

# Angular Distribution of Photoelectrons

Cite as: J. Chem. Phys. **48**, 942 (1968); <https://doi.org/10.1063/1.1668742>

Submitted: 28 August 1967 . Published Online: 05 September 2003

J. Cooper, and R. N. Zare



View Online



Export Citation

## ARTICLES YOU MAY BE INTERESTED IN

[Velocity map imaging of ions and electrons using electrostatic lenses: Application in photoelectron and photofragment ion imaging of molecular oxygen](#)

Review of Scientific Instruments **68**, 3477 (1997); <https://doi.org/10.1063/1.1148310>

[Two-dimensional charged particle image inversion using a polar basis function expansion](#)

Review of Scientific Instruments **75**, 4989 (2004); <https://doi.org/10.1063/1.1807578>

[Time-of-Flight Mass Spectrometer with Improved Resolution](#)

Review of Scientific Instruments **26**, 1150 (1955); <https://doi.org/10.1063/1.1715212>

Lock-in Amplifiers  
up to 600 MHz



## Angular Distribution of Photoelectrons\*

J. COOPER AND R. N. ZARE†

Joint Institute for Laboratory Astrophysics,‡ Boulder, Colorado

(Received 28 August 1967)

Recently, by means of photoionization and photo-detachment measurements (so-called "photoelectron spectroscopy"), it has been possible to obtain important quantities such as ionization potentials, electron affinities, cross sections for electron photoejection, relative transition probabilities to excited states, etc.<sup>1-9</sup> However, lack of knowledge of the angular distribu-

tion of ejected electrons has hampered really accurate measurements in most of these experiments.

We outline a simple calculation for determining the photoelectron differential cross section. For linearly polarized light the angular distribution has the general form

$$d\sigma/d\Omega = (\sigma_{\text{total}}/4\pi) [1 + \beta P_2(\cos\theta)], \quad (1)$$

where  $P_2(\cos\theta) = \frac{1}{2}(3\cos^2\theta - 1)$ ,  $\sigma_{\text{total}}$  represents the total cross section,  $\theta$  measures the angle between the direction of the ejected electron and the polarization of the incident light.  $\beta$  is an asymmetry parameter, given for an  $l$  (e.g.,  $s$ ,  $p$ ,  $d$ , ...) state by

$$\beta = \frac{l(l-1)\sigma_{l-1}^2 + (l+1)(l+2)\sigma_{l+1}^2 - 6l(l+1)\sigma_{l+1}\sigma_{l-1}\cos(\delta_{l+1} - \delta_{l-1})}{3(2l+1)[l\sigma_{l-1}^2 + (l+1)\sigma_{l+1}^2]}. \quad (2)$$

Here  $\beta$  ranges from  $\beta = 2(d\sigma/d\Omega \sim \cos^2\theta)$  to  $\beta = -1(d\sigma/d\Omega \sim \sin^2\theta)$ . In Eq. (2)  $\delta_l$  is the phase shift of the  $l$ th partial wave and

$$\sigma_{l\pm 1} = \int_0^\infty R_{nl} r R_{k,l\pm 1} dr$$

is the usual dipole radial matrix element. Equation (2) has been derived by Bethe<sup>10</sup> for a one-electron atom, but can apply to many electron atoms (even for equivalent  $l$ -electrons) provided the magnetic sublevels of the initial state are equally populated and the wavefunctions are represented by antisymmetrized products of spin orbitals. The same form as Eq. (1) is obtained

in the presence of configuration interaction and intermediate coupling. Averaging over the rotational orientations of molecules also gives this form.

Numerical calculations have been carried out for several negative ions ( $\text{C}^-$ ,  $\text{O}^-$ ,  $\text{F}^-$ ,  $\text{I}^-$ ) using the Robinson and Geltman<sup>11</sup> potential, which is adjusted to give the correct binding energy. For the photoejection of an  $s$ -type electron, as in  $\text{H}^-$ , only an outgoing  $p$  wave results. Then from (2) the angular distribution shows a  $\cos^2\theta$  behavior for all photon energies. For the photoejection of a non- $s$ -type electron, two competing outgoing channels exist and the form of the anisotropy will depend on the interference

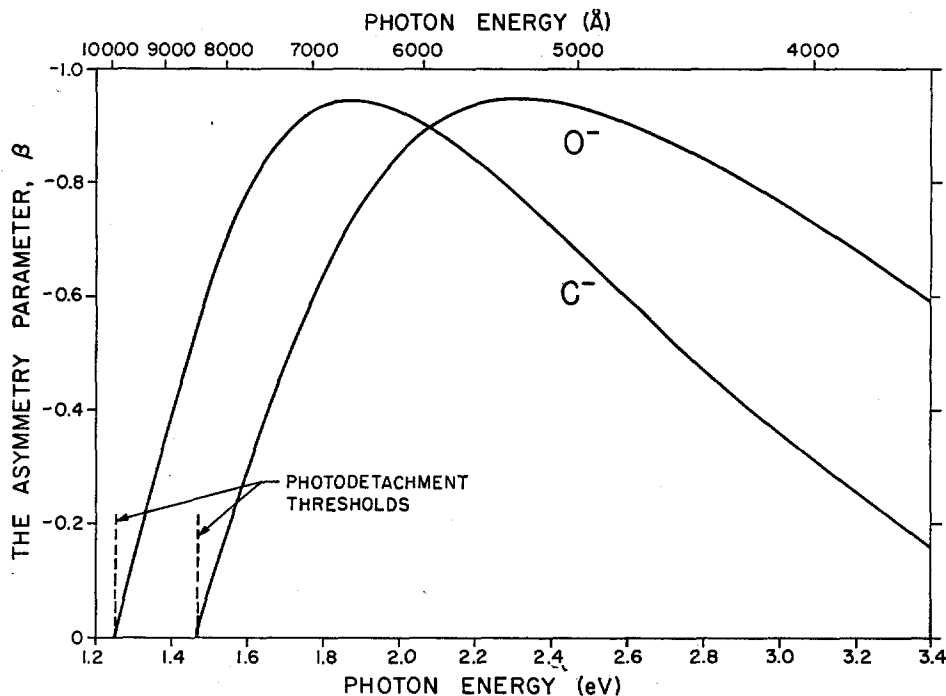


FIG. 1. The asymmetry parameter  $\beta$  as a function of photon energy for the photodetachment processes:  $\text{C}^-(^4S) + h\nu \rightarrow \text{C}(^3P) + e^-$ , and  $\text{O}^-(^2P) + h\nu \rightarrow \text{O}(^3P) + e^-$ . For unpolarized light the angular distribution is still represented by Eq. (1) if  $\beta$  is replaced by  $-(1/2)\beta$  and if  $\theta$  measures the angle between the ejected electron and the light beam.

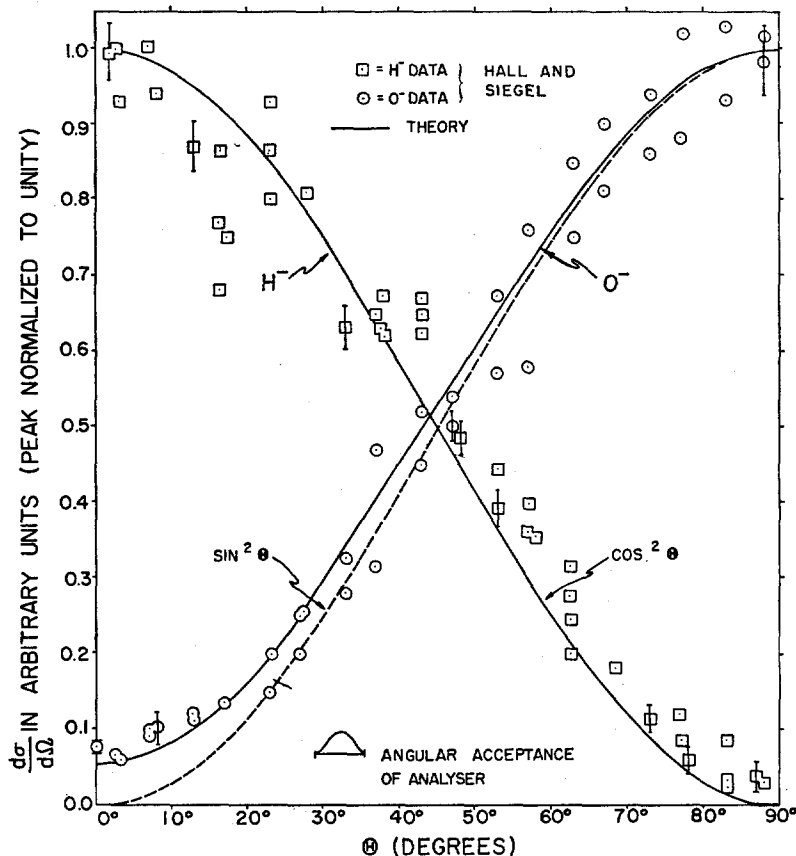


FIG. 2. Comparison of calculated and observed photoelectron distributions from  $H^-$  and  $O^-$ . The experimental measurements were obtained by Hall and Siegel<sup>12</sup> by passing a negative ion beam through the cavity of a high-power CW argon-ion laser operated at  $\lambda=4880 \text{ \AA}$ .

between the  $l'=l\pm 1$  partial waves. Results for the ejection of a  $p$  electron from  $C^-$  and  $O^-$  (typical of the negative ions investigated) are shown in Fig. 1. The remarkable finding is that for an energy of several electron volts close to threshold, the angular distribution of these photodetachment electrons is predicted to peak at right angles to the polarization vector, rather than along the polarization vector. At threshold,  $d\sigma/d\Omega$  is isotropic (see Fig. 1), as only outgoing  $s$  waves contribute, and far from threshold,  $d\sigma/d\Omega$  tends toward a  $\cos^2\theta$  distribution. However, preliminary calculations for photoionization of argon, krypton, and xenon show, a few volts from threshold, only positive  $\beta$  values, in qualitative agreement with Ref. (7).

Figure 2 compares our calculated angular distribution for the photodetachment of  $H^-$  and  $O^-$  with the experimental data of Hall and Siegel.<sup>12</sup> We conclude that measurements which are sensitive to the form of the photoelectron angular distribution (particularly for non- $s$  electrons) should be carefully examined for possible systematic errors.

\* Work supported by the Advanced Research Projects Agency (Project DEFENDER), monitored by the U.S. Army Research Office, Durham, under Contract DA-31-124-ARO(D)-139.

† Alfred P. Sloan Fellow.

‡ Of the University of Colorado and the National Bureau of Standards.

<sup>1</sup>B. L. Kurbatov, F. I. Vilesov, and A. N. Terenin, Dokl. Akad. Nauk SSSR **138**, 1329 (1961); **140**, 797 (1961) [English transl.: Soviet Phys.—Doklady **6**, 490, 883 (1961)].

<sup>2</sup>D. W. Turner and M. I. Al-Joboury, J. Chem. Phys. **37**, 3007 (1962). M. I. Al-Joboury, D. P. May, and D. W. Turner, J. Chem. Soc. **1965**, 616.

<sup>3</sup>R. I. Schoen, J. Chem. Phys. **40**, 1830 (1964).

<sup>4</sup>F. J. Comes and H. G. Sälzer, Z. Naturforsch. **19a**, 1230 (1964).

<sup>5</sup>D. C. Forst, C. A. McDowell, and D. A. Vroom, Phys. Rev. Letters **15**, 612 (1965).

<sup>6</sup>A. J. Blake and J. H. Carver, Phys. Letters **19**, 387 (1965).

<sup>7</sup>J. Berkowitz and H. Ehrhardt, Phys. Letters **21**, 531 (1966); J. Berkowitz, H. Ehrhardt and T. Tekaat, Z. Physik **200**, 69 (1967).

<sup>8</sup>L. M. Branscomb, Atomic and Molecular Processes. D. R. Bates, Ed. (Academic Press Inc., New York, 1962), p. 100ff.

<sup>9</sup>B. Brehm, M. A. Gusinow, and J. L. Hall, Phys. Rev. Letters **19**, 737 (1967).

<sup>10</sup>H. A. Bethe, Handbuch der Physik (Springer-Verlag, Berlin, 1933), Vol. 24, p. 483-484.

<sup>11</sup>E. J. Robinson and S. Geltman, Phys. Rev. **153**, 4 (1967).

<sup>12</sup>J. L. Hall and M. W. Siegel, J. Chem. Phys. **48**, 943 (1968), following Communication.

## Angular Dependence of the Laser Photodetachment of the Negative Ions of Carbon, Oxygen, and Hydrogen\*

J. L. HALL AND M. W. SIEGEL

Joint Institute for Laboratory Astrophysics of the National Bureau of Standards and The University of Colorado, Boulder, Colorado

(Received 23 October 1967)

In the preceding Communication, Cooper and Zare<sup>1</sup> show that in certain cases photodetachment differ-