Measurement of the absolute photoionization cross section of the $3p\ ^3P^o$ term of neutral magnesium

Gabriel G. Lombardi,* Peter L. Smith, and W. H. Parkinson
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
(Received 3 November 1980)

The photoionization cross section of the metastable $3p\ ^3P^o$ term of neutral Mg was measured at $\lambda = 248.6$ nm, near threshold. The Mg vapor was produced in a pulsed, hollow cathode, discharge tube. The density of metastable Mg atoms was determined by using the hook method. The cross section was determined by a photoelectric measurement of the absorption of light by the Mg vapor. The result is (46 ± 12) Mb. This value is larger than that derived from quantum-defect-theory calculations and from a previous measurement. Use of the larger value in models of the solar chromosphere improves the agreement with the observed solar spectrum.

I. INTRODUCTION

Various calculations[1,2] and the single measurement[3] of the photoionization cross section of the metastable, $3p\ ^3P^o$ term of neutral Mg differ by a factor of 2. Furthermore, the absolute scale of the measurement of Bötticher[3] relies upon an oscillator strength which is not known with high precision.

This cross section is required for models of the solar chromosphere[1,4] since Mg is an important source of opacity for wavelengths between 251 and 207 nm. The purpose of our experiment was to measure the cross section by a method different from that of Bötticher in an effort to resolve the discrepancies among the various values.

II. EXPERIMENT

The photoionization cross section was determined by measuring the optical depth, τ, of a known column density of Mg atoms in the $3p\ ^3P^o$ metastable term. Column density is defined by

$$N = \int_0^l n(x)dx\ , \tag{1}$$

where $n(x)$ is the number density of metastable Mg atoms at a point x in a column of length l. Optical depth is defined by the relation $\tau = N\sigma$, where σ is the photoionization cross section; i.e., if photoionization is the only absorption process, then light passing through a column density, N, of atoms is attenuated by a factor of $e^{-\tau}$. A similar technique has been used in our laboratory to measure photoionization cross sections of chromium,[5] iron,[6] and aluminum.[7]

A hollow cathode discharge[8] was used to produce the Mg vapor. In addition to the discharge tube, the apparatus consisted of a Mach-Zehnder interferometer coupled with a stigmatic, 3-m spectrograph-spectrometer. These basic components are described elsewhere.[9] The hollow cathode tube used is of the slot geometry[10,11] (Fig. 1). The cathode consisted of a cylindrical Mg rod, 30 cm in length and 3.5 cm in diameter, with a 2-mm wide by 6-mm deep slot cut parallel to the cylinder axis. The anode consisted of a steel screen spot welded to a steel frame. It was suspended approximately 5 mm from the cathode by Teflon discs at each end. The cathode and anode were inside a Pyrex pipe. The discharge tube was placed in one beam of the interferometer such that the center of the slot was co-aligned with the optical axis of the interferometer.

The hollow cathode tube was operated at 0.8-A dc with 250 Ω of ballast resistance in series. The tube was pulsed at a current of 10.5 ± 0.5 A by discharging a 120-μF capacitor, charged to 600 V, across the discharge tube with 35-Ω ballast resistance in series. The pulse was initiated by triggering a 1000 V, silicon controlled rectifier connected in series. The current pulse had a rise time of approximately 20 μs, and decayed exponentially with a time constant of 5 ms. The tube was operated with flowing Ar buffer gas at a pressure of 1.09 ± 0.02 Torr. The pressure was monitored with a capacitance manometer. The current in the discharge tube was determined by measuring, with an oscilloscope, the voltage across a 10-Ω resistor.

The hook method of interferometry[12,13] was used to determine the column density of atoms in the levels of the $^3P^o$ term by applying the equation

$$N_i = \frac{\pi K \Delta_{ij}^2}{r_0 \lambda_{ij}^3 f_{ij}}\ , \tag{2}$$

where N_i is the column density of atoms in the lower level of a transition, λ_{ij} is the wavelength of the transition, f_{ij} is its oscillator strength, $r_0 \equiv e^2/mc^2 = 2.82 \times 10^{-13}$ cm, Δ_{ij} is the hook separation, and K is the hook method parameter. Spectrally dispersed interferograms (hook spectra) were recorded on Kodak 2475 High Speed Record-

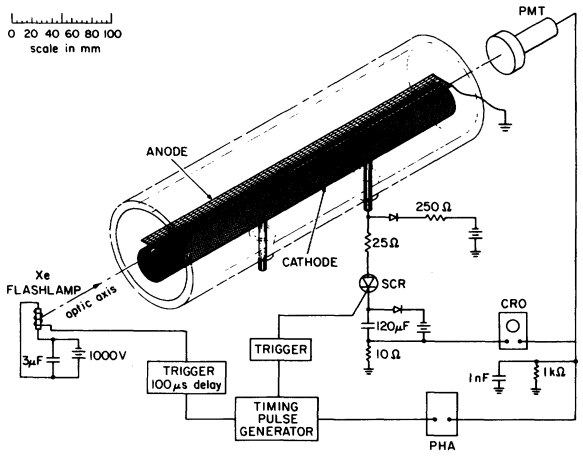

FIG. 1. Isometric drawing, approximately to scale, of the hollow cathode tube with a schematic of the accompanying electronics.

ing Film. A xenon flashlamp (EG&G model FX-12C-0.25), operated by discharging a 3-μF capacitor charged to 1000 V, was used as a background continuum light source for the hook spectra (wavelength near 384 nm) and for the optical depth measurements (near 250 nm). The flashlamp intensity had a rise time of less than 2 μs and a decay time of approximately 5 μs. Approximately 100 flashes were required to expose the film adequately using a spectrograph entrance slit of 100 μm. The $3p\,^3P^o$-$3d\,^3D$ multiplet at 384 nm was used for the column density determination. The films were read on a comparator and the data were reduced as described previously.[14,15] At a particular gas pressure and discharge current, the column density was found to be reproducible to within the uncertainties of the measurement.

For the optical depth measurements, light from the Xe flashlamp passed through the Mg vapor, entered the spectrometer through a 1 mm slit, and was detected with an EMR 542-F photomultiplier tube (PMT) operated with a 60-μm slit over the photocathode. The spectral resolution was 0.12 nm. The PMT signal was smoothed with a time constant of 1 μs, amplified, and stored in a pulse height analyzer (PHA). The linearity of the PMT-PHA combination was checked by using calibrated, metal mesh filters to attenuate the light from the flashlamp.

For each firing of the hollow cathode tube, the xenon flashlamp was fired twice: once, 100 μs after the beginning of the hollow cathode current pulse, and again after the end of the pulse. The PHA memory was divided into halves of 512 channels, and data were collected in groups of 100 counts in each half of the PHA and printed on a teletype. This permitted comparison of the PMT signal with a large and with a small amount of Mg vapor in the optical path. This comparison was made at two wavelengths: $\lambda_s \equiv 248.6$ nm (shortward of the photoionization threshold for the $^3P^o$ term at 251.4 nm) and $\lambda_l \equiv 258.2$ nm (longward of the threshold).

Let $I(\lambda)$ denote the intensity of light, unattenuated by the Mg vapor, reaching the PMT at wavelength λ. The signal $S(\lambda)$, i.e., the channel number, recorded by the PHA is

$$S(\lambda) = G(\lambda) I(\lambda) e^{-N\sigma} + Q(\lambda), \tag{3}$$

where $G(\lambda)$ represents the gain of the PMT and amplifier, σ is the photoionization cross section of the $^3P^o$ term, and $Q(\lambda)$ includes the plasma emission and electrical noise generated by pulsing the hollow cathode tube. Electrical noise was observed, with the oscilloscope, in the signal cable from the PMT. However, the plasma emission signal was negligible compared to the xenon flashlamp signal. As a result, one would expect $Q(\lambda)$ to be wavelength independent. This hypothesis was checked by determining $Q(\lambda_l)$ and $Q(\lambda_s)$ (cf. Sec. III).

III. DATA ANALYSIS AND RESULTS

At λ_s and λ_l, S_1 and S_2 were recorded by the PHA:

$$S_1(\lambda_s, \alpha) = G(\lambda_s) I(\lambda_s, \alpha) e^{-N_1\sigma}, \tag{4a}$$

$$S_2(\lambda_s, \beta) = G(\lambda_s) I(\lambda_s, \beta) e^{-N_2\sigma} + Q(\lambda_s), \tag{4b}$$

$$S_1(\lambda_l, \gamma) = G(\lambda_l) I(\lambda_l, \gamma), \tag{5a}$$

$$S_2(\lambda_l, \delta) = G(\lambda_l) I(\lambda_l, \delta) + Q(\lambda_l). \tag{5b}$$

In these equations N_1 and N_2 represent the column densities of $^3P^o$ Mg atoms with the dc current (0.8 A) and the pulsed current (10.5 A), respectively. S_1 and S_2 are signals recorded in the two halves of the PHA as described in Sec. II. The indexes α through δ refer to different firings of the xenon flashlamp. The median of each pulse height distribution of 100 counts will be denoted by a vinculum: $\overline{S(\lambda,\alpha)}$. Means of these medians over several pulse height distributions will be denoted by angular brackets: $\langle S(\lambda,\alpha)\rangle$. Values of $\overline{S(\lambda,\alpha)}$ ranged from 320 to 400 channels (with an average of 375), while the standard deviation of the distributions of $S(\lambda,\alpha)$ ranged from 9 to 12 channels (with an average of 10).

In order to determine if $Q(\lambda_l) = Q(\lambda_s)$, light from the flashlamp was directed through the reference beam of the interferometer, but not through the hollow cathode tube. This permitted us to evaluate Eqs. (4a) and (4b) with $N_1 = N_2 = 0$. Within the statistical uncertainties (cf. Sec. IV), $Q(\lambda_l) = Q(\lambda_s)$. Consequently, we assumed Q to be wavelength independent and adopted the mean of $Q(\lambda_s)$ and $Q(\lambda_l)$,

$\langle Q \rangle = 0.75 \pm 0.25$, as the value for $Q(\lambda)$. The uncertainty given is the uncertainty in the mean of the quantities involved.[16]

From Eqs. (4a) and (4b), we calculate the cross section:

$$\ln\left\langle \frac{\overline{S_1(\lambda_s, \alpha)}}{\overline{S_2(\lambda_s, \beta)} - Q(\lambda)} \right\rangle = (N_2 - N_1)\sigma . \quad (6)$$

The left-hand side of Eq. (6) has a numerical value of $(5.9 \pm 1.4) \times 10^{-3}$. The quoted uncertainty is that of the mean[16] of the quantity in angular brackets. The large fractional uncertainty is a consequence of the small absorption produced; the average decrease in intensity was 0.59%.

In order to find σ, we must know $N_2 - N_1$. The values shown in Table I are averages of measurements of the densities made from two hook spectra. The density was determined by using the multiplet $3p\,^3P^o$-$3d\,^3D$ at 384 nm. Results of recent calculations of the f value of this multiplet are summarized by Victor *et al.*,[17] who estimate that the value has an uncertainty of 5–10%. Both the value given by Victor *et al.*[17] and its uncertainty agree with those in the compilation of Wiese *et al.*[18] We have adopted the value of $f = 0.62$. The quantity N_2 is the sum of the values given in Table I. It was not possible to use the hook method to find N_1 because of the small values of Δ at this low density, but it was possible to set an upper limit of $N_1 \leq 1.5 \times 10^{13}$ cm^{-2}. Furthermore, measurements of the density at discharge currents of 5 A (pulsed) and 3 A (dc) are consistent with a linear dependence of metastable column density on discharge current. This dependence is also suggested by previous measurements of ground term densities in hollow cathodes made of other materials.[8] Consequently, we have used a linear extrapolation to arrive at $N_1 = 1.1 \times 10^{13}$ cm^{-2}. With this value for N_1, $\sigma = (46 \pm 12)$ Mb. The determination of the uncertainty is discussed in Sec. IV.

IV. UNCERTAINTIES

The uncertainties which arise in calculating σ from Eq. (6) are of two types: those on the left-hand side of Eq. (6), which are related to statistical fluctuations, and those in N_1 and N_2, which are caused by instrumental and measurement uncertainties. The first type may be calculated by using the measured properties of the distributions stored in the PHA, while the second may be estimated by the dispersion of measurements and on the basis of previous experience with hook spectra.[19]

The pulse height distributions, of 100 counts each, had a standard deviation of approximately 10 channels in 375. Thus, the median of the distributions had an uncertainty of approximately one channel ($10/\sqrt{100} = 1$). Eight to 13 pairs of distributions were used to determine $S(\lambda)$ and $Q(\lambda)$, so one would expect these to have uncertainties of approximately 0.3 channels ($1/\sqrt{13} \approx 1/\sqrt{8} \approx 0.3$). This agrees with the estimate of the uncertainty obtained by computing the uncertainty in mean[16] [cf. the uncertainties in $Q(\lambda_l)$ and $Q(\lambda_s)$ given in Sec. III]. The uncertainties quoted in Sec. III for $S(\lambda)$ and $Q(\lambda)$ are derived from the statistical properties of their medians $\overline{S(\lambda)}$ and $\overline{Q(\lambda)}$. These do not differ significantly from those calculated as outlined above.

Possible errors in N_2 stem from uncertainties in the measurements of Δ and K, and in the assumed value of f. The first two quantities were measured five times on two hook spectra. The uncertainties listed in Table I are standard deviations of the calculated N divided by $\sqrt{5}$ (i.e., uncertainty in the mean of N). The major source of uncertainty in N is in the measurement of Δ. The uncertainty in f has not been included in Table I. We have assumed this uncertainty to be 10% (cf. Sec. III). The resulting value of N_2 is $(1.41 \pm 0.17) \times 10^{14}$ cm^{-2}.

In order to compute σ, N_1 is also required. As discussed in Sec. III, the value of N_1 was calculated by a linear extrapolation to lower discharge current. We have taken the uncertainty in N_1 to be the difference between the results of this extrapolation and the upper limit placed on N_1 (cf. Sec. III), viz., 4×10^{12} cm^{-2}.

These uncertainties are combined to arrive at the value of ±12 Mb. Most of this uncertainty (11 Mb) is attributable to statistical fluctuations, i.e., uncertainties in $S(\lambda)$ and $Q(\lambda)$.

TABLE I. The measured column densities of atoms in the levels of the $3p\,^3P^o$ term of Mg, assuming a value of 0.62 for the oscillator strength of the $3p\,^3P^o$-$3d\,^3D$ multiplet. The uncertainties quoted do not include the possible error in f.

Level	$N(10^{13}$ cm$^{-2})$
$3p\,^3P_2^o$	7.9 ± 0.5
$3p\,^3P_1^o$	4.9 ± 0.5
$3p\,^3P_0^o$	1.3 ± 0.3
Sum	14.1 ± 0.8

V. DISCUSSION

Measured and calculated values of the $3p\,^3P^o$ photoionization cross section are listed in Table II. It is evident that experiment and theory are not in accord. This discrepancy between the results of the quantum defect theory and of the measurements is not unexpected in view of the approximations made in arriving at the former. The value of Bötticher[3] is corrected by using $f = 1.7 \times 10^{-2}$ for the transition $3p\,^3P^o$-$5s\,^3S$, rather than the val-

TABLE II. Measured and calculated values for the $3p\ ^3P^o$ photoionization cross section at 248.6 nm.

Investigator	Method	σ (Mb)
Travis and Matsushima[a]	Quantum-defect-theory calculation	20
Peach[b]	Quantum-defect-theory calculation	17
Bötticher[c]	Emission measurement	35[d]
This work	Absorption measurement	46±12

[a] Reference 1.
[b] Reference 2.
[c] Reference 3.
[d] Corrected using a revised f value; the uncertainty in the absolute cross section is estimated to be 25–50%, i.e., 9–18 Mb (cf. Sec. V).

ue $f = 1.85 \times 10^{-2}$ assumed by him in deducing the cross section from his measurements. This f value is not well established: There has only been one measurement[20] of $f = 1.7 \times 10^{-2}$, while calculated values range from $f = 0.78 \times 10^{-2}$ by Warner[21] to 1.68×10^{-2} by Victor.[17] Wiese *et al.*[18] recommend 1.7×10^{-2} but assign an uncertainty of 25–50%. Thus, although Bötticher's[3] estimate of the uncertainty in the cross section relative to this f value is only 10%, the possible error in the f value leads to a larger uncertainty in the absolute cross section. Our measurement relies upon an f value that is much better established, although our measurement uncertainties of ±26% are greater than those of Bötticher.

The Mg $^3P^o$ photoionization cross section is of some astrophysical significance (cf. Sec. I). A recent solar model[4] assumes 37 Mb at 248 nm; nevertheless the model cannot account for all of the opacity in the wavelength region 207–251 nm. The larger cross section found in this work leads to better agreement of solar models with observations.

ACKNOWLEDGMENTS

The authors are grateful to B. Cardon, L. Gardner, R. Knight, V. Kwong, and G. Lafyatis for their helpful suggestions and advice. We are indebted to D. Smith for the design and construction of several electronic components, and to J. Crawford for the design of the hollow cathode tube. We acknowledge the assistance of H. Griesinger and E. Thompson with the data acquisition electronics. Several discussions with J. R. McNeil concerning operation of the hollow cathode tube proved invaluable. We also are grateful to J. Esmond, N. Galluccio, A. MacKenzie, W. Menzi, and W. Millikin, Jr. for their technical assistance. This work was supported, in part, by the National Aeronautics and Space Administration under Grant No. NGL 22-007-006.

*Present address: National Bureau of Standards, Washington, D. C. 20234.

[1]L. D. Travis and S. Matsushima, Astrophys. J. 154, 689 (1968).
[2]G. Peach, Mem. R. Astron. Soc. 73, 1 (1970).
[3]W. Bötticher, Z. Phys. 150, 336 (1958).
[4]J. E. Vernazza, E. H. Avrett, and R. Loeser, Center for Astrophysics Report No. 1308 (unpublished); Astrophys. J. Suppl. Ser. 45, 619 (1981).
[5]M. C. E. Huber, R. J. Sandeman, E. F. Tubbs, Proc. R. Soc., London A 342, 431 (1975).
[6]G. G. Lombardi, P. L. Smith, and W. H. Parkinson, Phys. Rev. A 18, 2131 (1978).
[7]J. L. Kohl and W. H. Parkinson, Astrophys. J. 184, 641 (1973).
[8]G. G. Lombardi, P. L. Smith, and W. H. Parkinson, J. Opt. Soc. Am. 69, 1289 (1979) and references cited therein.
[9]F. P. Banfield, M. C. E. Huber, W. H. Parkinson, and E. F. Tubbs, Appl. Opt. 12, 1279 (1973).
[10]W. K. Schuebel, Appl. Phys. Lett. 30, 516 (1977).
[11]B. E. Warner, D. C. Gerstenberger, R. D. Reid, J. R. McNeil, R. Solanski, K. B. Persson, and G. J. Collins, IEEE J. Quantum Electron. QE-14, 568 (1978).
[12]W. C. Marlow, Appl. Opt. 6, 1715 (1967).
[13]M. C. E. Huber, *Modern Optical Methods in Gas Dynamic Research*, edited by D. S. Dosanjh (Plenum, New York, 1971), pp. 85–112.
[14]M. C. E. Huber and W. H. Parkinson, Astrophys. J. 172, 229 (1972).
[15]M. C. Huber and R. J. Sandeman, Proc. R. Soc. London A 357, 355 (1977).
[16]P. Bevington, *Data Reduction and Error Analysis in the Physical Sciences* (McGraw-Hill, New York, 1969).
[17]G. A. Victor, R. F. Stewart, and C. Laughlin, Astrophys. J. Suppl. Ser. 31, 237 (1976).

[18]W. L. Wiese, M. W. Smith, and B. M. Miles, *Atomic Transition Probabilities*, Vol. II (U. S. Government Printing Office, Washington, D. C., 1969).
[19]P. L. Smith and M. Kühne, Proc. R. Soc. London A 362, 263 (1978).
[20]A. R. Schaefer, Astrophys. J. 163, 411 (1971).
[21]B. Warner, Mon. Not. R. Astron. Soc. 139, 103 (1968).