defects for these levels and comparison with defects calculated for the $(^3P)5p$ resonance allows an assignment to be made. Thus we have tentatively given the same designations to these terms in the $(^3P)6p$ resonance having the same quantum defects as those assigned to the $(^3P)5p$ resonance in Table IV. In doing this, however, we note that those terms in Table IV, which are supposed by Connerade and Baig⁹ to have originated from the thermally populated $^2P_{3/2}$ ground state, no longer have the proper separation from those originating from the $^2P_{1/2}$ state. This implies that the designation in Table IV is not complete. For the $(^1P)5p$ resonance, if we preserve the dominance of the core coupling in the multiplet determination then fewer components of the multiplet are possible. This is borne out by the paucity of lines observed in the transitions. Unfortunately, at our resolution, the multiplet splitting in this state is unresolvable.

While detailed calculations are necessary in order to explain the behavior of both the partial cross section and β throughout these resonances, a qualitative description in the same sense as that applied to the $3d-4p$ resonance is also possible. In the absence of a resonance transition, direct ionization of the $4p$ electron should be a textbook case for removal of a p electron. As the $4s^2$ core possesses a 1S_0 structure, there can be no interaction be-

tween the departing electron and the core which would produce parity-unfavored transitions in the direct process. The parity-favored asymmetry parameter β is given at the bottom of Table II. The negative values of β , especially for the $(^3P)5p$ resonance, indicate that at the cross-section minimum, the departing electron is predominantly s wave for $^2P_{1/2}$ ionization based on a triplet core. On the other hand, the large positive value of β for the singlet core indicates dominance of d waves.

V. CONCLUSIONS

A summary glance at the data presented in Figs. 3–11 indicates that autoionization spectra from the open-shell gallium atom are rich and varied. Oscillator strengths are strong into practically all terms of the multiplets. Angular distributions vary considerably for the different terms and reflect, in some cases, strong parity-unfavored contributions. Unfortunately our resolution does not permit isolation of all terms, and in some cases the assignments of the terms are only tentative, making a detailed analysis of the coupling of each term with the continuum impossible. It is clear that much theoretical effort will be necessary in order to make a quantitative interpretation of our results.

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