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[1]M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

[2]A preliminary presentation of this material without the effect of lattice vibrations appeared in R. A. Carrigan, Jr., Fermilab Report No. FN-270, 1974 (unpublished). See also R. A. Carrigan, Jr., Bull. Amer. Phys. Soc. 20, 592 (1975).

[3]H. Primakoff, Phys. Rev. 81, 899 (1951). For a recent measurement see A. Browman, J. De Wire, B. Gittelman, K. M. Hanson, D. Larson, E. Loh, and R. Lewis, Phys. Rev. Lett. 33, 1400 (1974).

[4]B. Knapp *et al.*, Phys. Rev. Lett. 34, 1040 (1975).

[5]B. Margolis, Phys. Lett. 26B, 524 (1968).

[6]See, for example, U. Timm, Fortschr. Phys. 17, 765 (1969).

[7]R. F. Schwitters *et al.*, Phys. Rev. Lett. 27, 120 (1971).

[8]For recent reviews see D. S. Gemmell, Rev. Mod. Phys. 46, 129 (1974), and in *Channeling*, edited by D. V. Morgan (Wiley, New York, 1973).

[9]O. Fich, J. A. Golovchenko, K. O. Nielsen, E. Uggerhøj, G. Charpak, and F. Sauli, to be published.

[10]W. M. Gibson and A. Kanofsky, private communications.

[11]G. W. Temmer, in *Proceedings of a Symposium on the Structure of Low-Medium Mass Nuclei, Lexington, Kentucky, 1972,* edited by J. P. Davidson and B. Korn (Univ. of Kentucky Press, Lexington, Ky., 1973), p. 192.

[12]See, for example, C. Kittel, *Introduction to Solid State Physics* (Wiley, New York, 1956).

[13]T. L. Gilbert and J. E. Robinson, private communication.

Observation of Autoionizing Transitions in Helium Using the (*e*, 2*e*) Technique*

E. Weigold, A. Ugbabe, and P. J. O. Teubner
School of Physical Sciences, The Flinders University of South Australia, Bedford Park, South Australia, 5042, Australia
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Resonance ionization from the $(2s2p)\ ^1P$ and $(2p^2)\ ^1D$ levels of helium has been observed in an $(e,2e)$ experiment, in which the kinematics of all electrons is fully determined, at incident energies of 200 and 400 eV and a scattering angle of 10°. The results show that as the angle of emission approaches the direction $-\vec{Q}$, where $\vec{Q}$ is the momentum transfer to the helium atom, the resonance profile becomes more symmetric and the resonance cross section increases sharply.

The autoionization of helium excited by electron impact has been studied in recent years by measuring the spectra either of the scattered electrons[1] or of the emitted cascade or decay electrons.[2] Since the interference between the direct-ionization amplitude and the resonance or autoionization amplitude depends on the momenta of the scattered electrons, the more recent work has concentrated on observing the resonance profiles as a function of the angle of either the scattered or emitted electron. However, such experiments always involve integration over the momenta of the undetected electrons. On the other hand in an $(e,2e)$ experiment, where the two outgoing electrons are detected in coincidence, the kinematics of the electrons is completely determined. This means that information can be obtained on the resonance[3] and the direct cross sections as a function of the momentum $\vec{k}'$ of the emitted (or decay) electron for known values of the momentum transfer $\vec{Q}=\vec{k}_0-\vec{k}$, where $\vec{k}_0$ and $\vec{k}$ are the momenta of the incident and scattered electron, respectively.

One additional major advantage of the $(e,2e)$ technique for studying autoionizing states is that it provides information which can be compared directly with scattering theory without incurring any ambiguities from normalization of the experimental data. In this respect it is very similar to the electron-photon angular-correlation experiments of Eminyan *et al.*[4] and Arriola *et al.*[5] These experiments showed that when a scattered electron leaving an atom in an excited state is detected in coincidence with the cascade photon, fine details of electron-atom collision can be investigated. In particular it is possible to determine the ratios of excitation amplitudes leading to the various magnetic substates of the intermediate excited level, as well as to determine their relative phases.

This is also true for an $(e,2e)$ autoionization experiment if there is no direct contribution to the cross section. For instance, with neglect of the direct contribution and interference between the excitation amplitudes to the various magnetic substates, the angular correlations between the scattered and emitted electron should have[6,7] the form $[P_L(\cos\theta_e')]^2$ in the scattering plane for an electron emitted with angular momentum L, where θ_e' is the angle of emission relative to the symmetry axis $\vec{Q}$. Deviations from such a distribution are due to interference between the excitation amplitudes as well as the direct-background channels. On the other hand, if only the emitted electrons are detected, integration over the scattered-electron trajectories[6] yields a distribution which is symmetric about the incident-electron direction, rather than being related to the momentum-transfer direction $\vec{Q}$.

In the plane-wave Born approximation the $(e, 2e)$ cross section is given by[7]

$$\frac{d^3\sigma}{d\Omega_k d\Omega_{k'} dE'} = \frac{4a_0^2}{Q^4}\frac{k}{k_0}|T(\vec{k}',\vec{Q})|^2, \qquad (1)$$

where $d\Omega_k$ and $d\Omega_{k'}$ are the solid-angle elements in the direction of emission of the scattered electron and the emitted cascade electron, E' is the energy of the cascade electron, and a_0 is the Bohr radius. In the neighborhood of an isolated resonance the transition matrix element $T(\vec{k}',\vec{Q})$ can be expressed as the sum of the amplitude $t(\vec{k}',\vec{Q})$ of the direct process and the amplitude $t^L(\vec{k}',\vec{Q})$ for the resonance or autoionizing process. This latter term contains the sum over the magnetic substates.

The triple differential cross section can then be conveniently written in the form[7]

$$\frac{d^3\sigma}{d\Omega_k d\Omega_{k'} dE'} = f(\vec{k}',\vec{Q}) + \frac{a(\vec{k}',\vec{Q})\epsilon + b(\vec{k}',\vec{Q})}{\epsilon^2+1}, \qquad (2)$$

where

$$f(\vec{k}',\vec{Q}) = (4a_0^2k/Q^4k_0)|t(\vec{k}',\vec{Q})|^2, \qquad (3)$$

$$a(\vec{k}',\vec{Q}) = (8a_0^2/Q^4)(k/k_0)\,\mathrm{Re}\{t^*(\vec{k}',\vec{Q})t^L(\vec{k}',\vec{Q})[q(\vec{Q})-i]\}, \qquad (4)$$

$$b(\vec{k}',\vec{Q}) = (4a_0^2/Q^4)(k/k_0)\{|t^L(\vec{k}',\vec{Q})|^2[q^2(\vec{Q})+1] + 2\,\mathrm{Im}[t^*(\vec{k}',\vec{Q})t^L(\vec{k}',\vec{Q})(q(\vec{Q})-i)]\}, \qquad (5)$$

$q(Q)$ is the Fano profile parameter, and $\epsilon = 2(E'-E_r)\Gamma^{-1}$ is a measure of the deviation from the resonance of energy E_r and width Γ.

The first term $f(\vec{k}',\vec{Q})$ describes the cross section for the direct-ionization process, the term $b(\vec{k}',\vec{Q})$ gives the resonance contribution to the total cross section, and the term $a(\vec{k}',\vec{Q})$ characterizes the asymmetry of the resonance. In the absence of any direct amplitude $t(\vec{k}',\vec{Q})$, the terms $f(\vec{k}',\vec{Q})$ and $a(\vec{k}',\vec{Q})$ both vanish and the differential cross section is given by the first term of the resonant contribution $b(\vec{k}',\vec{Q})$. Since in the present case the $(2s2p)\,^1P$ and the $(2p^2)\,^1D$ levels were not resolved, the emitted electrons have $L=1$ and $L=2$, respectively, because the final ion state is an S state. Although it is well known that interference between the direct or continuum and the resonance contributions can produce marked asymmetries in the resonance profile, it can also have a significant influence on the intensity $b(\vec{k}',\vec{Q})$ of the resonance line through the second term of expression (5).

The apparatus used in the present work used coplanar geometry and has been described in a previous publication.[8] In brief, a helium beam emerging from a narrow stainless-steel tube is collimated by an aperture placed 2 mm below the interaction region, which is smaller than the viewing angles of two cylindrical-mirror analyzers. These analyzers are considerably smaller than those used previously, and their angular sensitivity was checked by measuring the angular distributions of electrons elastically scattered from argon at a number of energies and comparing them with previous measurements.[9]

The coincidence counting rate at each angular setting was observed over a range of emitted-electron energies E' covering the emission of electrons from the $(2s2p)\,^1P$ and $(2p^2)\,^1D$ autoionizing resonances. It was of course necessary to make a simultaneous adjustment to the energy E of the coincident scattered electrons, since $E'+E=E_0-E_b$, where E_0 is the incident energy and E_b the separation or ionization energy of helium. Measurements of the noncoincident emitted-electron spectra at the various angles and energies employed in this experiment showed that the $(2s^2)\,^1S$ state could be clearly resolved from the states of interest.

As pointed out by Balashov, Lipovetsky, and Senashenko[3] there should be an advantage in using antiquasielastic kinematics in investigating autoionizing states since the resonance contribution must be symmetrical about the inversion $\vec{Q}\to-\vec{Q}$, whereas the continuum contribution should peak in the quasielastic direction $\vec{Q}$. This was confirmed in the present experiments since the relative contribution of the resonance to the total cross section was reduced by almost a factor of 10 in going from the antiquasielastic direction $-\vec{Q}$ to the quasielastic direction.

Figure 1 shows the coincidence counting rate observed as a function of emitted-electron energy E' at a number of angles θ_e and at incident energies of 200 and 400 eV. The scattered-electron angle θ_s was 10° in all cases and $\varphi_s = \varphi_e = 0$, i.e., the scattered- and emitted-electron detectors were coplanar with the incident electron beam and on the same side of the beam. $|\vec{Q}|$ was 0.88 a.u. at 200 eV and 1.0 a.u. at 400 eV.

The resonance profile, unbroadened by finite experimental energy resolution, is given by expression (2). Since the area under the resonance is proportional to b, the relative cross section for the resonance process can be determined quite simply by measuring the area as a function of the angle of emission. This is still true for the broadened profile if the apparatus function is symmetric, which was the case in the present experiment. The experimental resolution was well described by a Gaussian of width 0.6 eV, considerably larger than the natural width of 0.038 eV[10] of the ^1P level. Since the excitation cross section for the ^1P level is greater than that for the ^1D level,[1] we have ignored the latter state in making a least-squares fit to the data with expression (2) broadened by the resolution function.[11] A PDP-11 computer was used, the purpose of the exercise being to emphasize the observed variation of the resonance profile with the angle of emitted electrons. At $\theta_e = 70°$ the contributions of the resonances at both energies were too small to be separated from the direct processes; the statistical errors were also very large.

Table I summarizes the results obtained for the resonance parameters at different angles of emission θ_e relative to the incident direction. The direction $-\vec{Q}$ is also given in the table. Since the shape of the resonance can also be described by the Fano formula, we have included in Table I the Fano profile parameters $q(E_0, \theta_e)$ which have been obtained from the relation $(q^2-1)/2q = b/a$. The resonance cross section b, normalized to unity at its maximum value at both energies, was obtained by measuring the area under the resonance and by fitting expression (2) to the data. The values of b in the table are the means of these two methods. The variation of the direct cross section with angle has also been included

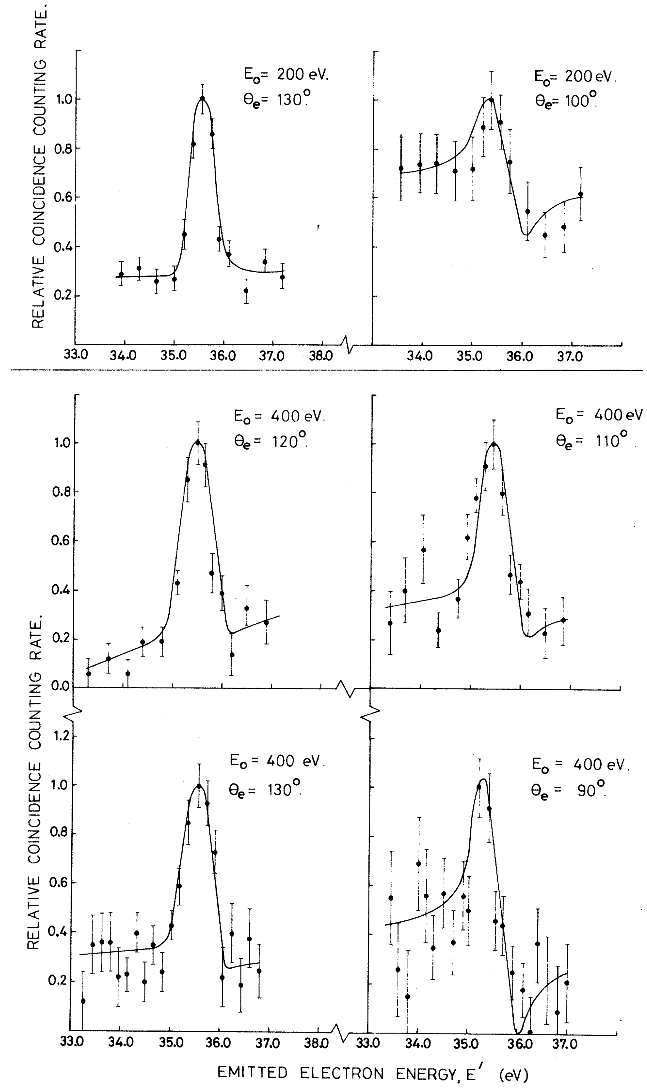

FIG. 1. Relative coincidence counting rate as a function of the energy and angle of the ejected electron for incident electron energies of 200 and 400 eV and a scattering angle of 10°.

in the table.

The results show that as the emission angle approaches the direction $-\vec{Q}$, the resonance profile becomes more symmetric and the resonance cross section increases. In the absence of any direct contribution and any interference between the ^1D and ^1P resonances, which are separated by several times their natural widths,[12] the Born approximation gives[7] a cross section proportional to

$$\sum_{l=1}^{2} (2l+1)^2 R_l^{\,2}(\vec{Q}) P_l^{\,2}(\cos\theta_e'),$$

TABLE I. Summary of the resonance profile parameters and resonance cross sections in the autoionization of the $(2s2p)\ ^1P$ and $(2p^2)\ ^1D$ states of helium for a scattering angle of 10°. For each incident energy E_0, the direct and resonance cross sections have been normalized to unity at the maximum values of b. The direction of the momentum transfer axis $-\vec{Q}$ is also shown.

E_0 (Q)	θ_e (deg)	$\theta_{-\vec{Q}}$ (deg)	a/b	q	$f(\vec{k},\vec{Q})$	$b(\vec{k},\vec{Q})$
200 eV	130	140	0.08	25	1.0 ± 0.10	1.0 ± 0.12
(0.88 a.u.)	100	140	-1.7	-1.75	1.71 ± 0.20	0.27 ± 0.12
	70	140	···	···	1.24 ± 0.38	<0.12
400 eV	130	120	-0.17	-11.8	1.4 ± 0.1	0.89 ± 0.12
(1.0 a.u.)	120	120	-0.16	-12.6	1.0 ± 0.1	1.0 ± 0.10
	110	120	-0.37	-5.6	1.3 ± 0.1	0.76 ± 0.10
	90	120	≤ -1.9	$-1.7 \leq q \leq 0$	0.75 ± 0.04	0.30 ± 0.17
	70	120			0.80 ± 0.04	<0.1

where $R_l(\vec{Q})$ is the radial part of the matrix element and θ_e' is the angle of emission relative to the direction $\vec{Q}$. A good fit to the 400-eV data can be obtained with such a function in which θ_e' is replaced by $\theta_e' + \delta_l$. The result of a least-squares fit to the data gives $\delta_1 = -12 \pm 6°$, $\delta_2 = -6 \pm 6°$, and $(R_2/R_1)^2 = 0.8^{+1.1}_{-0.4}$. A reasonable fit to the 200-eV data can also be obtained with these same parameters. The results of this first investigation show that the $(e, 2e)$ technique provides an extremely powerful new probe for investigating autoionizing transitions.

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[1]E. N. Lassettre and S. Silverman, J. Chem. Phys. 40, 1265 (1964); J. A. Simpson, G. E. Chamberlain, and S. R. Mielczarek, Phys. Rev. 139A, 1039 (1965).
[2]W. Melhorn, Phys. Lett. 21, 155 (1966); N. Oda, F. Nishimura, and S. Tahira, Phys. Rev. Lett. 24, 42 (1970); J. Comer and F. H. Read, J. Electron Spectrosc. Relat. Phenomena 1, 3 (1972); H. Suzuki, A. Konishi, M. Yamamoto, and K. Wakiya, J. Phys. Soc. Jpn. 28, 534 (1970); F. Gelebart, R. J. Tweed, and J. Peresse, J. Phys. B: Proc. Phys. Soc., London 7, L174 (1974).
[3]V. V. Balashov, S. S. Lipovetsky, and V. S. Senashenko, Phys. Lett. 39A, 103 (1972).
[4]M. Eminyan, K. B. MacAdam, J. Slevin, and H. Kleinpoppen, Phys. Rev. Lett. 31, 576 (1973), and J. Phys. B: Proc. Phys. Soc., London 7, 1519 (1974).
[5]H. Arriola, P. J. O. Teubner, A. Ugbabe, and E. Weigold, to be published.
[6]V. V. Balashov, S. S. Lipovetsky, A. V. Pavlichenkov, A. N. Polyudov, and V. S. Senashenko, Opt. Spektrosk. 32, 10 (1972) [Opt. Spectrosc. 32, 4 (1972)].
[7]V. V. Balashov, S. S. Lipovetsky, and V. S. Senashenko, Zh. Eksp. Teor. Fiz. 63, 1622 (1972) [Sov. Phys. JETP 36, 858 (1973)].
[8]I. E. McCarthy, A. Ugbabe, E. Weigold, and P. J. O. Teubner, Phys. Rev. Lett. 33, 459 (1974); A. Ugbabe, E. Weigold, and I. E. McCarthy, Phys. Rev. A 11, 576 (1975).
[9]B. R. Lewis, J. B. Furness, P. J. O. Teubner, and E. Weigold, J. Phys. B: Proc. Phys. Soc., London 7, 1083 (1974).
[10]R. P. Madden and K. Codling, Astrophys. J. 141, 364 (1965).
[11]J. Comer and F. H. Read, J. Electron Spectrosc. Relat. Phenomena 2, 87 (1973).
[12]A. Bordenave-Montesquieu, A. Gleizes, M. Rodiere, and P. Benoit-Cattin, J. Phys. B: Proc. Phys. Soc., London 6, 1997 (1973).