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MEASUREMENTS OF THE ABSOLUTE
FLUORESCENCE EFFICIENCY OF AIR
UNDER ELECTRON BOMBARDMENT

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**MEASUREMENTS OF THE ABSOLUTE
FLUORESCENCE EFFICIENCY OF AIR
UNDER ELECTRON BOMBARDMENT**

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ABSTRACT

Air at pressures between 10^{-1} and 10^{-2} mm Hg is excited by controlled electron beams of energies up to 1 keV. The light output is sampled as regards both geometry and spectrum, so that the total amount of light emitted and the fluorescence efficiency can be determined. This paper is concerned primarily with the emission of the 3914-Å (0,0) band of N_2^+ . Integration was done by three independent methods: (1) by using an optical integrating sphere in which the electron energy is deposited, (2) by sweeping a scanning detector around the glow, and (3) by sampling the glow produced in a transparent bell jar.

Calibrations are described in some detail. Among the disturbing influences in the work were the perturbing effects of very slow electrons. These are described but not thoroughly understood.

The results are in a preliminary state, but are as follows:

$$\eta_{\text{total}} = 1.8\%, \text{ from } 3000 \text{ to } 11,000 \text{ Å}$$

$$\eta_{3914} = 0.33\%.$$

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INTRODUCTION

When this work was initiated, a moratorium on the testing of nuclear explosives was in effect, and the detection of clandestine tests appeared to be of considerable importance to the world. While most of the publicized detection methods were related to earth-buried explosions (seismographic detection) or atmospheric explosions (microbarametric detection), less publicized effort was expended on the detection of explosions far out in space. This paper relates to this type of detection.

A nuclear device exploded well above the atmosphere is a very strong source of thermal radiation. After nuclear energy release, perhaps two-thirds of the total yield appears in the form of radiation in the wavelength range of 0.1 to 20 Å. On encountering the atmosphere in the process of absorption, the thermal x-rays create electrons which in turn dissipate their energy in further ionizations and excitations of the air constituents, with the release of light as the excited products decay. Collimated as well as all-sky systems have been designed to detect such light. The range of a practical detection system based on the use of this light depends on the fluorescence efficiency, η , of the electrons producing the light in the spectral

detection band of the system. Estimates of this quantity lead to a detection range for two different systems of $10^5 \sqrt{Y_x}$ km, where Y_x is the x-ray yield in kilotons, or in units of 4.2×10^{19} ergs.¹

From measurements on explosion "Teak" made at 76 km altitude (Johnston Island, 1958) in the 3914-Å band of nitrogen [the (0,0) transition in N_2^+ (IN)] a value for η_{3914} of 5×10^{-3} has been obtained with much uncertainty.² This result is very subject to error; intensity ratios of the observed band intensities were quite anomalous to what is known otherwise for them. This is now thought to be due to re-excitation of N_2^+ molecules by intense emitted 3914-Å (0,0) radiation and consequent redistribution of energy.

One can make a first guess of the value of η_{3914} from a very simple argument. A 750-volt electron created by an x-ray will make about 25 ion pairs in stopping, at the well-known 30 volts lost per ion pair formed. In a laboratory experiment, Stewart³ has determined that for each 50 ions formed one gets about a single excitation and emission of 3914-Å radiation, at 3 eV each. Thus, for 750 eV in, we get out about 1.5 eV in 3914-Å radiation for an efficiency, η_{3914} , of 0.2%.

Another simple estimate makes use of Stewart's measured collision cross-section curve and an electron range estimate made by extrapolating to low energies curves calculated at higher energies by Livingston and Bethe.⁴ For a 750-volt electron it is estimated that the range in air at 7.6×10^{-2} mm pressure (10^{-4} sea level density) is about 30 cm. This pressure corresponds to an altitude of 67 km. The collision cross

section, σ , for the production of 3914-Å radiation is about^{3,5} $3.7 \times 10^{-18} \text{ cm}^2$. Taking the number, n_{N_2} , of nitrogen molecules per cc at this altitude to be $2.2 \times 10^{15}/\text{cc}$, the number of collisions which lead to 3914-Å radiation is $\sigma n_{\text{N}_2} \times \text{Range} = 2.4 \times 10^{-1}$ for an eV output per 750-eV input of $2.4 \times 10^{-1} \times 3.1$ (eV per 3914-Å photon) = 0.76 eV, which gives $\eta_{3914} = 0.1\%$. Late in the work it was determined by measurement, in fair agreement with work reported in a paper of Lehman and Osgood,⁶ that this range is about twice too small, which would bring η_{3914} into approximate agreement with the first guess.

Because of the uncertainty in the all-important efficiency, some direct laboratory measurements were needed. This paper describes preliminary measurements of the quantity obtained during 1960-1961. In addition to tentative numbers from different approaches, considerable experimental detail is presented for the value it may have to others attempting absolute measurements of this sort.

METHODS USED

In a general way the problem of obtaining the fluorescence efficiency is simple, although in detail it is not. In principle, one injects a beam of monoenergetic electrons of known energy and numbers into air at a pressure appropriate to the altitude at which the efficiency is desired and then measures the absolute total light output over the spectral region of interest. If the interaction volume is small and the pressure low, so that the energy loss is small, excitation

cross sections may be obtained,⁵ and the fluorescence efficiency may be inferred from them.

Ideally, however, to simulate the detection situation, the injected beam should expend its entire energy in the volume seen by the detector and should be broad enough that few interaction products diffuse out of the beam. While a point emitter at the center of the volume would approach this, for various reasons it was decided to make use of pencil beams. Since one is interested in the limiting range of the detection system, one is concerned with threshold levels where, in all likelihood, secondary processes can be ignored, so that the use of broad beams is not as necessary as might be imagined.

Since most of the electrons injected into the atmosphere from a nuclear blast above the atmosphere have energies of a few kilovolts, which energy is largely expended at altitudes of from 60 to 100 km, the laboratory measurements were planned at appropriate pressures and at energies of up to 4 keV. On the basis of the best estimates of expected ranges, which turned out to be low, the scale of the apparatus was fixed at about one cubic meter, in a container somewhat longer than broad.

The system finally constructed allowed use of either of two methods for the integration of the light output. In the first, an optical integrating sphere may be used into which the electron beam is injected and in which the energy is all spent. Relative measurements are simply made by looking into the sphere at a wall in line with which

no direct glow is observed. To obtain absolute light output, both the sphere response and that of photodetectors are involved. In the second method, the integrating sphere is removed from the vacuum chamber, the walls of which are made black to simulate space. Around the glow produced by the injected electrons, and along a prime meridian, the plane of which contains the beam as axis with the beam entrance orifice as one pole, a detector is swung to sample the output as a function of latitude, as indicated in (d), Fig. 1. The beam energy and gas pressure are such that the entire glow is contained within the sphere defined by the scanning circle. From such sampling and after calibration of the detector, it is easy to obtain the whole light output.

Both methods presented difficulties. In the first method, the principal difficulty comes from the charging up of the interior, diffuse-reflecting surface of the sphere, which is of MgO and highly insulating. Such charging leads to ambiguity in the knowledge of the beam energy and to uncertainty in the beam current, even though the sphere connected to ground through a current meter should make an ideal Faraday collector. The second method is free of wall-charging effects but presents the problem of designing into the "scanning" detector the necessary cosine response such that the only parameter reducing the signal for radiation coming into its entrance aperture at a large angle is the projected area of the aperture. Current measurement here involves swinging a small Faraday cage into the beam. In both methods, current was also measured by running the entire gun "off-ground" and using a meter in the ground

Fig. 1 Procedures used in determining the light output (a) from the glow in the bell jar, and the spectral distribution (b) and (c) in that glow. (d) Glow sampling in the large scanning system.

side of the supply, but any method of measurement of the incident electron current may be in error if there is appreciable back-flow of positive ions along the potential trough created by the incoming electrons. Losses to the walls of products which might otherwise contribute light to the overall glow should be minimized. To help reduce such losses from charged products, the application of a magnetic field was provided, making possible also repetition of measurements of Meinel and Fan.⁷

A third method for determining the efficiency appeared possible after some preliminary work had been done in an ordinary glass bell jar to investigate guns, general light levels, current measurements, and the effects of insulating surfaces, to understand these problems, if possible, before they were encountered in the big system. It is useful to discuss this method in detail because it most conveniently points out the basic problems to be solved in determining the efficiency from any of the methods used.

It was found quite soon in the course of the bell jar studies that the appearance of the glow produced in the jar by an axial electron beam injected at one end was quite independent of the presence of a conducting surface around it. Thus the glow could be observed with only the glass wall intervening. At appropriate energies and pressures, while it might not extend to the far end of the jar, the glow would otherwise more or less fill the volume, with highest intensity along the beam direction fading away with distance from the entrance orifice.

The application of a weak magnetic field obtained with two Helmholtz coils placed around the jar very distinctly pulled the glow in well away from the walls. In this situation, the entire beam energy is assumed to be dissipated in the residual air enclosed, and if the total light output is known, together with the beam input, the efficiency can be obtained. One does this by sampling the glow with a detector located at a relatively large distance from it so that all points within the volume are essentially at equal distances from the detector. (This is necessary since, as will be noted later, the spectral distribution may be quite different in various parts of the glow.) Knowing what fraction the area of the detector is of the entire spherical surface centered on the glow and containing the detector, one can infer the total signal which would be produced if the detector totally surrounded the glow. With this conversion factor one can determine the total power radiated in the glow within the response band of the detector.

This last point, however, is somewhat complicated. The radiated energy from the glow is in a band spectrum over a broad range of wavelengths; the detector itself has a characteristic and individual response function; i.e., the microamperes produced per microwatt of incident radiation is a function of wavelength. It is thus obvious that one must ultimately know the average spectral distribution in the whole glow and the spectral response of the detector, on an absolute basis. In addition, to convert the detector signal to the power radiated when the detector is exposed to the whole glow, one must know the distribution

of detector signal level with wavelength when it is exposed to the average spectral distribution of the source. The procedures are indicated schematically in (a) and (b) of Fig. 1.

To do this one needs a spectrograph whose transmission is also a function of wavelength. Consider this determined, giving $\tau(\lambda)$ for the dispersing instrument. Consider also that one has determined the current produced in the detector under its "standard" operating conditions for each microwatt of power incident between wavelengths λ and $\lambda + d\lambda$, i.e., $r_{std}(\lambda)$ in $\mu A/\mu W$ vs λ . Let us make the situation more complicated, as was required in practice: the total glow is sampled by the detector operating at its calibrated and low, but "standard", sensitivity while the spectral distribution is taken through the spectrograph with the same detector operated at high sensitivity, since the signal is now so much smaller. The spectral response of the detector must not change with sensitivity. (This corresponds in practice to changing the photomultiplier voltage from the "standard" value used in its absolute calibration to a much higher value used when the spectrum of the glow is recorded.) Let the detector gain change between the two sensitivities be G (>1). If $i_1(\lambda)$ is the current the glow produces through the spectrograph (set at λ) from the detector used at its high sensitivity, and F_1 is the geometrical loss factor between the glow and the entrance aperture of the spectrograph (care being taken that no geometrical loss occurs in the spectrograph, not counting light diffracted into other orders in a grating instrument), then the power radiated at wavelength λ

in the interval $d\lambda$, (determined by the slit openings and instrument dispersion) is given by

$$dP_1 = \frac{i_1(\lambda)}{r_{\text{std}}(\lambda) G \tau(\lambda)} F_1 d\lambda$$

and the total power is

$$P_1 = \frac{F_1}{G} \int \frac{i_1(\lambda)}{r_{\text{std}}(\lambda) \tau(\lambda)} d\lambda . \quad (1)$$

Now $i_1(\lambda)$ vs λ may be a recorder trace of the glow spectrum. We divide individual ordinates on this by the appropriate product $r_{\text{std}}(\lambda)\tau(\lambda)$, plot this distribution, and integrate it with a planimeter.

We now want to know what total current, I_1 , this would have produced from the detector if the spectrograph transmission had been 100% throughout its range, to correspond to the situation when the open detector is exposed to the whole glow. We want

$$I_1 = \int \frac{i_1(\lambda)}{\tau(\lambda)} d\lambda .$$

This also we can get by dividing the recorder ordinates by the proper $\tau(\lambda)$, plotting, and planimentering.

Next we measure the whole glow at "standard" sensitivity and with, perhaps, a different geometrical factor, F_2 , between the detector and the glow. We obtain I_2 directly from the meter reading

where

$$I_2 = \frac{I_1}{Gk} \frac{F_1}{F_2} .$$

The constant, k (>1), is the factor by which the input beam current is reduced for this measurement from that required to give an adequate signal in obtaining the spectral distribution $i_1(\lambda)$. (Even though the detector is used at higher sensitivity, it may be that the ratio of signal current to dark current is otherwise too small in getting $i_1(\lambda)$, as was the case when using red-sensitive cells.) Thus

$$I_2 = \frac{F_1}{GkF_2} \int \frac{i_1(\lambda)}{\tau(\lambda)} d\lambda$$

or

$$\frac{F_1}{G} = kI_2F_2 \int \frac{i_1(\lambda)}{\tau(\lambda)} d\lambda$$

and the total power in this "whole" glow measurement is $P_2 = P_1/k$. This assumes no change in fluorescence efficiency and spectral distribution with beam current, which can be checked. So we have

$$P_2 = \frac{1}{k} \frac{F_1}{G} \int \frac{i_1(\lambda)}{r_{std}(\lambda)\tau(\lambda)} d\lambda$$

$$= I_2 F_2 \int \frac{i_1(\lambda)}{r_{std}(\lambda) \tau(\lambda)} d\lambda \bigg/ \int \frac{i_1(\lambda)}{\tau(\lambda)} d\lambda$$

$$= I_2 F_2 R$$

R is the ratio of the areas of the two planimetered curves above, obtained at any F_1 and G. Thus $i_1(\lambda)$ need not be obtained under conditions at which I_2 is obtained, provided F, G, and k are all independent of λ .

The ratio of P_2 to the input power is the fluorescence efficiency over the wavelength region taken. One can get the efficiency in particular spectral bands by taking the ratio of the relative areas over these bands (in the reduced power distribution vs λ) to the total area.

The general procedure outlined was also followed when the two methods planned for the big system were put to use. In the scanning method, the detector is regarded as the actual photo element plus the optical feed required to give it the necessary cosine response. To determine the spectral response of this detector to the glow, one mounts the combination at the exit slit aimed at the whole glow, either in the bell jar (as typical) or in the open port of the optical integrating sphere that encloses the glow in the big system. Similarly, the relative response function of the big sphere and its photodetector must be determined for the whole glow. In addition, the absolute response

of both detector systems must be determined. With these parameters, the reduction is similar to that described above.

In principle, one can get the efficiency directly by taking the result of Equation (1) and dividing by the input power used in getting the $i_1(\lambda)$ distribution. This procedure has not been very satisfactory, particularly with red-sensitive photomultipliers. However, simply as a practical matter, one would rather determine the ratio R once and not have to go through the entire reduction and spectral scan for every change of an input parameter, unless of course the spectrum changes. Indications are that no appreciable overall change occurs when parameters are altered.

Another way to proceed is to expose a detector to the fluorescent glow only over the small wavelength range defined by an interference filter of known pass band, and to determine the efficiency only over this band, the important one at $3914 \text{ \AA}$, for example. The absolute light output is determined by comparison of the response of the detector-filter combination to the glow from a known distance to its response at a known distance to the radiation from a standard ribbon filament of known geometry and temperature. To obtain the total efficiency from this, then, one needs to know the overall spectral distribution as outlined previously. The method, indicated in Fig. 2, is sound in principle and was used, but only results made with nonred-sensitive photodetectors are considered reliable.

The difficulties in each of these last alternatives will be dealt with when the calibrations are discussed.

Fig. 2 Procedures used in determining the energy in the $3914\text{-}\text{\AA}$ band of N_2^+ .
The bell jar glow is used.

APPARATUS AND INSTRUMENTATION

The general design of the large apparatus is indicated in Fig. 3. The measurements were carried out in a spherical volume somewhat less than a meter in diameter within the vacuum vessel. This was of non-magnetic stainless steel, except for the steel end covers which served to make more uniform the magnetic field provided by the coils around the outside of the vessel. Fields of up to about 100 gauss could be maintained over the region. The main tank has several quartz observation windows; a cover plate on the bottom with openings for rough pumping, a vacuum gauge, the electrical connection to the integrating sphere, and an air leak to establish the pressure within the volume; and a cover plate on top which carries the seal and rotating arm moving the scanning detector around the glow.

The pump on the right in Fig. 3 pumps on the tank directly and was used only when the integrating sphere was installed, to provide another stage of differential pumping between the sphere and the gun orifice. It served no purpose with the scanning system; in fact, with either system, air had to be leaked into the interaction volume to maintain adequately high pressure. The pump on the other end maintains a low pressure in the gun and pumps only slowly on the main vessel through the beam orifice itself--a hole about 1.5 mm in diameter and 3 mm long. With a pressure of 100μ in the main tank, the gun pressure was about 10^{-4} mm; with the same pressure in the integrating sphere and using the second stage of differential pumping, the pressure in the gun was a few times

Fig. 3 The large apparatus. Both the integrating sphere and scanning detector are indicated although only one can be in place at a time. The Faraday collector may be used with either. With the sphere in place, the sealed leads and tubes in the bottom are sealed also to the sphere; with it removed, they communicate only with the inside of the tank.

10^{-5} mm. Thus, electron energy loss between filament and interaction region should be negligible.

The integrating sphere is of spun aluminum $\frac{3}{4}$ in. in diameter, made in two halves screwed together and sealed with Apiezon-Q. The viewing port into the sphere is vacuum sealed to the outside quartz window by means of a connecting Pyrex tube and an O-ring seal at either end. Thus, pumping from the sphere is also mostly through the electron beam entrance aperture. Valving in the roughing pump system allows pulling it down simultaneously with the main tank. The final vacuum is determined by the setting of the air leak and is determined absolutely with a McLeod gauge isolated by a liquid N_2 trap and monitored continuously with a CVC Autovac gauge.

The inside of the sphere was sprayed with a mixture of MgO , water, and carboxymethylcellulose of the consistency of house paint, more binder being used than is recommended by Walsh.⁸ The coating was not as pure white as is obtainable in an MgO -smoked surface. A few strips on the inside of the sphere were left uncoated to provide a surface at ground potential to drain off low-energy electrons produced in the glow. Despite this step, there was still difficulty in measuring the beam current.

The scanning detector is supported on its arm through an O-ring seal in the top of the tank located so that the detector swings around well outside the periphery of the glow--on a circle 28 in. in diameter, defining the sphere for this integration. The detector, a photomultiplier,

was enclosed in a container at the end of the arm and sealed off from the vacuum by a quartz window through which the photocell looked. After various unsuccessful attempts, the desired cosine response for the head was provided by a small integrating sphere placed over the end of the detector. A circular hole admits the light to the sphere, and the detector looks through another small hole at a baffle on the inside, the entire inside being heavily smoked with MgO by burning magnesium. The detector head and its response is indicated in Fig. 4. It is obviously not usable in the presence of the externally applied magnetic field.

While space was made available to incorporate a wide variety of guns, the only one used was a small three-electrode arrangement shown in Fig. 5. This consisted of a small loop of 0.010-in. tungsten wire located about $1/8$ in. back of a $1/8$ -in. hole at the vertex of a conical surface in an electrode which serves both as grid and focusing element. This electrode faces a flat surface containing the exit aperture in a ball, against which the whole gun is spring-loaded to provide a means to aim the beam along the system axis. The gun aperture and the sphere entrance orifice are made to align by a sleeve, well perforated to make for fast pumping of the space between them. Beam transmission from the gun into the sphere of up to about 60% was obtainable when the grid bias was adjusted for the optimum. Pulsed or AC measurements are feasible with the gun by the application of the appropriate voltage wave to the control element.

Fig. 4 The scanning detector and its cosine response to a point source at constant distance from the sphere opening but on a radius making a variable angle θ between it and the normal to the opening.

Fig. 5 Pencil-beam electron gun used in the large system. Only one of two aiming screws and associated springs is shown. The keying pins allow the gun to be aimed, but prevent its rotation.

Prior to any measurements, concern for the measurement of beam current led to the installation of a movable Faraday collector which could be swung in and out of the beam where it enters the interaction volume. In the integrating sphere, it was very awkward to install and was dispensed with after agreement with other methods was established. The entire gun assembly was insulated from ground to permit also measuring the beam current by a meter in the return lead of the gun power supply.

Gun filament light was no real problem, even with tungsten as the electron source. In the large integrating sphere, a small easily-obtained correction removed it and was simpler to make than to blacken a portion of the sphere opposite the gun. With the scanning probe, to avoid overloading the detector, it was only necessary to remove the detector voltage when the head was opposite the gun hole. The readings for the glow, both in this region and in that close to the gun and not accessible by the head, can be inferred by extrapolating data on either side into the region.

To simulate space when the scanning probe is used, the inside of the tank must be dead black. This was done by burning acetylene from a hand torch set to allow very little air to the flame, and simply painting the inside of the vacuum tank with it. The coating was a very rich black, but doubtless had a small remaining albedo which contributed some undesirable light to the measurements.

The detectors in all cases were photomultipliers--principally the EMI 6097S--selected for low dark current and useful over the spectral range of 3000 to 6000 Å. In some measurements on the glow out to 12,000 Å, the RCA 7102 infrared multiplier was used, in spite of its unavoidable high dark current. The principal dispersive instrument used was a Bausch and Lomb grating monochromator. This had a dispersion of 33 Å per mm and a focal length of 50 cm, working at $f/5$. A synchronous motor, fastened to the case of the instrument, was used to drive the wavelength drum with a rubber O-ring belt. Photodetectors could be mounted at the exit slit, the output being fed into a Varian recorder driven synchronously with the spectrometer scan drive.

In all measurements utilizing the spectrograph or in its calibrations, care was taken to insure that no light fell outside the ruled portion of the grating but that it was rather well filled with light, whether it was used with or without external optics. Uniformity of performance over the whole of the ruled area was never determined quantitatively. Certainly one could visually discern variations over its surface. This could be of importance where various parts of the grating diffract light from different regions of the glow, as in the case when the spectrograph is simply aimed at the bell jar glow, with no intermediate optics before the entrance slit.

BELL JAR STUDIES

Work was carried out in the bell jar and attempts made to simulate the conditions expected in the large system. The principal differences lay in the reduction by a factor of 3 in scale and the absence of any scanning detector system in the bell jar. It was otherwise, though much more crude in all respects, operationally quite equivalent. Vacuum operations were similar, although no second stage of differential pumping was provided for the integrating sphere, in this case simply an internal can insulated from ground. Injection current metering was similar, including the movable Faraday cup. While various guns were tried (including broad-beam injection from a photocathode source), the gun used in the measurements to be discussed was essentially that described earlier for the big system.

Agreement among the three methods of beam-current measurement--the Faraday cup, the internal can as collector, and the return lead of the gun supply--was quite reasonable until the internal can was smoked on the inside with MgO to simulate the conditions expected of the large sphere. While the visual effect on the glow was nil, the current indicated then by the internal can as collector was far below that shown by the other two indicators. In high-vacuum physics one might expect that no beam could be injected following wall charging by the initial electrons injected. Here, however, the system is nonconservative in the sense that the electron loses kinetic energy continually to the gas, not merely to a retarding electrostatic field. Thus, since

the discharge is essentially unaffected, the wall is charged only by low-energy electrons. This was demonstrated when it was found that the agreement with the other two modes of current measurement could be obtained if a grounded, vacuum-valve control rod passing through the can were entirely withdrawn, or if the top cover of the bell jar, to which the control rod was connected, were left floating. One assumes that low-energy electrons could not reach the charged insulating surface and were deflected in large numbers to the higher-potential rod, by-passing the current meter and reducing its reading. On this basis it was decided to leave some exposed metal in the MgO coating laid down on the inside of the large integrating sphere, mentioned earlier.

Because of the surface charging by low-energy electrons, the inner potential of the sphere must change over that applied to it, namely, ground. To investigate this, a movable hot Langmuir probe study was made of the potential distribution within the MgO-coated collector can. While the behavior of the probe in this discharge was not so clean as is expected in the plasma of the ordinary gaseous discharge, the indications from its use were that the potential of the volume was, perhaps, 10 volts below ground. (Current vs bias characteristics of the integrating sphere made later in the large system also indicate that the potential of its surface is less than 10 volts below ground.) Because of its uncertainty and small magnitude, no correction has been made for this, the beam energy throughout the work being taken as the accelerating potential across the gun.

The gun transmission here was also high as in the later big system, injected currents ranging from 200 μA to $10^{-3} \mu\text{A}$. Some of the high yield may have resulted from possible ion-focusing effects in the beam. These effects may still be present in affecting either the beam current reading or the energy of the beam. It is conceivable that an ion current could stream back along the potential trough created by the incident beam. In one or two instances it is possible that this effect was seen. If this were the case, one would expect the indicated current to be markedly different when the Faraday cup directly over the emergent beam aperture was used from that when the large can encompassing the confined glow was used. However, these two currents were very nearly the same when wall effects were eliminated.

From the very beginning, the bell jar was used to obtain the spectral distribution in the glow and to attempt actual measurements of fluorescence efficiency. By pointing the B. and L. monochromator without external optics at the fine pencil beam and again at the diffuse part of the glow, it was quickly learned that the spectral distribution was not the same in all parts of the glow. In any part of the glow the N_2^+ is the dominant spectrum, but the N_2 spectrum was relatively brighter in the diffuse outer regions of the glow than in the region of the sharply-defined, high-energy, primary beam, when compared to the N_2^+ spectrum. The ratio of the two spectra changes by roughly a factor of 2 between the two extremes, the variation resulting almost entirely from the decrease in the N_2^+ spectrum away from the primary beam.

When even a fairly weak magnetic field is applied by two Helmholtz coils around the jar, both spectra are observed to increase in the outer glow, while in the vicinity of the primary beam the increase is largely in the N_2 spectrum. (With the field available in the large system, the glow is much more closely confined and the beam becomes noticeably pinker than that with no field.)

Such results indicated that fluorescence efficiency measurements could be made with the bell jar by positioning a detector far enough from the glow to weight all contributions from it equally, if a spectral distribution of the whole glow could be taken from a similar distance. The latter is a stringent requirement since the glows were not bright, but with the light-gathering power of the B. and L. monochromator used and with high voltages on the photomultiplier detectors (plus refrigeration in cases where the infrared sensitive multipliers were used) many preliminary measurements on the efficiency were made, leading to a value which must be taken seriously.

Another interesting result obtained with the bell jar, was a rough range measurement. At 10^{-1} mm, beams of 400- and 600-volt electrons, for example, clearly did not reach the top end cover of the jar. Ranges could thus be estimated. Ranges obtained were roughly twice those used as the basis for the scale of the large system design and used in the simple estimate of the efficiency made in the "Introduction". The increased range meant some restriction in the high energies to which one could go for a given "altitude" in the final system.

... Another useful measurement, which has not been bettered in the large system, was a check on the linearity of light output as a function of input current. This was done on the whole glow as seen by an RCA 7102 red-sensitive photomultiplier over five orders of magnitude. In the "best" run, a strict linear dependence resulted. Other runs showed some departure from linearity, light increasing a little faster than the beam current---variations up to the 1.05 power of the current occurring--- as though some reexcitation takes place. But it is not at all certain that it actually does. Measurements taken later on the big system, while over a much smaller range of beam current, also gave a fairly linear dependence. Some typical results are indicated in Fig. 6. The bell jar runs extend over a greater range of input current than the others because of both the larger signals obtained and the lack of background filament light.

Considerable work was done with the bell jar apparatus in looking at the spectrum out to 11,000 Å with the red-sensitive multipliers. These devices have inherently high dark current so that refrigeration becomes necessary to detect weak signals, as was the case in some of this work.

CALIBRATIONS

Whatever one uses to isolate a spectral region of the glow, he must determine the transmission of the device to obtain quantitative results. For the monochromator, a convergent beam of monochromatic

Fig. 6 Light output vs beam current input. Curves are not all at the same input conditions. In the three bell jar runs at various pressures, the beam input was held constant. The reality of the turn upward at low currents is somewhat doubtful.

light is focused onto the entrance slit, a detector is placed at the exit slit, and the grating is set for the appropriate wavelength. Then the same monochromator is placed in the incident beam, and the ratio of the two readings gives the transmission. This is indicated in Fig. 7 (a) and (b). To avoid trouble from variations in sensitivity across the detector's sensitive surface, care was taken to insure that the area illuminated was a large fraction of the whole by locating it well ahead of or behind the focused monochromatic images. The f-ratio of the incident light cone was always made to match the grating optics, and care was taken to insure that the grating was well filled with light. If there is a large variation in efficiency across the surface, such precaution will not eliminate error that may enter when an extended glow having wide spectral intensity or spectral variation across it is projected onto the grating.

For the transmission determination, the first monochromatizing was accomplished with a Perkin-Elmer spectrophotometer, their "Spectracord", which employs a double monochromator. The chopper was cut off, and mirrors installed to turn the monochromatic beam out of the instrument into a dark room and onto a 6-in. concave mirror. A small diagonal mirror turned the focused light from this out of the light path so the various units could be used at the final focus. For measurements from 11,000 to 4500 Å the initial source was an incandescent lamp, but below that a mercury source was used-- an H-4 lamp with the glass envelope removed. While intense line radiation

Fig. 7 Procedures used in determining the monochromator transmission by measuring incident monochromatic light (b) and that emerging from the instrument when it intercepts that light in (a). By measuring the absolute energy of the light in (c), one has the detector response from (b), for either the bare photomultiplier or the cosine detector.

from this lamp is rather nicely distributed, it is not an ideal source. There are variations of intensity with time, due both to change in operating conditions and to wandering of the arc in the capillary. Because one could not take both the incident and transmitted measurements at a single wavelength simultaneously (the inherent advantage of the double-beam spectrophotometer), it became necessary to monitor the emergent light from the source monochromator. This involved another photomultiplier (again the RCA 7102, to make use of the far red). This was always run at low voltage and very conservatively. It was first used in the reference beam position of the Perkin-Elmer "Spectracord", but because of moderate temperatures in the instrument was moved into the cooler dark room and placed so as to receive a portion of the light falling onto the concave mirror. Because of continued difficulty in getting results to agree with those obtained with the incandescent light, it was found that the only reproducible way to monitor the output was to divide the beam with a beam splitter in the return beam from the concave mirror, as indicated in Fig. 7, using most of the light for measurements and a small fraction for monitoring. This avoided difficulty found when the monitor sampled light at the beam edge. Since the exit slit of the initial monochromator essentially performs a Foucault knife edge test on the optics of that instrument when used with a spectral line source, the monitor was likely to be illuminated with quite a different intensity from that illuminating the unit under test which was in a different geometrical part of the beam. With the beam splitter

arrangement, one obtained rather good agreement from the two initial sources. The final transmission curve for the monochromator yielded a transmission somewhat lower than that stated by the manufacturer but of similar shape.

While they are difficult devices to use in absolute photometry, photomultipliers were used as the detectors throughout the work. To lend stability, they were always operated very conservatively and data were not generally taken until the tubes had been operating for a considerable period immediately beforehand. Twice, a marked change in the sensitivity of one cell seemed to have taken place unaccountably. Some of the spread in the bell jar results is felt to be a result of such variation.

The detector response is obtained by locating a small monochromatic image from the double monochromator and concave mirror arrangement onto a thermopile (or couple) to measure the incident energy and to then obtain the photocell response to the same radiation, as indicated in Fig. 7 (b) and (c). One must keep photomultiplier currents low, and yet one needs high energies to get usable signals from the thermal element. This necessitates the use of known filters to reduce the radiation between the two measurements or the operation of the multiplier well below its normal voltage, for which reduction the gain change must be known. A sensitive thermal element has a very small receiver, and extreme care must be taken that all the incident radiation falls upon it. The most sensitive available for this work was the Hilger-Watts

Schwartz semiconductor thermocouple with a rating of $70 \mu\text{V}/\mu\text{W}$. The measured sensitivity was less than this and was obtained by exposing it to the radiation of a ribbon filament at known distance and at known temperature determined with a Leeds and Northrup pyrometer previously checked against a lamp calibrated by NBS. Correction for the emissivity of the filament was made on the basis of the standard work of deVos.⁹ Two instruments were used to read the thermocouple voltages--a Perkin-Elmer breaker amplifier driving a Varian recorder and a Kiethley millivoltmeter driving the same recorder. The spectral response curves for the multipliers used agreed with the published shapes quite well.

With the instrument and detector parameters known, one can determine the fluorescence efficiency by the method outlined earlier.

Results were not satisfactory in applying Equation (1) directly to obtain the radiated power in a glow, particularly with red-sensitive detectors. In this method, the pass band of the B. and L. spectrometer becomes critical, but because of the inherent poor image quality at the exit slit this is not so well known, in spite of actual measurements made on it. Further trouble arises from the need to effect a large gain change and consequent need to refrigerate the red-sensitive photomultiplier in obtaining the scan. The relative spectral response was assumed not to change in doing this, but it is not so clear that the absolute response does not. Effort made to check this was not entirely satisfactory. No values obtained in this way for efficiency are included in the summary of results.

Use of a narrow-band, 3914-Å interference filter to determine the fluorescence efficiency over this single band in N_2^+ was similarly unsatisfactory when used with the red-sensitive detectors. Care was exercised in calibration and use that the interference filter passed nearly parallel light, that it was tipped in angle to maximize its response to the band, that adequate blocking filters were interposed to eliminate harmonic wavelengths, and that the transmission pass band was adequately well known. Small but appreciable differences in the last were obtained, depending on what instrument was used as the spectrophotometer in the determination. The effectiveness of the filter outside the pass band is also questionable, for with a tungsten calibrating source, the radiation level rises rapidly toward the red, and the infrared detector has a very wide spectral range. Appreciable error can arise even if the transmission of the filter out of its pass band is only a small fraction of a percent, perhaps not even indicated in the transmission record made with the spectrophotometer. In spite of precautions, considerable variance resulted with this method using red-sensitive cells in deriving efficiencies from values obtained otherwise. With blue-sensitive multipliers, however, the method led to efficiency values sufficiently in agreement with those felt to be more reliable to warrant inclusion in obtaining the final values quoted for the bell jar work.

EXPERIMENTAL RESULTS

Bell Jar. It was with the bell jar that the only spectral distribution curves covering from 3000 to 11,000 Å were made. A plot of the spectral output corrected for the monochromator transmission and photodetector response is indicated in Fig. 8. Beyond 6000 Å, the first positive system of N_2 is revealed, and over the range scanned is found to contain roughly a third of the energy radiated. The complicated correction for the absorption of the bell jar Pyrex glass wall has not been made. If the bell jar were ever to be made a serious technique for measuring the fluorescence efficiency, a large, clear, fused-silica container would make this correction almost unnecessary, at least if measurements were confined to wavelengths well above 2000 Å. As it is, the Pyrex causes error only below about 3500 Å, which region, however, does include the strong 3371-Å band and those at 3309 Å and 3159 Å. Internal reflection is not a problem if the absorption loss is negligible, since what is lost from one portion of the vessel is gained in reflection from another oppositely-facing portion. Practically the entire spectral distribution shown is accounted for by nitrogen radiation. It was made with the RCA 7102 refrigerated and operated at high voltage, with the B. and L. monochromator positioned so that the whole glow was seen by the grating optics. Efficiencies obtained with the bell jar varied considerably among themselves and from the values obtained in the same apparatus with this multiplier back of a 3914-Å filter calibrated against the tungsten source as described earlier. These values had a very large

Fig. 8 Reduced power plot of the energy distribution observed for the air glow in the bell jar. The energy below 3500 Å is in error because of neglect of the bell jar glass transmission.

spread--as much as 3 to 1. The situation was much better when the EMI multiplier was used in this way.

The average of most reliable measurements made with the bell jar gave a fluorescence efficiency for the 3914-Å band of about 0.26%. From the spectral scan this appeared to be about 18% of the total energy radiated between 3000 and 11,000 Å, which thus gives a total efficiency over the region of about 1.4%. Relative measurements indicated a fair degree of independence of the efficiency from beam energy, the pressure at which it was measured, and, as indicated by Fig. 6, beam intensity.

Scanning System. Integration of the fluorescent light with the scanning system depends on the azimuthal symmetry of the glow. A slight deflection of the beam in the earth's field took place, but light readings on opposite sides of the glow along the scanning circle, as indicated in Fig. 9, gave reasonably close agreement. The average of the two readings was taken to integrate the light for a given zone.

After an extended period of measurement, when the system was opened to install the integrating sphere, the albedo of the black coating on the end of the gun was found to be definitely greater than the black previously laid down. This region is, of course, closest to the brightest part of the glow and so some error on the high side comes into the results. On the other hand, maximum back scattering of injected electrons occurs in this region, which tends to compensate.

The signals obtained with the EMI multiplier back of the cosine detector sphere were not large, the collection efficiency having been

Fig. 9 Scanning detector readings of current distribution around glow. Shown are the zonal contributions to the total light at increasing voltages. The deposition of the energy at greater distances (and larger angles) from the gun orifice as the electron energy increases is apparent. An actual current response curve from the detector is also given (dotted curve).

sacrificed in the interest of obtaining the response required. Of the light entering the sphere, about 0.5% reached the photomultiplier. It was nevertheless quite easy to obtain the absolute overall detector response in $\mu\text{A}/\mu\text{W}$ by shining in the focused monochromatic light in the calibration arrangement described, which light was then measured with the thermocouple. While quite awkward, it was then not difficult to obtain the spectral response of the unit exposed to the glow in the bell jar by mounting it on the back end of the scanning B. and L. spectrometer collecting light from the whole glow. The reduction then proceeded as outlined for the bell jar.

The efficiencies obtained with this unit averaged about 0.43% for the 3914-Å band. The spread was considerably less than with the bell jar; there, however, the techniques were being worked out and underwent considerable variation. During any one scan, the beam current and tank pressure were maintained constant. Linearity of light output over two decades of beam current was observed, as indicated in Fig. 6. It was not possible to obtain any measurements with this system when an external magnetic field was applied to the glow, since it drastically affected the photomultiplier.

Integrating Sphere. There were unexpected problems in the use of the sphere. Light output was high but did not vary in a systematic way with the injected current. Indicated currents could not be made as large by almost two orders of magnitude as previously; they decayed with time, and, strangely, depended very sensitively on the resistance

of the external metering circuit. It was surmised that slow electrons (again) were the difficulty and that the sphere surface was charging up until the only place which could be reached by slow electrons was the end of the gun alignment sleeve which projected slightly into the sphere and which was held at ground potential, albeit through a meter. It was found that a small bias of 22 volts between this and the sphere (the sphere positive with respect to the gun) brought the current up to expected levels. It became stable, and the light output became almost linear with indicated current. The actual injected current is still a question. As a function of the bias, the current rose sharply and then turned over, rising very slowly thereafter more or less linearly with the voltage. This linear region was extrapolated back to zero bias and the intercept taken as the injected current. Later, when the movable Faraday cup was installed to check the procedure, a 10% higher current was indicated. The values for efficiency here given, however, were obtained from the lower current values but were also uncorrected for the sphere bias voltage. It is not clear why the exposed metal strips inside the sphere did not serve better to draw off slow electrons unless an aluminum oxide film served the same function as the MgO in charging. It was not observed in the smaller can within the bell jar, however.

The optical quality of the integrating sphere was not the best. The whiteness was off, and the detector coupling was very small so that the sphere efficiency was only about 0.005% for delivery of light to the photomultiplier. In addition, a small source waved around on the

inside of the sphere was later reported to cause a variation of about 10% in detector output. This kind of test, however, has to be done judiciously; detector output is certainly better than this when used with a broad diffuse type of source represented by the glow. An internal baffle might have flattened this response. Correction for the gun filament light must be made with the integrating sphere, but this is easily done.

The reduction of the measurements to efficiency is similar to that described before and is indicated in Fig. 10. Using the same calibrated photomultiplier used to measure the integrated light in the sphere, a spectral distribution curve was run with the B. and L. monochromator looking in the port window at the inner sphere surface illuminated with the glow so that as much of the grating was filled with light as possible. The obtained integrated photocurrent distribution corrected for the monochromator transmission is thus proportional to the current seen by the detector when used alone at the window. The photocell sensitivity in $\mu\text{A}/\mu\text{W}$ of power radiated by the glow in the sphere, as a function of wavelength, was determined by projecting into the sphere (the gun having been removed and the apparatus being at atmospheric pressure) a widely diverging beam of monochromatic light from the monochromator, used with either a mercury arc or tungsten ribbon source, and taking readings on the photomultiplier at the observing port. The microwatts of light projected into the sphere was determined by the calibrated multiplier with the beam much reduced by neutral-density

Fig. 10 Determination of light output from the large integrating sphere. The spectral response of the detector to the glow is obtained in (a) so that when it is exposed to the whole glow in (b), one knows how to weight the reading to obtain the power output from the glow. One gets the absolute response of the detector as a function of wavelength by shining in monochromatic light of measured energy in (d) and measures in (c) the resulting response of the detector used in (b).

filters of known transmission characteristics, to keep the photocell currents at reasonable levels. Alternatively, one can use an uncalibrated multiplier to measure both the input light and the light observed at the port window to get the sphere efficiency. This can be combined with the known response and sensitivity of the photomultiplier used to measure the glow light to obtain the output current of that cell per microwatt of power radiated in the sphere at each wavelength. Both methods were used. As always, stable sources of reproducible light level were a requisite. These were again monitored as was necessary in calibrating the other detectors.

The results for the efficiency obtained from the integrating sphere were fairly consistent and fell between the results obtained for the other two methods. A value of 0.29% was obtained for the efficiency of production of the 3914-Å band.

Measurements of the efficiency in the presence of the maximum magnetic field available, made with the sphere and a shielded photomultiplier, indicate no great change in the value over that obtained with no field. Knowledge of the actual beam current injected here is rather less certain than in the previous situations because of the more rounded nature of the sphere current vs the sphere-to-gun bias characteristic. One point was established, however. A normal spectral scan was made through the sphere window without the field applied. When the field was applied, both the glow and apparent beam current were observed to increase. The voltage on the multiplier at the spectrometer exit

slit was reduced to make the $3914\text{-}\text{\AA}$ peak the same height as before, and a scan was again taken, with the result that the two scans appeared identical. Thus, if the magnetic field prevents lateral diffusion of charged products to the walls with possible light loss, it increases the light in all bands by the same ratio. This seems highly unlikely. Of course, the EMI multiplier used in this experiment only sees to $6500\text{ }\text{\AA}$. Also, charged particles could still diffuse out of the volume longitudinally to lose light from the system which would not be lost in the real atmosphere.

SUMMARY

The average of the various methods employed gives an efficiency for the $3914\text{-}\text{\AA}$ band of 0.33%. Taking the results of the infrared scan in the bell jar, which indicate that this band contains about 18% of the light, the overall efficiency in the 3000- to $11,000\text{-}\text{\AA}$ region of the spectrum is about 1.8%. The N_2 first positive system contains about one third of the total energy. These results hold for electrons of energy between a few hundred volts and about two kilovolts.

The measurements lead to a result about twice that inferred at the start. Part of this discrepancy is certainly because the ranges assumed in the predictions appear to be about twice too small. The crude range measurements made visually through port windows in the large system, where the end of the beam was fairly easy to observe, particularly with the magnetic field applied, also indicated that the early guesses were

too small. More recent and quantitative results with the large system are in agreement on this point, and, particularly for measurements in the 10- μ pressure region, are in fair agreement with the results of Lehman and Osgood.⁶ Measured ranges are about 10-30% higher than would be inferred from their curve. Taking these ranges as about correct, using the ionization cross-section curves for nitrogen as a function of energy (assuming the electron loss arises primarily from this mechanism), and combining these with the excitation cross-section curve, say for the 3914- $\text{\AA}$ transition, one calculates an efficiency, η_{3914} , of 0.214%, only about 6% higher than the simple first estimate.

In view of the many uncertainties involved in the work, it can be seen that the values arrived at should be taken with some degree of reservation. It has been hoped that the measurements would be refined in all aspects of the work here described to allow reaching a more definite value for the efficiency. The international situation has thus far prevented this, and, rather than delay further, it was considered advisable to publish the work in this preliminary state for the importance the number seems to entail for a variety of workers and for the interest expressed following an oral presentation.¹⁰

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