Reprinted from APPLIED OPTICS, Vol. 10, page 34, January 1971

A Convenient Technique for Determining the Relative Quantum Efficiency of a Monochromator and Detector System

J. L. Kohl, L. J. Curtis, D. A. Chojnacki, and R. M. Schectman

A technique is described for determining the relative efficiency with wavelength of a monochromator and detector system using single photon detection. The method described utilizes a commercially available standard of spectral irradiance and provides a convenient, straightforward, and accurate technique for making the calibration, which is applicable over large ranges of wavelength and detector sensitivity. The calibration procedure has been designed to fill a need in atomic spectroscopy for a convenient method of determining the relative intensities of spectral lines in measurements which require single photon detection.

Introduction

In recent years, the technique of single photon counting[1–3] has proven to be extremely useful in detecting the low intensity radiation emitted by a variety of spectroscopic light sources.[4–6] Single photon counting leads to appreciable gains in the signal-to-noise ratio and also provides a method of determining the arrival time of a single photon to within a few nanoseconds.[7] Since this experimental information can be used to determine the mean lives of the upper energy levels of electric dipole allowed transitions in atoms, single photon detection is often used in such measurements.[8–10]

Because of the aforementioned advantages of the single photon counting method it is also desirable to use photon counting in measurements that require that the relative intensities (in photons $\sec^{-1}$) of various spectral lines of different wavelengths be known. In atomic physics, for example, a knowledge of the relative intensities of the spectral lines of the transitions out of an energy level and a separate measurement of the mean life of the level allows one to determine experimentally the absolute spontaneous transition probabilities or Einstein coefficients of each of these transitions.[11] Relative intensity information is also useful in making corrections to experimental values of the atomic mean life of an energy level which are introduced by cascade transitions into this level.[12,13]

It is, therefore, extremely useful to determine single photon relative efficiency vs wavelength calibrations of the optical systems and detectors used for these measurements. The present paper describes a convenient, straightforward, and accurate method for making calibrations of this kind using a readily available standard of spectral irradiance,[14] which has been used in this laboratory during the past year.

All authors were with the University of Toledo, Toledo, Ohio 43606, when this work was done; J. L. Kohl is now with the Harvard College Observatory.

Received 7 January 1970.

Experimental Arrangement

A schematic diagram of the apparatus for making the calibration is shown in Fig. 1. An Eppley Laboratory 1000-W quartz–iodine standard lamp (1) calibrated for spectral irradiance by the supplier against two NBS working standards is used as the calibration standard. It is calibrated at thirty-five wavelengths between 2500 Å and 26000 Å in milliwatts millimicron^{-1} centimeter^{-2} at 50 cm from the lamp along the optical axis. These units are easily converted to photons millimicron^{-1} centimeter^{-2} second^{-1}. The spectral irradiance of the lamp at the particular wavelengths of interest can be obtained by fitting the calibration points in that region of the spectrum to a power series using a standard computer program.

The combined optical system and detector to be calibrated, in the present case, consists of a Littrow mount grating monochromator (2), a lens and absorption filter (9), and a multiplier phototube operated as a single photon counter. However, the calibration methods described here are not limited to a particular type of monochromator.

When two photons cannot be time-resolved from each other by the detection system, only a single count results and the corresponding intensity is underestimated. Thus, intensity ratios can be accurate only if the measurements are carried out at equal counting rates or if a negligible number of photon coincidences occur. The latter procedure is much to be preferred and is adopted here. As will be described later, fast electronics are employed through the detection and counting system; the time resolution is ultimately

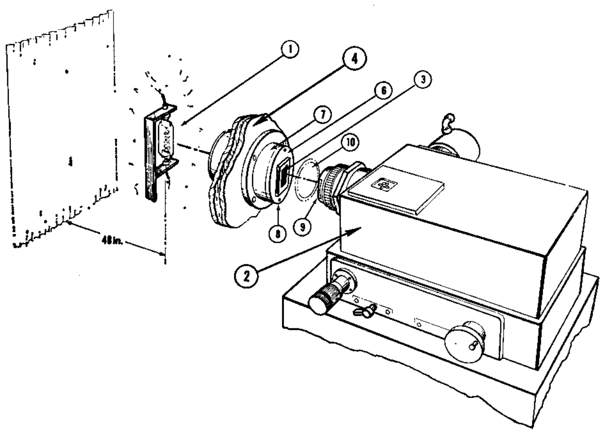

Fig. 1. Exploded view perspective of the experimental arrangement.

limited by the 10-nsec pulse pair resolving time of the scaler which records pulses resulting from photon detection. Since the fraction of these pulses which will overlap within a resolving time τ is $2R\tau$ (R denotes the average counting rate), the error due to random coincidences will be less than 1% if the average counting rate does not exceed 5×10^5 pulses sec^{-1}. In this measurement, counting rates are limited to values less than 2×10^5 counts sec^{-1}.

In the present work the output of the Eppley standard of spectral irradiance is much larger than will meet this counting rate requirement, so it is necessary to reduce the effective output of the lamp by several orders of magnitude. The reduction is accomplished[15] by introducing two inconel neutral density filters (3) between the lamp (1) and the optical system (2) (see Fig. 1). To avoid scattered light from the standard lamp at the entrance of the optical system that is to be calibrated, the lamp and optical system are placed in two dark rooms separated by a two-walled partition (4). A circular hole, which acts as a baffle, is cut in each wall and has its center on the optical axis. The neutral density filters (3) are permanently mounted in holders (6) and a filter holder mount (7) is secured to each wall. The outer ends of the holder mounts are beveled so that the filters are tipped at $\pm 16°$ with respect to the optical axis; the neutral density filters and holders are made to attach to the holder mounts with dow pins (8) so that they can be removed and replaced without disturbing their orientation or position. To eliminate overlapping orders in the monochromator, various color filters (9) are used. An ordinary Polaroid filter (10) is used to select the proper polarization component, and a lens (9) is used to focus the light beam onto the entrance slit of the monochromator (2), which selects the wavelength band desired. After leaving the exit slit of the monochromator, the light impinges on the photocathode of the photoelectric detector. In general, the gain and quantum efficiency may vary considerably over a photocathode surface, and it is often necessary to introduce diffusers between the exit slit and the detector. However, the ITT 4034 multiplier phototube used here incorporates design features which minimize this effect, making such a procedure unnecessary. The tube contains an electron lens which forms an image of the cathode on an aperture plane immediately preceding the first dynode. The aperture is chosen to be a 1-mm $\times$ 10-mm slit, and the tube is aligned so that only photoelectrons from the region of the cathode that accepts the light from the image of the monochromator exit slits reach the dynode. Thus, the same small area of photocathode is always used to view the monochromator, and electrons from this area always arrive at the center of the first dynode. The result is a relatively uniform variation of cathode efficiency over the small region employed. Measurements of efficiency along the slit show about 3% local variations from the mean value. The standard lamp is placed in the lamp holder and is aligned according to the manufacturer's recommended procedures. A black cloth (11) is placed 122 cm behind the lamp to reduce reflections.

The electronic circuit for the calibration is shown in Fig. 2. The lamp power supply (1) is an Eppley power supply, which contains a Hallmark Standards Inc., Model HAC standard current meter. The line voltage is controlled by a Sola constant voltage transformer (2). The detector employed here, the ITT Model multiplier phototube (7), has both a very fast rise time (less than 1 nsec, 10–90%) and a very low dark current (less than 10 counts sec^{-1} at 18°C with a discriminator setting corresponding to about 85% single photon counting efficiency). The output of the detector is sent to a fast leading-edge discriminator [Ortec Model 260 Time Pick-off Unit—(4)] which then furnishes a standardized 2-nsec wide pulse to one input of a dual 100-mHz scaler [Chronetics Model 100 nanocounter—(5)]. The time jitter for the multiplier phototube and the time pick-off together is less than 3 nsec. The output of the time pick-off unit is fed into one of the inputs of the Chronetics Model 100 nanocounter (5). The signal from a 60-Hz mercury switch pulse generator, which serves as a clock, is fed into the other input of the nanocounter. The two inputs are scaled simultaneously so that the number of single photon counts and the time can be recorded for each trial.

Figure 3 illustrates the way that the filter configuration is used to reduce the effect of scattered light to a negligible level. The filters are oriented at $\pm 16°$ with

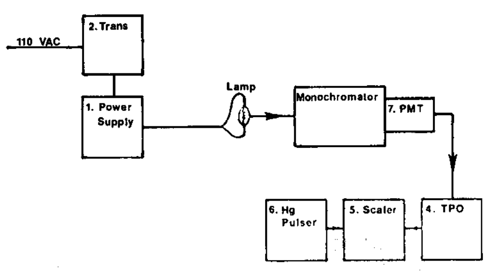

Fig. 2. Schematic diagram of the electronic circuitry used for the calibration.

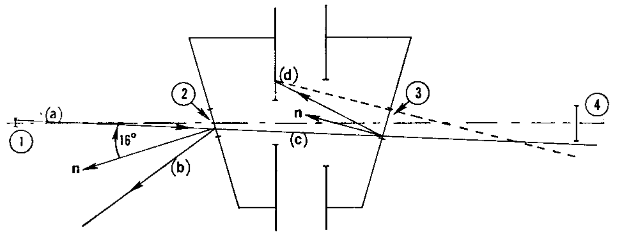

Fig. 3. Schematic diagram of the neutral density filter configuration.

respect to the optical axis and are separated by 15 cm in order to eliminate direct reflections between the filters. The walls of the cavity are coated with a good optical black material such as Eppley-Parsons optical black lacquer with a reflectivity of less than 2%.

Figure 3 shows a typical incident ray (a) from the lamp (1) which impinges on the filter (2) and may be reflected (b) or transmitted (c). The transmitted ray impinges on the second filter (3) and may be reflected, striking a black surface at the point (d), where it is 98% absorbed. The geometry is such that it is not possible for any directly reflected ray from point (d) to be accepted by the lens of the optical system (4). Further examination of Fig. 3 discloses that no rays other than those passing directly through the two neutral density filters will be accepted by the lens without undergoing at least two reflections from the black surfaces. Scattered light accepted by the lens (4) is therefore reduced by at least a factor of 4×10^{-4} below the intensity of the directly transmitted rays.

The transmission of a so-called neutral density filter does, of course, vary with wavelength. The transmission is also found to depend on the polarization of the incident light. Therefore, the filters must be calibrated for transmission as a function of wavelength for both the vertical and horizontal polarization components. Also, because of the small transmission of the combined filters (approximately 1×10^{-5}), it was convenient to calibrate the filters separately. The neutral density filter calibration does not require a standard lamp because the transmission is determined for one wavelength at a time. The standard lamp is therefore replaced by a uncalibrated lamp for the neutral density filter calibration. The ratio of the signal counting rate with the neutral density filter in place to the counting rate with the filter removed is a measure of the transmission of the filter for a particular wavelength, component of polarization, and filter orientation. For a three-density filter, a 200-counts $\sec^{-1}$ rate was used with the filter in place. This resulted in a signal-to-dark count ratio of greater than 20. With the filter removed, the rate was approximately 2×10^5 counts $\sec^{-1}$, which satisfies the maximum count rate requirement described earlier. The actual measured transmission at a given wavelength was found to be independent of count rate, provided the maximum rate did not exceed the prescribed limit. This method of neutral density filter calibration is independent of both the polarization of the light source and the changes in the efficiency of the optical system with polarization. Because the orientations of the filters eliminate any interdependence of their transmissions, and because all counting rates in the measurement are small enough so that accidental coincidences are unimportant, the total transmission of each polarization component for the set is just the product of their individual transmissions. This assumption was tested experimentally at several selected wavelengths and the results agreed to better than 1%.

It is well known that the efficiency of a grating monochromator depends on the polarization of the incident light, and that calibrations of this kind must take this fact into account.[16] The relative polarization efficiencies of the instrument at each wavelength for the perpendicular and parallel polarization components of the incident radiation are easily determined using an unpolarized light source and a Polaroid filter. The symbol F_λ will henceforth be used to represent the ratio of the efficiency of the perpendicular component to that of the parallel component for wavelength λ.

Data Analysis

After the data are taken, the following analysis is used to deduce the relative efficiency values. It is assumed that the efficiency of the optical and detector system and the output of the lamp are constant over the narrow wavelength band passed by the monochromator. The chief wavelength dependent geometrical factor which could cause difficulty with the present measurement is the change in the effective entrance aperture of the Littrow mount monochromator with the orientation of the grating. This effect can introduce significant errors in cases where either the standard light used for the calibration or the light from the spectroscopic source of interest does not completely fill the grating. This error can be reduced considerably by using a stationary grating mask between the collimator mirror and the grating which intercepts the light from the collimator that would otherwise miss the grating when it is turned at its largest angle away from normal incidence. Providing the spatial distribution of the light is not wavelength dependent, the fraction of the light from the collimator that is intercepted by the grating is now constant and no error is introduced. The total number of measured counts for any wavelength is given by

$$M_\lambda = E_\lambda d_\lambda (F_\lambda I_{\perp\lambda} + I_{\parallel\lambda}), \tag{1}$$

where E_λ is the efficiency of the optical system for the parallel (horizontal) polarization component of wavelength λ, d_λ is the reciprocal dispersion of plate factor of the monochromator at wavelength λ, and $I_{\perp\lambda}$ and $I_{\parallel\lambda}$ are the amount of light of each polarization component that is accepted by the optical system. They are defined by the equations

$$\begin{aligned} I_{\parallel\lambda} &= \tfrac{1}{2} T_{\parallel\lambda} R_\lambda G, \\ I_{\perp\lambda} &= \tfrac{1}{2} T_{\perp\lambda} R_\lambda G, \end{aligned} \tag{2}$$

where G contains only wavelength independent geometrical factors. $T_{\parallel\lambda}$ and $T_{\perp\lambda}$ are the product of the transmissions of the neutral density filters at λ for the parallel and perpendicular polarization components, respectively, and R_λ is the spectral irradiance of the lamp in photons millimicron^{-1} steradian^{-1} second^{-1}.

Solving Eq. (1) for E_λ and substituting Eq. (2), one obtains

$$E_\lambda = \frac{M_\lambda}{\frac{1}{2}R_\lambda d_\lambda(F_\lambda T_{\perp\lambda} + T_{\parallel\lambda})G}. \quad (3)$$

The efficiency of the optical system and the detector at λ for unpolarized light is given by

$$\mathrm{Eff}(\lambda) = (1 + F_\lambda)(E_\lambda/2), \quad (4)$$

and using Eq. (3)

$$\mathrm{Eff}(\lambda) = \frac{(1 + F_\lambda)M_\lambda}{R_\lambda d_\lambda(F_\lambda T_{\perp\lambda} + T_{\parallel\lambda})G}. \quad (5)$$

Since only the relative efficiency is desired, each of the Eff(λ) can be compared to the efficiency for a transition at any wavelength λ_0, and the relative efficiency factor for any wavelength is independent of G and is given by

$$R_{E\lambda} = \mathrm{Eff}(\lambda)/\mathrm{Eff}(\lambda_0). \quad (6)$$

Error Analysis

For the present calibration, the errors in $E_{R\lambda}$ were made up of an error in d_λ of about 1%, errors in $T_{\perp\lambda}$ and $T_{\parallel\lambda}$ of approximately 2% (i.e., 1% for the transmission of each neutral density filter), an error of 1% in $F_{p\lambda}$, and a quoted error in R_λ of 4.5% for wavelengths in the 3000-Å to 4500-Å region, 3% in the 4500-Å to 7500-Å region, and approximately 5% above 7500 Å. The errors in R_λ are for absolute spectral irradiance so that the relative values could be more accurate.

The calibration procedure which has been described is meant to fill a need in atomic spectroscopy and other fields for a convenient method for obtaining the relative intensities (in photons second^{-1}) of spectral lines from measurements that employ single photon detection. This technique is believed to be particularly valuable because it utilizes a well recognized and commercially available standard of spectral irradiance as the calibrated light source. The neutral density filters which have been used here to reduce the light level to the single photon range make it possible to calibrate optical and detector systems over large ranges of detector efficiencies. For example, in the present work, a filter transmission of approximately 1×10^{-5} was used at 6000 Å, while a transmission of only 1×10^{-2} was used at 8400 Å due to the differences in quantum efficiency of the S-20 photocathode and the dip in the reflectance of aluminum in the infrared.

This technique could also be modified for use in absolute calibrations of optical systems such as those necessary in the measurement of atomic excitation and emission cross sections.[17]

The authors wish to thank J. Ringlien and G. Buenning for their technical assistance, D. D. Eshbach and D. Shoffstall for the computer work, and E. H. Lawton for the diagram of the apparatus.

References

1. W. A. Hiltner, Ed., *Astronomical Techniques* (University of Chicago Press, Chicago, 1962), p. 23.
2. E. H. Eberhardt, Appl. Opt. **6**, 251 (1967).
3. J. P. Rodman and H. J. Smith, Appl. Opt. **2**, 181 (1963).
4. J. L. Kohl, L. J. Curtis, R. M. Schectman, and D. A. Chojnacki (to be published).
5. W. R. Bennett, Jr., and P. J. Kindlmann, Phys. Rev. **149**, 38 (1966).
6. W. S. Bickel, Appl. Opt. **6**, 1039 (1967).
7. G. A. Morton. Appl. Opt. **7**, 1 (1968).
8. L. Heroux, Phys. Rev. **153**, 157 (1966).
9. G. M. Lawrence, Phys. Rev. **175**, 40 (1968).
10. H. G. Berry, R. M. Schectman, I. Martinson, W. S. Bickel, and S. Bashkin (to be published).
11. W. L. Wiese, J. M. Bridges, R. L. Kornblith, and D. E. Kelleher, J. Opt. Soc. Amer. **59**, 1206 (1969).
12. J. L. Kohl, Phys. Lett. **24A**, 125 (1967).
13. J. L. Kohl, Ph.D. Thesis, University of Toledo, Toledo, 1969; J. Opt. Soc. Amer. **60**, 335 (1970).
14. R. Stair, W. E. Schneider, and J. K. Jackson, Appl. Opt. **2**, 1151 (1963).
15. An alternative approach is to use a standard of spectral radiance with a mirror and aperature system that spreads out the radiation of the lamp and selects a part of it to be used as a standard for extremely low values of spectral irradiance. [See R. Stair, W. B. Fussell, and W. E. Schneider, Appl. Opt. **4**, 85 (1965).]
16. D. C. Hammer, E. T. Arakawa, and R.D. Birkhoff, Appl. Opt. **3**, 79 (1964)
17. H. A. B. Gardiner, J. J. Merrill, W. R. Pendleton, Jr., and D. J. Baker, Appl. Opt. **8**, 799 (1969).