

Photoelectric K -Absorption Cross Section of Beryllium*

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The continuous photoelectric absorption cross section of Be has been measured for photon energies extending from the K edge energy, at 110 eV, to 180 eV. The measurements were carried out by the application of technical improvements which included a more precise electronic method for determining the surface density of absorbers and auxiliary equipment for transferring samples into the spectrograph without exposure to air. The theoretical results of the atomic photo-ionization cross section are also included for reference. The present data are compared with earlier measurements. The cross section ranges from a value of 1.01 Mb at 99.6 Å to a value of 0.63 Mb at 71.5 Å.

I. INTRODUCTION

THE present experimental investigation of the photoelectric absorption cross section of beryllium was prompted by several considerations. First, advantage was taken of the electronic method recently applied¹ to the determination of surface densities of thin layers of lithium deposited in vacuum. Secondly, unlike the technique used in previous studies,^{2,3} an evaporation assembly was attached to the grazing incidence spectrograph thereby making it possible to prepare absorbers in a good vacuum, to observe their surface densities and to irradiate them without exposure to air. Furthermore, experimental observations on the high-energy side of the lithium⁴ K discontinuity indicated an interesting agreement with atomic photo-ionization cross sections made available by recent calculations.⁵ It is the purpose of this paper to present measurements of the absolute photoelectric absorption cross section for beryllium at photon energies in excess of the K -ionization threshold.

II. EXPERIMENTAL

A. The Spectrograph

The essential features of the instrumental arrangement may be found in reference 4 and will not be repeated here. The source of radiation was a condensed spark discharge in a Pyrex capillary. The source characteristics and the declining grating response were such that lines at wavelengths shorter than 70 Å were not sufficiently intense for the purpose of making reliable intensity comparisons using photographic detection. Hence the observations were limited to the wavelength

region extending from 70 Å to the vicinity of the K edge at 110 Å.

B. Absorber Preparation

The absorber support was a small aluminum frame to which an electroformed nickel mesh⁶ had been cemented. A plastic (Zapon) film placed over the mesh served as the primary substrate for the deposition of beryllium which was evaporated from metal chips heated in a 20-mil tungsten conical basket. The deposition of the metal onto the backing was monitored by means of a quartz crystal placed alongside the absorber. The monitoring was based on the decrease in resonant frequency of the crystal resulting from an increase of mass⁷ condensed on the crystal. Deposition of 100 Å of Be corresponded to a resonant frequency change of 102 cps which could be detected easily as a variation in the difference frequency (several kilocycles/sec) between the outputs of two oscillator circuits. In one of these circuits, the monitoring crystal served as the frequency control element; while in the other a similar crystal mounted in a vacuum acted as the master frequency reference. The output of the master was constant to within a few cycles during the short times required for evaporations. The relationship between deposited mass and natural resonant frequency was determined by making an interferometric measurement⁸ of the thickness of an aluminum thin film deposited on a glass slide. This evaporation was performed in the system used for the Be evaporation. When a direct calibration was attempted using beryllium, it was observed that, in the early stages of the evaporation, the beryllium did not condense on the crystal face and on the test plate at the same rate. This type of behavior is not expected in the deposition of the beryllium layer which constitutes the absorber. In the latter case, the crystal as well as the absorber substrate have a coating of the metal prior

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¹D. J. Baker, Jr., and D. H. Tomboulian, *Bull. Am. Phys. Soc.* **7**, 70 (1960).

²R. W. Johnston and D. H. Tomboulian, *Phys. Rev.* **94**, 1585 (1954).

³A. P. Lukirskii, *Doklady Akad. Nauk, S.S.S.R.*, **25**, 910 (1961).

⁴D. J. Baker, Jr., and D. H. Tomboulian, *Phys. Rev.* **128**, 677 (1962).

⁵A. Burgess and M. J. Seaton, *Monthly Notices Roy. Astron. Soc.* **120**, 121 (1960).

⁶The mesh had 100 lines per inch and was used as a support for the fragile films. The mesh was purchased from the Buckbee Mears Co., Toni Building, St. Paul, Minnesota.

⁷S. J. Lins and H. S. Kukuk, *Transactions of the Vacuum Symposium, 1960* (Pergamon Press, New York, 1960), p. 333.

⁸G. D. Scott, T. A. McLaughlan, and R. S. Sennett, *J. Appl. Phys.* **21**, 843 (1950).

to the deposition and the measurement of the actual absorbing layers.

C. Experimental Procedures

The general procedures for absorption measurements have been reported in detail by one of the authors.⁹ Two significant departures from the usual methods were made in the present work. Previously, it was customary to prepare two identical absorber substrates and evaporate the desired element onto the surface of one; then during the operation of the source either the substrate alone or the substrate with absorbing layer could be introduced interchangeably into the beam. This intermixing of exposures was done in order that any long-term variations in the source intensity distribution be reflected both in the I_0 (substrate only) and I (absorber plus substrate) spectra.

The use of a single absorber assembly required completion of the I_0 exposure in one uninterrupted operation followed by the withdrawal of the assembly from the spectrograph to the evaporation chamber for deposition of the extra absorbing layer. The sample was then returned to the spectrograph for the I exposure. This type of experimental procedure requires that the relative intensity distribution of lines in the source be reproducible. Consistency was explored by following the usual sequence of exposure, removal, and re-exposure as described directly above except that the absorbing layer was not evaporated onto the substrate. This operation gave two I_0 spectra which were taken about an hour apart and the line intensities were found to be reproducible to within about 5%.

The second variation in procedure was that the reference spectrum was obtained by using an absorber consisting of a substrate plus a few hundred angstroms layer of Be. Thus the absorbing Be layer was evaporated onto a Be surface in the hope that the recorded absorption would be indicative only of the beryllium layer and not reflect anomalous interface effects which might arise from the metal-plastic or metal-vacuum boundaries. The present scheme for obtaining the surface density of the absorber involves the tacit assumption that the metal is collected at the same rate by the monitoring crystal and by the absorber surface. The presence of a "priming" layer of beryllium on both surfaces is a situation which is most favorable for attaining the desired equality in the condensation rates.

In addition to the light (of all wavelengths) scattered from the surface of the glass grating at grazing angles of incidence, visible and near ultraviolet light is refracted into the body of the grating blank and subsequently again appears as scattered radiation. The combined scatter from the grating can result in an undesirable background, specially when the source has considerable intensity in the visible. To minimize the effects due

to background, the exposures had to be kept relatively short. This requirement imposed the limitation that the absorbing layer had to be less than 1200 Å thick, which in turn meant that a larger error had to be tolerated in the measurement of the surface density of mass.

III. RESULTS AND DISCUSSION

The atomic absorption cross section σ is given by

$$\sigma = \ln(I_0/I) / N \text{ cm}^2, \quad (1)$$

where I_0 is the intensity of the radiation incident on an absorber with a surface density of N atoms/cm² and where I is the emergent intensity. Experimentally, the ratio (I_0/I) is obtained by comparing the incident and emergent intensities by a photometric reduction of the spectrograms. For the experimental arrangement, the calibration of the crystal led to the relation

$$N = 17.6 \times 10^{14} \Delta f \text{ atoms/cm}^2, \quad (2)$$

where Δf is the change in the frequency of the oscillator governed by the evaporation of metal on the monitoring crystal. In spite of the rather delicate techniques involved, three runs were successful and yielded independent determinations of the attenuation $\ln(I_0/I)$ for every suitable spectral line. The mixing of the I_0 and I exposures and the deposition of the absorbing layer at pressures considerably lower than 10^{-6} Torr would have constituted additional refinements in carrying out the measurements. The first of these was inherently impossible under the procedures of sample preparation adopted intentionally. However, the small concentration of impurity atoms trapped in the absorbing layers could have been reduced further by adopting improved high-vacuum techniques.

To test the internal consistency of the results derived from the various runs, the attenuation for every spectral line was plotted as a function of Δf , the change in the frequency of the monitoring oscillator. Typical plots of this kind are seen in Fig. 1. The slope of the straight

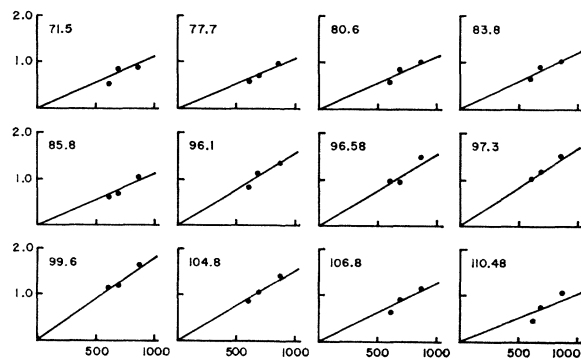


FIG. 1. Representative plots of the natural logarithm of the ratio of incident to transmitted intensity [$\ln(I_0/I)$] as a function of total oscillator frequency change (Δf). Each plot represents a different incident photon wavelength (in Angstroms) noted in the upper left corner.

⁹ D. H. Tomboulian, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 30, p. 246.

TABLE I. The experimental values of the K -absorption cross section of beryllium.

Wavelength (Å)	Cross section (Mb)	Wavelength (Å)	Cross section (Mb)
71.5	0.63	91.0	0.66
77.7	0.61	91.5	0.60
80.6	0.64	96.1	0.89
80.9	0.65	96.6	0.88
83.3	0.67	97.3	0.94
83.8	0.69	99.6	1.01
85.3	0.69	100.6	0.83
85.8	0.64	104.8	0.87
90.7	0.67	106.8	0.71
		110.5	0.59

line from the origin through the various points is represented by $17.6 \times 10^{14} \sigma$ and the value of σ for the given wavelength was computed from this slope. Inspection of the contents of Fig. 1 indicate that the individual determinations on the average exhibit a deviation of 5% from the straight line. The experimental cross sections evaluated as above are collected in Table I. A plot of σ against the wavelength of incident photons is shown in Fig. 2.

In calculating the atomic photoionization cross section a slight modification was introduced in the quantum defect method described by Burgess and Seaton.⁵ The approach is semiempirical in that one-electron wave functions are parametrized by means of term values¹⁰ arrived at experimentally. The scheme is generally applicable to outer electron ionization and the resulting change in core-electron wave functions is regarded to have a negligible effect on the prediction. Considering the absorber to be a collection of Be atoms with tightly bound K electrons and loosely bound outer electrons, then it is appropriate to use the Burgess and Seaton method utilizing term values belonging to doubly ionized Be. The influence of the vacancy in the core is

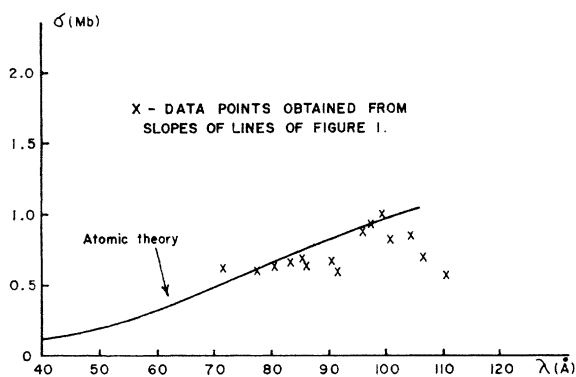


FIG. 2. The absolute values of the experimental cross sections are shown along with the curve calculated from the semi-empirical theory.

¹⁰ C. E. Moore, *Atomic Energy Levels*, National Bureau of Standards, Circular No. 467 (U. S. Government Printing Office, Washington, 1949), Vol. I, p. 12.

included in the calculations by considering the $2s$ overlap integrals. The latter contain hydrogenic wave functions with Slater's effective charges.¹¹ The procedure involves the adiabatic hypothesis, namely, that the perturbing energy is sufficiently larger than the energy difference involved in the shift from wave functions with effective charge Z_1e to those with effective charge Z_2e . In our case the incident photon energy exceeds 10 Ry while the difference due to the change in wave functions is less than 1 Ry.

The ionization energy for Be^{++} is 153.8 eV. For those wavelengths ($\lambda > 80.6 \text{ \AA}$) for which the incident photon energy is less than the ionization energy, that is for transitions involving bound states to bound states, the cross section was computed from the modified Burgess-Seaton formula by the inclusion of negative energy values.¹² The cross section obtained in this way increases monotonically with the wavelength and does not show structure. Along with the experimental points, the outcome of calculations based on the above considerations is shown as the solid line of Fig. 2. The fluctuation in the data near 90 Å is probably associated with the fine structure. Similar behavior is observed in connection with the K absorption spectrum of Li.⁴

Earlier measurements² of the Be K absorption were carried out using photographic registration and with a spark discharge source resembling the one used in the present work. The absorbing samples, comprised of thick unsupported Be foils and of Be layers evaporated onto a supporting substrate, were prepared in a separate vacuum system and were unavoidably exposed to air while being transferred to the spectrograph. The foil thicknesses were estimates based on the evaporation geometry and on the bulk density. A comparison of the earlier results with the present observations (See Fig. 3) indicates considerable divergence which probably arises from the presence of impurities and effectively from a much less precise thickness determination.

More recently, Lukirskii³ investigated the K absorption by irradiating the samples with the filtered continuous spectrum from a tungsten anode operated at 5kV. The radiation was detected by a GM counter. The absorbers used by him were presumably free from organic substrates since attempts were made to dissolve the celluloid film on which the metal was deposited. The samples were again exposed to air prior to introduction into the spectrograph. For the I_0 runs the source intensity was reduced materially, presumably by a constant but unknown factor. This circumstance, combined with the absence of information on the thickness or surface density of foils makes it impossible to arrive at absolute values of the cross section and the results are expressed in terms of $\ln(I_0/I)$ with an arbitrary zero.

¹¹ J. C. Slater, *Phys. Rev.* **36**, 57 (1930).

¹² H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms* (Academic Press Inc., New York, 1957), p. 298.

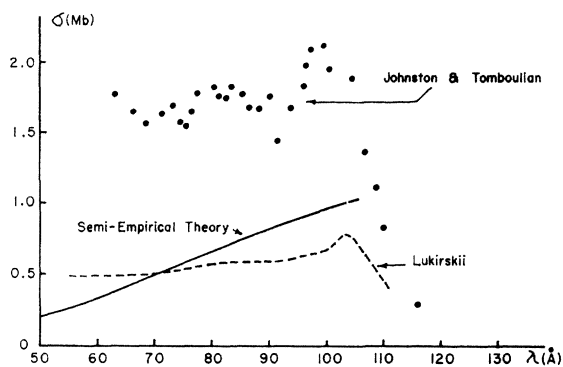


FIG. 3. A comparison of the results of earlier experiments with theory. The Lukirskii curve arbitrarily matched at 70\AA is presented for comparison of shape only.

Hence, one can only compare shapes of absorption curves and to do so we have arbitrarily normalized his curve to match the calculated cross section at 70\AA . As

seen in Fig. 3, the previous experimental results show a wavelength dependence which is at variance not only with that of the present determination but also with the general trend indicated by the results of calculations based on atomic theory.

The evidence suggests that surface contamination has a noticeable effect on the shape of the absorption curve. To verify this point, we carried out a determination of the absorption by the present instrumentation on a sample which intentionally was exposed to air for a short time. The observations indicated that such an exposure increased the magnitude of the individual values of the cross section and the shape of the absorption curve was distorted so as to approach that found in the earlier results.

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Alkali Polarizabilities by the Atomic Beam Electrostatic Deflection Method*†

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The electric dipole polarizabilities of the alkali atoms have been measured by observing the deflection of a collimated beam of neutral atoms in a two-wire-type inhomogeneous electric field. Beam deflection measurements are taken both for the case when s_B , the deflection of atoms with the most probable velocity in the source, is larger than the detector wire width w_d , and for $s_B < 0.1w_d$. The results in units of 10^{-24} cm³ are: $\alpha(\text{Li}) = 22 \pm 2$, $\alpha(\text{Na}) = 21.5 \pm 2$, $\alpha(\text{K}) = 38 \pm 4$, $\alpha(\text{Rb}) = 38 \pm 4$, and $\alpha(\text{Cs}) = 48 \pm 6$. These values are in reasonable agreement with other recent experimental and theoretical determinations of the alkali polarizabilities.

1. INTRODUCTION

KNOWLEDGE of the electric dipole polarizability α of atoms is of interest because of the direct relationship to excited state lifetimes, line strengths, and van der Waals interaction forces. Also, a comparison with experimental values affords a test of various approximation methods and wave functions used in the calculation of atomic properties.

The first atomic beam measurement of the dipole polarizabilities of the alkalis was done by Scheffers and Stark. In their measurements¹ a beam of atoms was deflected in a radial electric field and the polarizability

was deduced from an analysis of the deflected beam pattern. We had also reported² values obtained from the measured deflection of an atomic beam by an electric field which provides a uniform deflecting force for all atoms in the beam. Recently, however, Salop, Pollack, and Bederson have measured α for each alkali in terms of its effective magnetic moment with an atomic beam method in which electric and magnetic forces are balanced in congruent E and H fields, and in which the results are independent of the distribution of velocities in the beam.³ Their values are noticeably higher than the results from the earlier deflection experiments. Because of this we have done the experiment described here⁴ which is an improved version of our earlier work.

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† Based on a dissertation submitted by G. E. Chamberlain in fulfillment of the Ph.D. thesis requirement at Yale University.

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¹ H. Scheffers and J. Stark, *Physik Z.* **35**, 625 (1934).

² G. E. Chamberlain and J. C. Zorn, *Bull. Am. Phys. Soc.* **5**, 241 (1960).

³ A. Salop, E. Pollack, and B. Bederson, *Phys. Rev.* **124**, 1431 (1961).

⁴ G. E. Chamberlain and J. C. Zorn, *Bull. Am. Phys. Soc.* **7**, 70 (1962).