the present case, the electric quadrupole radiation is observed along the direction of the external static magnetic field, the polarization P can be defined in the same manner as for electric-dipole transitions. With the use of our measured results for I^+ and I^-, and the calculated value of C, we determined the polarization of the $^2S_{1/2}$ ionic ground state of the even isotopes of mercury to be approximately 15% in our experiment. We note that the sign of the ionic rf resonance signal reversed if we changed our observation at 2815 Å from I^+ to I^-. The signal disappeared when the 5461-Å metastable-state pumping light was turned off.

We are mainly interested, in this experiment, in the study of the phenomena of production of polarized ions and electrons. No special efforts were made therefore to determine accurately the spin-relaxation time of the ionic ground state. However, from the width of the observed rf resonance signal, it is found to be of the order of 10^{-5} sec.

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[1]S. D. Baker, E. B. Carter, D. O. Findley, L. L. Hatfield, G. C. Phillips, N. D. Stockwell, and G. K. Walters, Phys. Rev. Letters 20, 738 (1968).

[2]J. K. Mitchell and E. N. Fortson, Phys. Rev. Letters 21, 1621 (1968).

[3]L. D. Schearer, Phys. Rev. Letters 22, 629 (1969).

[4]M. V. McCusker, L. L. Hatfield, and G. K. Walters, Phys. Rev. Letters 22, 817 (1969).

[5]A. A. Kruithof and F. M. Penning, Physica 4, 430 (1937).

[6]N. P. Penkin and T. P. Redko, Opt. i Spectroscopiya 23, 650 (1967) [translation: Opt. Spectry. (USSR) 23, 353 (1967)].

[7]N. P. Penkin and T. P. Redko, Opt. i Spectroscopiya 20, 197 (1966) [translation: Opt. Spectry. (USSR) 20, 106 (1966)].

[8]R. E. Fox, J. Chem. Phys. 35, 1379 (1961).

[9]T. Hadeishi, O. A. McHarris, and W. A. Nierenberg, Phys. Rev. 138, A983 (1965).

[10]W. E. Bell and A. L. Bloom, Phys. Rev. Letters 6, 280 (1961).

[11]E. U. Condon and G. H. Shortley, The Theory of Atomic Spectra (Cambridge University Press, Cambridge, England, 1963), p. 95.

POLARIZATION EFFECT IN PHOTOIONIZATION OF CESIUM*

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Polarized cesium atoms were ionized by circularly polarized light. The cesium-ion intensities obtained with positive and negative photon helicities were measured at various wavelengths. The results demonstrate that the wave functions for the continuum states of cesium are perturbed by a spin-orbit interaction in accordance with the theoretical interpretations given by Seaton and Fano.

Recently Fano[1] predicted that the ionization of cesium atoms by circularly polarized light would produce spin-polarized photoelectrons. The basis of this prediction lies in the hypothesis set forth by Seaton[2] in 1951 that a spin-orbit interaction exists in the continuum state of the photoelectron before it becomes free of the field of the cesium ion. Seaton postulated this spin-orbit interaction in order to explain the anomalous behavior of the photoionization cross section of heavy alkali atoms. In the case of cesium, the cross section as a function of the photon energy, $\sigma(E)$, has a deep but nonzero minimum at approximately 0.8 eV above threshold.[3] Seaton argued that cross section calculations based on Hartree-Fock or central-potential wave functions "almost certainly" lead to a zero minimum. For a theoretical interpretation of the nonzero minimum he considered the wave-function perturbation arising from the interaction between the spin and orbital angular momentum of the outgoing electron.[4] Seaton's approach is similar to that used by Fermi in 1930 to resolve the line-strength anomaly in the doublets of heavy alkali atoms.[5,6] By assuming that the continuum P-state wave functions are similar to the discrete P-state wave functions at small radial distances, Seaton was able to obtain estimates for the minimum cross sections. For cesium and rubidium his results agree with the observed values within a factor of 2; for potassium, within a factor of 10. A critical comparison of estimates and measurements is precluded by the errors associated with both. More conclusive evidence of the spin-orbit interaction in continuum P states is certainly needed. This evidence, Fano pointed out, can be obtained through polarization measurements on the photoionization of cesium.

Fano suggested the measurement of the electron polarization, P_{el}, which results from ionization of unpolarized cesium atoms by circularly polarized light (photon polarization P_{ph}). This electron polarization is given by $P_{el} = P_{ph}P(E)$, where $P(E)$ is an energy-dependent polarization parameter determined experimentally. In the main part of his analysis Fano introduced a "perturbation parameter" x which is a function of the photon energy E. (The reader is referred to Fano's analysis for a theoretical interpretation of x.)[1,7] The polarization parameter P, averaged over all directions of photoelectron emission, can be expressed in terms of x as follows[7]:

$$P(x) \approx (2x+1)/(x^2+2), \tag{1}$$

where a term smaller than 0.01 has been neglected. Fano demonstrated that an estimate of $P(E)$ can be obtained with Eq. (1) and a first-order approximation of $x(E)$. From a semiempirical fit of $\sigma(E) = \sigma_{min}[1+\frac{1}{2}x(E)^2]$ to the measured cross-section curve, Fano found

$$x(E) \approx -(2\ \text{eV}^{-1})[E - E(\sigma_{min})], \tag{2}$$

where the minus sign of the coefficient results from theoretical considerations. Thus Fano's estimate of $P(E)$ is based on the assumption that the nonzero cross-section minimum is indeed caused by spin-orbit perturbation.[4] The immediate purpose of a polarization experiment on photoionization is a test of this assumption. Beyond that, polarization experiments can supply quantitative information about $x(E)$.

Our experiment is different from the one suggested by Fano. Instead of measuring the polarization of photoelectrons from unpolarized cesium atoms, we measured the counting rates of ions produced in the photoionization of polarized cesium atoms (electronic polarization of the atoms, P_{at}) by circularly polarized light of opposite helicities (photon polarization $+P_{ph}$ and $-P_{ph}$). The principle of our experiment is compared with that of Fano's proposal in Fig. 1.

In both experimental arrangements the observables are particle intensities I^+ and I^-, whose superscripts refer to different signs of the spin states preferentially transmitted in either a polarizer or an analyzer. In both cases the polarization effect, $\sigma = (I^+ - I^-)/(I^+ + I^-)$, gives the product of polarization and analyzing power. In Fano's proposal the photoionization with polarized photons is used as the electron polarizer; in our experiment it is used as the atom analyzer. In our experiment the analyzing power is given by $A_{at} = P_{ph}Q(E)$, where $Q(E)$ is another energy-dependent polarization parameter. With a derivation similar to that of Eq. (1), it can be shown that

$$Q(x) = (2x-1)/(x^2+2). \tag{3}$$

Unlike Eq. (1), Eq. (3) is an exact relation. Within the approximation of Eq. (1) the two polarization parameters are related by $P(x) = -Q(-x)$. Thus either one of the experiments illustrated in Fig. 1 can provide the information about the spin-orbit perturbation.

We decided to measure Q rather than P because previous experience with alkali atoms and polarized electrons[8,9] indicated that a better statistical accuracy could be obtained through a measurement of Q. The experimental arrangement is shown schematically in Fig. 2. A high-pressure mercury arc lamp was used as the light source. This lamp has a very intense line spectrum but a rather weak continuum spectrum. Therefore our first measurements were restricted to the wavelengths of the intense mercury

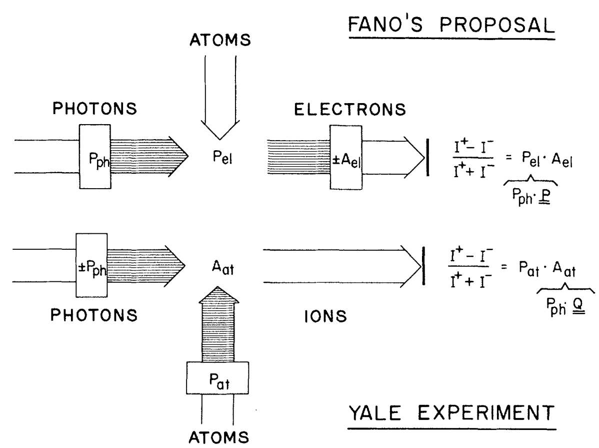

FIG. 1. Schematic illustration of the two polarization experiments which determine the parameters $\boldsymbol{P}$ and $\boldsymbol{Q}$. Particle beams are shown as arrows; polarized beams as hatched arrows. Boxes indicate polarizers (producing polarization P_i) and analyzers (having analyzing power A_i). In Fano's proposal the interaction is employed as an electron polarizer; in the Yale experiment, as an atom analyzer. The measured quantities are the intensities I^+ and I^- which are obtained with different signs either in polarization or in analyzing power.

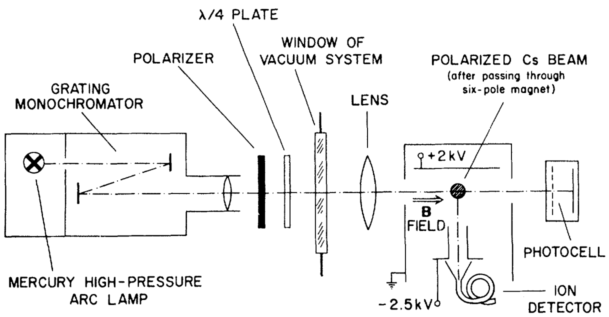

FIG. 2. Schematic diagram of the apparatus (not to scale).

lines.[10] The spectral resolution is determined by the variable slits in the grating monochromator. Data were taken with 60-, 30-, and 15-Å resolution. The polarization filters consist of dichroitic films evaporated onto quartz plates. The quarter-wave plate consists of two quartz-crystal sheets clamped together with their crystal axes oppositely oriented. These quartz sheets are of slightly different thickness, causing a wave retardation of $\frac{1}{4}\lambda$ at $\lambda = 2800$ Å. The degree of circular light polarization was determined as a function of wavelength in optical polarizer/analyzer measurements. Over the wavelength range covered, P_{ph} varied from 0.85 to 0.94. The sign of P_{ph} was determined by comparing the quarter-wave plate used in this experiment with another plate calibrated in an optical-pumping experiment.[11] Tests were made to insure that neither the lens inside the vacuum system nor the window which was exposed to a pressure difference of 1 atm affected the light polarization. The photocell current was recorded in order to correct the data for fluctuations in light intensity.

The atomic-beam system, consisting of oven, baffle, collimators, six-pole magnet, and hot-wire detector, is similar to that of the polarized electron source developed at Yale University.[8,9] The permanent six-pole magnet is 7 in. long with a gap of $\frac{1}{8}$-in. diam and a pole-tip field strength of about 8000 G. If the hyperfine structure (hfs) splitting of cesium were small, the six-pole magnet would produce almost complete selection of the high-field electronic states, m_s. In the weak field (2.5 G) of the ionization region the hfs coupling would reduce the electronic polarization of the atoms to the value of $1/(2I+1)$, where I is the nuclear spin. Since $I = \frac{7}{2}$ for cesium, the polarization would be reduced to 0.125. However, the hfs splitting of cesium is rather high; therefore, the field inside the six-pole magnet is not strong enough to completely decouple the electronic and nuclear spins. Thus the degree of high-field state selection depends on the nuclear magnetic quantum number, m_I, with a consequent increase of the weak-field electronic polarization. For our experiment we estimated $0.12 < P_{at} < 0.30$. The lower bound, $P_{at} > 0.12$, guarantees sufficient sensitivity for an experimental test of the existence of spin-orbit interaction in the continuum states. If this interaction exists, the function $P_{at}Q(E)$ can be determined. Since the extrema of $Q(E)$ must have the values $Q_{max} = +0.5$ for $x(E) = +2$ and $Q_{min} = -1.0$ for $x(E) = -1$, P_{at} can be determined indirectly if the photon energy range covered in the experiment includes at least one of the extrema.

Diatomic molecules can introduce substantial errors in alkali photoionization experiments.[8] Based on values for the molecular-photoionization cross sections,[12] the vapor pressures of Cs and Cs_2,[13] and estimates of the atom-focusing properties of the six-pole magnet, we conclude that at photon energies above the threshold for atomic ionization, the molecular ions contribute

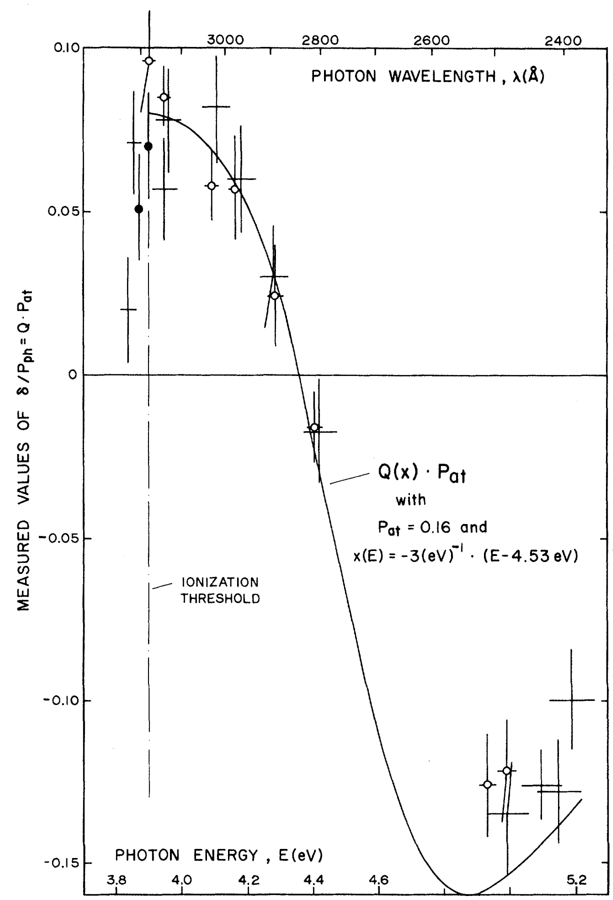

FIG. 3. Results of the polarization experiment on photoionization of cesium.

less than 1% to the counting rates.

The measured values of $\delta/P_{ph} = QP_{at}$ are given in Fig. 3 as points with 95%-confidence error bars. The data show that toward lower photon energies, the curve QP_{at} is cut off by the ionization threshold just before it goes through the maximum.[14,15] The other extremum, Q_{min}, seems to lie close to the data points at high photon energies, but not close enough for an unambiguous determination of P_{at}. The solid curve in Fig. 3 corresponds to $P_{at} = 0.16$, our best estimate for the atomic polarization, and to a linear function of $x(E)$ which fits the data points at low photon energies. The data points at high photon energies deviate from the solid curve, indicating a possible nonlinearity of $x(E)$.

Since the observed polarization effect displays an energy dependence consistent with the results of Fano's analysis, our measurements unequivocally confirm the existence of spin-orbit perturbation in the wave functions of the continuum P states of cesium.[16] With some obvious improvements in the experimental technique—elimination of background[10] and use of a more suitable light source—polarization experiments on photoionization will provide accurate values of $x(E)$ for the heavy alkali atoms. This information about the spin-orbit perturbation will be useful for a more quantitative interpretation of the various anomalies which have been explained as effects of such a perturbation.[6]

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[1]U. Fano, Phys. Rev. 178, 131 (1969).

[2]M. J. Seaton, Proc. Roy, Soc. (London), Ser. A 208, 418 (1951).

[3]G. V. Marr and D. M. Creek, Proc. Roy. Soc. (London), Ser. A 304, 233 (1968).

[4]In the absence of spin-orbit coupling, the cross section $\sigma(E)$ displays a zero minimum when the transition amplitude, determined by the radial matrix element $R(E)$, passes through zero. In the presence of a spin-orbit interaction, two different radial matrix elements, $R_3(E)$ and $R_1(E)$, have to be considered for the final-state angular momentum $j' = \frac{3}{2}$ and $\frac{1}{2}$, respectively. If R_3 and R_1 pass through zero at different photon energies, the cross section $\sigma \propto 2R_3^2 + R_1^2$ will have a nonzero minimum.

[5]E. Fermi, Z. Physik 59, 680 (1930).

[6]G. zu Putlitz, "On Fermi's Paper Concerning Spin-orbit Perturbation and the Intensity Ratios of Doublet Lines in Heavy Alkalis" (to be published).

[7]U. Fano, to be published.

[8]R. L. Long, Jr., W. Raith, and V. W. Hughes, Phys. Rev. Letters 15, 1 (1965).

[9]V. W. Hughes, M. S. Lubell, M. Posner, and W. Raith, in Proceedings of the Sixth International Conference on High Energy Accelerators, Cambridge, Massachusetts, September, 1967 (unpublished), p. A144.

[10]We observed a rather high background counting rate when the atomic beam was "on" and the light beam "off." We believe that the effect results from cesium atoms which are surface ionized at the electrode opposite the ion detector. This background does not introduce any errors in the data because it was measured separately and the data corrected accordingly. However, this effect prevented measurements at wavelengths at which the light source yields low intensity.

[11]The optical-pumping experiment was performed by Dr. E. Ensberg, whose cooperation we gratefully acknowledge.

[12]D. M. Creek and G. V. Marr, J. Quant. Spectr. Radiative Transfer 8, 1431 (1968).

[13]A. N. Nesmeyanov, Vapour Pressure of the Chemical Elements (Elsevier Publishing Company, Amsterdam, The Netherlands, 1963), p. 445.

[14]The curves $Q(E)$ and $P(E)$ cannot simply be extrapolated to photon energies below threshold because the states of different angular momenta are degenerate above threshold, but not below.

[15]When the photon energy was decreased below the threshold value a sharp drop in counting rate occured, but the signal was still high enough for several δ measurements below threshold. These data are included in Fig. 3 although at present we do not understand the processes which lead to ionization below threshold.

[16]In terms of the radial matrix elements mentioned in Ref. 4, our results show that the zero transitions of $R_3(E)$ and $R_1(E)$ which occur at $x = +2$ and $x = -1$, respectively, are separated by about 1 eV in photon energy.